Development of New Lewis Acid-Catalyzed Reaction with Indoles as Nucleophiles

明治大学大学院理工学研究科

2013 年度

博士学位請求論文

Development of New Lewis Acid-Catalyzed Reaction with Indoles as Nucleophiles

インドール類を求核剤とする新規ルイス酸触媒反応の開発

学位請求者　応用化学専攻

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Development of New Lewis Acid-Catalyzed Reaction with Indoles as Nucleophiles

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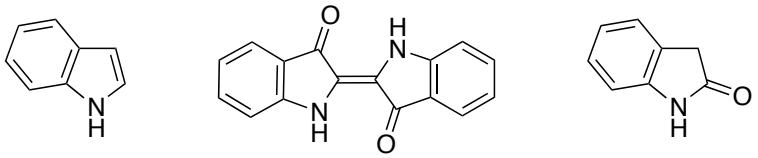
2013

Chapter I. General Introduction

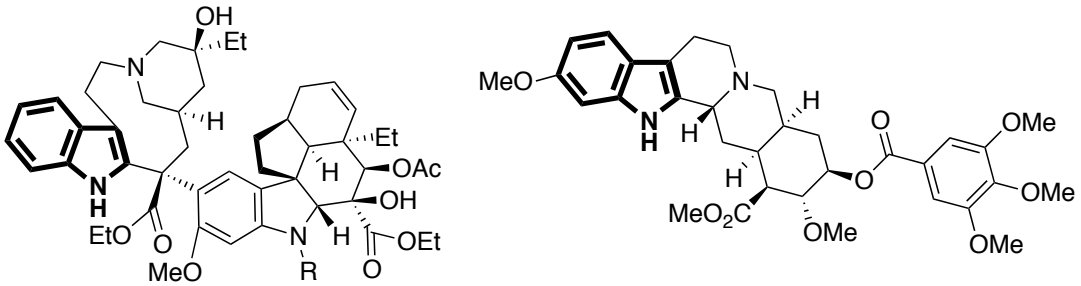
I-1. Historical Background

Indole is a heterocyclic aromatic organic compound in which a pyrrole ring is fused to a benzene ring (Scheme 1). The study of the chemistry of indole began with the study of "*indigo*", a natural dye with a distinctive blue color. Adolf von Baeyer, the recipient of the Nobel Prize in Chemistry in 1905, first prepared indole by zinc-dust distillation of oxyindole in 1866,[1] and later he assigned the structure of the compound in 1869.[2]



Scheme 1

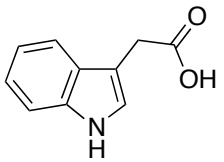
In 1952, the alkaloid reserpine, an antipsychotic and antihypertensive drug, was isolated from Indian snakeroot (*R. serpentina* Benth. ex Kurz.) (Scheme 2).[3] During the same period, the alkaloids, vinblastine and vincristine, the first plant-derived agents to advance into clinical use, were also isolated from the Madagascar periwinkle plant.[4] These are famous anticancer agents, also known as "vinca alkaloid". With the discovery of indole alkaloids indicating the interesting biological activity, indole derivatives have been attracted much attention in the field of medicinal chemistry.[5]



Scheme 2

Indole-3-acetic acid (IAA), the first discovered plant hormone, is one of the most important auxins (Scheme 3). In 1934–35, Kögl,[6] Thimann and Koepfli[7]

identified the structure of auxin as IAA.[8] Similar to all auxin, IAA also shows different effects such as inducing cell division and cell elongation that contribute to the growth and development of plants. Plants can synthesize IAA by several independent biosynthetic pathways. Four of those pathways start from tryptophan; however, there also exists a biosynthetic pathway which is independent of tryptophan.[9]



indole-3-acetic acid (IAA)

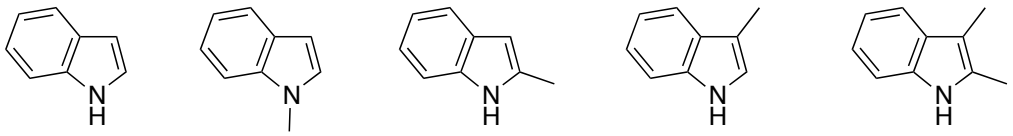
Scheme 3

About 140 years from the discovery, indole derivatives have been studied for their application in different fields such as dye chemistry, drug discovery, and botany. Indole has become an integral part in synthetic organic chemistry; different synthetic procedures or new reactions have been reported to use indole as a substrate.

I-2. Chemical Properties of Indole

I-2-1. Acidity of Indoles

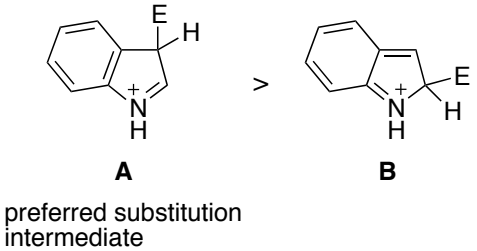
Indoles are very weak bases, but strong acids with typical pKa value –3.5, as reported by Hinman and Lang (Scheme 4).[10,11] Lower the value of pKa, higher is the acid strength. While there is a little decrease in acidity with 1-methyl substituent (–2.3), the acidity further decreases with 2-methylindole (0.28). On the other hand, a 3-methyl group increases the acidity of indole (–4.6), while a 2,3-disubstituted analogue decreases acidity (–1.5). The stabilization of the conjugate acid is the reason of the decrease in acidity in indole by 2-alkyl group substitution. In contrast, the increased acidity of the 3-alkylderivatives is attributed to the loss of stabilization when C3 is protonated and removed from conjugation. Similar trend is observed for many 5-substituted indoles.[12]



Scheme 4

I-2-2. General Reactivity of Indoles

In the unsubstituted indole, the 3-position possesses the highest nucleophilicity due to increased electron density and greater stability of the intermediate A compared to B (Scheme 5).[11]

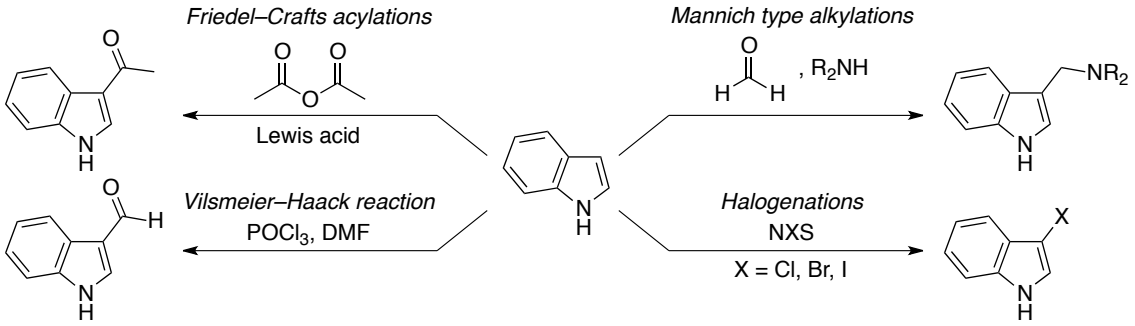


Scheme 5

Several studies have been carried out on relative nucleophilicity (*N*) by examining reactivity towards a series of benzhydryl carbocations.[13] It has been found

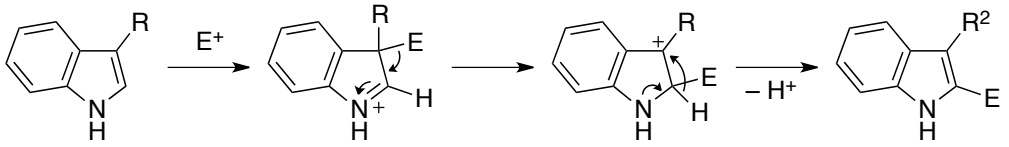
that the relative reactivity of indole is 5.55. The 1-methylindole (5.75) and 1,2-dimethylindole are more reactive than indole compared to 2-methylindole, which shows slightly less reactivity (4.42) due to its steric effects.[14] In a logarithmic scale, the results show that indole is approximately 15 times more reactive than pyrrole (4.63). A methyl group on N1 position of indole causes slightly enhanced reactivity while that on C2-position exerts a retarding steric effect toward this electrophile of about 20.[12] These results suggest a general order of reactivity of 1-methylindole > indole > 2-methylindole. However, the reference electrophiles are bulky and the 2-methyl group would be expected to show enhanced reactivity to smaller electrophiles. Actually, acid-catalyzed exchange at C3-position is approximately 80 times faster for 2-methylindole than for unsubstituted indole.[15]

Generally, the C3-position of indole is the typical site for electrophilic aromatic substitution reactions such as Friedel–Crafts acylations, Vilsmeier–Haack reaction, Mannich type alkylations and halogenations (Scheme 6).[16]



Scheme 6

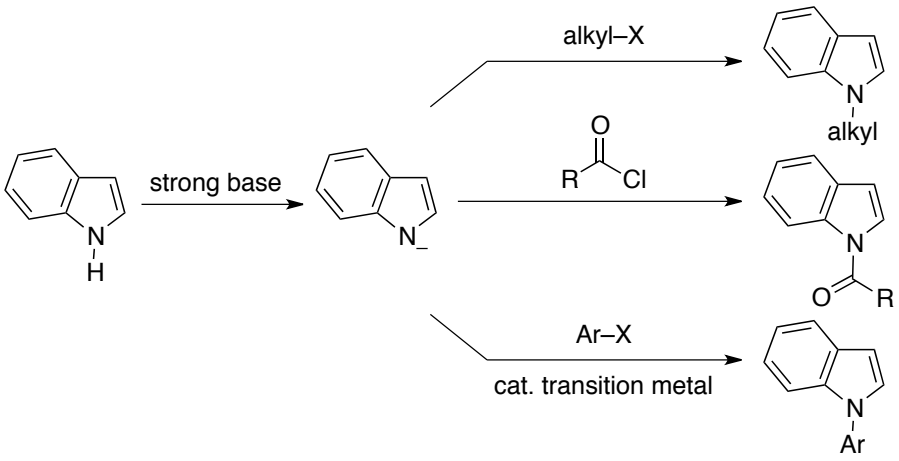
Electrophilic substitution at C2-position can be achieved even with the presence of a functional group at the C3-position. The reaction usually starts with electrophilic attack at C3-position, followed by Wagner–Meerwein rearrangement to produce the 2,3-disubstituted indole (Scheme 7).



Scheme 7

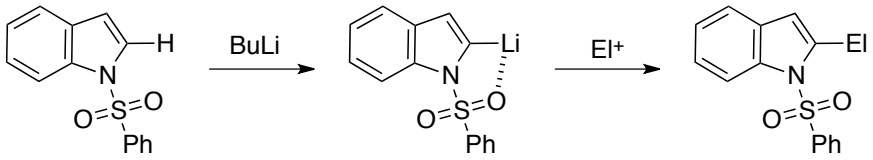
Strong bases allow to deprotonate the indole N–H, which is a weakly acidic

site (pK_a value ranging from 12.36 to 19.50 in water)[14] to give the indolyl anion. Therefore, substitution at the nitrogen can be achieved through base-promoted processes such as alkylations, acylations and, more recently, transition-metal-catalyzed arylations (known as "*Buchwald–Hartwig reaction*") (Scheme 8).



Scheme 8

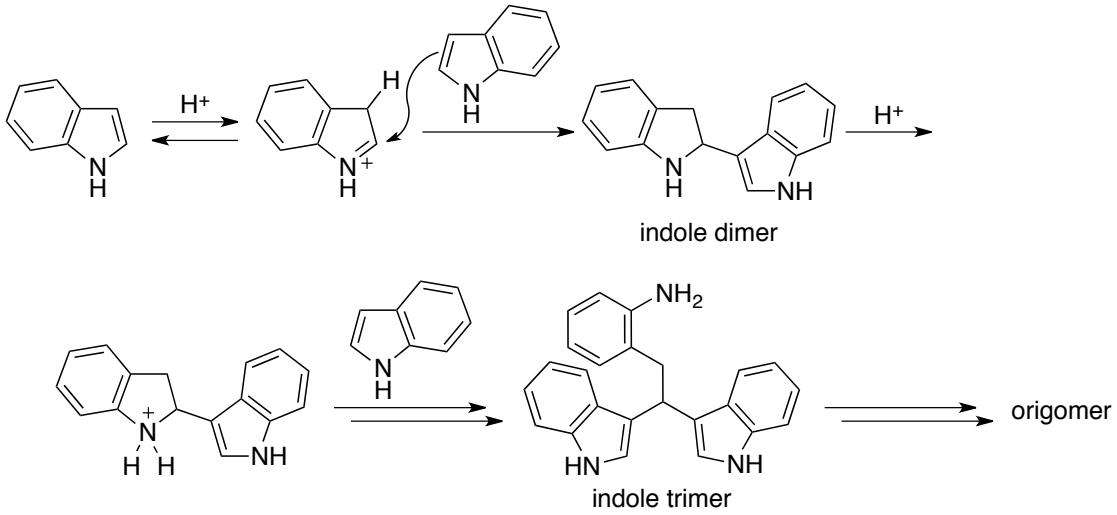
The most concise procedure of functionalization at C2 position is the heteroatom assisted metalation at C2 of *N*-acyl or *N*-sulfonylindoles, followed by reaction with an electrophile (Scheme 9).



Scheme 9

I-2-3. Protonation of indoles

Under various acidic conditions, it is known that indole forms a dimer, trimer and oligomer (Scheme 10). 3-Protonated indoles are easily exchanged to the dimer by electrophilic attack on other indole. The structure of the trimer, first proposed by Smith,[17] was later proven by synthesis.[18] Trimer results from acid-catalyzed opening of the indoline ring in the dimer, followed by an electrophilic attack on a second indole. The dimerization-trimerization process is evidently reversible in 0.5 M H_2SO_4. A composition of approximately 1:0.4:0.3 (indole:dimer:trimer) is reached from the indole, the dimer or the trimer.[19]



Scheme 10

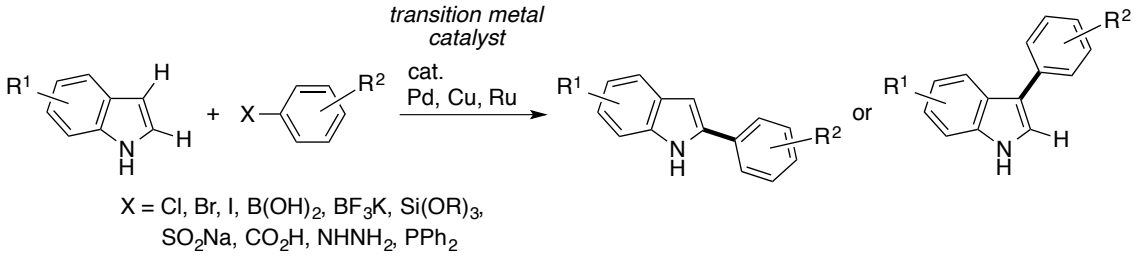
I-3. Metal-Catalyzed Transformation of Indoles

I-3-1. Transition-Metal-Catalyzed Functionalization of Indoles

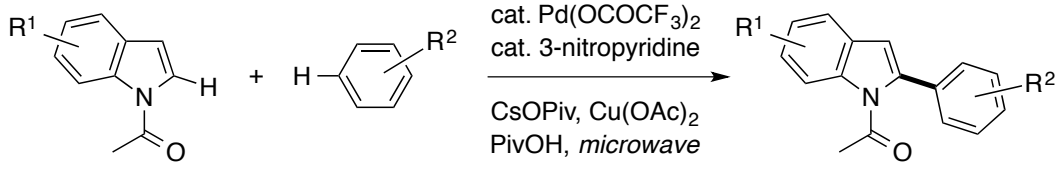
Recently, the development of transition-metal-catalyzed functionalization of indoles has attracted much attention. Among them, the methodologies, where N–H and C–H bonds of indoles have participated in the catalytic reaction, are excellent from both an environment friendly and atom-economical point of views. In this section, the author discusses the representative examples of the transition-metal-catalyzed direct functionalization reactions of indoles.

I-3-1-1. Direct Arylation of Indoles

Aryl-substituted indoles are an increasing demand in the field of materials science due to their extended π-conjugation. This has driven much attention towards direct arylation of indoles through transition-metal-catalyzed transformation reaction. In the following representative example, N-arylation of an indole ring can be achieved easily by the reaction with aryl halides in presence of a catalytic amount of palladium salts and base, and the methodology is known as Buchwald–Hartwig reaction.[20,21] In recent years, direct arylation of C2 and C3 positions of indoles using not only Pd[22] but also using Cu,[23] and Ru,[24] as the efficient catalysts has been reported (Scheme 11). In 2007, Fagnou and co-workers have achieved noteworthy success using unsubstituted arenes as coupling partner for direct arylation of indoles (Scheme 12).[25]



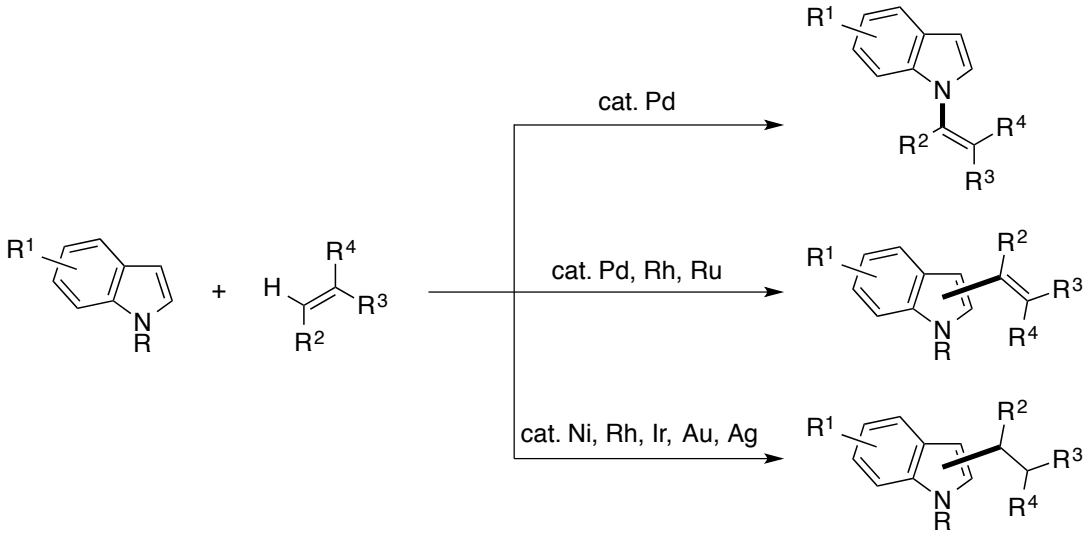
Scheme 11



Scheme 12

I-3-1-2. Reaction of Indoles with Alkenes

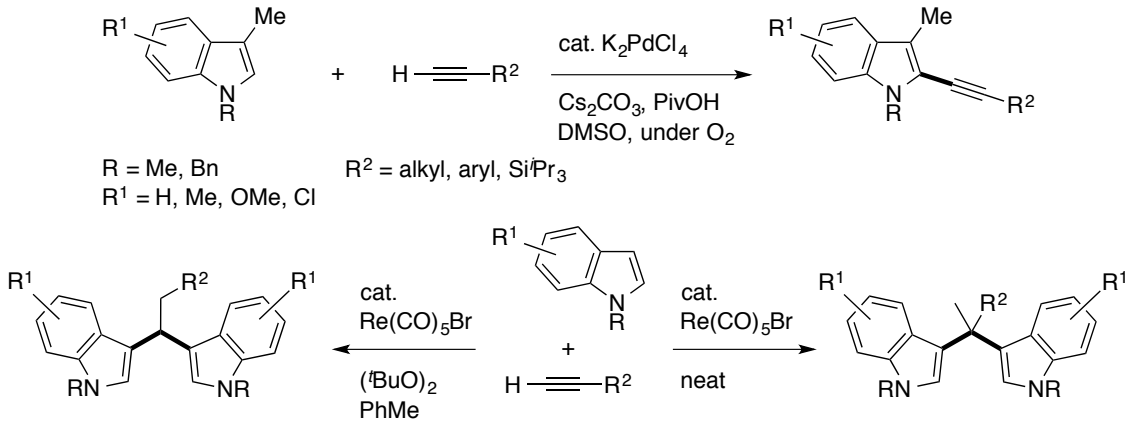
Direct functionalization of indoles catalyzed with transition-metal can be applied not only to aryl halides but also to unsaturated hydrocarbon molecules such as alkenes and alkynes. The oxidative coupling, a strong point in transition-metal-catalyzed reaction of indoles and various alkenes catalyzed by palladium,[26] rhodium,[27] and ruthenium,[28] have been reported to be the key for the success of N1, C2-, and C3-alkenylation reactions (Scheme 13). On the other hand, some examples exist where alkylation of indoles with olefins includes two processes, oxidative coupling and hydrogenation.[29]



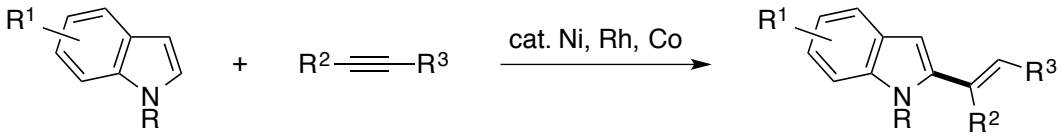
Scheme 13

I-3-1-3. Reaction of Indoles with Alkynes

C2-alkynylation of indoles via oxidative coupling with terminal alkynes have also been reported (Scheme 14).[30] Additionally, the synthesis of diindolylmethanes by the treatment of indoles with terminal alkynes under rhenium catalysis has been achieved by Wang.[31] Recently, catalytic alkenylation reactions of indoles via selective activation of a C2–H bond have been achieved using transition-metal catalysts such as Ni, Rh, and Co (Scheme 15).[32]



Scheme 14



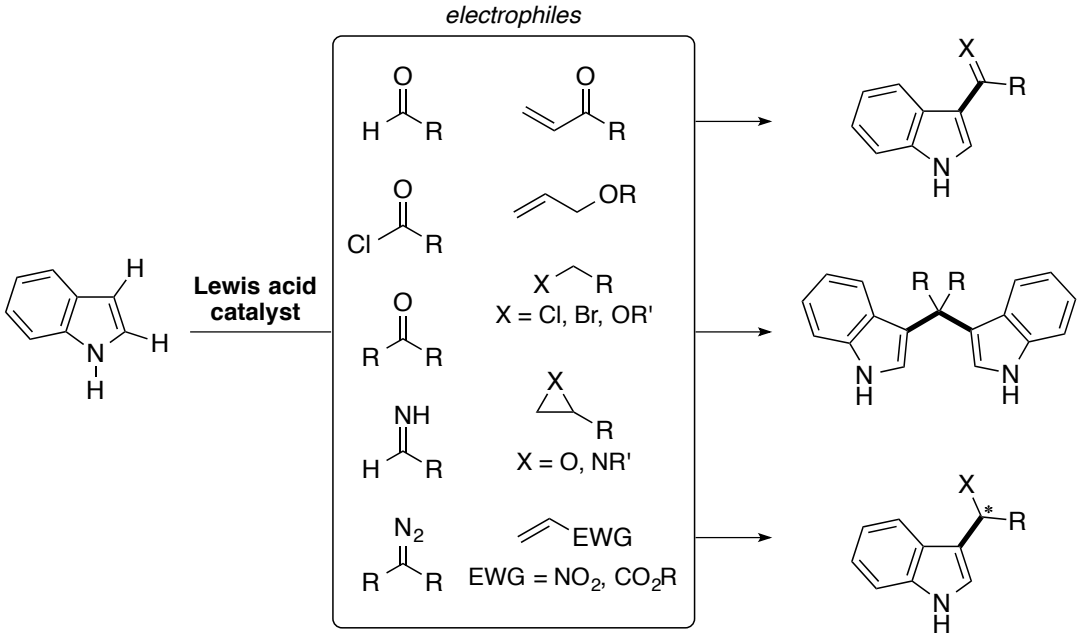
Scheme 15

As mentioned above, there are many cases of direct functionalization of indoles via activation of N–H or C–H bonds of an indole ring by transition-metal catalysts.

I-3-2. Lewis Acid-Catalyzed Functionalization of Indoles

I-3-2-1. Activation of Carbon–Hetero Atom Bonds

A different type to transition-metal-catalyzed reaction, known as Lewis acid-catalyzed functionalization of indoles, is another area of research interest. In sharp contrast to transition-metal-catalyzed reaction, where the N–H or C–H bonds on indoles are activated in the first step, the basic style of the reaction under Lewis acid catalysis is electrophilic aromatic substitution via activation of electrophiles by Lewis acid. Lewis acids have been used as a catalyst so far mainly for activation of hetero atom-containing compounds such as carbonyl compounds, imines, and alkyl halides. In functionalization of indoles utilizing a Lewis acid catalyst, the typical reactions with aldehydes, [33] acyl halides, [34] ketones, [35] imines, [36] α,β-unsaturated carbonyl compounds, [37] allyl alcohols, [38] (pseudo)haloalkanes, [39] tetra- and dihydrofurans, [40] aziridines,[41] and electron deficient alkenes[42] are presented below (Scheme 16). Most of these reactions give C3-alkylated indoles or diindolylmethanes as the products. In addition, indoles are often used as convenient nucleophiles for the development of asymmetric alkylation reaction.[43]

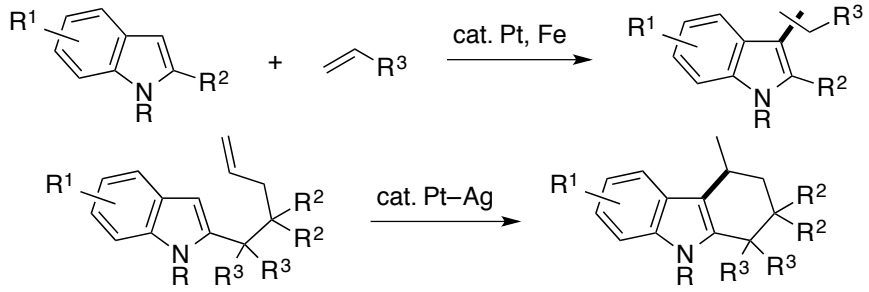


Scheme 16

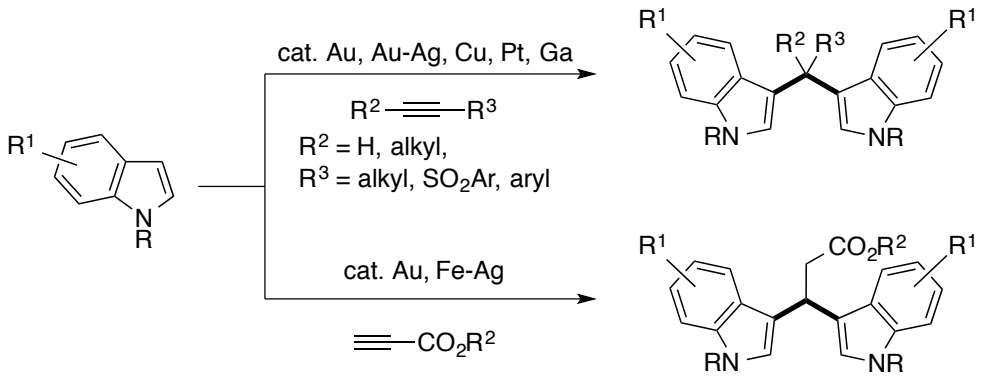
I-3-2-2. Activation of Unsaturated Carbon–Carbon Bonds

Unlike the activation of hetero atom-containing compounds, the activation of hydrocarbons (which show the smaller polarization) by a Lewis acid catalyst is the challenging aspect for the development of new transformation reaction. However, there are fewer reports on the use of Lewis acid as catalyst compared to the use of transition-metal as catalyst in functionalization of indoles via activation of hydrocarbons. This section discusses more recent reports on the reaction of indoles with hydrocarbons in the presence of a catalytic amount of Lewis acids.

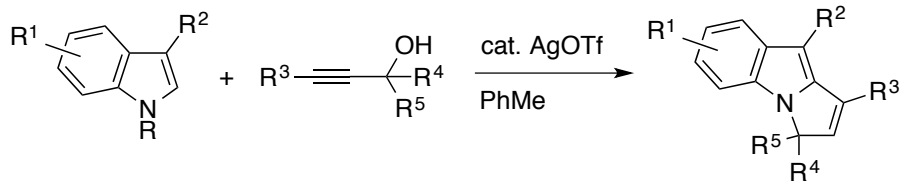
More recently, inter- and intramolecular addition reactions under platinum or iron catalysis have been reported (Scheme 17).[44] However, the products in these reactions are limited to 3-alkylindoles or tetrahydrocarbazoles. Lewis acid catalysts such as gold, copper, platinum, gallium, and iron salts have been studied as activators for carbon–carbon triple bond to synthesize diindolylmethanes (Scheme 18).[45] In addition, the cyclization reaction to form two new bonds at N1- and C2-positions of indoles has been reported to have success using propargyl alcohols under silver catalysis (Scheme 19).[46] Furthermore, the syntheses of indoles having a seven-membered ring via the activation of two carbon–carbon bonds by a catalytic amount of gold salts have also been achieved (Scheme 20).[47]



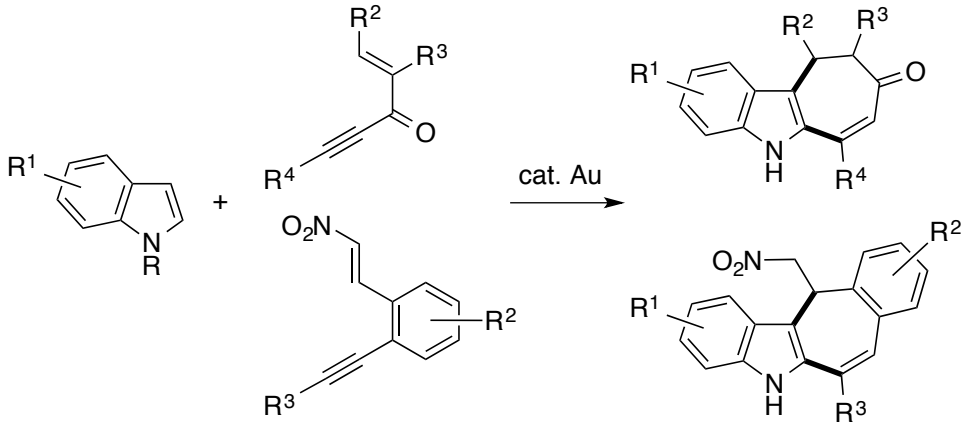
Scheme 17



Scheme 18



Scheme 19

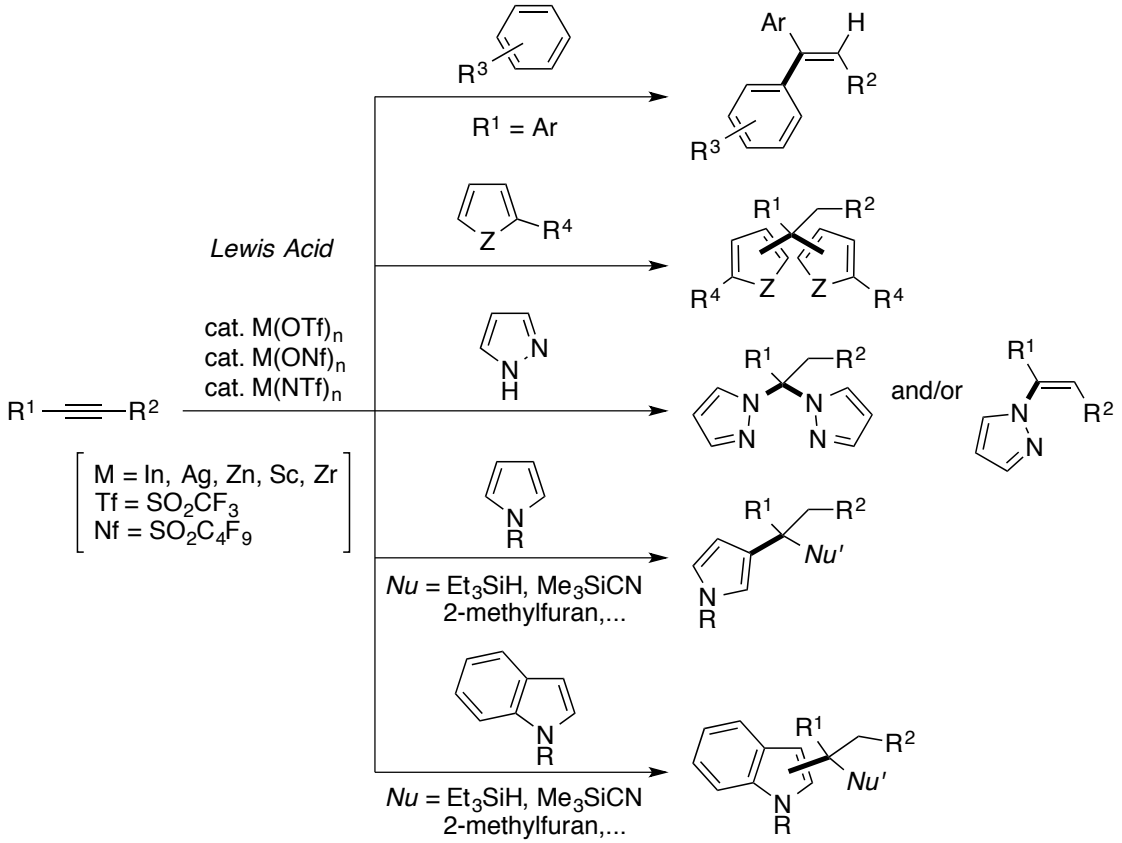


Scheme 20

I-4. Purpose and Scope of This Thesis

In this thesis, the purpose is the development of novel Lewis-acid catalyzed reactions of indoles. As discussed in the previous section, there have been fewer reports on the methodologies to functionalize an indole ring using a Lewis acid catalyst compared to those which use a transition metal catalyst. However, it is of extreme importance to study the Lewis acid-catalyzed reactions, which occur via a different activation pathway, for the development of catalytic transformation of indoles. This has prompted to undertake the current studies discussed in the following chapters of this thesis.

Our research group has already reported the addition reaction of various arenes and heteroarenes by activation of alkynes in the presence of a metal sulfonate catalyst (Scheme 21).[48] On the basis of the previous research of the group, the author expected to achieve the unprecedented Lewis acid-catalyzed transformation of indoles using metal sulfonates, which act as effective catalyst to activate C–H bonds.



Scheme 21

The chapters II–IV discuss the studies of a new synthetic method of aryl- and heteroaryl-annulated carbazoles (AHACs). The framework of the AHACs was efficiently constructed by the two carbon–carbon bond-forming cascade in one batch through annulation of indole derivatives with propargyl ethers, wherein an indium catalyst played a dual role for activating both C≡C and C–O bonds of propargyl ethers. The development of this annulation reaction provided us with a great opportunity to evaluate photoluminescent properties of the AHACs. Such structure–property correlations of aryl- and heteroaryl-annulated carbazoles should be important fundamental information for creating optoelectronic devices. Due to significance of AHACs in diverse areas like natural products, biological molecules, drugs, and optoelectronic materials, this study will attract attention of a reasonable number of readers engaged in a variety of research fields such as organic, organometallic, biological, and material chemistries.

Chapter V discusses the synthesis of bi-, ter-, and quater-heteroaryls under indium catalysis by nucleophilic aromatic substitution (S_NAr). This is the first example of catalytic heteroaryl–heteroaryl bond formation based on S_NAr between two heteroaryl substrates without any activating groups to enhance their reactivity.

Chapter VI describes a new type of direct cyanation reaction of an indolyl C–H bond. In marked contrast to previously reported studies of transition metal catalyzed reaction, the present method is the first example showing that a Lewis acid is able to catalyze cyanation of a C(aryl)–H bond with a cyanating agent having no CN group. Thus, a C–H bond of indole and pyrrole can be converted directly to a C–CN bond using $MeNO_2$ and Ph_2SiH_2 in the presence of $Zn(OTf)_2$ as a Lewis acid catalyst. Accordingly, the process developed by the author has an advantage of being performed under noxious metal-cyanide-free and expensive transition-metal-free conditions. These experimental results would enhance the utility and reliability of the zinc-catalyzed cyanation reaction. Due to significance of cyanoindoles and pyrroles as core structures in a variety of compounds, the author believes that the present reaction will attract attention of a number of readers from different areas of chemistry, organic, organometallic, biological and also material.

I-5. References and Notes

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Chapter II. Indium-Catalyzed Annulation of 2-Aryl- and 2-Heteroarylindoles with Propargyl Ethers: Concise Synthesis and Photophysical Properties of Diverse Aryl- and Heteroaryl-Annulated[*a*]carbazoles

II-1. Introduction

Aryl- and heteroaryl-annulated carbazoles (AHACs) have received considerable attention in view of their remarkable biological and pharmacological activities.[1] AHACs are classified into [*a*]-, [*b*]- and [*c*]-annulated carbazoles based on the position at which an aryl or a heteroaryl ring is fused to a carbazole nucleus (Chart 1). In the case of heteroaryl derivatives, each positional isomer is further sorted according to the mode of annulation, as exemplified by tetracyclic heteroaryl[2,3-*a*]- and -[3,2-*a*]carbazoles. Among these derivatives, indolo[2,3-*a*]carbazole alkaloids including tjipanazoles and staurosporine (**A**, **B** and **C** in Chart 1) are the most abundant among AHACs. Actually, indolo[2,3-*a*]carbazoles with diverse biological activities,[1] such as antimicrobial,[2] antifungal[3] and antitumor[4] activities in addition to protein kinase C inhibitory action,[5] have appeared in the literature. Although other analogues are rather rare in nature,[6] a variety of synthetic compounds and some natural products have been targets of research because of their broad spectrum of potential applications. In this context, the first total syntheses of furostifoline,[7] furoclausine A[8] and eustifoline D[9] (**D**, **E** and **F** in Chart 1) consisting of a furocarbazole framework have been accomplished by Knölker and co-workers and also Beccalli and co-workers.

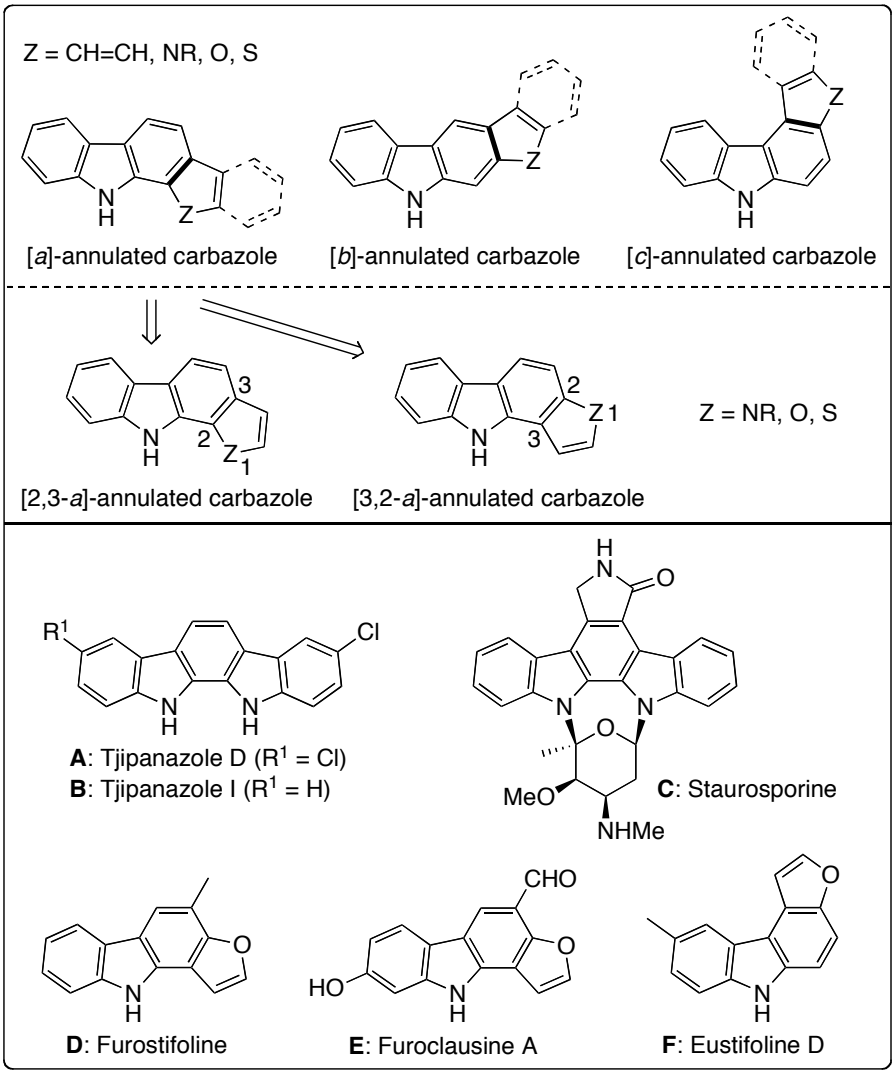
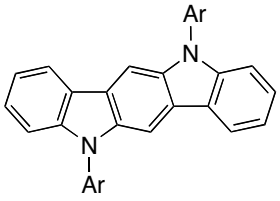


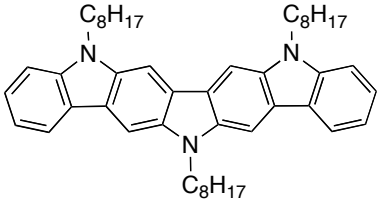
Chart 1. Classification of AHACs (Bold lines indicate the position of [*a*], [*b*] and [*c*] in a carbazole nucleus.) and structural examples of indolo[2,3-*a*]-, furo[3,2-*a*]- and furo[2,3-*c*]carbazole alkaloids.

On the other hand, applications of AHACs have recently been increasing in the field of material chemistry. In this regard, benzo[*a*]-, benzo[*c*]- and indolo[3,2-*b*]carbazoles have been utilized as molecular platforms for luminescent, hole-transporting and host materials in organic light-emitting diodes (OLEDs) (**G** in Chart 2).[10] Benzofuro[2,3-*c*]oxazolocarbazoles are of interest as donor–acceptor π-conjugated fluorescent dyes.[11] The starburst monodisperse macromolecules with a diindolo[3,2-*a*:3',2'-*c*]carbazole core have recently been synthesized as promising blue luminescent materials.[12] Moreover, *N*,*N*'-disubstituted indolo[3,2-*b*]carbazoles exhibit high performance as p-channel semiconductors (**H** in Chart 2).[13] As ladder-type

molecules, diindolo[3,2-*b*:2',3'-*h*]carbazoles with amphiphilic side chains have been shown to have potential for fabricating well-defined thin films (**I** in Chart 2).[14] Incorporation of indolo[3,2-*b*]carbazoles into a polymer chain and its effect on optical, electrochemical, magnetic and conductive properties have also been investigated.[15] Besides their organic electronic applications, indolo[2,3-*a*]carbazoles are important as anion sensors[16] and diindolo[3,2-*a*:3',2'-*c*]carbazoles as liquid crystals.[17]



G: hole-transporting material (Ar = 1-naphtyl)
H: semiconducting material (Ar = 4-octylphenyl)

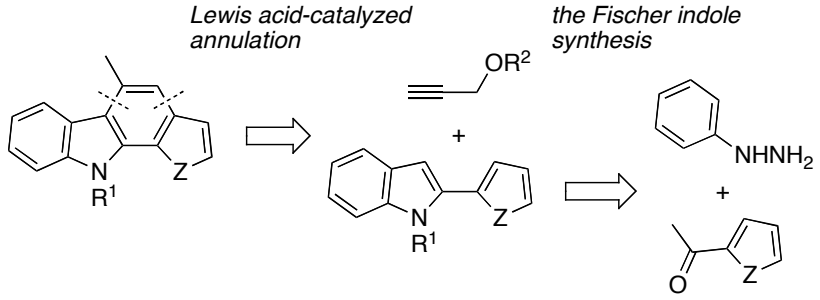


I: semiconducting material

Chart 2. Structural examples of electroactive indolocarbazoles.

Obviously, AHACs play a vital role in a variety of aspects. However, a major concern as photoactive and electroactive materials has been poured into indolo[3,2-*b*]carbazole frameworks probably due to the structural accessibility. Scarcity of straightforward synthetic methods for other AHACs could potentially restrict their application. Therefore, development of convenient and practical synthetic routes for various aryl- and heteroaryl[*a*]carbazoles (AHA[*a*]Cs) surely opens up a further opportunity to utilize AHA[*a*]Cs as material sources. Although a vast amount of synthetic research on individual AHA[*a*]Cs has been performed so far,[1,18] only two strategies have been reported for synthesis of a variety of AHA[*a*]Cs to the best of his knowledge. Thus, Marchesini and co-workers have synthesized benzo[*a*]-, thieno[*a*]-, furo[3,2-*a*]-, benzofuro[3,2-*a*]-, pyrido[*a*]-, pyrrolo[3,2-*a*]- and indolo[2,3-*a*]carbazoles by photochemical cyclization of 3-(2-styryl)indole derivatives.[19] Photochemical cyclization of 3-indolyl-4-arylmaleimides or the Mizoroki–Heck-type cyclization of 3-indolyl-4-bromoarylmaleimides reported by Sanchez-Martinez and co-workers is another approach for synthesis of benzo[*a*]-, naphtho[*a*]-, tetrahydronaphtho[2,1-*a*]-, thieno[*a*]-, benzothieno[2,3-*a*]-, imidazolo[4,5-*a*]-, pyrido[*a*]- and 7-aza-indolo[2,3-*a*]carbazoles.[20] However, none of these examples that focus on biological research seem to provide suitable structures for material design.

Recently, the author's group demonstrated that metal sulfonates like indium triflate [$In(OTf)_3$, Tf = SO_2CF_3] are efficient catalysts for addition of arenes and heterocyclic arenes to alkynes,[21] where activation of C≡C bonds with metal sulfonates is crucial.[22,23] His group have reported also that metal triflates catalyze alkylation of arenes with alcohols or acetals via activation of C–O bonds.[24] His group thus envisaged that the metal sulfonate-catalyzed annulation of 2-aryl- and 2-heteroarylindoles with propargyl ethers through two successive carbon–carbon bond-forming reactions utilizing the activation of both the C≡C and C–O bonds in one-pot would lead to a short-step synthesis of various AHA[*a*]Cs. A variety of starting indoles are readily accessible through an established protocol such as the Fischer indole synthesis. The overview of his group's strategy is summarized in Scheme 1. Herein he report a new method for synthesis of a wide range of AHA[*a*]Cs utilizing an indium-catalyzed addition–substitution sequence of various 2-aryl- and 2-heteroarylindoles with propargyl ethers.[25] Furthermore, the development of the protocol with substrate versatility gave him an opportunity to understand the effect of frameworks and substituents on the optical properties of AHA[*a*]Cs.



Scheme 1. Retrosynthetic strategy for the synthesis of AHA[*a*]Cs (Z = CH=CH, S, O, NH, NMe; R^1 = H, Me, aryl; R^2 = alkyl)

II-2. Results & Discussion

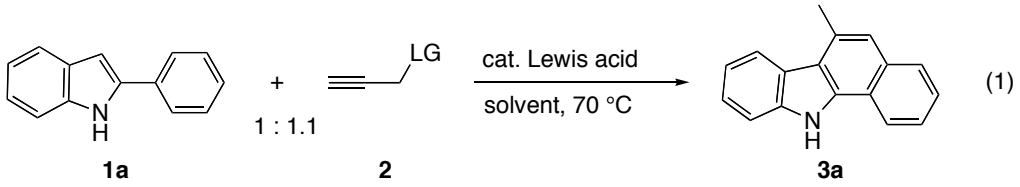
II-2-1. Optimization of Reaction Conditions.

The author first investigated the effect of Lewis acid catalysts (entries 1–9 of Table 1), solvents (entries 10–17) and leaving groups (LGs) at the propargylic position of propargyl alcohol derivatives **2** (entries 18–22) in the reaction of commercially available 2-phenylindole (**1a**) (Eq. 1). The use of 30 mol% of $In(OTf)_3$, which exhibited high performance for the activation of alkynes in the addition of arenes or heterocyclic arenes,[21] for the reaction of **1a** with methyl propargyl ether (**2a**, LG = OMe) in dibutyl ether (Bu_2O) at 70 °C for 72 h gave 6-methyl-11*H*-benzo[*a*]carbazole (**3a**)[26] in 62% yield (entry 1). This involves two successive inter- and intramolecular carbon–carbon bond-forming reactions. Replacing the catalyst with the corresponding nonaflate salt [$In(ONf)_3$, Nf = $SO_2C_4F_9$] accelerated the reaction and increased the yield up to 69% (entry 2). The higher activity of $In(ONf)_3$ should be due partially to the stronger Lewis acidity[27] based on the higher electron-withdrawing character of the ligand.[28] The other important factor is likely to be the superior solubility of $In(ONf)_3$ in Bu_2O, giving an almost homogeneous solution. A prolonged reaction period reduced the yield slightly, in spite of the complete consumption of **1a** (entry 3). With a lower loading of $In(ONf)_3$ (10 mol%), the annulation also proceeded but sluggishly (entry 4). In contrast to the promising activity of indium sulfonates, triflates of other metals and halide salts were totally inactive (entries 5–9). The soft character of indium[29] is likely to contribute to the reliable activity of indium sulfonates, which shows strong affinity for soft Lewis bases such as the alkyne moiety in **2a** on the basis of the hard and soft acids and bases (HSAB) principle.[30]

With $In(ONf)_3$ as a catalyst, he next investigated the effect of solvents and found that less-coordinating solvents such as Bu_2O and chlorobenzene (PhCl) were superior to strong-coordinating solvents such as 1,2-dimethoxyethane (DME), 1,4-dioxane and acetonitrile (MeCN). Solvents of the latter type plausibly make $In(ONf)_3$ inactive by the coordination (entries 2 and 10–16). Methylcyclohexane, a non-coordinating and non-polar solvent, was ineffective because of the low solubility of both $In(ONf)_3$ and substrate **1a** in the medium (entry 17).

The yield of **3a** depends also on the nature of LGs in **2**. The reaction of **1a** with propargyl alcohol (LG = OH) gave **3a** in a moderate yield (entry 18). However,

the use of 3-trimethylsilyloxy-1-propyne (LG = $OSiMe_3$) and propargyl electrophiles **2** having a good leaving functionality such as OCO_2Et, OCOBu or OSO_2Me resulted in a low yield albeit relatively high conversion of **1a**, as was confirmed by the formation of a considerable amount of unidentified oligomeric products including a moiety of **1a** and/or **2** (entries 19–22). These results show that **2a** with an alkoxy leaving group is the substrate of choice for the annulation.



(1)

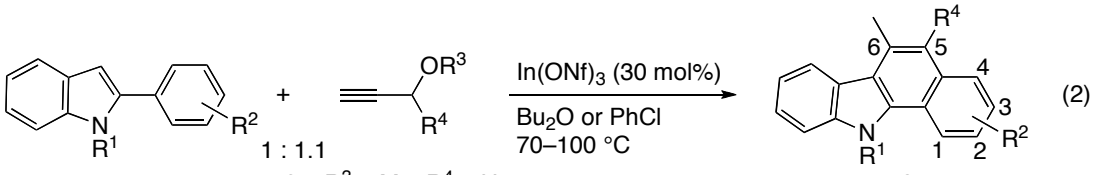
Table 1. Lewis acid-catalyzed annulation of 2-phenylindole with propargyl alcohol derivatives: optimization of reaction conditions[a]

entry	Lewis acid	LG in **2**	solvent	time (h)	conv. (%)[b] of **1a**	yield (%)[b] of **3a**
1	$In(OTf)_3$	OMe (**2a**)	Bu_2O	72	78	62
2	***$In(ONf)_3$***	***OMe (2a)***	***Bu_2O***	***24***	***87***	***69***
3	$In(ONf)_3$	OMe (**2a**)	Bu_2O	35	>99	64
4	$In(ONf)_3$[c]	OMe (**2a**)	Bu_2O	120	68	53
5	$Sc(OTf)_3$	OMe (**2a**)	Bu_2O	24	1	<1
6	$Zr(OTf)_4$	OMe (**2a**)	Bu_2O	24	1	<1
7	$InCl_3$	OMe (**2a**)	Bu_2O	24	1	<1
8	BF_3•OEt_2	OMe (**2a**)	Bu_2O	24	1	<1
9	$TiCl_4$	OMe (**2a**)	Bu_2O	24	14	<1
10	$In(ONf)_3$	OMe (**2a**)	DME	24	3	1
11	$In(ONf)_3$	OMe (**2a**)	1,4-dioxane	24	1	<1
12	$In(ONf)_3$	OMe (**2a**)	MeCN	24	2	1
13	$In(ONf)_3$	OMe (**2a**)	$MeNO_2$	24	45	29
14	$In(ONf)_3$	OMe (**2a**)	$(CH_2Cl)_2$	24	53	50
15	***$In(ONf)_3$***	***OMe (2a)***	***PhCl***	***24***	***72***	***66***
16	$In(ONf)_3$	OMe (**2a**)	PhH	24	49	48
17	$In(ONf)_3$	OMe (**2a**)	CyMe[d]	24	49	13
18	$In(ONf)_3$	OH	Bu_2O	24	96	56
19	$In(ONf)_3$	$OSiMe_3$	Bu_2O	24	94	27
20	$In(ONf)_3$	OCO_2Et	Bu_2O	24	84	23
21	$In(ONf)_3$	OCOBu	Bu_2O	24	82	29
22	$In(ONf)_3$	OSO_2Me	Bu_2O	24	67	16

[a] The reaction was carried out in a solvent (1.5 mL) at 70 °C using **1a** (0.10 mmol) and **2** (0.11 mmol) in the presence of a Lewis acid (30 μmol). [b] Determined by GC using *o*-dichlorobenzene as an internal standard. [c] $In(ONf)_3$ (10 μmol) was used. [d] CyMe = methylcyclohexane.

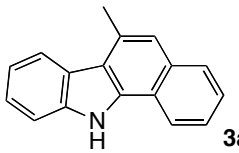
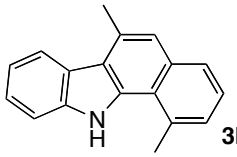
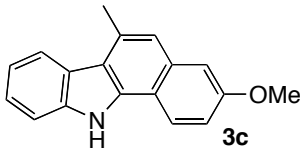
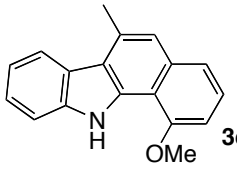
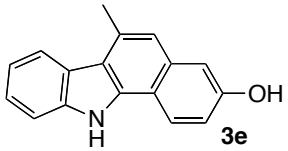
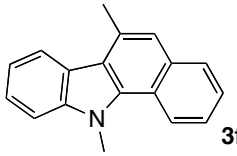
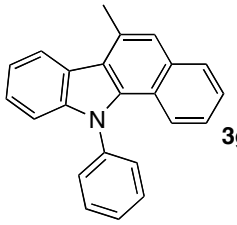
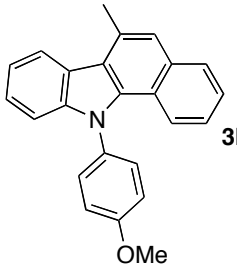
II-2-2. Synthesis of Aryl-Annulated[*a*]carbazoles (AA[*a*]Cs).

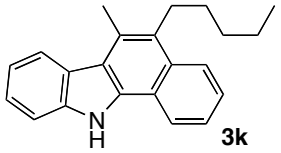
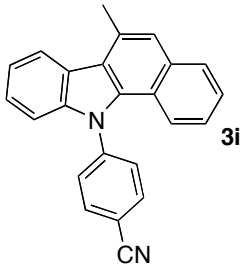
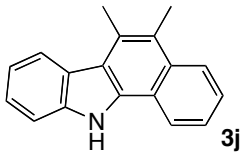
The optimized reaction conditions were applied to the synthesis of various AA[*a*]Cs (Eq. 2 and Table 2). Besides **1a**, 2-arylindoles **1b**–**1e** having a methyl, methoxy or hydroxy group on the phenyl group underwent the indium-catalyzed annulation with methyl propargyl ether (**2a**) to give the corresponding AA[*a*]Cs (**3b**–**3e**) in moderate to good yields (entries 1–5). With respect to the reaction of 2-(*o*-tolyl)indole (**1b**) in Bu_2O instead of PhCl, solvent Bu_2O itself reacted with **1b** to produce undesired 3-butyl-2-(*o*-tolyl)indole in 6% yield, along with 59% yield of **3b**. Therefore, in such cases, PhCl was used as a solvent in subsequent experiments. 2-Phenylindoles **1f**–**1i**[31] bearing an alkyl or aryl group with diverse electronic character on the nitrogen atom also reacted with **2a** to afford desired **3f**, **3g**, **3h** and **3i** (entries 6–9). Among these, 6,11-dimethyl-11*H*-benzo[*a*]carbazole (**3f**) reportedly exhibits a pronounced antitumor activity against leukemia, renal tumor, colon cancer and malignant melanoma tumor cell lines.[32] Remarkably, the indium-catalyzed annulation provides **3f** in only one-step from commercially available **1f** and **2a**, in contrast to the five-step synthesis reported by Fürstner and co-workers.[18x] It is worth noting that the methyl group derived from **2a** is always located at the C6 of annulation products **3**. In addition to **2a**, propargyl ethers with an alkyl group at the propargylic position such as 3-butoxy-1-butyne (**2b**, R^3 = Bu, R^4 = Me) and 3-butoxy-1-octyne (**2c**, R^3 = Bu, R^4 = *n*-pentyl) participated in the annulation with **1a** in perfect regioselectivities (entries 10 and 11). On the other hand, the synthesis of **3a** having a phenyl group at the C5 could not be achieved successfully due to dominant oligomerization between **1a** and propargyl ether **2d**, **2e**, **2f**, **2g** or propargyl alcohol **2h** (Chart 3). No annulation proceeded in the reaction of **1a** with internal alkynes **2i**–**2k** (Chart 3).



1 **2a**: R^3 = Me, R^4 = H; **2b**: R^3 = Bu, R^4 = Me; **2c**: R^3 = Bu, R^4 = *n*-pentyl **3**

Table 2. $In(ONf)_3$-catalyzed annulation of 2-arylindoles with propargyl ethers[a]

entry	2-aryl-indole **1**	propargyl ether **2**	solvent	time (h)	conv. (%) of **1**	product **3**	yield (%)[b] of **3**
1	**1a**	**2a**	Bu_2O	24	91	 **3a**	65
2[c]	**1b**	**2a**	PhCl	22	75	 **3b**	72
3[d]	**1c**	**2a**	Bu_2O	11	78	 **3c**	67
4[d]	**1d**	**2a**	Bu_2O	10	88	 **3d**	59
5[d]	**1e**	**2a**	Bu_2O	45	90	 **3e**	48
6[e]	**1f**	**2a**	Bu_2O	11	76	 **3f**	52
7	**1g**	**2a**	PhCl	20	73	 **3g**	57
8[c]	**1h**	**2a**	PhCl	60	64	 **3h**	60

9	**1i**	**2a**	PhCl	85	80	 **3k**	48
10	**1j**	**2b**	Bu_2O	18	77	 **3i**	68
11	**1k**	**2c**	Bu_2O	20	82	 **3j**	74

[a] The reaction was carried out in Bu_2O or PhCl (3.0 mL) at 70 °C using **1** (0.20 mmol) and **2** (0.22 mmol) in the presence of $In(ONf)_3$ (60 μmol). [b] Isolated yield based on the 2-arylindole (**1**). [c] In PhCl (9.0 mL). [d] In Bu_2O (9.0 mL) at 100 °C. [e] In Bu_2O (9.0 mL).

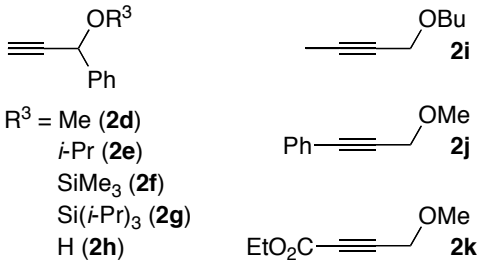
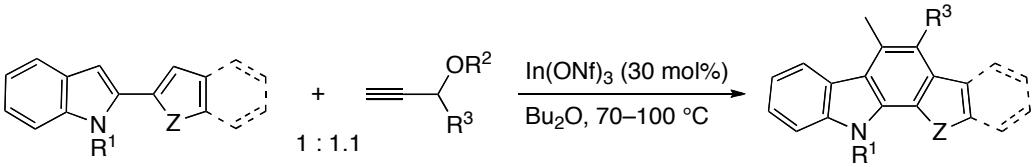


Chart 3. Incompatible alkynes in the $In(ONf)_3$-catalyzed annulation reaction.

II-2-3. Synthesis of Heteroaryl-Annulated[2,3-*a*]carbazoles (HA[2,3-*a*]Cs).

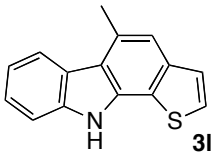
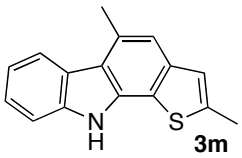
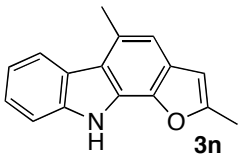
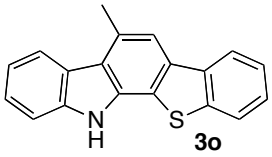
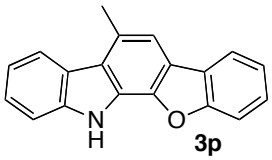
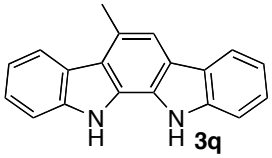
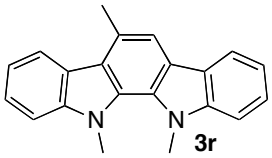
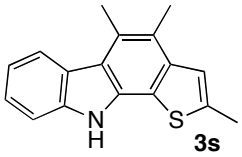
The author next examined the annulation of 2-(2-heteroaryl)indoles **1j–1p** with propargyl ether **2a** or **2b** (Eq. 3 and Table 3). The treatment of 2-(2-thienyl)- and 2-(2-furyl)indoles **1j–1l** with methyl propargyl ether (**2a**) in Bu_2O in the presence of $In(ONf)_3$ as a catalyst brought about the formation of tetracyclic HA[2,3-*a*]Cs in 57–79% yields (entries 1–3). In spite of nucleophilic character of α-positions of thiophene,[33] no problematic side reactions were observed in the reaction of **1j**. However, application of his strategy to 2-(2-pyrrolyl)- and 2-(5-methyl-2-pyrrolyl)indole was unsuccessful; only a trace amount of the desired annulation products were produced due to low solubility of the substrates in Bu_2O. In contrast, a series of pentacyclic analogues **3o–3r** comprising two heterocyclic rings such as thiophene, furan or pyrrole were prepared successfully (entries 4–7). In these cases, no competing butylation of 2-(2-heteroaryl)indoles occurred even with Bu_2O as a solvent. Note that the perfect regioselectivities of the methyl groups were observed here again in all cases. The use of 3-butoxy-1-butyne (**2b**) instead of **2a** allowed him to introduce another methyl group onto a thieno[2,3-*a*]carbazole framework giving **3s** in 74% yield (entry 8).



(3)

1 1 : 1.1 **2a**: R^2 = Me, R^3 = H; **2b**: R^2 = Bu, R^3 = Me **3**

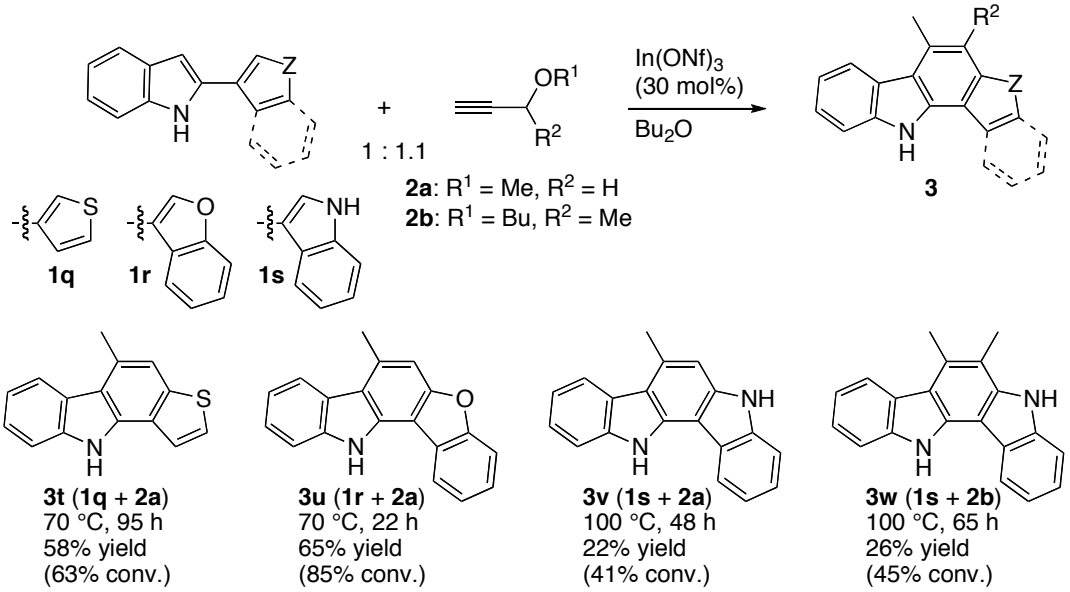
Table 3. $In(ONf)_3$-catalyzed annulation of 2-(2-heteroaryl)indoles with propargyl ethers[a]

entry	2-heteroaryl-indole **1**	propargyl ether **2**	time (h)	conv. (%) of **1**	product **3**	yield (%)[b] of **3**
1	**1j**	**2a**	25	80	 **3l**	70
2	**1k**	**2a**	50	83	 **3m**	79
3	**1l**	**2a**	8	61	 **3n**	57
4	**1m**	**2a**	8	76	 **3o**	61
5	**1n**	**2a**	40	87	 **3p**	60
6[c]	**1o**	**2a**	24	73	 **3q**	54
7	**1p**	**2a**	25	89	 **3r**	64
8	**1q**	**2b**	110	84	 **3s**	74

[a] The reaction was carried out in Bu_2O (3.0 mL) at 70 °C using **1** (0.20 mmol) and **2** (0.22 mmol) in the presence of $In(ONf)_3$ (60 μmol). [b] Isolated yield based on the 2-heteroarylindole (**1**). [c] At 100 °C.

II-2-4. Synthesis of Heteroaryl-Annulated[3,2-*a*]carbazoles (HA[3,2-*a*]Cs).

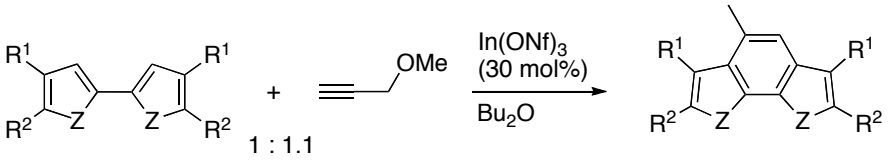
The author found that the annulation protocol is compatible also with 2-(3-heteroaryl)indoles, being transformed into HA[3,2-*a*]Cs (Scheme 2). 2-(3-Thienyl)indole (**1q**) thus reacted with methyl propargyl ether (**2a**) to give 5-methyl-10*H*-thieno[3,2-*a*]carbazole (**3t**) as the sole product. To his delight, no [3,4-*a*]-isomer, which would be produced by the participation of the C4 atom instead of the C2 in the thienyl part, was observed at all. Benzofuro[3,2-*a*]carbazole **3u** was produced in 65% yield by the annulation between 2-(3-benzofuranyl)indole (**1r**) and **2a**. The reaction of 2,3'-biindolyl (**1s**)[34] with **2a** or **2b** also proceeded, albeit in a lower yield probably due to the low solubility of **1s** in Bu_2O.



Scheme 2. $In(ONf)_3$-catalyzed synthesis of HA[3,2-*a*]Cs

II-2-5. Application to Synthesis of Benzodiheteroarenes.

In order to demonstrate further the potential of his method, he performed the annulation of symmetric dimers of heteroarenes leading to benzodiheteroarenes (Scheme 3), which also are important frameworks as electroactive materials.[35] Both 4,4',5,5'-tetramethyl-2,2'-bithiophene (**4a**) and the diethyl analogue (**4b**) reacted with methyl propargyl ether (**2a**) under similar conditions to afford benzodithiophenes **5a** and **5b**, respectively.[36] In the reaction of **4a**, the formation of 1:1 adduct **6** was observed, which contributed to his understanding of the reaction mechanism (*vide infra*). Benzodifuran **5c** also was synthesized in 43% yield by the reaction of tetramethylbifuran **4c** with **2a**.[37]

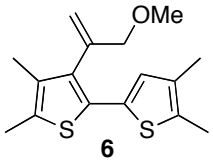


4a: $R^1 = R^2$ = Me, Z = S
4b: R^1 = H, R^2 = Et, Z = S
4c: $R^1 = R^2$ = Me, Z = O

2a

5a: $R^1 = R^2$ = Me, Z = S
5b: R^1 = H, R^2 = Et, Z = S
5c: $R^1 = R^2$ = Me, Z = O

4	time	temp.	conv. of **4**	yield of **5**
4a	2 h	90 °C	69%	40% (**6**: 13%)
4b	5 h	70 °C	46%	40%
4c	20 h	70 °C	76%	43%



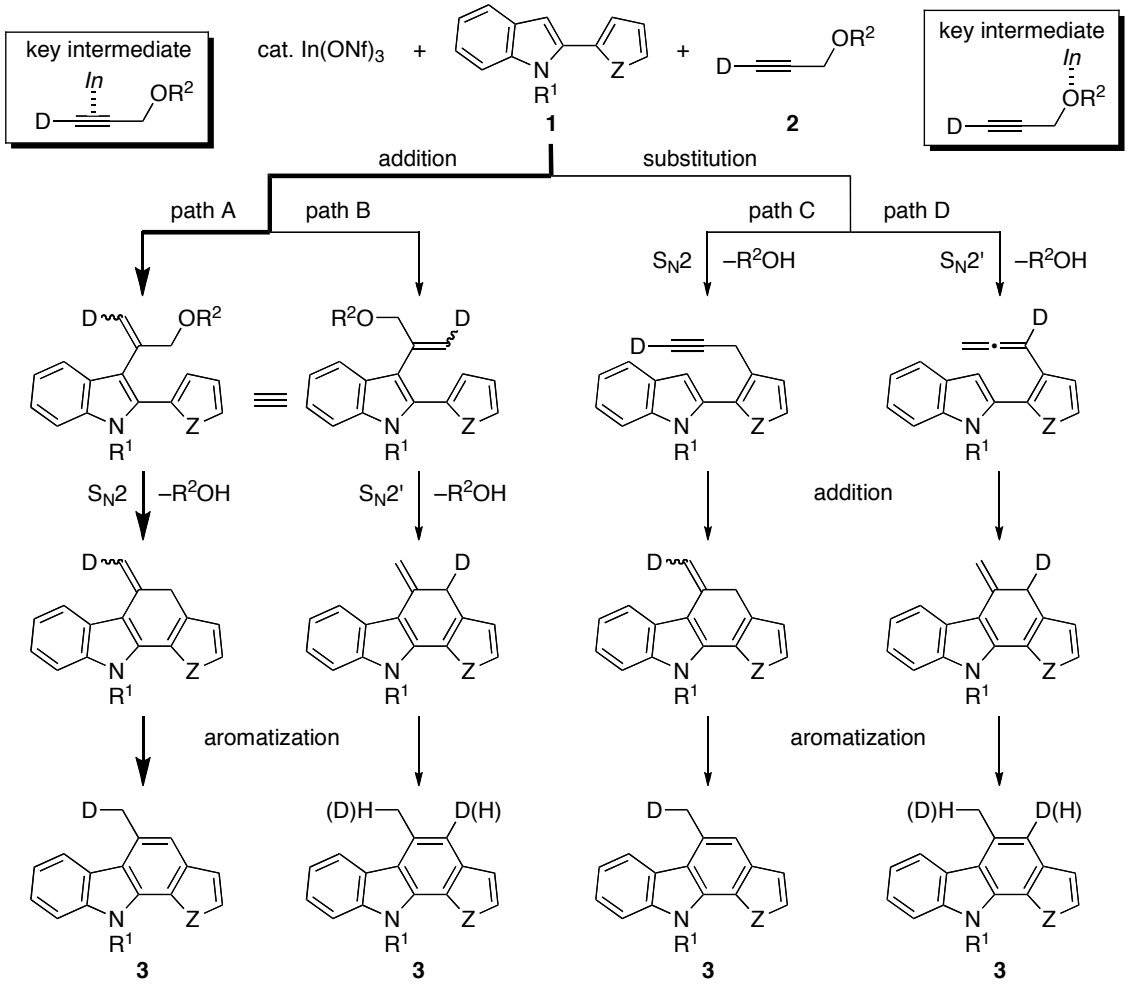
6

Scheme 3. $In(ONf)_3$-catalyzed annulation of bithiophenes or a bifuran with methyl propargyl ether

II-2-6. Reaction Mechanism.

