Investigation of the Reaction of *N*-Substituted Indolylborates: Palladium Catalyzed Cross-Coupling Reactions and Intramolecular Alkyl Migration Reactions

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The palladium catalyzed cross-coupling reaction of indolylborates with various *N*-protecting groups was investigated, where *N*-Methyl, *N*-methoxy, and *N-tert*-butoxycarbonyl groups were found to be useful. However, triethyl(1-methoxymethylindol-2-yl)borate could not be used for this reaction. It was also found that the alkyl migration reaction of trialkyl(1-methoxymethylindol-2-yl)borate produced 2-alkyl-1-methylindole accompanied by the unexpected reduction of 1-methoxymethyl group to 1-methyl group.

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Recent reports from our laboratory demonstrate that indolylborate acts as a potential synthetic intermediate for the preparation of indole derivatives, in which the palladium catalyzed cross-coupling reaction of indolylborate has been developed as a versatile synthetic procedure [1]. In this context, we have investigated the reactivity of indolylborates **2** with various *N*-protecting groups for the palladium catalyzed cross-coupling reaction, and also found that the intramolecular alkyl migration reaction of triethyl(1-methoxymethylindol-2-yl)borate **2f** produced 2-ethyl-1-methylindole **5a**. The present paper describes these results including the full details of the previously reported results [2,3].

The palladium catalyzed cross-coupling reaction of 1-substituted indolylborates **2** was initially examined (Scheme 1). Generation of indolylborates **2** *in situ* was simply effected by the lithiation of the corresponding indoles **1** with *n*- or *tert*-butyllithium in tetrahydrofuran under an argon atmosphere, followed by the treatment with triethylborane. With a variety of halides and triflates **3**, the reaction of indolylborates **2** in the presence of a catalytic amount of dichlorobis(triphenylphosphine)palladium(II) in tetrahydrofuran under an argon atmosphere was studied, and the results are summarized in Table 1. As shown in Table 1, indolylborates **2a**, **2c**, **2d** with methyl, methoxy, and *tert*-butoxycarbonyl groups at 1-position, respectively, worked well under the present reaction conditions to give rise to 2-substituted indoles **4** in moderate to good yields. The strong electron-withdrawing effect of the *N*-phenylsulfonyl group retarded the reaction of indolylborate **2e**. Contrary to expectation, 1-methoxymethylindolylborate **2f** was found to be uneffective on the present cross-coupling reaction, providing no isolable product.

On the other hand, quenching 1-methoxymethylindolylborates **2f**, **2i**, **2j** with methanol, 2-alkyl-1-methylindoles **5a** [4] (in 65% yield), **5b** (in 61% yield), and **5d** [5] (in 28% yield) were readily produced through an intramolecular alkyl migration process, noticeably accompanied by the reduction of the methoxymethyl group to a methyl group (Scheme 2). We carried out some experiments in order to gain an understanding of the mechanism of this unexpected transformation. To clarify the source of the proton of the methyl group, indolylborates **2f** and **2j** were, thus, treated with methanol-d_4 at room temperature for 2 hours and subsequently, water was added. This turned out that the incorporation of a deuterium atom into the *N*-methyl group took place to give **5c** (in 61% yield) and **5e** (in 28% yield), whose structures were assigned based on comparison of the integrations of the *N*-methyl signals of the ^{1}H nmr spectra of **5c** and **5e** with those of **5a** (at 3.61 ppm) and **5d** (at 3.66 ppm), respectively. However, no incorporation of deuterium atom into 3-position of the indole ring of them was observed. When **2f** was exposed to the reaction with methanol-d_4 at a lower temperature (-30°) and for a shorter time (30 minutes), incorporation of a deuterium atom was completely suppressed and only **5a** was obtained. To gain further insight into these results, indolylborate **2h** possessing a deuterium atom at the 3-position of the indole ring was

