Indium-catalyzed Annulation of Indoles with Ethyl (2-Ethynylaryl)methyl Carbonates: Synthesis and Photoluminescent Properties of Aryl- and Heteroaryl[b]carbazoles

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Two successive carbon–carbon bond-forming annulation of indoles with ethyl (2-ethynylaryl)methyl carbonates and their heteroaryl analogs under indium catalysis provided aryl- and heteroaryl[*b*]carbazoles, photoluminescent properties of which were then evaluated and compared with those of the corresponding [*a*]- and [*c*]-types, thereby showing that the order of light-emitting efficiency is [a] - < [b] - < [c]-type.

Aryl- and heteroaryl-annulated carbazoles (AHACs) have attracted much attention due to their biological and pharmacological activities¹ 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, we first 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 us 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 $C \equiv C$ and C-O bonds of propargyl ethers. We 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} We present 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.

Initially, we 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: SO₂C₄F₉) in Bu₂O as a useful system found in our preceding studies,^{3,4} treating **1a** and 2-ethynylbenzyl methyl ether (2a) at 85 °C 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 silvloxy or acyloxy group gave no marked improvement in the yield, but 2g with OCO₂Me 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-Ethynylbenzyl alcohol (21) as a commercial source was ineffective (Entry 12). The studies on the ratio of 1a and 2h showed that the use of 2 molar equivalents of 1a relative to 2h is suitable (Entries 8, 13, and 14). Due to different nucleophilicity of the C2 and C3 of indoles, achievement of S_EAr-based carboncarbon bond-forming annulation of indoles that react with two different functionalities seems not to be an easy task, and in fact,

Table 1. Indium-catalyzed annulation of *N*-methylindole with 2-ethynylbenzyl ether derivatives 2^{a}

× +	RO 1 2 In(ONf) ₃ (20 mol%) Bu ₂ O, 85 °C		6+	N 42
Entry	D in 2	Time	Yield	3a.1ab
Enuy	K III Z	/h	/% ^b	Ja.4a
1	Me (2a)	24	11	9:91
2	SiMe ₃ (2b)	3	29	87:13
3	$SiMe_2t$ -Bu (2c)	7	18	76:24
4	COMe (2d)	24	11	64:36
5	COt-Bu (2e)	24	<1	—
6	COCF ₃ (2f)	24	19	67:33
7	$CO_2Me(2g)$	24	58	84:16
8	CO ₂ Et (2h)	24	79	86:14
9	CO ₂ <i>i</i> -Pr (2i)	24	54	83:17
10	CO ₂ <i>t</i> -Bu (2j)	24	16	74:26
11	CO_2Ph (2k)	24	69	87:13
12	Н (21)	7	17	73:27
13 ^c	CO ₂ Et (2h)	24	53	84:16
14 ^d	CO ₂ Et (2h)	24	80	85:15

^aReagents: **1a** (0.20 mmol), **2** (0.10 mmol), In(ONf)₃ (20 μ mol), and Bu₂O (0.10 mL). ^bDetermined by ¹H NMR. ^c**1a:2h** = 1.5:1. ^d**1a:2h** = 2.5:1.

only a handful of related works have emerged in literature, to our knowledge.¹¹ The present reaction would thus be an important new entry for such indole-based annulation.

Having the suitable reaction conditions in hand, we 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 to be 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

The strategy can be extended to synthesize heteroaryl derivatives. Thus, the reaction of thienyl electrophile 20 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.

 Table 2. Indium-catalyzed annulation of indoles with ethyl

 2-ethynylbenzyl carbonates^a



^aReagents: **1** (0.20 mmol), **2** (0.10 mmol), $In(ONf)_3$ (20 µmol), and Bu_2O (0.10 mL). ^bIsolated yield based on **2**. ^cDetermined by ¹H NMR. ^dBn: benzyl. ^eIn(ONf)₃ (30 µmol) was used. ^fAr: 4-MeOC₆H₄.



On the basis of our 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.

Finally, we investigated the photoluminescent properties of aryl[*b*]carbazoles **3f**, **3a**, and **3e** as representatives and compared



Scheme 1. Plausible reaction mechanisms.

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

	AACs			
	[a]-type	[b]-type	[c]-type	
$\lambda_{ m max}/ m nm^b$ $\Phi_{ m F}{}^{ m c}$	6f (R = H) 360, 378, 397 0.165	3f (R = H) 401, 423 0.240	7f (R = H) 362, 380, 399sh 0.334	
$\lambda_{ m max}/ m nm^b$ ${arPsi_F}^c$	6a (R = Me) 371, 389, 408sh 0.184	3a (R = Me) 414, 438, 464sh 0.327	7a (R = Me) 374, 392, 413sh 0.391	
$\lambda_{ m max}/ m nm^b$ $\Phi_{ m F}^{ m c}$	6e (R = Ar ^d) 367, 385, 404sh 0.264	$3e (R = Ar^{d}) 411, 432 0.368$	7e (R = Ard) 372, 388, 408sh 0.481	
^a Fluorescence spectra excited at 265 nm were measured in				

^aFluorescence 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 refs 3b and 4, respectively. ^bsh: shoulder. ^cDetermined with reference to the quantum yield of *p*-terphenyl. ^dAr: 4-MeOC₆H₄.

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 $\Phi_{\rm F}$ 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.

In closing, we have developed a new synthetic method of (hetero)aryl[b]carbazoles by the indium-catalyzed annulation of

indoles with ethyl (2-ethynylaryl)methyl carbonates. The reaction proceeds in one batch through the two carbon–carbon bondforming cascade. The development of this reaction gave us a great opportunity to investigate some unique structure–property correlations concerning photoluminescent properties of AACs reflecting all the three types.

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We will further study the scope of the seven-membered ringforming annulation and report the result in due course.

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