In the present annulation, 2-(hetero)arylindoles **1** behave as nucleophiles, and character of propargyl ethers **2** should be electrophilic through the coordination of the π-electrons of the C≡C bond or the lone pair of the oxygen atom to indium(III).[21,24] The fact that **2** loses one degree of unsaturation and the alkoxy group through the annulation reaction strongly suggests that the reaction mechanism includes both addition and substitution as crucial steps. Taking into consideration that terminal alkynes such as **2** accept attack of arenes and heterocyclic arenes exclusively at the internal carbon atom of the C≡C bond[21] as well as S_N2 or S_N2' reaction takes place as the substitution process, he draw all possibilities leading to the same structure as **3** (Scheme 4). This is

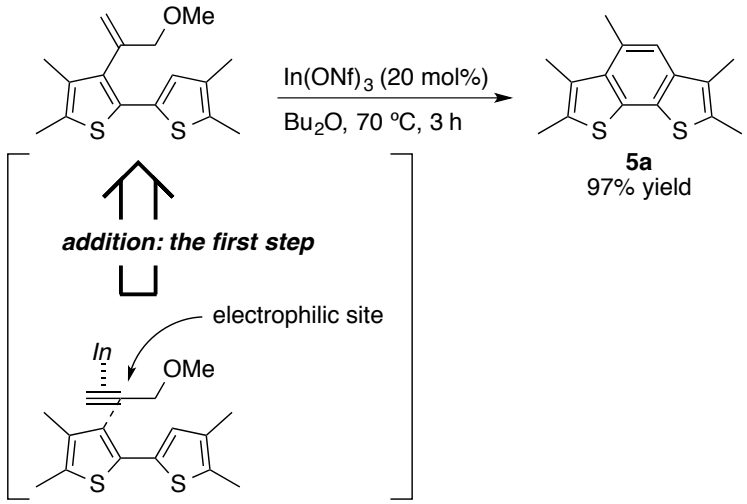
exemplified by the formation of tetracyclic AHA[*a*]Cs using deuterated propargyl ether **2**. In both paths A and B, the first step is the addition of the indolyl C3–H bond to the C≡C bond in a Markovnikov fashion, and the next stage is intramolecular S_N2 or S_N2' cyclization. In contrast, paths C and D start with the intermolecular S_N2 and S_N2' reactions, respectively, by the nucleophilic attack of the (hetero)aryl part of **1**, followed by the intramolecular addition. In all cases, isomerization of the resulting C=C bond via a 1,3-hydrogen shift, i.e., aromatization, is the final step.[38]



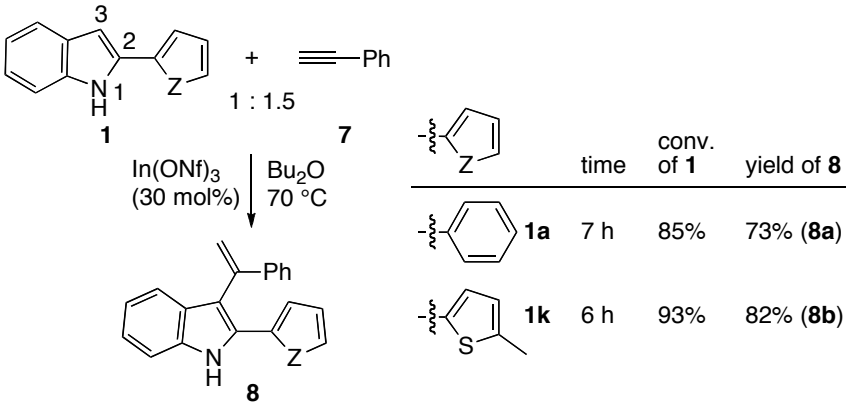
Scheme 4. Possible reaction mechanisms

Some pieces of experimental observations are available to specify the most plausible route among paths A–D. He first focused on the result of the reaction of tetramethylbithiophene **4a** with methyl propargyl ether (**2a**) giving 1:1 adduct **6** and desired **5a** (Scheme 3), though no formation of 1:1 adducts was observed in the

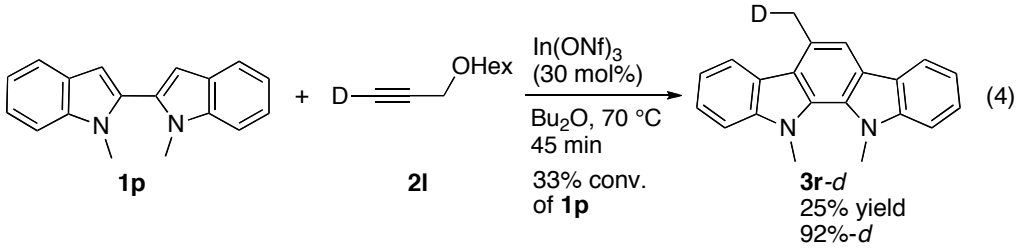
annulation of 2-(hetero)arylindoles. Thus, the treatment of **6** under milder conditions [20 mol% of $In(ONf)_3$, 70 °C] than those in Scheme 3 gave **5a** in an almost quantitative yield (Scheme 5).[39] This result implies the followings: 1:1 adduct **6** is an intermediate for **5a**, and thus the first step of the annulation is addition and the internal carbon atom of the C≡C bond of **2** is the most electrophilic among the three possible electrophilic sites. Next, he carried out the indium-catalyzed reaction of **1** with phenylacetylene (**7**) and found that both **1a** and **1k** add to **7** at the C3 of the indole nucleus regioselectively (Scheme 6).[40] These results clearly show that the C3 position of **1** is the most nucleophilic to add to C≡C bonds, which reasonably excludes the possibilities of paths C and D starting with the nucleophilic attack by the (hetero)aryl ring. Therefore, it is reasonable to consider that the present annulation starts with the regioselective addition as in paths A and B. Among two possibilities, S_N2 (path A) or S_N2' (path B), after the addition process, the fact that the indium-catalyzed reaction of 2,2'-bis(*N*-methylindolyl) (**1p**) with 1-deuterio-3-hexyloxy-1-propyne (**2l**) gave **3r**-*d* with the deuterium atom exclusively at the methyl group supports the probability of path A (Eq. 4). Supposing that path B via S_N2' process works, the deuterium atom should be observed mainly on the aromatic ring, whereas a part of the deuterium atom may migrate onto the methyl group according to deuterium isotope effects through the aromatization.[41] Thus, path A proceeding in the order of addition, S_N2 cyclization and aromatization is concluded to be the most plausible pathway. It is noteworthy that high selectivities for the annulation should be attributed to the first contact of indium with C≡C bonds that triggers regioselective carbon–carbon bond formation.



Scheme 5. In(ONf)$_3$-catalyzed annulation of 1:1 adduct **6**



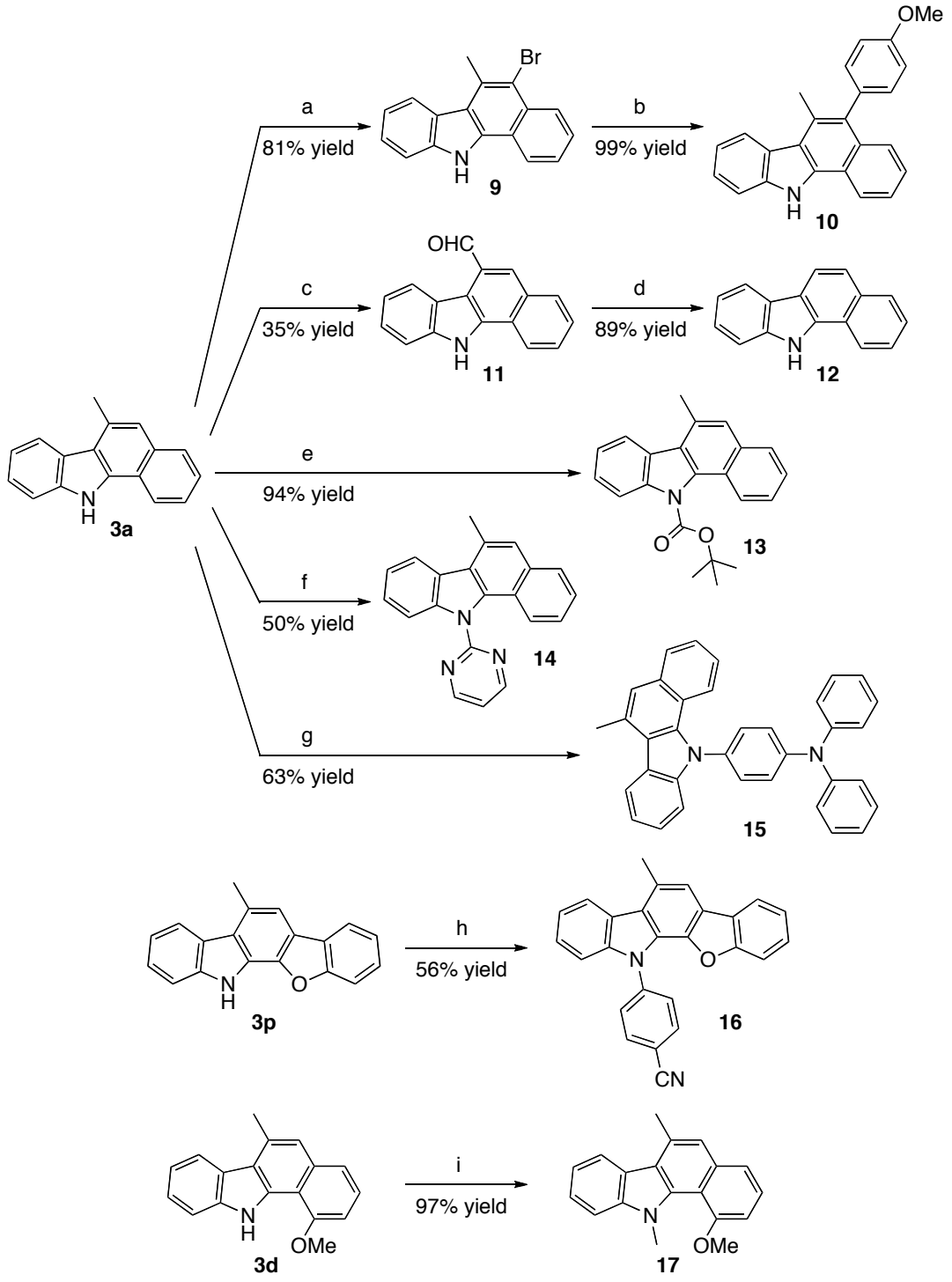
Scheme 6. In(ONf)$_3$-catalyzed addition of 2-phenyl- or 2-(5-methyl-2-thienyl)indole to phenylacetylene



II-2-7. Transformation of AHA[*a*]Cs.[42]

The utility of his method can be enhanced by the synthetic application of AHA[*a*]Cs (Scheme 7). Regioselective mono-bromination of **3a** was chosen as the first application. After screening various conditions for bromination, he found that a bromine atom can be introduced exclusively at the C5 of **3a** using an *N*-bromosuccinimide (NBS)–$FeCl_3$ system.[43, 44] Palladium-catalyzed cross-coupling reaction is highly useful for extending the π-system of bromide **9**. For example, the Suzuki–Miyaura cross-coupling of **9** with 4-methoxyphenylboronic acid gave **10** quantitatively.[45] SeO_2 oxidation[46] and rhodium-catalyzed decarbonylation[47] sequence enabled him to remove the methyl group of **3a**, giving 11*H*-benzo[*a*]carbazole (**12**).

The author has demonstrated that the annulation of 2-(hetero)arylindoles having alkyl or aryl groups on the nitrogen atom proceeds efficiently (entries 6–9 of Table 2 and entry 7 of Table 3). In addition to the installation of these groups prior to the annulation, various organic functional groups were found to be introduced successfully onto the nitrogen atom of AHA[*a*]Cs after the annulation. Thus, annulation product **3a** reacted with di-*tert*-butyl dicarbonate [$(Boc)_2O$] with the aid of 4-(*N*,*N*-dimethylamino)pyridine (DMAP) to give **13** in a high yield.[48] The **3a**–Na complex prepared *in situ* from **3a** and NaH reacted with 2-chloropyrimidine through S_NAr process to give **14**.[49] The Buchwald *N*-arylation also worked well for the transformation of **3a** or **3p** to **15** or **16**, respectively.[31] Furthermore, the treatment of **3d** with MeI and KOH in DMSO gave *N*-methylated compound **17** in a high yield.[50] Such flexible behavior of AHA[*a*]Cs that accepts a variety of organic transformations is promising, for instance, for structural design in the case of their application to electroactive materials as shown in the next section.



Scheme 7. Transformation of AHA[*a*]Cs[a]

[a] Reagents and conditions: (a) NBS (1.0 equiv.), $FeCl_3$ (30 mol%), CH_2Cl_2, 0 °C, 30 min; (b) 4-MeO–$C_6H_4B(OH)_2$ (2.0 equiv.), $Pd(PPh_3)_4$ (20 mol%), K_3PO_4 (3.0 equiv.), DMF, 100 °C, 24 h; (c) SeO_2 (1.5 equiv.), K_2CO_3 (0.5 equiv.), pyridine, 115 °C, 19 h; (d) $RhCl(CO)(PPh_3)_2$ (10 mol%), $Ph_2P(CH_2)_3PPh_2$ (25 mol%), xylenes, 140 °C, 24 h; (e)

$(Boc)_2O$ (2.0 equiv.), DMAP (1.0 equiv.), MeCN, rt, 5 h; (f) 2-Cl–pyrimidine (1.8 equiv.), NaH (2.2 equiv.), DMF, 130 °C, 25 h; (g) 4-Br–$C_6H_4NPh_2$ (1.0 equiv.), CuI (5.0 mol%), $(CH_2NHMe)_2$ (20 mol%), K_3PO_4 (2.1 equiv.), toluene, 110 °C, 65 h; (h) 4-Br–C_6H_4CN (1.0 equiv.), CuI (20 mol%), $(CH_2NHMe)_2$ (40 mol%), K_3PO_4 (2.1 equiv.), toluene, 110 °C, 60 h; (i) MeI (2.0 equiv.), KOH (4.0 equiv.), DMSO, rt, 2.5 h.

II-2-8. Photophysical Properties of AHA[*a*]Cs.

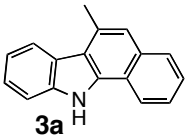
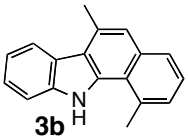
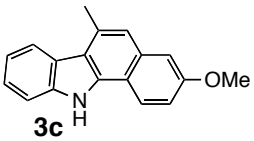
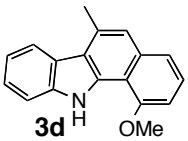
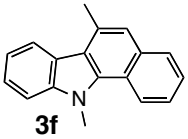
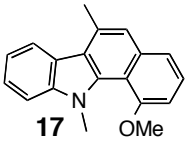
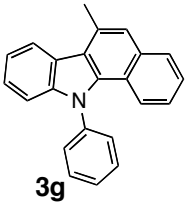
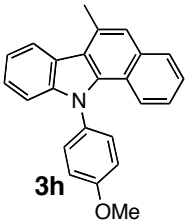
Because of the broad substrate diversity on the indium-catalyzed annulation, the author was intensely interested in the potential of the AHA[*a*]Cs as electroactive materials. He therefore investigated the photophysical properties of the AHA[*a*]Cs; the results are collected in Table 4.

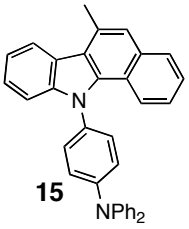
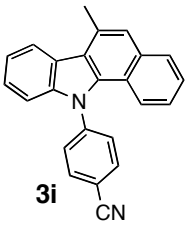
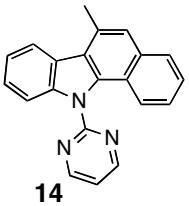
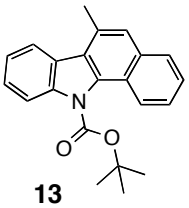
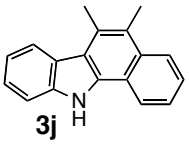
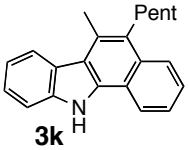
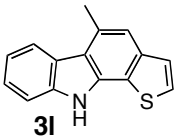
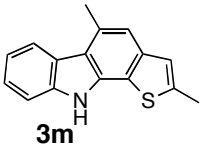
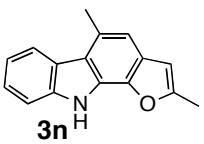
First, he focused on evaluating the effect of substituents on AA[*a*]Cs and HA[*a*]Cs. For example, in the UV-vis spectrum of 6-methyl-11*H*-benzo[*a*]carbazole (**3a**), the absorption bands ascribed to the π–π* transitions with the relatively large extinction coefficients were detected, ranging from 260 to 300 nm.[51] It was then found that **3a** (Φ_F = 0.165) exhibits purple emission derived from the emission λ_{max} around 360–400 nm.[52] Although the absorption and emission patterns of **3b**, **3f**, **3j** and **3k** that have another alkyl group at the different position of **3a** resemble those of **3a**, the introduction of the alkyl group was always accompanied by a red-shift of the emission spectra regardless of the position of the alkyl group (**3a** vs. **3b**, **3f**, **3j** or **3k**). A similar correlation was observed also between indolo[2,3-*a*]carbazoles **3q** and **3r**. Moreover, FL efficiency was found to be highly dependent on the methoxy group (**3a** vs. **3c** or **3d**). Thus, though the Φ_F value of **3c** slightly decreased compared with that of **3a**, the installation of the methoxy group onto the C1 position resulted in higher Φ_F value. Comparisons between **3a** and the *N*-arylated derivatives (**3a** vs. **3g**, **3h**, **15** or **3i**) also showed significant differences in photophysical properties. Phenyl and electron-rich aryl groups on **3a** (**3g**: –Ph, **3h**: –C_6H_4–*p*-OMe, **15**: –C_6H_4–*p*-NPh_2) made their absorption bands around 250–260 nm indefinite, whereas the corresponding band of **3i** having an aryl group with electron-deficient character (–C_6H_4–*p*-CN) was intensified. Furthermore, the structural change from **3a** to **3g**, **3h** or **15** resulted in a red-shift of the FL spectra and an increase in the FL quantum yield. Interestingly, the electron-deficient aryl group caused a drastic color change from purple to green light (**3a** vs. **3i**, $\Delta\lambda_{max}$ = 92 nm). The effect of –C_6H_4–*p*-CN holds true also for benzofuro[2,3-*a*]carbazole **3p**, where blue-emitting **16** was derived from purple-fluorescent **3p** (**3p** vs.

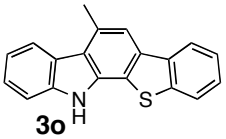
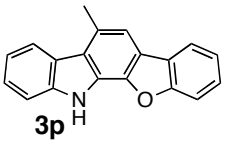
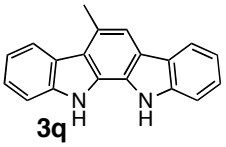
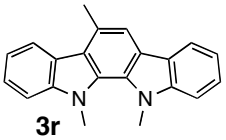
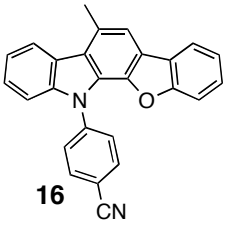
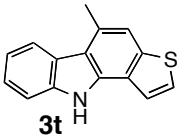
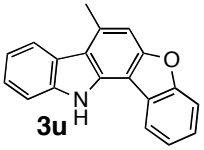
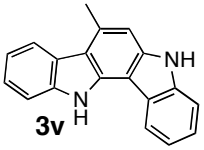
16, $\Delta\lambda_{max}$ = 51 nm). Compound **14** with a 2-pyrimidyl group resulted in quenching of fluorescence. In contrast to the bathochromic effect in the FL maxima wavelengths of alkyl, methoxy and aryl groups, only a Boc group exhibited a hypsochromic effect (**3a** vs. **13**).

Next, the author focused on evaluating structure–property correlations of HA[*a*]Cs. Among a series of pentacyclic HA[2,3-*a*]Cs **3o**, **3p** and **3q**, benzofuro[2,3-*a*]carbazole **3p** having a furan ring was found to be the most emissive,[53] which is likely to be responsible for the largest extinction coefficients. Although he could not synthesize a pyrrolo[2,3-*a*]carbazole, tetracyclic **3n** (Φ_F = 0.200) with the furan moiety also showed higher FL efficiency in comparison to the corresponding thiophene derivative (**3m**, Φ_F = 0.047). The trend holds true for HA[3,2-*a*]Cs and thus a larger Φ_F value of benzofuro[3,2-*a*]carbazole **3u** (Φ_F = 0.485) was confirmed compared with that of indolo[3,2-*a*]carbazole **3v** (Φ_F = 0.223). The consistency that HA[3,2-*a*]Cs are always superior to HA[2,3-*a*]Cs in view of the FL efficiency is of particular importance (**3l** vs. **3t**, **3p** vs. **3u**, and **3q** vs. **3v**).

Table 4. Photophysical properties of AHA[*a*]Cs[a]

AHA[*a*]Cs	UV-vis λ_{max}/nm (log ε)	fluorescence[b] λ_{max}/nm[c]	Φ_F[d]
 **3a**	259 (4.64), 278 (4.70), 300 (4.38)	360, 378, 397	0.165
 **3b**	261 (4.53), 276 (4.52), 296 (4.25)	364, 382, 402	0.223
 **3c**	262 (4.60), 284 (4.73), 305 (4.37)	363, 378, 395sh	0.109
 **3d**	262 (4.71), 297 (4.41), 360 (4.13)	365, 384, 404	0.284
 **3f**	264 (4.51), 281 (4.56), 300 (4.31)	371, 389, 408sh	0.184
 **17**	268 (4.66), 304 (4.39), 370 (3.95)	380, 398, 420sh	0.215
 **3g**	279 (4.64), 303 (4.37)	366, 384, 403sh	0.239
 **3h**	280 (4.63), 303 (4.35)	367, 385, 404sh	0.264

 **15**	281 (4.73), 304 (4.61)	404	0.262
 **3i**	256 (4.68), 274 (4.61), 303 (4.31)	470	0.040
 **14**	257 (4.69), 303 (4.31)	nd[e]	nd[e]
 **13**	271 (4.76), 300 (4.33)	355, 373, 391	0.185
 **3j**	264 (4.61), 281 (4.64), 302 (4.38)	370, 388, 407sh	0.156
 **3k**	264 (4.60), 282 (4.62), 302 (4.37)	369, 388, 407	0.167
 **3l**	253 (4.70), 310 (4.34)	351, 367, 383sh	0.037
 **3m**	255 (4.74), 312 (4.38)	351, 367, 383sh	0.047
 **3n**	252 (4.79), 302 (4.32)	338, 353, 368sh	0.200

 **3o**	258 (4.62), 295 (4.46), 320 (4.60)	365, 383, 400sh	0.058
 **3p**	254 (4.78), 280 (4.57), 314 (4.58)	353, 369, 385sh	0.444
 **3q**	259 (4.76), 287 (4.45), 323 (4.54)	371, 388, 403sh	0.075
 **3r**	275 (4.76), 329 (4.57)	391, 410, 431sh	0.114
 **16**	254 (4.76), 316 (4.63), 354 (4.26)	420	0.267
 **3t**	245 (4.69), 290 (4.41)	346, 362, 378sh	0.053
 **3u**	271 (4.63), 297 (4.53), 337 (4.05)	342, 357, 375sh	0.485
 **3v**	268 (4.68), 282 (4.61), 305 (4.47)	355, 370	0.223

[a] Dichloromethane was used as a solvent for measurement of UV-vis (c = 1.5 x 10^{-5} M) and fluorescence (c = 1.5 x 10^{-6} M) spectra. [b] Excited at 265 nm. [c] sh = shoulder. [d] Determined with reference to the quantum yield of *p*-terphenyl. [e] nd = not detected.

To gain further insight into the photophysical properties of AHA[*a*]Cs, the author investigated their spectral dependence on solvent polarity. When benzo[*a*]carbazole **3a** and benzofuro[2,3-*a*]carbazole **3p** were excited at 265 nm in three kinds of solvents, i.e., ethyl acetate (AcOEt), dichloromethane (CH_2Cl_2) and dimethyl sulfoxide (DMSO),[54] their emission spectra were not affected regardless of the solvent polarity. In contrast, significant positive solvatochromism in the fluorescence spectrum of **15**, which has an *N*,*N*-diphenylaminophenyl group on the nitrogen atom of **3a**, was observed as the solvent polarity increased (Figure 1). Thus, a 42 nm red-shift was confirmed by changing the solvent from AcOEt to DMSO. In addition to **15**, *p*-cyanophenyl substituted **16** derived from **3p** similarly exhibited solvatochromic behavior as shown in Figure 2 (61 nm red-shift from AcOEt to DMSO). These results clearly show that the solvatochromic properties appear for the *N*-aryl-AHA[*a*]Cs. The considerable red-shift observed in **15** and **16** should be due mainly to the charge transfer character of the fluorescent state leading to the significant change in the dipole moment from the ground to the excited state in polar solvents.[55]

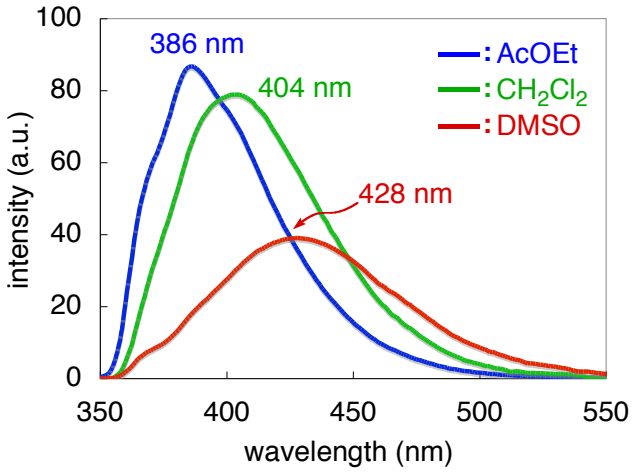


Figure 1. Solvent-dependent fluorescence spectra of **15** (c = 1.1 x 10^{-6} M in each solvent) excited at 265 nm. a.u. = arbitrary units.

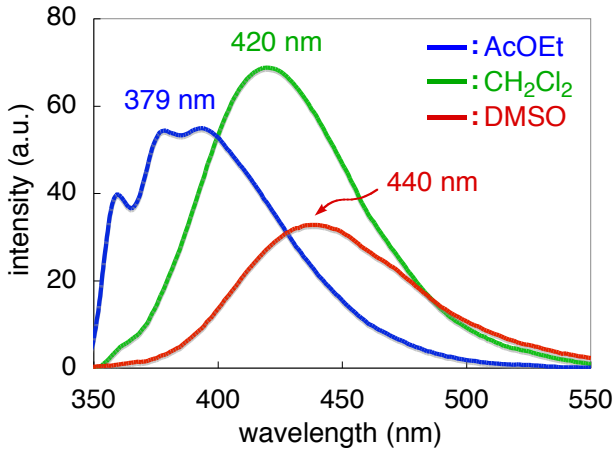


Figure 2. Solvent-dependent fluorescence spectra of **16** (c = 1.1 x 10^{-6} M in each solvent) excited at 265 nm. a.u. = arbitrary units.

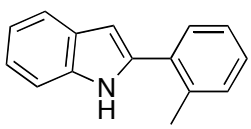
II-3. Experimental

General Remarks. All manipulations were conducted with a standard Schlenk technique under a nitrogen or argon atmosphere. Nuclear magnetic resonance spectra were taken on a Varian Gemini 2000 (^{13}C, 75 MHz), a JEOL JMN-ECA 400 (^{1}H, 400 MHz; ^{13}C, 100 MHz), a JEOL JMN-ECA 500 (^{1}H, 500 MHz; ^{13}C, 125 MHz) or a Varian INOVA 500 (^{13}C, 125 MHz) spectrometer using tetramethylsilane (^{1}H), chloroform-*d* (^{2}H), $CDCl_3$ (^{13}C) or dimethyl sulfoxide (DMSO) in DMSO-d_6 (^{1}H and ^{13}C) as an internal standard. Analytical gas chromatography was performed on a Shimadzu model GC-18A or GC-17A instrument equipped with a capillary column of CP-SIL 5 CB (100% dimethyl polysiloxane, 30 m x 0.25 mm x 0.25 μm) using helium as carrier gas. Preparative recycling gel permeation chromatography was performed with JAI LC-908 equipped with JAIGEL-1H and -2H using chloroform as an eluent. High-resolution mass spectra (HRMS) were obtained with a Bruker Bio APEX 70e or a JEOL JMS-HX110A spectrometer. Elemental analyses were performed on a Vario EL III elemental analysis instrument or at the Microanalytical Center, Kyoto University. All melting points were measured with a Yanaco Micro Melting Point apparatus and uncorrected. UV-vis Absorption spectra were recorded with a JASCO V-550 spectrophotometer at room temperature. Fluorescence spectra were recorded with a JASCO FP-6500 spectrofluorometer at room temperature using an excitation wavelength of 265 nm. A solution of *p*-terphenyl in cyclohexane was used as a quantum yield standard (Φ_F = 0.87 at 265 nm excitation). Unless otherwise noted, reagents were commercially available and used without further purification. Tetrahydrofuran (THF), diethyl ether (Et_2O), 1,4-dioxane, 1,2-dimethoxyethane (DME) and dibutyl ether (Bu_2O) were distilled under nitrogen from sodium benzophenone ketyl just prior to use. Chlorobenzene (PhCl), benzene (PhH), 1,2-dichloroethane ($ClCH_2CH_2Cl$), dichloromethane (CH_2Cl_2), nitromethane ($MeNO_2$) and methylcyclohexane were distilled under nitrogen from calcium chloride just prior to use. Acetonitrile (MeCN) was distilled under nitrogen from calcium hydride just before use. Anhydrous dimethyl sulfoxide (DMSO) and anhydrous *N*,*N*-dimethylformamide (DMF) were purchased from Aldrich Chemical Co. 2-Arylindoles **1b–1e** and 2-heteroarylindoles **1j–1o**, **1q** and **1r** were synthesized by the well-known Fischer indole synthesis.[53] 1-Aryl-2-phenylindoles **1h** and **1i** were prepared from

commercially available **1a** and the corresponding aryl halide according to the procedure reported by Buchwald and co-workers.[54] 2,2'-Bis(*N*-methylindolyl) (**1p**) was prepared according to the literature procedure.[55] 2,3'-Biindolyl (**1s**) was prepared according to the literature procedure.[56] 4,4',5,5'-Tetramethyl-2,2'-bithiophene (**4a**) and 5,5'-diethyl-2,2'-bithiophene (**4b**) were prepared according to reported procedures.[57] 4,4',5,5'-Tetramethyl-2,2'-bifuran (**4c**) was synthesized according to the literature method.[58]

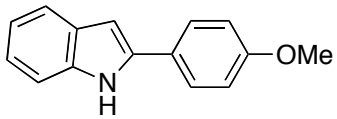
Preparation of Indium Nonafluorobutanesulfonate [In(ONf)$_3$]. In_2O_3 (597 mg, 2.15 mmol) was placed in a 50 mL two necked, round-bottomed flask equipped with a reflux condenser. To this were added H_2O (10 mL) and nonafluorobutanesulfonic acid (2.49 g, 8.30 mmol) successively, and the resulting mixture was stirred at 100 °C for 10 h. Filtration to remove excess In_2O_3 and evaporation of H_2O gave hydrate of $In(ONf)_3$. The resulting hydrate was slowly warmed up to 150 °C over a period of 5 h under vacuum and the heating was continued for additional 10 h to give $In(ONf)_3$ (2.73 g, 97% yield) as a white powder. ^{19}F NMR (470 MHz, CD_3CN) δ –80.4, –113.6, –120.8, –125.3. Anal. Calcd for $C_{12}F_{27}InO_9S_3$: C, 14.24; S, 9.50. Found: C, 14.18; S, 9.56.

Spectral and analytical data of 2-aryl- and 2-heteroarylindoles prepared follow. 2-Aryl- and 2-heteroarylindoles that only ^1H NMR data are provided have been already reported in the literature and their spectral and analytical data are in good agreement with those. Since 2-phenylindole (**1a**), 1-methyl-2-phenylindole (**1f**) and 1,2-diphenylindole (**1g**) were commercially available, their spectral and analytical data were omitted.

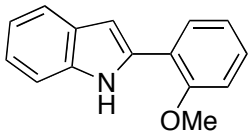


2-(*o*-Tolyl)-1*H*-indole (1b).[59] The title compound prepared from 2'-methylacetophenone phenylhydrazone (6.7 g, 30 mmol) by the Fischer indole synthesis

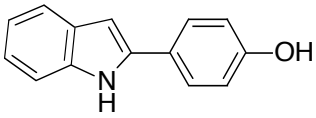
was obtained in 63% yield (3.92 g) through isolation by column chromatography on silica gel (hexane/EtOAc = 30/1). ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.51 (s, 3 H), 6.62 (dd, *J* = 2.3, 1.1 Hz, 1 H), 7.14 (td, *J* = 7.6, 1.2 Hz, 1 H), 7.21 (td, *J* = 7.7, 1.2 Hz, 1 H), 7.27–7.34 (m, 3 H), 7.41 (dd, *J* = 8.0, 1.0 Hz, 1 H), 7.48 (dd, *J* = 5.6, 3.7 Hz, 1 H), 7.65 (dd, *J* = 8.0, 1.2 Hz, 1 H), 8.14 (bs, 1 H).



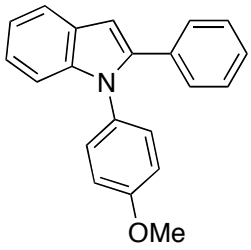
2-(4-Methoxyphenyl)-1*H*-indole (1c).[7] The title compound prepared from 4'-methoxyacetophenone phenylhydrazone (5.3 g, 22 mmol) by the Fischer indole synthesis was obtained in 47% yield (2.31 g) through isolation by column chromatography on silica gel (hexane/EtOAc = 6/1). ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.86 (s, 3 H), 6.72 (dd, *J* = 2.3, 1.2 Hz, 1 H), 6.98 (dt, *J* = 8.6, 2.4 Hz, 2 H), 7.11 (td, *J* = 7.5, 1.2 Hz, 2 H), 7.17 (td, *J* = 7.7, 1.2 Hz, 1 H), 7.38 (dd, *J* = 8.0, 1.2 Hz, 1 H), 7.56–7.63 (m, 3 H), 8.24 (bs, 1 H).



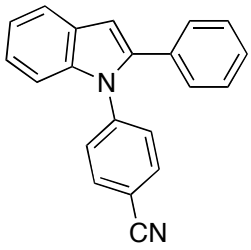
2-(2-Methoxyphenyl)-1*H*-indole (1d).[60] The title compound prepared from 2'-methoxyacetophenone phenylhydrazone (3.6 g, 15 mmol) by the Fischer indole synthesis was obtained in 61% yield (2.04 g) through isolation by column chromatography on silica gel (hexane/EtOAc = 4/1) followed by washing with *n*-pentane. ^{1}H NMR (500 MHz, $CDCl_3$) δ 4.02 (s, 3 H), 6.90 (dd, *J* = 2.0, 1.2 Hz, 1 H), 7.03 (d, *J* = 8.0 Hz, 1 H), 7.06 (td, *J* = 7.5, 1.2 Hz, 1 H), 7.10 (td, *J* = 7.5, 1.2 Hz, 1 H), 7.17 (ddd, *J* = 8.2, 7.0, 1.2 Hz, 1 H), 7.28 (ddd, *J* = 8.3, 7.2, 1.4 Hz, 1 H), 7.41 (d, *J* = 8.0 Hz, 1 H), 7.63 (dd, *J* = 8.0, 1.2 Hz, 1 H), 7.84 (dd, *J* = 8.0, 1.7 Hz, 1 H), 9.66 (bs, 1 H).



2-(4-Hydroxyphenyl)-1*H*-indole (1e).[1b] The title compound prepared from 4'-hydroxyacetophenone phenylhydrazone (2.9 g, 13 mmol) by the Fischer indole synthesis was obtained in 6% yield (163 mg) through isolation by recrystallization from benzene. ^{1}H NMR (400 MHz, CD_3COCD_3) δ 6.71 (dd, *J* = 2.3, 0.9 Hz, 1 H), 6.93 (dt, *J* = 8.7, 2.4 Hz, 2 H), 6.98 (td, *J* = 7.4, 1.1 Hz, 1 H), 7.05 (td, *J* = 7.6, 1.2 Hz, 1 H), 7.34–7.40 (m, 1 H), 7.51 (d, *J* = 7.8 Hz, 1 H), 7.70 (dt, *J* = 8.7, 2.5 Hz, 2 H), 8.49 (s, 1 H), 10.47 (bs, 1 H).

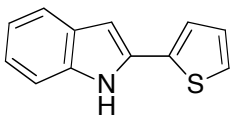


1-(4-Methoxyphenyl)-2-phenyl-1*H*-indole (1h). [61] The title compound prepared from 2-phenyl-1*H*-indole (1.50 g, 7.76 mmol) and *p*-iodoanisole (1.51 g, 6.47 mmol) according to the reported procedure[2] was obtained in 74% yield (1.72 g) through isolation by column chromatography on silica gel (hexane/EtOAc = 30/1). ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.84 (s, 3 H), 6.78 (s, 1 H), 6.93 (dt, *J* = 8.6, 2.8 Hz, 2 H), 7.14–7.31 (m, 10 H), 7.64–7.70 (m, 1 H).

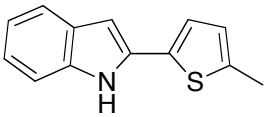


1-(4-Cyanophenyl)-2-phenyl-1*H*-indole (1i).[62] The title compound prepared from 2-phenyl-1*H*-indole (1.64 g, 8.50 mmol) and *p*-bromobenzonitrile (1.46 g, 8.00 mmol) according to the reported procedure[2] was obtained in 65% yield (1.53 g) through isolation by column chromatography on silica gel (hexane/EtOAc = 15/1). ^{1}H NMR

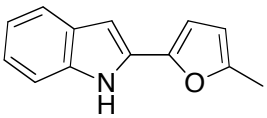
(400 MHz, $CDCl_3$) δ 6.83 (d, *J* = 0.9 Hz, 1 H), 7.17–7.38 (m, 10 H), 7.66–7.72 (m, 3 H).



2-(Thien-2-yl)-1*H*-indole (1j).[63] The title compound prepared from 1-(thien-2-yl)ethanone phenylhydrazone (2.2 g, 10 mmol) by the Fischer indole synthesis was obtained in 67% yield (1.34 g) through isolation by column chromatography on silica gel (hexane/EtOAc = 25/1 to 10/1). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.73 (dd, *J* = 2.0, 1.2 Hz, 1 H), 7.03–7.12 (m, 2 H), 7.19 (ddd, *J* = 8.0, 6.9, 1.2 Hz, 1 H), 7.26 (dd, *J* = 3.5, 1.2 Hz, 1 H), 7.28 (dd, *J* = 5.2, 1.2 Hz, 1 H), 7.37 (dt, *J* = 7.8, 1.2 Hz, 1 H), 7.59 (dd, *J* = 7.8, 1.2 Hz, 1 H), 8.20 (bs, 1 H).

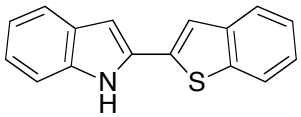


2-(5-Methylthien-2-yl)-1*H*-indole (1k). The title compound prepared from 1-(5-methylthien-2-yl)ethanone phenylhydrazone (6.9 g, 30 mmol) by the Fischer indole synthesis was obtained in 41% yield (2.62 g) through isolation by column chromatography on silica gel (hexane/EtOAc = 20/1) followed by washing with *n*-pentane. A white solid, mp 128–129 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.52 (d, *J* = 1.2 Hz, 3 H), 6.64 (d, *J* = 2.9 Hz, 1 H), 6.71–6.75 (m, 1 H), 7.04 (d, *J* = 3.4 Hz, 1 H), 7.10 (td, *J* = 7.5, 1.2 Hz, 1 H), 7.17 (ddd, *J* = 8.0, 6.9, 1.1 Hz, 1 H), 7.35 (dd, *J* = 8.0, 1.1 Hz, 1 H), 7.57 (dd, *J* = 7.8, 1.2 Hz, 1 H), 8.14 (bs, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 15.3, 99.7, 110.7, 120.41, 120.44, 122.4, 122.8, 126.1, 129.2, 132.7, 133.4, 136.5, 139.6. HRMS (ESI) Calcd for $C_{13}H_{12}NS$: M^++H, 214.0690. Found: *m/z* 214.0696.

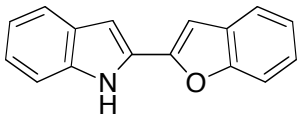


2-(5-Methylfuran-2-yl)-1*H*-indole (1l). The title compound prepared from 1-(5-methylfuran-2-yl)ethanone phenylhydrazone (4.3 g, 20 mmol) by the Fischer indole

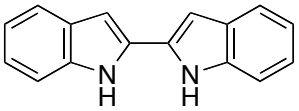
synthesis was obtained in 13% yield (510 mg) through isolation by column chromatography on silica gel (hexane/EtOAc = 25/1). A white solid, mp 85–86 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.38 (s, 3 H), 6.08 (dt, *J* = 3.2, 0.9 Hz, 1 H), 6.51 (d, *J* = 3.2 Hz, 1 H), 6.65–6.69 (m, 1 H), 7.10 (td, *J* = 7.5, 0.9 Hz, 1 H), 7.17 (td, *J* = 7.6, 0.9 Hz, 1 H), 7.33–7.40 (m, 1 H), 7.58 (d, *J* = 7.8 Hz, 1 H), 8.38 (bs, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 13.6, 97.9, 106.3, 107.8, 110.7, 120.2, 120.4, 122.1, 129.0, 129.6, 135.9, 146.0, 151.7. HRMS (ESI) Calcd for $C_{13}H_{11}NO$: M^+, 197.0840. Found: *m*/*z* 197.0833.



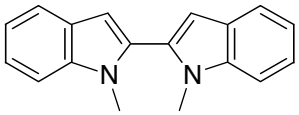
2-{Benzo[*b*]thien-2-yl}-1*H*-indole (1m).[11] The title compound prepared from 1-{benzo[*b*]then-2-yl}ethanone phenylhydrazone (7.2 g, 27 mmol) by the Fischer indole synthesis was obtained in 27% yield (1.82 g) through isolation by column chromatography on silica gel (hexane/EtOAc = 10/1). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.87 (dd, *J* = 2.3, 1.2 Hz, 1 H), 7.14 (td, *J* = 7.5, 1.2 Hz, 1 H), 7.23 (ddd, *J* = 8.3, 7.2, 1.2 Hz, 1 H), 7.33 (ddd, *J* = 8.2, 7.0, 1.2 Hz, 1 H), 7.37 (td, *J* = 7.5, 1.2 Hz, 1 H), 7.41 (d, *J* = 7.5 Hz, 1 H), 7.47 (s, 1 H), 7.63 (dd, *J* = 7.7, 1.2, Hz, 1 H), 7.78 (dd, *J* = 7.7, 1.2 Hz, 1 H), 7.83 (dd, *J* = 8.1, 1.2 Hz, 1 H), 8.35 (bs, 1 H).



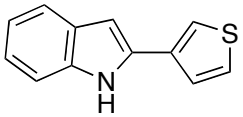
2-{Benzo[*b*]furan-2-yl}-1*H*-indole (1n).[11] The title compound prepared from 1-{benzo[*b*]furan-2-yl}ethanone phenylhydrazone (2.2 g, 8.8 mmol) by the Fischer indole synthesis was obtained in 78% yield (1.60 g) through isolation by column chromatography on silica gel (hexane/EtOAc = 10/1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.97–7.02 (m, 2 H), 7.15 (ddd, *J* = 7.9, 7.0, 0.9 Hz, 1 H), 7.20–7.34 (m, 3 H), 7.43 (dd, *J* = 8.2, 0.9 Hz, 1 H), 7.49–7.55 (m, 1 H), 7.56–7.62 (m, 1 H), 7.65 (d, *J* = 8.2 Hz, 1 H), 8.64 (bs, 1 H).



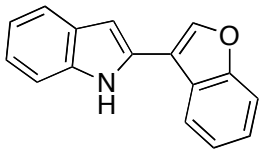
2,2'-Biindolyl (1o).[11a, 64] The title compound prepared from 1-(indol-2-yl)ethanone phenylhydrazone (4.5 g, 18 mmol) by the Fischer indole synthesis was obtained in 28% yield (1.17 g) through isolation by recrystallization from ethanol. ^{1}H NMR (400 MHz, DMSO-d_6) δ 6.91 (d, J = 1.4 Hz, 2 H), 7.01 (td, J = 7.6 Hz, 2 H), 7.11 (ddd, J = 8.3, 6.9, 0.9 Hz, 2 H), 7.40 (d, J = 8.2 Hz, 2 H), 7.56 (d, J = 7.8 Hz, 2 H), 11.52 (s, 2 H); ^{13}C NMR (75 MHz, DMSO-d_6) δ 98.4, 111.0, 119.3, 120.0, 121.6, 128.4, 131.4, 136.9.



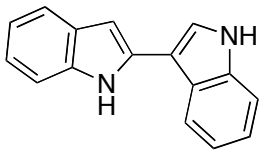
2,2'-Bis(*N*-methylindolyl) (1p).[3] The title compound prepared from *N*-methylindole (6.03 g, 46.0 mmol) according to the reported procedure[3] was obtained in 33% yield (1.98 g) through isolation by recrystallization from hexane/CH_2Cl_2. ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.70 (s, 6 H), 6.65 (s, 2 H), 7.18 (t, J = 7.5 Hz, 2 H), 7.29 (t, J = 7.7 Hz, 2 H), 7.40 (d, J = 8.0 Hz, 2 H), 7.68 (d, J = 8.0 Hz, 2 H).



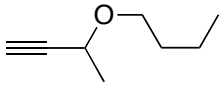
2-(Thien-3-yl)-1*H*-indole (1q). The title compound prepared from 1-(thien-3-yl)ethanone phenylhydrazone (6.2 g, 29 mmol) by the Fischer indole synthesis was obtained in 12% yield (693 mg) through isolation by column chromatography on silica gel (hexane/EtOAc = 10/1). A white solid, mp 172–174 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.71 (d, J = 1.8 Hz, 1 H), 7.11 (t, J = 7.5 Hz, 1 H), 7.19 (t, J = 7.4 Hz, 1 H), 7.38 (d, J = 8.0 Hz, 1 H), 7.40–7.44 (m, 3 H), 7.61 (d, J = 8.0 Hz, 1 H), 8.21 (bs, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 100.0, 110.7, 119.1, 120.3, 120.6, 122.3, 125.7, 126.6, 129.1, 133.9, 134.1, 136.4. HRMS (ESI) Calcd for $C_{12}H_9NS$: M^+, 199.0456. Found: m/z 199.0452.



2-{Benzo[*b*]furan-3-yl}-1*H*-indole (1r). The title compound prepared from 1-{benzo[*b*]furan-3-yl}ethanone phenylhydrazone (5.2 g, 21 mmol) by the Fischer indole synthesis was obtained in 28% yield (1.37 g) through isolation by column chromatography on silica gel (hexane/EtOAc = 7/1). A white solid, mp 133–135 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.88 (d, *J* = 2.3 Hz, 1 H), 7.16 (td, *J* = 7.6, 0.9 Hz, 1 H), 7.23 (td, *J* = 7.6, 0.9 Hz, 1 H), 7.34–7.46 (m, 3 H), 7.57 (dd, *J* = 7.1, 2.1 Hz, 1 H), 7.67 (d, *J* = 7.8 Hz, 1 H), 7.91 (s, 1 H), 7.94 (dd, *J* = 6.6, 2.1 Hz, 1 H), 8.25 (bs, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 101.4, 110.7, 111.9, 114.8, 120.3, 120.48, 120.54, 122.4, 123.4, 125.1, 125.7, 129.0, 129.3, 136.3, 140.8, 155.6. HRMS (ESI) Calcd for $C_{16}H_{12}NO$: M^++H, 234.0919. Found: *m*/*z* 234.0919.

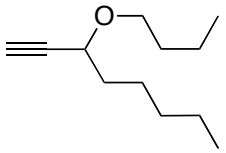


2,3'-Biindolyl (1s).[4,65] The title compound prepared from indole (2.93 g, 25.0 mmol) according to the known procedure[4] was obtained in 66% yield (1.92 g) through isolation by recrystallization from hexane/CH_2Cl_2. ^{1}H NMR (400 MHz, DMSO-d_6) δ 6.76 (d, *J* = 1.4 Hz, 1 H), 6.96 (ddd, *J* = 7.8, 6.9, 0.9 Hz, 1 H), 7.03 (td, *J* = 7.6, 1.1 Hz, 1 H), 7.11–7.24 (m, 2 H), 7.36 (d, *J* = 7.8 Hz, 1 H), 7.43–7.55 (m, 2 H), 7.86 (d, *J* = 2.7 Hz, 1 H), 8.00 (d, *J* = 7.3 Hz, 1 H), 11.19 (s, 1 H), 11.38 (s, 1 H).

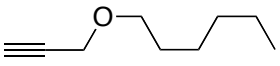


Preparation of 3-Butoxy-1-butyne (2b). A General Synthetic Procedure of a Propargyl Ether. A 100 mL two necked round-bottomed flask was charged with a 55% dispersion of NaH (1.20 g, 50.0 mmol) in paraffin oil, which was washed with hexane (5 mL x 2). To this was added THF (30 mL) and the suspension was cooled to 0 °C. 1-Butyn-3-ol (3.50 g, 50.0 mmol) was added dropwise and the resulting solution was warmed up to room temperature. After being stirred for 1 h, 1-iodobutane (7.36 g, 40.0 mmol) was added dropwise over a period of 5 min, and the mixture was stirred for

20 h. The solution was diluted with Et_2O (50 mL) and washed with saturated NH_4Cl aqueous solution (5 mL x 2). The aqueous solution was extracted with Et_2O (10 mL x 2) and the combined organic layer was washed with saturated $NaHCO_3$ aqueous solution (5 mL) and brine (5 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by distillation (70 °C/100 mmHg) gave 3-butoxy-1-butyne (2.02 g, 40% yield) as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.92 (t, *J* = 7.3 Hz, 3 H), 1.32–1.45 (m, 2 H), 1.44 (d, *J* = 6.4 Hz, 3 H), 1.52–1.63 (m, 2 H), 2.39 (d, *J* = 2.3 Hz, 1 H), 3.38 (dt, *J* = 9.2, 6.5 Hz, 1 H), 3.72 (dt, *J* = 9.2, 6.8 Hz, 1 H), 4.13 (qd, *J* = 6.8, 1.8 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.8, 19.3, 22.1, 31.7, 65.0, 68.6, 72.4, 84.2. Anal. Calcd for $C_8H_{14}O$: C, 76.14; H, 11.18. Found: C, 75.95; H, 11.41.

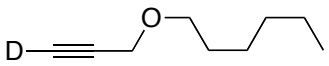


3-Butoxy-1-octyne (2c). The title compound was prepared by the reaction of 1-octyne-3-ol (5.05 g, 40.0 mmol) with 1-iodobutane (5.52 g, 30.0 mmol) according to the above general procedure and purified by column chromatography on silica gel (hexane/EtOAc = 100/1, 2.24 g, 41% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.80–1.01 (m, 6 H), 1.20–1.51 (m, 8 H), 1.57 (quint, *J* = 7.3 Hz, 2 H), 1.62–1.81 (m, 2 H), 2.40 (d, *J* = 1.8 Hz, 1 H), 3.36 (dt, *J* = 9.2, 6.7 Hz, 1 H), 3.73 (dt, *J* = 9.2, 6.6 Hz, 1 H), 3.99 (td, *J* = 6.6, 2.3 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.9, 14.0, 19.3, 22.5, 24.9, 31.5, 31.7, 35.7, 68.7, 69.4, 73.0, 83.6. Anal. Calcd for $C_{12}H_{22}O$: C, 79.06; H, 12.16. Found: C, 79.31; H, 12.28.



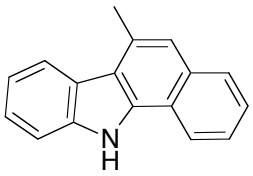
3-Hexyloxy-1-propyne. The title compound for the synthesis of 1-deuterio-3-hexyloxy-1-propyne (**2l**) was prepared by the reaction of propargyl alcohol (2.52 g, 45.0 mmol) with 1-iodohexane (8.06 g, 38.0 mmol) according to the above general procedure and purified by column chromatography on silica gel (pentane/Et_2O = 250/1, 2.29 g, 43% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.89 (t, *J* = 6.9 Hz, 3 H), 1.24–1.40 (m, 6 H), 1.60 (quint, *J* = 7.0 Hz, 2 H), 2.41 (t, *J* = 2.3 Hz, 1 H), 3.51 (t, *J* = 6.6 Hz, 2 H), 4.14

(d, J = 2.3 Hz, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.9, 22.5, 25.7, 29.4, 31.6, 58.0, 70.3, 74.0, 80.1. Anal. Calcd for $C_9H_{16}O$: C, 77.09; H, 11.50. Found: C, 77.27; H, 11.77.



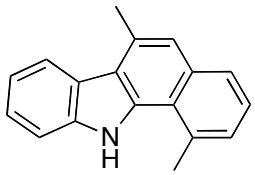
Preparation of 1-Deuterio-3-hexyloxy-1-propyne (2l). A 50 mL two necked, round-bottomed flask was charged with 3-hexyloxy-1-propyne (1.50 g, 10.7 mmol). To this was added Et_2O (20 mL) and the solution was cooled to –78 °C. Hexane solution of BuLi (1.54 M, 6.95 mL, 10.7 mmol) was added dropwise over a period of 10 min. After being stirred for 1 h at –78 °C, D_2O solution of DCl (1.6 M, 6.3 mL) was added and the mixture was slowly warmed up to room temperature. The solution was diluted with Et_2O (50 mL) and washed with saturated NH_4Cl aqueous solution (5 mL). The aqueous solution was extracted with Et_2O (10 mL x 2) and the combined organic layer was washed with brine (5 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (pentane/Et_2O = 250/1) gave 1-deuterio-3-hexyloxy-1-propyne (1.26 g, 84% yield) as a colorless oil. ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.86–0.93 (m, 3 H), 1.24–1.40 (m, 6 H), 1.56–1.63 (m, 2 H), 3.51 (t, J = 6.9 Hz, 2 H), 4.14 (s, 2 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 14.0, 22.6, 25.8, 29.5, 31.7, 58.0, 70.3, 73.7 (t, J = 37.9 Hz), 79.7 (t, J = 7.2 Hz). Anal. Calcd for $C_9H_{15}OD$: C, 76.54; H, 12.13. Found: C, 76.24; H, 11.85.

Synthesis of Aryl- and Heteroaryl-Annulated[*a*]carbazoles Utilizing In(ONf)$_3$-Catalyzed Reaction of 2-Aryl- and 2-Heteroarylindoles with Propargyl Ethers. A General Procedure. In(ONf)$_3$ (60.7 mg, 60.0 μmol) was placed in a 20 mL Schlenk tube, which was heated at 150 °C in vacuo for 2 h. The tube was cooled down to room temperature and filled with nitrogen. Dibutyl ether (3.0 or 9.0 mL) or PhCl (9.0 mL) was added to the tube and stirred for 10 min at room temperature. To this were added a 2-aryl- or 2-heteroarylindole (0.20 mmol) and a propargyl ether (0.22 mmol) successively, and the resulting mixture was stirred at 70 or 100 °C. After the time specified in Table 2, Table 3 and Scheme 2, the mixture was diluted with ethyl acetate (10 mL) and washed with saturated $NaHCO_3$ aqueous solution (1 mL) and brine (1 mL), and then dried over anhydrous sodium sulfate. Filtration through a pad of Celite and evaporation of the solvent followed by column chromatography on silica gel gave the corresponding aryl- or heteroaryl-annulated[*a*]carbazole. For aryl-annulated[*a*]carbazoles, further purification was performed with recycling gel permeation chromatography. The results are summarized in Table 2, Table 3, Scheme 2 and Eq. 4. All aryl- and heteroaryl-annulated[*a*]carbazoles were characterized by ^{1}H and ^{13}C NMR spectroscopy, and elemental analysis and/or HRMS spectroscopy.

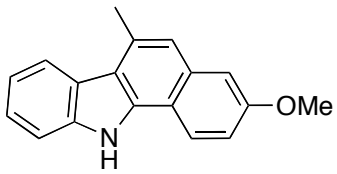


6-Methyl-11*H*-benzo[*a*]carbazole (3a). The title compound prepared from 2-phenyl-1*H*-indole (38.6 mg, 0.200 mmol) and 3-methoxy-1-propyne (15.4 mg, 0.220 mmol) was obtained in 65% yield (30.0 mg) through isolation by column chromatography on silica gel (hexane/EtOAc = 10/1) followed by further purification using recycling gel permeation chromatography (entry 1 of Table 2). A white solid, mp 119–120 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.01 (d, J = 0.9 Hz, 3 H), 7.32 (td, J = 7.6, 1.1 Hz, 1 H), 7.42 (s, 1 H), 7.45 (td, J = 7.6, 1.2 Hz, 1 H), 7.48–7.58 (m, 2 H), 7.62 (d, J = 7.8 Hz, 1 H), 7.93 (dd, J = 7.1, 2.1 Hz, 1 H), 8.09–8.14 (m, 1 H), 8.26 (d, J = 8.2 Hz, 1 H), 8.83 (bs, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 21.3, 110.9, 118.2, 119.7, 120.0, 120.1, 120.2, 122.1, 124.4, 124.6, 124.8, 125.4, 128.1, 132.2, 132.5, 134.9, 138.6. HRMS (ESI) Calcd for $C_{17}H_{13}N$: M^+, 231.1047. Found: m/z 231.1039.

Anal. Calcd for $C_{17}H_{13}N$: C, 88.28; H, 5.67; N, 6.06. Found: C, 88.48; H, 5.47; N, 6.15.

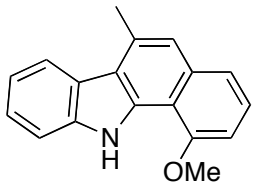


1,6-Dimethyl-11*H*-benzo[*a*]carbazole (3b). The title compound prepared from 2-(2-methylphenyl)-1*H*-indole (41.5 mg, 0.200 mmol) and 3-methoxy-1-propyne (15.4 mg, 0.220 mmol) was obtained in 72% yield (35.3 mg) through isolation by column chromatography on silica gel (hexane/EtOAc = 20/1) followed by further purification using recycling gel permeation chromatography (entry 2 of Table 2). A white solid, mp 125–127 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.00 (s, 3 H), 3.15 (s, 3 H), 7.29–7.36 (m, 2 H), 7.39 (dd, *J* = 8.0, 6.9 Hz, 1 H), 7.42 (s, 1 H), 7.46 (ddd, *J* = 8.3, 7.2, 1.1 Hz, 1 H), 7.64 (dd, *J* = 8.0, 1.2 Hz, 1 H), 7.80 (d, *J* = 8.1 Hz, 1 H), 8.30 (d, *J* = 8.1 Hz, 1 H), 9.22 (bs, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 21.4, 23.8, 110.9, 118.9, 119.8, 120.0, 121.1, 122.0, 123.5, 124.2, 124.9, 126.6, 127.0, 131.5, 131.9, 133.6, 135.5, 138.2. HRMS (ESI) Calcd for $C_{18}H_{15}N$: M^+, 245.1205. Found: *m*/*z* 245.1202. Anal. Calcd for $C_{18}H_{15}N$: C, 88.13; H, 6.16; N, 5.71. Found: C, 87.96; H, 6.23; N, 5.50.

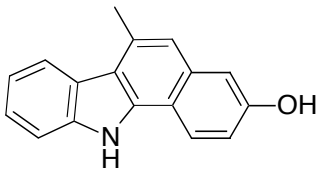


3-Methoxy-6-methyl-11*H*-benzo[*a*]carbazole (3c). The title compound prepared from 2-(4-methoxyphenyl)-1*H*-indole (44.7 mg, 0.200 mmol) and 3-methoxy-1-propyne (15.4 mg, 0.220 mmol) was obtained in 67% yield (35.0 mg) through isolation by column chromatography on silica gel (hexane/EtOAc = 4/1) followed by further purification using recycling gel permeation chromatography (entry 3 of Table 2). A white solid, mp 139–140 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.98 (d, *J* = 0.9 Hz, 3 H), 3.96 (s, 3 H), 7.20 (dd, *J* = 8.9, 2.5 Hz, 1 H), 7.26–7.35 (m, 3 H), 7.41 (td, *J* = 7.7, 0.9 Hz, 1 H), 7.58 (d, *J* = 7.8 Hz, 1 H), 8.00 (d, *J* = 8.7 Hz, 1 H), 8.22 (d, *J* = 7.8 Hz, 1

H), 8.71 (bs, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 21.3, 55.4, 107.3, 110.8, 114.7, 116.5, 116.8, 119.3, 119.9, 121.7, 121.8, 123.9, 124.9, 132.9, 133.9, 135.3, 138.5, 157.6. HRMS (ESI) Calcd for $C_{18}H_{15}NO$: M^+, 261.1153. Found: *m*/*z* 261.1130. Anal. Calcd for $C_{18}H_{15}NO$: C, 82.73; H, 5.79; N, 5.36. Found: C, 82.77; H, 5.46; N, 5.00.

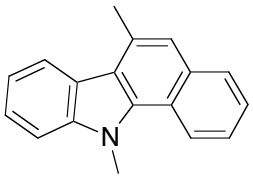


1-Methoxy-6-methyl-11*H*-benzo[*a*]carbazole (3d). The title compound prepared from 2-(2-methoxyphenyl)-1*H*-indole (44.7 mg, 0.200 mmol) and 3-methoxy-1-propyne (15.4 mg, 0.220 mmol) was obtained in 59% yield (30.8 mg) through isolation by column chromatography on silica gel (hexane/EtOAc = 9/1) followed by further purification using recycling gel permeation chromatography (entry 4 of Table 2). A white solid, mp 154–155 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.01 (d, *J* = 0.9 Hz, 3 H), 4.20 (s, 3 H), 6.93 (d, *J* = 7.3 Hz, 1 H), 7.31 (td, *J* = 7.6, 0.9 Hz, 1 H), 7.37 (d, *J* = 0.9 Hz, 1H), 7.38–7.48 (m, 2 H), 7.54 (d, *J* = 8.2 Hz, 1 H), 7.65 (d, *J* = 8.2 Hz, 1 H), 8.28 (d, *J* = 7.8 Hz, 1 H), 10.09 (bs, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 21.2, 55.7, 103.5, 111.0, 111.7, 117.8, 119.3, 119.5, 120.5, 121.9, 123.5, 124.0, 125.3, 133.0, 134.3, 134.4, 138.0, 156.1. HRMS (ESI) Calcd for $C_{18}H_{15}NO$: M^+, 261.1153. Found: *m*/*z* 261.1131. Anal. Calcd for $C_{18}H_{15}NO$: C, 82.73; H, 5.79; N, 5.36. Found: C, 82.86; H, 5.50; N, 5.58.

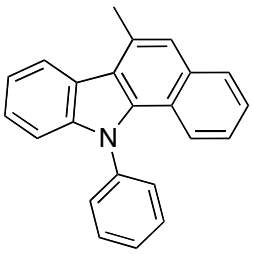


3-Hydroxy-6-methyl-11*H*-benzo[*a*]carbazole (3e). The title compound prepared from 2-(4-hydroxyphenyl)-1*H*-indole (41.8 mg, 0.200 mmol) and 3-methoxy-1-propyne (15.4 mg, 0.220 mmol) was obtained in 48% yield (23.7 mg) through isolation by column chromatography on silica gel (hexane/EtOAc = 2/1) followed by further purification using recycling gel permeation chromatography (entry 5 of Table 2).

A white solid, mp 180–182 °C. ^{1}H NMR (400 MHz, CD_3COCD_3) δ 2.93 (d, *J* = 1.4 Hz, 3 H), 7.16 (dd, *J* = 8.7, 2.3 Hz, 1 H), 7.19–7.25 (m, 2 H), 7.29 (d, *J* = 2.8 Hz, 1 H), 7.34 (ddd, *J* = 8.1, 7.2, 0.9 Hz, 1 H), 7.56–7.62 (m, 1 H), 8.18 (d, *J* = 7.8 Hz, 1 H), 8.30 (d, *J* = 9.2 Hz, 1 H), 8.53 (s, 1 H), 11.12 (bs, 1 H); ^{13}C NMR (100 MHz, CD_3COCD_3) δ 21.5, 110.9, 111.8, 115.7, 116.6, 117.0, 119.2, 120.2, 122.2, 123.7, 124.3, 125.5, 133.2, 135.3, 136.9, 139.9, 156.2. HRMS (ESI) Calcd for $C_{17}H_{13}NO$: M^+, 247.0996. Found: *m*/*z* 247.0987. Anal. Calcd for $C_{17}H_{13}NO$: C, 82.57; H, 5.30; N, 5.66. Found: C, 82.19; H, 5.48; N, 5.50.

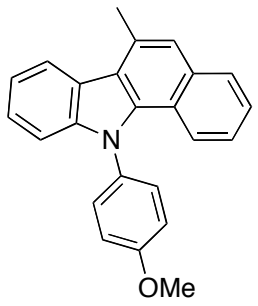


6,11-Dimethyl-11*H*-benzo[*a*]carbazole (3f).[66] The title compound prepared from 1-methyl-2-phenyl-1*H*-indole (41.5 mg, 0.200 mmol) and 3-methoxy-1-propyne (15.4 mg, 0.220 mmol) was obtained in 52% yield (25.5 mg) through isolation by column chromatography on silica gel (hexane/EtOAc = 150/1) followed by further purification using recycling gel permeation chromatography (entry 6 of Table 2). A white solid, mp 138–139 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.02 (s, 3 H), 4.43 (s, 3 H), 7.32 (t, *J* = 7.3 Hz, 1 H), 7.42 (s, 1 H), 7.47–7.56 (m, 3 H), 7.59 (d, *J* = 8.2 Hz, 1 H), 7.96 (dd, *J* = 6.9, 2.8 Hz, 1 H), 8.31 (d, *J* = 8.2 Hz, 1 H), 8.70 (dd, *J* = 6.9, 2.3 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 21.6, 34.1, 108.9, 118.5, 119.4, 120.6, 121.2, 122.0, 122.1, 123.5, 124.1, 124.2, 124.7, 128.5, 132.0, 133.5, 135.7, 140.8. HRMS (ESI) Calcd for $C_{18}H_{15}N$: M^+, 245.1204. Found: *m*/*z* 245.1199. Anal. Calcd for $C_{18}H_{15}N$: C, 88.13; H, 6.16; N, 5.71. Found: C, 87.93; H, 6.20; N, 5.89.

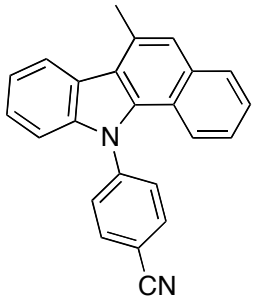


6-Methyl-11-phenyl-11*H*-benzo[*a*]carbazole (3g). The title compound prepared from 1,2-diphenyl-1*H*-indole (53.9 mg, 0.200 mmol) and 3-methoxy-1-

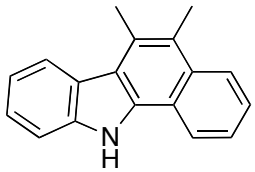
propyne (15.4 mg, 0.220 mmol) was obtained in 57% yield (35.0 mg) through isolation by column chromatography on silica gel (hexane/EtOAc = 60/1) followed by further purification using recycling gel permeation chromatography (entry 7 of Table 2). A white solid, mp 105–107 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.07 (s, 3 H), 7.13 (ddd, 8.6, 6.9, 1.3 Hz, 1 H), 7.18 (dd, *J* = 7.5, 1.2 Hz, 1 H), 7.31–7.42 (m, 4H), 7.48 (s, 1 H), 7.50–7.55 (m, 2 H), 7.61–7.69 (m, 3 H), 7.90 (d, *J* = 8.0 Hz, 1 H), 8.32–8.37 (m, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 21.6, 110.3, 119.0, 120.2, 120.5, 121.2, 121.9, 122.2, 123.8, 124.0, 124.4, 124.8, 128.2, 128.8, 129.2, 130.1, 131.9, 133.4, 135.6, 140.2, 142.1. HRMS (ESI) Calcd for $C_{23}H_{17}N$: M^+, 307.1361. Found: *m*/*z* 307.1374. Anal. Calcd for $C_{23}H_{17}N$: C, 89.87; H, 5.57; N, 4.56. Found: C, 89.91; H, 5.78; N, 4.36.



11-(4-Methoxyphenyl)-6-methyl-11*H*-benzo[*a*]carbazole (3h). The title compound prepared from 1-(4-methoxyphenyl)-2-phenyl-1*H*-indole (59.9 mg, 0.200 mmol) and 3-methoxy-1-propyne (15.4 mg, 0.220 mmol) was obtained in 60% yield (40.5 mg) through isolation by column chromatography on silica gel (hexane/EtOAc = 25/1) followed by further purification using recycling gel permeation chromatography (entry 8 of Table 2). A white solid, mp 122–124 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.07 (s, 3 H), 3.98 (s, 3 H), 7.13–7.20 (m, 4 H), 7.34 (td, *J* = 7.6, 1.2 Hz, 1 H), 7.36–7.45 (m, 5 H), 7.46 (s, 1 H), 7.90 (d, *J* = 8.1 Hz, 1 H), 8.33 (d, *J* = 7.6 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 21.6, 55.7, 110.3, 115.3, 118.9, 120.1, 120.7, 121.1, 121.9, 122.2, 123.7, 124.0, 124.3, 124.8, 128.2, 130.3, 131.9, 132.8, 133.4, 135.9, 142.5, 159.9. HRMS (ESI) Calcd for $C_{24}H_{19}NO$: M^+, 337.1467. Found: *m*/*z* 337.1488. Anal. Calcd for $C_{24}H_{19}NO$: C, 85.43; H, 5.68; N, 4.15. Found: C, 85.39; H, 5.83; N, 4.04.

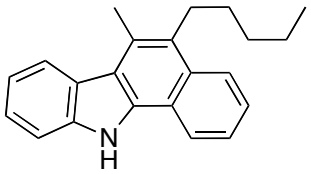


11-(4-Cyanophenyl)-6-methyl-11*H*-benzo[*a*]carbazole (3i). The title compound prepared from 1-(4-cyanophenyl)-2-phenyl-1*H*-indole (58.9 mg, 0.200 mmol) and 3-methoxy-1-propyne (15.4 mg, 0.220 mmol) was obtained in 48% yield (31.9 mg) through isolation by column chromatography on silica gel (hexane/EtOAc = 15/1) followed by further purification using recycling gel permeation chromatography (entry 9 of Table 2). A white solid, mp 146–148 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.06 (s, 3 H), 7.17–7.23 (m, 2 H), 7.23–7.28 (m, 1 H), 7.35 –7.46 (m, 3 H), 7.53 (s, 1 H), 7.67 (d, *J* = 8.6 Hz, 2 H), 7.93 (d, *J* = 8.1 Hz, 1 H), 7.96 (d, *J* = 8.0 Hz, 2 H), 8.34 (d, *J* = 8.0 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 21.5, 109.9, 112.6, 118.1, 120.2, 121.2, 121.9, 122.30, 122.32, 124.5, 124.6, 125.0, 125.2, 128.6, 129.9, 131.9, 133.5, 134.0, 135.2, 141.7, 144.7 (One carbon signal is missing due to overlapping.). HRMS (ESI) Calcd for $C_{24}H_{16}N_2$: M^+, 332.1314. Found: *m*/*z* 332.1301. Anal. Calcd for $C_{24}H_{16}N_2$: C, 86.72; H, 4.85; N, 8.43. Found: C, 86.50; H, 4.88; N, 8.32.