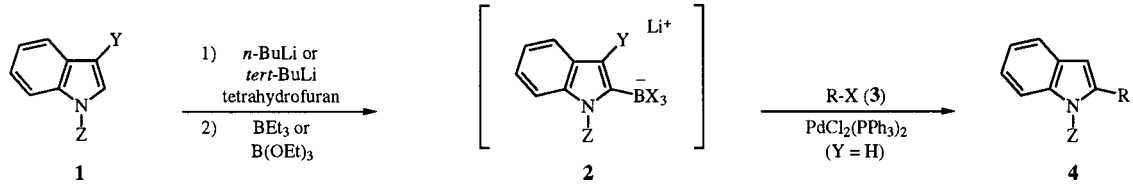
Table 1

The Palladium Catalyzed Cross-Coupling Reaction of **2** with **3**

3	2	Yield (%) of **4** [a]	3	2	Yield (%) of **4** [a]
3a	**2a**	80 (**4a**)	**3c**	**2d**	41 (**4k**)
	2b	60 (**4a**)		**2f**	—
	2c	70 (**4b**)	**3d**	**2a**	80 (**4l**)
	2d	80 (**4c**)		**2b**	48 (**4l**)
	2e	35 (**4d**)		**2c**	60 (**4m**)
	2f	—		**2d**	78 (**4n**)
3b	**2a**	73 (**4e**)		**2e**	15 (**4o**)
	2b	56 (**4e**)		**2f**	—
	2c	70 (**4f**)		**2g**	40 (**4p**)
	2d	72 (**4g**)	**3e**	**2a**	80 (**4q**)
	2f	—		**2c**	73 (**4r**)
	2g	60 (**4h**)		**2d**	77 (**4s**)
3c	**2a**	60 (**4i**)		**2f**	—
	2c	20 (**4j**)			

[a] Isolated yields (%) based on indoles **1**.

Scheme 1



1

2

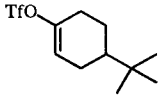
4

1a:	Z = Me	Y = H	
b:	Z = Me	Y = D	
c:	Z = OMe	Y = H	
d:	Z = *t*-butoxycarbonyl	Y = H	
e:	Z = SO_2Ph	Y = H	
f:	Z = CH_2OMe	Y = H	
g:	Z = CH_2OMe	Y = D	
h:	Z = CH_2OMe	Y = Me	

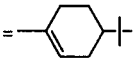
2a:	Z = Me	Y = H	$BX_3 = BEt_3$
b:	Z = Me	Y = H	$BX_3 = B(OEt)_3$
c:	Z = OMe	Y = H	$BX_3 = BEt_3$
d:	Z = *t*-butoxycarbonyl	Y = H	$BX_3 = BEt_3$
e:	Z = SO_2Ph	Y = H	$BX_3 = BEt_3$
f:	Z = CH_2OMe	Y = H	$BX_3 = BEt_3$
g:	Z = CH_2OMe	Y = H	$BX_3 = B(OEt)_3$
h:	Z = CH_2OMe	Y = D	$BX_3 = BEt_3$
i:	Z = CH_2OMe	Y = H	$BX_3 = B(sec\text{-}Bu)_3$
j:	Z = CH_2OMe	Y = Me	$BX_3 = BEt_3$

4a:	Z = Me	R = Ph
b:	Z = OMe	R = Ph
c:	Z = *t*-butoxycarbonyl	R = Ph
d:	Z = SO_2Ph	R = Ph
e:	Z = Me	R = *p*-Ph-COOEt
f:	Z = OMe	R = *p*-Ph-COOEt
g:	Z = *t*-butoxycarbonyl	R = *p*-Ph-COOEt
h:	Z = CH_2OMe	R = *p*-Ph-COOEt
i:	Z = Me	R = 2-pyridyl
j:	Z = OMe	R = 2-pyridyl
k:	Z = *t*-butoxycarbonyl	R = 2-pyridyl
l:	Z = Me	R = -CH=CH-Ph
m:	Z = OMe	R = -CH=CH-Ph
n:	Z = *t*-butoxycarbonyl	R = -CH=CH-Ph
o:	Z = SO_2Ph	R = -CH=CH-Ph
p:	Z = CH_2OMe	R = -CH=CH-Ph

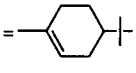
R-X (3): **a**: bromobenzene
b: ethyl 4-bromobenzoate
c: 2-bromopyridine
d: β-bromostyrene
e:



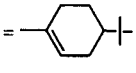
q: Z = Me R =



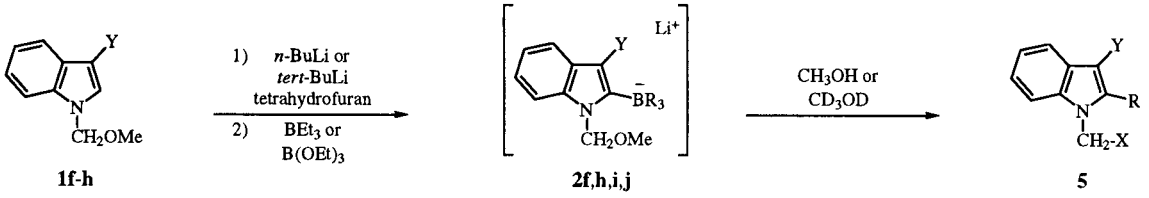
r: Z = OMe R =



s: Z = *t*-butoxycarbonyl R =



Scheme 2



1f-h

2f,h,i,j

5

a:	Y = H	R = Et	X = H
b:	Y = H	R = *sec*-Bu	X = H
c:	Y = H	R = Et	X = D
d:	Y = Me	R = Et	X = H
e:	Y = Me	R = Et	X = D

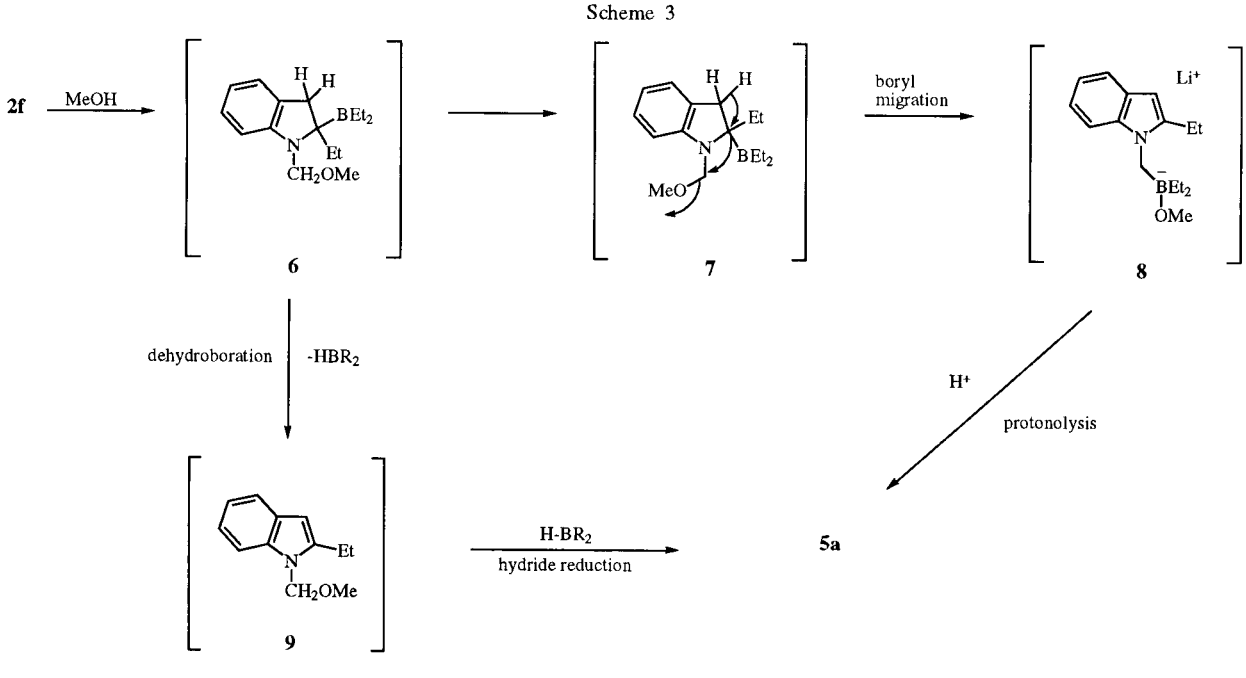
subjected to the reaction with methanol-d_4 at room temperature for 2 hours, resulting in the formation of **5c**, solely, accompanied by the hydrogen-deuterium exchange at the 3-position. This was also true to a fair extent even when **2h** was treated with methanol-d_4 for 2 hours under an argon atmosphere at room temperature, subsequently with deuterium oxide, and the whole was then extracted with dehydrated diethyl ether, leading to **5c**. Therefore the observed hydrogen-deuterium exchange may possibly occur during the purification stage.