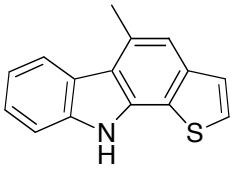


5,6-Dimethyl-11*H*-benzo[*a*]carbazole (3j). The title compound prepared from 2-phenyl-1*H*-indole (38.6 mg, 0.200 mmol) and 3-butoxy-1-butyne (27.8 mg, 0.220 mmol) was obtained in 68% yield (33.5 mg) through isolation by column chromatography on silica gel (hexane/EtOAc = 15/1) followed by further purification using recycling gel permeation chromatography (entry 10 of Table 2). A white solid, mp 182–183 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.75 (s, 3 H), 3.02 (s, 3 H), 7.30 (ddd, *J* = 8.0, 6.9, 1.1 Hz, 1 H), 7.43 (ddd, *J* = 8.0, 6.9, 1.2 Hz, 1 H), 7.52–7.64 (m, 3 H), 8.10–8.15 (m, 1 H), 8.16–8.22 (m, 1 H), 8.34 (d, *J* = 8.0 Hz, 1 H), 8.76 (bs, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 14.3, 17.7, 110.9, 118.3, 119.8, 119.9, 120.7, 122.47,

122.54, 124.18, 124.22, 125.0, 125.30, 125.34, 129.8, 131.9, 133.6, 138.7. HRMS (ESI) Calcd for $C_{18}H_{15}N$: M^+, 245.1205. Found: *m*/*z* 245.1195. Anal. Calcd for $C_{18}H_{15}N$: C, 88.13; H, 6.16; N, 5.71. Found: C, 88.12; H, 6.23; N, 5.66.

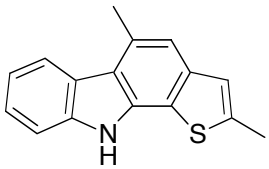


6-Methyl-5-pentyl-11*H*-benzo[*a*]carbazole (3k). The title compound prepared from 2-phenyl-1*H*-indole (38.6 mg, 0.200 mmol) and 3-butoxy-1-octyne (40.1 mg, 0.220 mmol) was obtained in 74% yield (44.6 mg) through isolation by column chromatography on silica gel (hexane/EtOAc = 13/1) followed by further purification using recycling gel permeation chromatography (entry 11 of Table 2). A white solid, mp 141–142 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.95 (t, *J* = 7.2 Hz, 3 H), 1.43 (sext, *J* = 7.3 Hz, 2 H), 1.53 (quint, *J* = 7.5 Hz, 2 H), 1,70 (quint, *J* = 7.7 Hz, 2 H), 3.01 (s, 3 H), 3.21 (t, *J* = 8.3 Hz, 2 H), 7.29 (t, *J* = 7.5 Hz, 1 H), 7.43 (t, *J* = 7.4 Hz, 1 H), 7.50–7.61 (m, 3 H), 8.09–8.15 (m, 1 H), 8.15–8.21 (m, 1 H), 8.33 (d, *J* = 8.0 Hz, 1 H), 8.76 (bs, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 14.2, 17.4, 22.7, 28.2, 30.8, 32.4, 110.9, 118.2, 119.7, 120.1, 120.8, 122.5, 124.1, 124.2, 125.0, 125.2, 125.3, 127.8, 129.5, 131.1, 133.6, 138.7. HRMS (ESI) Calcd for $C_{22}H_{23}N$: M^+, 301.1831. Found: *m*/*z* 301.1827. Anal. Calcd for $C_{22}H_{23}N$: C, 87.66; H, 7.69; N, 4.65. Found: C, 87.50; H, 7.80; N, 4.46.

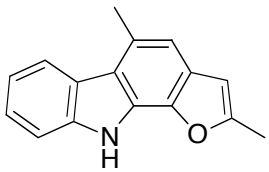


5-Methyl-10*H*-thieno[2,3-*a*]carbazole (3l). The title compound prepared from 2-(thien-2-yl)-1*H*-indole (39.9 mg, 0.200 mmol) and 3-methoxy-1-propyne (15.4 mg, 0.220 mmol) was obtained in 70% yield (33.2 mg) through isolation by column chromatography on silica gel (hexane/EtOAc = 25/1) (entry 1 of Table 3). A white solid, mp 167–168 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.97 (s, 3 H), 7.30 (td, *J* = 7.6, 1.1 Hz, 1 H), 7.39–7.46 (m, 3 H), 7.48 (d, *J* = 1.2 Hz, 1 H), 7.53 (d, *J* = 8.0 Hz, 1 H),

8.23 (d, J = 8.0 Hz, 1 H), 8.32 (bs, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 21.1, 110.8, 116.5, 118.4, 120.0, 120.1, 122.2, 124.0, 124.6, 124.7, 125.0, 130.4, 133.9, 139.0, 139.1. HRMS (ESI) $C_{15}H_{11}NS$: M^+, 237.0612. Found: m/z 237.0588. Anal. Calcd for $C_{15}H_{11}NS$: C, 75.91; H, 4.67; N, 5.90; S, 13.51. Found: C, 75.92; H, 4.38; N, 5.89; S, 13.83.

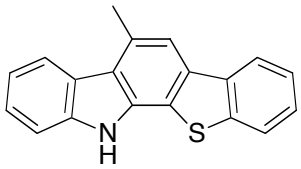


2,5-Dimethyl-10*H*-thieno[2,3-*a*]carbazole (3m). The title compound prepared from 2-(5-methylthien-2-yl)-1*H*-indole (42.7 mg, 0.200 mmol) and 3-methoxy-1-propyne (15.4 mg, 0.220 mmol) was obtained in 79% yield (39.7 mg) through isolation by column chromatography on silica gel (hexane/EtOAc = 20/1) (entry 2 of Table 3). A white solid, mp 169–170 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.65 (d, J = 1.2 Hz, 3 H), 2.94 (s, 3 H), 7.07 (d, J = 1.2 Hz, 1 H), 7.28 (ddd, J = 8.0, 6.9, 1.2 Hz, 1 H), 7.31 (s, 1 H), 7.40 (td, J = 7.7, 1.1 Hz, 1 H), 7.51 (dd, J = 8.0, 1.2 Hz, 1 H), 8.16–8.24 (m, 2 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 16.1, 21.0, 110.7, 115.9, 118.0, 119.5, 119.9, 122.1, 122.9, 124.4, 124.9, 130.2, 133.7, 138.9, 139.0, 139.8. HRMS (ESI) Calcd for $C_{16}H_{13}NS$: M^+, 251.0768. Found: m/z 251.0759. Anal. Calcd for $C_{16}H_{13}NS$: C, 76.46; H, 5.21; N, 5.57; S, 12.76. Found: C, 76.53; H, 5.10; N, 5.23; S, 12.91.

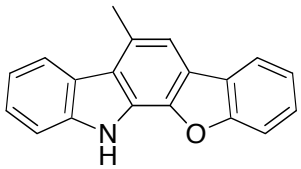


2,5-Dimethyl-10*H*-furo[2,3-*a*]carbazole (3n). The title compound prepared from 2-(5-methylfuran-2-yl)-1*H*-indole (39.4 mg, 0.200 mmol) and 3-methoxy-1-propyne (15.4 mg, 0.220 mmol) was obtained in 57% yield (26.8 mg) through isolation by column chromatography on silica gel (hexane/EtOAc = 10/1) (entry 3 of Table 3). A white solid, mp 121–122 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.52 (d, J = 0.9 Hz, 3 H), 2.91 (d, J = 0.9 Hz, 3 H), 6.46 (dd, J = 2.3, 0.9 Hz, 1 H), 7.08 (d, J = 0.9 Hz, 1 H),

7.27 (ddd, *J* = 7.8, 6.9, 0.9 Hz, 1 H), 7.40 (ddd, *J* = 8.1, 7.2, 0.9 Hz, 1 H), 7.51 (dd, *J* = 6.9, 0.9 Hz, 1 H), 8.20 (dd, *J* = 7.8, 0.9 Hz, 1 H), 8.36 (bs, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.1, 21.0, 103.6, 110.7, 112.5, 119.1, 119.7, 121.9, 124.3, 124.4, 125.0, 127.1, 127.9, 138.92, 139.00, 154.4. HRMS (ESI) Calcd for $C_{16}H_{13}NO$: M^+, 235.0996. Found: *m*/*z* 235.0995. Anal. Calcd for $C_{16}H_{13}NO$: C, 81.68; H, 5.57; N, 5.95. Found: C, 81.63; H, 5.33; N, 5.87.

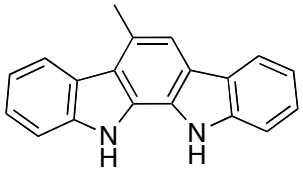


5-Methyl-12*H*-benzothieno[2,3-*a*]carbazole (3o). The title compound prepared from 2-{benzo[*b*]thien-2-yl}-1*H*-indole (49.9 mg, 0.200 mmol) and 3-methoxy-1-propyne (15.4 mg, 0.220 mmol) was obtained in 61% yield (35.1 mg) through isolation by column chromatography on silica gel (hexane/EtOAc = 10/1) (entry 4 of Table 3). A white solid, mp 205–206 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.04 (s, 3 H), 7.32 (t, *J* = 7.5 Hz, 1 H), 7.41–7.48 (m, 2 H), 7.50 (ddd, *J* = 7.7, 7.1, 1.2 Hz, 1 H), 7.57 (d, *J* = 8.6 Hz, 1 H), 7.82 (s, 1 H), 7.92 (d, *J* = 7.6 Hz, 1 H), 8.23 (d, *J* = 7.6 Hz, 1 H), 8.26 (d, *J* = 7.6 Hz, 1H), 8.31 (bs, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 21.1, 110.9, 114.6, 118.9, 120.1, 120.6, 121.8, 122.4, 123.1, 124.56, 124.60, 125.1, 126.1, 130.5, 134.0, 134.2, 136.6, 138.9, 139.4. HRMS (ESI) $C_{19}H_{13}NS$: M^+, 287.0768. Found: *m*/*z* 287.0786. Anal. Calcd for $C_{19}H_{13}NS$: C, 79.41; H, 4.56; N, 4.87; S, 11.16. Found: C, 79.28; H, 4.30; N, 4.51; S, 11.28.

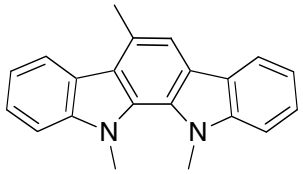


5-Methyl-12*H*-benzofuro[2,3-*a*]carbazole (3p). The title compound prepared from 2-{benzo[*b*]furan-2-yl}-1*H*-indole (46.7 mg, 0.200 mmol) and 3-methoxy-1-propyne (15.4 mg, 0.220 mmol) was obtained in 60% yield (32.6 mg) through isolation by column chromatography on silica gel (hexane/EtOAc = 10/1) (entry 5 of Table 3). A white solid, mp 168–169 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.02 (s, 3 H), 7.32 (td,

J = 8.1, 1.2 Hz, 1H), 7.38 (td, *J* = 7.6, 1.2 Hz, 1H), 7.42–7.50 (m, 2 H), 7.55–7.60 (m, 2 H), 7.63 (dd, *J* = 7.4, 1.1 Hz, 1H), 8.00 (d, *J* = 6.9 Hz, 1H), 8.27 (d, *J* = 8.6 Hz, 1H), 8.56 (bs, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 21.1, 110.9, 111.6, 112.4, 120.0, 120.4, 121.5, 122.2, 122.3, 122.8, 124.5, 124.7, 125.2, 125.3, 126.1, 128.2, 139.5, 140.4, 156.2. HRMS (ESI) $C_{19}H_{13}NO$: M^+, 271.0996. Found: *m*/*z* 271.0978. Anal. Calcd for $C_{19}H_{13}NO$: C, 84.11; H, 4.83; N, 5.16. Found: C, 84.05; H, 4.47; N, 4.90.

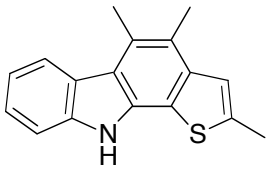


5-Methyl-11*H*,12*H*-indolo[2,3-*a*]carbazole (3q). The title compound prepared from 2,2'-biindolyl (46.5 mg, 0.200 mmol) and 3-methoxy-1-propyne (15.4 mg, 0.220 mmol) was obtained in 54% yield (29.2 mg) through isolation by column chromatography on silica gel (hexane/EtOAc = 3/1) (entry 6 of Table 3). A white solid, mp 225–227 °C. ^{1}H NMR (400 MHz, DMSO-d_6) δ 2.94 (s, 3 H), 7.14–7.27 (m, 2 H), 7.33–7.45 (m, 2 H), 7.63–7.75 (m, 3 H), 8.10 (d, *J* = 7.8 Hz, 1 H), 8.19 (d, *J* = 7.8 Hz, 1 H), 10.90 (s, 1 H), 11.13 (s, 1 H); ^{13}C NMR (125 MHz, DMSO-d_6) δ 20.9, 111.3, 111.5, 112.0, 118.7, 118.8, 118.9, 119.6, 119.8, 121.5, 123.45, 123.47, 123.9, 124.1, 124.2, 124.3, 125.5, 139.0, 139.1. HRMS (ESI) Calcd for $C_{19}H_{14}N_2$: M^+, 270.1157. Found: *m*/*z* 270.1165.

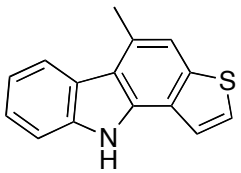


5,11,12-Trimethyl-11*H*,12*H*-indolo[2,3-*a*]carbazole (3r). The title compound prepared from 2,2'-bis(*N*-methylindolyl) (52.1 mg, 0.200 mmol) and 3-methoxy-1-propyne (15.4 mg, 0.220 mmol) was obtained in 64% yield (38.2 mg) through isolation by column chromatography on silica gel (hexane/EtOAc = 40/1) (entry 7 of Table 3). A white solid, mp 188–189 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.01 (s, 3 H), 4.15 (s, 3 H), 4.19 (s, 3 H), 7.27–7.36 (m, 2 H), 7.44–7.55 (m, 4 H), 7.71 (d, *J* = 1.2 Hz, 1 H), 8.11 (d, *J* = 7.5 Hz, 1 H), 8.29 (d, *J* = 8.1 Hz, 1 H); ^{13}C NMR (100

MHz, $CDCl_3$) δ 21.3, 36.3, 36.6, 109.8, 110.1, 113.5, 119.7, 119.80, 119.82, 122.0, 122.2, 123.3, 124.6, 124.9, 125.2, 125.58, 125.60, 128.3, 129.8, 143.6, 144.2. HRMS (ESI) Calcd for $C_{21}H_{18}N_2$: M^+, 298.1469. Found: *m*/*z* 298.1487. Anal. Calcd for $C_{21}H_{18}N_2$: C, 84.53; H, 6.08; N, 9.39. Found: C, 84.77; H, 5.88; N, 9.72.

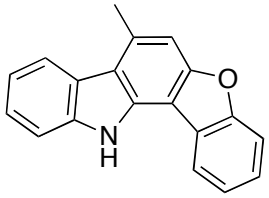


2,4,5-Trimethyl-10*H*-thieno[2,3-*a*]carbazole (3s). The title compound prepared from 2-(5-methylthien-2-yl)-1*H*-indole (42.7 mg, 0.200 mmol) and 3-butoxy-1-butyne (27.8 mg, 0.220 mmol) was obtained in 74% yield (39.3 mg) through isolation by column chromatography on silica gel (hexane/EtOAc = 35/1) (entry 8 of Table 3). A white solid, mp 176–178 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.64 (s, 3 H), 2.67 (d, *J* = 1.2 Hz, 3 H), 2.90 (s, 3 H), 7.21 (q, *J* = 1.2 Hz, 1 H), 7.23–7.29 (m, 1 H), 7.39 (td, *J* = 7.8, 1.2 Hz, 1 H), 7.50 (d, *J* = 8.1 Hz, 1 H), 8.11 (bs, 1 H), 8.26 (d, *J* = 8.0 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 15.9, 16.3, 16.5, 110.6, 118.4, 119.1, 119.6, 121.4, 122.2, 122.3, 124.2, 124.9, 127.5, 132.1, 138.2, 139.1, 139.7. HRMS (ESI) Calcd for $C_{17}H_{15}NS$: M^+, 265.0924. Found: *m*/*z* 265.0904. Anal. Calcd for $C_{17}H_{15}NS$: C, 76.94; H, 5.70; N, 5.28; S, 12.08. Found: C, 76.96; H, 5.32; N, 5.31; S, 11.69.

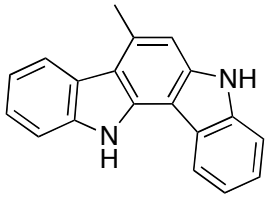


5-Methyl-10*H*-thieno[3,2-*a*]carbazole (3t). The title compound prepared from 2-(thien-3-yl)-1*H*-indole (39.9 mg, 0.200 mmol) and 3-methoxy-1-propyne (15.4 mg, 0.220 mmol) was obtained in 58% yield (27.5 mg) through isolation by column chromatography on silica gel (hexane/EtOAc = 15/1) (Scheme 2). A white solid, mp 150–152 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.97 (d, *J* = 0.9 Hz, 3 H), 7.30 (ddd, *J* = 8.0, 7.1, 1.2 Hz, 1 H), 7.39–7.47 (m, 2 H), 7.50 (s, 1 H), 7.52–7.58 (m, 2 H), 8.23 (d, *J* = 7.8 Hz, 1 H), 8.48 (bs, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 21.2, 110.7, 114.6, 117.9, 119.0, 119.8, 122.0, 122.8, 124.4, 124.6, 130.5, 134.0, 138.45, 138.53 (One carbon

signal is missing due to overlapping.). HRMS (ESI) Calcd for $C_{15}H_{11}NS$: M^+, 237.0612. Found: *m*/*z* 237.0602. Anal. Calcd for $C_{15}H_{11}NS$: C, 75.91; H, 4.67; N, 5.90; S, 13.51. Found: C, 75.74; H, 4.71; N, 5.73; S, 13.53.

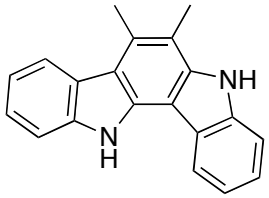


7-Methyl-12*H*-benzofuro[3,2-a]carbazole (3u). The title compound prepared from 2-{benzo[*b*]furan-3-yl}-1*H*-indole (46.7 mg, 0.200 mmol) and 3-methoxy-1-propyne (15.4 mg, 0.220 mmol) was obtained in 65% yield (35.3 mg) through isolation by column chromatography on silica gel (hexane/EtOAc = 8/1) (Scheme 2). A white solid, mp 157–158 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.01 (s, 3 H), 7.26 (d, *J* = 8.7 Hz, 1 H), 7.33 (t, *J* = 7.6 Hz, 1 H), 7.38–7.50 (m, 3 H), 7.60 (d, *J* = 7.8 Hz, 1 H), 7.64 (dd, *J* = 7.1, 2.1 Hz, 1 H), 7.96–8.06 (m, 1 H), 8.22 (d, *J* = 8.2 Hz, 1 H), 8.55 (bs, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 21.6, 105.3, 105.8, 110.7, 111.7, 117.4, 120.1, 120.2, 121.9, 122.7, 123.3, 124.2, 124.4, 125.5, 133.1, 133.5, 139.3, 155.5, 155.9. HRMS (ESI) Calcd for $C_{19}H_{13}NO$: M^+, 271.0997. Found: *m*/*z* 271.1025. Anal. Calcd for $C_{19}H_{13}NO$: C, 84.11; H, 4.83; N, 5.16. Found: C, 84.34; H, 4.71; N, 5.08.

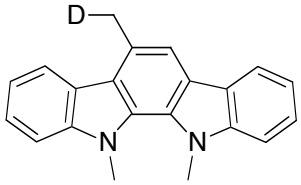


5-Methyl-7*H*,12*H*-indolo[3,2-a]carbazole (3v). The title compound prepared from 2,3'-biindolyl (46.5 mg, 0.200 mmol) and 3-methoxy-1-propyne (15.4 mg, 0.220 mmol) was obtained in 22% yield (11.9 mg) through isolation by column chromatography on silica gel (hexane/EtOAc = 5/1) (Scheme 2). A white solid, mp 248–250 °C. ^{1}H NMR (400 MHz, DMSO-d_6) δ 2.94 (s, 3 H), 7.13 (d, *J* = 0.8 Hz, 1 H), 7.20 (td, *J* = 7.4, 1.0 Hz, 1 H), 7.26 (t, *J* = 7.6 Hz, 1 H), 7.31–7.41 (m, 2 H), 7.53 (d, *J* = 8.4 Hz, 1 H), 7.65 (d, *J* = 8.4 Hz, 1 H), 8.13 (d, *J* = 7.6 Hz, 1 H), 8.60 (d, *J* = 7.6 Hz, 1 H), 11.39 (s, 1 H), 11.72 (s, 1 H); ^{13}C NMR (125 MHz, DMSO-d_6) δ 21.4, 104.46, 104.54, 110.6, 110.8, 113.3, 118.5, 118.9, 120.67, 120.74, 121.4, 122.8, 123.6, 124.0,

131.0, 133.6, 138.6, 139.2, 139.3. HRMS (ESI) Calcd for $C_{19}H_{14}N_2$: M^+, 270.1157. Found: *m*/*z* 270.1143.



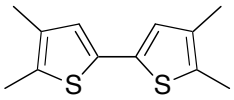
5,6-Dimethyl-7*H*,12*H*-indolo[3,2-a]carbazole (3w). The title compound prepared from 2,3'-biindolyl (46.5 mg, 0.200 mmol) and 3-butoxy-1-butyne (27.8 mg, 0.220 mmol) was obtained in 26% yield (14.8 mg) through isolation by column chromatography on silica gel (hexane/EtOAc = 4/1) (Scheme 2). A white solid, mp 207–209 °C. ^{1}H NMR (400 MHz, DMSO-d_6) δ 2.62 (s, 3 H), 2.90 (s, 3 H), 7.18 (td, *J* = 7.6, 0.9 Hz, 1 H), 7.26 (td, *J* = 7.6, 0.9 Hz, 1 H), 7.32 (td, *J* = 7.7, 1.1 Hz, 1 H), 7.37 (td, *J* = 7.6, 0.8 Hz, 1 H), 7.57 (d, *J* = 7.8 Hz, 1 H), 7.63 (d, *J* = 7.8 Hz, 1 H), 8.19 (d, *J* = 7.8 Hz, 1 H), 8.60 (d, *J* = 7.8 Hz, 1 H), 11.27 (s, 1 H), 11.61 (s, 1 H) ; ^{13}C NMR (125 MHz, DMSO-d_6) δ 13.2, 16.6, 104.1, 109.9, 110.7, 110.8, 113.8, 118.5, 118.7, 120.8, 120.9, 121.9, 122.6, 123.6, 124.1, 128.3, 132.0, 138.8, 139.2, 139.3. HRMS (ESI) Calcd for $C_{20}H_{16}N_2$: M^+, 284.1314. Found: *m*/*z* 284.1333.



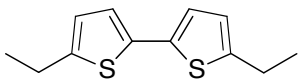
5-Monodeuteriomethyl-11,12-dimethyl-11*H*,12*H*-indolo[2,3-*a*]carbazole (3r-*d*). The title compound prepared from 2,2'-bis(*N*-methylindolyl) (52.1 mg, 0.200 mmol) and 1-deuterio-3-hexyloxy-1-propyne (15.6 mg, 0.220 mmol) was obtained in 25% yield (15.0 mg) through isolation by column chromatography on silica gel (hexane/EtOAc = 35/1) (Eq. 4). A white solid, mp 188–189 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.01 (d, *J* = 0.92 Hz, 3 H), 4.15 (s, 3 H), 4.20 (s, 3 H), 7.26–7.37 (m, 2 H), 7.44–7.57 (m, 4 H), 7.71 (s, 1 H), 8.11 (dt, *J* = 7.8, 0.9 Hz, 1 H), 8.28 (dd, *J* = 7.8, 0.9 Hz, 1 H); ^{2}H NMR (76 MHz, $CHCl_3$) δ 3.03 (s); ^{13}C NMR (100 MHz, $CDCl_3$) δ 21.1 (t, *J* = 19.5 Hz), 36.4, 36.6, 109.8, 110.2, 113.5, 119.77, 119.82, 119.9, 122.0, 122.2,

123.4, 124.7, 124.9, 125.1, 125.2, 125.6, 128.4, 129.9, 143.7, 144.2. HRMS (ESI) Calcd for $C_{21}H_{17}DN_2$: M^+, 299.1531. Found: *m/z* 299.1515.

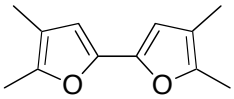
Spectral and analytical data of bithiophenes and a bifuran prepared follow.



4,4',5,5'-Tetramethyl-2,2'-bithiophene (4a). The title compound prepared from bromo(4,5-dimethylthien-2-yl) magnesium (7.5 g, 35 mmol) and 2-bromo-4,5-dimethylthiophene (5.69 g, 29.8 mmol) according to the reported method[5] was obtained in 39% yield (2.63 g) through isolation by recrystallization from hexane. A white solid, mp 104–105 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.10 (s, 6 H), 2.31 (s, 6 H), 6.75 (s, 2 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 13.0, 13.5, 125.7, 131.3, 132.9, 133.6. HRMS (ESI) Calcd for $C_{12}H_{14}S_2$: M^+, 222.0536. Found: *m/z* 222.0529.



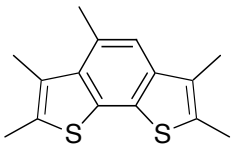
5,5'-Diethyl-2,2'-bithiophene (4b). The title compound prepared from bromo(5-ethylthien-2-yl) magnesium (6.5 g, 30 mmol) and 2-bromo-5-ethylthiophene (3.82 g, 20.0 mmol) according to the literature method[5] was obtained in 87% yield (3.89 g) through isolation by column chromatography on silica gel (hexane) followed by distillation (108 °C/0.6 mmHg). A pale yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.31 (t, *J* = 7.3 Hz, 6 H), 2.82 (q, *J* = 7.5 Hz, 4 H), 6.66 (d, *J* = 3.2 Hz, 2 H), 6.90 (d, *J* = 3.6 Hz, 2 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 15.8, 23.5, 122.7, 123.9, 135.2, 146.2. HRMS (ESI) Calcd for $C_{12}H_{14}S_2$: M^+, 222.0536. Found: *m/z* 222.0530.



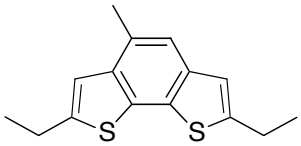
4,4',5,5'-Tetramethyl-2,2'-bifuran (4c). The title compound prepared from 2,3-dimethylfuran (5.00 g, 52.0 mmol) according to the reported procedure[6] was obtained in 10% yield (0.500 g) through isolation by distillation (130 °C/0.1 mmHg). A white solid, mp 50–51 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.95 (s, 6 H), 2.23 (s, 6

H), 6.22 (s, 2 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 9.9, 11.4, 107.3, 115.6, 144.0, 146.4. HRMS (ESI) Calcd for $C_{12}H_{14}O_2$: M^+, 190.0993. Found: *m/z* 190.0985.

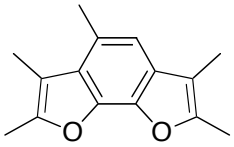
Synthesis of Benzodithiophenes or a Benzodifuran Utilizing In(ONf)$_3$-Catalyzed Reaction of Bithiophenes or a Bifuran with Methyl Propargyl Ether. A General Procedure. In(ONf)$_3$ (60.7 mg, 60.0 μmol) was placed in a 20 mL Schlenk tube, which was heated at 150 °C in vacuo for 2 h. The tube was cooled down to room temperature and filled with nitrogen. Dibutyl ether (1.0 mL) was added to the tube and stirred for 10 min at room temperature. To this were added a bithiophene or a bifuran (0.20 mmol), and 3-methoxy-1-propyne (15.4 mg, 0.220 mmol) successively, and the resulting mixture was stirred at 70 or 90 °C. After the time specified in Scheme 3, the mixture was diluted with ethyl acetate (10 mL) and then washed with saturated $NaHCO_3$ aqueous solution (1 mL) and brine (1 mL), and then dried over anhydrous sodium sulfate. Filtration through a pad of Celite and evaporation of the solvent followed by column chromatography on silica gel gave the corresponding benzodithiophenes or a benzodifuran. The results are summarized in Scheme 3.



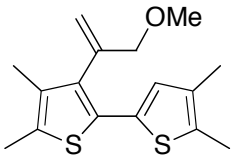
2,3,4,6,7-Pentamethylbenzo[2,1-*b*:3,4-*b'*]dithiophene (5a). The title compound prepared from 4,4',5,5'-tetramethyl-2,2'-bithiophene (44.5 mg, 0.200 mmol) and 3-methoxy-1-propyne (15.4 mg, 0.220 mmol) was obtained in 40% yield (20.8 mg) through isolation by column chromatography on silica gel (hexane). A white solid, mp 137–139 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.29 (d, *J* = 1.2 Hz, 3 H), 2.47 (s, 3 H), 2.48 (s, 3 H), 2.54 (s, 3 H), 2.83 (d, *J* = 1.2 Hz, 3 H), 7.21 (d, *J* = 1.2 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 11.7, 13.7, 14.1, 15.4, 22.2, 120.1, 127.4, 129.3, 129.5, 130.6, 131.3, 131.6, 136.4, 137.5 (One carbon signal is missing due to overlapping.). HRMS (ESI) Calcd for $C_{15}H_{16}S_2$: M^+, 260.0693. Found: *m/z* 260.0698. Anal. Calcd for $C_{15}H_{16}S_2$: C, 69.18; H, 6.91; S, 24.63. Found: C, 68.96; H, 6.88, S, 24.85.



2,7-Diethyl-4-methylbenzo[2,1-*b*:3,4-*b'*]dithiophene (5b). The title compound prepared from 5,5'-diethyl-2,2'-bithiophene (44.5 mg, 0.200 mmol) and 3-methoxy-1- propyne (15.4 mg, 0.220 mmol) was obtained in 40% yield (20.8 mg) through isolation by column chromatography on silica gel (hexane). A pale yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.39 (t, *J* = 7.8 Hz, 3 H), 1.40 (t, *J* = 7.3 Hz, 3 H), 2.61 (s, 3 H), 2.89–3.03 (m, 4 H), 6.99 (t, *J* = 1.1 Hz, 1 H), 7.11 (t, *J* = 1.2 Hz, 1 H), 7.36 (d, *J* = 0.9 Hz, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 15.5, 15.6, 19.7, 23.9, 24.1, 119.0, 119.7, 120.3, 128.7, 130.2, 132.2, 137.0, 137.3, 145.6, 145.8. HRMS (ESI) Calcd for $C_{15}H_{16}S_2$: M^+, 260.0693. Found: *m/z* 260.0699. Anal. Calcd for $C_{15}H_{16}S_2$: C, 69.18; H, 6.91; S, 24.63. Found: C, 68.81; H, 6.84, S, 25.03.



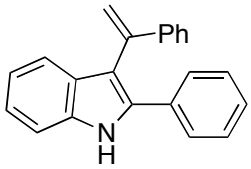
2,3,4,6,7-Pentamethylbenzo[2,1-*b*:3,4-*b'*]difuran (5c). The title compound prepared from 4,4',5,5'-tetramethyl-2,2'-bifuran (38.0 mg, 0.200 mmol) and 3-methoxy-1- propyne (15.4 mg, 0.220 mmol) was obtained in 43% yield (19.6 mg) through isolation by column chromatography on silica gel (hexane/EtOAc = 200/1). A white solid, mp 107–109 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.15 (s, 3 H), 2.34 (s, 3 H), 2.38–2.42 (m, 6 H), 2.68 (s, 3 H), 6.91 (s, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 8.2, 10.7, 11.6, 11.8, 19.5, 110.2, 111.2, 113.6, 124.9, 125.5, 127.3, 137.0, 138.1, 148.9, 149.2. HRMS (ESI) Calcd for $C_{15}H_{16}O_2$: M^+, 228.1149. Found: *m/z* 228.1138. Anal. Calcd for $C_{15}H_{16}O_2$: C, 78.92; H, 7.06. Found: C, 78.72; H, 6.86.



3-(3-Methoxy-1-propen-2-yl)-4,4',5,5'-tetramethyl-2,2'-bithiophene (6). The title compound prepared from 4,4',5,5'-tetramethyl-2,2'-bithiophene (44.5 mg, 0.200 mmol) and 3-methoxy-1-propyne (15.4 mg, 0.220 mmol) was obtained in 13%

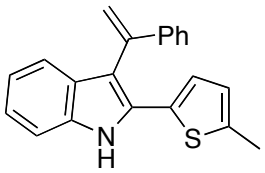
yield (7.6 mg) through isolation by column chromatography on silica gel (hexane/EtOAc = 50/1). A pale yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.00 (s, 3 H), 2.08 (s, 3 H), 2.29 (s, 3 H), 2.32 (s, 3 H), 3.39 (s, 3 H), 3.92 (t, *J* = 1.6 Hz, 2 H), 5.18 (q, *J* = 1.7 Hz, 1 H), 5.63 (q, *J* = 2.0 Hz, 1 H), 6.81 (s, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 12.7, 13.0, 13.3, 13.5, 58.6, 74.4, 116.7, 127.8, 129.1, 130.8, 131.5, 132.5, 133.0, 133.5, 136.8, 142.3. HRMS (ESI) Calcd for $C_{16}H_{20}OS_2Na$: M^++Na, 315.0852. Found: *m*/*z* 315.0854. Anal. Calcd for $C_{16}H_{20}OS_2$: C, 65.71; H, 6.89; S, 21.93. Found: C, 65.44; H, 6.49; S, 22.01.

In(ONf)$_3$-Catalyzed Addition of 2-Phenyl- or 2-(5-Methylthien-2-yl)indole to Phenylacetylene. In(ONf)$_3$ (60.7 mg, 60.0 μmol) was placed in a 20 mL Schlenk tube, which was heated at 150 °C in vacuo for 2 h. The tube was cooled down to room temperature and filled with nitrogen. Dibutyl ether (3.0 mL) was added to the tube and stirred for 10 min at room temperature. To this were added 2-phenylindole (38.6 mg, 0.200 mmol) or 2-(5-methylthien-2-yl)indole (42.7 mg, 0.200 mmol), and phenylacetylene (30.6 mg, 0.300 mmol) successively, and the resulting mixture was stirred at 60 °C. After the time specified in Scheme 4, the mixture was diluted with ethyl acetate (10 mL) and then washed with saturated $NaHCO_3$ aqueous solution (1 mL) and brine (1 mL), and then dried over anhydrous sodium sulfate. Filtration through a pad of Celite and evaporation of the solvent followed by column chromatography on silica gel (hexane/EtOAc = 15/1) gave the corresponding adduct **8a** or **8b**. The results are summarized in Scheme 6. Spectral and analytical data of **8a** and **8b** are as follows.

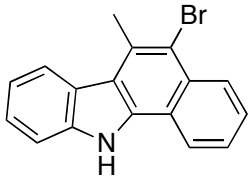


2-Phenyl-3-(1-phenylethenyl)-1*H*-indole (8a). The title compound was obtained in 73% yield (43.1 mg) according to the above described procedure. A white solid, mp 43–45 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.36 (d, *J* = 1.8 Hz, 1 H), 5.83 (d, *J* = 1.4 Hz, 1 H), 7.05 (ddd, *J* = 8.0, 7.1, 0.9 Hz, 1 H), 7.17–7.27 (m, 5 H), 7.27–7.35 (m, 3 H), 7.40–7.47 (m, 3 H), 7.54–7.59 (m, 2 H), 8.26 (bs, 1 H); ^{13}C NMR (125 MHz,

$CDCl_3$) δ 110.7, 114.6, 116.9, 120.1, 120.3, 122.5, 127.0, 127.5, 127.6, 128.1, 128.5, 129.4, 132.5, 135.2, 135.7, 140.9, 142.0 (One carbon signal is missing due to overlapping.). HRMS (ESI) Calcd for $C_{22}H_{18}N$: M^++H, 196.1439. Found: *m*/*z* 196.1436.

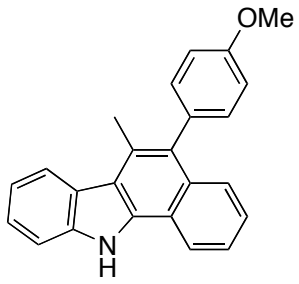


2-(5-Methylthien-2-yl)-3-(1-phenylethenyl)-1*H*-indole (8b). The title compound was obtained in 82% yield (51.7 mg) according to the above described procedure. A white solid, mp 42–44 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.43 (d, *J* = 0.9 Hz, 3 H), 5.49 (d, *J* =1.4 Hz, 1 H), 5.98 (d, *J* = 1.8 Hz, 1 H), 6.60–6.64 (m, 1 H), 6.97 (d, *J* = 3.2 Hz, 1 H), 7.03 (ddd, *J* = 8.0, 7.1, 0.9 Hz, 1H), 7.18 (ddd, *J* = 8.0, 7.1, 1.1 Hz, 1 H), 7.21–7.28 (m, 3H), 7.30 (d, *J* = 8.2 Hz, 1 H), 7.37 (d, *J* = 8.3 Hz, 1 H), 7.41–7.46 (m, 2 H), 8.14 (bs, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 15.2, 110.4, 114.5, 117.7, 119.9, 120.2, 122.6, 124.9, 125.6, 126.8, 127.6, 128.2, 129.55, 129.61, 132.0, 135.6, 140.1, 140.6, 141.6. HRMS (ESI) Calcd for $C_{21}H_{18}NS$: M^++H, 316.1160. Found: *m*/*z* 316.1135.

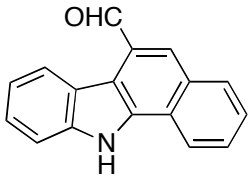


Preparation of 5-Bromo-6-methyl-11*H*-benzo[*a*]carbazole (9). A flame-dried 20 mL Schlenk tube was filled with argon and then charged with NBS (17.8 mg, 0.100 mmol) and CH_2Cl_2 (0.4 mL). To this were added $FeCl_3$ (4.9 mg, 30 μmol) and **3a** (23.1 mg, 0.100 mmol) successively at 0 °C. After being stirred at the same temperature for 30 min, the mixture was quenched with saturated $NaHCO_3$ aqueous solution (1 mL). The aqueous solution was extracted with CH_2Cl_2 (10 mL x 3) and the combined organic layer was washed with brine (5 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column

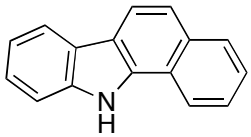
chromatography on silica gel (hexane/EtOAc = 15/1) gave 5-bromo-6-methyl-11*H*-benzo[*a*]carbazole (25.2 mg, 81% yield) as a white solid (Scheme 7). mp 130–131 °C (decomp.). ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.10 (s, 3 H), 7.31 (td, *J* = 7.6, 0.9 Hz, 1 H), 7.45 (td, *J* = 7.6, 0.9 Hz, 1 H), 7.52–7.58 (m, 2 H), 7.60 (ddd, *J* = 8.3, 6.9, 1.4 Hz, 1 H), 7.97 (dd, *J* = 8.0, 1.4 Hz, 1 H), 8.21 (d, *J* = 7.2 Hz, 1 H), 8.46 (dd, *J* = 8.5, 1.4 Hz, 1 H), 8.67 (bs, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 21.6, 111.1, 115.7, 118.2, 120.2, 120.3, 120.4, 122.3, 124.3, 124.8, 125.3, 126.5, 128.7, 130.5, 132.4, 133.9, 138.4. Anal. Calcd for $C_{17}H_{12}BrN$: C, 65.83; H, 3.90; N, 4.52. Found: C, 65.72; H, 3.91; N, 4.55.



Preparation of 5-(4-methoxyphenyl)-6-methyl-11*H*-benzo[*a*]carbazole (10). A flame-dried 20 mL Schlenk tube was filled with argon and then charged with $Pd(PPh_3)_4$ (29.6 mg, 25.6 μmol), **9** (39.7 mg, 0.128 mmol), 4-methoxyphenylboronic acid (38.9 mg, 0.256 mmol) and K_3PO_4 (81.5 mg, 0.384 mmol). To this was added DMF (1.3 mL) that was degassed by three freeze-thaw cycles, and the resulting solution was stirred at 100 °C for 24 h. The reaction mixture was cooled to room temperature and then diluted with EtOAc (10 mL). Filtration through a pad of Celite and evaporation of the solvent followed by column chromatography on silica gel (hexane/EtOAc = 5/1) gave 5-(4-methoxyphenyl)-6-methyl-11*H*-benzo[*a*]carbazole (42.8 mg, 99% yield) as a white solid (Scheme 7). mp 259–260 °C. ^{1}H NMR (400 MHz, DMSO-d_6) δ 2.66 (s, 3 H), 3.87 (s, 3 H), 7.12 (dt, *J* = 9.2, 2.4 Hz, 2 H), 7.20–7.27 (m, 3 H), 7.37–7.46 (m, 3 H), 7.57 (ddd, *J* = 8.0, 5.5, 2.3 Hz, 1 H), 7.69 (d, *J* = 8.2 Hz, 1 H), 8.23 (d, *J* = 8.2 Hz, 1 H), 8.54 (d, *J* = 8.2 Hz, 1 H), 12.29 (s, 1 H); ^{13}C NMR (100 MHz, DMSO-d_6) δ 18.6, 55.1, 111.3, 113.8, 116.5, 119.2, 119.8, 121.7, 121.9, 123.8, 124.1, 124.3, 125.2, 126.7, 129.1, 129.4, 131.6, 131.7, 132.0, 134.6, 139.0, 158.1. HRMS (ESI) Calcd for $C_{24}H_{20}NO$: M^++H, 338.15449. Found: *m*/*z* 338.15605.

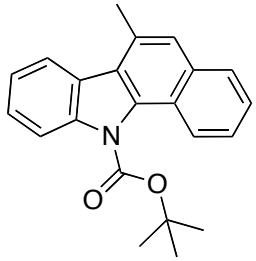


Preparation of 11*H*-Benzo[*a*]carbazole-6-carboxyaldehyde (11). SeO_2 (16.6 mg, 0.150 mmol) was placed in a 20 mL Schlenk tube, which was heated at 110 °C in vacuo for 1 h. The tube was cooled to room temperature and filled with argon. To this were added **3a** (23.1 mg, 0.100 mmol), K_2CO_3 (6.9 mg, 50 μmol) and pyridine (0.3 mL), and the resulting mixture was stirred at 115 ºC for 19 h. After cooling to room temperature, the solution was diluted with EtOAc (10 mL). Filtration through a pad of Celite and evaporation of the solvent followed by column chromatography on silica gel (hexane/EtOAc = 5/1) gave 11*H*-benzo[*a*]carbazole-6-carboxyaldehyde (8.8 mg, 35% yield) as a yellow solid (Scheme 7). mp 237–238 °C. ^{1}H NMR (400 MHz, DMSO-d_6) δ 7.24–7.31 (m, 1 H), 7.48 (dd, J = 8.4, 6.9 Hz, 1 H), 7.67–7.75 (m, 2 H), 7.87 (t, J = 7.6 Hz, 1 H), 8.28 (d, J = 7.6 Hz, 1 H), 8.44 (s, 1 H), 8.64 (d, J = 7.6 Hz, 1 H), 9.01 (d, J = 8.4 Hz, 1 H), 10.42 (s, 1 H), 12.60 (bs, 1 H); ^{13}C NMR (125 MHz, DMSO-d_6) δ 111.3, 112.9, 119.4, 122.0, 122.5, 123.8, 124.7, 125.2, 126.4, 129.1, 130.1, 130.2, 131.2, 131.7, 136.3, 139.2, 194.0. HRMS (ESI) Calcd for $C_{17}H_{12}NO$: M^++H, 246.0919. Found: *m/z* 246.0950.

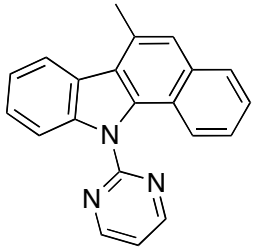


Preparation of 11*H*-Benzo[*a*]carbazole (12).[67] A flame-dried 20 mL Schlenk tube was filled with argon and then charged with $RhClCO(PPh_3)_2$ (6.9 mg, 10 μmol) and xylenes (0.7 mL). After degassing by three freeze-thaw cycles, the solution was stirring at 80 °C for 30 min. To this was added 1,3-bis(diphenylphosphino)propane (10.3 mg, 25.0 μmol) at 80 °C and the solution was further stirred at the same temperature for 30 min. To this solution was added **11** (24.5 mg, 0.100 mmol), and the mixture was heated with stirring at 140 ºC for 24 h. After cooling to room temperature, the solution was diluted with ethyl acetate (10 mL). Filtration through a pad of Celite and evaporation of the solvent followed by column chromatography on silica gel (hexane/EtOAc = 10/1) gave 11*H*-benzo[*a*]carbazole (19.5 mg, 89% yield) as

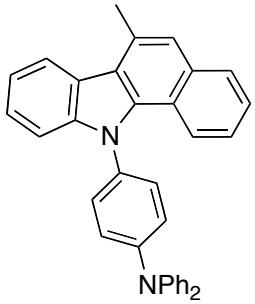
a white solid (Scheme 7). mp 230–231 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.32 (td, *J* = 7.5, 1.1 Hz, 1 H), 7.45 (ddd, *J* = 8.2, 7.1, 1.1 Hz, 1 H), 7.55 (ddd, *J* = 8.1, 7.0, 1.2 Hz, 1 H), 7.58–7.64 (m, 2 H), 7.68 (d, *J* = 8.2 Hz, 1 H), 8.03 (d, *J* = 7.4 Hz, 1 H), 8.12–8.18 (m, 3H), 8.78 (bs, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 111.0, 118.4, 119.3, 119.9, 120.0, 120.2, 120.4, 121.1, 124.2, 124.9, 125.2, 125.5, 129.0, 132.4, 134.8, 138.5. HRMS (ESI) Calcd for $C_{16}H_{11}N$: M^+, 217.0892. Found: *m*/*z* 217.0888.



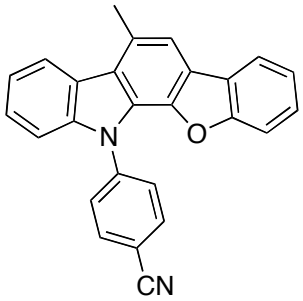
Preparation of 11-(*tert*-Butoxycarbonyl)-6-methyl-11*H*-benzo[*a*]carbazole (13). A flame-dried 20 mL Schlenk tube was filled with nitrogen and then charged with 4-(*N*,*N*-dimethylamino)pyridine (36.7 mg, 0.300 mmol), di-*tert*-butyl dicarbonate (131.0 mg, 0.6000 mmol), **3a** (69.4 mg, 0.300 mmol) and MeCN (1.25 mL). The solution was stirred at room temperature for 5 h and then diluted with EtOAc (15 mL). The resulting solution was washed with saturated NH_4Cl aqueous solution (2 mL), saturated $NaHCO_3$ aqueous solution (2 mL), brine (2 mL), and then dried over anhydrous sodium sulfate. Filtration through a pad of Celite and evaporation of the solvent followed by column chromatography on silica gel (hexane/EtOAc = 25/1) gave 11-(*tert*-butoxycarbonyl)-6- methyl-11*H*-benzo[*a*]carbazole (93.5 mg, 94% yield) as a white solid (Scheme 7). mp 109–111 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.70 (s, 9 H), 2.97 (d, *J* = 1.2 Hz, 3 H), 7.37–7.44 (m, 1H), 7.45–7.52 (m, 3 H), 7.58 (s, 1 H), 7.85–7.90 (m, 1 H), 8.17–8.22 (m, 2 H), 8.25 (d, *J* = 8.0 Hz, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 21.5, 28.2, 84.6, 115.1, 122.25, 122.28, 123.3, 123.5, 124.3, 125.1, 125.5, 125.6, 126.1, 127.2, 128.2, 130.9, 133.6, 135.2, 140.7, 152.2. HRMS (ESI) Calcd for $C_{22}H_{21}NO_2$: M^+, 331.1572. Found: *m*/*z* 331.1599. Anal. Calcd for $C_{22}H_{21}NO_2$: C, 79.73; H, 6.39; N, 4.23. Found: C, 79.99; H, 6.14; N, 4.18.



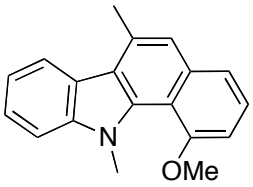
Preparation of 6-Methyl-11-(pyrimidin-2-yl)-11*H*-benzo[*a*]carbazole (14). A flame-dried 20 mL Schlenk tube was filled with nitrogen and then charged with a 55% dispersion of NaH (15.8 mg, 0.660 mmol) in paraffin oil, which was washed with hexane (1 mL x 2). To this were added DMF (1.8 mL) and **3a** (69.4 mg, 0.300 mmol) successively at room temperature. After being stirred at room temperature for 30 min, 2-chloropyrimidine (61.9 mg, 0.540 mmol) was added and the solution was stirred at 130 °C for 25 h. After cooling to room temperature, the solution was diluted with EtOAc (5 mL) and washed with saturated NH_4Cl aqueous solution (2 mL). The aqueous solution was extracted with EtOAc (5 mL x 2) and the combined organic layer was washed with saturated $NaHCO_3$ aqueous solution (2 mL), brine (2 mL), and then dried over anhydrous sodium sulfate. Filtration through a pad of Celite and evaporation of the solvent followed by column chromatography on silica gel (hexane/EtOAc = 5/1) gave 6-methyl-11- (pyrimidin-2-yl)-11*H*-benzo[*a*]carbazole (46.6 mg, 50% yield) as a white solid (Scheme 7). mp 171–173 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.04 (d, J = 0.9 Hz, 3 H), 7.19–7.25 (m, 2 H), 7.35–7.48 (m, 4 H), 7.56 (s, 1 H), 7.91 (d, J = 8.2 Hz, 1 H), 8.08 (dd, J = 7.6, 1.2 Hz, 1 H), 8.29 (dd, J = 7.1, 1.1 Hz, 1 H), 8.94 (d, J = 5.0 Hz, 2 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 21.5, 111.9, 118.9, 121.0, 122.1, 122.2, 123.6, 123.8, 123.9, 124.9, 125.3, 126.2, 128.3, 131.4, 133.4, 135.2, 141.3, 159.0, 159.9 (One carbon signal is missing due to overlapping.). HRMS (ESI) Calcd for $C_{21}H_{15}N_3$: M^+, 309.1266. Found: m/z 309.1262. Anal. Calcd for $C_{21}H_{15}N_3$: C, 81.53; H, 4.89; N, 13.58. Found: C, 81.58; H, 4.87; N, 13.44.



Preparation of 11-(4-*N*,*N*-Diphenylaminophenyl)-6-methyl-11*H*-benzo[*a*] carbazole (15). The title compound was prepared by the reaction of **3a** with 4-bromo-*N*,*N*-diphenylaniline according to the reported procedure:[2] A flame-dried 20 mL Schlenk tube was filled with nitrogen and then charged with CuI (2.9 mg, 15 μmol), **3a** (69.4 mg, 0.300 mmol), K_3PO_4 (134 mg, 0.630 mmol), 4-bromo-*N*,*N*-diphenylaniline (97.3 mg, 0.300 mmol), *N*,*N*'-dimethylethylenediamine (5.3 mg, 60 μmol) and toluene (0.4 mL). After being stirred at 110 °C for 65 h, the solution was directly filtered through a short silica gel column and eluted with EtOAc (40 mL). Evaporation of the solvent followed by column chromatography on silica gel (hexane/EtOAc = 35/1) gave 11-(4-*N*,*N*- diphenylaminophenyl)-6-methyl-11*H*-benzo[*a*]carbazole (89.6 mg, 63% yield) as a white solid (Scheme 7). Further purification was performed by recrystallization from CH_2Cl_2/hexane. mp 171–173 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.06 (s, 3 H), 7.11 (tt, *J* = 7.3, 1.2 Hz, 2 H), 7.21–7.45 (m, 17 H), 7.46 (s, 1 H), 7.58 (d, *J* = 8.7 Hz, 1 H), 7.91 (d, *J* = 8.2 Hz, 1 H), 8.33 (d, *J* = 7.8 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 21.6, 110.4, 118.8, 120.1, 120.6, 121.1, 121.9, 122.2, 123.6, 123.67, 123.70, 123.9, 124.3, 124.8, 125.0, 128.2, 129.6, 129.9, 132.0, 133.36, 133.38, 135.7, 142.3, 147.4, 148.3. HRMS (ESI) Calcd for $C_{35}H_{26}N_2$: M^+, 474.2096. Found: *m*/*z* 474.2096. Anal. Calcd for $C_{35}H_{26}N_2$: C, 88.58; H, 5.52; N, 5.90. Found: C, 87.68; H, 5.55; N, 5.71.



Preparation of 12-(4-Cyanophenyl)-5-methyl-12*H*-benzofuro[2,3-*a*] carbazole (16). Similarly as above, the title compound was synthesized in 56% yield (62.6 g) by the reaction of **3p** (81.4 mg, 0.300 mmol) with 4-bromobenzonitrile (54.6 mg, 0.300 mmol) using CuI (11.4 mg, 60.0 μmol), *N*,*N*'-dimethylethylenediamine (13.9 mg, 0.120 mmol) and K_3PO_4 (134 mg, 0.630 mmol) in toluene (0.4 mL) at 110 °C for 60 h (Scheme 7).[2] A white solid. mp 236–237 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.07 (s, 3 H), 7.31–7.50 (m, 5 H), 7.53 (dd, *J* = 8.2, 0.9 Hz, 1H), 7.67 (s, 1 H), 7.83 (d, *J* = 8.2 Hz, 2 H), 7.95 (dd, *J* = 8.0, 0.9 Hz, 2 H), 8.00 (dd, *J* = 7.3, 0.9 Hz, 1 H), 8.34 (d, *J* = 7.3 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 21.4, 109.6, 111.0, 111.7, 113.9, 118.6, 120.3, 121.3, 122.66, 122.71, 122.9, 123.0, 124.5, 125.1, 125.4, 125.7, 126.5, 128.3, 128.5, 133.1, 140.2, 140.4, 142.2, 156.0. HRMS (ESI) Calcd for $C_{26}H_{16}N_2O$: M^+, 372.1263. Found: *m*/*z* 372.1254.



Preparation of 1-Methoxy-6,11-dimethyl-11*H*-benzo[*a*]carbazole (17). A flame-dried 20 mL Schlenk tube was filled with nitrogen and then charged with **3d** (78.4 mg, 0.300 mmol) and DMSO (0.7 mL). To this was added KOH (67.3 mg, 1.20 mmol) at room temperature and the resulting solution was stirred for 45 min. Methyl iodide (85.2 mg, 0.600 mmol) was successively added to this solution. After being stirred for 2.5 h at room temperature, the solution was directly filtered through a short silica gel column to remove the white precipitate and eluted with EtOAc (40 mL). Evaporation of the solvent followed by recrystallization twice from Et_2O/hexane gave 1-methoxy-6,11-dimethyl-11*H*- benzo[*a*]carbazole (80.1 mg, 97% yield) as a white solid (Scheme 7). mp 108–109 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.98 (d, *J* = 0.9 Hz, 3 H), 4.05 (s,

3H), 4.09 (s, 3 H), 6.92 (d, *J* = 7.3 Hz, 1 H), 7.31 (td, *J* = 7,6, 1.1 Hz, 1 H), 7.36 (s, 1 H), 7.41 (t, *J* = 7.8 Hz, 1 H), 7.45–7.55 (m, 2 H), 7.57 (d, *J* = 8.2 Hz, 1 H), 8.26 (d, *J* = 7.8 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 21.5, 37.9, 55.2, 104.3, 110.4, 112.9, 119.7, 120.1, 120.6, 120.7, 121.8, 124.0, 124.3, 125.2, 132.4, 135.4, 137.3, 143.6, 154.7. HRMS (ESI) Calcd for $C_{19}H_{17}NO$: M^+, 275.1310. Found: *m*/*z* 275.1298. Anal. Calcd for $C_{19}H_{17}NO$: C, 82.88; H, 6.22; N, 5.09. Found: C, 82.93; H, 6.44; N, 4.84.

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Chapter III. Indium-Catalyzed Annulation of 3-Aryl- and 3-Heteroarylindoles with Propargyl Ethers: Synthesis and Photoluminescent Properties of Aryl- and Heteroaryl-Annulated[*c*]carbazoles

III-1. Introduction

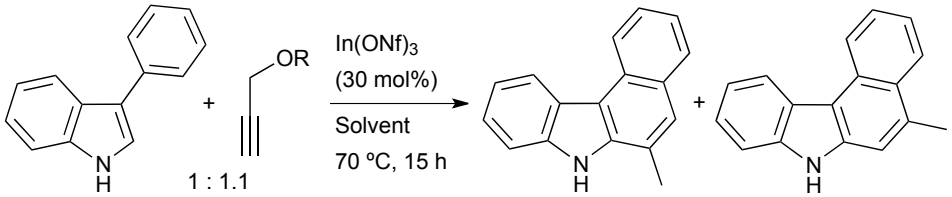
Aryl- and heteroaryl-annulated carbazoles (AHACs) are key constituents found in natural products, biologically active molecules and drugs[1] as well as optoelectronic materials.[2] AHACs are classified into [*a*]-, [*b*]- and [*c*]-types based on the position at which the (hetero)aryl ring is fused to the carbazole nucleus. Among the three types, the author's group firstly developed a new synthetic strategy for the [*a*]-type, by the indium-catalyzed annulation of 2-(hetero)arylindoles with propargyl ethers.[3] The strategy features two carbon–carbon bond-forming cascade in one batch, where direct use of two C–H bonds of 2-(hetero)arylindoles for an addition–substitution sequence to propargyl ethers is included as a key ingredient. His prime concern on this research project is to refine the strategy so as to be a more practical and general tool capable of synthesizing other types of AHACs. The author now found that the strategy works well also for [*c*]-types, simply by replacing 2-(hetero)arylindoles with their 3-analogs. Diverse synthetic methods for AHACs have thus far been developed due to their importance in a variety of aspects.[1,2] However, a powerful strategy with a broad substrate scope applicable to both [*a*]- and [*c*]-types has remained yet to be explored.[4–11] Taking advantage of this strategy which allows to access the two types, he also disclose interesting structure–property correlations by evaluating their photoluminescent properties.

III-2. Results & Discussion

Due to the potent activity of $In(ONf)_3$ (Nf = $SO_2C_4F_9$) found in his group's preceding research,[3] study on this topic began with its testing in the reaction of 3-phenylindole (**1a**) with methyl propargyl ether (**2a**) (Table 1). Thus, the reaction with $In(ONf)_3$ (30 mol%) in Bu_2O at 70 ºC for 15 h gave 6-methyl-7*H*-benzo[*c*]carbazole (**3a**) in 54% yield as a single isomer on the methyl group (entry 1).[12] The non-formation of the other isomer (**4a**) is noteworthy. Although the use of propargyl alcohol (**2b**) instead of **2a** provided no improvement in the yield, 3-trimethylsilyloxy-1-propyne (**2c**) reacted with **1a** more efficiently (entries 2 and 3). With **2c**, the reaction under higher dilution conditions raised the yield to 71% (entry 4). Interestingly, using

2 with a good leaving functionality was found to afford **4a** predominantly. Among such types of **2d**–**2f** examined, the highest selectivity for **4a** was achieved in the use of **2f** with OCO_2Et as the leaving group (entries 5–7). In this case, replacing Bu_2O with PhCl improved both the yield and selectivity (entry 8). Here again, increasing the solvent volume enhanced the yield of the products (entry 9).

Table 1. Indium-catalyzed annulation of 3-phenylindole with propargyl alcohol derivatives **2**[a].



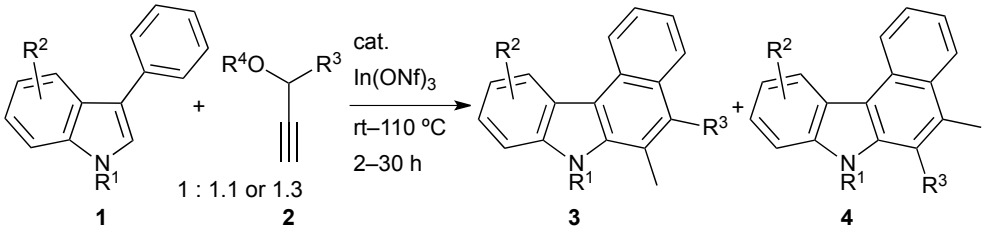
Entry	R	Solvent	Conv. (%) of **1a**[b]	Yield (%) of **3a** and **4a**[b]	**3a**:**4a**[c]
1	Me (**2a**)	Bu_2O	79	54	>99:1
2	H (**2b**)	Bu_2O	70	54	>99:1
3	$SiMe_3$ (**2c**)	Bu_2O	84	66	>99:1
4[d,e]	$SiMe_3$ (**2c**)	Bu_2O	93	71	>99:1
5	COBu (**2d**)	Bu_2O	84	13	48:52
6	SO_2Me (**2e**)	Bu_2O	68	33	32:68
7	CO_2Et (**2f**)	Bu_2O	77	21	13:87
8	CO_2Et (**2f**)	PhCl	83	41	9:91
9[d]	CO_2Et (**2f**)	PhCl	88	53	10:90

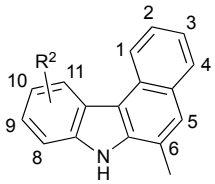
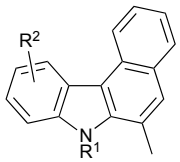
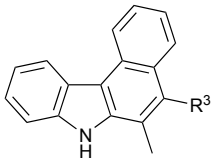
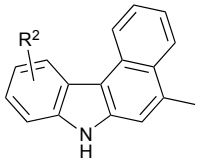
[a] Reagents: **1a** (0.20 mmol), **2** (0.22 mmol), $In(ONf)_3$ (60 μmol), solvent (3.0 mL). [b] Determined by ^1H NMR. [c] Determined by GC. [d] The solvent (3.5 mL) was used. [e] Reaction time = 12 h.

With both sets of the suitable reaction conditions in hand, the author examined the substrate scope of the reaction (Table 2). Besides **1a**, Me-, MeO-, or Br-substituted 3-phenylindole reacted with **2c** to give **3b**–**3g** in a regioselective fashion (entries 1–7). Aryl groups on the nitrogen atom of substrates did not participate in the annulation, thus showing remarkable reaction-site selectivity (entries 8–9).[13] Using propargyl ethers with a substituent at the propargylic position allows to introduce an additional carbon framework regioselectively (entries 10–11). With **2f** instead of **2c** as a C3 source, **4b** and **4d** were obtained selectively as in the case of **4a** (entries 12–14).

The strategy can be also applied to synthesis of heteroaryl derivatives. The predominant formation of thieno[*c*]carbazole **3l** was thus attained in the reaction of thienylindole **1b** with **2c** [eqn (1)]. For the synthesis of indolo[*c*]carbazole **3m**, **2a** was a superior electrophile [eqn (2)]. The reaction of benzothienylindole **1d** with **2f** provided **4n** as a single regioisomer [eqn (3)].

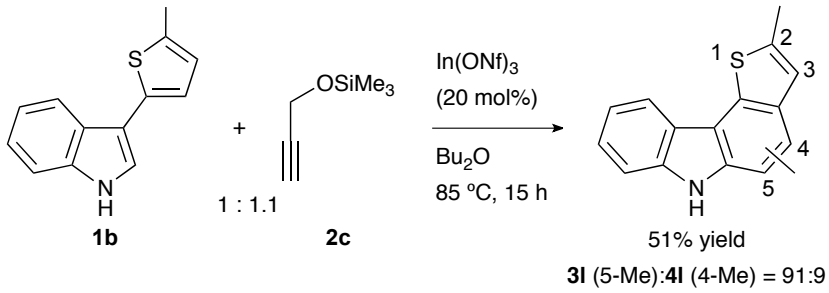
Table 2. Indium-catalyzed annulation of 3-arylindoles **1** with propargyl ethers **2**[a]



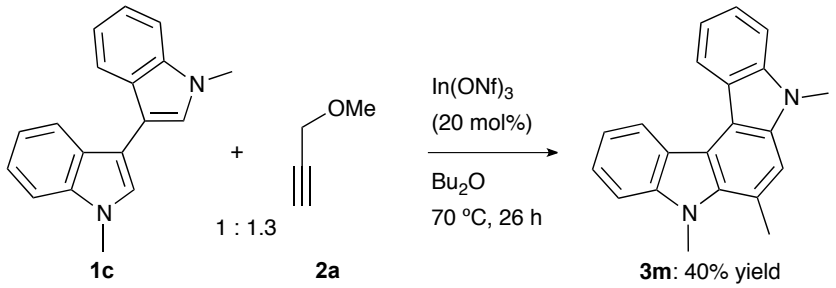
Entry	Major product, conditions		Yield (%)[b]	**3**:**4**[c]
1		**3a**: R^2 = H	70	>99:1
2		**3b**: R^2 = 3-Me	60	>99:1
3		**3c**: R^2 = 10-Me	61	>99:1
4		**3d**: R^2 = 3-MeO	62	>99:1
5	conditions A	**3e**: R^2 = 10-Br	49	>99:1
6		**3f**: R^1 = Me, R^2 = H	78	>99:1
7		**3g**: R^1 = Me, R^2 = 3-Me	86	>99:1
8[d]		**3h**: R^1 = Ph, R^2 = H	51	>99:1
9	conditions A	**3i**: R^1 = *p*-MeO–C_6H_4, R^2 = H	53	>99:1
10[e]		**3j**: R^3 = Me	56[f]	–
11[g]		**3k**: R^3 = *n*-pentyl	64[h]	>99:1
	conditions A			
12		**4a**: R^2 = H	52	10:90
13		**4b**: R^2 = 3-Me	66	6:94
14	conditions B	**4d**: R^2 = 3-MeO	60	5:95

[a] Conditions A: **1** (0.20 mmol), **2c** (0.22 or 0.26 mmol), $In(ONf)_3$ (40 or 60 μmol, 20 or 30 mol%), Bu_2O (3.5 mL); conditions B: **1** (0.20 mmol), **2f** (0.22 mmol), $In(ONf)_3$ (60 μmol, 30 mol%), PhCl (3.5 mL). See experimental section for further details. [b] Isolated yield based on **1**. [c] Determined by GC. [d] PhCl instead of Bu_2O was used as a solvent. [e] 3-Trimethylsilyloxy-1-butyne instead of **2c** was used. [f] 5-Ethyl-7*H*-benzo[*c*]carbazole was also formed in 1% yield. [g] 3-Trimethylsilyloxy-1-octyne

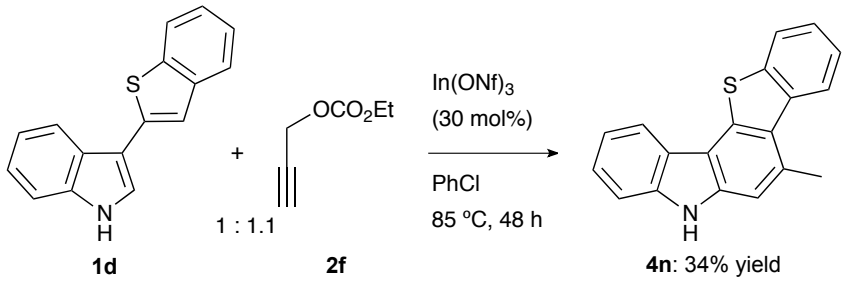
instead of **2c** was used. [h] 5-(1-Hexyl)-7*H*-benzo[*c*]carbazole was also formed in 1% yield.



(1)

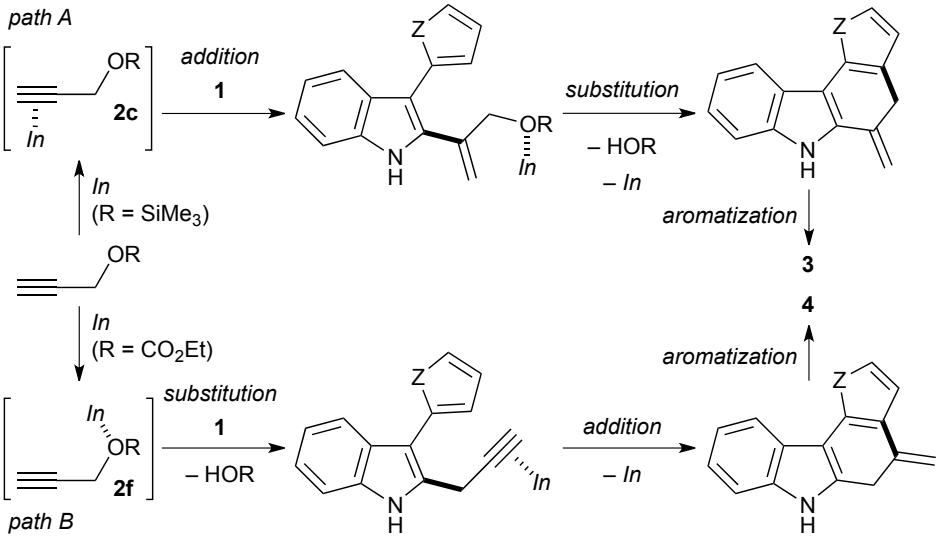


(2)



(3)

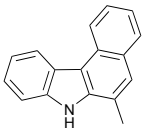
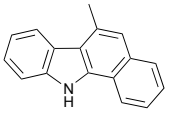
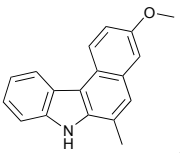
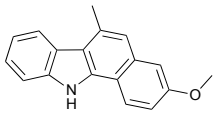
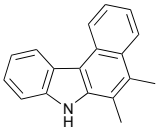
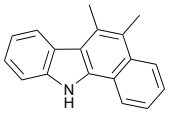
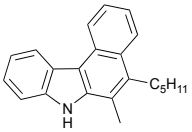
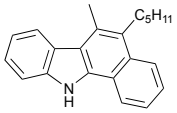
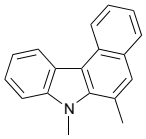
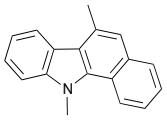
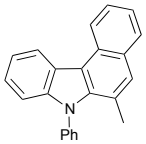
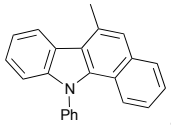
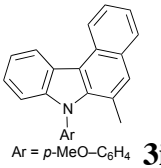
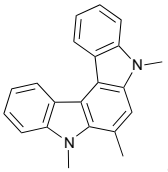
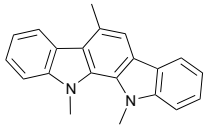
Plausible reaction mechanisms based on his earlier studies are shown as paths A and B in Scheme 1.[3] Path A in which **2c** acts as the C3 unit starts with addition of the indolyl C–H bond to the C≡C bond activated by the indium salt (*In*).[14] The next stage is intramolecular S_N2 cyclization followed by aromatization to provide **3**. On the other hand, substitution between **1** and the **2f**–*In* complex would precede addition in path B because **2f** has OCO_2Et as a good leaving group.[15] The final step is aromatization leading to **4**. Considering such reversed order of the addition and substitution processes in paths A and B, the regiochemistry concerning the methyl group of **3** and **4** would be rationally understood.



Scheme 1. Plausible reaction mechanisms

Finally, the author investigated the photoluminescent properties of some (hetero)aryl[*c*]carbazoles, and compared to those of the corresponding [*a*]-type, respectively (Table 3).[3,16] The emission maxima of the [*c*]-types ranged from 360 to 400 nm, similarly as [*a*]-analogs. Methyl and electron-rich aryl groups including a phenyl group on the nitrogen atom (**3f**, **3h** and **3i**) contributed to enhancing quantum efficiency in comparison to basic structure **3a**, as observed in the [*a*]-types (**5a** vs. **5f**, **5h** or **5i**). Interestingly, the quantum yields of each [*c*]-type were found to be always higher than those of the corresponding [*a*]-type. These structure–property correlations on AHACs might be a useful guide to create optoelectronic devices.

Table 3. Photoluminescent properties of (hetero)aryl[*c*]- and -[*a*]carbazoles[a]

(H)A[*c*]C[b]	λ_{max}/nm[c] Φ_F[d]	(H)A[*a*]C[e]	λ_{max}/nm[c] Φ_F[d]
 **3a**	362, 380, 399sh 0.334	 **5a**	360, 378, 397 0.165
 **3d**	383, 400 0.298	 **5d**	363, 378, 395sh 0.109
 **3j**	366, 383, 401sh 0.343	 **5j**	370, 388, 407sh 0.156
 **3k**	366, 384, 402sh 0.358	 **5k**	369, 388, 407 0.167
 **3f**	374, 392, 413sh 0.391	 **5f**	371, 389, 408sh 0.184
 **3h**	369, 387, 405sh 0.416	 **5h**	366, 384, 403sh 0.239
 Ar = *p*-MeO–C_6H_4 **3i**	372, 388, 408sh 0.481	 Ar = *p*-MeO–C_6H_4 **5i**	367, 385, 404sh 0.264
 **3m**	370, 385 0.314	 **5m**	391, 410, 431sh 0.114

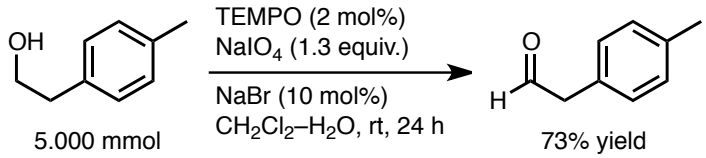
[a] Fluorescence spectra excited at 265 nm were measured in CH_2Cl_2 (c = 1.5 x 10^{-6} M). Photoluminescent data of [*a*]-types collected herein were derived from reference 3b. [b] (H)A[*c*]C = (hetero)aryl[*c*]carbazole. [c] sh = shoulder. [d] Determined with reference to the quantum yield of *p*-terphenyl. [e] (H)A[*a*]C = (hetero)aryl[*a*]carbazole.