Though an intramolecular reduction process was tentatively postulated in our previous paper [3], the following reaction mechanism was postulated to assume the formation of **5** from 1-methoxymethylindolylborates **2f-j** and methanol, on the basis of the results described above (Scheme 3). Initially, electrophilic attack of a proton to **2** promotes alkyl migration, leading to borane **6** [6]. Thus, dehydroboration from **6** and subsequent hydride reduction of **9** present a plausible route to **5a**. However, this seems not to be likely, as an attempted hydride reduction of 1-methoxymethylindole **1f** with 9-borabicyclo[3.3.1]nonane in tetrahydrofuran at room temperature and even under refluxing condition resulted in only the recovery of indole **1f**. Therefore, more likely, the present formation of **5a** possibly involves facile migration of diethylborane facilitated by the labile methoxy group of the carbinolamine moiety (from **7** to **8**), followed by the protonolytic cleavage of the carbon-borane bond of **8**.

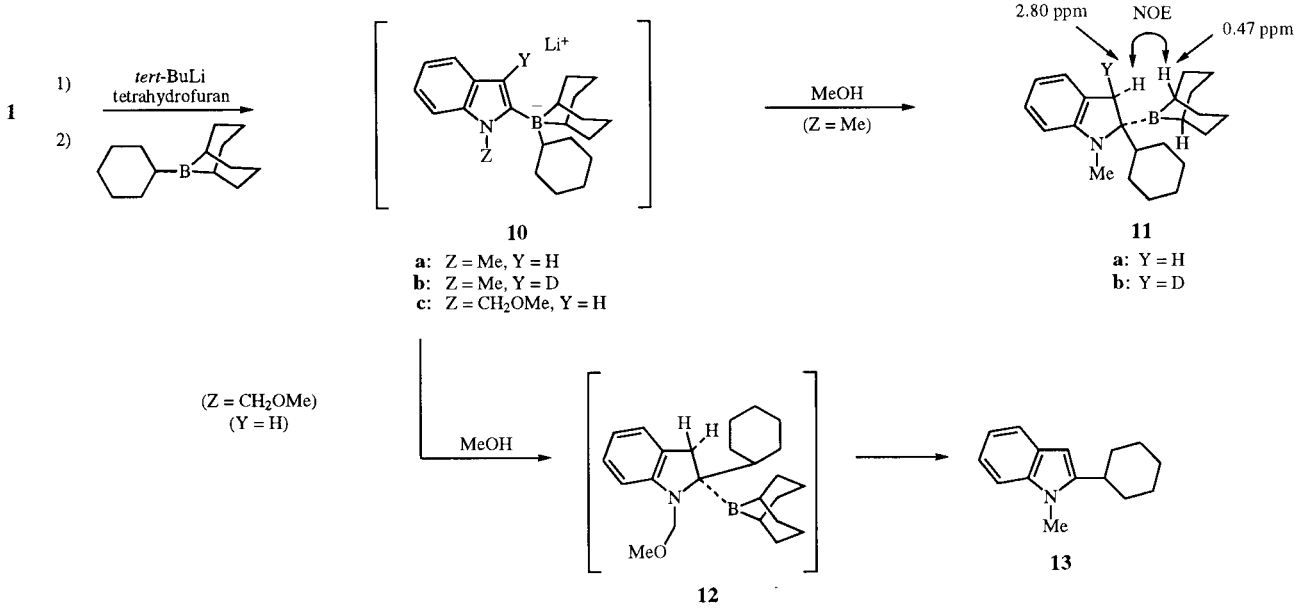
This reaction mechanism was also supported by the following experiments. Treatment of indolylborates **10a** with methanol at room temperature for 2 hours allowed the isolation of boranes **11a** as stable crystals through an intramolecular alkyl migration. Irradiation of the proton at 2.80 ppm of **11a** produced a positive nuclear overhauser effect on the peak at 0.47 ppm (methine proton of the 9-borabicyclo[3.3.1]nonane ring), which enabled us to establish the arrangement of the deuterium atom of **11b**, generated from **10b**. Unlike the case with **10a**, exposure of indolylborate **10c** to methanol readily afforded **13**, in which the presence of carbinolamine moiety in **12** seems to be highly responsible for the observed facile elimination of boryl group leading to **13** (Scheme 4).

Furthermore, we examined the cross-coupling reaction of **2b** and **2g** having triethoxyboryl group, which would not undergo the alkyl migration reaction intramolecularly [7]. As seen in Table 1, **2b** reacted with **3a**, **3b** and **3d**, to provide **4a**, **4b** and **4l**, being less effective than the cases of **2a**, and the reaction of **2g**, even with *N*-methoxymethyl group, with **3b** and **3d** was feasibly effected to give **4h** and **4p**. In summary, **2a**, **2c**, **2d** with 1-methyl, 1-methoxy and 1-*tert*-butoxycarbonyl groups have been employed for the palladium catalyzed cross-coupling reaction. Otherwise, the intramolecular alkyl migration reaction of 1-methoxymethylindolylborate **2f** produced 2-alkyl-1-methylindoles **5**, which involved the unexpected reduction of methoxymethyl group to methyl group. Experiments on this reduction process have proven that the lability of the methoxy group of the carbinolamine moiety is largely responsible for the reduction process.

Scheme 3



Scheme 4



EXPERIMENTAL

Melting points were recorded on Yamato MP 21. All melting points and boiling points are uncorrected. Mass spectra were recorded on Shimadzu GC-MS 9100-MK or JEOL JMS DX-303 spectrometer. The ^1H and ^{13}C nmr spectra were recorded on a JEOL JNM-LA300 or JNM-EX400 spectrometer in deuteriochloroform. Chemical shifts are expressed in ppm (δ) with tetramethylsilane as an internal reference. The ir spectra were measured on a Hitachi Model 270-30 spectrometer. Medium pressure liquid chromatography was performed on silica gel (Silica Gel 60N purchased from Kanto Chemical Co., Inc.). Dehydrated tetrahydrofuran and diethyl ether were purchased from Kanto Chemical Co., Inc.

Triethyl(1-methylindol-2-yl)borate **2a** and Triethoxy(1-methylindol-2-yl)borate **2b**.

tert-Butyllithium (1.6 *M* solution in pentane, 1.5 ml, 2.4 mmoles) was added to a solution of 2 mmoles of 1-methylindole **1a** in tetrahydrofuran (10 ml) under an argon atmoshere at 0°, and the mixture was stirred for 1 hour at room temperature. Then, triethylborane (1 *M* solution in hexane, 2.4 ml, 2.4 mmoles) or triethoxyborane (0.41 ml, 2.4 mmoles) was added, and the entire reaction mixture was stirred for an additional 1 hour at room temperature. The resulting solution of **2a** or **2b** was used for the next reaction.