III-3. Experimental

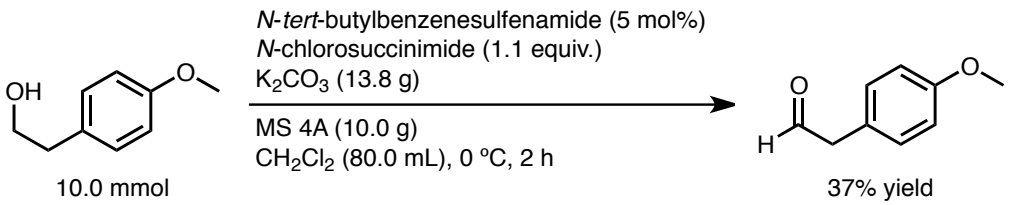
General Remarks. All manipulations were conducted with a standard Schlenk technique under an argon atmosphere. Nuclear magnetic resonance (NMR) spectra were taken on a JEOL JMN-ECA 400 (^{1}H, 400 MHz; ^{13}C, 100 MHz) or a JEOL JMN-ECA 500 (^{1}H, 500 MHz; ^{13}C, 125 MHz) spectrometer using tetramethylsilane (^{1}H and ^{13}C) as an internal standard. Analytical gas chromatography (GC) was performed on a Shimadzu model GC-2014 instrument equipped with a capillary column of Inert Cap 5 (5% phenyl polysilphenylene-siloxane, 30 m x 0.25 mm x 0.25 μm) using nitrogen as carrier gas. Gas chromatography–mass spectrometry (GC–MS) analyses were performed with a Shimadzu model GCMS-QP2010 instrument equipped with a capillary column of ID-BPX5 by electron ionization at 70 eV using helium as carrier gas. Preparative recycling high-performance liquid chromatography (HPLC) was performed with JAI LC-9104 equipped with JAIGEL-GS320 column using a mixture of hexane–ethyl acetate (EtOAc) as eluent. Preparative recycling gel permeation chromatography (GPC) was performed with JAI LC-9105 equipped with JAIGEL-1H and JAIGEL-2H columns using chloroform as eluent. All melting points were measured with a Yanaco Micro Melting Point apparatus and uncorrected. High-resolution mass spectra (HRMS) were measured at National Institute of Advanced Industrial Science and Technology (AIST). Elemental analyses were performed on a Vario EL III elemental analysis instrument. UV-vis absorption spectra were recorded with a JASCO V-550 spectrophotometer at room temperature. Fluorescence spectra were recorded with a JASCO FP-6500 spectrofluorometer at room temperature using an excitation wavelength of 265 nm. A solution of *p*-terphenyl in cyclohexane was used as a quantum yield standard (Φ_F = 0.87 at 265 nm excitation). Dibutyl ether (Bu_2O) was distilled under argon from sodium just prior to use. Tetrahydrofuran (THF) and diethyl ether (Et_2O) were distilled under argon from sodium benzophenone ketyl just before use. Chlorobenzene (PhCl), toluene (PhMe), and dichloromethane (CH_2Cl_2) were distilled under argon from calcium chloride just prior to use. Anhydrous dimethyl sulfoxide (DMSO) was purchased from Sigma-Aldrich Co. LLC. and used without further purification. 3-Phenyl-1*H*-indole (**1a**)[17] and 3,3'-biindolyl[18] were synthesized according to the respective literature methods. $In(ONf)_3$ (Nf = $SO_2C_4F_9$)[19] and $In(NTf_2)_3$ (Tf = SO_2CF_3)[20] were prepared by the respective literature procedures.

Unless otherwise noted, reagents were commercially available and used as received without further purification.

Synthesis of Arylacetaldehydes



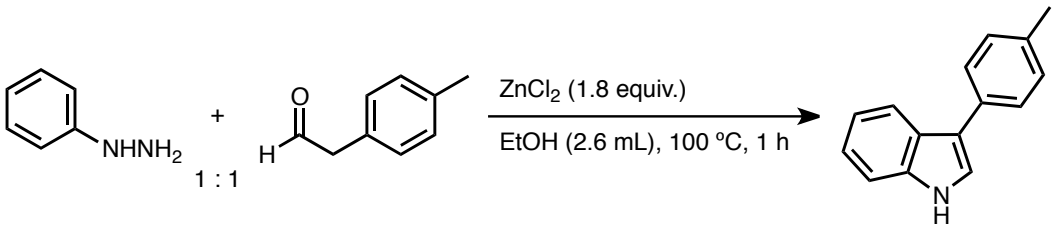
4-Methylphenylacetaldehyde. The title compound was synthesized according to the literature method.[21] In a 100 mL Schlenk tube, 2-(4-methylphenyl)ethanol (681.0 mg, 5.000 mmol) and 2,2,6,6-tetramethyl-1-piperidinyloxy (TEMPO) (15.8 mg, 0.101 mmol) were dissolved in CH_2Cl_2 (10.0 mL). To this were added an aqueous solution of $NaIO_4$ (1367 mg, 6.392 mmol) and NaBr (51.5 mg, 0.500 mmol) in H_2O (12.0 mL). After being stirred vigorously at room temperature for 24 h, the resulting solution was extracted with CH_2Cl_2 (10 mL x 3). The combined organic layer was washed with a 10% NaS_2O_3 aqueous solution (10 mL), a saturated $NaHCO_3$ aqueous solution (10 mL) and brine (10 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (hexane/EtOAc = 5/1) gave 4-methylphenylacetaldehyde (467.5 mg, 73% yield) as a colorless liquid. This compound has been already synthesized in literature, and their spectral and analytical data are in good agreement with those reported in reference 22.[22] Therefore, only ^{1}H NMR data are provided here. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.35 (s, 3 H), 3.65 (d, *J* = 2.3 Hz, 2 H), 7.11 (d, *J* = 8.0 Hz, 2 H), 7.18 (d, *J* = 8.0 Hz, 2 H), 9.73 (t, *J* = 2.3 Hz, 1 H).



4-Methoxyphenylacetaldehyde. The title compound was synthesized according to the reported procedure.[23] A 300 mL Schlenk tube was charged with

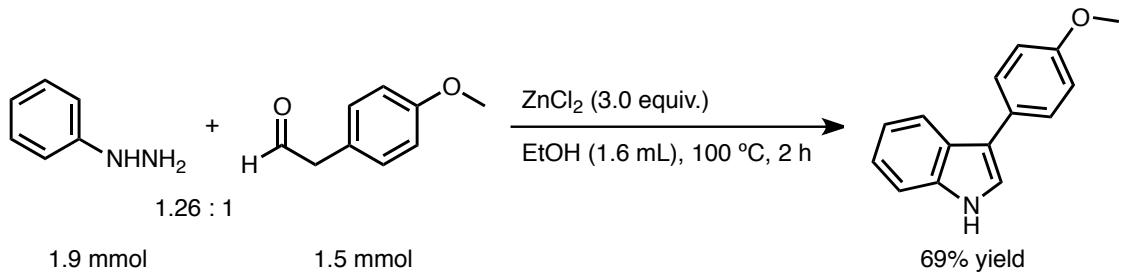
molecular sieves 4A (10.0 g), K_2CO_3 (13.8 g, 99.8 mmol), *N*-chlorosuccinimide (1.46 g, 10.9 mmol) and CH_2Cl_2 (20.0 mL). To this were successively added a solution of 2-(4-methoxyphenyl)ethanol (1.52 g, 10.0 mmol) in CH_2Cl_2 (30.0 mL) and a solution of *N-tert*-butylbenzenesulfenamide (90.7 mg, 0.500 mmol) in CH_2Cl_2 (30.0 mL) at 0 ºC. After being stirred at 0 °C for 2 h, the reaction mixture was quenched with water (80 mL). The resulting solution was filtered through a pad of Celite, and the aqueous phase was extracted with CH_2Cl_2 (80 mL x 3). The combined organic layer was washed with water (80 mL) and brine (80 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (hexane/EtOAc = 5/1) gave 4-methoxyphenylacetaldehyde (590.3 mg, 37% yield) as a colorless liquid. This compound has been already synthesized in literature, and their spectral and analytical data are in good agreement with those reported in reference 22.[22] Therefore, only ^{1}H NMR data are provided here. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.63 (d, *J* = 2.3 Hz, 2 H), 3.81 (s, 3 H), 6.89–6.93 (m, 2 H), 7.11–7.16 (m, 2 H), 9.72 (t, *J* = 2.1 Hz, 1 H).

Synthesis of 3-(4-methylphenyl)-1*H*-indole and 3-(4-methoxyphenyl)- 1*H*-indole. 3-(4-Methylphenyl)-1*H*-indole and 3-(4-methoxyphenyl)-1*H*-indole were synthesized according to the same procedure as for the synthesis of **1a**.[17] Their spectral and analytical data are as follows:

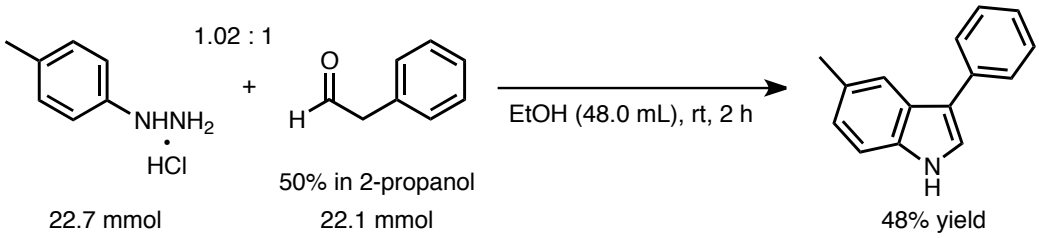


3-(4-Methylphenyl)-1*H*-indole. The title compound was isolated by column chromatography on silica gel (hexane/EtOAc = 5/1). A white solid. This compound has been already synthesized in literature, and their spectral and analytical data are in good agreement with those reported in reference 24.[24] Therefore, only ^{1}H NMR data are provided here. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.41 (s, 3 H), 7.19 (t, *J* = 7.4 Hz 1

H), 7.22–7.29 (m, 3 H), 7.34 (d, *J* = 2.3 Hz, 1 H), 7.43 (d, *J* = 8.1 Hz, 1 H), 7.57 (d, *J* = 8.0 Hz, 2 H), 7.93 (d, *J* = 8.0 Hz, 1 H), 8.19 (bs, 1 H).

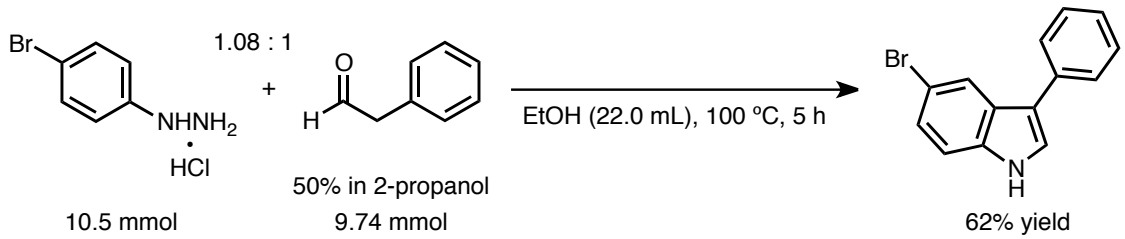


3-(4-Methoxyphenyl)-1*H*-indole. The title compound was isolated by column chromatography on silica gel (hexane/EtOAc = 5/1). A white solid. This compound has been already synthesized in literature, and their spectral and analytical data are in good agreement with those reported in reference 25.[25] Therefore, only ^{1}H NMR data are provided here. ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.87 (s, 3 H), 7.01 (d, *J* = 8.6 Hz, 2 H), 7.19 (td, *J* = 6.9, 1.1 Hz, 1 H), 7.22–7.28 (m, 1 H), 7.31 (d, *J* = 2.3 Hz, 1 H), 7.43 (dd, *J* = 8.0, 0.6 Hz, 1 H), 7.60 (d, *J* = 8.6 Hz, 2 H), 7.90 (d, *J* = 8.0 Hz, 1 H), 8.19 (bs, 1 H).

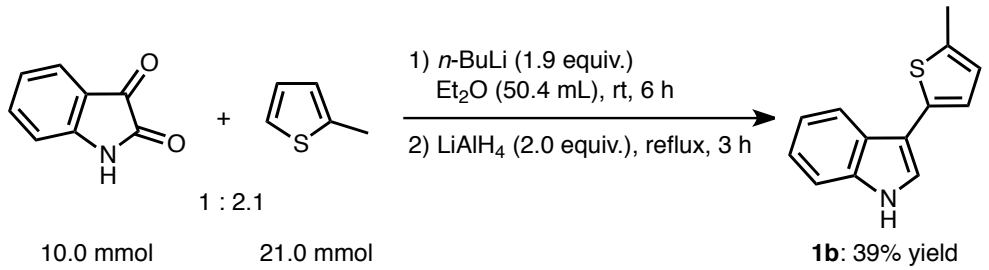


Synthesis of 5-Methyl-3-phenyl-1*H*-indole. 5-Methyl-3-phenyl-1*H*-indole was synthesized according to the following modified literature procedure.[17] Under an argon atmosphere, 4-methylphenylhydrazine hydrochloride (2.77 g, 22.7 mmol), a 50% 2-propanol solution of phenylacetaldehyde (5.30 g, 22.1 mmol) and EtOH (48.0 mL) were placed in a 300 mL Schlenk tube, the mixture in which was stirred at room temperature for 2 h. The resulting solution was filtered, and the solvent was removed under reduced pressure. To this was added a 4% HCl aqueous solution (40 mL), and the aqueous phase was extracted with CH_2Cl_2 (20 mL x 3). The combined organic layer was washed with brine (20 mL) and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica

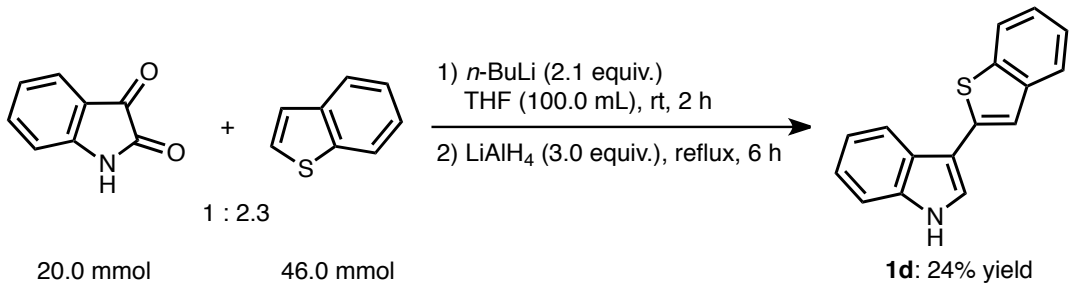
gel (hexane/EtOAc = 5/1) gave 5-methyl-3-phenyl-1*H*-indole (2.19 g, 48% yield) as a white solid. This compound has been already synthesized in literature, and their spectral and analytical data are in good agreement with those reported in reference 26.[26] Therefore, only ^{1}H NMR data measured in $CDCl_3$ and also in DMSO-d_6 are provided here. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.48 (s, 3 H), 7.08 (dd, *J* = 8.3, 1.5 Hz, 1 H), 7.29 (tt, *J* = 7.5, 1.3 Hz, 1 H), 7.31–7.35 (m, 2 H), 7.45 (tt, *J* = 7.7, 1.8 Hz, 2 H), 7.64–7.69 (m, 2 H), 7.73 (d, *J* = 1.7 Hz, 1 H), 8.14 (bs, 1 H); ^{1}H NMR (400 MHz, DMSO-d_6) δ 3.79 (s, 3 H), 6.81 (dd, *J* = 8.7, 2.3 Hz, 1 H), 7.22 (t, *J* = 7.3 Hz, 1 H), 7.30 (d, *J* = 1.8 Hz, 1 H), 7.35 (d, *J* = 8.7 Hz, 1 H), 7.43 (t, *J* = 7.6 Hz, 2 H), 7.62 (d, *J* = 2.3 Hz, 1 H), 7.67 (d, *J* = 7.3 Hz, 2 H), 11.21 (bs, 1 H).



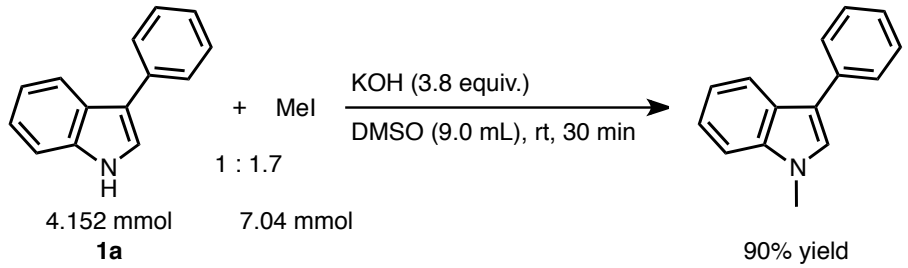
Synthesis of 5-Bromo-3-phenyl-1*H*-indole. 5-Bromo-3-phenyl-1*H*-indole was synthesized according to the following modified literature procedure.[17] Under an argon atmosphere, 4-bromophenylhydrazine hydrochloride (2.35 g, 10.5 mmol), a 50% 2-propanol solution of phenylacetaldehyde (1.17 g, 9.74 mmol) and EtOH (22.0 mL) were placed in a 300 mL Schlenk tube, the mixture in which was stirred at 100 °C for 5 h. The resulting solution was filtered, and the solvent was removed under reduced pressure. To this was added a 4% HCl aqueous solution (20 mL), and the aqueous phase was extracted with CH_2Cl_2 (10 mL x 3). The combined organic layer was washed with brine (10 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (hexane/EtOAc = 5/1) gave 5-bromo-3-phenyl-1*H*-indole (1.63 g, 62% yield) as a white solid. This compound has been already synthesized in literature, and their spectral and analytical data are in good agreement with those reported in reference 27.[27] Therefore, only ^{1}H NMR data are provided here. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.28–7.36 (m, 3 H), 7.36 (d, *J* = 2.8 Hz, 1 H), 7.46 (tt, *J* = 7.7, 1.7 Hz, 2 H), 7.58–7.64 (m, 2 H), 8.05 (d, *J* = 1.4 Hz, 1 H), 8.26 (bs, 1 H).



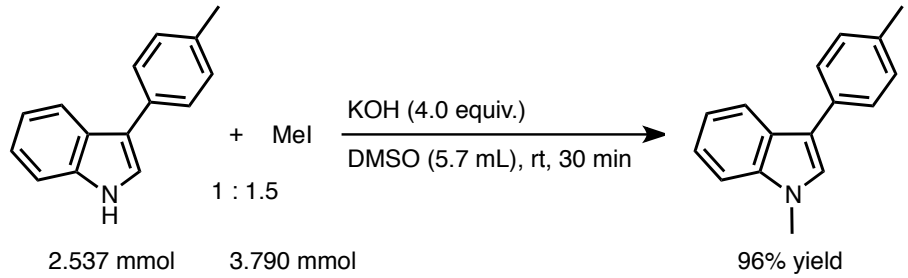
Synthesis of 3-(5-Methylthiophen-2-yl)-1*H*-indole (1b). Compound **1b** was synthesized according to the literature method.[18a] Under an argon atmosphere, 2-methylthiophene (2.06 g, 21.0 mmol) and Et_2O (15.2 mL) were placed in a 300 mL two-necked round-bottomed flask equipped with a dropping funnel and a dimroth condenser attached to a three-way stopcock. To this was slowly added *n*-BuLi (11.5 mL, 19.0 mmol, 1.56 M in hexane) cooled to 0 °C through the dropping funnel, and the resulting solution was stirred at 0 °C for 1.5 h. After being warmed to room temperature, a solution of isatin (1.47 g, 10.0 mmol) in Et_2O (35.2 mL) was added in five portions through the dropping funnel, and the mixture was stirred at room temperature for 6 h. $LiAlH_4$ (763.9 mg, 20.12 mmol) was then added, and the resulting mixture was heated to reflux for 3 h. After being cooled to room temperature, the mixture was treated carefully with water (1.0 mL) to decompose excess $LiAlH_4$. The resulting suspension was filtered, and the filtrate was extracted with Et_2O (20 mL x 3). The combined organic layer was washed with brine (15 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (hexane/EtOAc = 5/1) and further purification by recycling GPC gave 3-(5-methylthiophen-2-yl)-1*H*-indole (847.9 mg, 39% yield) as a white solid, mp 82–83 ºC. ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.52 (d, *J* = 0.9 Hz, 3 H), 6.73–6.78 (m, 1 H), 7.06 (d, *J* = 3.7 Hz, 1 H), 7.20 (td, *J* = 7.4, 1.1 Hz, 1 H), 7.25 (td, *J* = 7.6, 1.2 Hz, 1 H), 7.36 (d, *J* = 2.3 Hz, 1 H), 7.40 (dd, *J* = 7.6, 1.2 Hz, 1H), 7.95 (d, *J* = 7.8 Hz, 1 H), 8.15 (bs, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 15.3, 111.3, 112.3, 120.0, 120.4, 121.4, 122.5, 122.6, 125.5, 125.6, 135.3, 136.4, 137.0. HRMS (EI) Calcd for $C_{13}H_{11}NS$: M^+, 213.0607. Found: *m*/*z* 213.0608.



Synthesis of 3-(Benzo[*b*]thiophen-2-yl)-1*H*-indole (1d). Compound **1d** was synthesized according to the literature method.[18a] Under an argon atmosphere, benzo[*b*]thiophene (6.18 g, 46.0 mmol) and THF (30.0 mL) were placed in a 500 mL two-necked round-bottomed flask equipped with a dropping funnel and a dimroth condenser attached to a three-way stopcock. To this was slowly added *n*-BuLi (25.0 mL, 42.0 mmol, 1.65 M in hexane) cooled to –18 ºC through the dropping funnel, and the resulting solution was stirred at –18 °C for 6 h. After being warmed to room temperature, a THF (70.0 mL) solution of isatin (2.94 g, 20.0 mmol) was added in five portions through the dropping funnel, and the mixture was stirred at room temperature for 2 h. $LiAlH_4$ (2.28 g, 60.0 mmol) was then added, and the resulting mixture was heated to reflux for 6 h. After being cooled to room temperature, the mixture was treated carefully with water (3.0 mL) to decompose excess $LiAlH_4$. The resulting suspension was filtered, and the filtrate was extracted with Et_2O (60 mL x 3). The combined organic layer was washed with brine (30 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (hexane/EtOAc = 10/1) gave 3-(benzo[*b*]thiophen-2-yl)-1*H*-indole (1.24 g, 24% yield) as a white solid, mp 155–156 ºC. ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.26–7.32 (m, 3 H), 7.35 (td, *J* = 7.6, 0.8 Hz, 1 H), 7.45 (dd, *J* = 6.9, 1.7 Hz, 1 H), 7.53 (s, 1 H), 7.55 (d, *J* = 2.3 Hz, 1 H), 7.77 (d, *J* = 8.0 Hz, 1 H), 7.82 (d, *J* = 8.0 Hz, 1 H), 8.09 (dd, *J* = 6.9, 1.7 Hz, 1 H), 8.29 (bs, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 111.5, 112.1, 118.5, 120.1, 120.9, 122.0, 122.8, 122.95, 122.99, 123.5, 124.3, 125.4, 136.6, 138.0, 138.4, 140.9. HRMS (EI) Calcd for $C_{16}H_{11}NS$: M^+, 249.0607. Found: *m*/*z* 249.0603.

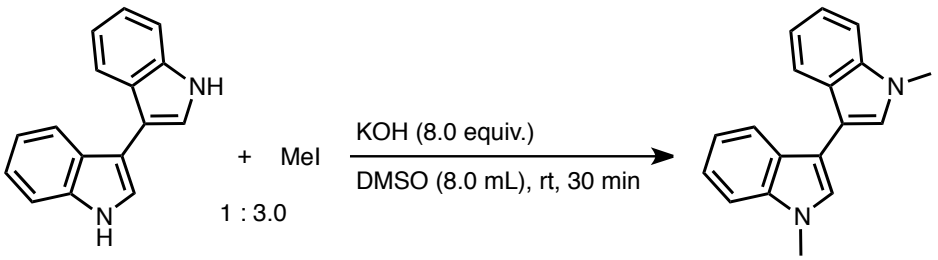


Synthesis of 1-Methyl-3-phenyl-1*H*-indole. Under an argon atmosphere, potassium hydroxide (913.5 mg, 16.28 mmol) and anhydrous DMSO (9.0 mL) were placed in a 50 mL Schlenk tube, which was immersed in a water bath at 22 ºC. To this was added 3-phenyl-1*H*-indole (**1a**; 802.5 mg, 4.152 mmol), and the mixture was stirred for 1 h. Iodomethane (1.00 g, 7.04 mmol) was added dropwise to the tube, and the resulting mixture was further stirred for 30 min. To this was added water (5 mL), and the aqueous phase was extracted with Et_2O (40 mL x 3). The combined organic layer was washed with water (10 mL x 5) and brine (5 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (hexane/EtOAc = 35/1) gave 1-methyl-3-phenyl-1*H*-indole (775.8 mg, 90% yield) as a white solid. This compound has been already synthesized in literature, and their spectral and analytical data are in good agreement with those reported in references 27 and 28.[27,28] Therefore, only ^{1}H NMR data are provided here. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.84 (s, 3 H), 7.19 (ddd, *J* = 8.0, 6.9, 1.2 Hz, 1 H), 7.23 (s, 1 H), 7.24–7.31 (m, 2 H), 7.36 (dt, *J* = 8.3, 0.9 Hz, 1 H), 7.43 (tt, *J* = 7.7, 1.7 Hz, 2 H), 7.63–7.68 (m, 2 H), 7.94 (dd, *J* = 6.9, 0.9 Hz, 1 H).



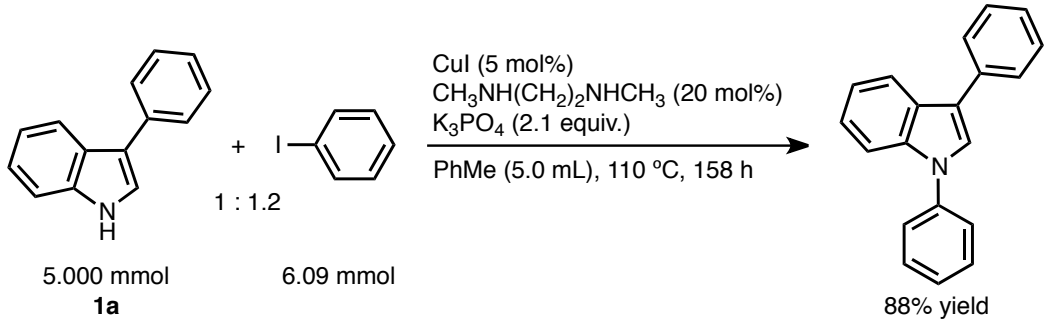
Synthesis of 1-Methyl-3-(4-methylphenyl)-1*H*-indole. Under an argon atmosphere, potassium hydroxide (561.0 mg, 10.00 mmol) and anhydrous DMSO (5.7 mL) were placed in a 50 mL Schlenk tube, which was immersed in a water bath at 22 ºC. To this was added 3-(4-methylphenyl)-1*H*-indole (526.0 mg, 2.537 mmol), and

then the mixture was stirred for 1 h. Iodomethane (538.0 mg, 3.790 mmol) was added dropwise to the tube, and the resulting mixture was further stirred for 30 min. To this was added water (5 mL), and the aqueous phase was extracted with Et_2O (30 mL x 3). The combined organic layer was washed with water (5 mL x 5) and brine (5 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (hexane/EtOAc = 7/1) gave 1-methyl-3-(4-methylphenyl)-1*H*-indole (543.4 mg, 96% yield) as a white solid. This compound has been already synthesized in literature, and their spectral and analytical data are in good agreement with those reported in references 27 and 29.[27,29] Therefore, only ^{1}H NMR data are provided here. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.40 (s, 3 H), 3.83 (s, 3 H), 7.18 (ddd, *J* = 8.0, 6.9, 1.2 Hz, 1 H), 7.20 (s, 1 H), 7.22–7.30 (m, 3 H), 7.36 (dd, *J* = 7.5, 1.2 Hz, 1 H), 7.55 (ddd, *J* = 8.0, 2.3, 1.8 Hz, 2 H), 7.92 (dt, *J* = 8.0, 1.2 Hz, 1 H).

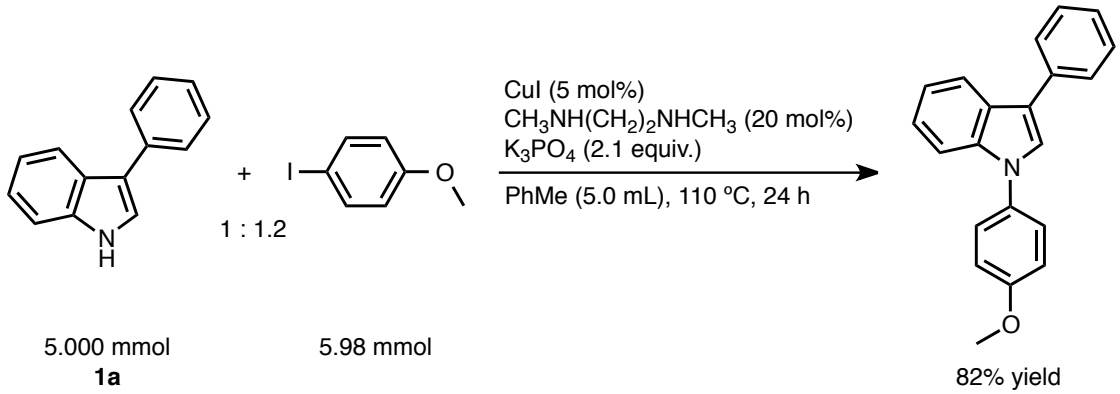


Synthesis of 1,1'-Dimethyl-3,3'-biindolyl (1c). Under an argon atmosphere, potassium hydroxide (1.57 g, 27.9 mmol) and anhydrous DMSO (8.0 mL) were placed in a 50 mL Schlenk tube, which was immersed in a water bath at 22 ºC. To this was added 3,3'-biindolyl[18] (812.4 mg, 3.497 mmol), and then the mixture was stirred for 1 h. Iodomethane (1.50 g, 10.5 mmol) was added dropwise to the tube, and the resulting mixture was further stirred for 30 min. To this was added water (5 mL), and the aqueous phase was extracted with Et_2O (40 mL x 3). The combined organic layer was washed with water (8 mL x 5) and brine (5 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (hexane/EtOAc = 7/1) gave 1,1'-dimethyl-3,3'-biindolyl (**1c**; 837.3 mg, 91% yield) as a white solid, mp 186–187 ºC. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.87 (s, 6 H), 7.16 (ddd, *J* = 8.1, 6.8, 1.0 Hz, 2 H), 7.28 (ddd, *J* = 8.2, 6.9, 0.9 Hz, 2 H), 7.31 (s, 2 H), 7.38 (ddd, *J* = 8.3, 1.4, 0.9 Hz, 2 H), 7.83 (dt, *J* = 7.8, 0.9 Hz, 2 H); ^{13}C NMR (100

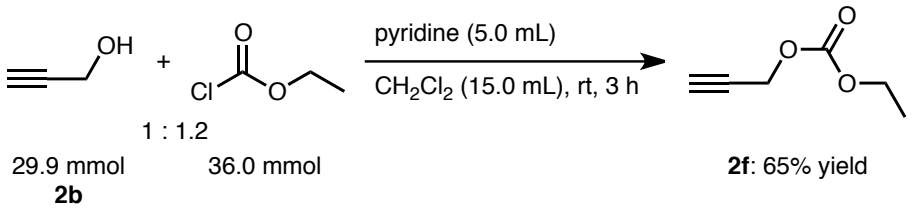
MHz, $CDCl_3$) δ 32.8, 109.3, 109.5, 119.2, 120.3, 121.8, 126.0, 127.2, 137.1. Anal. Calcd for $C_{18}H_{16}N_2$: C, 83.04; H, 6.19; N, 10.76. Found: C, 83.06; H, 6.18; N, 10.74.



Synthesis of 1,3-Diphenyl-1*H*-indole. 1,3-Diphenyl-1*H*-indole was synthesized according to the literature method.[30] Into a 50 mL Schlenk tube was placed CuI (47.6 mg, 0.249 mmol), 3-phenyl-1*H*-indole (**1a**; 966.2 mg, 5.000 mmol) and K_3PO_4 (2.22 g, 10.4 mmol), and then the tube was evacuated and filled with argon. Iodobenzene (1.24 g, 6.09 mmol), *N*,*N*'-dimethylethylenediamine (88.2 mg, 1.00 mmol) and PhMe (5.0 mL) were added successively to the tube, and the mixture was stirred at 110 °C for 158 h. Filtration through a pad of Celite and evaporation of the solvent followed by column chromatography on silica gel (hexane/EtOAc = 30/1) gave 1,3-diphenyl-1*H*-indole (1433.9 mg, 88% yield) as a white solid. This compound has been already synthesized in literature, and their spectral and analytical data are in good agreement with those reported in reference 31.[31] Therefore, only ^{1}H NMR data are provided here. ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.22–7.30 (m, 2 H), 7.32 (tdd, *J* = 7.4, 1.7, 1.1 Hz, 1 H), 7.39 (tt, *J* = 6.7, 1.9 Hz, 1 H), 7.47 (tt, *J* = 7.7, 1.7 Hz, 2 H), 7.51 (s, 1 H), 7.52–7.59 (m, 4 H), 7.61 (dd, *J* = 7.2, 1.4 Hz, 1 H), 7.69–7.74 (m, 2 H), 7.99 (ddd, *J* = 7.7, 1.7, 0.9 Hz, 1 H).

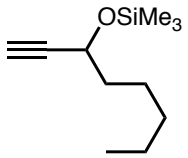


Synthesis of 1-(4-Methoxyphenyl)-3-phenyl-1*H*-indole. 1-(4-Methoxyphenyl)-3-phenyl-1*H*-indole was synthesized according to the literature method.[30] Into a 50 mL Schlenk tube was placed CuI (47.6 mg, 0.249 mmol), 3-phenyl-1*H*-indole (**1a**; 966.2 mg, 5.000 mmol) and K_3PO_4 (2.22 g, 10.4 mmol), and then the tube was evacuated and filled with argon. 4-Methoxyiodobenzene (1.40 g, 5.98 mmol), *N*,*N*-dimethylethylenediamine (88.2 mg, 1.00 mmol) and PhMe (5.0 mL) were added successively to the tube, and the mixture was stirred at 110 °C for 24 h. Filtration through a pad of Celite and evaporation of the solvent followed by column chromatography on silica gel (hexane/EtOAc = 15/1) gave 1-(4-methoxyphenyl)-3-pheny-1*H*-lindole (1440.0 mg, 82% yield) as a white solid, mp 112–113 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.89 (s, 3 H), 7.05 (dt, *J* = 9.6, 3.2 Hz, 2 H), 7.19–7.28 (m, 2 H), 7.30 (tt, *J* = 7.5, 1.4 Hz, 1 H), 7.41–7.52 (m, 6 H), 7.67–7.74 (m, 2 H), 7.95–8.02 (m, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 55.6, 110.7, 114.8, 118.4, 120.0, 120.6, 122.6, 125.9, 126.1, 126.7, 127.5, 128.8, 132.4, 135.2, 137.1, 158.4 (One carbon signal is missing due to overlapping). HRMS (EI) Calcd for $C_{21}H_{17}NO$: M^+, 299.1305. Found: *m*/*z* 299.1298.



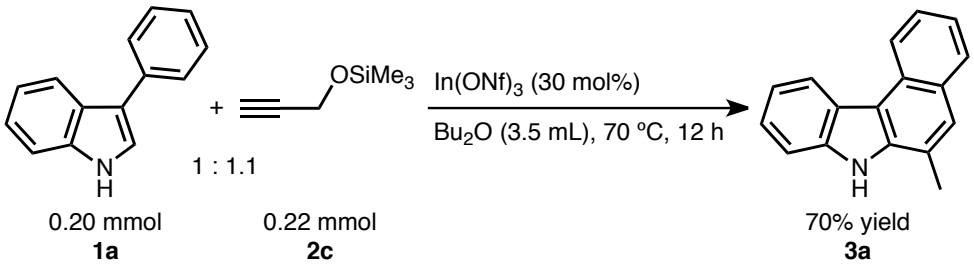
Synthesis of Ethyl prop-2-yn-1-yl carbonate (2f). Under an argon atmosphere, propargyl alcohol (**2b**; 1.68 g, 29.9 mmol), pyridine (5.0 mL) and CH_2Cl_2 (15.0 mL) were placed in a 50 mL Schlenk tube, to which was added dropwise ethyl

chloroformate (3.91 g, 36.0 mmol) at 0 ºC. After being stirred at room temperature for 3 h, the reaction mixture was quenched with water (5 mL), and the aqueous phase was extracted with Et_2O (40 mL x 3). The combined organic layer was washed with brine (15 mL) and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by short-path distillation under reduced pressure (72 ºC/30 mmHg) gave ethyl prop-2-yn-1-yl carbonate (**2f**; 2.50 g, 65% yield) as a colorless liquid. ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.33 (t, *J* = 7.2 Hz, 3 H), 2.53 (t, *J* = 2.3 Hz, 1 H), 4.24 (q, *J* = 7.1 Hz, 2 H), 4.73 (d, *J* = 2.3 Hz, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.2, 55.1, 64.6, 75.6, 77.1, 154.5. Anal. Calcd for $C_6H_8O_3$: C, 56.24; H, 6.29. Found: C, 56.14; H, 6.28.

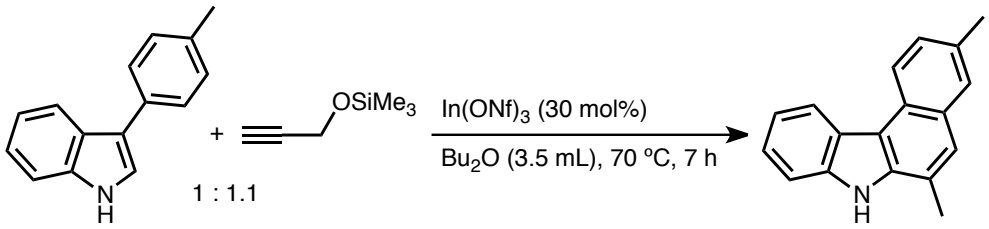


Synthesis of 3-Trimethylsilyloxy-1-octyne. 3-Trimethylsilyloxy-1-octyne as a colorless liquid was synthesized according to the reported procedure.[32] ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.17 (s, 9 H), 0.89 (t, *J* = 6.9 Hz, 3 H), 1.23–1.36 (m, 4 H), 1.36–1.48 (m, 2 H), 1.61–1.73 (m, 2 H), 2.39 (d, *J* = 2.3 Hz, 1 H), 4.32 (td, *J* = 6.6, 2.1 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 0.1, 14.0, 22.6, 24.8, 31.4, 38.5, 62.5, 72.0, 85.6. Anal. Calcd for $C_{11}H_{22}OSi$: C, 66.60; H, 11.18. Found: C, 66.83; H, 10.76.

Synthesis of Aryl- and Heteroaryl[*c*]carbazoles Utilizing Indium-Catalyzed Annulation of 3-Aryl- and 3-Heteroarylindoles with Propargyl Ethers. A General Procedure for Table 2 and Equations 1–3. $In(ONf)_3$ [(40.4 mg, 20.0 μmol) or (60.7 mg, 60.0 μmol)] was placed in a 20 or 50 mL Schlenk tube, which was heated at 150 °C in vacuo for 2 h. The tube was cooled down to room temperature and filled with argon. Bu_2O (3.5 or 7.5 mL) or PhCl (3.5 mL) was added to the tube and then the mixture was stirred at room temperature for 10 min. To this were added 3-(hetero)arylindole (0.200 mmol) and propargyl ether (0.220 or 0.260 mmol) successively, and the resulting mixture was stirred at 70, 85, 100 or 110 °C. After the time specified in Table 2 and Equations 1–3, the mixture was diluted with EtOAc (10 mL) and washed with a saturated $NaHCO_3$ aqueous solution (1 mL) and brine (1 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel using hexane–EtOAc as eluent gave the corresponding (hetero)aryl[*c*]carbazoles. In case that purity of **3** or **4** is insufficient, further purification was performed with recycling HPLC or GPC. Products **3** and **4** synthesized here were fully characterized by ^1H and ^{13}C NMR spectroscopy, and elemental analysis or HRMS.

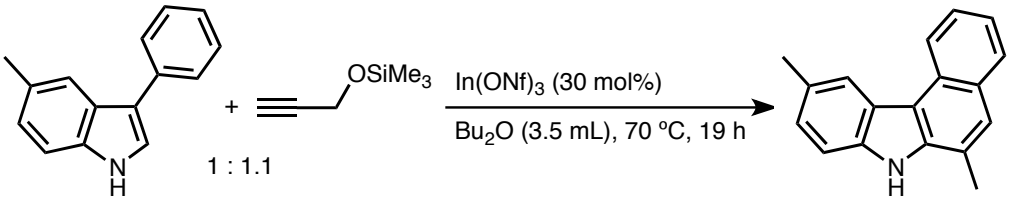


6-Methyl-7*H*-benzo[*c*]carbazole (3a). The title compound was isolated by recycling GPC after column chromatography on silica gel (hexane/EtOAc = 5/1). A white solid, mp 154–155 °C. ^1H NMR (400 MHz, $CDCl_3$) δ 2.68 (d, J = 0.9 Hz, 3 H), 7.38 (ddd, J = 8.3, 6.9, 0.9 Hz 1 H), 7.448 (tdd, J = 7.6, 1.4, 0.9 Hz, 1 H), 7.449 (s, 1 H), 7.59 (ddd, J = 7.9, 1.3, 0.8 Hz, 1 H), 7.62–7.69 (m, 2 H), 7.93 (d, J = 8.2 Hz, 1 H), 8.35 (bs, 1 H), 8.56 (dd, J = 8.2, 0.5 Hz, 1 H), 8.74 (dd, J = 8.2, 0.4 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 17.3, 111.2, 115.0, 120.3, 121.4, 122.1, 122.98, 123.03, 124.2, 124.4, 126.0, 126.5, 128.4, 128.8, 129.6, 137.3, 138.3. Anal. Calcd for $C_{17}H_{13}N$: C, 88.28; H, 5.67; N, 6.06. Found: C, 88.51; H, 5.88; N, 6.04.



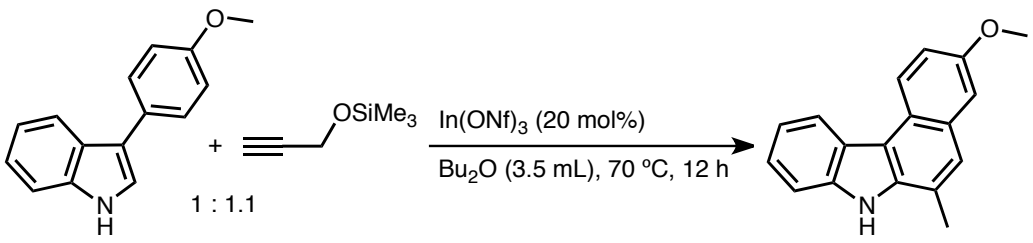
0.20 mmol 0.22 mmol **2c** 60% yield **3b**

3,6-Dimethyl-7*H*-benzo[*c*]carbazole (3b). The title compound was isolated by recycling HPLC after column chromatography on silica gel (hexane/EtOAc = 5/1). A white solid, mp 176–177 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.56 (s, 3 H), 2.70 (d, *J* = 0.9 Hz, 3 H), 7.37 (td, *J* = 7.6, 1.2 Hz, 1 H), 7.44 (td, *J* = 7.6, 1.1 Hz, 1 H), 7.49 (dd, *J* = 8.2, 1.8 Hz, 1 H), 7.58 (s, 1 H), 7.60 (dt, *J* = 7.8, 0.9 Hz, 1 H), 7.71 (s, 1 H), 8.33 (bs, 1 H), 8.54 (dd, *J* = 7.8, 0.9 Hz, 1 H), 8.64 (dd, *J* = 8.2, 0.5 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 17.2, 21.8, 110.8, 114.7, 121.5, 122.0, 122.8, 123.0, 124.6, 125.6, 125.9, 126.3, 128.4, 128.8, 129.47, 129.52, 136.5, 137.6. Anal. Calcd for $C_{18}H_{15}N$: C, 88.13; H, 6.16; N, 5.71. Found: C, 87.91; H, 5.77; N, 5.74.

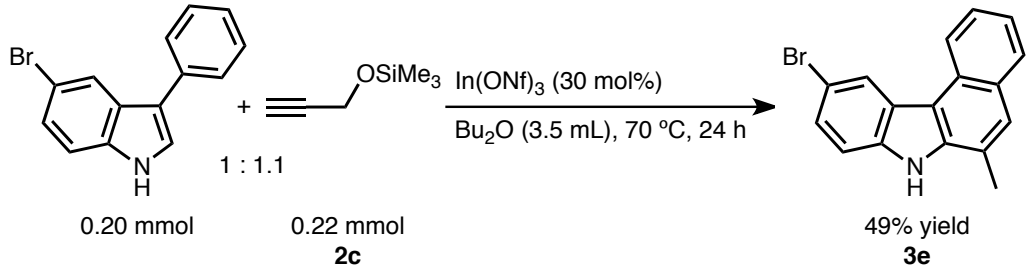


0.20 mmol 0.22 mmol **2c** 61% yield **3c**

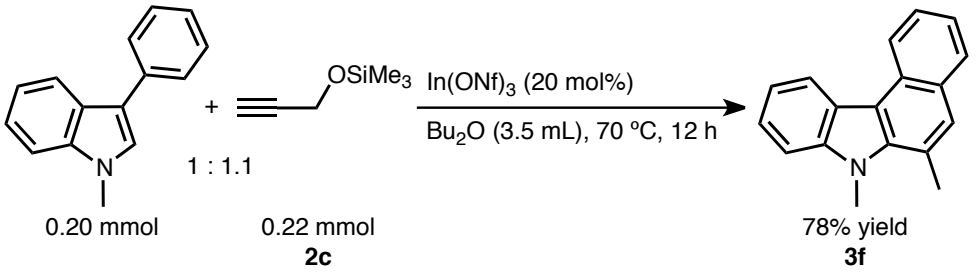
6,10-Dimethyl-7*H*-benzo[*c*]carbazole (3c). The title compound was isolated by column chromatography on silica gel (hexane/EtOAc = 5/1). A white solid, mp 181–182 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.63 (s, 3 H), 2.70 (d, *J* = 1.2 Hz, 3 H), 7.28 (dd, *J* = 8.6, 1.2 Hz, 1 H), 7.44 (ddd, *J* = 8.0, 6.9, 1.2 Hz, 1 H), 7.50 (dd, *J* = 8.0, 0.6 Hz, 1 H), 7.61–7.68 (m, 2 H), 7.93 (d, *J* = 8.0 Hz, 1 H), 8.28 (bs, 1 H), 8.36 (s, 1 H), 8.75 (dd, *J* = 8.0, 0.6 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 17.3, 21.8, 110.8, 114.7, 121.5, 122.0, 122.8, 123.0, 124.7, 125.6, 125.9, 126.3, 128.4, 128.9, 129.5, 129.6, 136.6, 137.6. Anal. Calcd for $C_{18}H_{15}N$: C, 88.13; H, 6.16; N, 5.71. Found: C, 88.02; H, 5.80; N, 5.74.



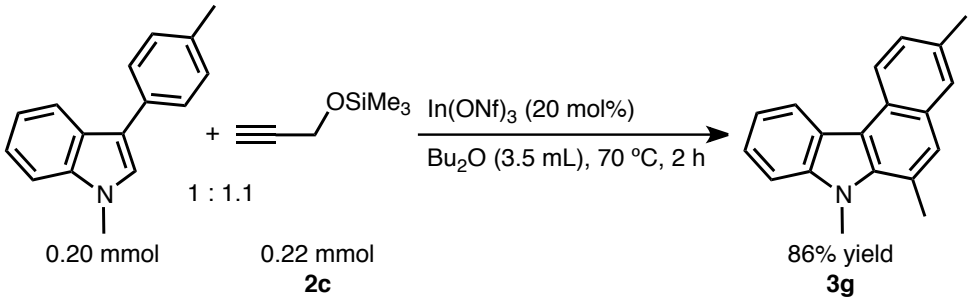
3-Methoxy-6-methyl-7*H*-benzo[*c*]carbazole (3d). The title compound was isolated by column chromatography on silica gel (hexane/EtOAc = 5/1). A white solid, mp 140–141 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.67 (d, *J* = 0.6 Hz, 3 H), 3.95 (s, 3 H), 7.28–7.38 (m, 3 H), 7.43 (td, *J* = 7.7, 1.2 Hz, 1 H), 7.53–7.60 (m, 2 H), 8.27 (bs, 1 H), 8.51 (dd, *J* = 8.0, 0.6 Hz, 1 H), 8.65 (d, *J* = 8.6 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 17.3, 55.4, 107.8, 111.2, 115.3, 117.40, 117.41, 120.1, 121.9, 123.7, 124.2, 124.41, 124.42, 125.6, 130.6, 136.1, 138.4, 155.5. Anal. Calcd for $C_{18}H_{15}NO$: C, 82.73; H, 5.79; N, 5.36. Found: C, 82.88; H, 5.54; N, 5.40.



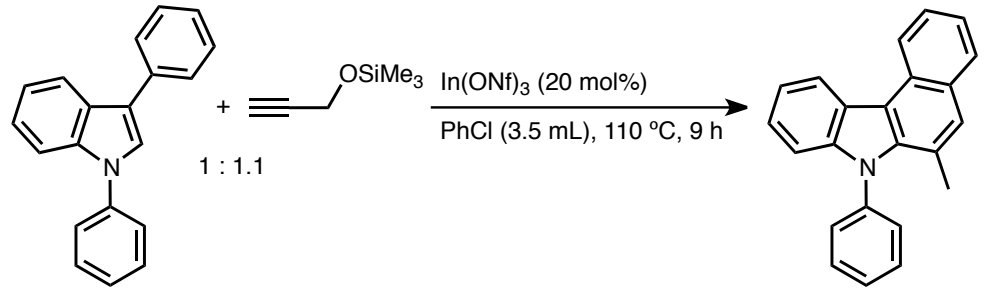
10-Bromo-6-methyl-7*H*-benzo[*c*]carbazole (3e). The title compound was isolated by recycling HPLC after column chromatography on silica gel (hexane/EtOAc = 5/1). A white solid, mp 181–182 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.70 (s, 3 H), 7.44–7.50 (m, 2 H), 7.53 (ddd, *J* = 8.6, 1.7, 0.6 Hz, 1 H), 7.62–7.71 (m, 2 H), 7.93 (dd, *J* = 8.0, 0.6 Hz, 1 H), 8.38 (bs, 1 H), 8.63 (dd, *J* = 8.0, 0.6 Hz, 1 H), 8.67 (d, *J* = 1.2 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 17.2, 112.5, 113.3, 114.2, 121.3, 122.8, 123.4, 124.6, 126.1, 126.4, 126.9, 127.3, 128.51, 128.54, 129.6, 136.8, 137.9. Anal. Calcd for $C_{17}H_{12}BrN$: C, 65.83; H, 3.90; N, 4.52. Found: C, 65.79; H, 3.51; N, 4.57.



6,7-Dimethyl-7*H*-benzo[*c*]carbazole (3f). The title compound was isolated by column chromatography on silica gel (hexane/EtOAc = 10/1). A white solid, mp 156–157 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.01 (d, *J* = 1.1 Hz, 3 H), 4.27 (s, 3 H), 7.38 (td, *J* = 6.9, 1.1 Hz, 1 H), 7.43 (td, *J* = 7.5, 1.1 Hz, 1 H), 7.51 (td, *J* = 7.8, 1.1 Hz, 1 H), 7.55 (dd, *J* = 8.0, 0.6 Hz, 1 H), 7.60 (d, *J* = 1.1 Hz, 1 H), 7.64 (ddd, *J* = 8.6, 6.9, 1.1 Hz, 1 H), 7.90 (dd, *J* = 8.0, 0.6 Hz, 1 H), 8.61 (dd, *J* = 8.0, 0.6 Hz, 1 H), 8.79 (dd, *J* = 8.0, 0.6 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 21.6, 32.6, 109.2, 115.7, 119.8, 122.0, 122.3, 122.9, 122.9, 123.5, 124.0, 126.1, 128.1, 128.92, 128.98, 129.1, 138.2, 140.6. Anal. Calcd for $C_{18}H_{15}N$: C, 88.13; H, 6.16; N, 5.71. Found: C, 87.88; H, 6.25; N, 5.72.

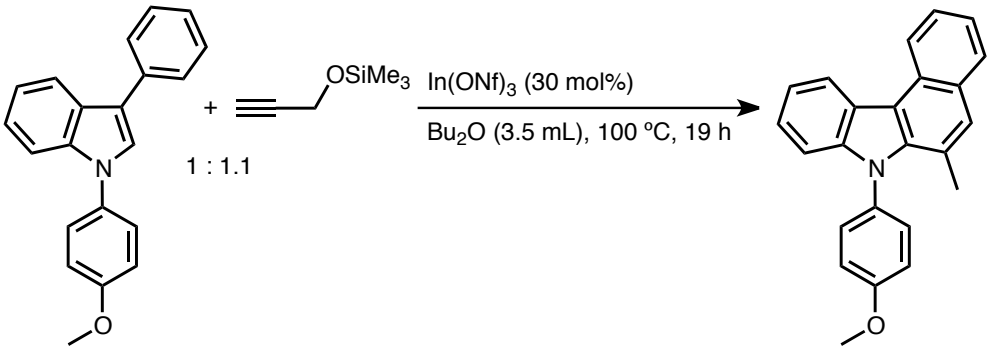


3,6,7-Trimethyl-7*H*-benzo[*c*]carbazole (3g). The title compound was isolated by column chromatography on silica gel (hexane/EtOAc = 10/1). A white solid, mp 167–168 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.55 (s, 3 H), 2.97 (d, *J* = 1.2 Hz, 3 H), 4.22 (s, 3 H), 7.36 (ddd, *J* = 8.3, 6.6, 1.1 Hz, 1 H), 7.44–7.54 (m, 4 H), 7.66 (s, 1 H), 8.57 (d, *J* = 8.0 Hz, 1 H), 8.67 (d, *J* = 8.6 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 21.50, 21.53, 32.5, 109.1, 115.7, 119.6, 121.9, 122.2, 122.7, 123.4, 123.8, 126.9, 127.3, 128.1, 128.4, 129.3, 132.2, 137.7, 140.6. Anal. Calcd for $C_{19}H_{17}N$: C, 87.99; H, 6.61; N, 5.40. Found: C, 88.09; H, 6.61; N, 5.38.



0.20 mmol 0.22 mmol **2c** 51% yield **3h**

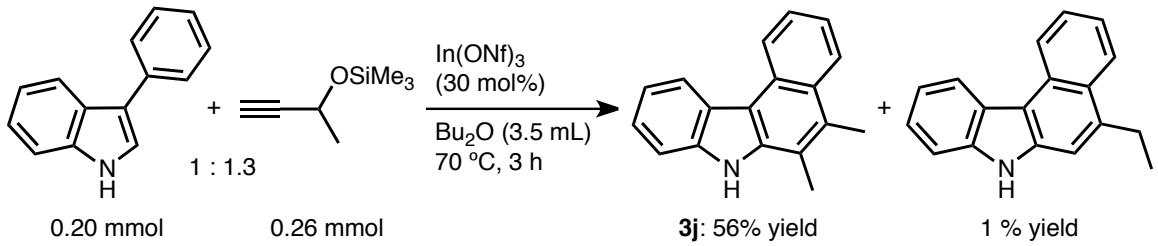
6-Methyl-7-phenyl-7*H*-benzo[*c*]carbazole (3h). The title compound was isolated by recycling HPLC after column chromatography on silica gel (hexane/EtOAc = 5/1). A white solid, mp 119–120 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.13 (d, *J* = 1.2 Hz, 3 H), 7.14 (dd, *J* = 7.2, 1.4 Hz, 1 H), 7.35–7.43 (m, 2 H), 7.44–7.52 (m, 3 H), 7.53–7.61 (m, 4 H), 7.67 (ddd, *J* = 8.3, 6.6, 1.1 Hz, 1 H), 7.92 (dd, *J* = 8.0, 0.6 Hz, 1 H), 8.64 (dd, *J* = 6.9, 1.2 Hz, 1 H), 8.85 (dd, *J* = 8.6, 0.6 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 20.5, 110.7, 116.1, 120.5, 121.8, 123.00, 123.04, 123.2, 123.5, 124.2, 126.1, 128.1, 128.66, 128.70, 128.9, 129.2, 129.4, 129.8, 138.4, 139.7, 142.1. Anal. Calcd for $C_{23}H_{17}N$: C, 89.87; H, 5.57; N, 4.56. Found: C, 90.26; H, 5.66; N, 4.58.



0.20 mmol 0.22 mmol **2c** 53% yield **3i**

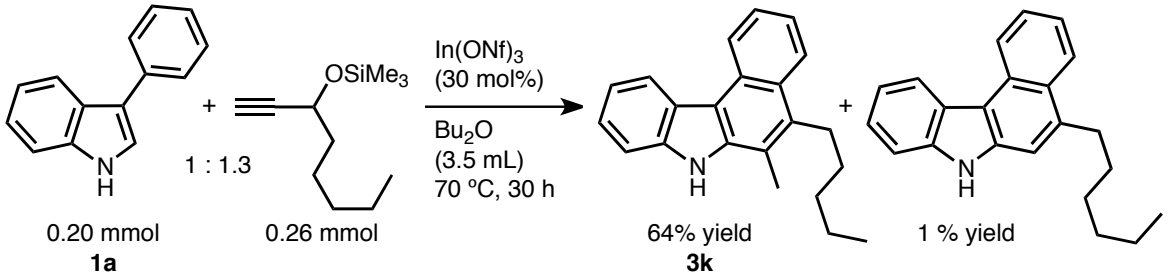
7-(4-Methoxyphenyl)-6-methyl-7*H*-benzo[*c*]carbazole (3i). The title compound was isolated by recycling GPC after column chromatography on silica gel (hexane/EtOAc = 15/1). A white solid, mp 154–155 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.17 (d, *J* = 0.6 Hz, 3 H), 3.94 (s, 3 H), 7.07 (dt, *J* = 9.5, 2.6 Hz, 2 H), 7.13 (dd, *J* = 6.9, 2.3 Hz, 1 H), 7.35–7.42 (m, 4 H), 7.46 (ddd, *J* = 8.0, 6.9, 1.2 Hz, 1 H), 7.56 (d, *J* = 0.6 Hz, 1 H), 7.66 (ddd, *J* = 8.0, 6.9, 1.2 Hz, 1 H), 7.91 (d, *J* = 8.0 Hz, 1 H), 8.63 (dd, *J* = 6.6, 2.0 Hz, 1H), 8.84 (dd, *J* = 8.0, 0.6 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ

20.5, 55.6, 110.8, 114.3, 115.9, 120.4, 121.8, 123.0, 123.05, 123.10, 123.4, 124.2, 126.0, 128.1, 128.6, 128.9, 129.4, 130.8, 132.2, 138.5, 142.4, 159.7. Anal. Calcd for $C_{24}H_{19}NO$: C, 85.43; H, 5.68; N, 4.15. Found: C, 85.51; H, 5.89; N, 4.15.



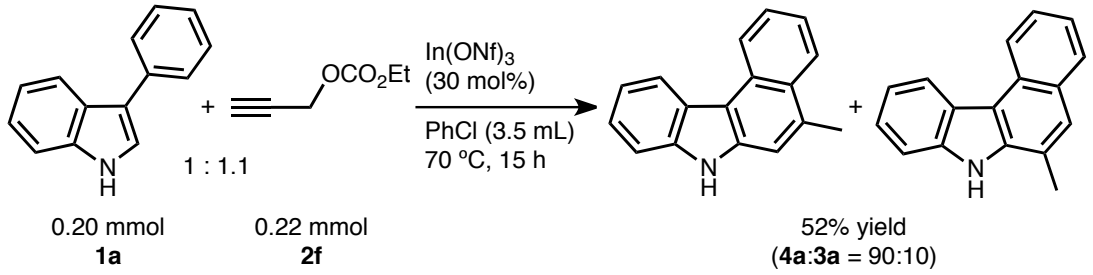
5,6-Dimethyl-7*H*-benzo[*c*]carbazole (3j). The title compound was isolated by recycling GPC after column chromatography on silica gel (hexane/EtOAc = 5/1). A white solid, mp 216–217 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.68 (s, 3 H), 2.78 (s, 3 H), 7.37 (td, *J* = 7.4, 0.6 Hz, 1 H), 7.42 (td, *J* = 7.5, 1.2 Hz, 1 H), 7.51 (ddd, *J* = 8.6, 6.9, 1.2 Hz, 1 H), 7.59 (dd, *J* = 8.0, 0.6 Hz, 1 H), 7.66 (ddd, *J* = 8.0, 6.9, 1.1 Hz, 1 H), 8.19 (dd, *J* = 8.6, 0.6 Hz, 1 H), 8.33 (bs, 1 H), 8.54 (dd, *J* = 8.0, 0.6 Hz, 1 H), 8.79 (dd, *J* = 8.0, 0.6 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 14.4, 15.1, 111.0, 113.3, 119.1, 120.2, 121.9, 122.9, 123.5, 123.8, 124.7, 125.1, 125.6, 128.9, 129.0, 130.1, 137.6, 138.1. Anal. Calcd for $C_{18}H_{15}N$: C, 88.13; H, 6.16; N, 5.71. Found: C, 87.97; H, 5.99; N, 5.70.

5-Ethyl-7*H*-benzo[*c*]carbazole. The title compound was isolated by recycling GPC after column chromatography on silica gel (hexane/EtOAc = 5/1). A white solid, mp 107–108 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.46 (t, *J* = 7.6 Hz, 3 H), 3.24 (qd, *J* = 7.6, 0.6 Hz, 2 H), 7.36 (td, *J* = 7.6, 1.3 Hz, 1 H), 7.42 (ddd, *J* = 8.0, 6.9, 1.2 Hz, 1 H), 7.47 (d, *J* = 0.5 Hz, 1 H), 7.48–7.56 (m, 2 H), 7.70 (td, *J* = 6.9, 1.4 Hz, 1 H), 8.20 (dd, *J* = 8.7, 0.5 Hz, 1 H), 8.30 (bs, 1 H), 8.53 (dd, *J* = 7.9, 0.9 Hz, 1 H), 8.81 (dd, *J* = 8.7, 0.9 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 15.1, 26.6, 111.0, 111.4, 114.1, 120.1, 121.7, 122.9, 123.86, 123.94, 124.2, 124.9, 126.4, 127.8, 130.5, 137.1, 138.3, 139.9. HRMS (EI) Calcd for $C_{18}H_{15}N$: M^+, 245.1199. Found: *m*/*z* 245.1193.

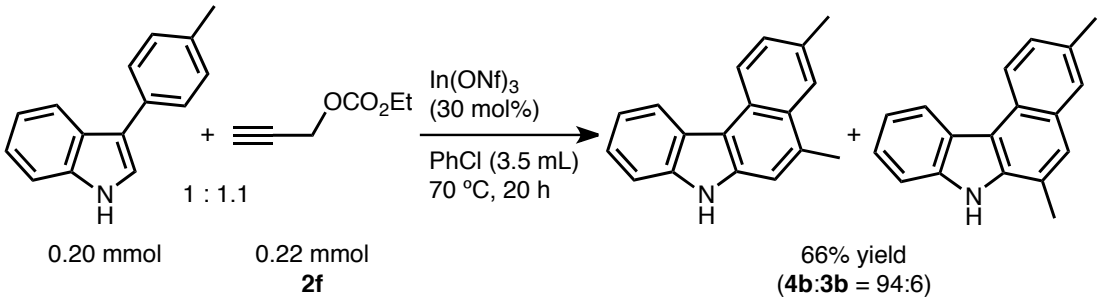


6-Methyl-5-pentyl-7*H*-benzo[*c*]carbazole (3k). The title compound was isolated by recycling HPLC after column chromatography on silica gel (hexane/EtOAc = 5/1). A white solid, mp 144–145 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.95 (t, *J* = 7.5 Hz, 3 H), 1.43 (sext, *J* = 7.5 Hz, 2 H), 1.48–1.57 (m, 2 H), 1.66–1.76 (m, 2 H), 2.68 (s, 3 H), 3.23 (t, *J* = 8.0 Hz, 2 H), 7.37 (td, *J* = 7.4, 0.6 Hz, 1 H), 7.42 (td, *J* = 7.4, 0.6 Hz, 1 H), 7.50 (ddd, *J* = 8.6, 6.9, 1.2 Hz, 1 H), 7.60 (d, *J* = 8.1 Hz, 1 H), 7.66 (td, *J* = 7.5, 0.6 Hz, 1 H), 8.19 (d, *J* = 8.6 Hz, 1 H), 8.35 (bs, 1 H), 8.54 (d, *J* = 8.0 Hz, 1 H), 8.79 (dd, *J* = 8.0, 0.6 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 14.0, 14.2, 22.7, 29.0, 30.5, 32.4, 111.0, 113.4, 118.7, 120.2, 121.9, 122.9, 123.7, 123.8, 124.6, 125.1, 125.5, 128.1, 129.2, 135.2, 137.6, 138.2. Anal. Calcd for $C_{22}H_{23}N$: C, 87.66; H, 7.69; N, 4.65. Found: C, 87.99; H, 7.99; N, 4.72.

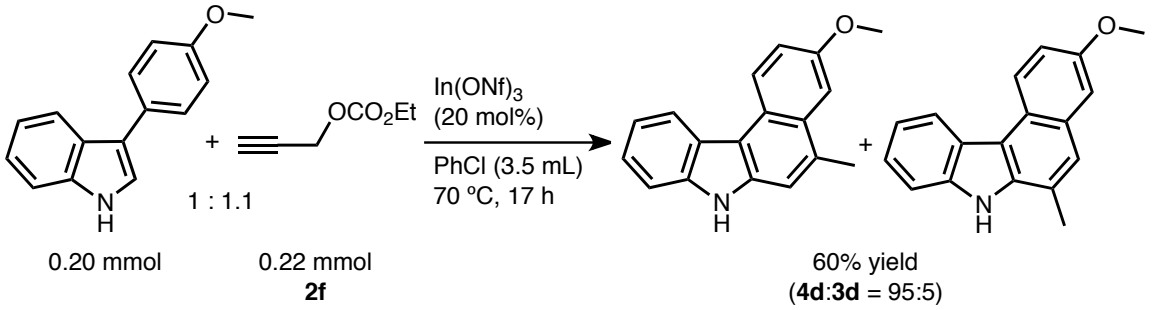
5-(1-Hexyl)-7*H*-benzo[*c*]carbazole. The title compound was isolated by recycling HPLC after column chromatography on silica gel (hexane/EtOAc = 5/1). A white solid, mp 104–105 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.90 (t, *J* = 6.9 Hz, 3 H), 1.27–1.41 (m, 4 H), 1.48 (quint, *J* = 7.3 Hz, 2 H), 1.81 (quint, *J* = 7.6 Hz, 2 H), 3.17 (t, *J* = 7.6 Hz, 2 H), 7.36 (t, *J* = 6.9 Hz, 1 H), 7.39–7.46 (m, 2 H), 7.47–7.55 (m, 2 H), 7.69 (td, *J* = 7.6, 0.8 Hz, 1 H), 8.18 (d, *J* = 8.2 Hz, 1 H), 8.26 (bs, 1 H), 8.52 (d, *J* = 7.8 Hz, 1 H), 8.80 (d, *J* = 8.2 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 14.1, 22.7, 29.6, 30.9, 31.8, 34.0, 111.0, 112.4, 114.1, 120.1, 121.7, 122.8, 123.8, 123.9, 124.1, 125.1, 126.4, 127.8, 130.5, 137.0, 138.3, 138.6. HRMS (EI) Calcd for $C_{22}H_{23}N$: M^+, 301.1825. Found: *m*/*z* 301.1844.



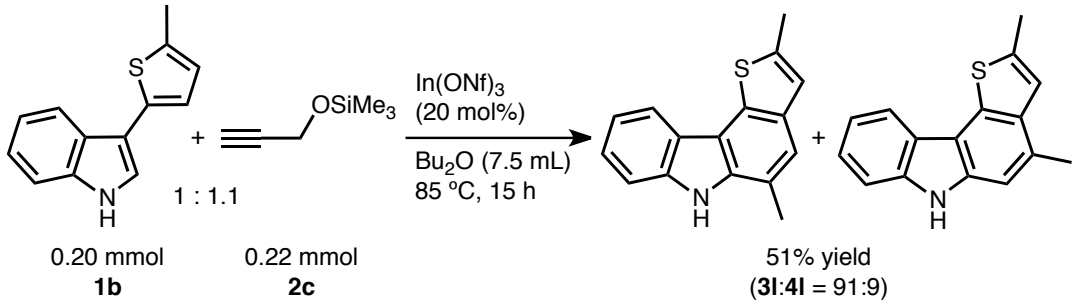
5-Methyl-7*H*-benzo[*c*]carbazole (4a). The title compound was isolated by recycling GPC after column chromatography on silica gel (hexane/EtOAc = 5/1). A white solid, mp 201–202 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.84 (d, *J* = 1.2 Hz, 3 H), 7.37 (td, *J* = 7.7, 1.2 Hz, 1 H), 7.43 (ddd, *J* = 8.0, 6.9, 1.2 Hz, 1 H), 7.49 (d, *J* = 1.2 Hz, 1 H), 7.53 (ddd *J* = 8.6, 6.9, 1.2 Hz, 1 H), 7.56 (dd, *J* = 8.0, 1.2 Hz, 1 H), 7.72 (ddd, *J* = 8.4, 6.7, 1.3 Hz, 1 H), 8.15 (dd, *J* = 8.6, 1.2 Hz, 1 H), 8.33 (bs, 1 H), 8.54 (dd, *J* = 8.6, 0.6 Hz, 1 H), 8.80 (dd, *J* = 8.0, 0.6 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 20.5, 111.0, 113.2, 114.0, 120.1, 121.7, 122.9, 123.7, 123.8, 124.1, 125.3, 126.6, 128.6, 130.1, 133.8, 137.0, 138.2. Anal. Calcd for $C_{17}H_{13}N$: C, 88.28; H, 5.67; N, 6.06. Found: C, 88.51; H, 5.88; N, 6.04.



3,5-Dimethyl-7*H*-benzo[*c*]carbazole (4b). The title compound was isolated by recycling HPLC after column chromatography on silica gel (hexane/EtOAc = 5/1). A white solid, mp 222–223 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.61 (s, 3 H), 2.81 (d, *J* = 0.6 Hz, 3 H), 7.35 (ddd, *J* = 7.5, 6.9, 0.6 Hz, 1 H), 7.41 (ddd, *J* = 7.5, 6.9, 0.6 Hz, 1 H), 7.46 (d, *J* = 0.6 Hz, 1 H), 7.52–7.58 (m, 2 H), 7.91 (s, 1 H), 8.28 (bs, 1 H), 8.51 (d, *J* = 8.0 Hz, 1 H), 8.69 (dd, *J* = 8.6, 0.6 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 20.5, 21.9, 111.0, 113.2, 114.1, 120.0, 121.6, 123.6, 123.7, 124.1, 124.7, 128.1, 128.5, 128.8, 132.2, 133.3, 136.5, 138.2. Anal. Calcd for $C_{18}H_{15}N$: C, 88.13; H, 6.16; N, 5.71. Found: C, 88.18; H, 6.03; N, 5.70.