Triethyl(1-methoxyindol-2-yl)borate **2c** and Triethyl(1-methoxymethylindol-2-yl)borate **2f**, Triethoxy(1-methoxymethylindol-2-yl)borate **2g**, [Tris(1-methylpropyl)-2-(1-methoxymethyl)indolyl]borate **2h** and Triethyl(1,3-dimethylindol-2-yl)-borate **2i**.

n-Butyllithium (1.6 *M* solution in pentane, 1.5 ml, 2.4 mmoles) was added to a solution of 2 mmoles of 1-methoxyindole **1c**, 1-methoxymethylindole **1f** or 1-methoxymethyl-3-methylindole **1h** in tetrahydrofuran (10 ml) under an argon atmosphere at -30°. The mixture was stirred for 20 minutes. Then, trialkylborane (1 *M* solution in hexane, 2.4 ml, 2.4 mmoles), or triethoxyborane (0.41 ml, 2.4 mmoles) was added, and the entire reaction mixture was stirred for an additional 1 hour at -30°. The resulting solutions of **2c**, **2f**, **2g**, **2h** or **2i** were used for the next reactions.

Triethyl(1-*tert*-butoxycarbonylindol-2-yl)borate **2d**.

tert-Butyllithium (1.6 *M* solution in pentane, 1.5 ml, 2.4 mmoles) was added to a solution of 2 mmoles of 1-*tert*-butoxycarbonylindole **1d** [8] in tetrahydrofuran (10 ml) under an argon atmosphere at -78°. The mixture was stirred for 2 hours. Then, triethylborane (1 *M* solution in hexane, 2.4 ml, 2.4 mmoles) was added, then the entire reaction mixture was gradually raised to room temperature over 1 hour and stirred for an additional 1 hour at room temperature. The resulting solution of **2d** was used for the next reaction.

Triethyl(1-phenylsulfonylindol-2-yl)borate **2e**.

tert-Butyllithium (1.6 *M* solution in pentane, 1.5 ml, 2.4 mmoles) was added to a solution of 2 mmoles of 1-phenylsulfonylindole **1e** [9] in tetrahydrofuran (10 ml) under an argon atmosphere at 0°. The mixture was stirred for 1 hour at room temperature. Then, triethylborane (1 *M* solution in hexane, 2.4 ml, 2.4 mmoles) was added, then the entire reaction mixture was stirred for an additional 1 hour at room temperature. The resulting solution of **2e** was used for the next reaction.

General Procedure for the Palladium Catalyzed Cross-Coupling Reaction of Indolylborate **2**.

To a solution of indolylborate **2**, generated *in situ* in tetrahydrofuran from indole **1** (2 mmoles) described as above, were added dichlorobis(triphenylphosphine)palladium(II) (0.1 mmole)

and halide or triflate **3** (3 mmoles), and the mixture was heated at 60° for 30 minutes. Then, the mixture was treated with 10% aqueous sodium hydroxide (10 ml) and 30% aqueous hydrogen peroxide (2 ml) with ice-cooling for 10 minutes. The mixture was diluted with ethyl acetate, washed with brine, and dried over anhydrous magnesium sulfate. The solvent was removed, and the residue was separated by medium pressure liquid chromatography with hexane:ethyl acetate to give **4**.

1-Methyl-2-phenylindole **4a**.