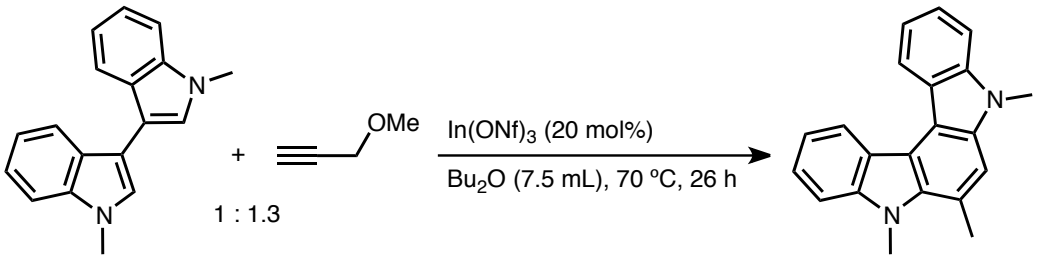
3-Methoxy-5-methyl-7*H*-benzo[*c*]carbazole (4d). The title compound was isolated by recycling GPC after column chromatography on silica gel (hexane/EtOAc = 5/1). A white solid, mp 209–210 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.80 (d, *J* = 1.2 Hz, 3 H), 4.00 (s, 3 H), 7.35 (ddd, *J* = 8.0, 6.9, 1.2 Hz, 1 H), 7.38–7.44 (m, 2 H), 7.47 (dd, *J* = 2.9, 0.6 Hz, 1 H), 7.50 (d, *J* = 1.2 Hz, 1 H), 7.55 (dd, *J* = 8.0, 1.2 Hz, 1 H), 8.28 (bs, 1 H), 8.49 (dd, *J* = 8.0, 0.6 Hz, 1 H), 8.73 (dd, *J* = 9.2, 0.6 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 20.6, 55.4, 105.7, 111.0, 113.7, 114.4, 117.5, 120.0, 121.6, 123.86, 123.94, 125.07, 125.12, 129.7, 132.6, 135.8, 138.3, 155.5. Anal. Calcd for $C_{18}H_{15}NO$: C, 82.73; H, 5.79; N, 5.36. Found: C, 82.71; H, 5.43; N, 5.39.



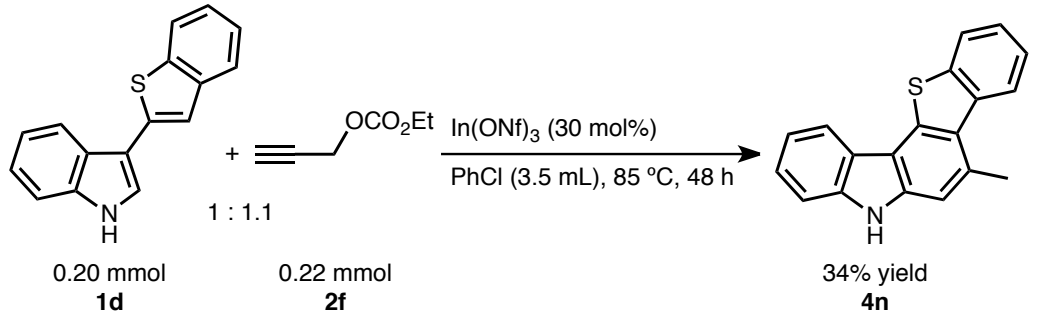
2,5-Dimethyl-6*H*-thieno[3,2-*c*]carbazole (3l). The title compound was isolated by recycling HPLC after column chromatography on silica gel (hexane/EtOAc = 7/1). A white solid, mp 170–171 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.61 (d, *J* = 0.9 Hz, 3 H), 2.67 (d, *J* = 1.4 Hz, 3 H), 7.06 (dd, *J* = 2.5, 1.1 Hz, 1 H), 7.34 (td, *J* = 7.1, 0.9 Hz, 1 H), 7.43 (ddd, *J* = 8.3, 6.9, 0.9 Hz, 1 H), 7.51 (tt, *J* = 4.1, 0.9 Hz, 2 H), 8.07 (bs, 1 H), 8.13 (d, *J* = 7.4 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 16.0, 17.0, 110.7, 116.0, 117.5, 119.9, 120.8, 121.5, 121.6, 122.8, 125.0, 130.3, 134.4, 136.3, 136.8, 138.8. Anal. Calcd for $C_{16}H_{13}NS$: C, 76.46; H, 5.21; N, 5.57; S, 12.76. Found: C, 76.00; H, 5.16; N, 5.58; S, 12.83.

2,4-Dimethyl-6*H*-thieno[3,2-*c*]carbazole (4l). The title compound was isolated by recycling HPLC column chromatography on silica gel (hexane/EtOAc =

7/1). A white solid, mp 184–185 ºC. ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.695 (s, 3 H), 2.698 (s, 3 H), 7.14–7.20 (m, 2 H), 7.32 (ddd, *J* = 8.0, 6.6, 1.1 Hz, 1 H), 7.38–7.47 (m, 2 H), 8.06 (bs, 1 H), 8.10 (ddd, *J* = 7.8, 1.8, 0.9 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 16.2, 20.5, 108.8, 110.5, 114.8, 119.7, 120.2, 121.0, 122.5, 124.7, 130.4, 132.3, 133.9, 136.4, 136.9, 138.7. HRMS (EI) Calcd for $C_{16}H_{13}NS$: M^+, 251.0763. Found: *m*/*z* 251.0760.



5,8-Dihydro-5,6,8-trimethylindolo[2,3-*c*]carbazole (3m). The title compound was isolated by column chromatography on silica gel (hexane/EtOAc = 7/1). A white solid, mp 262–263 ºC. ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.09 (s, 3 H), 3.95 (s, 3 H), 4.25 (s, 3 H), 7.31 (s, 1 H), 7.34–7.40 (m, 2 H), 7.48–7.57 (m, 4 H), 8.85 (d, *J* = 8.0 Hz, 1 H), 8.90 (d, *J* = 8.0 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 22.0, 29.3, 33.0, 108.4, 108.7, 110.4, 114.5, 117.7, 118.2, 118.4, 119.8, 122.5, 122.6, 123.25, 123.30, 124.3, 124.8, 135.3, 136.3, 140.7, 141.7. Anal. Calcd for $C_{21}H_{18}N_2$: C, 84.53; H, 6.08; N, 9.39. Found: C, 84.63; H, 5.87; N, 9.39.



7-Methyl-5*H*-benzo[*b*]thieno[3,2-*c*]carbazole (4n). The title compound was isolated by recycling GPC column chromatography on silica gel (hexane/EtOAc = 7/1). A white solid, mp 178–179 ºC. ^{1}H NMR (400 MHz, CD_2Cl_2) δ 2.68 (d, *J* = 0.6 Hz, 3 H),

7.32 (td, J = 7.4, 1.1 Hz, 1 H), 7.36 (td, J = 7.7, 1.5 Hz, 1 H), 7.43 (tt, J = 7.6, 1.2 Hz, 2 H), 7.54 (dd, J = 8.0, 1.2 Hz, 1 H), 7.90 (dd, J = 8.6, 1.2 Hz, 1 H), 7.99 (d, J = 0.6 Hz, 1 H), 8.10–8.18 (m, 2 H), 8.38 (bs, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 17.1, 110.8, 116.4, 117.5, 119.5, 120.2, 120.7, 121.6, 122.96, 122.99, 124.4, 125.0, 125.5, 128.7, 130.4, 136.1, 138.2, 138.7, 139.0. Anal. Calcd for $C_{19}H_{13}NS$: C, 79.41; H, 4.56; N, 4.87; S, 11.16. Found: C, 79.03; H, 4.54; N, 4.87; S, 11.17.

III-4. References and Notes

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8 For Matsubara's method capable of providing two [*a*]-types and one [*c*]-type on phenyl-annulated carbazoles, see: Yamamoto, M.; Matsubara, S. *Chem. Lett.* **2007**, *36*, 172.

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Chapter IV. Indium-Catalyzed Annulation of Indoles with Ethyl (2-Ethylaryl)methyl Carbonates: Synthesis and Photoluminescent Properties of Aryl- and Heteroaryl-Annulated[*b*]carbazoles

IV-1. Introduction

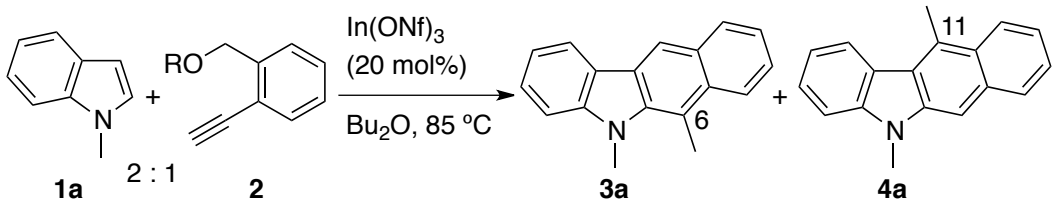
Aryl- and heteroaryl-annulated carbazoles (AHACs) have attracted much attention due to their biological and pharmacological activities[1] as well as unique optoelectronic properties.[2] AHACs are classified into [*a*]-, [*b*]- and [*c*]-types based on the position at which the (hetero)aryl ring is fused to the carbazole core. Of these three types, the author's group firstly established a new synthetic strategy for the [*a*]-type that is constructed by annulation of 2-(hetero)arylindoles with propargyl ethers under indium catalysis.[3] Replacing 2-(hetero)arylindoles with their 3-analogs also allowed him to address the [*c*]-type.[4] The strategy features a two carbon–carbon bond-forming cascade in one batch, where an indium salt activates both the C≡C and C–O bonds of propargyl ethers. The author envisioned that its application to the [*b*]-type which remains unaddressed would further enhance the generality and reliability of the strategy. Although numerous synthetic approaches to AHACs have been reported due to their interests in a variety of aspects,[1,2] no powerful strategy with a broad substrate scope capable of offering all the three types has appeared in literature.[5–8] The author presents herein a new avenue for synthesizing the [*b*]-type as a final target of this research project.[9] Structural characteristics governing light-emitting efficiency of the three types are also discussed.

IV-2. Results & Discussion

Initially, the author examined the effect of the leaving group OR of **2** in the reaction of *N*-methylindole (**1a**) (Table 1). Thus, with $In(ONf)_3$ (20 mol%, Nf = $SO_2C_4F_9$) in Bu_2O as a useful system found in his preceding studies,[3,4] treating **1a** and (2-ethynyl)benzyl methyl ether (**2a**) at 85 ºC for 24 h gave a mixture of 5,6- and 5,11-dimethyl-5*H*-benzo[*b*]carbazoles (**3a** and **4a**), albeit in a low yield (entry 1). Using **2b**–**2f** with the silyloxy or acyloxy group gave no marked improvement in the yield, but **2g** with OCO_2Me as a carbonate functionality showed much better performance (entries 2–7). After the continuous survey of other carbonate derivatives **2h**–**2k**, ethyl analog **2h** proved to be the most promising, giving **3a** preferentially in 79% yield (entries 8–11).[10] (2-Ethynyl)benzyl alcohol (**2l**) as a commercial source was ineffective (entry

12). On comparison of the ratio between **1a** and **2h**, the case of 1:1.5 reduced the reaction efficiency, and no differences in the yield were observed in the presence of over 2 equiv. of **2h** (entries 13 and 14). Due to different nucleophilicity of the C2 and C3 of indoles, achievement of S_EAr-based carbon–carbon bond-forming annulation of indoles that react with two different functionalities seems not to be an easy task, and in fact, only a handful of related works have emerged in literature, to his knowledge.[11] The present reaction would thus be an important new entry for such indole-based annulation.

Table 1. Indium-catalyzed annulation of *N*-methylindole with (2-ethynyl)benzyl ether derivatives **2**[a]



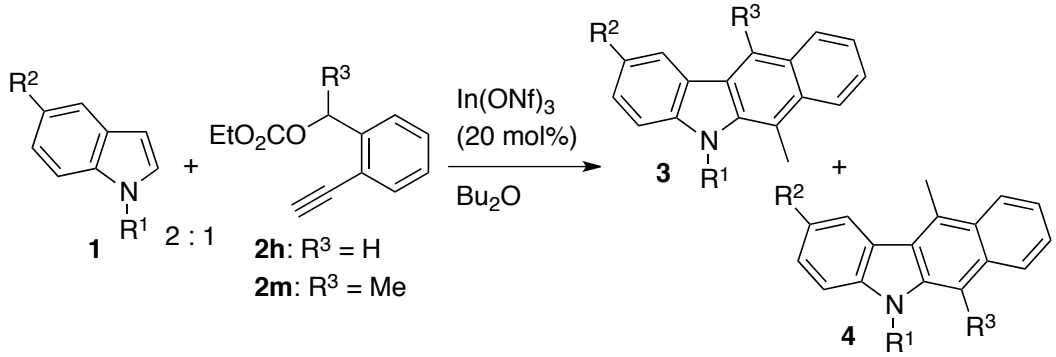
Entry	R in **2**	Time/h	Yield/%[b]	**3a**:**4a**[b]
1	Me (**2a**)	24	11	9:91
2	$SiMe_3$ (**2b**)	3	29	87:13
3	$SiMe_2$*t*-Bu (**2c**)	7	18	76:24
4	COMe (**2d**)	24	11	64:36
5	CO*t*-Bu (**2e**)	24	<1	–
6	$COCF_3$ (**2f**)	24	19	67:33
7	CO_2Me (**2g**)	24	58	84:16
8	CO_2Et (**2h**)	24	79	86:14
9	CO_2*i*-Pr (**2i**)	24	54	83:17
10	CO_2*t*-Bu (**2j**)	24	16	74:26
11	CO_2Ph (**2k**)	24	69	87:13
12	H (**2l**)	7	17	73:27
13[c]	CO_2Et (**2h**)	24	53	84:16
14[d]	CO_2Et (**2h**)	24	80	85:15

[a] Reagents: **1a** (0.20 mmol), **2** (0.10 mmol), $In(ONf)_3$ (20 μmol), Bu_2O (0.10 mL). [b] Determined by ^1H NMR. [c] **1a**:**2h** = 1.5:1. [d] **1a**:**2h** = 2.5:1.

Having the suitable reaction conditions in hand, he next explored the scope of the indium-catalyzed annulation (Table 2). Besides **1a**, MeO- and Br-substituted *N*-

methylindoles reacted with **2h** to give the corresponding annulation products as a mixture of two isomers (entries 1–3). *N*-Benzyl- and *N*-(4-methoxyphenyl)indoles as well as the *N*-unsubstituted indole also worked as nucleophiles (entries 4–6). The use of indole acceptor **2m** bearing a methyl group at the benzylic position provided 6,11-dimethyl derivatives **3g** and **3h** as sole products (entries 7 and 8). The annulation reaction of **2m** was found much faster than that of **2h** (entries 1 vs. 7, and 3 vs. 8). On the other hand, using an electrophile having an internal alkynyl group resulted in no desired annulation.[12]

Table 2. Indium-catalyzed annulation of indoles with (2-ethynyl)benzyl ethyl carbonates[a]

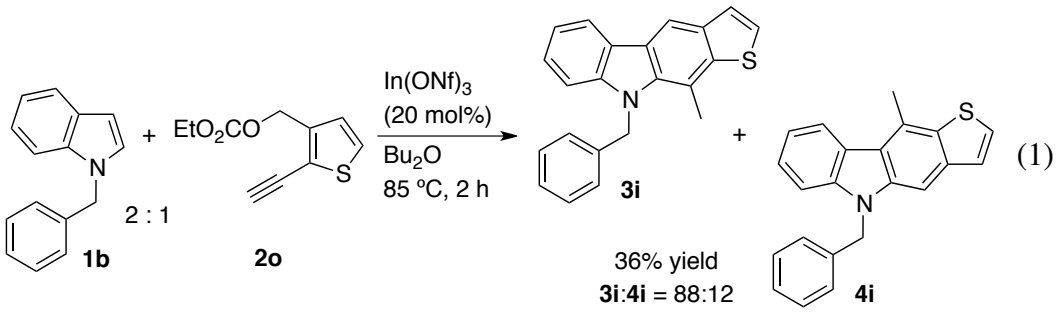


Entry	R^1	R^2	R^3	Temp./ºC	Time/h	Yield/%[b]	**3**:**4**[c]
1	Me	H	H	85	24	78 (**3a**, **4a**)	86:14
2	Me	OMe	H	70	20	50 (**3b**, **4b**)	86:14
3	Me	Br	H	90	12	48 (**3c**, **4c**)	82:18
4	Bn[d]	H	H	80	16	58 (**3d**, **4d**)	83:17
5[e]	Ar[f]	H	H	90	12	35 (**3e**, **4e**)	85:15
6[e]	H	H	H	70	40	44 (**3f**, **4f**)	82:18
7	Me	H	Me	85	4	44 (**3g**)	–
8	Me	Br	Me	85	4	53 (**3h**)	–

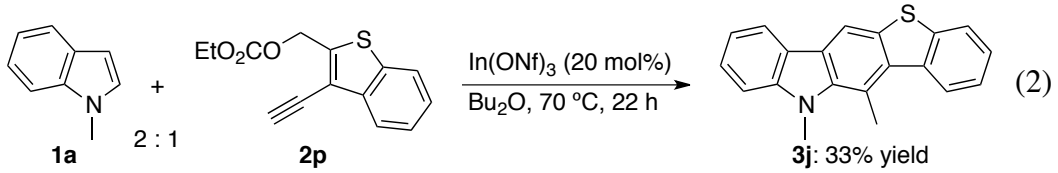
[a] Reagents: **1** (0.20 mmol), **2** (0.10 mmol), $In(ONf)_3$ (20 μmol), Bu_2O (0.10 mL). [b] Isolated yield based on **2**. [c] Determined by ^1H NMR. [d] Bn = benzyl. [e] $In(ONf)_3$ (30 μmol) was used. [f] Ar = 4-$MeOC_6H_4$.

The strategy can be extended to synthesize heteroaryl derivatives. Thus, the reaction of thienyl electrophile **2o** led to the predominant formation of isomer **3i**, as was

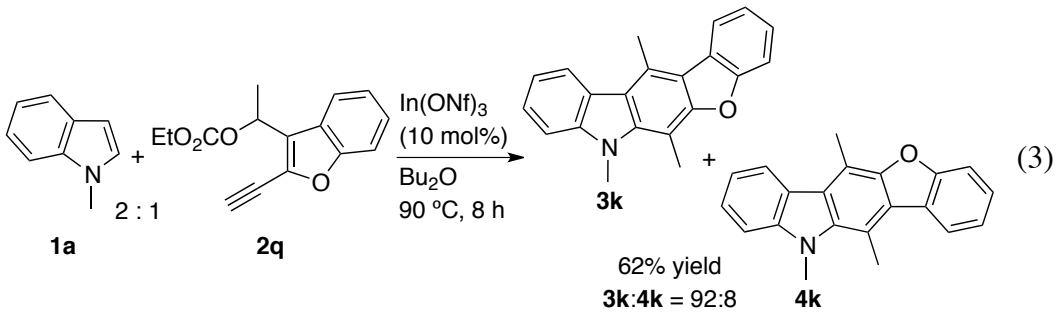
observed in the case of aryl[*b*]carbazoles (eq 1). The pentacyclic system including benzothienyl and benzofuranyl rings could also be prepared as target structures (eqs 2 and 3). In the use of **2p**, [3,2-*b*]-type **3j** was obtained as a single isomer.



(1)

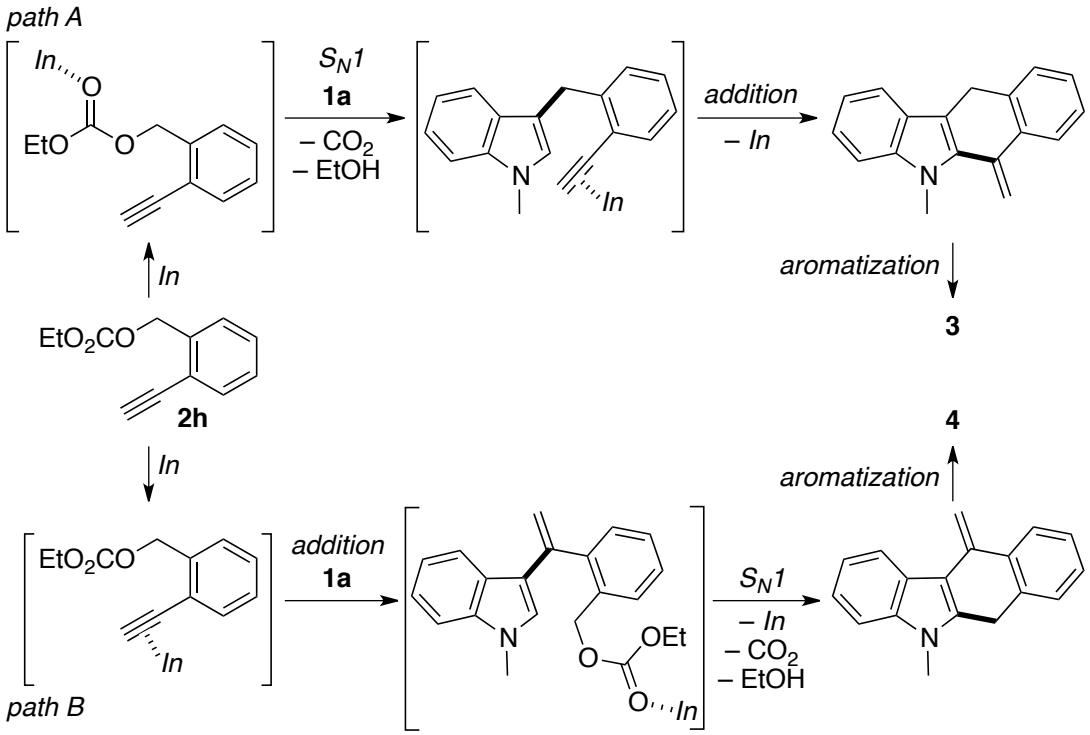


(2)



(3)

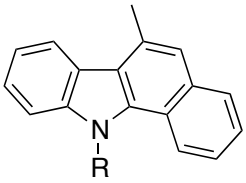
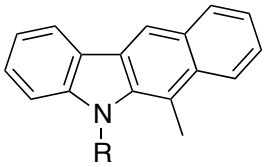
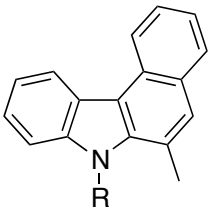
On the basis of his earlier observations[3,4] and other related studies, plausible reaction mechanisms that exemplify the reaction of **1a** with **2h** are depicted as paths A and B in Scheme 1. In path A, **2h** activated by $In(ONf)_3$ (*In*) first undergoes nucleophilic substitution at the benzylic position by the most nucleophilic C3 of **1a**.[13] Owing to the higher reaction rate of **2m** with the 2° benzylic reaction site compared to **2h** with the 1° one, S_N1 rather than S_N2 might be possible as the first step. The next is intramolecular addition of the indolyl C2–H bond to the internal carbon atom of the C≡C bond followed by aromatization to give **3**.[14] On the other hand, the route in which addition precedes S_N1 is path B, and another isomer **4** is formed through aromatization as in path A. Considering such reversed order of the S_N1 and addition, the regiochemistry with respect to the methyl group of **3** and **4** would be rationally understood.



Scheme 1. Plausible reaction mechanisms

Finally, the author investigated the photoluminescent properties of aryl[*b*]carbazoles **3f**, **3a** and **3e** as representatives, and compared the results to those of the corresponding [*a*]-types **6** and [*c*]-types **7** (Table 3).[3b,4,15] The emission maxima of the [*b*]-types appeared in longer wavelength region (400–465 nm) than those of the other two types (360–415 nm). As observed in all the three types, the existence of methyl and 4-methoxyphenyl groups on the nitrogen atom tends to make the Φ_F value increase (**6f** vs. **6a** or **6e**, **3f** vs. **3a** or **3e**, and **7f** vs. **7a** or **7e**). Interestingly, the order of the light-emitting efficiency of aryl-annulated carbazoles (AACs) was found to be [*a*]- < [*b*]- < [*c*]-type (**6f** vs. **3f** vs. **7f**, **6a** vs. **3a** vs. **7a**, and **6e** vs. **3e** vs. **7e**). These structure–property correlations for AACs should contribute to developing optoelectronic devices.

Table 3. Photoluminescent properties of aryl[*a*]-, -[*b*]-, and -[*c*]carbazoles[a]

AACs			
	[*a*]-type	[*b*]-type	[*c*]-type
	6f (R = H)	**3f** (R = H)	**7f** (R = H)
λ_{max}/nm[b]	360, 378, 397	401, 423	362, 380, 399sh
Φ_F[c]	0.165	0.240	0.334
	6a (R = Me)	**3a** (R = Me)	**7a** (R = Me)
λ_{max}/nm[b]	371, 389, 408sh	414, 438, 464sh	374, 392, 413sh
Φ_F[c]	0.184	0.327	0.391
	6e (R = Ar[d])	**3e** (R = Ar[d])	**7e** (R = Ar[d])
λ_{max}/nm[b]	367, 385, 404sh	411, 432	372, 388, 408sh
Φ_F[c]	0.264	0.368	0.481

[a] Fluorescence spectra excited at 265 nm were measured in CH_2Cl_2 ($c = 1.5 \times 10^{-6}$ M). Photoluminescent data of [*a*]- and [*c*]-types collected herein were derived from ref. 3b and 4, respectively. [b] sh = shoulder. [c] Determined with reference to the quantum yield of *p*-terphenyl. [d] Ar = 4-$MeOC_6H_4$.

IV-3. Experimental

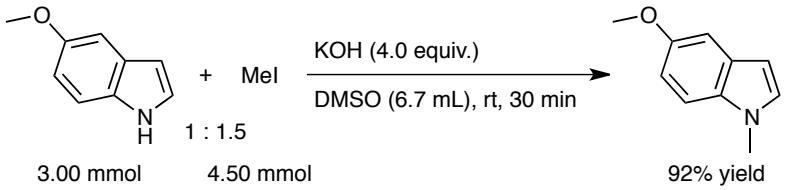
General Remarks

All manipulations were conducted with a standard Schlenk technique under an argon atmosphere. Nuclear magnetic resonance (NMR) spectra were taken on a JEOL JMN-ECA 400 (^{1}H, 400 MHz; ^{13}C, 100 MHz) or a JEOL JMN-ECA 500 (^{1}H, 500 MHz; ^{13}C, 125 MHz) spectrometer using tetramethylsilane (^{1}H and ^{13}C) as an internal standard. Analytical gas chromatography (GC) was performed on a Shimadzu model GC-2014 instrument equipped with a capillary column of InertCap 5 (5% phenyl polysilphenylene-siloxane, 30 m x 0.25 mm x 0.25 μm) using nitrogen as carrier gas. Gas chromatography–mass spectrometry (GC–MS) analyses were performed with a Shimadzu model GCMS-QP2010 instrument equipped with a capillary column of ID-BPX5 (5% phenyl polysilphenylene-siloxane, 30 m x 0.25 mm x 0.25 μm) by electron ionization at 70 eV using helium as carrier gas. Preparative recycling high-performance liquid chromatography (HPLC) was performed with JAI LC-9104 equipped with JAIGEL-GS320 column using a mixture of hexane–ethyl acetate (EtOAc) as eluent. Preparative recycling gel permeation chromatography (GPC) was performed with JAI LC-9105 equipped with JAIGEL-1H and JAIGEL-2H columns using chloroform as eluent. All melting points were measured with a Yanaco Micro Melting Point apparatus and uncorrected. High-resolution mass spectra (HRMS) were obtained with a JEOL JMS-T100GCV spectrometer. Elemental analyses were performed on a Vario EL III elemental analysis instrument. UV-vis absorption spectra were recorded with a JASCO V-550 spectrophotometer at room temperature. Fluorescence spectra were recorded with a JASCO FP-6500 spectrofluorometer at room temperature using an excitation wavelength of 265 nm. A solution of *p*-terphenyl in cyclohexane was used as a quantum yield standard (Φ_F = 0.87 at 265 nm excitation). Dibutyl ether (Bu_2O) was distilled under argon from sodium just prior to use. Tetrahydrofuran (THF) and diethyl ether (Et_2O) were distilled under argon from sodium benzophenone ketyl just before use. Toluene (PhMe), dichloromethane (CH_2Cl_2) and chloroform ($CHCl_3$) were distilled under argon from calcium chloride just prior to use. Anhydrous dimethyl sulfoxide (DMSO) and anhydrous *N*, *N*-dimethylformamide (DMF) were purchased from Sigma-Aldrich Co. LLC. and used without further purification. Methanol (MeOH) was purchased from Kanto Chemical Co., Inc. and

used without further purification. Fluorobenzene (PhF) was purchased from Tokyo Chemical Industry Co., LTD. and used without further purification. Triethylamine (Et_3N), diisopropylamine (i-Pr_2NH), pyridine, and 1-methylimidazole were stored over potassium hydroxide pellets under argon. 2-(Trimethylsilylethynyl)acetophenone[16] and 2-(hexyn-1-yl)benzyl alcohol[17] were synthesized according to the respective literature method. $In(ONf)_3$ (Nf = $SO_2C_4F_9$)[18] and $Fe(OTf)_3$ (Tf = SO_2CF_3)[19] were prepared by the respective reported procedure. Unless otherwise noted, reagents were commercially available and used as received without further purification.

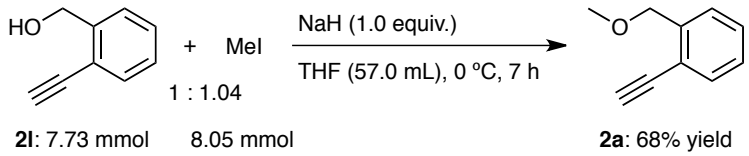
Preparation of Starting Materials

Preparation of 5-Methoxy-1-methyl-1*H*-indole



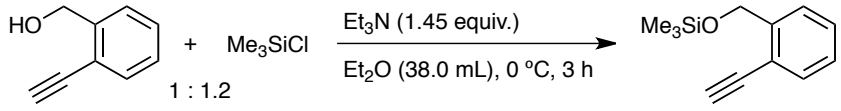
5-Methoxy-1-methyl-1*H*-indole.[20] The title compound was synthesized according to the reported method[21] and isolated in 92% yield by column chromatography on silica gel (hexane/EtOAc = 10/1). A white solid. This compound has already been synthesized in literature, and its spectral and analytical data are in good agreement with those reported in reference 20. Therefore, only ^{1}H NMR data are provided here. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.77 (s, 3 H), 3.85 (s, 3 H), 6.40 (dd, J = 3.2, 0.9 Hz, 1 H), 6.89 (dd, J = 8.7, 2.7 Hz, 1 H), 7.02 (dd, J = 3.2, 0.4 Hz, 1 H), 7.09 (dd, J = 2.3, 0.4 Hz, 1 H), 7.21 (d, J = 8.7 Hz, 1 H).

Preparation of (2-Ethynyl)benzyl Ether Derivatives 2a–2f and 2j

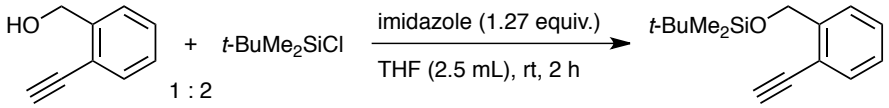


1-Ethynyl-2-(methoxymethyl)benzene (2a). The title compound was synthesized according to the following modified literature procedure.[22] Under an

argon atmosphere, a 200 mL two-necked round-bottomed flask was charged with a 55% dispersion of NaH (0.340 g, 7.78 mmol) in paraffin oil, which was washed with hexane (15 mL x 3). To this was added THF (57.0 mL), and the resulting suspension was cooled to 0 °C. Iodomethane (1.14 g, 8.05 mmol) and 2-ethynylbenzyl alcohol (**2l**; 1.02 g, 7.73 mmol) were added, and the mixture was stirred at 0 ºC for 7 h. Then, water (50 mL) was added and stirred until a clear solution was obtained, and THF was removed under reduced pressure. The resulting aqueous solution was extracted with Et_2O (20 mL x 3), and the combined organic layer was washed with a saturated NH_4Cl aqueous solution (5 mL) and brine (5 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (pentane/Et_2O = 8/1) gave **2a** (0.778 g, 68% yield) as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.30 (s, 1 H), 3.45 (s, 3 H), 4.65 (s, 2 H), 7.25 (td, *J* = 7.6, 1.4 Hz, 1 H), 7.37 (td, *J* = 7.8, 1.4 Hz, 1 H), 7.46 (dd, *J* = 7.8, 0.9 Hz, 1 H), 7.50 (dd, *J* = 7.8, 1.4 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 58.5, 72.5, 81.3, 81.6, 120.7, 127.3, 127.5, 129.0, 132.7, 140.6. HRMS (FI) Calcd for $C_{10}H_{10}O$: M, 146.0732. Found: *m*/*z* 146.0717.

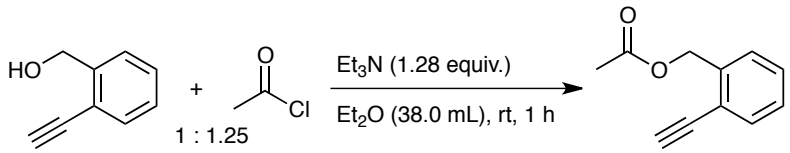


1-Ethynyl-2-(trimethylsiloxymethyl)benzene (2b). Under an argon atmosphere, **2l** (1.00 g, 7.63 mmol), Et_3N (1.12 g, 11.1 mmol) and Et_2O (38.0 mL) were placed in a 200 mL two-necked round-bottomed flask. To this was slowly added trimethylsilyl chloride (1.00 g, 9.24 mmol) at 0 ºC. After being stirred for 3 h, the mixture was diluted with Et_2O (30 mL). The resulting solution was washed with water (10 mL), a saturated NH_4Cl aqueous solution (10 mL) and brine (10 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (hexane/Et_2O = 25/1) gave **2b** (1.30 g, 83% yield) as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.18 (s, 9 H), 3.30 (s, 1 H), 4.87 (s, 2 H), 7.21 (t, *J* = 7.3 Hz, 1 H), 7.37 (t, *J* = 7.6 Hz, 1 H), 7.46 (d, *J* = 7.3 Hz, 1 H), 7.53 (d, *J* = 7.8 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ –0.4, 62.6, 81.1, 81.9, 119.1, 126.2, 126.6, 129.0, 132.4, 143.4. HRMS (FI) Calcd for $C_{12}H_{16}OSi$: M, 204.0970. Found: *m*/*z* 204.0969.



2l: 1.02 mmol 2.00 mmol **2c**: 87% yield

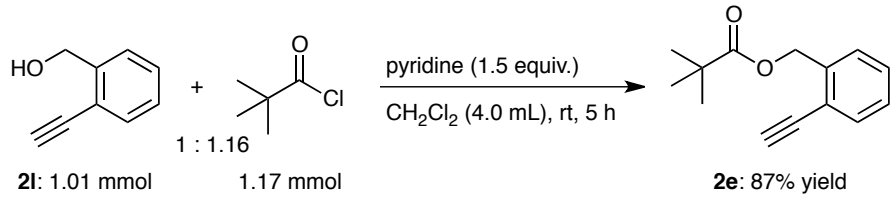
1-Ethynyl-2-(*tert*-butyldimethylsilyloxymethyl)benzene (2c).[23] The title compound was synthesized according to the following modified reported procedure.[24] Under an argon atmosphere, **2l** (0.135 g, 1.02 mmol), imidazole (88.4 mg, 1.30 mmol) and THF (2.5 mL) were placed in a 20 mL Schlenk tube. To this was slowly added *tert*-butyldimethylsilyl chloride (0.301 g, 2.00 mmol) at 0 ºC. After being stirred at room temperature for 2 h, the reaction mixture was poured into a mixture of 1 M HCl aqueous solution (5 mL) and Et_2O (5 mL). The organic layer was separated, and the aqueous layer was extracted with Et_2O (10 mL x 3). The combined organic layer was washed with brine (3 mL) and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (hexane/Et_2O = 20/1) gave **2c** (0.219 g, 87% yield) as a colorless oil. This compound has already been synthesized in literature, and its spectral and analytical data are in good agreement with those reported in reference 23. ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.12 (s, 6 H), 0.96 (s, 9 H), 3.29 (s, 1 H), 4.90 (s, 2 H), 7.20 (t, *J* = 7.3 Hz, 1 H), 7.37 (t, *J* = 7.3 Hz, 1 H), 7.45 (d, *J* = 7.8 Hz, 1 H), 7.56 (d, *J* = 7.8 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ –5.3, 18.4, 26.0, 63.1, 81.0, 82.0, 118.8, 125.8, 126.4, 129.0, 132.3, 143.8. HRMS (FI) Calcd for $C_{15}H_{22}OSi$: M, 246.1440. Found: *m*/*z* 246.1438.



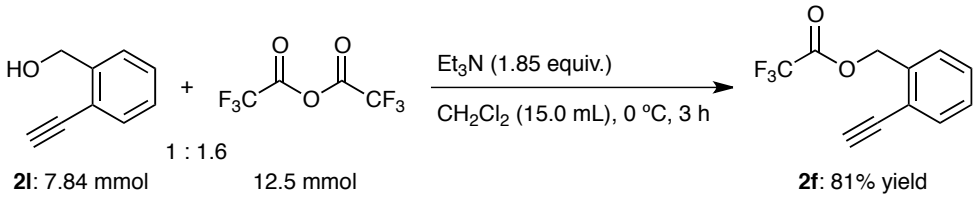
2l: 7.67 mmol 9.61 mmol **2d**: >99% yield

2-Ethynylbenzyl Acetate (2d).[25] Under an argon atmosphere, **2l** (1.01 g, 7.67 mmol), Et_3N (0.995 g, 9.83 mmol) and Et_2O (38.0 mL) were placed in a 200 mL two-necked round-bottomed flask. To this was slowly added acetyl chloride (0.754 g, 9.61 mmol) at 0 ºC. After being stirred at room temperature for 1 h, the reaction mixture was diluted with Et_2O (30 mL). The resulting solution was washed with water (10 mL), a saturated NH_4Cl aqueous solution (10 mL) and brine (5 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (hexane/Et_2O = 5/1) gave **2d** (1.33 g, >99% yield)

as a colorless oil. This compound has already been synthesized in literature, and its spectral and analytical data are in good agreement with those reported in reference 25. Therefore, only ^{1}H NMR data are provided here. ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.13 (s, 3 H), 3.31 (s, 1 H), 5.29 (s, 2 H), 7.29 (td, *J* = 7.3, 1.8 Hz, 1 H), 7.37 (td, *J* = 7.3, 1.4 Hz, 1 H), 7.41 (dd, *J* = 7.3, 1.4 Hz, 1 H), 7.53 (dd, *J* = 7.8, 0.9 Hz, 1 H).

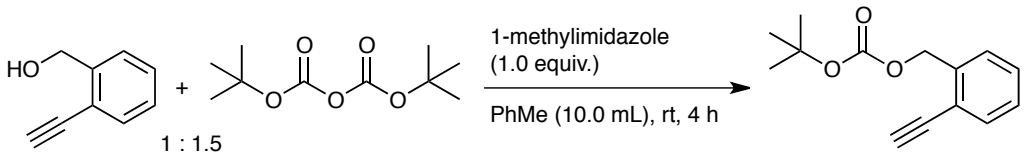


2-Ethynylbenzyl Pivalate (2e). The title compound was synthesized according to the following modified literature procedure.[26] Under an argon atmosphere, **2l** (0.133 g, 1.01 mmol), pyridine (0.122 g, 1.54 mmol) and CH_2Cl_2 (4.0 mL) were placed in a 20 mL Schlenk tube. To this was slowly added pivaloyl chloride (0.141 g, 1.17 mmol) at 0 ºC. After being stirred at room temperature for 5 h, the reaction mixture was diluted with CH_2Cl_2 (5 mL). The resulting solution was washed with water (1 mL), a saturated NH_4Cl aqueous solution (1 mL) and brine (1 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (hexane/Et_2O = 8/1) gave **2e** (0.191 g, 87% yield) as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.25 (s, 9 H), 3.30 (s, 1 H), 5.27 (s, 2 H), 7.25–7.31 (m, 1 H), 7.32–7.41 (m, 2 H), 7.52 (dd, *J* = 7.3, 0.9 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.2, 38.9, 64.4, 80.8, 82.2, 121.2, 127.7, 127.8, 128.9, 132.8, 138.7, 178.2. HRMS (FI) Calcd for $C_{14}H_{16}O_2$: M, 216.1150. Found: *m*/*z* 216.1153.



2-Ethynylbenzyl Trifluoroacetate (2f). The title compound was synthesized according to the following modified reported procedure.[27] Under an argon atmosphere, **2l** (1.03 g, 7.84 mmol), Et_3N (1.47 g, 14.5 mmol) and CH_2Cl_2 (15.0 mL) were placed in a 200 mL two-necked round-bottomed flask. To this was slowly added trifluoroacetic

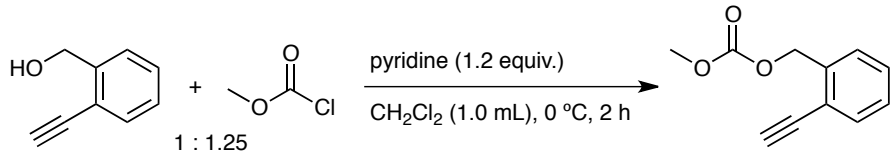
anhydride (2.63 g, 12.5 mmol) at 0 ºC. After being stirred for 3 h, the reaction mixture was diluted with CH_2Cl_2 (30 mL). The resulting solution was washed with water (5 mL), a saturated NH_4Cl aqueous solution (5 mL) and brine (5 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (hexane/Et_2O = 5/1) gave **2f** (1.45 g, 81% yield) as a colorless oil. ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.35 (s, 1 H), 5.53 (s, 2 H), 7.37 (td, *J* = 7.0, 2.5 Hz, 1 H), 7.38–7.44 (m, 2 H), 7.57 (dd, *J* = 6.9, 1.1 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 67.8, 80.2, 82.8, 114.6 (q, *J* = 285.5 Hz), 122.1, 128.8, 129.1, 129.3, 133.2, 135.4, 157.3 (q, *J* = 42.4 Hz). HRMS (FI) Calcd for $C_{11}H_7F_3O_2$: M, 228.0398. Found: *m*/*z* 228.0399.



***tert*-Butyl 2-Ethynylbenzyl Carbonate (2j).** The title compound was synthesized according to the following modified literature procedure.[28] Under an argon atmosphere, **2l** (0.133 g, 1.01 mmol), di-*tert*-butyl dicarbonate (0.327 g, 1.50 mmol) and PhMe (10.0 mL) were placed in a 50 mL Schlenk tube. To this was added 1-methylimidazole (82.0 mg, 1.00 mmol), and the resulting solution was stirred at room temperature for 4 h. The mixture was diluted with $CHCl_3$ (10 mL) and washed with a 5% HCl aqueous solution (2 mL) and brine (2 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (hexane/Et_2O = 8/1) gave **2j** (0.209 g, 89% yield) as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.51 (s, 9 H), 3.31 (s, 1 H), 5.30 (s, 2 H), 7.25–7.32 (m, 1 H), 7.36 (td, *J* = 7.6, 1.4 Hz, 1 H), 7.44 (dd, *J* = 7.8, 1.4 Hz, 1 H), 7.51 (dd, *J* = 7.8, 1.4 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.8, 66.7, 80.7, 82.2, 82.3, 121.2, 127.9, 128.0, 129.0, 132.8, 138.0, 153.4. HRMS (FI) Calcd for $C_{14}H_{16}O_3$: M, 232.1099. Found: *m*/*z* 232.1102.

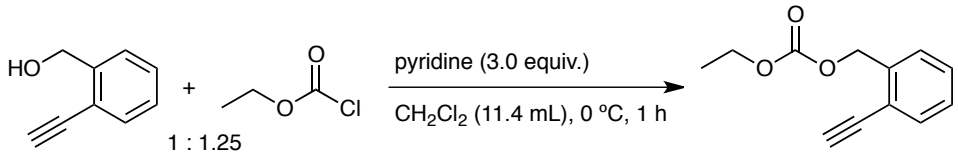
Preparation of (2-Ethynylaryl)methyl Carbonates 2g–2i and 2k, and Ethyl 2-(Hexyn-1-yl)benzyl Carbonate (2n)

A General Procedure. Carbonates **2g–2i**, **2k** and **2n** were synthesized according to the following modified literature procedure.[29] Under an argon atmosphere, **2l** or 2-(hexyn-1-yl)benzyl alcohol, pyridine and CH_2Cl_2 were placed in a Schlenk tube. Alkyl chloroformate was added dropwise over 45 min at 0 ºC. After being stirred for 1–4 h, the reaction mixture was diluted with EtOAc. The resulting solution was washed with a 1 M HCl aqueous solution, and the organic layer was separated. The aqueous layer was extracted twice with EtOAc. The combined organic layer was washed with brine, and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel using hexane–EtOAc as eluent gave the corresponding (2-ethynylaryl)methyl carbonate. Carbonates **2g–2i**, **2k** and **2n** were fully characterized by ^{1}H and ^{13}C NMR spectroscopy, and HRMS. Their spectral and analytical data are thus as follows:



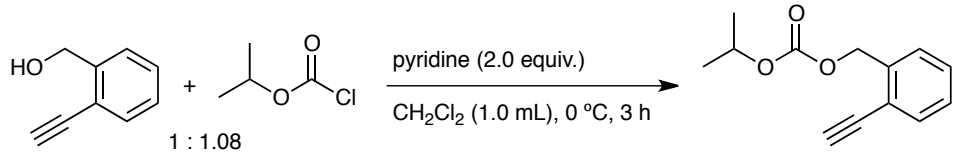
2l: 1.01 mmol 1.27 mmol **2g**: 87% yield

2-Ethynylbenzyl Methyl Carbonate (2g). The title compound was isolated in 87% yield by column chromatography on silica gel (hexane/EtOAc = 8/1). A white solid, mp 33–34 ºC. ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.33 (s, 1 H), 3.82 (s, 3 H), 5.36 (s, 2 H), 7.30 (td, J = 7.4, 1.1 Hz, 1 H), 7.37 (td, J = 7.7, 1.1 Hz, 1 H), 7.44 (dd, J = 7.4, 0.6 Hz, 1 H), 7.53 (dd, J = 7.4, 0.6 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 55.0, 67.7, 80.6, 82.3, 121.4, 128.1, 128.2, 129.1, 132.9, 137.5, 155.7. HRMS (FI) Calcd for $C_{11}H_{10}O_3$: M, 190.0630. Found: m/z 190.0604.



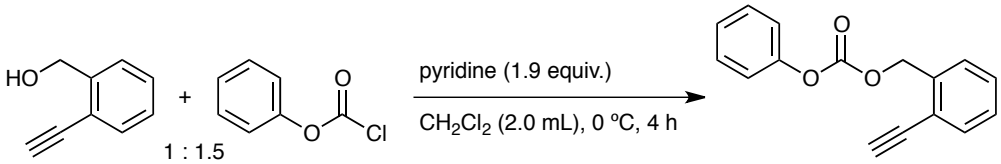
2l: 6.64 mmol 8.36 mmol **2h**: 94% yield

Ethyl 2-Ethynylbenzyl Carbonate (2h). The title compound was isolated in 94% yield by column chromatography on silica gel (hexane/EtOAc = 8/1). A white solid, mp 37–38 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.32 (t, *J* = 7.2 Hz, 3 H), 3.32 (s, 1 H), 4.23 (q, *J* = 7.3 Hz, 2 H), 5.36 (s, 2 H), 7.30 (td, *J* = 7.4, 1.1 Hz, 1 H), 7.37 (td, *J* = 7.6, 1.3 Hz, 1 H), 7.45 (dd, *J* = 7.7, 0.9 Hz, 1 H), 7.52 (dd, *J* = 7.4, 1.1 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 14.3, 64.2, 67.5, 80.7, 82.3, 121.3, 128.1, 128.2, 129.1, 132.9, 137.6, 155.1. HRMS (FI) Calcd for $C_{12}H_{12}O_3$: M, 204.0786. Found: *m*/*z* 204.0785.



2l: 1.00 mmol 1.08 mmol **2i**: 89% yield

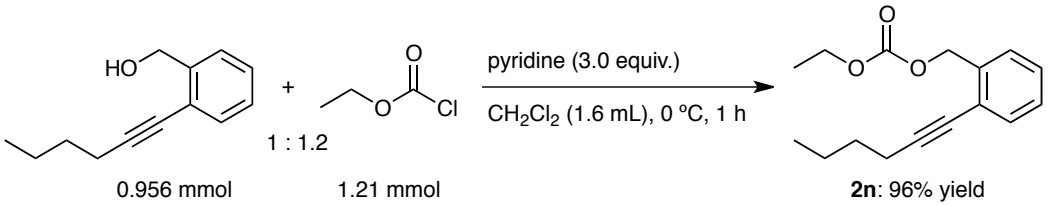
2-Ethynylbenzyl Isopropyl Carbonate (2i). The title compound was isolated in 89% yield by column chromatography on silica gel (hexane/EtOAc = 8/1). A colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.31 (d, *J* = 6.4 Hz, 6 H), 3.32 (s, 1 H), 4.92 (sept, *J* = 6.3 Hz, 1 H), 5.34 (s, 2 H), 7.29 (t, *J* = 7.8 Hz, 1 H), 7.36 (t, *J* = 7.3 Hz, 1 H), 7.45 (d, *J* = 7.8 Hz, 1 H), 7.52 (d, *J* = 7.8 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 21.8, 67.3, 72.2, 80.7, 82.3, 121.3, 128.09, 128.12, 129.0, 132.8, 137.7, 154.6. HRMS (FI) Calcd for $C_{13}H_{14}O_3$: M, 218.0943. Found: *m*/*z* 218.0932.



2l: 1.00 mmol 1.49 mmol **2k**: 95% yield

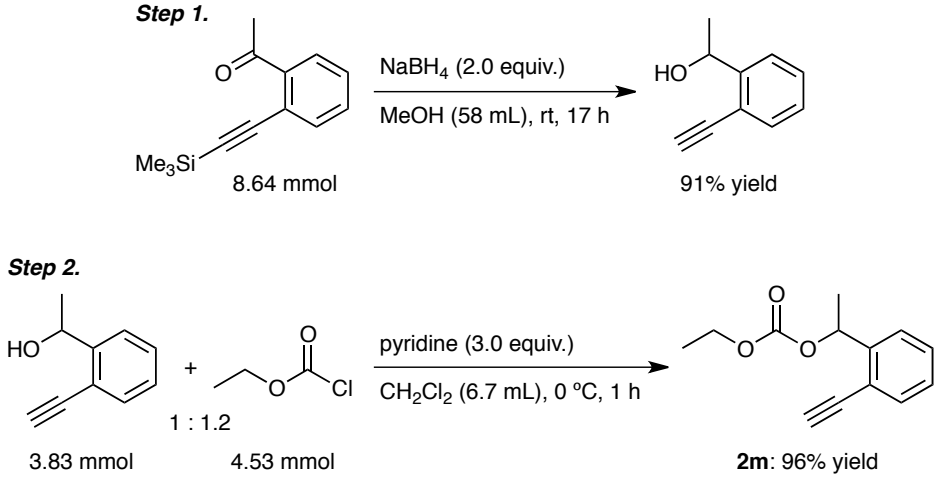
2-Ethynylbenzyl Phenyl Carbonate (2k). The title compound was isolated in 95% yield by column chromatography on silica gel (hexane/EtOAc = 8/1). A colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.35 (s, 1 H), 5.47 (s, 2 H), 7.17–7.22 (m, 2 H),

7.22–7.28 (m, 1 H), 7.33 (td, *J* = 7.6, 1.4 Hz, 1 H), 7.35–7.44 (m, 3 H), 7.51 (dd, *J* = 6.9, 1.4 Hz, 1 H), 7.56 (dd, *J* = 7.8, 1.4 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 68.4, 80.6, 82.5, 121.0, 121.6, 126.0, 128.5, 129.1, 129.5, 133.0, 137.0, 151.1, 153.6, (One carbon signal is missing due to overlapping.). HRMS (FD) Calcd for $C_{16}H_{12}O_3$: M, 252.0786. Found: *m*/*z* 252.0770.



Ethyl 2-(Hexyn-1-yl)benzyl Carbonate (2n). The title compound was isolated in 96% yield by column chromatography on silica gel (hexane/EtOAc = 30/1). A colorless oil. ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.95 (t, *J* = 7.4 Hz, 3 H), 1.33 (t, *J* = 7.2 Hz, 3 H), 1.44–1.53 (m, 2 H), 1.56–1.64 (m, 2 H), 2.44 (t, *J* = 7.2 Hz, 2 H), 4.23 (q, *J* = 7.1 Hz, 2 H), 5.32 (s, 2 H), 7.22–7.30 (m, 2 H), 7.36–7.44 (m, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.6, 14.3, 19.3, 22.0, 30.8, 64.1, 67.9, 77.7, 95.8, 123.3, 127.7, 127.9, 128.1, 132.2, 136.7, 155.2. HRMS (FI) Calcd for $C_{16}H_{20}O_3$: M, 260.1412. Found: *m*/*z* 260.1418.

Preparation of Ethyl 1-(2-Ethynylphenyl)ethyl Carbonate (2m)

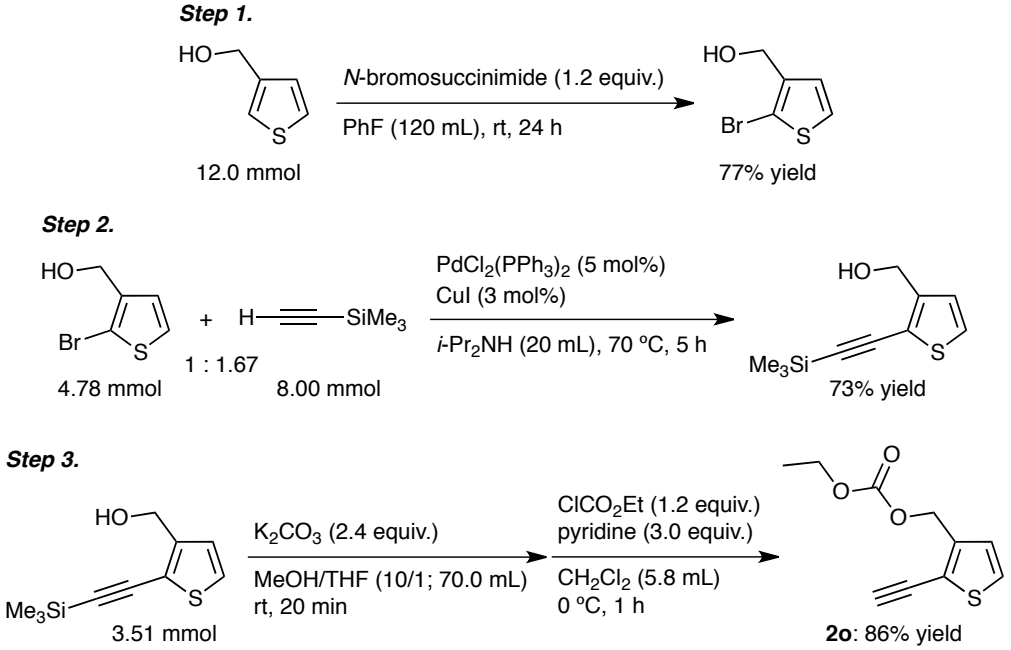


***Step 1*: Synthesis of 1-(2-Ethynylphenyl)ethanol.** To a 300 mL Schlenk tube that contains a solution of 2-(trimethylsilylethynyl)acetophenone[16] (1.87 g, 8.64 mmol) in MeOH (58 mL) was added sodium borohydride (0.656 g, 17.3 mmol) at 0 ºC. After being stirred at room temperature for 17 h, a saturated NH_4Cl aqueous solution (5 mL) was added to the reaction mixture. The aqueous solution was extracted with EtOAc (30 mL x 3) and the combined organic layer was washed with water (10 mL) and brine (10 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (hexane/EtOAc = 5/1) gave 1-(2-ethynylphenyl)ethanol (1.16 g, 91% yield) as a pale yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.53 (d, *J* = 6.4 Hz, 3 H), 2.06 (d, *J* = 3.7 Hz, 1 H), 3.34 (s, 1 H), 5.24–5.43 (m, 1 H), 7.23 (t, *J* = 7.6 Hz, 1 H), 7.39 (t, *J* = 7.6 Hz, 1 H), 7.48 (d, *J* = 7.8 Hz, 1 H), 7.55 (d, *J* = 7.8 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 24.0, 68.3, 81.4, 82.1, 119.2, 124.8, 127.1, 129.4, 133.0, 148.2. HRMS (FI) Calcd for $C_{10}H_{10}O$: M, 146.0732. Found: *m*/*z* 146.0718.

***Step 2*: Synthesis of Ethyl 1-(2-Ethynylphenyl)ethyl Carbonate (2m).** Carbonate **2m** was prepared by the procedure described in section "**Preparation of (2-Ethynylaryl)methyl Carbonates 2g–2i and 2k, and Ethyl 2-(Hexyn-1-yl)benzyl Carbonate (2n)**" and isolated in 96% yield by column chromatography on silica gel (hexane/EtOAc = 8/1). A colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.30 (t, *J* = 7.1 Hz, 3 H), 1.59 (d, *J* = 6.9 Hz, 3 H), 3.34 (s, 1 H), 4.08–4.27 (m, 2 H), 6.18 (q, *J* = 6.6 Hz, 1 H), 7.25 (td, *J* = 7.6, 1.4 Hz, 1 H), 7.38 (td, *J* = 7.8, 1.4 Hz, 1 H), 7.45–7.52 (m, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.3, 21.8, 64.0, 74.1, 80.8, 82.4, 119.7, 124.7,

127.6, 129.4, 132.9, 144.0, 154.4. HRMS (FI) Calcd for $C_{13}H_{14}O_3$: M, 218.0943. Found: *m*/*z* 218.0932.

Preparation of Ethyl (2-Ethynylthien-3-yl)methyl Carbonate (2o)



***Step 1*: Synthesis of (2-Bromothien-3-yl)methanol.** According to the reported procedure,[30] (2-bromothien-3-yl)methanol was prepared by the bromination of 3-thienylmethanol (1.37 g, 12.0 mmol) with *N*-bromosuccinimide (2.56 g, 14.4 mmol) in PhF (120 mL), and isolated in 77% yield (1.80 g) as a light orange oil by column chromatography on silica gel (hexane/EtOAc = 3/1). Its spectral and analytical data are shown below because they were not provided in reference 30. ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.67 (bs, 1 H), 4.64 (s, 2 H), 7.03 (d, *J* = 5.5 Hz, 1 H), 7.26 (d, *J* = 5.5 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 59.5, 110.5, 126.2, 127.8, 140.5. HRMS (FI) Calcd for C_5H_5BrOS: M, 191.9244. Found: *m*/*z* 191.9237.

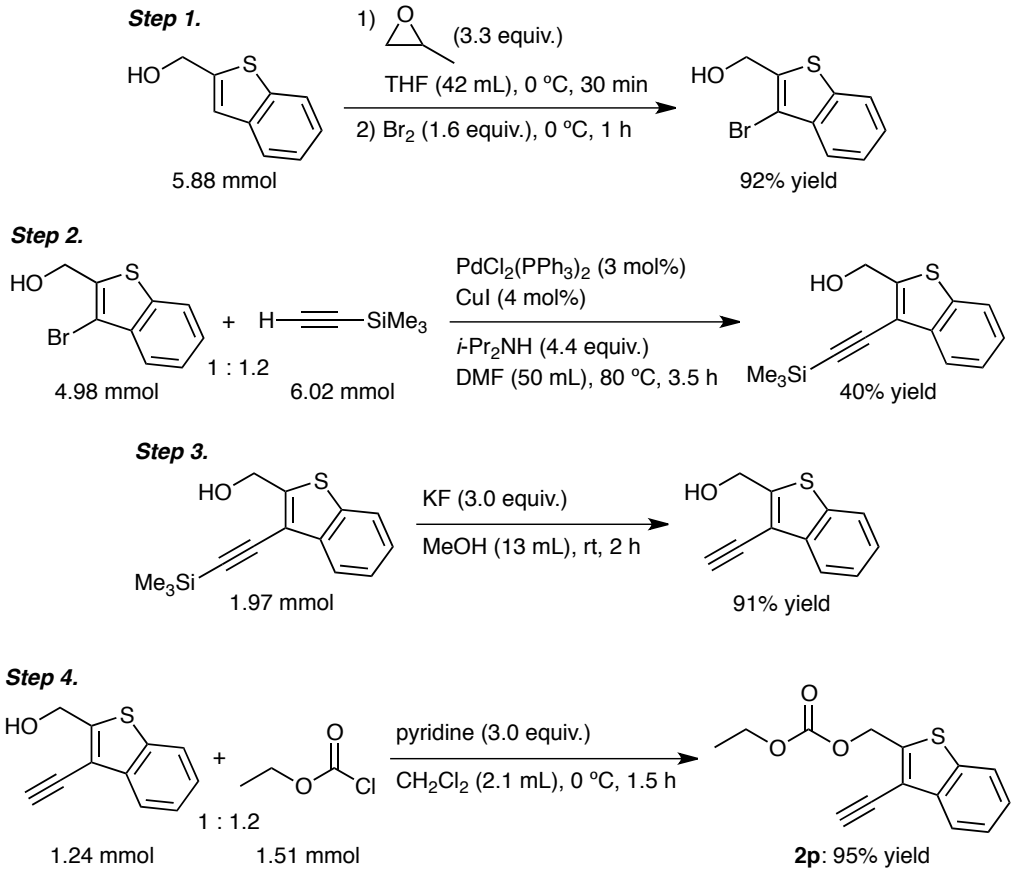
***Step 2*: Synthesis of [2-(Trimethylsilylethynyl)thien-3-yl]methanol.** The compound in the title was synthesized according to the following modified literature procedure.[31] A flame-dried 100 mL Schlenk tube was filled with argon and then charged with $PdCl_2(PPh_3)_2$ (0.182 g, 0.257 mmol), CuI (30.6 mg, 0.160 mmol) and *i*-Pr_2NH (20 mL). After degassing by three freeze-thaw cycles, (2-bromothien-3-yl)methanol (0.924 g, 4.78 mmol) and trimethylsilylacetylene (0.786 g, 8.00 mmol)

were added to the tube, and the mixture was stirred at 70 ºC for 5 h. After cooling to room temperature, the solution was diluted with $CHCl_3$ (20 mL). The resulting solution was washed with water (10 mL x 2) and brine (5 mL), and then dried over anhydrous sodium sulfate. Filtration through a pad of Celite and evaporation of the solvent followed by column chromatography on silica gel (hexane/EtOAc = 4/1) gave [2-(trimethylsilylethynyl)thien-3-yl]methanol (0.740 g, 73% yield) as a light orange oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.25 (s, 9 H), 1.79 (t, *J* = 6.2 Hz, 1 H), 4.74 (d, *J* = 6.4 Hz, 2 H), 7.05 (d, *J* = 5.0 Hz, 1 H), 7.20 (d, *J* = 5.0 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ –0.1, 59.6, 96.0, 102.5, 119.8, 126.8, 127.3, 146.6. HRMS (FI) Calcd for $C_{10}H_{14}OSSi$: M, 210.0535. Found: *m/z* 210.0532.

***Step 3*: Synthesis of Ethyl (2-Ethynylthien-3-yl)methyl Carbonate (2o).** Desilylation was performed according to the following modified literature procedure.[32] Under an argon atmosphere, a 200 mL two-necked round-bottomed flask was charged with [2-(trimethylsilylethynyl)thien-3-yl]methanol (0.740 g, 3.51 mmol) and MeOH/THF (10/1; 70.0 mL). To this was added K_2CO_3 (1.17 g, 8.39 mmol), and the mixture was stirred at room temperature for 20 min. The solution was filtered, and the volatile solvent was removed under reduced pressure. The resulting mixture was diluted with Et_2O (20 mL), and the solution was washed with water (5 mL x 2) and brine (5 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent gave a light brown oil (0.454 g), which was used directly for the next step without purification. Thus, under an argon atmosphere, the crude oil, pyridine (0.820 g, 10.4 mmol) and CH_2Cl_2 (1.5 mL) were placed in a 50 mL Schlenk tube. Ethyl chloroformate (0.475 g, 4.37 mmol) was then added dropwise over 45 min at 0 ºC. After being stirred at 0 ºC for 1 h, the reaction mixture was diluted with EtOAc (5 mL). The resulting solution was washed with a 1 M HCl aqueous solution (2 mL), and the organic layer was separated. The aqueous layer was extracted with EtOAc (5 mL x 2). The combined organic layer was washed with brine (2 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (hexane/EtOAc = 9/1) gave **2o** (0.641 g, 86% yield based on [2-(trimethylsilylethynyl)thien-3-yl]methanol) as a light orange oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.31 (t, *J* = 7.1 Hz, 3 H), 3.53 (s, 1 H), 4.22 (q, *J* = 7.0 Hz, 2 H), 5.23 (s, 2 H), 7.08 (d, *J* = 5.5 Hz, 1 H), 7.23 (d, *J* = 5.0 Hz, 1 H); ^{13}C

NMR (100 MHz, $CDCl_3$) δ 14.3, 63.0, 64.3, 75.0, 85.1, 121.3, 127.0, 127.8, 141.0, 155.0. HRMS (FI) Calcd for $C_{10}H_{10}O_3S$: M, 210.0351. Found: *m/z* 210.0349.

Preparation of Ethyl (3-Ethynylbenzo[*b*]thien-2-yl)methyl Carbonate (2p)



***Step 1*: Synthesis of (3-Bromobenzo[*b*]thien-2-yl)methanol.** The compound in the title was prepared according to the following modified literature procedure.[33] Under an argon atmosphere, to a 200 mL Schlenk tube that contains a solution of benzo[*b*]thiophene-2-methanol (0.966 g, 5.88 mmol) in THF (42 mL) was added 2-methyloxirane (1.13 g, 19.5 mmol) at 0 °C, and the mixture was stirred for 30 min. To this was added bromine (1.54 g, 9.63 mmol), and the resulting solution was stirred at 0 °C for 1 h. The reaction was quenched by adding a 10% $Na_2S_2O_3$ aqueous solution (10 mL) and a 10% $NaHCO_3$ aqueous solution (10 mL) successively. The mixture was extracted with EtOAc (30 mL x 3), and the combined organic layer was dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (hexane/EtOAc = 5/1) gave (3-

bromobenzo[*b*]thien-2-yl)methanol (1.32 g, 92% yield) as a white solid, mp 93–94 ºC. ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.00 (t, *J* = 5.7 Hz, 1 H), 4.99 (d, *J* = 6.0 Hz, 2 H), 7.40 (td, *J* = 7.6, 0.9 Hz, 1 H), 7.46 (td, *J* = 7.6, 0.9 Hz, 1 H), 7.73–7.89 (m, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 60.0, 105.7, 122.6, 123.0, 125.1, 125.5, 137.7, 138.1, 139.1. HRMS (FI) Calcd for C_9H_7BrOS: M, 241.9401. Found: *m*/*z* 241.9399.

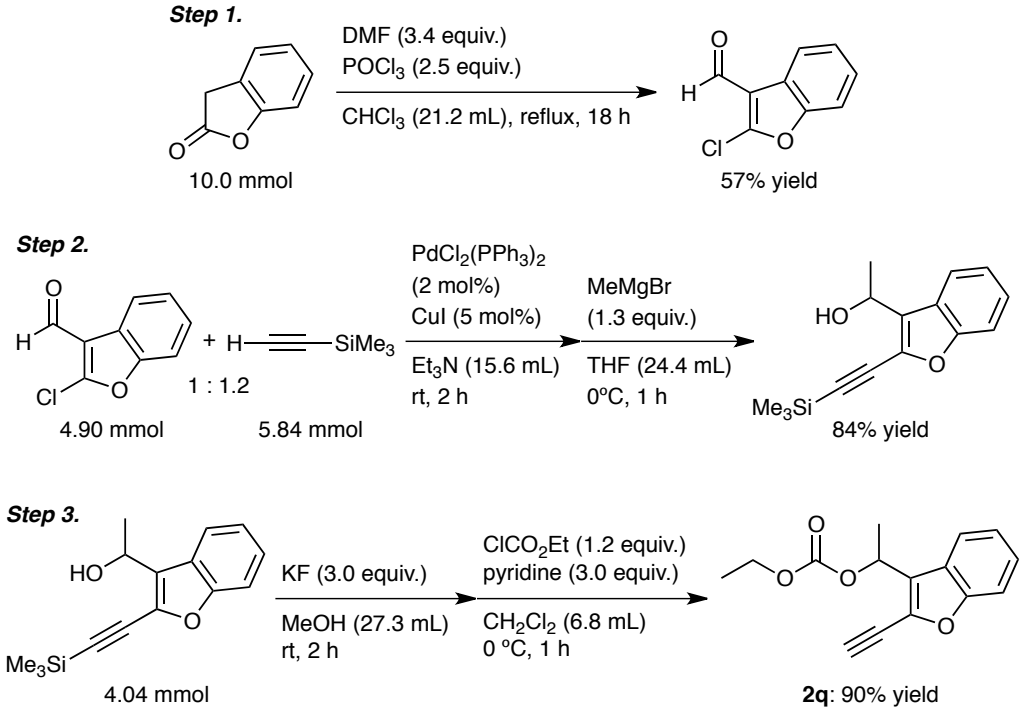
***Step 2*: Synthesis of [3-(Trimethylsilylethynyl)benzo[*b*]thien-2-yl]methanol.** The compound in the title was synthesized according to the following modified literature procedure.[34] Under an argon atmosphere, a flame-dried 500 mL two-necked round-bottomed flask equipped with a dropping funnel and a dimroth condenser attached to a three-way stopcock was charged with (3-bromobenzo[*b*]thien-2-yl)methanol (1.21 g, 4.98 mmol) and DMF (40 mL). To this were added $PdCl_2(PPh_3)_2$ (0.105 g, 0.150 mmol) and CuI (38.8 mg, 0.204 mmol). After the mixture was stirred at room temperature for 5 min, *i*-Pr_2NH (2.22 g, 21.9 mmol) was added, and then the solution was heated to 80 ºC. A solution of trimethylsilylacetylene (0.591 g, 6.02 mmol) in anhydrous DMF (10 mL) was added dropwise over 10 min through the dropping funnel, and the resulting solution was stirred at 80 ºC for 3.5 h. After cooling to room temperature, the mixture was diluted with EtOAc (30 mL). The resulting solution was washed with a saturated NH_4Cl aqueous solution (10 mL x 2), water (10 mL x 3) and brine (5 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (hexane/EtOAc = 10/1) provided [3-(trimethylsilylethynyl)benzo[*b*]thien-2-yl]methanol (0.520 g, 40% yield) as a white solid, mp 77–78 ºC. ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.31 (s, 9 H), 2.14 (t, *J* = 6.4 Hz, 1 H), 5.06 (d, *J* = 6.4 Hz, 2 H), 7.36 (t, *J* = 7.6 Hz, 1 H), 7.43 (t, *J* = 7.3 Hz, 1 H), 7.79 (d, *J* = 7.8 Hz, 1 H), 7.85 (d, *J* = 7.8 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 0.1, 60.0, 96.9, 101.1, 115.4, 122.4, 123.0, 124.8, 125.1, 137.9, 139.5, 149.4. HRMS (FI) Calcd for $C_{14}H_{16}OSSi$: M, 260.0691. Found: *m*/*z* 260.0698.

***Step 3*: Synthesis of (3-Ethynylbenzo[*b*]thien-2-yl)methanol.** The compound in the title was synthesized according to the following modified literature procedure.[35] Under an argon atmosphere, a 50 mL Schlenk tube was charged with [3-(trimethylsilylethynyl)benzo[*b*]thien-2-yl]methanol (0.514 g, 1.97 mmol) and MeOH (13 mL). To this was added KF (0.345 g, 5.93 mmol), and the mixture was stirred at room temperature for 2 h. The reaction was quenched by adding a saturated NH_4Cl

aqueous solution (5 mL), and the aqueous solution was extracted with CH_2Cl_2 (15 mL x 3). The combined organic layer was washed with water (5 mL) and brine (5 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (hexane/EtOAc = 3/1) provided (3-ethynylbenzo[*b*]thien-2-yl)methanol (0.338 g, 91% yield) as a white solid, mp 71–72 ºC. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.12 (t, *J* = 6.3 Hz, 1 H), 3.49 (s, 1 H), 5.08 (d, *J* = 6.3 Hz, 2 H), 7.38 (td, *J* = 7.4, 1.0 Hz, 1 H), 7.43 (td, *J* = 7.2, 0.6 Hz, 1 H), 7.81 (dd, *J* = 8.0, 0.6 Hz, 1 H), 7.89 (dd, *J* = 8.0, 0.6 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 60.0, 76.1, 83.4, 114.1, 122.5, 122.9, 124.9, 125.2, 137.9, 139.6, 150.1. HRMS (FD) Calcd for $C_{11}H_8OS$: M, 188.0296. Found: *m*/*z* 188.0303.