This compound was obtained as colorless crystals (recrystallized from ethyl acetate-hexane) and had mp 102-103° (lit [10] mp 100-101°); ^{1}H nmr (deuteriochloroform): δ 3.74 (s, 3H), 6.51 (s, 1H), 7.14 (ddd, 1H, J = 1, 6.8, 8.3 Hz), 7.25 (ddd, 1H, J = 1, 6.8, 8.3 Hz), 7.36 (d, 1H, J = 8.3 Hz), 7.40 (d, 1H, J = 8.3 Hz), 7.45 (d, 2H, J = 8.3 Hz), 7.51 (d, 2H, J = 8.3 Hz), 7.63 (d, 1H, J = 8.3 Hz); ^{13}C nmr (deuteriochloroform): δ 31.2, 101.8, 109.7, 119.9, 120.5, 121.7, 127.9, 128.1, 128.5, 129.4, 132.9, 138.5, 141.6.

Anal. Calcd. for $C_{15}H_{13}N$: C, 86.92; H, 6.32; N, 6.76. Found: C, 87.16; H, 6.58; N, 6.73.

1-Methoxy-2-phenylindole **4b**.

This compound was colorless crystals (recrystallized from ethanol) and had mp 51-52° (lit [11] mp 49-50°); ^{1}H nmr (deuteriochloroform): δ 3.72 (s, 3H), 6.58 (s, 1H), 7.13 (t, 1H, J = 6.8 Hz), 7.25 (t, 1H, J = 6.8 Hz), 7.38 (t, 1H, J = 6.8 Hz), 7.40-7.50 (m, 3H), 7.59 (d, 1H, J = 7.8 Hz), 7.85 (dd, 2H, J = 1.5, 8.3 Hz); ^{13}C nmr (deuteriochloroform): δ 64.1, 98.2, 108.7, 120.6, 120.8, 122.5, 124.1, 127.5, 127.9, 128.6, 130.6, 133.7, 136.2.

Anal. Calcd. for $C_{15}H_{13}NO$: C, 80.69; H, 5.87; N, 6.27. Found: C, 80.73; H, 5.87; N, 6.24.

tert-Butyl 2-Phenylindole-1-carboxylate **4c**.

This compound was obtained as colorless crystals (recrystallized from ethyl acetate-hexane) and had mp 75-76°; ir (chloroform): 1724 cm^{-1}; ^{1}H nmr (deuteriochloroform): δ 1.30 (s, 3H), 6.55 (s, 1H), 7.25 (t, 1H, J = 6.8 Hz), 7.30-7.45 (m, 6H), 7.55 (d, 1H, J = 7.8 Hz), 8.21 (d, 1H, J = 8.3 Hz); ^{13}C nmr (deuteriochloroform): δ 27.5, 83.3, 109.8, 115.1, 120.4, 122.9, 124.2, 127.5, 127.6, 128.7, 129.2, 135.0, 137.4, 140.4, 150.2.

Anal. Calcd. for $C_{19}H_{19}NO_2$: C, 77.79; H, 6.52; N, 4.77. Found: C, 77.58; H, 6.62; N, 4.71.

2-Phenyl-1-phenylsulfonylindole **4d**.

This compound was obtained as colorless crystals (recrystallized from ethyl acetate-hexane) and had mp 103-104°; ^{1}H nmr (deuteriochloroform): δ 6.54 (s, 1H), 7.20-7.30 (m, 4H), 7.35-7.53 (m, 9H), 8.31 (d, 1H, J = 8.3 Hz); ^{13}C nmr (deuteriochloroform): δ 113.6, 116.5, 120.7, 124.4, 124.8, 126.6, 127.5, 128.5, 128.7, 130.3, 130.5, 132.2, 133.5, 137.5, 138.3, 142.1.

Anal. Calcd. for $C_{20}H_{15}NO_2S$: C, 72.05; H, 4.53, N, 4.20. Found: C, 72.11; H, 4.49; N, 4.40.

Ethyl 4-(1-Methylindol-2-yl)benzoate **4e**.