***Step 4*: Synthesis of Ethyl (3-Ethynylbenzo[*b*]thien-2-yl)methyl Carbonate (2p).** Carbonate **2p** was prepared by the procedure described in section **II-3** and isolated in 95% yield by column chromatography on silica gel (hexane/EtOAc = 15/1). A dark red oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.33 (t, *J* = 7.1 Hz, 3 H), 3.51 (s, 1 H), 4.25 (q, *J* = 7.0 Hz, 2 H), 5.55 (s, 2 H), 7.39 (td, *J* = 7.6, 1.4 Hz, 1 H), 7.44 (td, *J* = 7.6, 1.4 Hz, 1 H), 7.80 (dd, *J* = 7.8, 1.4 Hz, 1 H), 7.91 (dd, *J* = 7.3, 1.4 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.3, 63.1, 64.6, 75.7, 83.9, 117.4, 122.4, 123.3, 125.0, 125.8, 138.6, 139.1, 142.7, 154.9. HRMS (FD) Calcd for $C_{14}H_{12}O_3S$: M, 260.0507. Found: *m*/*z* 260.0531.

Preparation of Ethyl 1-(2-Ethynylbenzo[*b*]furan-3-yl)ethyl Carbonate (2q)



***Step 1*: Synthesis of 2-Chloro-3-benzofurancarboxaldehyde.** According to the literature procedure,[36] 2-chloro-3-benzofurancarboxaldehyde was prepared by the reaction of 2-coumaranone (1.34 g, 10.0 mmol) with anhydrous DMF (2.49 g, 34.1 mmol) and $POCl_3$ (3.88g, 25.3 mmol) in $CHCl_3$ (21.2 mL), and isolated in 57% yield (1.03 g) as a pale yellow solid by column chromatography on silica gel (hexane/EtOAc = 10/1). Its spectral and analytical data are shown below because they were not provided in reference 36. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.36–7.41 (m, 2 H), 7.45–7.51 (m, 1 H), 8.07–8.19 (m, 1 H), 10.16 (s, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 111.0, 116.3, 121.8, 124.1, 125.4, 126.1, 151.8, 153.6, 184.2. HRMS (FI) Calcd for $C_9H_5ClO_2$: M, 179.9978. Found: *m*/*z* 179.9951.

***Step 2*: Synthesis of 1-[2-(Trimethylsilylethynyl)benzo[*b*]furan-3-yl]ethanol.** A flame-dried 50 mL Schlenk tube was filled with argon and then charged with $PdCl_2(PPh_3)_2$ (68.9 mg, 98.1 μmol), CuI (47.1 mg, 0.247 mmol) and Et_3N (15.6 mL). After degassing by three freeze-thaw cycles, 2-chloro-3-benzofurancarboxaldehyde (0.886 g, 4.90 mmol) and trimethylsilylacetylene (0.574 g, 5.84 mmol) were added, and the mixture was stirred at room temperature for 2 h. After cooling to room temperature, the solution was diluted with EtOAc (10 mL), and filtered through a pad of Celite. The volatile solvent was removed under reduced pressure, and the resulting

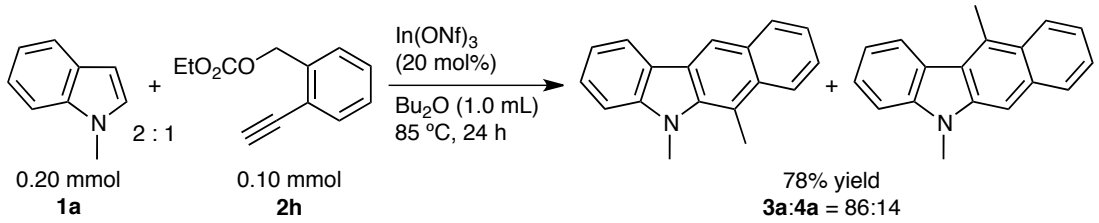
mixture was then diluted with hexane/EtOAc (40/1; 30 mL). Filtration through a pad of silica gel and evaporation of the solvent gave a pale yellow oil (1.17 g), which was used directly for the next step without purification. Under an argon atmosphere, a flame-dried 200 mL two-necked round-bottomed flask equipped with a dropping funnel and a three-way stopcock was charged with the crude product and THF (24.4 mL). After cooling to 0 ºC, MeMgBr (8.1 mL, 6.34 mmol, 0.93 M in THF) was slowly added through the dropping funnel, and the mixture was stirred at 0 ºC for 1 h and then quenched by adding a saturated NH_4Cl aqueous solution (5 mL). The mixture was extracted with EtOAc (15 mL x 3), and the combined organic layer was washed with water (10 mL x 2) and brine (5 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (hexane/EtOAc = 5/1) gave 1-[2-(trimethylsilylethynyl)benzo[*b*]furan-3-yl]ethanol (1.06 g, 84% yield based on 2-chloro-3-benzofurancarboxaldehyde) as a pale yellow oil. ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.30 (s, 9 H), 1.69 (d, *J* = 6.3 Hz, 3 H), 1.99 (d, *J* = 4.0 Hz, 1 H), 5.27 (qd, *J* = 6.5, 3.4 Hz, 1 H), 7.25 (ddd, *J* = 8.0, 6.9, 1.1 Hz, 1 H), 7.35 (ddd, *J* = 8.3, 7.2, 1.1 Hz, 1 H), 7.42 (dd, *J* = 7.4, 1.1 Hz, 1 H), 7.80 (dd, *J* = 8.0, 1.1 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ –0.4, 23.0, 63.9, 93.2, 105.4, 111.5, 121.3, 123.1, 125.7, 126.0, 129.0, 134.4, 154.7. HRMS (FI) Calcd for $C_{15}H_{18}O_2Si$: M, 258.1076. Found: *m*/*z* 258.1082.

***Step 3*: Synthesis of Ethyl 1-(2-Ethynylbenzo[*b*]furan-3-yl)ethyl Carbonate (2q).** A 200 mL Schlenk tube was filled with argon and then charged with 1-[2-(trimethylsilylethynyl)benzo[*b*]furan-3-yl]ethanol (1.05 g, 4.04 mmol) and MeOH (27.3 mL). To this was added KF (0.704 g, 12.1 mmol), and the mixture was stirred at room temperature for 2 h. The reaction was then quenched by adding a saturated NH_4Cl aqueous solution (5 mL), and the resulting mixture was extracted with EtOAc (15 mL x 3). The combined organic layer was washed with water (5 mL) and brine (5 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent gave a pale yellow solid (0.752 g). The crude product was used directly for the next step without purification. Thus, under an argon atmosphere, the crude solid, pyridine (0.959 g, 12.1 mmol) and CH_2Cl_2 (6.8 mL) were placed in a 50 mL Schlenk tube. Ethyl chloroformate (0.526 g, 4.84 mmol) was added dropwise over 45 min at 0 ºC. After being stirred at 0 ºC for 1 h, the reaction mixture was diluted with EtOAc (10 mL). The resulting solution was washed with a 1 M HCl aqueous solution (2 mL), and

the organic layer was separated. The aqueous layer was extracted with EtOAc (5 mL x 2). The combined organic layer was washed with brine (2 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (hexane/EtOAc = 20/1) gave **2q** (0.950 g, 90% yield based on 1-[2-(trimethylsilylethynyl)benzo[*b*]furan-3-yl]ethanol) as a dark red oil. ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.28 (t, *J* = 7.2 Hz, 3 H), 1.76 (d, *J* = 6.3 Hz, 3 H), 3.70 (s, 1 H), 4.10–4.25 (m, 2 H), 6.08 (q, *J* = 6.7 Hz, 1 H), 7.26–7.30 (m, 1 H), 7.37 (td, *J* = 7.7, 1.1 Hz, 1 H), 7.45 (dd, *J* = 8.0, 0.6 Hz, 1 H), 7.77 (dd, *J* = 8.0, 0.6 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 14.2, 20.6, 64.1, 69.4, 72.6, 86.9, 111.6, 121.1, 123.5, 125.2, 125.6, 126.3, 134.8, 154.4, 154.6. HRMS (FD) Calcd for $C_{15}H_{14}O_4$: M, 258.0892. Found: *m*/*z* 258.0888.

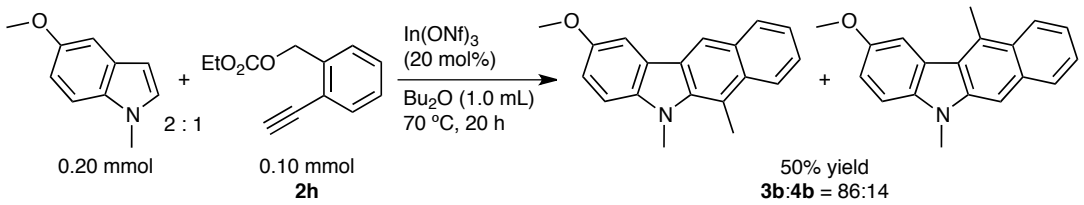
Synthesis of Aryl- and Heteroaryl[*b*]carbazoles Utilizing Indium-Catalyzed Annulation of Indoles with (2-Ethynylaryl)methyl Ethyl Carbonates. A General Procedure for Table 2 and Equations 1–3

$In(ONf)_3$ [(20.2 mg, 20.0 μmol) or (30.3 mg, 30.0 μmol)] was placed in a 20 mL Schlenk tube, which was heated at 150 °C in vacuo for 2 h. The tube was cooled down to room temperature and filled with argon. Bu_2O (1.0 or 2.0 mL) was added to the tube and stirred for 10 min at room temperature. To this were added indole derivative **1** (0.200 mmol) and (2-ethynylaryl)methyl ethyl carbonate **2** (0.100 mmol) successively, and the resulting mixture was stirred at 70, 80, 85 or 90 °C. After the time specified in Table 2 and Equations 1–3, the mixture was diluted with EtOAc (10 mL) and washed with a saturated $NaHCO_3$ aqueous solution (1 mL) and brine (1 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel using hexane–EtOAc as eluent gave the corresponding (hetero)aryl[*b*]carbazole. In case that purity of **3** or **4** is insufficient, further purification was performed with recycling HPLC or GPC. Products **3** and **4** synthesized here were fully characterized by ^{1}H and ^{13}C NMR spectroscopy, and elemental analysis or HRMS.



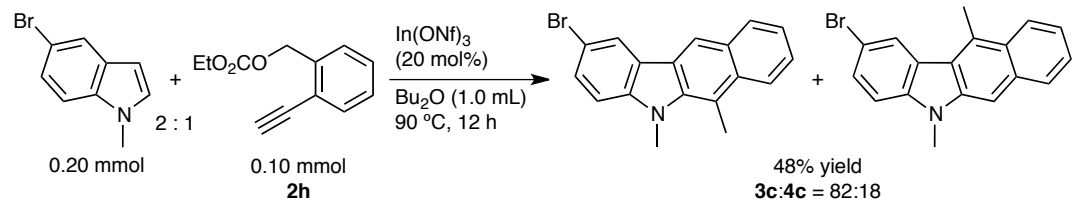
5,6-Dimethyl-5*H*-benzo[*b*]carbazole (3a). The title compound was isolated by recycling GPC after column chromatography on silica gel (hexane/EtOAc = 10/1). A white solid, mp 159–160 ºC. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.15 (s, 3 H), 4.15 (s, 3 H), 7.21–7.26 (m, 1 H), 7.36 (dd, *J* = 8.2, 0.5 Hz, 1 H), 7.42 (td, *J* = 7.3, 1.1 Hz, 1 H), 7.50–7.57 (m, 2 H), 8.03 (dd, *J* = 8.2, 0.9 Hz, 1 H), 8.15–8.22 (m, 2 H), 8.44 (s, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 14.3, 34.2, 108.5, 112.4, 116.8, 119.0, 120.5, 122.4, 122.9, 123.0, 124.9, 125.9, 127.2, 128.5, 128.9, 132.2, 140.0, 145.2. Anal. Calcd for $C_{18}H_{15}N$: C, 88.13; H, 6.16; N, 5.71. Found: C, 87.71; H, 5.82; N, 5.74.

5,11-Dimethyl-5*H*-benzo[*b*]carbazole (4a). The title compound was difficult to be isolated as a pure form, in spite of performance of recycling GPC and HPLC after column chromatography on silica gel. A pure product could, however, be obtained by N-methylation of **4f**, and its ^{1}H NMR, GC and GC–MS spectra were in good agreement with those of the minor product formed by the annulation of **1a** with **2h**. Spectral and analytical data of the title compound are thus shown below. A white solid, mp 174–175 ºC. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.21 (s, 3 H), 3.81 (s, 3 H), 7.26 (td, *J* = 7.6, 0.9 Hz, 1 H), 7.36 (d, *J* = 7.8 Hz, 1 H), 7.43 (ddd, *J* = 8.5, 6.6, 1.4 Hz, 1 H), 7.49 (ddd, *J* = 8.0, 6.6, 1.4 Hz, 1 H), 7.50–7.56 (m, 2 H), 7.96 (dd, *J* = 7.8, 1.4 Hz, 1 H), 8.29 (dd, *J* = 8.2, 0.9 Hz, 1 H), 8.37 (d, *J* = 7.8 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 15.5, 29.0, 101.2, 107.6, 118.6, 122.3, 123.2, 123.6, 123.7, 124.1, 124.8, 126.5, 127.0, 127.6, 129.2, 132.7, 140.7, 143.6. HRMS (FD) Calcd for $C_{18}H_{15}N$: M, 245.1204. Found: *m*/*z* 245.1213.



2-Methoxy-5,6-dimethyl-5*H*-benzo[*b*]carbazole (3b). The title compound was isolated by recycling GPC after column chromatography on silica gel (hexane/EtOAc = 20/1). A pale yellow solid, mp 127–128 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.10 (s, 3 H), 3.95 (s, 3 H), 4.08 (s, 3 H), 7.15 (dd, *J* = 8.7, 2.7 Hz, 1 H), 7.22–7.27 (m, 1 H), 7.40 (ddd, *J* = 8.0, 6.6, 1.4 Hz, 1 H), 7.52 (ddd, *J* = 8.7, 6.4, 1.4 Hz, 1 H), 7.67 (d, *J* = 2.3 Hz, 1 H), 8.01 (dd, *J* = 8.2, 0.9 Hz, 1 H), 8.15 (dd, *J* = 8.7, 0.9 Hz, 1 H), 8.38 (s, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.3, 34.4, 56.2, 104.1, 109.3, 112.5, 115.7, 116.7, 122.3, 122.9, 123.4, 124.9, 125.9, 128.2, 128.9, 132.2, 140.2, 140.7, 153.7. HRMS (FD) Calcd for $C_{19}H_{17}NO$: M, 275.1310. Found: *m*/*z* 275.1339.

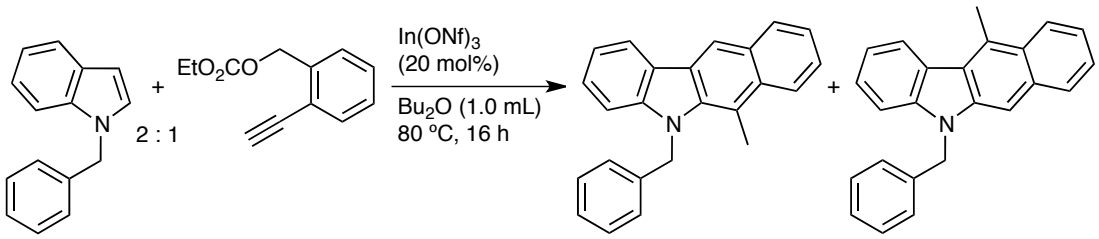
2-Methoxy-5,11-dimethyl-5*H*-benzo[*b*]carbazole (4b). The title compound was isolated by recycling GPC and HPLC after column chromatography on silica gel (hexane/EtOAc = 20/1). A pale yellow solid, mp 175–176 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.24 (s, 3 H), 3.85 (s, 3 H), 3.98 (s, 3 H), 7.19 (dd, *J* = 8.7, 2.3 Hz, 1 H), 7.30 (d, *J* = 8.7 Hz, 1 H), 7.43 (ddd, *J* = 8.5, 6.6, 1.6 Hz, 1 H), 8.48 (ddd, *J* = 8.2, 6.4, 1.4 Hz, 1 H), 7.54 (s, 1 H), 7.93–8.00 (m, 2 H), 8.30 (dd, *J* = 8.7, 0.9 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 15.4, 29.2, 56.5, 101.2, 107.9, 109.0, 113.9, 122.1, 123.2, 124.1, 124.2, 124.9, 126.8, 127.6, 129.3, 132.8, 138.7, 141.3, 153.3. HRMS (FD) Calcd for $C_{19}H_{17}NO$: M, 275.1310. Found: *m*/*z* 275.1338.



2-Bromo-5,6-dimethyl-5*H*-benzo[*b*]carbazole (3c). The title compound was isolated by recycling GPC after column chromatography on silica gel (hexane/EtOAc = 20/1). A white solid, mp 163–164 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.08 (s, 3 H), 4.06 (s, 3 H), 7.18 (d, *J* = 8.7 Hz, 1 H), 7.42 (ddd, *J* = 8.2, 6.9, 0.9 Hz, 1 H), 7.54 (ddd, *J* = 8.7, 6.9, 1.4 Hz, 1 H), 7.58 (dd, *J* = 8.7, 2.3 Hz, 1 H), 8.00 (dd, *J* = 8.2, 0.9 Hz, 1 H), 8.15 (d, *J* = 8.7 Hz, 1 H), 8.23 (d, *J* = 2.3 Hz, 1 H), 8.33 (s, 1 H); ^{13}C NMR (100 MHz,

$CDCl_3$) δ 14.1, 34.1, 109.8, 111.5, 112.7, 117.1, 122.7, 123.0, 123.2, 124.6, 124.7, 125.3, 128.4, 129.0, 129.7, 132.4, 139.8, 143.6. HRMS (FD) Calcd for $C_{18}H_{14}BrN$: M, 323.0310. Found: *m*/*z* 323.0346.

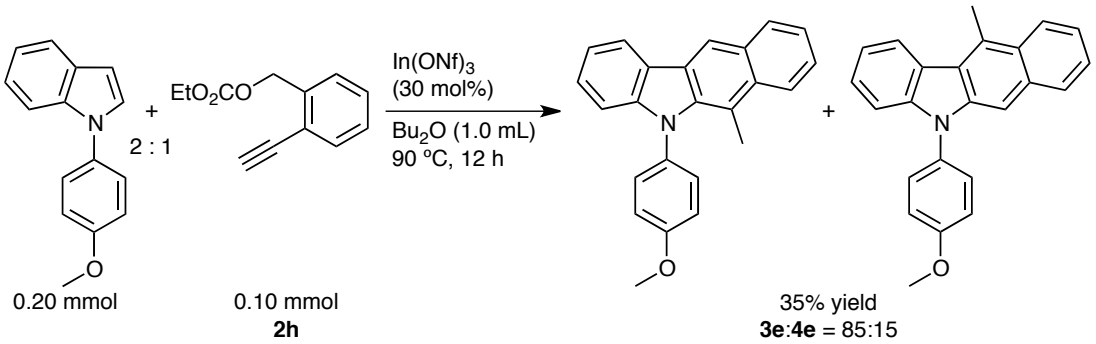
2-Bromo-5,11-dimethyl-5*H*-benzo[*b*]carbazole (4c). The title compound was isolated by recycling GPC after column chromatography on silica gel (hexane/EtOAc = 20/1). A white solid, mp 153–154 ºC. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.21 (s, 3 H), 3.85 (s, 3 H), 7.24–7.28 (m, 1 H), 7.46 (ddd, *J* = 8.7, 6.4, 1.4 Hz, 1 H), 7.51 (ddd, *J* = 8.1, 6.3, 1.0 Hz, 1 H), 7.57 (s, 1 H), 7.63 (dd, *J* = 8.7, 1.8 Hz, 1 H), 7.98 (dd, *J* = 8.2, 1.4 Hz, 1 H), 8.31 (d, *J* = 8.7 Hz, 1 H), 8.47 (d, *J* = 1.8 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 15.5, 29.2, 101.6, 109.0, 111.3, 122.1, 122.6, 124.3, 125.2, 125.4, 126.3, 127.1, 127.7, 129.0, 129.8, 132.9, 140.7, 142.3. HRMS (FD) Calcd for $C_{18}H_{14}BrN$: M, 323.0310. Found: *m*/*z* 323.0319.



5-Benzyl-6-methyl-5*H*-benzo[*b*]carbazole (3d). The title compound was isolated by recycling GPC after column chromatography on silica gel (hexane/EtOAc = 40/1). A white solid, mp 176–177 ºC. ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.90 (s, 3 H), 5.77 (s, 2 H), 7.18–7.35 (m, 7 H), 7.38–7.48 (m, 2 H), 7.52 (ddd, *J* = 8.7, 6.4, 1.4 Hz, 1 H), 8.05 (dd, *J* = 8.2, 0.9 Hz, 1 H), 8.13 (dd, *J* = 8.7, 0.9 Hz, 1 H), 8.22 (dd, *J* = 8.7, 0.9 Hz, 1 H), 8.50 (s, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.8, 49.8, 108.8, 112.5, 116.9, 119.5, 120.6, 122.6, 123.1, 123.2, 125.0, 125.8, 126.0, 127.2, 127.5, 128.6, 128.91, 128.94, 132.2, 138.7, 139.5, 144.9. HRMS (FD) Calcd for $C_{24}H_{19}N$: M, 321.1517. Found: *m*/*z* 321.1567.

5-Benzyl-11-methyl-5*H*-benzo[*b*]carbazole (4d). The title compound was difficult to be isolated as a pure form, in spite of performance of recycling GPC and HPLC after column chromatography on silica gel. A pure product could, however, be obtained by N-benzylation of **4f**, and its ^{1}H NMR, GC and GC–MS spectra were in good agreement with those of the minor product formed by the annulation of **1b** with

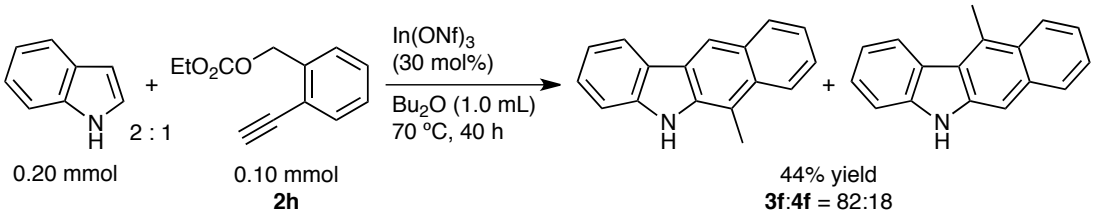
2h. Spectral and analytical data of the title compound are thus shown below. A white solid, mp 168–169 ºC. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.27 (s, 3 H), 5.54 (s, 2 H), 7.14–7.32 (m, 6 H), 7.33 (d, *J* = 7.8 Hz, 1 H), 7.40–7.52 (m, 3 H), 7.55 (s, 1 H), 7.85–7.93 (m, 1 H), 8.26–8.34 (m, 1 H), 8.43 (d, *J* = 7.8 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 15.6, 46.4, 101.7, 108.2, 119.1, 122.5, 123.3, 123.85, 123.88, 124.1, 124.9, 126.4, 126.7, 127.3, 127.4, 127.7, 128.8, 129.5, 132.7, 137.0, 140.3, 143.3. HRMS (FD) Calcd for $C_{24}H_{19}N$: M, 321.1517. Found: *m*/*z* 321.1553.



5-(4-Methoxyphenyl)-6-methyl-5*H*-benzo[*b*]carbazole (3e). The title compound was isolated by recycling GPC after column chromatography on silica gel (hexane/EtOAc = 40/1). A white solid, mp 150–151 ºC. ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.39 (s, 3 H), 3.94, (s, 3 H), 7.05 (d, *J* = 7.8 Hz, 1 H), 7.06–7.11 (m, 2 H), 7.24–7.29 (m, 1 H), 7.35–7.46 (m, 4 H), 7.51 (ddd, *J* = 9.2, 5.8, 1.9 Hz, 1 H), 8.04–8.12 (m, 2 H), 8.22 (dd, *J* = 7.3, 0.9 Hz, 1 H), 8.51 (s, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.9, 55.6, 109.8, 113.4, 114.7, 116.8, 119.7, 120.5, 122.7, 123.0, 123.1, 124.9, 126.1, 127.2, 128.8, 129.0, 130.1, 132.3, 133.5, 139.5, 146.0, 159.1. Anal. Calcd for $C_{24}H_{19}NO$: C, 85.43; H, 5.68; N, 4.15. Found: C, 85.11; H, 5.52; N, 4.09.

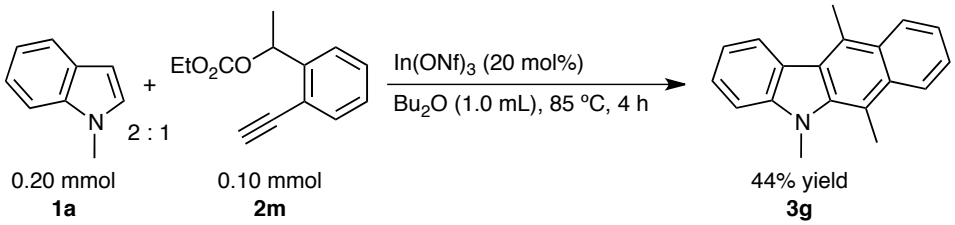
5-(4-Methoxyphenyl)-11-methyl-5*H*-benzo[*b*]carbazole (4e). The title compound was difficult to be isolated as a pure form, in spite of performance of recycling GPC and HPLC after column chromatography on silica gel. A pure product could, however, be obtained by N-*p*-methoxyphenylation of **4f**, and its ^{1}H NMR, GC and GC–MS spectra were in good agreement with those of the minor product formed by the annulation of *N*-(*p*-methoxyphenyl)indole with **2h**. Spectral and analytical data of the title compound are thus shown below. A white solid, mp 136–137 ºC. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.29 (s, 3 H), 3.93 (s, 3 H), 7.12–7.18 (m, 2 H), 7.25–7.35 (m, 2 H), 7.40–7.53 (m, 6 H), 7.78–7.88 (m, 1 H), 8.27–8.36 (m, 1 H), 8.45 (d, *J* = 7.8 Hz, 1

H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 15.6, 55.6, 102.6, 109.0, 115.2, 119.5, 122.6, 123.3, 123.7, 123.9, 124.1, 124.8, 126.6, 127.5, 127.7, 129.1, 129.2, 130.3, 132.7, 141.2, 144.1, 159.0. HRMS (FD) Calcd for $C_{24}H_{19}NO$: M, 337.1467. Found: *m*/*z* 337.1514.

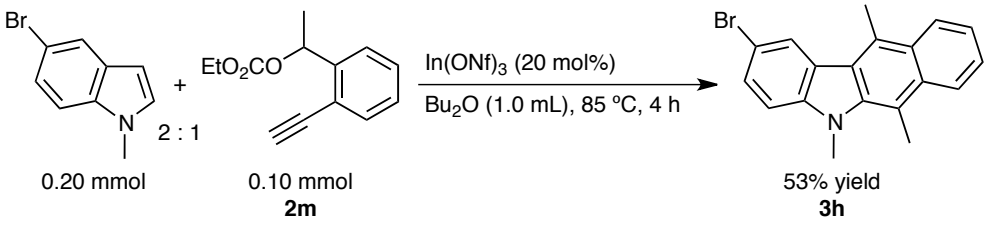


6-Methyl-5*H*-benzo[*b*]carbazole (3f). The title compound was isolated by recycling GPC after column chromatography on silica gel (hexane/EtOAc = 10/1). A white solid, mp 163–164 ºC. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.84 (s, 3 H), 7.22–7.29 (m, 1 H), 7.39–7.51 (m, 3 H), 7.53 (ddd, *J* = 8.6, 6.9, 1.1 Hz, 1 H), 7.84 (bs, 1 H), 8.06 (d, *J* = 8.6 Hz, 1 H), 8.12 (dd, *J* = 8.6, 1.1 Hz, 1 H), 8.18 (dd, *J* = 7.4, 1.1 Hz, 1 H), 8.44 (s, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 12.8, 110.3, 111.3, 116.7, 119.5, 121.1, 122.4, 122.8, 123.8, 124.9, 125.0, 127.3, 128.7, 129.2, 131.1, 138.3, 142.0. Anal. Calcd for $C_{17}H_{13}N$: C, 88.28; H, 5.67; N, 6.06. Found: C, 88.07; H, 5.57; N, 6.12.

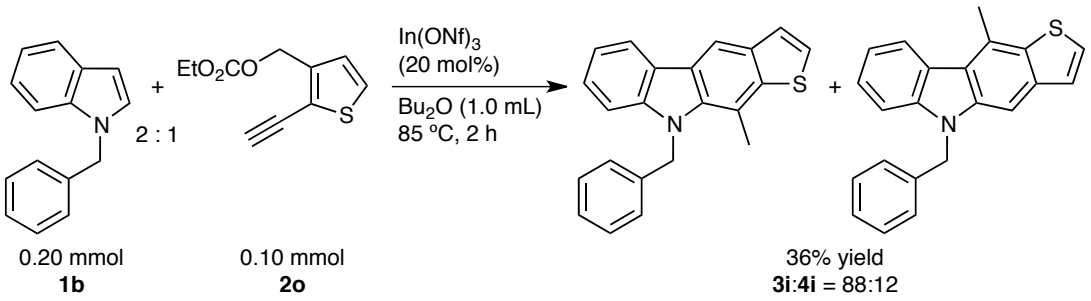
11-Methyl-5*H*-benzo[*b*]carbazole (4f). The title compound was isolated by recycling GPC after column chromatography on silica gel (hexane/EtOAc = 10/1). A white solid, mp 217–218 ºC. ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.26 (s, 3 H), 7.25–7.30 (m, 1 H), 7.39–7.53 (m, 4 H), 7.66 (s, 1 H), 7.93 (dd, *J* = 7.4, 1.1 Hz, 1 H), 7.95 (bs, 1 H), 8.31 (dd, *J* = 8.6, 1.1 Hz, 1 H), 8.39 (d, *J* = 8.0 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 15.5, 103.3, 110.0, 119.3, 122.5, 123.8, 124.15, 124.17, 124.8, 126.6, 127.4, 127.5, 129.3, 132.8, 139.0, 142.1, (One carbon signal is missing due to overlapping.). HRMS (FD) Calcd for $C_{17}H_{13}N$: M, 231.1048. Found: *m*/*z* 231.1030.



5,6,11-Trimethyl-5*H*-benzo[*b*]carbazole (3g). The title compound was isolated by column chromatography on silica gel (hexane/EtOAc = 30/1). A white solid, mp 185–186 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.10 (s, 3 H), 3.20 (s, 3 H), 4.09 (s, 3 H), 7.25 (ddd, *J* = 7.6, 6.8, 0.9 Hz, 1 H), 7.36 (d, *J* = 8.2 Hz, 1 H), 7.47 (ddd, *J* = 8.2, 6.4, 1.4 Hz, 1 H), 7.49–7.56 (m, 2 H), 8.19 (dd, *J* = 8.7, 1.4 Hz, 1 H), 8.33 (dd, *J* = 8.7, 0.9 Hz, 1 H), 8.36 (d, *J* = 7.8 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.8, 15.5, 34.6, 108.3, 110.0, 118.9, 122.2, 123.3, 123.8, 124.1, 124.5, 124.6, 126.5, 126.96, 126.97, 127.6, 132.3, 140.1, 145.6. HRMS (FD) Calcd for $C_{19}H_{17}N$: M, 259.1361. Found: *m*/*z* 259.1366.

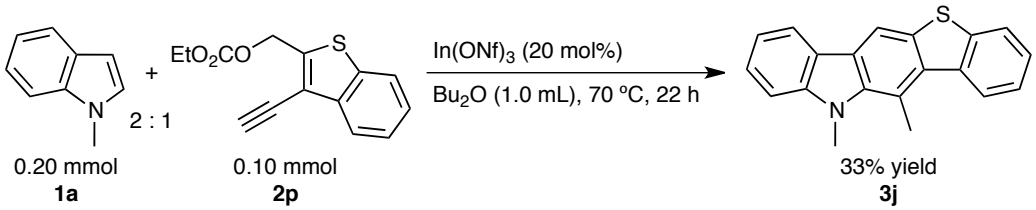


2-Bromo-5,6,11-trimethyl-5*H*-benzo[*b*]carbazole (3h). The title compound was isolated by column chromatography on silica gel (hexane/EtOAc = 20/1). A white solid, mp 165–166 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.05 (s, 3 H), 3.09 (s, 3 H), 4.01 (s, 3 H), 7.18 (d, *J* = 8.7 Hz, 1 H), 7.47 (ddd, *J* = 8.7, 6.4, 1.4 Hz, 1 H), 7.52–7.61 (m, 2 H), 8.17 (d, *J* = 8.2 Hz, 1 H), 8.29 (dd, *J* = 8.7, 1.4 Hz, 1 H), 8.38 (d, *J* = 1.8 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.6, 15.5, 34.6, 109.5, 110.3, 111.5, 122.5, 123.0, 123.4, 124.6, 125.0, 125.8, 126.2, 127.5, 127.6, 129.0, 132.5, 139.9. 144.2. HRMS (FD) Calcd for $C_{19}H_{16}BrN$: M, 337.0466. Found: *m*/*z* 337.0493.



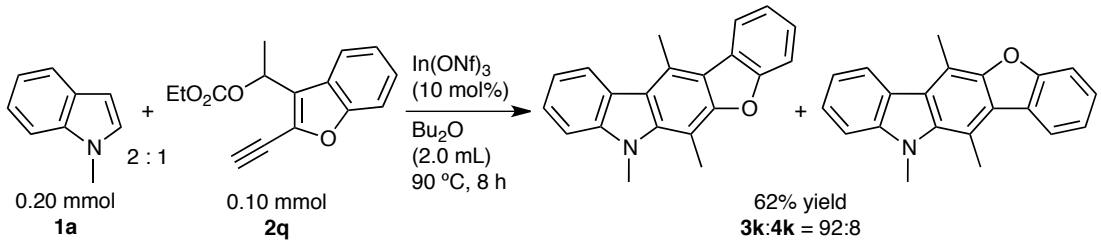
9-Benzyl-10-methyl-9*H*-thieno[2,3-*b*]carbazole (3i). The title compound was isolated by recycling GPC after column chromatography on silica gel (hexane/EtOAc = 40/1). A white solid, mp 192–193 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.81 (s, 3 H), 5.79 (s, 2 H), 7.09 (d, *J* = 7.4 Hz, 2 H), 7.20–7.31 (m, 5 H), 7.33 (d, *J* = 5.2 Hz, 1 H), 7.43 (ddd, *J* = 8.0, 6.9, 1.1 Hz, 1 H), 7.47 (d, *J* = 5.2 Hz, 1 H), 8.17 (d, *J* = 7.4 Hz, 1 H), 8.44 (s, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 17.5, 48.7, 108.8, 112.3, 112.5, 119.3, 120.0, 123.2, 123.3, 124.0, 124.7, 125.6, 126.3, 127.3, 128.9, 133.0, 137.5, 138.6, 141.0, 142.8. HRMS (FD) Calcd for $C_{22}H_{17}NS$: M, 327.1082. Found: *m*/*z* 327.1125.

5-Benzyl-10-methyl-5*H*-thieno[3,2-*b*]carbazole (4i). The title compound was isolated by recycling GPC and HPLC after column chromatography on silica gel (hexane/EtOAc = 40/1). A white solid, mp 205–206 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.14 (s, 3 H), 5.56 (s, 2 H), 7.11–7.18 (m, 2 H), 7.21–7.31 (m, 4 H), 7.37 (d, *J* = 8.2 Hz, 1 H), 7.38 (d, *J* = 5.5 Hz, 1 H), 7.46 (ddd, *J* = 8.4, 7.0, 1.0 Hz, 1 H), 7.47 (d, *J* = 5.5 Hz, 1 H), 7.60 (s, 1 H), 8.31 (d, *J* = 7.8 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 19.0, 46.6, 99.8, 108.3, 119.1, 120.4, 122.7, 123.1, 124.4, 125.7, 126.3, 126.4, 126.5, 127.4, 128.8, 133.0, 137.1, 137.9, 140.3, 142.0. HRMS (FD) Calcd for $C_{22}H_{17}NS$: M, 327.1082. Found: *m*/*z* 327.1126.



11,12-Dimethyl-11*H*-benzothieno[3,2-*b*]carbazole (3j). The title compound was isolated by column chromatography on silica gel (hexane/EtOAc = 30/1). A white solid, mp 234–235 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.36 (s, 3 H), 4.17 (s, 3 H), 7.23–7.28 (m, 1 H), 7.41 (d, *J* = 8.2 Hz, 1 H), 7.43–7.50 (m, 2 H), 7.52 (ddd, *J* = 8.2,

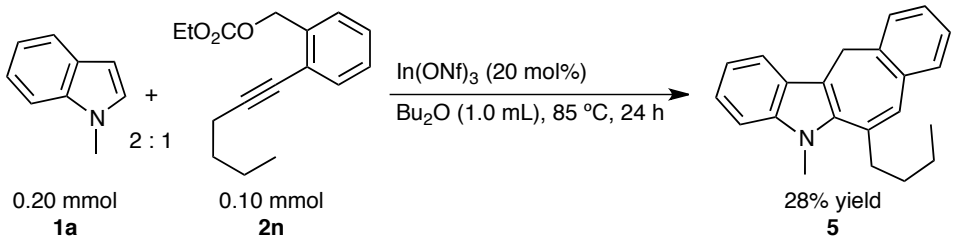
6.9, 0.9 Hz, 1 H), 7.84–7.93 (m, 1 H), 8.11 (d, *J* = 7.3 Hz, 1 H), 8.37 (s, 1 H), 8.43–8.49 (m, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 17.9, 34.7, 109.0, 111.2, 117.4, 119.2, 120.2, 122.2, 122.9, 123.7, 124.5, 125.4, 125.5, 126.5, 131.5, 133.4, 137.0, 140.2, 140.5, 144.3. HRMS (FD) Calcd for $C_{20}H_{15}NS$: M, 301.0925. Found: *m*/*z* 301.0956.



6,7,12-Trimethyl-7*H*-benzofuro[2,3-*b*]carbazole (3k). The title compound was isolated by recycling GPC after column chromatography on silica gel (hexane/EtOAc = 40/1). A white solid, mp 210–211 °C (decomp.). ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.02 (s, 3 H), 3.26 (s, 3 H), 4.16 (s, 3 H), 7.24–7.30 (m, 1 H), 7.34 (td, *J* = 7.3, 1.4 Hz, 1 H), 7.36–7.43 (m, 2 H), 7.48 (ddd, *J* = 8.2, 6.9, 0.9 Hz, 1 H), 7.58 (dd, *J* = 7.8, 0.9 Hz, 1 H), 8.16 (dd, *J* = 7.8, 0.9 Hz, 1 H), 8.31 (d, *J* = 7.8 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 11.7, 17.0, 32.5, 100.2, 108.2, 111.0, 116.1, 119.0, 119.2, 121.7, 122.2, 122.3, 123.8, 124.5, 125.1, 125.5, 126.1, 139.9, 142.6, 154.9, 156.3. HRMS (FD) Calcd for $C_{21}H_{17}NO$: M, 299.1310. Found: *m*/*z* 299.1345.

6,11,12-Trimethyl-11*H*-benzofuro[3,2-*b*]carbazole (4k). The title compound was isolated by recycling GPC and HPLC after column chromatography on silica gel (hexane/EtOAc = 40/1). A white solid, mp 230–231 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.08 (s, 3 H), 3.27 (s, 3 H), 4.19 (s, 3 H), 7.23–7.28 (m, 1 H), 7.35 (td, *J* = 7.6, 0.9 Hz, 1 H), 7.39–7.55 (m, 3 H), 7.62 (dd, *J* = 8.2, 0.9 Hz, 1 H), 8.18 (d, *J* = 7.8 Hz, 1 H), 8.29 (d, *J* = 7.8 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.9, 16.0, 33.8, 108.5, 111.4, 111.7, 112.5, 118.7, 119.0, 121.9, 122.5, 122.6, 122.7, 123.8, 125.4, 126.1, 126.2, 127.5, 137.4, 143.6, 156.9. HRMS (FD) Calcd for $C_{21}H_{17}NO$: M, 299.1310. Found: *m*/*z* 299.1345.

Indium-Catalyzed Annulation of *N*-Methylindole with Ethyl 2-(Hexyn-1-yl)benzyl Carbonate



6-Butyl-5,12-dihydro-5-methyl-benzo[4,5]cyclohept[1,2-*b*]indole (5). The title compound was synthesized by the procedure described in section **III** and isolated in 28% yield by recycling GPC and HPLC after column chromatography on silica gel (hexane/EtOAc = 10/1). A colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.88 (t, *J* = 7.3 Hz, 3 H), 1.35 (sext, *J* = 7.3 Hz, 2 H), 2.85 (t, *J* = 7.3 Hz, 2 H), 2.59–3.10 (m, 2 H), 3.70 (bs 2 H), 3.72 (s, 3 H), 7.08 (s, 1 H), 7.10–7.16 (m, 2 H), 7.16–7.29 (m, 5 H), 7.72 (d, *J* = 7.8 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.9, 22.2, 30.3, 31.9, 32.4, 37.1, 109.2, 116.8, 118.2, 119.1, 121.9, 125.3, 125.6, 127.1, 127.8, 128.5, 130.8, 134.8, 134.9, 135.7, 139.6, 140.3. HRMS (FD) Calcd for $C_{22}H_{23}N$: M, 301.1830. Found: *m*/*z* 301.1852.

IV-4. References and Notes

1 For selected recent reviews, see: a) Knölker, H.-J.; Reddy, K. R. *Chem. Rev.* **2002**, *102*, 4303. b) Prudhomme, M. *Eur. J. Med. Chem.* **2003**, *38*, 123. c) Prudhomme, M. *Curr. Med. Chem.: Anti-Cancer Agents* **2004**, *4*, 509. d) Agarwal, S.; Cämmerer, S.; Filali, S.; Fröhner, W.; Knöll, J.; Krahl, M. P.; Reddy, K. R.; Knölker, H.-J. *Curr. Org. Chem.* **2005**, *9*, 1601. e) Bellina, F.; Rossi, R. *Tetrahedron* **2006**, *62*, 7213. f) Janosik, T.; Wahlström, N.; Bergman, J. *Tetrahedron* **2008**, *64*, 9159. g) Nakano, H.; Omura, S. *J. Antibiot.* **2009**, *62*, 17. h) Schmidt, A. W.; Reddy, K. R.; Knölker, H.-J. *Chem. Rev.* **2012**, *112*, 3193.

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4 Nagase, Y.; Shirai, H.; Kaneko, M.; Shirakawa, E.; Tsuchimoto, T. *Org. Biomol. Chem.* **2013**, *11*, 1456.

5 For Brown's and Eastwood's method capable of providing one [*a*]-type, one [*b*]-type and one [*c*]-type on phenyl-annulated carbazoles, see: Brown, R. F. C.; Couston, K. J.; Eastwood, F. W.; Moffat, M. R. *Tetrahedron* **1992**, *48*, 7763.

6 For Martin's and Rossi's method capable of providing one [*a*,*c*]-type, one [*b*]-type and one [*c*]-type on phenyl-annulated carbazoles, see: Budén, M. E.; Vaillard, V. A.; Martin, S. E.; Rossi, R. A. *J. Org. Chem.* **2009**, *74*, 4490.

7 For Nagarajan's method capable of providing one [*a*]-type, two [*b*]-types and seven [*c*]-types on pyrido-annulated carbazoles, see: Viji, M.; Nagarajan, R. *Synthesis* **2012**, *44*, 253.

8 His method can offer twenty-three [*a*]-types and seventeen [*c*]-types on (hetero)aryl-annulated carbazoles. See references 3 and 4.

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10 Results on the effect of other Lewis acid catalysts examined under the conditions shown in entry 8 are as follows: $In(OTf)_3$ (21%, 85:15), $In(NTf_2)_3$ (29%, 69:31), $Fe(OTf)_3$ (<1%), $Zn(OTf)_2$ (<1%), $Bi(OTf)_3$ (<1%). Tf = SO_2CF_3.

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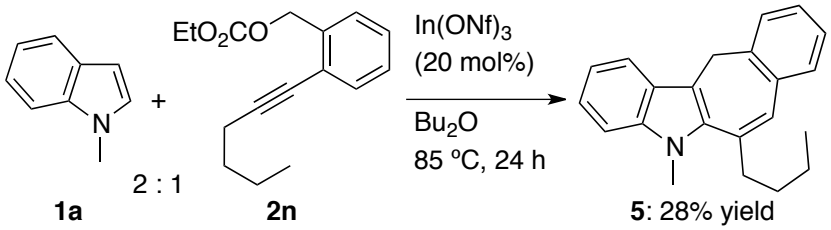

He will further study the scope of the seven-membered ring-forming annulation and report the result in due course.

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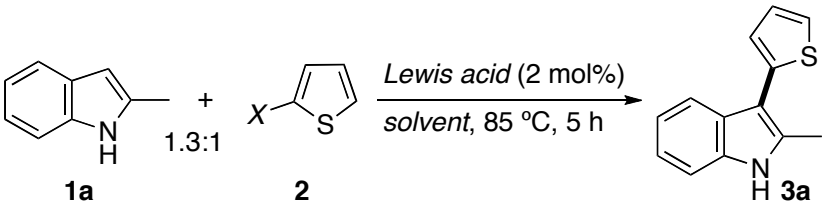
Chapter V. Indium-Catalyzed Heteroaryl–Heteroaryl Bond Formation through Nucleophilic Aromatic Substitution

V-1. Introduction

Heteroaromatic molecules bearing heteroaryl–heteroaryl bonds are an important class of building blocks found in a variety of aspects, for example, optoelectronic materials,[1] liquid crystals,[2] biological compounds[3] and also ligands for asymmetric catalysis.[4] Over the past 35 years, transition metal-catalyzed cross-coupling has been a chief contributor to offer (hetero)aryl–(hetero)aryl bonds,[5] but nucleophilic aromatic substitution (S_NAr) has actually been studied to construct such biaryl linkages for a longer period.[6] However, aromatic compounds, which are intrinsically electron-rich, are in general unreactive toward nucleophilic substitution.[7] Therefore, two aryl substrates with entirely opposite electronic demands must be arranged to realize biaryl synthesis by the S_NAr reaction. Thus, electron-rich aryl nucleophiles with highly electropositive metals (e.g., Li^+, Mg^{2+}, Zn^{2+}) and/or electron-poor aryl electrophiles with one or more strong electron-withdrawing groups (EWGs, e.g., CF_3, NO_2, CN, CO_2R) have been each aryl substrate of choice.[8] Over a stoichiometric amount of promoters also is often necessary.[8c,8p,8q] These requisites may have limited the widespread applicability of the S_NAr-based biaryl synthesis. The author envisioned that catalytic biaryl synthesis by S_NAr reaction independent of such two activated aryl substrates would be an attractive alternative to the transition metal-catalyzed cross-coupling strategy. Herein he thus reports the first example of catalytic S_NAr-based heteroaryl–heteroaryl bond forming reaction without using both heteroarylmetal nucleophiles and EWG-substituted heteroaryl electrophiles.

V-2. Results & Discussion

Initially, the author studied the effect of leaving groups *X* in thiophene derivatives **2** as electrophiles in the indium-catalyzed reaction of 2-methylindole (**1a**) as a nucleophile [Eq. 1, Table 1]. On treatment of **1a** and **2** bearing halides (*X* = I, Br, Cl) with 2 mol% of $In(OTf)_3$ (Tf = SO_2CF_3) in 1,4-dioxane at 85 °C for 5 h, no desired reaction occurred. None of nitro and cyano groups, which often behave as leaving groups in S_NAr reaction, also worked at all. In sharp contrast, **2a** with methoxy group accepted **1a** to give thienylindole **3a** in 35% yield, while the related oxygen-based leaving groups such as OAc (Ac = acetyl) and OTf were disappointing, despite their better leaving ability in general than OMe.[9] Next, he tested other solvents in the reaction of **1a** with **2a** [Eq. 1, Table 2]. The ethereal solvent, DME, similar to 1,4-dioxane was efficient, while others made the reaction sluggish. After subsequent thorough investigations on a co-solvent for 1,4-dioxane and DME, he was pleased to find that the yield of **3a** was markedly increased to 80% in the mixed solvent, consisting of 1,4-dioxane and toluene. Other indium salts as well as metal triflates were less or no effective [Eq. 1, Table 3]. No reaction occurred without a catalyst. With $In(OTf)_3$ as a catalyst, the fine-tuning of the solvent volume finally raised the yield up to 86%. The results in Table 3 might indicate that Lewis acids consisting of a rather soft metal and strong electron-withdrawing ligands tend to be favorable as catalysts, due to the lower catalytic activity of the hard Lewis acids with strong electron-withdrawing ligands such as Sc-, Y- and $Yb(OTf)_3$ and of the soft Lewis acid with weaker electron-withdrawing ones like $InCl_3$.[10] Noteworthy is that **3a** is accessible in one-step from **1a** and **2a** as commercial sources because pre-synthesis of heteroarylmetal nucleophiles and EWG-substituted heteroaryl electrophiles is not required.



1a **2** **3a**

Table 1.[b]

X	conv. [%] of **2**[c]	yield [%] of **3a**[d]
I	3	<1
Br	2	<1
Cl	5	<1
NO_2	9	<1
CN	5	<1
OMe (**2a**)	99	35
OAc	24	<1
OTf	>99	<1

Table 2.[e]

solvent	conv. [%] of **2a**[c]	yield [%] of **3a**[d]
1,4-dioxane	99	35
$(CH_2OCH_3)_2$ (DME)	71	53
CH_3CH_2CN	44	25
$ClCH_2CH_2Cl$	36	21
PhCl	10	2
$PhCH_3$	12	8
1,4-dioxane/$PhCH_3$[f]	99	80
DME/$PhCH_3$[f]	95	73

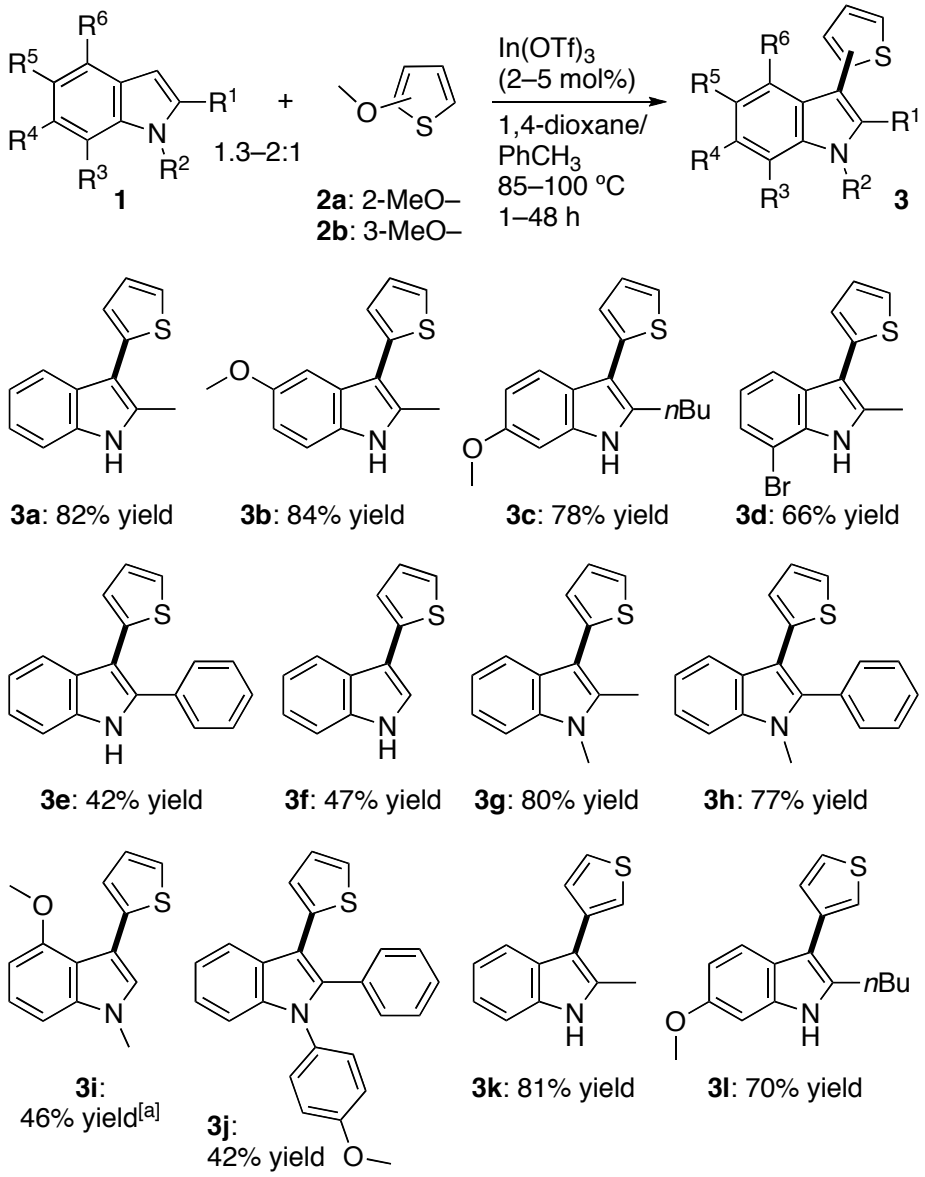
Table 3.[g]

Lewis acid	conv. [%] of **2a**[c]	yield [%] of **3a**[d]	*Lewis acid*	conv. [%] of **2a**[c]	yield [%] of **3a**[d]
$In(OTf)_3$	99	80	$Bi(OTf)_3$	98	73
$In(ONf)_3$[h]	>99	74	$Sc(OTf)_3$	45	18
$In(NTf_2)_3$	38	18	$Y(OTf)_3$	13	4
$InCl_3$	<1	<1	$Yb(OTf)_3$	24	8
$Cu(OTf)_2$	81	59	none	<1	<1
AgOTf	99	73	$In(OTf)_3$	>99[i]	86[i]

[a] **1a** (0.325 mmol), **2** (0.250 mmol), *Lewis acid* (5.00 μmol), *solvent* (1.0 mL). [b] *Solvent* = 1,4-dioxane, *Lewis acid* = $In(OTf)_3$. [c] Determined by GC. [d] Determined by ^1H NMR. [e] *X* = OMe, *Lewis acid* = $In(OTf)_3$. [f] The major solvent (1.0 mL)/$PhCH_3$ (40 μL) = 25/1. [g] *X* = OMe, *solvent* = 1,4-dioxane/$PhCH_3$ (25/1). [h] Nf = $SO_2C_4F_9$. [i] The number was obtained by carried out in 1,4-dioxane (0.5 mL)/$PhCH_3$ (40 μL) (12.5/1).

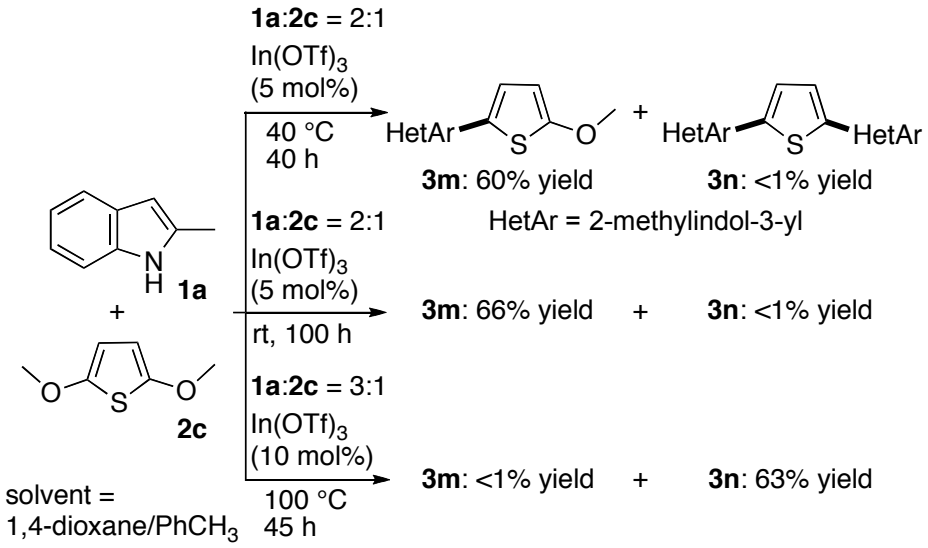
The author next examined the substrate scope. As shown in Scheme 1, indoles **1** with Me, *n*Bu OMe, Br, Ph and/or C_6H_4–*p*-OMe kicked out the OMe from **2a** to afford **3b**–**3j** in moderate to high yields, where 1,2,3-triarylindole **3j** with the fully extended π-conjugation system is included. The OMe groups on indole substrates were intact, thus showing remarkable chemoselectivities (see, **3b**, **3c**, **3i**, **3j** and **3l**). 3-Methoxythiophene (**2b**) also accepted **1** successfully, giving **3k** and **3l**. Even more electron-rich 2,5-dimethoxythiophene (**2c**) than **2a** participated well in this strategy (Scheme 2). The interesting aspect is that a proper choice of the reaction conditions enables exclusive access to either the single or double substitution, leading to **3m** or **3n**,

respectively.[11] The single substitution proceeded even at room temperature in a higher yield. Potentially useful tetraheteroaryl **3o** was obtained directly by the double substitution of dimethoxybithiophene **2d** with indole **1b** [Eq. 2].

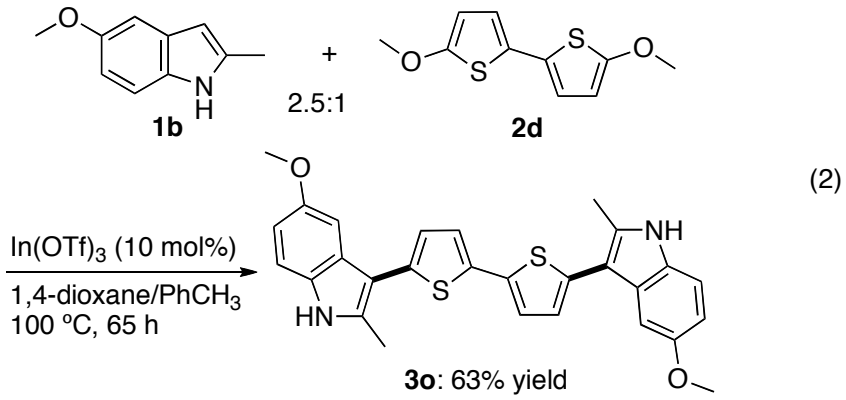


Scheme 1. Indium-catalyzed S_NAr reaction of various indoles **1** with **2a** or **2b**

Further details on reaction conditions for each reaction are provided in Experimental section. [a] $In(ONf)_3$ (10 mol%) instead of $In(OTf)_3$ was used as a catalyst.

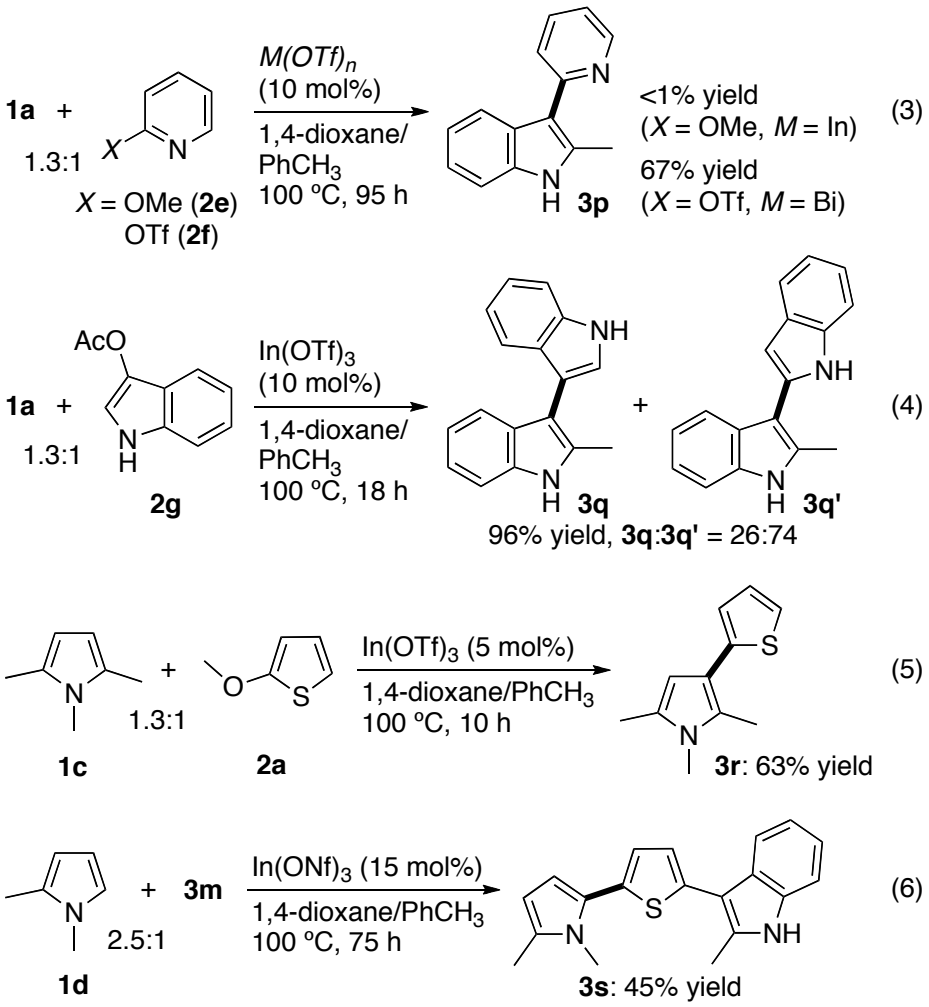


Scheme 2. Indium-catalyzed S_NAr reaction of **1a** with **2c**

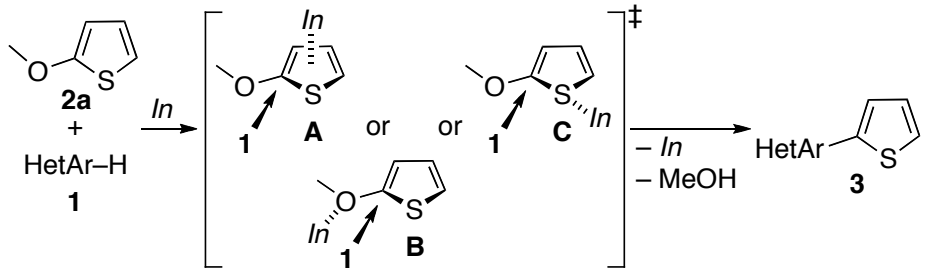


(2)

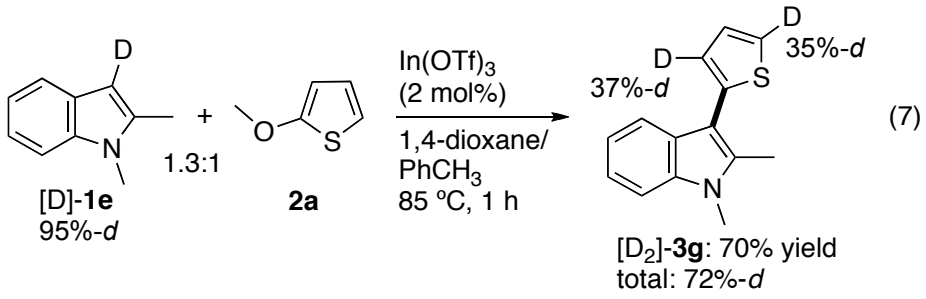
As well as thienylindoles, the strategy is applicable to synthesis of other bi- and triheteroaryls. While the $In(OTf)_3$-catalyzed reaction of **1a** with **2e** bearing OMe delivered no desired product, replacing **2e** with **2f** having OTf and also $In(OTf)_3$ with $Bi(OTf)_3$ altered the result drastically, giving pyridylindole **3p** in 67% yield [Eq. 3]. 3-Acetoxyindole (**2g**) is an excellent electrophile in terms of the reaction efficiency, but unfortunately not the regiochemistry [Eq. 4].[12] He then turned his attention toward other heteroaryl nucleophiles and found that pyrroles **1c** and **1d** work well, similarly as indoles [Eqs. 5 and 6]. As Eq. 6 shows, the substitution of OMe in **3m**, which has been prepared in Scheme 2, with 1,2-dimethylpyrrole (**1d**) provided triheteroaryl **3s**, connected regularly in the order of pyrrole, thiophene and indole rings. In this case, $In(ONf)_3$ was a superior catalyst to its triflate salt.[13]



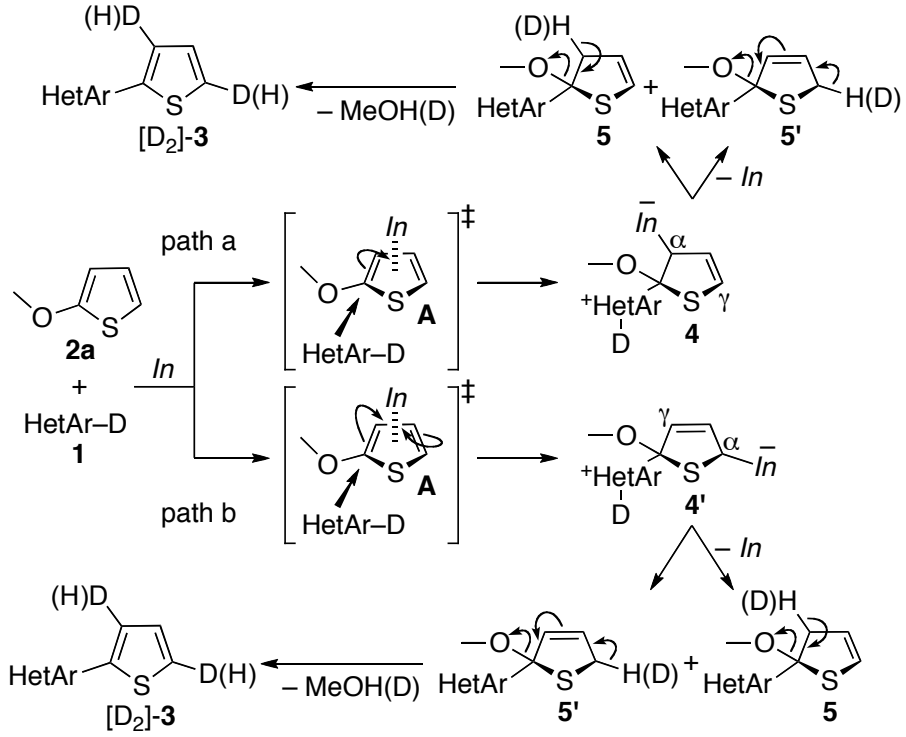
A possible reaction route is roughly depicted in Scheme 3, which exemplifies the reaction of **2a** with HetAr–H **1**. At least, three coordination modes of **2a** to InX_3 (*In*), i.e., **A**, **B** and **C**, appear to be possible as triggers of this reaction. To gain insight into the detail, he performed the reaction of deuterium-labeled indole [D]-**1e** (95%-*d*) with **2a** under the standard conditions [Eq. 7]. The reaction gave [D_2]-**3g** incorporating deuterium atoms on the C3' and C5' of the thiophene ring with 72% total D-content. This observation suggests that a carbon–indium bond trapped by D^+ is formed during the reaction. Complex **A** in which the carbon atoms of **2a** coordinate directly to the *In* thus appears to be the most plausible, as also well demonstrated in the S_NAr reaction via transition metal–arene π-complexes.[14] Heteroaryl rings with higher π-electron density are thought to be more favorable for complexation with an electrophilic *In*(III),[15] thereby activated more efficiently. Accordingly, the both facts that **2c** with two methoxy groups is much more reactive than **2a** and that thiophenes **2** with electron-withdrawing leaving groups (halides, NO_2, CN, OAc, OTf) are inactive also supports the validity of complex **A** (Schemes 1 and 2, and Table 1).



Scheme 3. A possible reaction route through **A**, **B** or **C**



Taking the above into consideration, possible mechanisms are shown in Scheme 4, which is depicted as the reaction of **2a** and HetAr–D **1**.[16] Although which route of path a or b mainly operates is unclear at present, allylindium type intermediates **4** and/or **4'** would be formed first via the nucleophilic attack of **1** to complex **A**, in which the *In* moiety can be regarded as a tentative EWG to make **2a** electrophilic enough.[17] Subsequent D atom transfer from the $HetAr^{+}$–D to the α- and γ-sites in the allylindium unit would give **5** and **5'**.[18] The elimination of MeOH(D) for the re-aromatization would lead to [D_2]-**3**. The 23% loss of the D atom (95%-*d* of [D]-**1e** to 72%-*d* of [D_2]-**3g**) should be ascribed to the final step in which both MeOH and MeOD can eliminate.

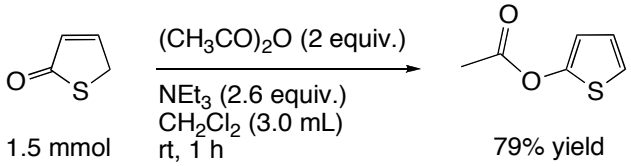


Scheme 4. Possible reaction mechanisms

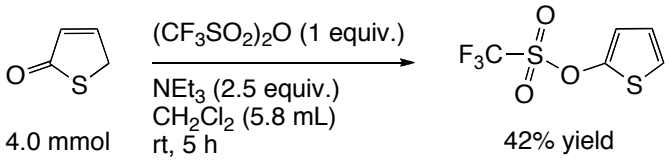
V-3. Experimental

General Remarks. All manipulations were conducted with a standard Schlenk technique under an argon atmosphere. Nuclear magnetic resonance (NMR) spectra were taken on a JEOL JMN-ECA 400 (^{1}H, 400 MHz; ^{13}C, 100 MHz) or a JEOL JMN-ECA 500 (^{1}H, 500 MHz; ^{13}C, 125 MHz) spectrometer using tetramethylsilane as an internal standard. ^{2}H NMR spectral data were recorded at 61 MHz using a JEOL JMN-ECA 400 and chemical shifts are reported relative to $CDCl_3$ (7.26 ppm) as an internal standard. Analytical gas chromatography (GC) was performed on a Shimadzu model GC-17A or GC-2014 instrument equipped with a capillary column of ENV-5MS (5% phenyl polysilphenylene-siloxane, 30 m x 0.25 mm x 0.25 μm) using nitrogen as carrier gas. Preparative recycling high-performance liquid chromatography (HPLC) was performed with JAI LC-9104 equipped with a JAIGEL-GS320 column using a mixture of hexane–ethyl acetate (EtOAc) as eluent. Preparative recycling gel permeation chromatography (GPC) was performed with JAI LC-9105 equipped with JAIGEL-1H and JAIGEL-2H columns using chloroform as eluent. High-resolution mass spectra (HRMS) were obtained with a Mariner spectrometer. All melting points were measured with a Yanaco Micro Melting Point apparatus and uncorrected. Unless otherwise noted, reagents were commercially available and used as received without further purification. 1,4-Dioxane was distilled under argon from sodium just prior to use. Chlorobenzene (PhCl) and dichloromethane (CH_2Cl_2) were distilled under argon from calcium chloride just prior to use. Triethylamine was stored over potassium hydroxide pellets. $In(OTf)_3$ (Tf = SO_2CF_3) was purchased from Aldrich Chemical Co. $In(ONf)_3$[19] (Nf = $SO_2C_4F_9$) and $In(NTf_2)_3$[20] were prepared according to the respective reported procedures. 2-*n*-Butyl-6-methoxy-1*H*-indole, [21] 1-(4-Methoxyphenyl)-2-phenyl-1*H*-indole,[22] 1,2-dimethylpyrrole (**1d**),[23] 2,5-dimethoxythiophene (**2c**)[24] and 3-deuterium-1,2-dimethylindole ([D]-**1e**) [25] were prepared according to the respective literature procedures.

Synthesis of Starting Substrates

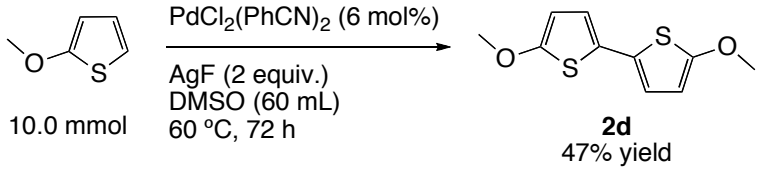


Synthesis of 2-Thienyl Acetate. Under an argon atmosphere, 2(5*H*)-thiophenone (154.7 mg, 1.500 mmol), acetic anhydride (310.3 mg, 3.100 mmol), triethylamine (388.5 mg, 3.900 mmol) and CH_2Cl_2 (3.0 mL) were placed in a 20 mL Schlenk tube, which was stirred at room temperature for 1 h. To this was added 1% aqueous HCl solution (2 mL), and the aqueous phase was extracted with CH_2Cl_2 (8 mL x 3). The combined organic layer was washed with water (3 mL) and brine (3 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel using hexane–CH_2Cl_2 (4/1) gave 2-thienyl acetate (175.1 mg, 79% yield) as a colorless oil. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.31 (s, 3 H), 6.69 (dd, *J* = 4.1, 1.7 Hz, 1 H), 6.82 (dd, *J* = 6.0, 3.7 Hz, 1 H), 6.88 (dd, *J* = 5.8, 1.7 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 20.7, 113.3, 118.0, 123.3, 151.9, 167.5. HRMS (ESI) Calcd for $C_6H_7O_2S$: M^++H, 143.0161. Found: *m/z* 143.0191.



Synthesis of 2-Thienyl Trifluoromethanesulfonate.[26] The title compound was prepared according to the following modified literature procedure.[6] Under an argon atmosphere, 2(5*H*)-thiophenone (0.40 g, 4.0 mmol), trifluoromethanesulfonic anhydride (1.12 g, 4.00 mmol), triethylamine (1.01 g, 10.0 mmol) and CH_2Cl_2 (5.8 mL) were placed in a 50 mL Schlenk tube, which was stirred at room temperature for 5 h. To this was added 1% aqueous HCl solution (6 mL), and the aqueous phase was extracted with CH_2Cl_2 (20 mL x 3). The combined organic layer was washed with water (10 mL) and brine (10 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel using hexane gave 2-thienyl trifluoromethanesulfonate (396.5 mg, 42% yield) as a colorless

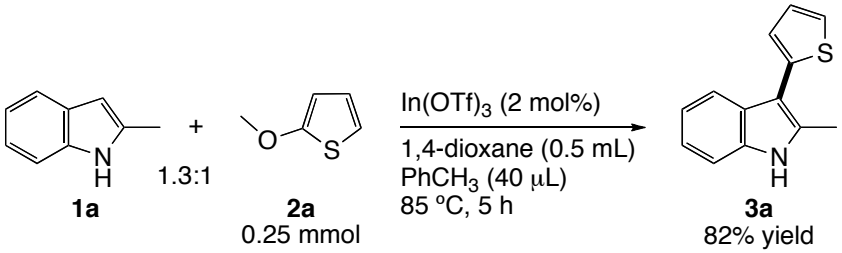
oil. Spectral and analytical data of 2-thienyl trifluoromethanesulfonate are reported in reference 7. Therefore, only ^{1}H NMR data are presented here. ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.87 (dd, *J* = 5.8, 4.0 Hz, 1 H), 6.90 (dd, *J* = 4.0, 1.7 Hz, 1 H), 7.05 (dd, *J* = 5.7, 1.7 Hz, 1 H).



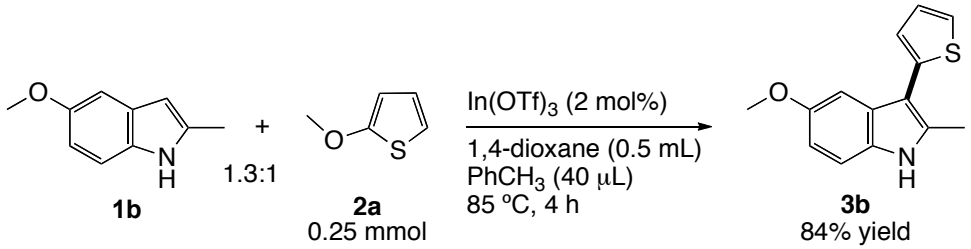
Synthesis of 5,5'-Dimethoxy-2,2'-bithiophene (2d). The title compound was prepared by the literature method.[27] $PdCl_2(PhCN)_2$ (0.23 g, 0.60 mmol), 2-methoxythiophene (1.19 g, 10.0 mmol) and DMSO (60.0 mL) were placed in a Schlenk tube. To this was added silver(I) fluoride (2.64 g, 20.0 mmol), and the resulting mixture was stirred at 60 °C for 72 h. The resulting mixture was cooled to room temperature and passed through a pad of Celite, which was successively washed well with $CHCl_3$. The filtrate was washed with water (60 mL) and the aqueous layer was extracted with $CHCl_3$ (100 mL x 3). The combined organic layer was dried over anhydrous sodium sulfate and then concentrated under reduced pressure to leave a crude product. Purification by column chromatography on silica gel using hexane–EtOAc (30/1) gave 5,5'-dimethoxy-2,2'-bithiophene (564.5 mg, 47% yield). A white solid, mp 84–85 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.88 (s, 6 H), 6.07 (d, *J* = 4.0 Hz, 2 H), 6.61 (d, *J* = 4.0 Hz, 2 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 60.3, 104.2, 119.9, 124.4, 164.7. HRMS (ESI) Calcd for $C_{10}H_{10}O_2S_2$: M^+, 226.0117. Found: *m*/*z* 226.0105.

Catalytic Heteroaryl–Heteroaryl Bond Formation through Nucleophilic Aromatic Substitution.

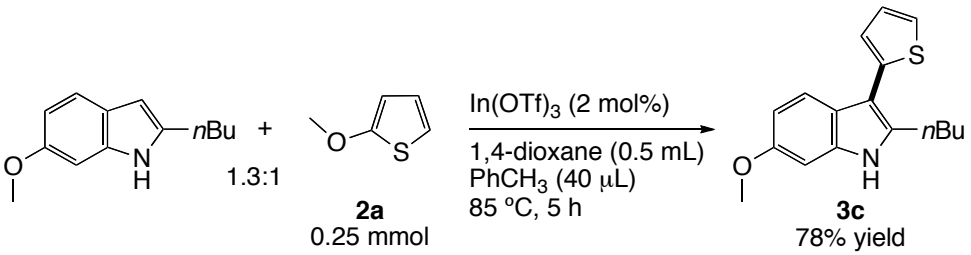
A General Procedure. $In(OTf)_3$ [(2.8 mg, 5.0 μmol), (7.00 mg, 12.5 μmol) or (14.0 mg, 25.0 μmol)], $Bi(OTf)_3$ (16.4 mg, 25.0 μmol) or $In(ONf)_3$ (37.9 mg, 37.5 μmol) was placed in a 20 mL Schlenk tube, which was heated at 150 °C in vacuo for 2 h. The tube was cooled down to room temperature and filled with argon. 1,4-Dioxane (0.4 or 0.5 mL) and toluene (40 μL) were added to the tube, and the resulting solution was stirred at room temperature for 10 min. To this were added **1** (0.325–0.750 mmol) and **2** (0.250–0.400 mmol) successively, and the resulting mixture was stirred at room temperature, 40, 85 or 100 °C for 4–100 h. A saturated $NaHCO_3$ aqueous solution (0.5 mL) was added to the mixture, and the aqueous phase was extracted with EtOAc (5 mL x 3). The combined organic layer was washed with brine (2.0 mL) and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel using hexane–EtOAc as eluent gave the corresponding bi-, tri- or tetraheteroaryl **3**. The results are summarized in Schemes 1–2 and Eqs. (2)–(6). Compounds **3** synthesized according to the above procedure were fully characterized by ^1H NMR, ^{13}C NMR and HRMS spectroscopy as the following.



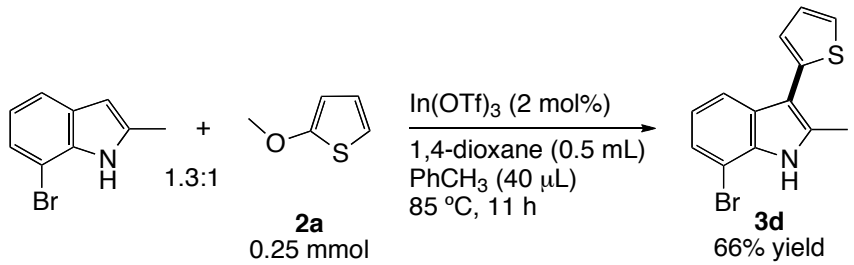
2-Methyl-3-(thiophen-2-yl)-1*H*-indole (3a). The title compound was obtained in 82% yield (45.6 mg) after isolation by column chromatography on silica gel (hexane/EtOAc = 6/1). A white solid, mp 80–81 °C. ^1H NMR (500 MHz, $CDCl_3$) δ 2.58 (s, 3 H), 7.12–7.21 (m, 4 H), 7.29–7.34 (m, 2 H), 7.82 (d, J = 7.5 Hz, 1 H), 7.98 (bs, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.0, 107.9, 110.3, 119.1, 120.3, 121.8, 123.4, 124.5, 127.2, 127.8, 132.4, 135.0, 137.2. HRMS (ESI) Calcd for $C_{13}H_{12}NS$: M^++H, 214.0685. Found: m/z 214.0690.



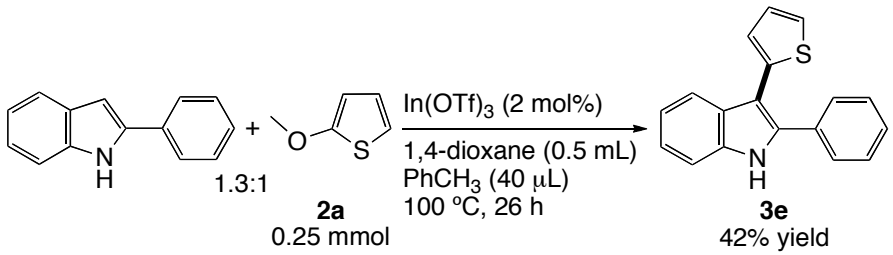
5-Methoxy-2-methyl-3-(thiophen-2-yl)-1*H*-indole (3b). The title compound was obtained in 84% yield (52.6 mg) after isolation by column chromatography on silica gel (hexane/EtOAc = 6/1). A white solid, mp 103–105 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.54 (s, 3 H), 3.85 (s, 3 H), 6.82 (dd, *J* = 8.6, 2.3 Hz, 1 H), 7.12 (dd, *J* = 3.4, 1.2 Hz, 1 H), 7.16 (dd, *J* = 5.2, 3.4 Hz, 1 H), 7.18 (d, *J* = 8.6 Hz, 1 H), 7.29 (d, *J* = 1.7 Hz, 1 H), 7.31 (d, *J* = 5.2 Hz, 1 H), 7.88 (bs, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.0, 55.9, 101.3, 107.8, 111.0, 111.6, 123.3, 124.4, 127.3, 128.2, 130.1, 133.3, 137.4, 154.7. HRMS (ESI) Calcd for $C_{14}H_{14}NOS$: M^++H, 244.0791. Found: *m*/*z* 244.0767.



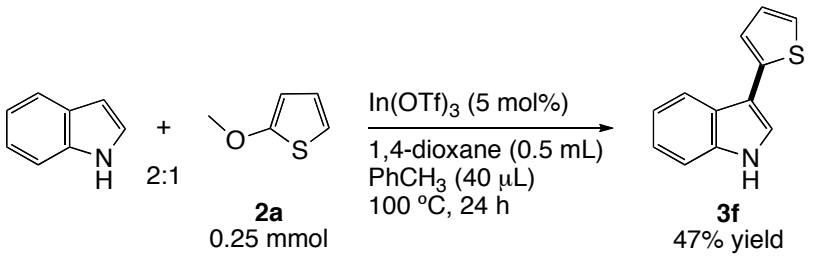
2-*n*-Butyl-6-methoxy-3-(thiophen-2-yl)-1*H*-indole (3c). The title compound was obtained in 78% yield (55.7 mg) after isolation by column chromatography on silica gel (hexane/EtOAc = 7/1). A white solid, mp 77–78 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.93 (t, *J* = 7.6 Hz, 3 H), 1.42 (sext, *J* = 7.4 Hz, 2 H), 1.63–1.75 (m, 2 H), 2.91 (t, *J* = 7.8 Hz, 2 H), 3.85 (s, 3 H), 6.81 (dd, *J* = 8.7, 2.3 Hz, 1 H), 6.84 (d, *J* = 2.3 Hz, 1 H), 7.08–7.16 (m, 2 H), 7.29 (dd, *J* = 5.0, 1.4 Hz, 1 H), 7.65 (d, *J* = 8.2 Hz, 1 H), 7.88 (bs, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.9, 22.5, 26.5, 32.0, 55.8, 94.5, 107.2, 109.5, 119.8, 122.3, 123.4, 124.5, 127.2, 135.8, 135.9, 137.2, 156.3. HRMS (ESI) Calcd for $C_{17}H_{20}NOS$: M^++H, 286.1260. Found: *m*/*z* 286.1265.



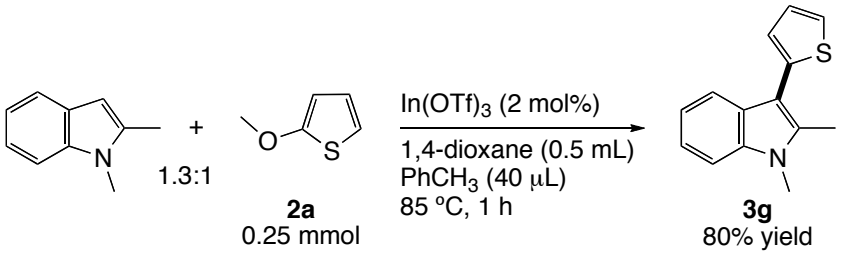
7-Bromo-2-methyl-3-(thiophen-2-yl)-1*H*-indole (3d). The title compound was obtained in 66% yield (50.5 mg) after isolation by column chromatography on silica gel (hexane/EtOAc = 20/1). A white solid, mp 92–93 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.58 (s, 3 H), 7.01 (t, *J* = 7.8 Hz, 1 H), 7.11 (dd, *J* = 3.2, 1.4 Hz, 1 H), 7.14 (dd, *J* = 5.3, 3.4 Hz, 1 H), 7.26–7.35 (m, 2 H), 7.72 (d, *J* = 7.8 Hz, 1 H), 8.15 (bs, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 13.0, 104.0, 109.1, 118.3, 121.4, 123.9, 124.1, 124.9, 127.3, 128.9, 133.2, 133.7, 136.6. HRMS (ESI) Calcd for $C_{13}H_{11}BrNS$: M^++H, 291.9790. Found: *m*/*z* 291.9776.



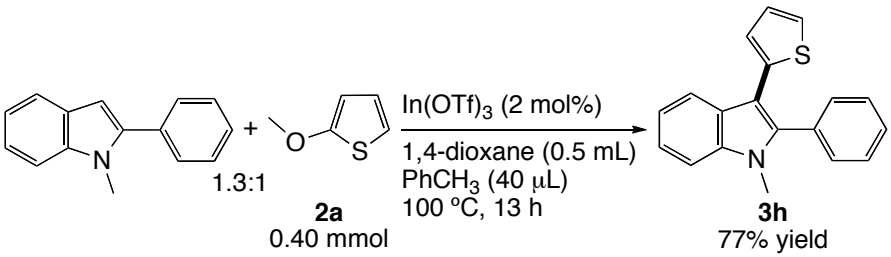
2-Phenyl-3-(thiophen-2-yl)-1*H*-indole (3e). The title compound was obtained in 42% yield (30.0 mg) after isolation by column chromatography on silica gel (hexane/EtOAc = 10/1) and subsequent further purification using recycling GPC. A white solid, mp 128–129 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.05 (dd, *J* = 3.4, 1.1 Hz, 1 H), 7.07 (dd, *J* = 5.2, 3.4 Hz, 1 H), 7.19 (ddd, *J* = 8.0, 6.9, 1.1 Hz, 1 H), 7.22–7.27 (m, 1 H), 7.29 (dd, *J* = 5.2, 1.2 Hz, 1 H), 7.31–7.39 (m, 3 H), 7.40 (d, *J* = 8.1 Hz, 1 H), 7.48–7.53 (m, 2 H), 7.79 (d, *J* = 7.5 Hz, 1 H), 8.22 (bs, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 108.0, 110.8, 119.9, 120.7, 122.9, 124.6, 126.2, 127.2, 128.1, 128.4, 128.7, 128.9, 132.3, 135.2, 135.6, 136.4. HRMS (ESI) Calcd for $C_{18}H_{14}NS$: M^++H, 276.0841. Found: *m*/*z* 276.0844.



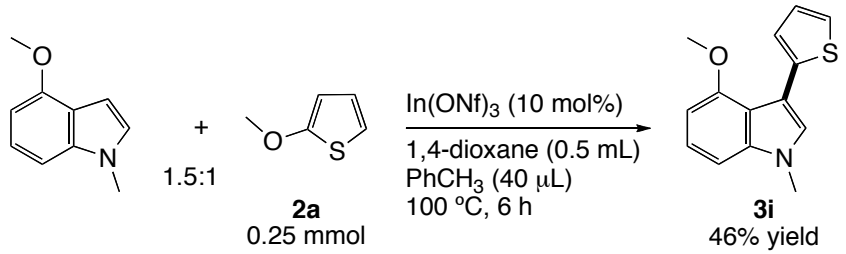
3-(Thiophen-2-yl)-1*H*-indole (3f). The title compound was obtained in 47% yield (24.3 mg) after isolation by column chromatography on silica gel (hexane/EtOAc = 10/1). A white solid, mp 91–92 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.12 (dd, *J* = 5.0, 3.6 Hz, 1 H), 7.18–7.28 (m, 3 H), 7.29 (dd, *J* = 3.6, 0.9 Hz, 1 H), 7.39–7.45 (m, 2 H), 7.98 (d, *J* = 7.8 Hz, 1 H), 8.19 (bs, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 111.4, 112.0, 120.0, 120.6, 121.8, 122.5, 122.6, 122.7, 125.5, 127.5, 136.4, 137.6. HRMS (ESI) Calcd for $C_{12}H_{10}NS$: M^++H, 200.0528. Found: *m*/*z* 200.0531.



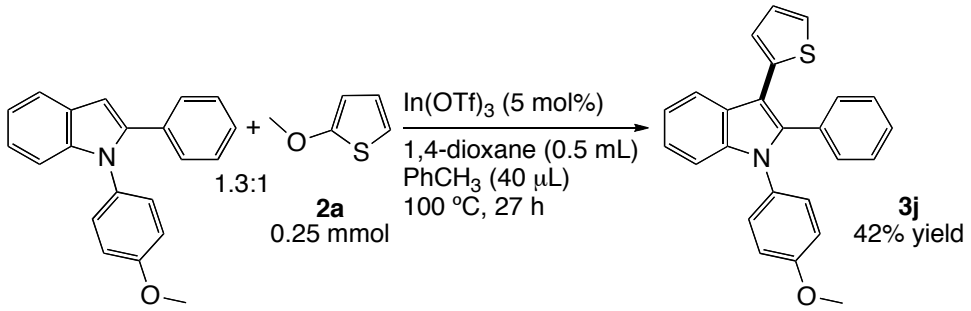
1,2-Dimethyl-3-(thiophen-2-yl)-1*H*-indole (3g). The title compound was obtained in 80% yield (45.4 mg) after isolation by column chromatography on silica gel (hexane/EtOAc = 30/1). A white solid, mp 92–93 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.56 (s, 3 H), 3.73 (s, 3 H), 7.09 (dd, *J* = 3.7, 0.9 Hz, 1 H), 7.11–7.18 (m, 2 H), 7.22 (ddd, *J* = 8.0, 7.1, 0.9 Hz, 1 H), 7.27–7.35 (m, 2 H), 7.80 (d, *J* = 7.8 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 11.3, 29.7, 107.1, 108.7, 118.9, 119.9, 121.4, 123.5, 124.8, 127.0, 127.2, 134.5, 136.5, 137.5. HRMS (ESI) Calcd for $C_{14}H_{14}NS$: M^++H, 228.0842. Found: *m*/*z* 228.0804.



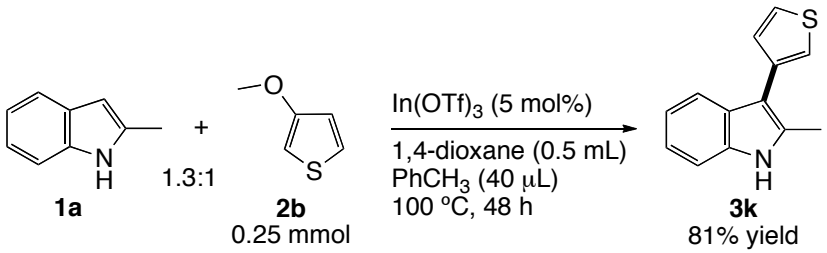
1-Methyl-2-phenyl-3-(thiophen-2-yl)-1*H*-indole (3h). The title compound was obtained in 77% yield (87.6 mg) after isolation by column chromatography on silica gel (hexane/EtOAc = 90/1) and subsequent further purification using recycling HPLC. A white solid, mp 100–101 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.60 (s, 3 H), 6.91 (dd, *J* = 3.4, 1.1 Hz, 1 H), 6.95 (dd, *J* = 5.0, 3.6 Hz, 1 H), 7.11 (dd, *J* = 5.0, 0.9 Hz, 1 H), 7.23 (ddd, *J* = 7.9, 6.8, 1.3 Hz, 1 H), 7.31 (ddd, *J* = 8.3, 6.9, 1.4 Hz, 1 H), 7.34–7.46 (m, 6 H), 7.95 (d, *J* = 7.8 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 30.9, 108.5, 109.5, 119.9, 120.5, 122.4, 123.3, 124.7, 126.7, 126.8, 128.5, 128.6, 131.2, 131.7, 137.0, 137.2, 138.3. HRMS (ESI) Calcd for $C_{19}H_{16}NS$: M^++H, 290.0998. Found: *m*/*z* 290.1017.



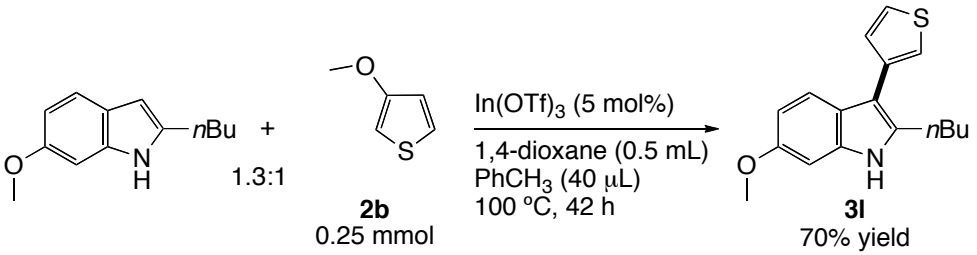
4-Methoxy-1-methyl-3-(thiophen-2-yl)-1*H*-indole (3i). The title compound was obtained in 46% yield (28.0 mg) after isolation by column chromatography on silica gel (hexane/EtOAc = 20/1). A white solid, mp 67–68 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.77 (s, 3 H), 3.90 (s, 3 H), 6.58 (d, *J* = 7.8 Hz, 1 H), 6.94 (d, *J* = 8.2 Hz, 1 H), 7.04 (dd, *J* = 5.0, 3.7 Hz, 1 H), 7.12 (s, 1 H), 7.14–7.22 (m, 2 H), 7.31 (d, *J* = 3.2 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 33.0, 55.1, 100.4, 102.8, 110.1, 115.7, 122.9, 123.0, 125.4, 126.9, 127.1, 138.1, 139.0, 154.5. HRMS (ESI) Calcd for $C_{14}H_{14}NOS$: M^++H, 224.0791. Found: *m*/*z* 224.0785.



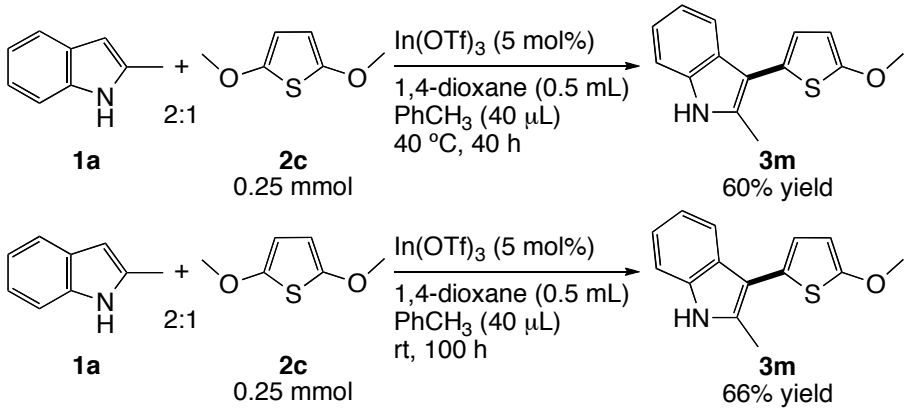
1-(4-Methoxyphenyl)-2-phenyl-3-(thiophen-2-yl)-1*H*-indole (3j). The title compound was obtained in 42% yield (42.3 mg) after isolation by column chromatography on silica gel (hexane/EtOAc = 30/1). A white solid, mp 190–191 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.81 (s, 3 H), 6.87 (dt, *J* = 9.2, 2.6 Hz, 2 H), 6.98 (dd, *J* = 3.5, 1.2 Hz, 1 H), 7.01 (dd, *J* = 4.9, 3.7 Hz, 1 H), 7.13 (dt, *J* = 9.2, 2.7 Hz, 2 H), 7.18–7.25 (m, 9 H), 7.92–7.97 (m, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 55.4, 109.5, 110.7, 114.3, 119.8, 121.0, 122.8, 124.0, 125.6, 126.9, 127.1, 127.8, 128.0, 129.4, 130.6, 131.35, 131.45, 136.8, 138.0, 138.1, 158.6. HRMS (ESI) Calcd for $C_{25}H_{20}NOS$: M^++H, 382.1260. Found: *m*/*z* 382.1292.



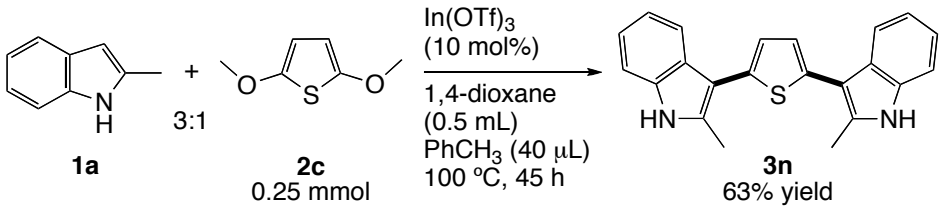
2-Methyl-3-(thiophen-3-yl)-1*H*-indole (3k). The title compound was obtained in 81% yield (45.2 mg) after isolation by column chromatography on silica gel (hexane/EtOAc = 6/1). A white solid, mp 79–80 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.53 (s, 3 H), 7.12 (td, *J* = 7.5, 1.2 Hz, 1 H), 7.17 (td, *J* = 7.4, 1.2 Hz, 1 H), 7.28 (dd, *J* = 3.2, 1.4 Hz, 1 H), 7.32 (dd, *J* = 8.0, 1.2 Hz, 1 H), 7.35 (dd, *J* = 4.6, 1.2 Hz, 1 H), 7.43 (dd, *J* = 5.2, 2.9 Hz, 1 H), 7.68 (d, *J* = 7.4 Hz, 1 H), 7.93 (bs, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 12.7, 109.7, 110.3, 118.9, 120.0, 120.7, 121.5, 125.1, 127.9, 128.5, 131.6, 135.1, 135.5. HRMS (ESI) Calcd for $C_{13}H_{12}NS$: M^++H, 214.0685. Found: *m*/*z* 214.0691.



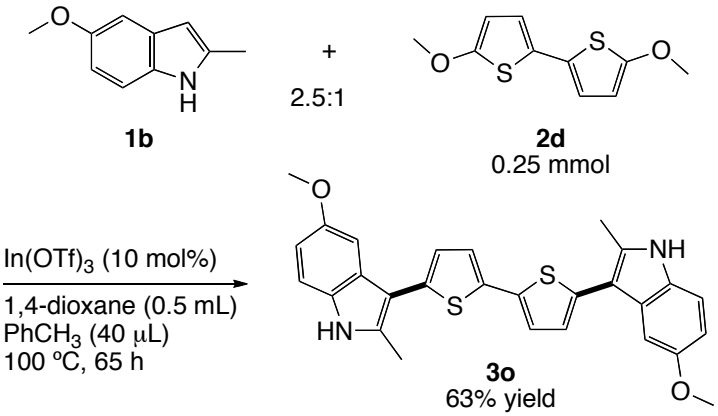
2-*n*-Butyl-6-methoxy-3-(thiophen-3-yl)-1*H*-indole (3l). The title compound was obtained in 70% yield (50.0 mg) after isolation by column chromatography on silica gel (hexane/EtOAc = 7/1). A white solid, mp 90–91 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.91 (t, *J* = 7.2 Hz, 3 H), 1.39 (sext, *J* = 7.5 Hz, 2 H), 1.61–1.70 (m, 2 H), 2.83 (t, *J* = 7.8 Hz, 2 H), 3.84 (s, 3 H), 6.78 (dd, *J* = 8.6, 2.3 Hz, 1 H), 6.83 (d, *J* = 1.7 Hz, 1 H), 7.24 (dd, *J* = 2.9, 1.1 Hz, 1 H), 7.29 (dd, *J* = 5.2, 1.2 Hz, 1 H), 7.41 (dd, *J* = 5.2, 2.9 Hz, 1 H), 7.52 (d, *J* = 8.6 Hz, 1 H), 7.83 (bs, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 13.9, 22.5, 26.4, 32.0, 55.8, 94.5, 109.1, 109.3, 119.6, 120.7, 122.4, 125.0, 128.7, 135.0, 135.6, 135.8, 156.1. HRMS (ESI) Calcd for $C_{17}H_{20}NOS$: M^++H, 286.1260. Found: *m*/*z* 286.1265.



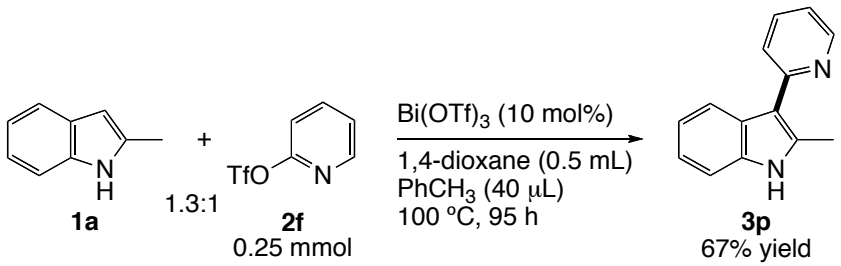
3-(5-Methoxythiophen-2-yl)-2-methyl-1*H*-indole (3m). The title compound was obtained in 60% yield (37.8 mg) or 66% yield (39.9 mg) after isolation by column chromatography on silica gel (hexane/EtOAc = 5/1). A white solid, mp 67–68 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.54 (s, 3 H), 3.94 (s, 3 H), 6.24 (d, *J* = 4.1 Hz, 1 H), 6.71 (d, *J* = 3.5 Hz, 1 H), 7.13 (td, *J* = 7.4, 1.5 Hz, 1 H), 7.16 (td, *J* = 7.3, 1.6 Hz, 1 H), 7.29 (dd, *J* = 6.9, 1.2 Hz, 1 H), 7.76 (d, *J* = 7.5 Hz, 1 H), 7.92 (bs, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.8, 60.2, 103.9, 108.0, 110.2, 119.0, 120.1, 121.7, 122.2, 123.4, 127.9, 132.3, 134.9, 164.9. HRMS (ESI) Calcd for $C_{14}H_{14}NOS$: M^++H, 244.0791. Found: *m*/*z* 244.0797.



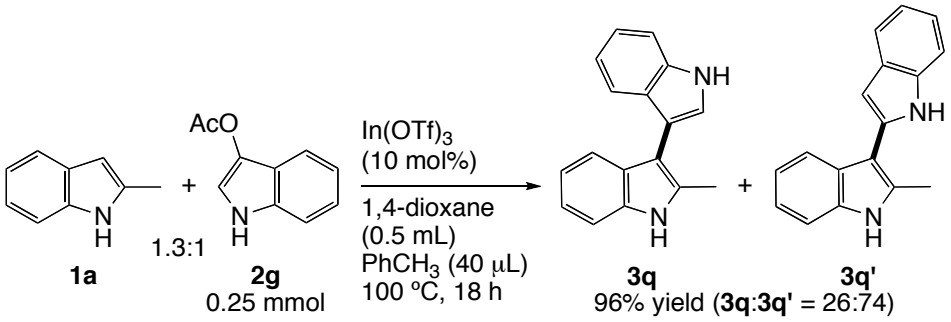
2,5-Bis(2-methyl-1*H*-indol-3-yl)thiophene (3n). The title compound was obtained in 63% yield (55.1 mg) after isolation by column chromatography on silica gel (hexane/EtOAc = 3/1). A white solid, mp 153–154 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.65 (s, 6 H), 7.11–7.22 (m, 6 H), 7.29–7.35 (m, 2 H), 7.89–7.95 (m, 2 H), 7.98 (bs, 2 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 13.2, 108.1, 110.3, 119.2, 120.2, 121.8, 124.7, 127.7, 132.2, 135.0, 135.2. HRMS (ESI) Calcd for $C_{22}H_{18}N_2S$: M^+, 342.1185. Found: *m*/*z* 342.1192.



5,5'-Bis(5-methoxy-2-methyl-1*H*-indol-3-yl)-2,2'-bithiophene (3o). The title compound was obtained in 63% yield (78.9 mg) after isolation by column chromatography on silica gel (hexane/EtOAc = 1.5/1). A yellow solid, mp 218–219 °C. ^{1}H NMR (500 MHz, acetone-d_6) δ 2.63 (s, 6 H), 3.84 (s, 6 H), 6.79 (dd, *J* = 8.9, 2.6 Hz, 2 H), 7.13 (d, *J* = 3.5 Hz, 2 H), 7.28 (d, *J* = 8.6 Hz, 2 H), 7.32 (d, *J* = 4.0 Hz, 2 H), 7.35 (d, *J* = 2.3 Hz, 2 H), 10.29 (bs, 2 H); ^{13}C NMR (100 MHz, acetone-d_6) δ 13.3, 55.9, 101.7, 107.5, 111.9, 112.3, 124.3, 125.4, 128.7, 131.5, 135.0, 135.5, 137.9, 155.7. HRMS (ESI) Calcd for $C_{28}H_{24}N_2O_2S_2$: M^+, 484.1274. Found: *m*/*z* 484.1247.



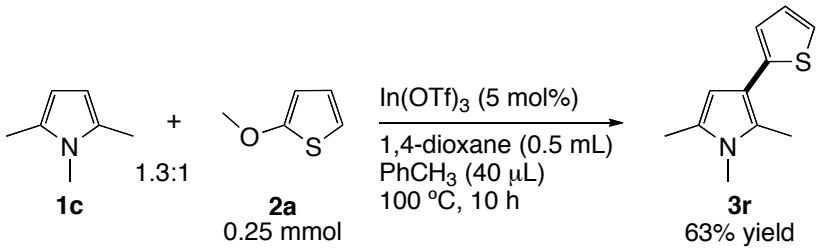
2-Methyl-3-(pyridin-2-yl)-1*H*-indole (3p). The title compound was obtained in 67% yield (35.3 mg) after isolation by column chromatography on silica gel (hexane/EtOAc = 1.5/1). A white solid, mp 133–134 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.68 (s, 3 H), 7.11–7.20 (m, 3 H), 7.30–7.35 (m, 1 H), 7.59 (d, *J* = 7.5 Hz, 1 H), 7.74 (td, *J* = 7.7, 2.1 Hz, 1 H), 7.90–7.95 (m, 1 H), 8.12 (bs, 1 H), 8.68–8.76 (m, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 13.2, 110.4, 113.5, 119.2, 120.0, 120.4, 121.6, 123.2, 127.3, 134.6, 135.2, 136.1, 149.5, 155.4. HRMS (ESI) Calcd for $C_{14}H_{13}N_2$: M^++H, 209.1073. Found: *m/z* 209.1061.



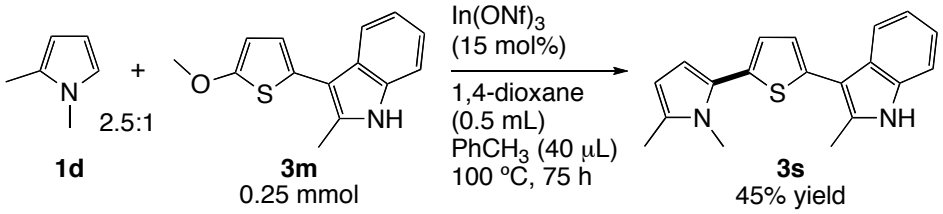
2-Methyl-1*H*,1'*H*-3,3'-biindole (3q). A mixture of **3q** and **3q'** was obtained in 96% yield (59.9 mg) after isolation by column chromatography on silica gel (hexane/EtOAc = 3/1). The mixture of **3q** and **3q'** was further separated by recycling GPC. A white solid, mp 205–206 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.46 (s, 3 H), 7.04–7.09 (m, 1 H), 7.09–7.19 (m, 2 H), 7.22–7.28 (m, 2 H), 7.35 (d, *J* = 7.8 Hz, 1 H), 7.46 (d, *J* = 8.2 Hz, 1 H), 7.52 (d, *J* = 7.8 Hz, 1 H), 7.56 (dd, *J* = 7.8, 0.9 Hz, 1 H), 7.99 (bs, 1 H), 8.24 (bs, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.7, 107.1, 110.2, 110.5, 111.1, 119.46, 119.49, 119.51, 120.7, 121.2, 122.0, 122.8, 127.7, 129.1, 131.9, 135.4, 136.2. HRMS (ESI) Calcd for $C_{17}H_{14}N_2$: M^+, 246.1151. Found: *m/z* 246.1181.

2'-Methyl-1*H*,1'*H*-2,3'-biindole (3q'). A white solid, mp 73–74 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.62 (s, 3 H), 6.58 (dd, *J* = 2.3, 0.9 Hz, 1 H), 7.14 (td, *J* = 7.3, 1.4 Hz, 1 H), 7.15–7.23 (m, 3 H), 7.33–7.37 (m, 1 H), 7.40–7.45 (m, 1 H), 7.65 (dd, *J* = 8.2, 0.92 Hz, 1 H), 7.79 (dd, *J* = 6.9, 1.8 Hz, 1 H), 8.05 (bs, 1 H), 8.26 (bs, 1 H); ^{13}C

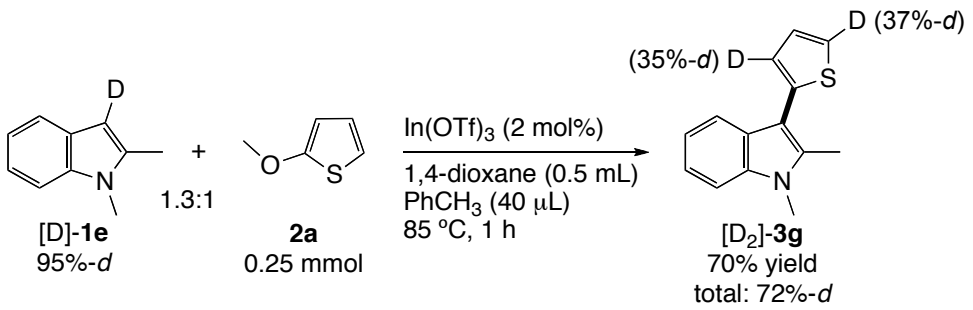
NMR (100 MHz, $CDCl_3$) δ 13.0, 100.8, 106.3, 110.55, 110.62, 118.7, 119.88, 119.92, 120.5, 121.3, 121.9, 127.3, 129.2, 133.1, 133.3, 135.1, 136.1. HRMS (ESI) Calcd for $C_{17}H_{15}N_2$: M^++H, 247.1230. Found: *m/z* 247.1232.



3-(Thiophen-2-yl)-1,2,5-trimethyl-1*H*-pyrrole (3r). The title compound was obtained in 63% yield (31.5 mg) after isolation by column chromatography on silica gel (hexane/EtOAc = 40/1). A white solid, mp 74–75 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.22 (s, 3 H), 2.36 (s, 3 H), 3.42 (s, 3 H), 6.02 (d, *J* = 1.2 Hz, 1 H), 6.91 (dd, *J* = 3.4, 1.1 Hz, 1 H), 7.01 (dd, *J* = 5.2, 3.5 Hz, 1 H), 7.12 (dd, *J* = 5.2, 1.2 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 11.3, 12.3, 30.4, 105.8, 113.6, 121.9, 122.1, 124.8, 127.1, 127.9, 140.3. HRMS (ESI) Calcd for $C_{11}H_{14}NS$: M^++H, 192.0841. Found: *m/z* 192.0842.



3-[5-(1,5-Dimethyl-1*H*-pyrrol-2-yl)thiophen-2-yl]-2-methyl-1*H*-indole (3s). The title compound was obtained in 45% yield (34.2 mg) after isolation by column chromatography on silica gel (hexane/EtOAc = 5/1). A yellow solid, mp 142–143 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.30 (s, 3 H), 2.61 (s, 3 H), 3.64 (s, 3 H), 5.95 (d, *J* = 3.5 Hz, 1 H), 6.27 (d, *J* = 3.5 Hz, 1 H), 7.01 (d, *J* = 3.4 Hz, 1 H), 7.09 (d, *J* = 3.5 Hz, 1 H), 7.11–7.21 (m, 2 H), 7.31 (dd, *J* = 6.9, 1.7 Hz, 1 H), 7.87 (d, *J* = 7.5 Hz, 1 H), 7.98 (bs, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 12.8, 13.2, 31.7, 106.5, 107.9, 108.6, 110.3, 119.2, 120.3, 121.8, 124.5, 125.1, 126.6, 127.6, 130.8, 132.3, 133.4, 135.0, 136.3. HRMS (ESI) Calcd for $C_{19}H_{19}N_2S$: M^++H, 306.1263. Found: *m/z* 306.1358.



1,2-Dimethyl-3-(3-deuteriumthien-2-yl)indole and 1,2-Dimethyl-3-(5-deuteriumthien-2-yl)indole ([D_2]-3g). The title compound was obtained in 70% yield (40.4 mg) after isolation by column chromatography on silica gel (hexane/EtOAc = 30/1). A white solid, mp 92–93 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.56 (s, 3 H), 3.73 (s, 3 H), 7.09 (dd, *J* = 3.4, 1.2 Hz, 0.65 H), 7.11–7.18 (m, 2 H), 7.21 (ddd, *J* = 8.1, 7.0, 1.3 Hz, 1 H), 7.27–7.34 (m, 1.63 H), 7.79 (d, *J* = 7.8 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 11.3, 29.7, 107.1, 108.7, 118.9, 119.9, 121.4, 123.5, 124.8, 126.9–127.19 (m), 127.21, 134.5, 136.5, 137.3, 137.5 (t, *J* = 5.6 Hz).; ^{2}H NMR (61 MHz, $CHCl_3$) δ 7.19 (bs), 7.40 (bs). HRMS (ESI) Calcd for $C_{14}H_{13}DNS$: M^++H, 229.094. Found: *m*/*z* 229.095.

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Chapter VI. Zinc-Catalyzed Direct Cyanation of Indoles and Pyrroles: Nitromethane as a Source of a Cyano Group

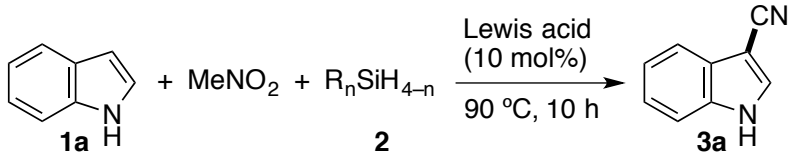
VI-1. Introduction

Aryl and heteroaryl nitriles represent an important class of core structures found in natural products, pharmaceuticals, agrochemicals, and functional materials.[1] The CN group has also been recognized as a versatile scaffold for elaboration of functional groups, for instance, CHO, CO_2H, CO_2R, $CONH_2$, CH_2NH_2, and others.[2] The most common way to construct (hetero)aryl–CN linkages is likely to be treatment of pre-activated (hetero)arenes with metal cyanides under transition metal catalysis,[3,4,5] which has developed since the advent of Sandmeyer[6] and Rosenmund–von Braun[7] reactions. However, due to recent trends towards reducing his dependence on the pre-activation and toxic metal reagent,[8] a major concern has been rapidly shifting to direct (hetero)aryl C–H cyanation[9] with inexpensive, harmless and readily available non-metallic reagents.[10] Of particular interest is to use cyanating agents that have no CN group but act as CN sources. In this regard, the pioneering research by Yu and colleagues has disclosed that nitromethane cyanates 2-phenylpyridine with the aid of a stoichiometric amount of $Cu(OAc)_2$, based on a chelation-assisted strategy.[11] Approaches with DMF,[12] DMF–NH_3(NH_4I),[13] DMSO–NH_4HCO_3[14] and *t*-BuNC[15] as CN suppliers have emerged also in succession recently, but, here again, as transition metal-based systems: Pd catalysts–Cu co-oxidants or a stoichiometric amount of Cu salts.[5j,16] In sharp contrast, the author's group found for the first time that a Lewis acid can participate as a catalyst in this category.[17] The author discloses herein a conceptually new cyanation reaction using a nitromethane–hydrosilane system under zinc catalysis.

VI-2. Results & Discussion

The author first examined suitable reaction conditions for cyanation of indole (**1a**) (Table 1). Treating **1a** with 10 mol% of $Zn(OTf)_2$ (Tf = SO_2CF_3) at 90 °C for 10 h in $MeNO_2$, which was used not only as a reagent but also as a reaction medium, resulted in no cyanation of **1a** (entry 1). Although the addition of monohydrosilanes **2a**–**2c** provided no improvement, 3-cyanoindole (**3a**) was formed by using di- and trihydrosilanes **2d**–**2f** (entries 2–7). Among them, Ph_2SiH_2 (**2e**) is the most preferable, giving **3a** in 76% yield (entry 6). Reducing the amount of **2e** from 3 to 2.5 molar equiv. lowered the yield, and its higher loading was unnecessary (entries 8 and 9). Investigating the effect of other Lewis acids clearly showed that only zinc salts are valid as catalysts, and $Zn(OTf)_2$ is the most promising for the cyanation (entries 6 and 10–20). No cyanation occurred without a catalyst (entry 21). The use of a co-solvent had no positive effect, and the simple reduction of the quantity of $MeNO_2$ resulted in a poor yield (entries 22–26).

Table 1. Lewis acid-catalyzed cyanation of indole[a]

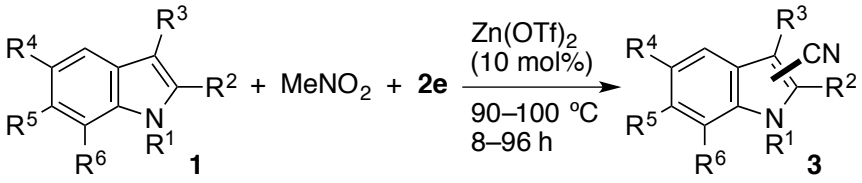


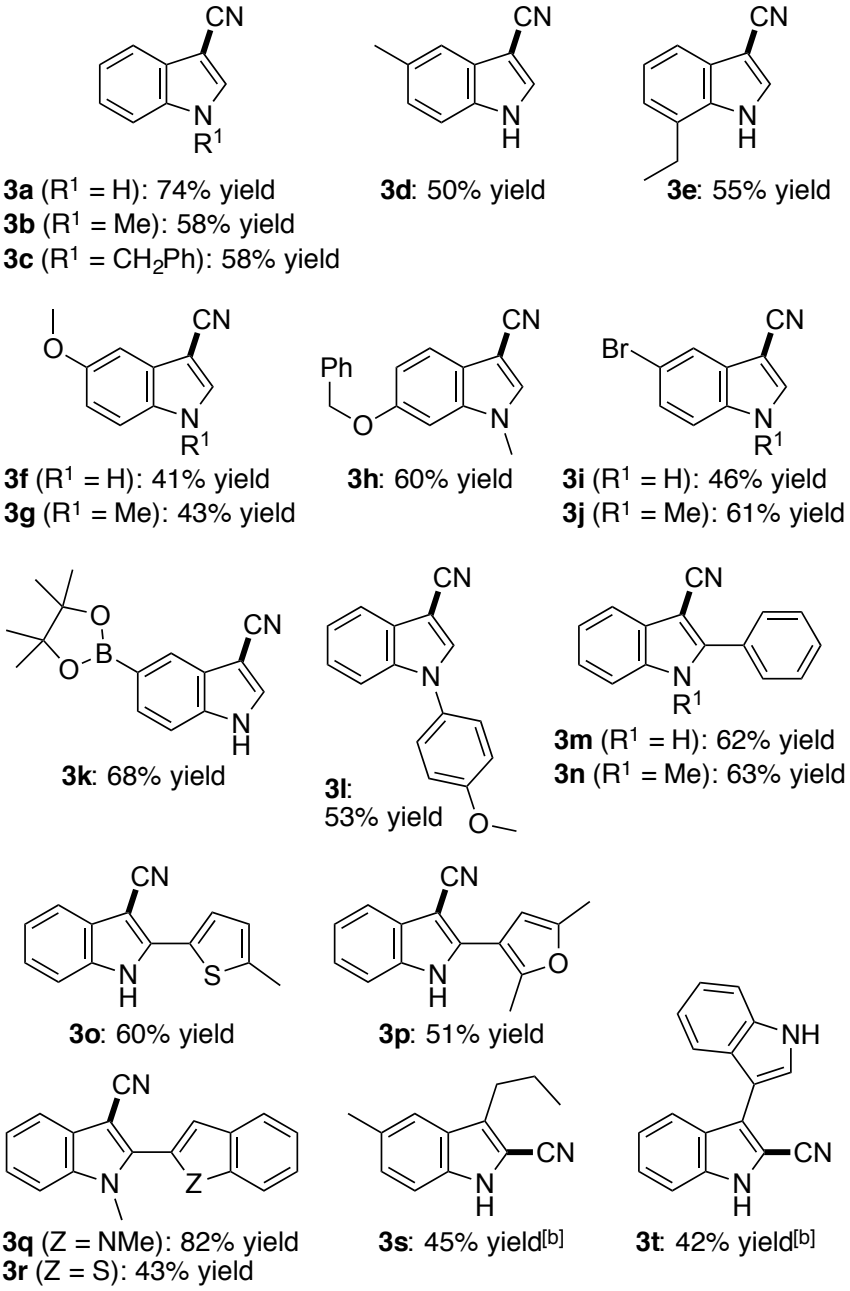
Entry	Lewis acid	R_nSiH_{4-n} (equiv.)	Co-solvent	Yield [%][b]
1	$Zn(OTf)_2$	none	none	<1
2	$Zn(OTf)_2$	Et_3SiH **2a** (6)	none	1
3	$Zn(OTf)_2$	Me_2PhSiH **2b** (6)	none	<1
4	$Zn(OTf)_2$	$MePh_2SiH$ **2c** (6)	none	<1
5	$Zn(OTf)_2$	$MePhSiH_2$ **2d** (3)	none	35
6	$Zn(OTf)_2$	Ph_2SiH_2 **2e** (3)	none	76
7	$Zn(OTf)_2$	$PhSiH_3$ **2f** (2)	none	40
8	$Zn(OTf)_2$	**2e** (2.5)	none	66
9	$Zn(OTf)_2$	**2e** (3.5)	none	63
10	$Cu(OTf)_2$	**2e** (3)	none	<1
11	AgOTf	**2e** (3)	none	<1
12	$In(OTf)_3$	**2e** (3)	none	<1
13	$Bi(OTf)_3$	**2e** (3)	none	<1
14	$Fe(OTf)_3$	**2e** (3)	none	<1
15	$Sc(OTf)_3$	**2e** (3)	none	<1
16	$Zn(ONf)_2$[c]	**2e** (3)	none	51
17	$Zn(NTf_2)_2$	**2e** (3)	none	10
18	ZnI_2	**2e** (3)	none	2
19	$ZnBr_2$	**2e** (3)	none	25
20	$ZnCl_2$	**2e** (3)	none	20
21	none	**2e** (3)	none	<1
22[d]	$Zn(OTf)_2$	**2e** (3)	toluene	72
23[d]	$Zn(OTf)_2$	**2e** (3)	Bu_2O	47
24[d]	$Zn(OTf)_2$	**2e** (3)	dioxane[e]	6
25[d]	$Zn(OTf)_2$	**2e** (3)	EtCN	40
26[f]	$Zn(OTf)_2$	**2e** (3)	none	11

[a] Reagents: **1a** (0.80 mmol), $MeNO_2$ (7.4 mmol, 0.40 mL), **2** (1.6–4.8 mmol), Lewis acid (80 μmol). [b] Determined by GC. [c] Nf = $SO_2C_4F_9$. [d] Performed in $MeNO_2$ (0.30 mL) and the co-solvent (0.10 mL). [e] dioxane = 1,4-dioxane. [f] Performed in $MeNO_2$ (0.20 mL).

With the suitable reaction conditions in hand, he explored the scope of the indole substrate (Table 2). Besides *N*-unsubstituted indole **1a**, *N*-methyl- and *N*-benzylindoles participated in the cyanation reaction (see **3a**–**3c**). Indoles **1** with alkyl, alkoxy and bromo groups on the carbon atom were also cyanated to afford **3d**–**3j** in moderate to good yields. The acid-labile benzyloxy moiety was retained here (see **3h**).[18] In contrast to the preceding copper-based systems,[4,11–15] the aryl–boron bond that is useful for further transformation also remained intact (see **3k**). This is an advantage of the present zinc catalysis.[19] Despite that a series of 1- and 2-(hetero)arylindoles have multiple possible reaction sites, only mono-cyanation at the indolyl-C3 occurred to provide **3l**–**3r**, thus showing remarkable chemo- and regioselectivity. This should be because the indolyl-C3 is the most nucleophilic among the aromatic carbons,[20] and an electron-withdrawing character of the CN group decreases nucleophilicity of the products to retard extra cyanation. The less nucleophilic C2, compared to a C3, also worked as a reaction site (see **3s** and **3t**).

Table 2. Zinc-catalyzed cyanation of indoles with $MeNO_2$ and Ph_2SiH_2[a]

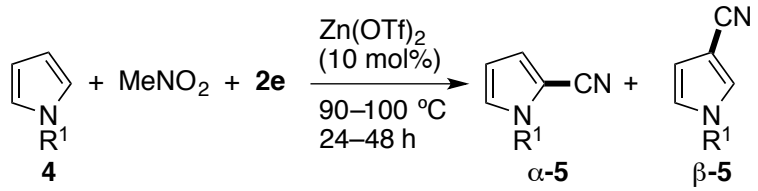


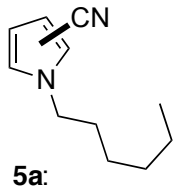


[a] Yields of isolated **3** based on **1** are shown here. Further details on reaction conditions for each reaction are given in Experimental section. [b] $Zn(OTf)_2$ (15 mol%) was used.

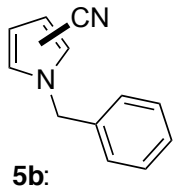
This zinc process is also applicable to the cyanation of pyrroles (Table 3). Thus, 1-hexylpyrrole was cyanated with $MeNO_2$ and **2e** under zinc catalysis to afford **5a** as a separable mixture of α- and β-isomers. Pyrroles with other alkyl and aryl groups on the nitrogen atom also participated in this protocol (see **5b**–**5d**), whereas the size of the substituent did not affect significantly the α/β ratio. Here again, no extra cyanation on and except on the pyrrole ring was observed. In contrast, other aromatic substrates such as 3,4-ethylenedioxythiophene and $PhNMe_2$ were not cyanated successfully (≤5%), due probably to their low nucleophilicity. However, such reactivity would have contributed to the selective mono-cyanation.

Table 3. Zinc-catalyzed cyanation of pyrroles with $MeNO_2$ and Ph_2SiH_2[a]

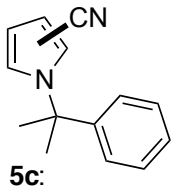




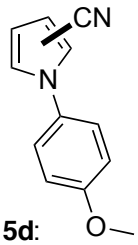
5a:
43% yield
α/β = 51:49



5b:
51% yield
α/β = 52:48



5c:
69% yield
α/β = 41:59

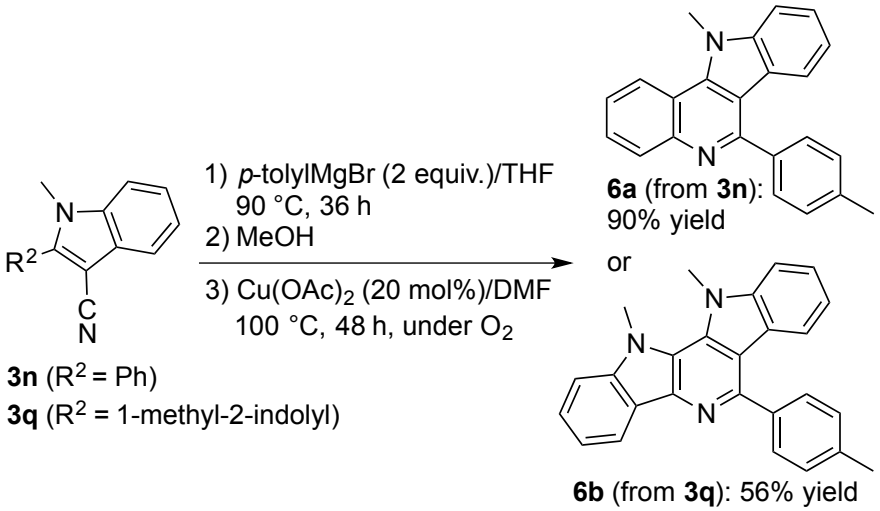


5d:
55% yield
α/β = 59:41

[a] Yields of isolated **5** based on **4** are shown here. Further details on reaction conditions for each reaction are provided in Experimental section.

Importantly, practical application is accomplished by synthesis on a preparative scale. For example, cyanation of **1a** on a 10-mmol scale provided him with 1.03 g (72% yield) of **3a**.

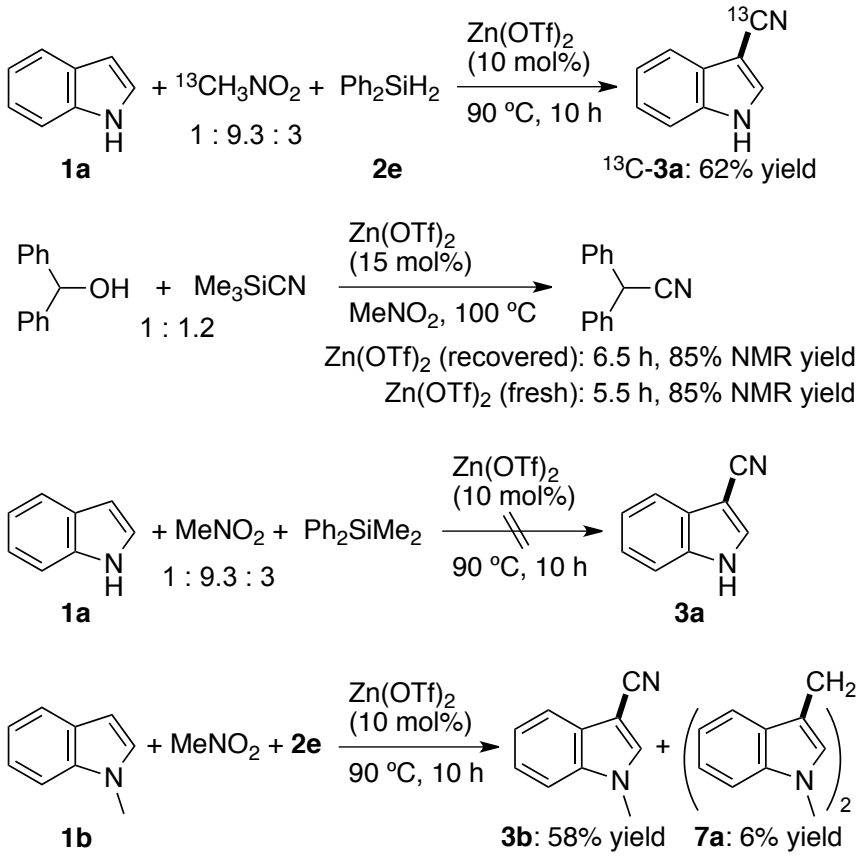
The utility of the present reaction can be demonstrated by transforming the product into a biologically important structure, an indolo[3,2-*c*]quinoline,[21] which is found, for instance, in natural isocryptolepine[22] showing antimalarial activity (Scheme 1). Thus, nucleophilic attack of *p*-tolylMgBr to the CN group of **3n** followed by protonation with MeOH and Cu-catalyzed oxidative N–C bond-forming annulation gave **6a** in 90% yield.[23] This one-pot reaction is also effective for **3q**, thus indicating its good flexibility.



Scheme 1. One-pot annulation of 3-cyano-2-(hetero)arylindoles

Some pieces of experimental observations might be available for the mechanistic studies (Scheme 2). The author first addressed the role of $MeNO_2$. When ^{13}C-labeled nitromethane was used, the ^{13}C atom was incorporated exclusively into the CN group of the product (^{13}C-**3a**), thus showing that the CN group comes from $MeNO_2$. In order to clarify the role of $Zn(OTf)_2$, he next tried its recovery after the cyanation reaction and then used the recovered solid for other reaction in which $Zn(OTf)_2$ has been found to act as a Lewis acid catalyst.[24] Thus, a solid recovered with 97% efficiency after the cyanation of **1a** nicely catalyzed the transformation of benzhydrol to diphenylacetonitrile in 85% NMR yield, which is fully comparable to that obtained with fresh $Zn(OTf)_2$. Accordingly, $Zn(OTf)_2$ would exist without changing the form during the cyanation process, and its role in the cyanation would be a Lewis acid catalyst. He successively examined the role of silicon reagent **2e** and carried out the reaction of **1a** with Ph_2SiMe_2 having no hydrogen atom instead of **2e**, which, however, led to no cyanation. This result clearly shows that the Si–H part is essential

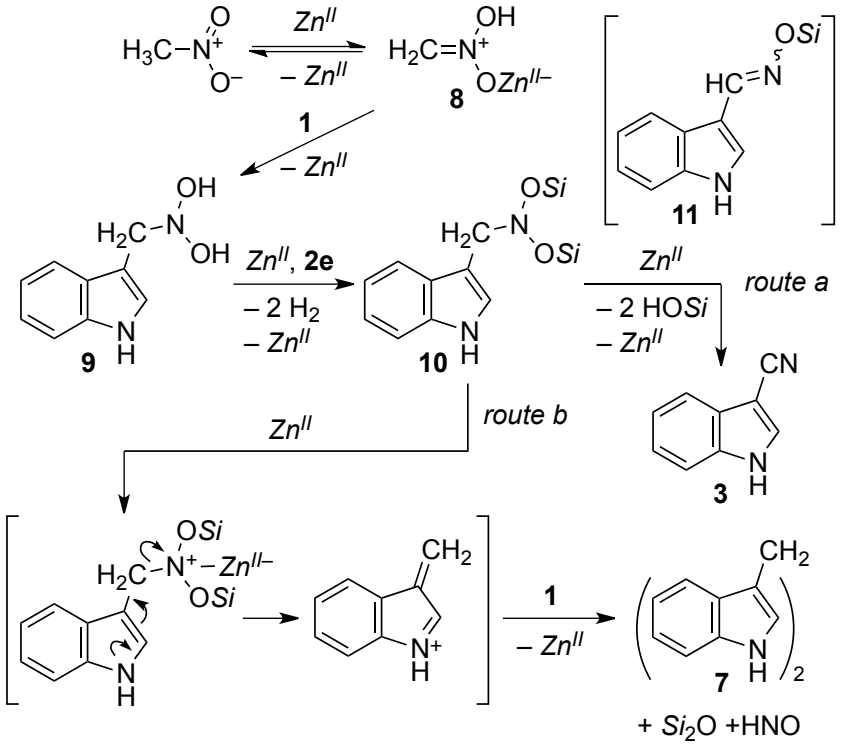
for the cyanation reaction. The hydride character of the Si–H might thus play an important role in this reaction. A final observation is that the reaction of *N*-methylindole (**1b**) (Table 2, **3b**) provided a non-negligible amount of 3,3'-diindolylmethane **7a** as a by-product in addition to **3b**.[25] Based on the literature, where $MeNO_2$ activated by a Lewis acid reacts with 1,3-dicarbonyl compounds as nucleophiles to be incorporated as a methylene unit into products,[26] **7a** might be formed via a similar type of process triggered by activation of $MeNO_2$ by $Zn(OTf)_2$.[27]



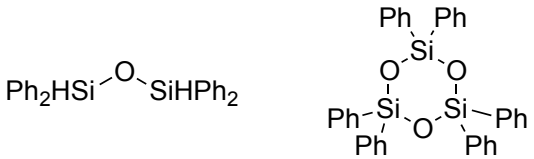
Scheme 2. Mechanistic studies

Although further studies are required to verify the reaction mechanism, its tentative interpretation is proposed in Scheme 3, where substituents of **1** are omitted for clarity. The first should be nucleophilic attack of **1** to *aci*-nitromethane **8** activated by Zn^{II}, just like the attack of water occurring in the Nef reaction.[28] In the present reaction, generation of **12** and **13** as non-polymeric siloxanes, which would be derived from self-dehydration of the corresponding silanol, is always observed (Figure 1). Accordingly, **9** might be converted to silylated form **10** rapidly via zinc-catalyzed dehydrogenative

silylation.[29] The sequential elimination of two molecules of HO*Si* from **10** by way of the formation of silyl oxime **11** should lead to **3** (*route a*).[30] On the other hand, the C–N bond cleavage followed by nucleophilic attack of **1** should give **7** and also release Si_2O and HNO, similarly as in the Nef reaction (*route b*).[31]



Scheme 3. A proposed reaction mechanism
Zn^{II} = $Zn(OTf)_2$. *Si* = SiR_3.



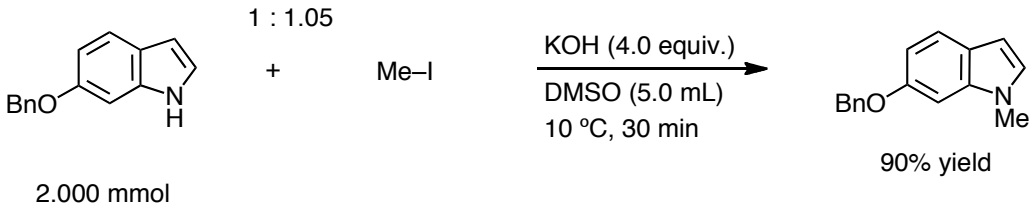
12 **13**

Figure 1. Non-polymeric Si-containing by-products

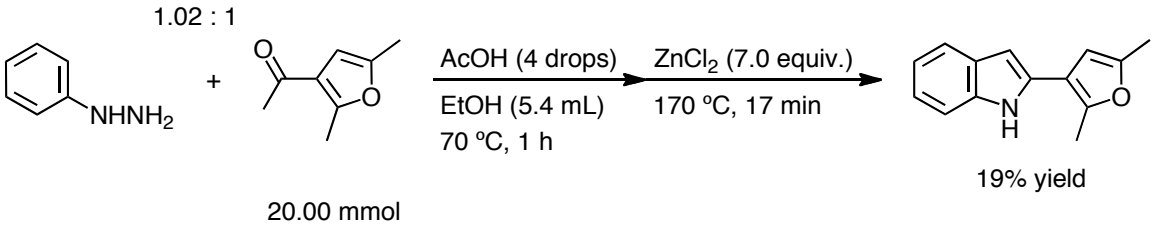
VI-3. Experimental

General Remarks. All manipulations were conducted with a standard Schlenk technique under an argon atmosphere. Nuclear magnetic resonance (NMR) spectra were taken on a JEOL JMN-ECA 400 (^{1}H, 400 MHz; ^{13}C, 100 MHz) or JEOL JMN-ECA 500 (^{1}H, 500 MHz; ^{13}C, 125 MHz) spectrometer using tetramethylsilane (^{1}H and ^{13}C) as an internal standard. Analytical gas chromatography (GC) was performed on a Shimadzu model GC-2014 instrument equipped with a capillary column of InertCap 5 (5% phenyl polysilphenylene-siloxane, 30 m x 0.25 mm x 0.25 μm) using nitrogen as carrier gas. Gas chromatography–mass spectrometry (GC–MS) analyses were performed with a Shimadzu model GCMS-QP2010 instrument equipped with a capillary column of ID-BPX5 (5% phenyl polysilphenylene-siloxane, 30 m x 0.25 mm x 0.25 μm) by electron ionization at 70 eV using helium as carrier gas. Preparative recycling gel permeation chromatography (GPC) was performed with JAI LC-9105 equipped with JAIGEL-1H and JAIGEL-2H columns using chloroform as the eluent. All melting points were measured with a Yanaco Micro Melting Point apparatus and uncorrected. High-resolution mass spectra (HRMS) were obtained with a JEOL JMS-T100GCV. Liquid indoles and pyrroles, nitromethane ($MeNO_2$), hydrosilanes and toluene were stored over molecular sieves 4A (MS 4A) under argon. Dibutyl ether (Bu_2O) and 1,4-dioxane were distilled under argon from sodium just prior to use. Propionitrile (EtCN) was distilled under argon from P_2O_5 just prior to use. MeOH was stored over molecular sieves 3A (MS 3A) under argon. Anhydrous *N*,*N*-dimethylformamide (DMF) and anhydrous dimethylsulfoxide (DMSO) were purchased from Sigma-Aldrich and Wako Pure Chemical Industries, respectively, and used as received without further purification. Tetrahydrofuran (THF) was distilled under argon from sodium benzophenone ketyl just prior to use. 1-Benzyl-1*H*-indole,[32] 2-(5-methylthiophen-2-yl)-1*H*-indole, [33] 2,2'-bis(*N*-methylindolyl), [34] 2-{benzo[*b*]thien-2-yl}-1*H*-indole,[33d] 3,3'-bi-1*H*-indole[35] and 1-(2-phenylpropan-2-yl)-1*H*-pyrrole[36] were synthesized according to the respective literature method. Unless otherwise noted, other substrates and reagents were commercially available and used as received without further purification.

Synthesis of Indole and Pyrrole Substrates.

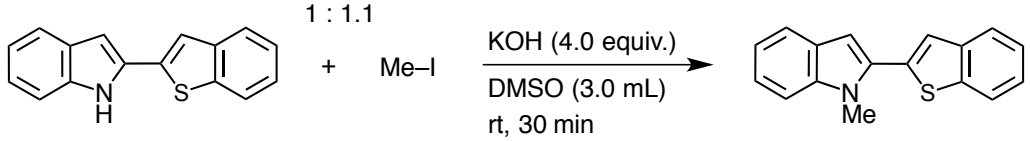


6-Benzyloxy-1-methyl-1*H*-indole. [37] The title compound was synthesized according to the following modified literature procedure.[32] Under an argon atmosphere, potassium hydroxide (448.8 mg, 8.000 mmol) and DMSO (5.0 mL) were placed in a flame-dried 20 mL Schlenk tube, which was immersed in a water bath at 10 °C and stirred for 10 min. To the tube was added 6-benzyloxy-1*H*-indole (446.5 mg, 2.000 mmol), and then iodomethane (298.1 mg, 2.100 mmol) was slowly added dropwise with stirring. After stirring at 10 °C for 30 min, the reaction mixture was filtered to remove an excess amount of potassium hydroxide, and the filtrate was diluted with Et_2O (100 mL). The organic layer was washed with water (10 mL x 4) and brine (10 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (*n*-hexane/EtOAc = 5/1, R_f = 0.47) gave 6-benzyloxy-1-methyl-1*H*-indole (431.5 mg, 90% yield) as a light yellow solid. This compound has already appeared in the literature, and its spectral and analytical data are in good agreement with those reported. Accordingly, only ^{1}H NMR data are provided here. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.73 (s, 3 H), 5.14 (s, 2 H), 6.41 (d, *J* = 3.2 Hz, 1 H), 6.82–6.90 (m, 2 H), 6.95 (d, *J* = 3.2 Hz, 1 H), 7.30–7.35 (m, 1 H), 7.36–7.42 (m, 2 H), 7.44–7.55 (m, 3 H).



2-(2,5-Dimethylfuran-3-yl)-1*H*-indole. The title compound was synthesized according to the following modified literature procedure.[33] Under an argon atmosphere, 3-acetyl-2,5-dimethylfuran (2.763 g, 20.00 mmol), EtOH (5.4 mL), phenylhydrazine (2.206 g, 20.40 mmol) and four drops of acetic acid (AcOH) were placed in a 100 mL

round-bottomed flask, and the mixture was then stirred at 70 °C for 1 h. The resulting mixture was filtered, and the solvent was removed under reduced pressure to yield a black liquid. To this was added zinc chloride (19.08 g, 140.0 mmol), and the mixture was heated at 170 °C for 17 min with stirring. After cooling to room temperature, the mixture was quenched with H_2O (64 mL) and a 12 N HCl aqueous solution (2 mL), and the aqueous phase was extracted with EtOAc (100 mL x 3). The combined organic layer was washed with a saturated $NaHCO_3$ aqueous solution (20 mL x 3) and brine (30 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (*n*-hexane/EtOAc = 15/1, R_f = 0.30) gave 2-(2,5-dimethylfuran-3-yl)-1*H*-indole (845.0 mg, 19% yield) as an orange solid, mp 119–120 ºC. ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.30 (s, 3 H), 2.50 (s, 3 H), 6.14 (d, *J* = 0.9 Hz, 1 H), 6.47 (dd, *J* = 1.8, 0.9 Hz, 1 H), 7.10 (td, *J* = 7.3, 1.2 Hz, 1 H), 7.15 (td, *J* = 7.6, 1.2 Hz, 1 H), 7.33–7.39 (m, 1 H), 7.56–7.61 (m, 1 H), 7.99 (bs, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.2, 13.4, 99.6, 105.4, 110.5, 113.7, 120.0, 121.6, 129.2, 132.1, 136.0, 146.7, 150.4 (One carbon signal is missing due to overlapping). HRMS (FD) Calcd for $C_{14}H_{13}NO$: M, 211.0997. Found: *m*/*z* 211.1029.

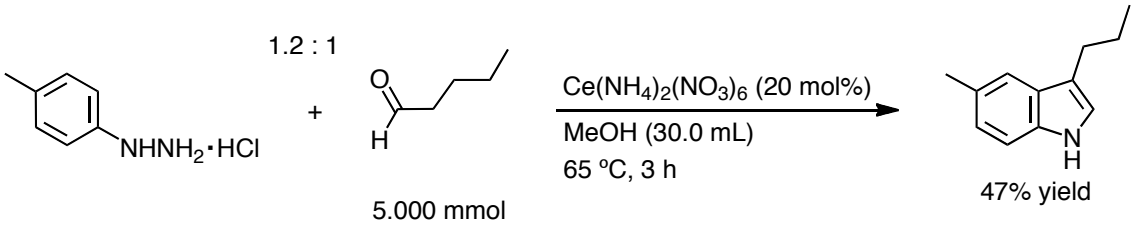


1.560 mmol

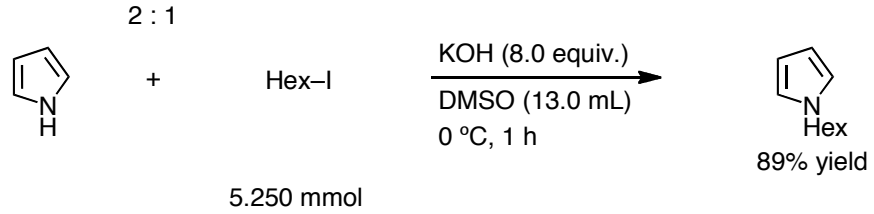
80% yield

2-{Benzo[*b*]thien-2-yl}-1-methyl-1*H*-indole. Under an argon atmosphere, potassium hydroxide (355.2 mg, 6.330 mmol) and anhydrous DMSO (3.0 mL) were placed in a flame-dried 20 mL Schlenk tube, which was stirred at room temperature for 10 min. To the tube was added 2-{benzo[*b*]thien-2-yl}-1*H*-indole (389.2 mg, 1.560 mmol), and then iodomethane (245.6 mg, 1.730 mmol) was slowly added dropwise with stirring. After stirring at room temperature for 30 min, the reaction mixture was filtered to remove an excess amount of potassium hydroxide, and the filtrate was diluted with Et_2O (100 mL). The organic layer was washed with water (10 mL x 4) and brine (10 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (*n*-hexane/EtOAc = 20/1, R_f = 0.42) gave 2-{benzo[*b*]thien-2-yl}-1-methyl-1*H*-indole (331.2 mg, 80% yield) as a white solid, mp

136–137 ºC. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.94 (s, 3 H), 6.79 (d, *J* = 0.9 Hz, 1 H), 7.15 (ddd, *J* = 7.8, 6.9, 0.9 Hz, 1 H), 7.28 (ddd, *J* = 8.1, 7.2, 0.9 Hz, 1 H), 7.33–7.41 (m, 3 H), 7.41 (d, *J* = 0.9 Hz, 1 H), 7.64 (dt, *J* = 7.8, 0.9 Hz, 1 H), 7.80–7.89 (m, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 31.4, 103.9, 109.6, 120.2, 120.8, 122.1, 122.5, 122.8, 123.7, 124.62, 124.65, 127.7, 133.8, 134.5, 138.7, 140.0, 140.1. HRMS (FI) Calcd for $C_{17}H_{13}NS$: M, 263.0769. Found: *m*/*z* 263.0802.

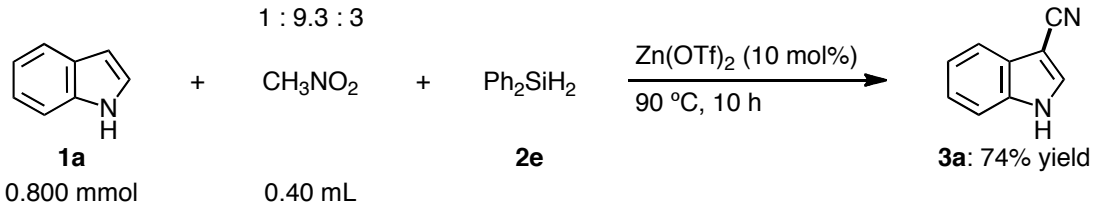


5-Methyl-3-propyl-1*H*-indole. The title compound was synthesized according to the following modified literature procedure.[38] Under an argon atmosphere, *p*-tolylhydrazine hydrochloride (951.8 mg, 6.000 mmol), valeraldehyde (430.7 mg, 5.000 mmol) and anhydrous MeOH (30.0 ml) were placed in a flame-dried 100 mL Schlenk tube. To this was added ceric ammonium nitrate (548.3 mg, 1.000 mmol) and the mixture was heated at 65 °C for 3 h in an oil bath. The reaction mixture was cooled to room temperature and poured into water (80 mL). The aqueous phase was extracted with EtOAc (80 mL x 3), and the combined organic layer was washed with brine (30 mL) and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (*n*-hexane/$CHCl_3$ = 2/1, R_f = 0.47) gave 5-methyl-3-propyl-1*H*-indole (415.6 mg, 47% yield) as a dark yellow oil. ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.99 (t, *J* = 7.2 Hz, 3 H), 1.73 (sext, *J* = 7.4 Hz, 2 H), 2.46 (s, 3 H), 2.70 (t, *J* = 7.7 Hz, 2 H), 6.92–6.95 (m, 1 H), 7.00 (dd, *J* = 8.6, 1.2 Hz, 1 H), 7.24 (d, *J* = 8.1 Hz, 1 H), 7.39 (s, 1 H), 7.78 (bs, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 14.2, 21.5, 23.3, 27.3, 110.7, 116.4, 118.7, 121.3, 123.4, 127.8, 128.2, 134.7. HRMS (FD) Calcd for $C_{12}H_{15}N$: M, 173.1205. Found: *m*/*z* 173.1206.

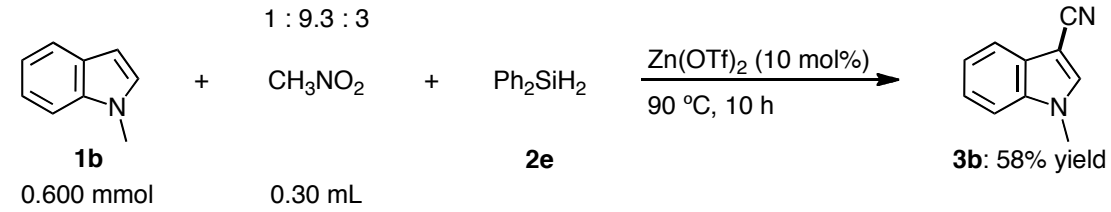


1-Hexyl-1*H*-pyrrole.[39] The title compound was synthesized according to the following modified literature procedure[1]. Under an argon atmosphere, potassium hydroxide (2.356 g, 42.00 mmol) and DMSO (13.0 mL) were placed in a flame-dried 100 mL Schlenk tube, which was immersed in a water bath at 0 °C and stirred for 10 min. To this was added pyrrole (704.4 mg, 10.50 mmol), and then 1-iodohexane (1.113 g, 5.250 mmol) was slowly added dropwise to the tube with stirring. After stirring at 0 °C for 1, the reaction mixture was filtered to remove an excess amount of potassium hydroxide, and the filtrate was diluted with Et_2O (200 mL). The organic layer was washed with water (15 mL x 4) and brine (15 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (*n*-hexane/EtOAc = 20/1, R_f = 0.43) and then bulb-to-bulb distillation (80 ºC/600 Pa) gave 1-hexyl-1*H*-pyrrole (710.6 mg, 89% yield) as a colorless oil. This compound has already appeared in the literature, and its spectral and analytical data are in good agreement with those reported. Accordingly, only ^{1}H NMR data are provided here. ^{1}H NMR (400 Mz, $CDCl_3$) δ 0.88 (t, *J* = 6.7 Hz, 3 H), 1.23–1.36 (m, 6 H), 1.76 (quint, *J* = 7.1 Hz, 2 H), 3.86 (t, *J* = 7.3 Hz, 2 H), 6.13 (t, *J* = 2.1 Hz, 2 H), 6.65 (t, *J* = 2.1 Hz, 2 H).

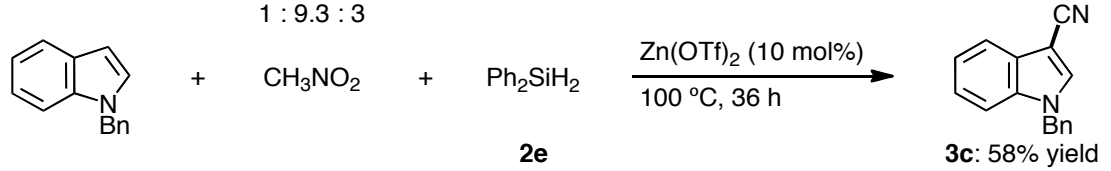
Zinc-Catalyzed Direct Cyanation of Indoles and Pyrroles with $MeNO_2$ and Ph_2SiH_2. A General Procedure for Table 2 and Table 3. As a typical example, the following shows the procedure performed in 0.400 mmol scale of indoles **1**: $Zn(OTf)_2$ (Tf = SO_2CF_3) (14.5 mg, 40.0 μmol) was placed in a 20 mL Schlenk tube, which was heated at 150 °C in vacuo for 2 h. The tube was cooled down to room temperature and filled with argon. $MeNO_2$ (0.20 mL, 3.72 mmol) was added to the tube, and then the mixture was stirred at room temperature for 3 min. To this were added indoles **1** (0.400 mmol) and diphenylsilane (**2e**) **[**(221 mg, 1.20 mmol) or (258 mg, 1.40 mmol)] successively, and the resulting mixture was stirred at 90 or 100 °C for 10–96 h. A saturated $NaHCO_3$ aqueous solution (0.5 mL) was added, and the aqueous phase was extracted with EtOAc (7 mL x 3). The combined organic layer was washed with brine (1 mL) and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel using *n*-hexane–EtOAc as eluent gave the corresponding product (**3** or **5**). In a case that the purity of the product is insufficient, further purification was performed with silica gel column chromatography using other eluent (*n*-hexane–CH_2Cl_2 and *n*-hexane–$CHCl_3$), recycling GPC or bulb-to-bulb distillation. Unless otherwise noted, products **3** or **5** synthesized here were fully characterized by ^1H and ^{13}C NMR spectroscopy, and HRMS.



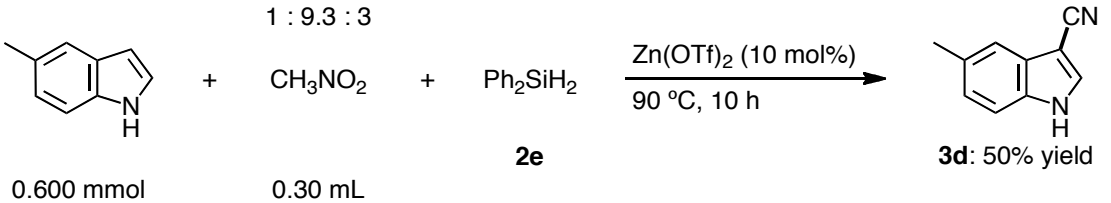
1*H*-Indole-3-carbonitrile (3a). The title compound was isolated as a light yellow solid by column chromatography on silica gel (*n*-hexane/EtOAc = 3/1, R_f = 0.43). The title compound is commercially available, and its spectral and analytical data are in good agreement with those of the commercial 1*H*-indole-3-carbonitrile. ^1H NMR (500 MHz, $CDCl_3$) δ 7.30–7.37 (m, 2 H), 7.47 (dd, *J* = 7.7, 1.5 Hz, 1 H), 7.74 (d, *J* = 2.9 Hz, 1 H), 7.79 (d, *J* = 8.6 Hz, 1 H), 8.59 (bs, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 87.6, 112.0, 115.8, 119.7, 122.4, 124.4, 126.9, 131.8, 134.8. HRMS (FD) Calcd for $C_9H_6N_2$: M, 142.0531. Found: *m*/*z* 142.0516.



1-Methyl-1*H*-indole-3-carbonitrile (3b). The title compound was isolated by column chromatography on silica gel (*n*-hexane/EtOAc = 5/2, R_f = 0.23). A dark red paste. ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.86 (s, 3 H), 7.31 (ddd, *J* = 8.0, 6.9, 1.2 Hz, 1 H), 7.33–7.43 (m, 2 H), 7.57 (s, 1 H), 7.77 (dt, *J* = 8.0, 1.2 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 33.6, 85.4, 110.3, 116.0, 119.8, 122.1, 123.8, 127.8, 135.5, 136.0. HRMS (FD) Calcd for $C_{10}H_8N_2$: M, 156.0688. Found: *m*/*z* 156.0674.

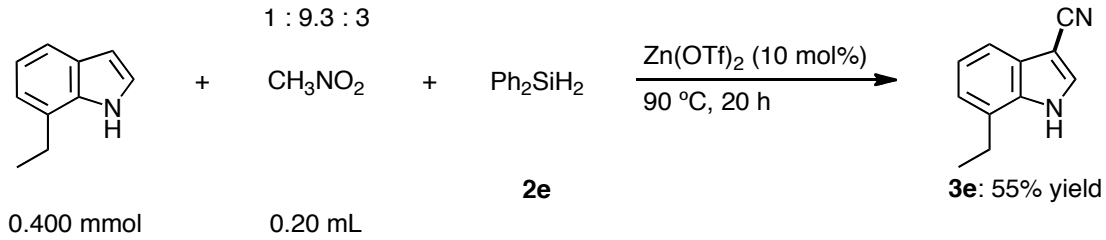


1-Benzyl-1*H*-indole-3-carbonitrile (3c).[40] The title compound was isolated as a white solid by column chromatography on silica gel twice (first: *n*-hexane/EtOAc = 5/1, R_f = 0.33; second: *n*-hexane/CH_2Cl_2 = 2/3, R_f = 0.43). This compound has already appeared in the literature, and its spectral and analytical data are in good agreement with those reported. Accordingly, only ^{1}H NMR data are provided here. ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.34 (s, 2 H), 7.12–7.17 (m, 2 H), 7.26–7.39 (m, 6 H), 7.60 (s, 1 H), 7.75–7.82 (m, 1 H).

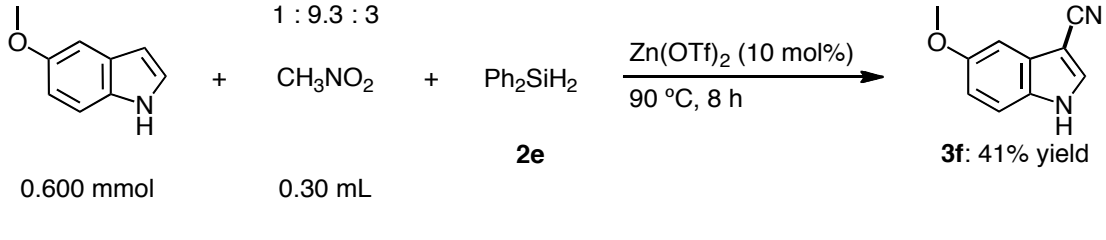


5-Methyl-1*H*-indole-3-carbonitrile (3d). The title compound was isolated by column chromatography on silica gel (*n*-hexane/EtOAc = 4/3, R_f = 0.38). A light brown solid, mp 141–142 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.49 (s, 3 H), 7.16 (dd, *J* = 8.4, 1.4

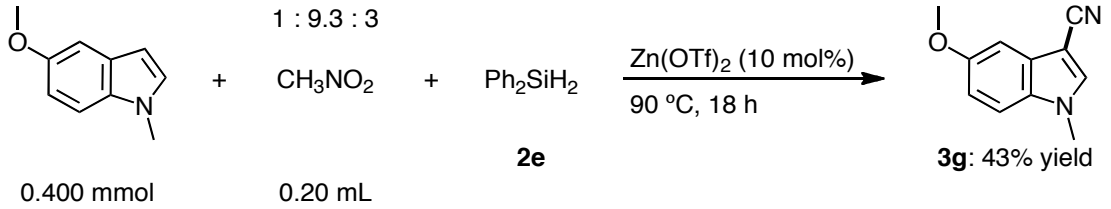
Hz, 1 H), 7.35 (d, *J* = 8.4 Hz, 1 H), 7.57 (s, 1 H), 7.69 (d, *J* = 2.8 Hz, 1 H), 8.54 (bs, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 21.4, 86.9, 111.7, 116.0, 119.3, 126.0, 127.2, 131.7, 132.1, 133.1. HRMS (FD) Calcd for $C_{10}H_8N_2$: M, 156.0688. Found: *m*/*z* 156.0667.



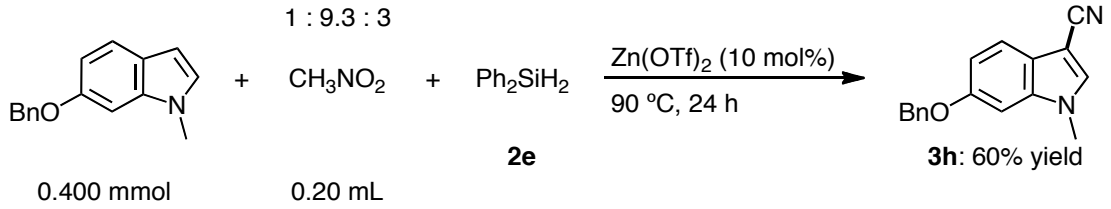
7-Ethyl-1*H*-indole-3-carbonitrile (3e). The title compound was isolated by recycling GPC after column chromatography on silica gel (*n*-hexane/EtOAc = 5/2, R_f = 0.33). A light brown solid, mp 141–142 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.38 (t, *J* = 7.8 Hz, 3 H), 2.90 (q, *J* = 7.5 Hz, 2 H), 7.17 (d, *J* = 7.5 Hz, 1 H), 7.26 (t, *J* = 7.8 Hz, 1 H), 7.63 (d, *J* = 8.1 Hz, 1 H), 7.75 (d, *J* = 2.9 Hz, 1 H), 8.86 (bs, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 13.9, 24.0, 87.1, 116.4, 117.1, 122.6, 122.8, 126.9, 128.0, 131.8, 133.9. HRMS (FD) Calcd for $C_{11}H_{10}N_2$: M, 170.0844. Found: *m*/*z* 170.0811.



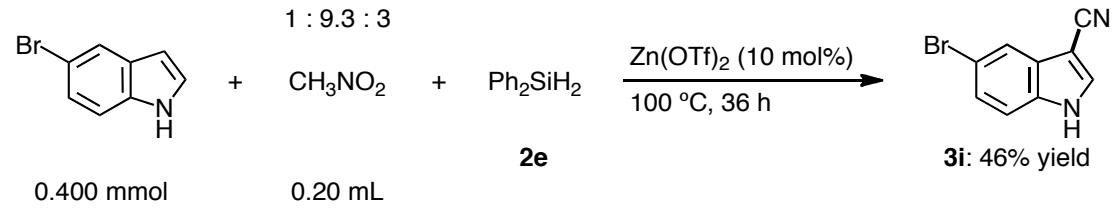
5-Methoxy-1*H*-indole-3-carbonitrile (3f). The title compound was isolated by column chromatography on silica gel (*n*-hexane/EtOAc = 4/3, R_f = 0.43). An ocher solid, mp 137–138 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.88 (s, 3 H), 6.97 (dd, *J* = 8.9, 2.5 Hz, 1 H), 7.18 (d, *J* = 2.3 Hz, 1 H), 7.35 (d, *J* = 8.7 Hz, 1 H), 7.69 (d, *J* = 3.2 Hz, 1 H), 8.65 (bs, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 55.8, 87.2, 100.6, 112.9, 115.2, 116.1, 127.9, 129.7, 131.8, 156.1. HRMS (FI) Calcd for $C_{10}H_8N_2O$: M, 172.0637. Found: *m*/*z* 172.0627.



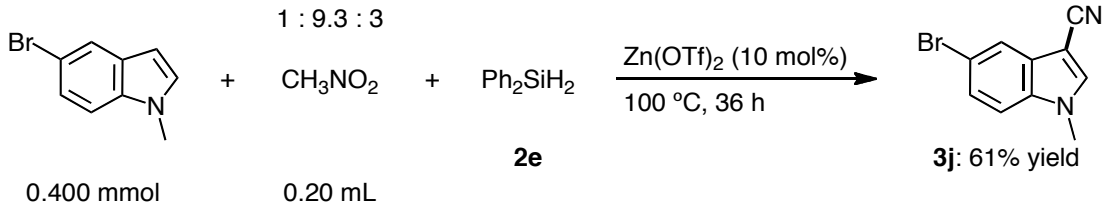
5-Methoxy-1-methyl-1*H*-indole-3-carbonitrile (3g).[40] The title compound was isolated as a light yellow solid by column chromatography on silica gel (*n*-hexane/EtOAc = 5/3, R_f = 0.40). This compound has already appeared in the literature, and its spectral and analytical data are in good agreement with those reported. Accordingly, only ^{1}H NMR data are provided here. ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.82 (s, 3 H), 3.88 (s, 3 H), 6.98 (dd, *J* = 8.9, 2.6 Hz, 1 H), 7.16 (d, *J* = 2.3 Hz, 1 H), 7.27 (d, *J* = 8.6 Hz, 1 H), 7.51 (s, 1 H).



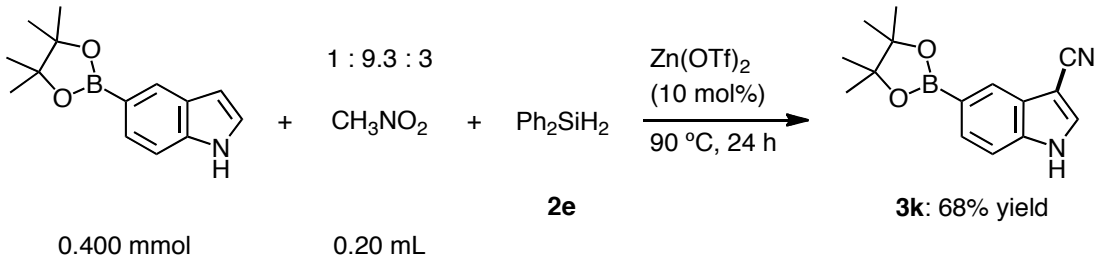
6-Benzyloxy-1-methyl-1*H*-indole-3-carbonitrile (3h). The title compound was isolated by column chromatography on silica gel (*n*-hexane/EtOAc = 2/1, R_f = 0.33). A deep yellow solid, mp 137–138 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.77 (s, 3 H), 5.14 (s, 2 H), 6.90 (d, *J* = 2.3 Hz, 1 H), 7.04 (dd, *J* = 8.7, 2.3 Hz, 1 H), 7.32–7.37 (m, 1 H), 7.38–7.43 (m, 2 H), 7.45–7.49 (m, 3 H), 7.63 (d, *J* = 8.7 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 33.6, 70.7, 85.4, 95.1, 112.6, 116.1, 120.6, 121.9, 127.5, 128.1, 128.7, 134.8, 136.77, 136.82, 156.8. HRMS (FD) Calcd for $C_{17}H_{14}N_2O$: M, 262.1106. Found: *m*/*z* 262.1128.



5-Bromo-1*H*-indole-3-carbonitrile (3i). The title compound was isolated by column chromatography on silica gel (*n*-hexane/EtOAc = 1/1, R_f = 0.43). An ocher solid, mp 177–178 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.36 (d, *J* = 8.7 Hz, 1 H), 7.44 (dd, *J* = 8.7, 1.8 Hz, 1 H), 7.74 (d, *J* = 1.8 Hz, 1 H), 7.93 (d, *J* = 1.8 Hz, 1 H), 8.74 (bs, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 87.4, 113.5, 115.0, 116.0, 122.4, 127.6, 128.5, 132.7, 133.5. HRMS (FI) Calcd for $C_9H_5BrN_2$: M, 219.9636. Found: *m*/*z* 219.9633.

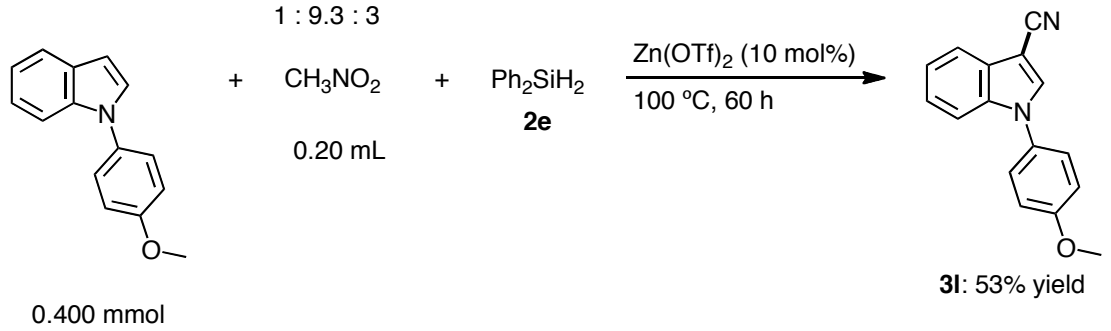


5-Bromo-1-methyl-1*H*-indole-3-carbonitrile (3j).[41] The title compound was isolated as a white solid by column chromatography on silica gel (*n*-hexane/EtOAc = 4/3, R_f = 0.33). This compound has already appeared in the literature, and its spectral and analytical data are in good agreement with those reported. Accordingly, only ^{1}H NMR data are provided here. ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.86 (s, 3 H), 7.28 (d, *J* = 8.6 Hz, 1 H), 7.45 (dd, *J* = 8.6, 1.7 Hz, 1 H), 7.57 (s, 1 H), 7.91 (d, *J* = 1.8 Hz, 1 H).

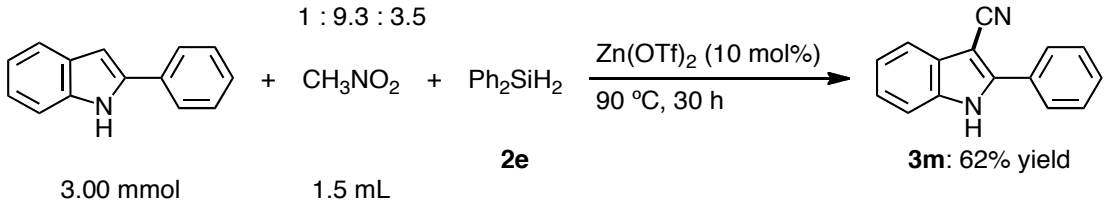


5-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolan-2-yl)-1*H*-indole-3-carbonitrile (3k). The title compound was isolated by column chromatography on silica gel (*n*-hexane/EtOAc = 2/1, R_f = 0.33). A white solid, mp 195–196 °C. ^{1}H NMR (400 MHz,

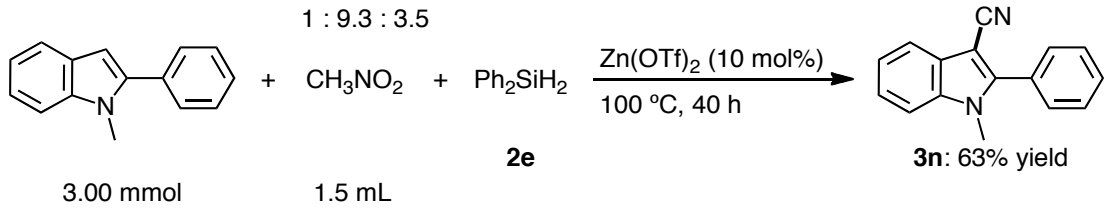
$CDCl_3$) δ 1.38 (s, 12 H), 7.46 (d, J = 8.2 Hz, 1 H), 7.73 (d, J = 2.8 Hz, 1 H), 7.77 (dd, J = 8.2, 0.9 Hz, 1 H), 8.33 (s, 1 H), 8.75 (bs, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 24.9, 83.9, 87.8, 111.5, 115.8, 126.6, 127.2, 130.2, 132.2, 136.8 (One carbon signal is missing due to overlapping). HRMS (FD) Calcd for $C_{15}H_{17}BN_2O_2$: M, 268.1383. Found: *m*/*z* 268.1392.



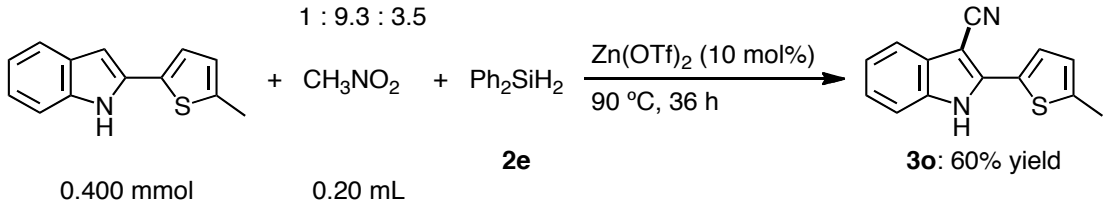
1-(4-Methoxyphenyl)-1*H*-indole-3-carbonitrile (3l).[42] The title compound was isolated as a white solid by recycling GPC after column chromatography on silica gel (*n*-hexane/EtOAc = 4/1, R_f = 0.50). This compound has already appeared in the literature, and its spectral and analytical data are in good agreement with those reported. Accordingly, only ^{1}H NMR data are provided here. ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.90 (s, 3 H), 7.05–7.09 (m, 2 H), 7.30–7.46 (m, 5 H), 7.75 (s, 1 H), 7.80–7.85 (m, 1 H).



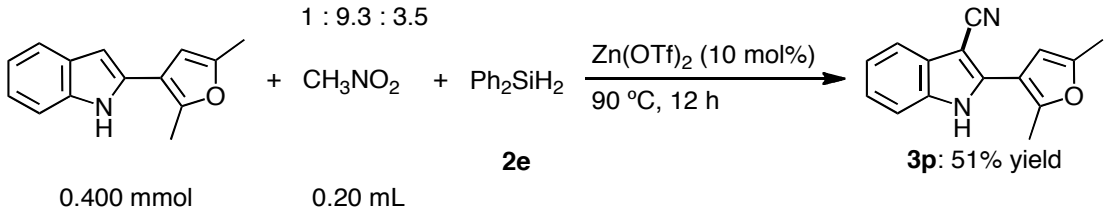
2-Phenyl-1*H*-indole-3-carbonitrile (3m).[43] The title compound was isolated as a white solid by column chromatography on silica gel twice (first: *n*-hexane/EtOAc = 2/1, R_f = 0.30; second: *n*-hexane/CH_2Cl_2 = 1/5, R_f = 0.53). This compound has already appeared in the literature, and its spectral and analytical data are in good agreement with those reported. Accordingly, only ^{1}H NMR data are provided here. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.28–7.37 (m, 2 H), 7.45–7.58 (m, 4 H), 7.79 (dd, J = 6.6, 2.1 Hz, 1 H), 7.85–7.93 (m, 2 H), 8.67 (bs, 1 H).



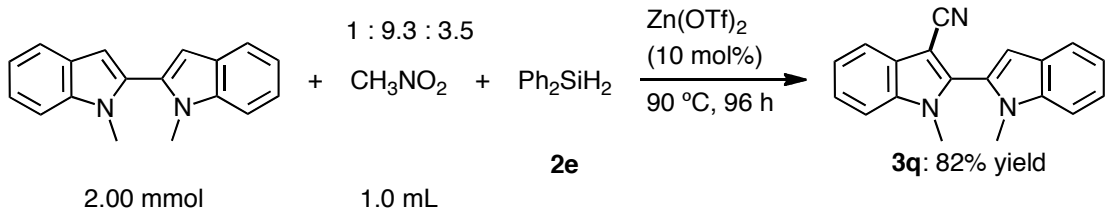
1-Methyl-2-phenyl-1*H*-indole-3-carbonitrile (3n).[43] The title compound was isolated as a light yellow solid by column chromatography on silica gel twice (first: *n*-hexane/EtOAc = 3/1, R_f = 0.33; second: *n*-hexane/$CHCl_3$ = 1/2, R_f = 0.43). This compound has already appeared in the literature, and its spectral and analytical data are in good agreement with those reported. Accordingly, only ^{1}H NMR data are provided here. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.77 (s, 3 H), 7.33 (ddd, *J* = 8.3, 6.9, 1.4 Hz, 1 H), 7.38 (ddd, *J* = 8.0, 6.9, 1.2 Hz, 1 H), 7.41–7.46 (m, 1 H), 7.50–7.65 (m, 5 H), 7.76–7.81 (m, 1 H).



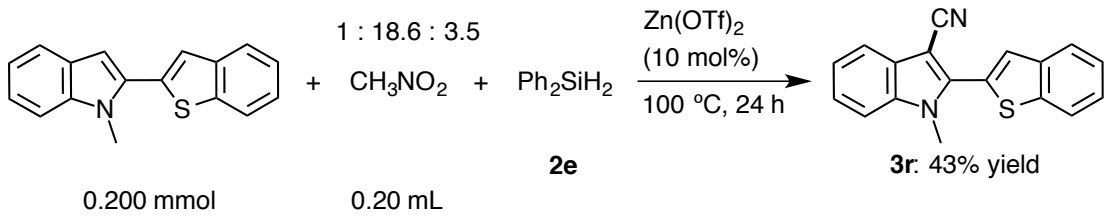
2-(5-Methylthiophen-2-yl)-1*H*-indole-3-carbonitrile (3o). The title compound was isolated by column chromatography on silica gel twice (first: *n*-hexane/EtOAc = 3/1, R_f = 0.33; second: *n*-hexane/$CHCl_3$ = 1/5, R_f = 0.33). A light yellow solid, mp 195–196 °C. ^{1}H NMR (400 MHz, acetone-d_6) δ 2.59 (s, 3 H), 6.94–6.99 (m, 1 H), 7.23–7.32 (m, 2 H), 7.47–7.51 (m, 1 H), 7.61–7.67 (m, 2 H), 11.40 (bs, 1 H); ^{13}C NMR (100 MHz, acetone-d_6) δ 15.3, 82.6, 112.9, 116.9, 119.3, 123.0, 124.9, 127.6, 128.3, 129.4, 130.1, 136.5, 140.3, 143.9. HRMS (FD) Calcd for $C_{14}H_{10}N_2S$: M, 238.0565. Found: *m*/*z* 238.0583.



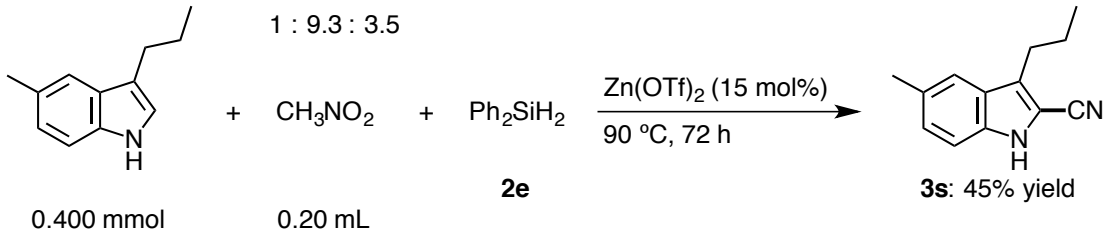
2-(2,5-Dimethylfuran-3-yl)-1*H*-indole-3-carbonitrile (3p). The title compound was isolated by column chromatography on silica gel twice (first: *n*-hexane/EtOAc = 3/1, R_f = 0.60; second: *n*-hexane/CH_2Cl_2 = 1/2, R_f = 0.47). A white solid, mp 214–215 °C. ^{1}H NMR (400 MHz, acetone-d_6) δ 2.32 (s, 3 H), 2.52 (s, 3 H), 6.46 (d, *J* = 0.92 Hz, 1 H), 7.22–7.32 (m, 2 H), 7.49–7.55 (m, 1 H), 7.61–7.68 (m, 1 H), 11.09 (bs, 1 H); ^{13}C NMR (100 MHz, acetone-d_6) δ 13.2, 13.8, 84.5, 107.3, 112.7, 113.0, 117.0, 119.1, 122.7, 124.4, 129.1, 136.6, 140.8, 150.2, 152.0. HRMS (FD) Calcd for $C_{15}H_{12}N_2O$: M, 236.0950. Found: *m*/*z* 236.0976.



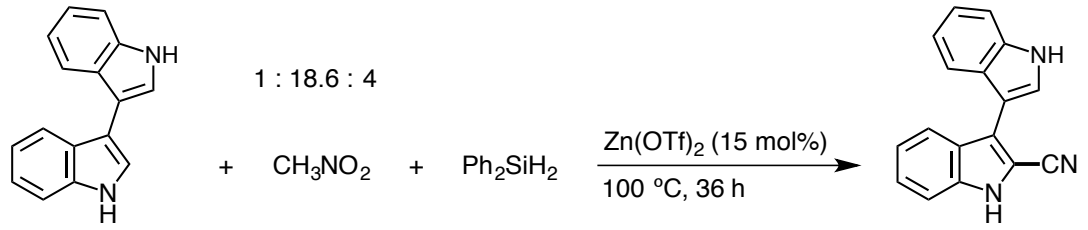
1,1'-Dimethyl-[2,2'-bi-1*H*-indole]-3-carbonitrile (3q).[44] The title compound was isolated by column chromatography on silica gel twice (first: *n*-hexane/EtOAc = 5/1, R_f = 0.30; second: *n*-hexane/CH_2Cl_2 = 1/2, R_f = 0.50). This compound has already appeared in the literature, and its spectral and analytical data are in good agreement with those reported. A white solid, mp 148–149 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.77 (s, 3 H), 3.78 (s, 3 H), 6.81 (s, 1 H), 7.23 (t, *J* = 7.6 Hz, 1 H), 7.34–7.40 (m, 2 H), 7.41–7.50 (m, 3 H), 7.72 (d, *J* = 7.8 Hz, 1 H), 7.83 (d, *J* = 7.8 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 31.3, 31.6, 88.3, 106.7, 110.1, 110.7, 115.9, 119.8, 120.6, 121.4, 122.7, 123.4, 124.4, 127.0, 127.4, 127.5, 136.9, 138.5, 138.8. HRMS (FI) Calcd for $C_{19}H_{15}N_3$: M, 285.1266. Found: *m*/*z* 285.1275.



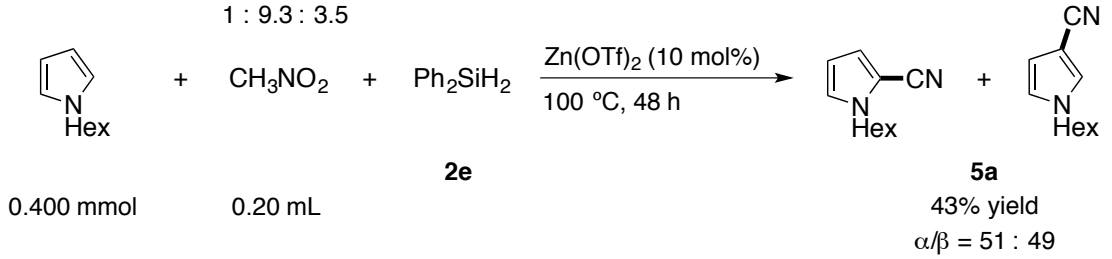
2-{Benzo[*b*]thien-2-yl}-1-methyl-1*H*-indole-3-carbonitrile (3r). The title compound was isolated by column chromatography on silica gel twice (first: *n*-hexane/EtOAc = 5/1, R_f = 0.37; second: *n*-hexane/CH_2Cl_2 = 1/2, R_f = 0.40). A white solid, mp 152–153 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.95 (s, 3 H), 7.34 (ddd, *J* = 8.0, 6.6, 1.1 Hz, 1 H), 7.38–7.49 (m, 4 H), 7.71 (s, 1 H), 7.79 (ddd, *J* = 7.8, 1.4, 0.9 Hz, 1 H), 7.87–7.95 (m, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 32.0, 87.3, 110.5, 116.2, 119.7, 122.2, 122.7, 124.5, 124.6, 125.1, 125.8, 127.4, 127.6, 128.9, 137.2, 139.2, 140.5, 141.0. HRMS (FI) Calcd for $C_{18}H_{12}N_2S$: M, 288.0721. Found: *m*/*z* 288.0739.



5-Methyl-3-propyl-1*H*-indole-2-carbonitrile (3s). The title compound was isolated by recycling GPC after column chromatography on silica gel (*n*-hexane/$CHCl_3$ = 1/10, R_f = 0.33). A light yellow solid, mp 95–96 °C. ^{1}H NMR (400 MHz, acetone-d_6) δ 0.97 (t, *J* = 7.6 Hz, 3 H), 1.77 (sext, *J* = 7.4 Hz, 2 H), 2.42 (s, 3 H), 2.89 (t, *J* = 7.6 Hz, 2 H), 7.19 (dd, *J* = 8.5, 1.6 Hz, 1 H), 7.36 (d, *J* = 8.7 Hz, 1 H), 7.50 (quint, *J* = 0.9 Hz, 1 H), 10.83 (bs, 1 H); ^{13}C NMR (100 MHz, acetone-d_6) δ 14.1, 21.5, 24.4, 27.4, 105.6, 112.8, 114.9, 120.4, 127.0, 128.5, 128.6, 130.5, 136.8. HRMS (FD) Calcd for $C_{13}H_{14}N_2$: M, 198.1157. Found: *m*/*z* 198.1163.



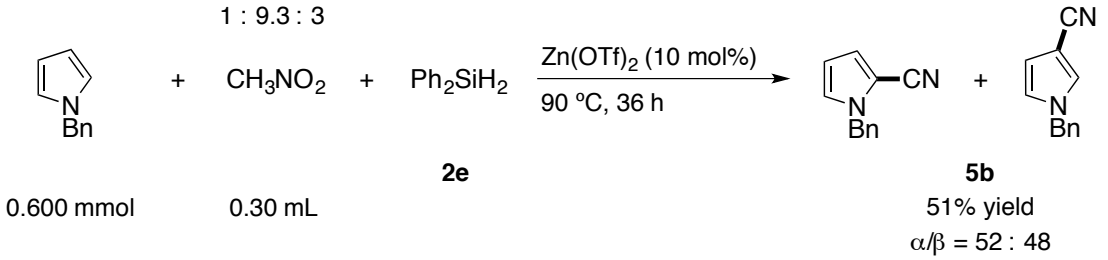
[3,3'-Bi-1*H*-indole]-2-carbonitrile (3t).[45] The title compound was isolated by column chromatography on silica gel (*n*-hexane/EtOAc = 3/1, R_f = 0.30). This compound has already appeared in the literature, but only its NMR spectra recorded in DMSO-d_6 are available. Therefore, its NMR spectra recorded in acetone-d_6 are provided here. A yellowish green solid, mp 222–223 °C. ^{1}H NMR (400 MHz, acetone-d_6) δ 7.13 (ddd, *J* = 8.0, 7.0, 1.1 Hz, 1 H), 7.17–7.27 (m, 2 H), 7.42 (ddd, *J* = 8.3, 7.0, 1.1 Hz, 1 H), 7.56 (dt, *J* = 8.2, 0.9 Hz, 1 H), 7.58 (dt, *J* = 8.5, 0.9 Hz, 1 H), 7.69 (d, *J* = 7.8 Hz, 1 H), 7.70–7.73 (m, 1 H), 7.76 (d, *J* = 8.2 Hz, 1 H), 10.70 (bs, 1 H), 11.25 (bs, 1 H); ^{13}C NMR (100 MHz, acetone-d_6) δ 104.8, 107.6, 112.7, 113.1, 115.5, 120.4, 120.8, 121.7, 122.5, 122.9, 123.5, 125.2, 125.4, 126.8, 127.4, 137.9, 138.6. HRMS (FD) Calcd for $C_{17}H_{11}N_3$: M, 257.0953. Found: *m*/*z* 257.0975.



1-Hexyl-1*H*-pyrrole-2-carbonitrile (α-5a). The title compound was isolated by bulb-to-bulb distillation (150 °C/300 Pa) after column chromatography on silica gel (*n*-hexane/EtOAc = 5/1, R_f = 0.67). A colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.83–0.94 (m, 3 H), 1.23–1.37 (m, 6 H), 1.74–1.88 (m, 2 H), 4.03 (t, *J* = 7.3 Hz, 2 H), 6.16 (dd, *J* = 3.9, 2.6 Hz, 1 H), 6.77 (dd, *J* = 4.0, 1.6 Hz, 1 H), 6.83 (dd, *J* = 2.6, 1.6 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.9, 22.5, 26.1, 31.1, 31.2, 49.0, 103.6, 109.3, 113.9, 119.8, 126.3. HRMS (FI) Calcd for $C_{11}H_{16}N_2$: M, 176.1314. Found: *m*/*z* 176.1296.

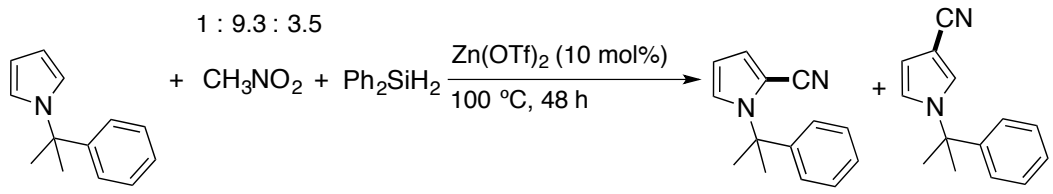
1-Hexyl-1*H*-pyrrole-3-carbonitrile (β-5a). The title compound was isolated by bulb-to-bulb distillation (200 °C/300 Pa) after column chromatography on silica gel (*n*-

hexane/EtOAc = 5/1, R_f = 0.47). A light yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.85–0.92 (m, 3 H), 1.20–1.36 (m, 6 H), 1.69–1.82 (m, 2 H), 3.87 (t, *J* = 7.2 Hz, 2 H), 6.40 (dd, *J* = 2.9, 1.6 Hz, 1 H), 6.61 (dd, *J* = 2.8, 2.2 Hz, 1 H), 7.11 (t, *J* = 1.9 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.9, 22.4, 26.1, 31.1, 31.2, 50.3, 92.4, 112.0, 117.0, 121.8, 127.6. HRMS (FI) Calcd for $C_{11}H_{16}N_2$: M, 176.1314. Found: *m/z* 176.1306.



1-Benzyl-1*H*-pyrrole-2-carbonitrile (α-5b).[46] The title compound was isolated as a dark yellow oil by column chromatography on silica gel twice (first: *n*-hexane/$CHCl_3$ = 1/5, R_f = 0.50; second: *n*-hexane/EtOAc = 5/1, R_f = 0.50). This compound has already appeared in the literature, and its spectral and analytical data are in good agreement with those reported. Accordingly, only ^{1}H NMR data are provided here. ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.21 (s, 2 H), 6.20 (dd, *J* = 4.0, 2.8 Hz, 1 H), 6.83 (dd, *J* = 3.8, 1.4 Hz, 1 H), 6.85 (dd, *J* = 2.8, 2.0 Hz, 1 H), 7.19 (d, *J* = 7.2 Hz, 2 H), 7.29–7.40 (m, 3 H).

1-Benzyl-1*H*-pyrrole-3-carbonitrile (β-5b).[46] The title compound was isolated as a dark yellow oil by column chromatography on silica gel twice (first: *n*-hexane/$CHCl_3$ = 1/5, R_f = 0.27; second: *n*-hexane/EtOAc = 3/1, R_f = 0.50). This compound has already appeared in the literature, and its spectral and analytical data are in good agreement with those reported. Accordingly, only ^{1}H NMR data are provided here. ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.07 (s, 2 H), 6.45 (dd, *J* = 3.0, 1.8 Hz, 1 H), 6.66 (dd, *J* = 2.6, 2.4 Hz, 1 H), 7.11–7.15 (m, 2 H), 7.16 (t, *J* = 1.8 Hz, 1 H), 7.31–7.41 (m, 3 H).



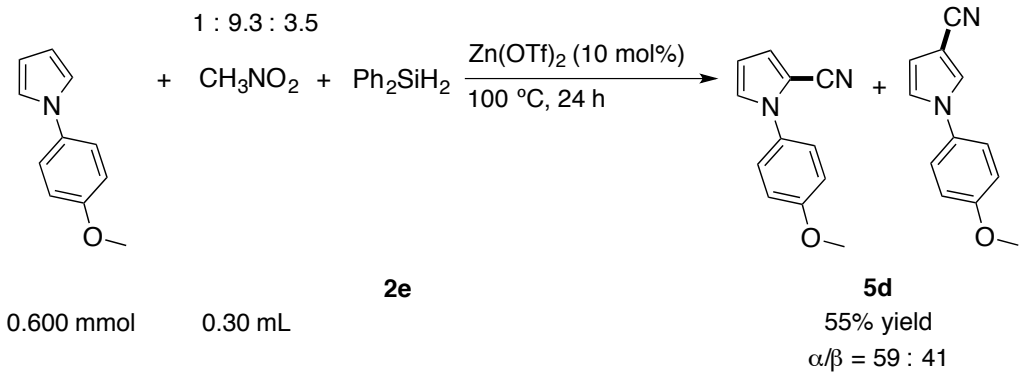
2e **5c**

0.400 mmol 0.20 mL 69% yield

α/β = 41 : 59

1-(2-Phenylpropan-2-yl)-1*H*-pyrrole-2-carbonitrile (α-5c). The title compound was isolated by column chromatography on silica gel twice (first: *n*-hexane/EtOAc = 8/1, R_f = 0.50; second: *n*-hexane/$CHCl_3$ = 1/2, R_f = 0.27). A light yellow solid, mp 94–95 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.00 (s, 6 H), 6.18 (dd, *J* = 4.1, 2.8 Hz, 1 H), 6.86 (dd, *J* = 4.1, 1.8 Hz, 1 H), 7.07–7.11 (m, 2 H), 7.15 (dd, *J* = 2.8, 1.8 Hz, 1 H), 7.27–7.37 (m, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 30.5, 62.6, 103.0, 107.9, 114.4, 123.0, 124.6, 125.1, 127.7, 128.7, 145.4. HRMS (FD) Calcd for $C_{14}H_{14}N_2$: M, 210.1157. Found: *m*/*z* 210.1160.

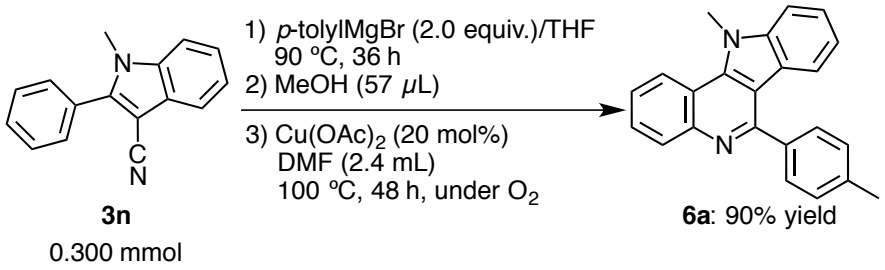
1-(2-Phenylpropan-2-yl)-1*H*-pyrrole-3-carbonitrile (β-5c). The title compound was isolated by column chromatography on silica gel twice (first: *n*-hexane/EtOAc = 8/1, R_f = 0.40; second: *n*-hexane/$CHCl_3$ = 1/4, R_f = 0.33). A light yellow solid, mp 91–92 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.89 (s, 6 H), 6.45 (dd, *J* = 3.1, 1.7 Hz, 1 H), 6.69 (dd, *J* = 3.0, 2.4 Hz, 1 H), 7.00–7.05 (m, 2 H), 7.24–7.35 (m, 4 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 30.4, 61.7, 92.4, 111.8, 117.0, 120.7, 124.9, 126.6, 127.7, 128.7, 145.9. HRMS (FD) Calcd for $C_{14}H_{14}N_2$: M, 210.1157. Found: *m*/*z* 210.1146.



1-(4-Methoxyphenyl)-1*H*-pyrrole-2-carbonitrile (α-5d).[47] The title compound was isolated as a light yellow solid by column chromatography on silica gel twice (first: *n*-hexane/EtOAc = 5/1, R_f = 0.43; second: *n*-hexane/$CHCl_3$ = 1/5, R_f = 0.50). This compound has already appeared in the literature, and its spectral and analytical data are in good agreement with those reported. Accordingly, only ^{1}H NMR data are provided here. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.86 (s, 3 H), 6.32 (dd, *J* = 4.0, 2.7 Hz, 1 H), 6.96 (dd, *J* = 4.0, 1.7 Hz, 1 H), 6.97–7.04 (m, 3 H), 7.34–7.39 (m, 2 H).

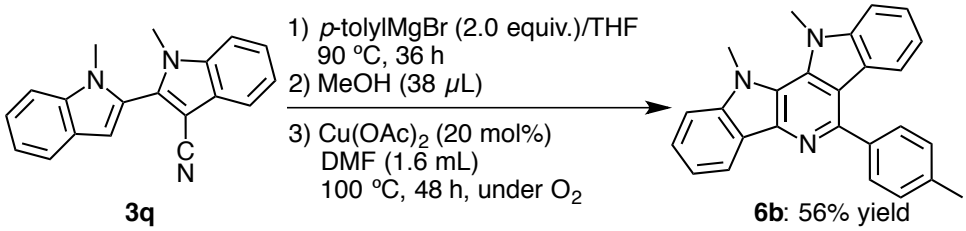
1-(4-Methoxyphenyl)-1*H*-pyrrole-3-carbonitrile (β-5d). The title compound was isolated by column chromatography on silica gel twice (first: *n*-hexane/EtOAc = 5/1, R_f = 0.30; second: *n*-hexane/$CHCl_3$ = 1/10, R_f = 0.50). A dark yellow solid, mp 80–81 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.85 (s, 3 H), 6.57 (dd, *J* = 3.0, 1.7 Hz, 1 H), 6.94 (dd, *J* = 3.0, 2.2 Hz, 1 H), 6.96–7.01 (m, 2 H), 7.25–7.31 (m, 2 H), 7.42 (dd, *J* = 2.2, 1.7 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 55.6, 94.4, 113.0, 114.9, 116.5, 121.5, 123.0, 126.8, 132.7, 159.0. HRMS (FD) Calcd for $C_{12}H_{10}N_2O$: M, 198.0793. Found: *m*/*z* 198.0769.

One-Pot Annulation of 3n and 3q (Scheme 1).



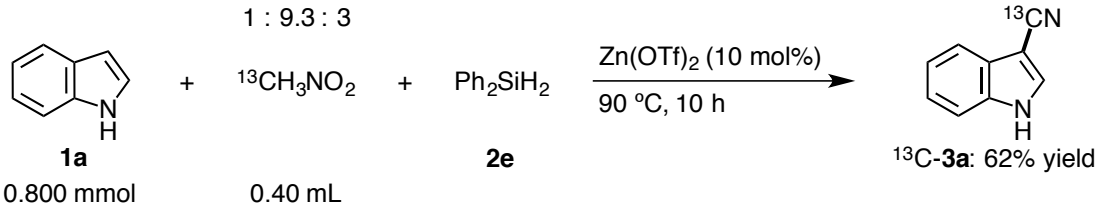
Synthesis of 11-Methyl-6-(*p*-tolyl)-11*H*-indolo[3,2-*c*]quinoline (6a). The compound (**6a**) in the title was prepared according to the following modified literature

procedure.[48] A flame-dried 20 mL Schlenk tube was filled with argon and then charged with **3n** (69.7 mg, 0.300 mmol) and THF (0.30 mL). To this was added dropwise a THF solution of *p*-tolylmagnesium bromide (0.60 mL, 0.60 mmol, 1.0 M) at 0 °C. The reaction mixture was stirred at 90 °C for 36 h and then treated with anhydrous MeOH (57 μL) at room temperature. Anhydrous copper acetate (10.9 mg, 60.0 μmol) and anhydrous DMF (2.40 mL) were then added. The reaction mixture was further stirred at 100 °C under an oxygen atmosphere for 48 h. The reaction was quenched by addition of a saturated NH_4Cl aqueous solution (0.5 mL) and the aqueous phase was extracted with Et_2O (7 mL x 3). The combined organic layer was washed with water (2 mL) and brine (2 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (*n*-hexane/EtOAc = 3/1 containing 3 vol% of Et_3N, R_f = 0.60) gave 11-methyl-6-(*p*-tolyl)-11*H*- indolo[3,2-*c*]quinoline (87.1 mg, 90% yield) as a white solid, mp 182–183 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.51 (s, 3 H), 4.45 (s, 3 H), 7.12–7.19 (m, 1 H), 7.37–7.42 (m, 2 H), 7.47–7.52 (m, 1 H), 7.54–7.65 (m, 3 H), 7.69–7.77 (m, 3 H), 8.35 (dd, *J* = 8.7, 0.9 Hz, 1 H), 8.68 (dd, *J* = 8.7, 0.9 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 21.5, 33.6, 109.6, 113.3, 117.4, 120.6, 121.7, 121.9, 122.1, 125.1, 125.3, 127.8, 128.9, 129.3, 130.7, 138.2, 138.6, 140.6, 140.8, 146.6, 156.5. HRMS (FD) Calcd for $C_{23}H_{18}N_2$: M, 322.1470. Found: *m*/*z* 322.1493.

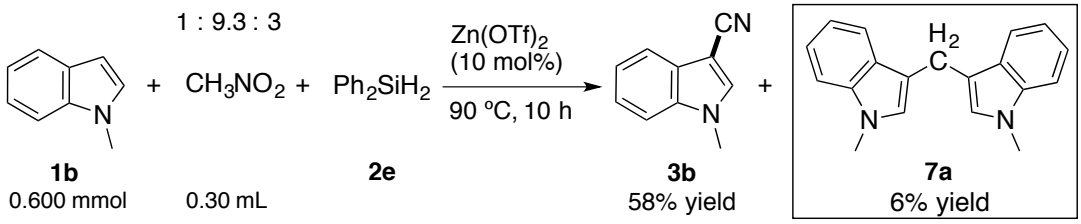


Synthesis of 11,12-Dihydro-11,12-dimethyl-6-(*p*-tolyl)pyrido[3,2-*b*:4,5-*b*']diindole (6b). The compound (**6b**) was prepared by the same procedure as in the synthesis of **6a**. A flame-dried 20 mL Schlenk tube was filled with argon and then charged with **3q** (57.1 mg, 0.200 mmol) and THF (0.20 mL). To this was added dropwise a THF solution of *p*-tolylmagnesium bromide (0.40 mL, 0.40 mmol, 1.0 M) at 0 °C. The reaction mixture was stirred at 90 °C for 36 h and then treated with anhydrous MeOH (38 μL) at room temperature. Anhydrous copper acetate (8.60 mg, 40.0 μmol)

and anhydrous DMF (1.60 mL) were then added. The reaction mixture was further stirred at 100 °C under an oxygen atmosphere for 48 h. The reaction was quenched by addition of a saturated NH_4Cl aqueous solution (0.5 mL) and the aqueous phase was extracted with Et_2O (7 mL x 3). The combined organic layer was washed with water (2 mL) and brine (2 mL), and then dried over anhydrous sodium sulfate. Filtration and evaporation of the solvent followed by column chromatography on silica gel (*n*-hexane/EtOAc = 2/1 containing 3 vol% of Et_3N, R_f = 0.43) gave 11,12-dihydro-11,12-dimethyl-6-(*p*-tolyl)pyrido[3,2-*b*:4,5-*b*']diindole (42.3 mg, 56% yield) as a white solid, mp 224–225 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.51 (s, 3 H), 4.23 (s, 3 H), 4.28 (s, 3 H), 7.08–7.15 (m, 1 H), 7.31–7.37 (m, 1 H), 7.39 (d, *J* = 7.8 Hz, 2 H), 7.44–7.59 (m, 5 H), 7.71 (d, *J* = 7.8 Hz, 2 H), 8.49 (d, *J* = 7.8 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 21.5, 35.7, 36.5, 109.4, 109.8, 116.3, 120.3, 120.4, 120.9, 121.9, 122.1, 123.3, 124.2, 125.7, 126.7, 129.2, 129.3, 134.1, 138.0, 138.5, 139.6, 142.2, 143.5, 149.4. HRMS (FD) Calcd for $C_{26}H_{21}N_3$: M, 375.1736. Found: *m*/*z* 375.1772.



1*H*-Indole-3-carbonitrile-*cyano*-^{13}C (^{13}C-3a). The title compound was isolated by column chromatography on silica gel (*n*-hexane/EtOAc = 3/1, R_f = 0.30). A light yellow solid, mp 156–157 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.28–7.37 (m, 2 H), 7.48 (d, *J* = 8.0 Hz, 1 H), 7.73 (t, *J* = 2.6 Hz, 1 H), 7.79 (d, *J* = 7.4 Hz, 1 H), 8.76 (bs, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 87.0 (d, *J* = 94.4 Hz), 112.1, 115.9, 119.7, 122.4, 124.3, 127.0 (d, *J* = 3.3 Hz), 131.9 (d, *J* = 6.7 Hz), 134.9 (d, *J* = 4.8 Hz). HRMS (FD) Calcd for $^{12}C_8{}^{13}CH_6N_2$: M, 143.0565. Found: *m*/*z* 143.0587.



3,3'-Methylenebis[1-methyl-1*H*-indole] (7a). The title compound (**7a**) was produced as a by-product in the reaction of *N*-methylindole (**1b**), and isolated in 6% yield by column chromatography on silica gel twice (first: *n*-hexane/EtOAc = 5/2, R_f = 0.60; second: *n*-hexane/$CHCl_3$ = 2/1, R_f = 0.40). Compound **7a** was fully characterized by ^1H and ^{13}C NMR spectroscopy and HRMS, as follows: A dark red paste. ^1H NMR (500 MHz, acetone-d_6) δ 3.74 (s, 6 H), 4.18 (s, 2 H), 6.95–7.00 (m, 4 H), 7.13 (t, *J* = 7.7 Hz, 2 H), 7.32 (d, *J* = 8.2 Hz, 2 H), 7.57 (d, *J* = 8.0 Hz, 2 H); ^{13}C NMR (125 MHz, acetone-d_6) δ 21.5, 32.5, 110.0, 114.9, 119.1, 119.8, 121.9, 127.9, 128.9, 138.2. HRMS (FI) Calcd for $C_{19}H_{18}N_2$: M, 274.1470. Found: *m/z* 274.1474.

Recovery of $Zn(OTf)_2$. After cyanation reaction of **1a** (375 mg, 3.20 mmol) performed at 90 °C for 10 h by using 10 mol% of $Zn(OTf)_2$ (116 mg, 0.320 mmol), the reaction mixture was diluted with Et_2O (50 mL). The resulting solution was extracted with deionized water (20 mL x 7), and the collected aqueous layer was washed with hexane (50 mL x 3). To the aqueous solution was added activated carbon (3.3 g), and the resulting mixture was stirred for 2 min. Filtration to remove the activated carbon and evaporation of H_2O gave hydrate of $Zn(OTf)_2$. The resulting hydrate was warmed slowly to 150 °C over a period of 1 h under vacuum and the heating was continued for additional 10 h to give $Zn(OTf)_2$ (113 mg, 97% recovery efficiency) as a reddish brown powder whereas its original color is white.

VI-4. References and Notes

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2 a) Larock, R. C. *Comprehensive Organic Transformations*, Wiley-VCH, New York, **1999**; b) Sun, M.; Zhang, H.-Y.; Han, Q.; Yang, K.; Yang, S.-D. *Chem. Eur. J.* **2011**, *17*, 9566.

3 For reviews on cyanation of aryl halides, see: a) Sundermeier, M.; Zapf, A.; Beller, M. *Eur. J. Inorg. Chem.* **2003**, 3513. b) Anbarasan, P.; Schareina, T.; Beller, M. *Chem. Soc. Rev.* **2011**, *40*, 5049. For selected recent reports on cyanation of aryl halides, see: c) Ushkov, A. V.; Grushin, V. V. *J. Am. Chem. Soc.* **2011**, *133*, 10999. d) Yu, H.; Richey, R. N.; Miller, W. D.; Xu, J.; May, S. A. *J. Org. Chem.* **2011**, *76*, 665. e) Chen, J.; Sun, Y.; Liu, B.; Liu, D.; Cheng, J. *Chem. Commun.* **2012**, *48*, 449.

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5 Cyanation reactions of pre-activated (hetero)arenes with organic cyanides have also appeared in literature. For selected recent examples, see: a) Anbarasan, P.; Neumann, H.; Beller, M. *Chem. Eur. J.* **2010**, *16*, 4725. b) Anbarasan, P.; Neumann, H.; Beller, M. *Angew. Chem., Int. Ed.* **2011**, *50*, 519. c) Anbarasan, P.; Neumann, H.; Beller, M. *Chem. Eur. J.* **2011**, *17*, 4217. d) Schareina, T.; Zapf, A.; Cotté, A.; Gotta, M.; Beller, M. *Adv. Synth. Catal.* **2011**, *353*, 777. e) Zhang, G.; Ren, X.; Chen, J.; Hu, M.; Cheng, J. *Org. Lett.* **2011**, *13*, 5004. f) Jiang, Z.; Huang, Q.; Chen, S.; Long, L.; Zhou, X. *Adv. Synth. Catal.* **2012**, *354*, 589. g) Song, R.-J.; Wu, J.-C.; Liu, Y.; Deng, G.-B.; Wu, C.-Y.; Wei, W.-T.; Li, J.-H. *Synlett* **2012**, *23*, 2491. h) Wen, Q.; Jin, J.; Hu, B.; Lu, P.; Wang, Y. *RSC Adv.* **2012**, *2*, 6167. i) Wen, Q.; Jin, J.; Mei, Y.; Lu, P.; Wang, Y. *Eur. J. Org. Chem.* **2013**, 4032. See also the following

important review for more related studies: j) Kim, J.; Kim, H. J.; Chang, S. *Angew. Chem., Int. Ed.* **2012**, *51*, 11948.

6 *Comprehensive Organic Name Reactions and Reagents, Vol. 3* (Ed. Z. Wang), Wiley, New York, **2009**, pp. 2471–2475.

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Chapter VII. Conclusions and Prospects

This thesis discusses a novel transformation of indoles in the presence of a catalytic amount of Lewis acid having perfluoroalkylsulfonyloxy ligands.

Chapter II discusses the first annulation reaction, developed by the author, which allows the assembly of two readily accessible building blocks, 2-(hetero)arylindoles and propargyl ethers, into aryl- and heteroaryl-annulated[*a*]carbazoles (AHA[*a*]Cs). The methodology with substrate diversity enables us to synthesize various AA[*a*]Cs, HA[2,3-*a*]Cs, and HA[3,2-*a*]Cs. The achievement of the short-step process is attributed to the indium-catalyzed annulation including two carbon–carbon bond-forming reactions in combination with the reliable Fischer indole synthesis. The reaction can be applied also to bithiophene and bifuran derivatives. The annulation most likely proceeded in the following order: intermolecular addition reaction followed by intramolecular S_N2 reaction and aromatization, which reasonably explains the regiochemical outcome of AHA[*a*]Cs. In the transformation of AHA[*a*]Cs, some organic functional groups were efficiently introduced. Furthermore, a methyl group on an AHA[*a*]C was successfully removed. Based on the novel annulation reaction, photophysical properties of AHA[*a*]Cs were described. The evaluation of fluorescence spectra showed that almost all their emission bands appear in the visible region (purple to green) and that FL quantum yields are highly dependent on the core structures, nature of substituents, and position of substituents attached. Some structure–property correlations on AHA[*a*]Cs elucidated in the present study are as follows: (1) Introduction of an electron-rich aryl group onto the nitrogen atom enhances fluorescence efficiency and causes a red-shift of fluorescence spectra. (2) A *p*-cyanophenyl group on the nitrogen atom has a large bathochromic effect. (3) Furan rings are more effective than pyrrole and thiophene rings for achieving higher quantum yield (Φ_F). (4) HA[3,2-*a*]Cs are more fluorescent compared to the corresponding HA[2,3-*a*]Cs. (5) AHA[*a*]Cs having an aryl group on the nitrogen atom exhibit positive solvatochromic behavior as solvent polarity increased.

The author has developed a new synthetic method of (hetero)aryl[*c*]carbazoles, which can be efficiently constructed by the two carbon–carbon bond-forming cascade in one batch through the annulation of 3-(hetero)arylindoles with propargyl ethers. One important aspect is the selective synthesis of **3** and **4** with the proper choice of the C3 source. The development of this reaction gave us a great opportunity to evaluate emission properties of the product, thereby showing that the [*c*]-type is more emissive than the [*a*]-type. As a continuation of this research project, the application of this

strategy to the [*b*]-type that remains yet unaddressed would be suitable.

In Chapter IV, the author describes a new synthetic method of (hetero)aryl[*b*]carbazoles by the indium-catalyzed annulation of indoles with (2-ethynylaryl)methyl ethyl carbonates. The reaction proceeds in one batch through the two carbon–carbon bond-forming cascade. The development of this reaction gave the author a great opportunity to investigate some unique structure–property correlations with regard to the photoluminescent properties of AACs reflecting all the three types.

In Chapter V, the author describes the catalytic S_NAr based-heteroaryl–heteroaryl bond-forming reaction using easily available two heteroaryl substrates both of which require no activating groups. This is so far the first report of such synthetic route. The author proposed a possible reason, why heteroaryl electrophiles **2** with no electron-withdrawing groups work well, based on the mechanistic studies on which complex **A** is the plausible coordination mode. In general, transition metal-catalyzed cross-coupling using indolyl- and pyrrolylmetals is not an easy task since their pre-synthesis requires multistep. This new method will thus be highly useful in such cases.

In Chapter VI, the author described the zinc-catalyzed cyanation of indoles and pyrroles with nitromethane and Ph_2SiH_2. This is the first demonstration of the Lewis acid-catalyzed direct cyanation of C(aryl)–H bonds with no CN group-containing cyanating agent. In terms of the promotion of sustainable chemistry, the use of a common metal, such as zinc as the catalyst, is an advantage of this approach.

The author also found that some Lewis acids such as metal triflates are quite unique and efficient to functionalize indole derivatives. In particular, readily available indium salts containing perfluoroalkylsulfonyloxy units [$In(ONf)_3$ and $In(OTf)_3$] effectively activate electron-rich unsaturated carbon–carbon bonds such as a carbon–carbon triple bond and an aromatic ring. The success of these reactions is attributed to the ligand effect that the perfluoroalkylsulfonyloxy ligand is more electron-withdrawing than halides. Furthermore, the author also found that $Zn(OTf)_2$-hydrosilanes-nitromethane system is effective cyanation reagent to indoles.

The studies discussed in this thesis have successfully demonstrated Lewis acid-catalyzed reactions using metal triflates to be attractive not only for synthetic organic synthesis but also for potential applications in environmental and industrial chemistry. Therefore, studies on Lewis acid catalyzed transformation of indoles will continue to be significant and challenging even in the future

List of Publications

Chapter II

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Acknowledgment

The research work described in this thesis was carried out under the supervision of Associate Professor Teruhisa Tsuchimoto at the Department of Applied Chemistry, School of Science and Technology, Meiji University from 2004 until 2014. The author would like to express his deepest gratitude to Associate Professor Teruhisa Tsuchimoto for his instructive directions, helpful suggestions, and continuous encouragement through the course of this work.

The author wishes to thank Dr. Shinji Kanehashi, Mr. Kazuki Aoki, Mr. Takuhiro Miyamura, and Mr. Tatsuya Wagatsuma for their daily discussion and suggestion, hearty encouragement, and many advices. Special thanks are due to Associate Professor Eiji Shirakawa, Mr. Hiromichi Matsubayashi, Mr. Masayoshi Kaneko, Ms. Mami Iwabuchi, Mr. Hiroyuki Shirai, Mr. Hiroshi Takahashi, Mr. Kensuke Inoue, Mr. Kenji Oki, Mr. Tetsuya Sugiyama, and Mr. Kyohei Yonekura for their contribution to a part of this thesis. The author thanks to all members of the Tsuchimoto Groups for their valuable discussion, kind help, and friendship.

Finally, the author would like to appreciate his parents, Yu Nagase and Yoko Nagase, and his wife, Hiromi Nagase for their constant support, endless encouragement, and confidence in him, when he needed the most.

March, 2014

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