This compound was obtained as colorless crystals (recrystallized from ethyl acetate-hexane) and had mp 101-102°; ir (chloroform): 1710 cm^{-1}; ^{1}H nmr (deuteriochloroform): δ 1.42 (t, 3H, J = 7 Hz), 3.77 (s, 3H), 4.42 (q, 2H, J = 7 Hz), 6.64 (s, 1H), 7.15 (dt, 1H, J = 1, 6.8 Hz), 7.27 (dt, 1H, J = 1, 6.8 Hz), 7.37 (d, 1H, J = 8.3 Hz), 7.58 (d, 2H, J = 7.8 Hz), 7.64 (d, 1H, J = 7.8 Hz), 8.14 (d, 2H, J = 7.8 Hz); ^{13}C nmr (deuteriochloroform): δ 14.3, 31.3, 61.0, 102.8, 109.7, 120.1, 120.7, 122.2, 127.8, 128.9, 129.6, 129.7, 137.1, 138.8, 140.3, 166.3.

Anal. Calcd. for $C_{18}H_{17}NO_2$: C, 77.39; H, 6.13; N, 5.01. Found: C, 77.50; H, 6.30; N, 5.01.

Ethyl 4-(1-Methoxyindol-2-yl)benzoate **4f**.

This compound was obtained as a syrup and had ir (neat): 1712 cm^{-1}; ^{1}H nmr (deuteriochloroform): δ 1.42 (t, 3H, J = 7 Hz), 3.75 (s, 3H), 4.41 (q, 2H, J = 7 Hz), 6.69 (s, 1H), 7.15 (t, 1H, J = 6.8 Hz), 7.28 (t, 1H, J = 6.8 Hz), 7.48 (d, 1H, J = 7 Hz), 7.60 (d, 1H, J = 7.8 Hz), 7.93 (d, 2H, J = 8.3 Hz), 8.13 (d, 2H, J = 8.3 Hz); ^{13}C nmr (deuteriochloroform): δ 14.3, 61.0, 64.1, 99.7, 108.9, 120.9, 121.1, 123.3, 124.0, 126.9, 129.5, 129.9, 134.1, 134.8, 134.9, 166.3; hrms: Calcd. for $C_{18}H_{17}NO_3$: 295.1204. Found: 295.1183.

Ethyl 4-(1-*tert*-Butyloxycarbonylindol-2-yl)benzoate **4g**.

This compound was obtained as colorless crystals (recrystallized from ethyl acetate-hexane) and had mp 102-103°; ir (chloroform): 1726, 1710, 1612 cm^{-1}; ^{1}H nmr (deuteriochloroform): δ 1.33 (s, 9H), 1.42 (t, 3H, J = 7 Hz), 4.41 (q, 2H, J = 7 Hz), 6.62 (s, 1H), 7.26 (t, 1H, J = 6.8 Hz), 7.35 (dt, 1H, J = 1, 6.8 Hz), 7.50 (d, 2H, J = 8.3 Hz), 7.57 (d, 1H, J = 7.8 Hz), 8.08 (d, 2H, J = 8 Hz), 8.20 (d, 1H, J = 8.3 Hz); ^{13}C nmr (deuteriochloroform): δ 14.3, 27.6, 61.0, 83.8, 110.9, 115.3, 120.7, 123.1, 124.8, 128.5, 129.0, 129.4, 137.7, 139.3, 150.0, 166.3.

Anal. Calcd. for $C_{23}H_{23}NO_4$: C, 72.31; H, 6.34; N, 3.83. Found: C, 72.37; H, 6.45; N, 3.84.

Ethyl 4-(1-Methoxymethylindol-2-yl)benzoate **4h**.

This compound was obtained as a syrup and had ir (chloroform): 1714, 1610 cm^{-1}; ^{1}H nmr (deuteriochloroform): δ 1.41 (t, 3H, J = 7.3 Hz), 3.31 (s, 3H), 4.40 (q, 2H, J = 7.3 Hz), 5.39 (s, 2H), 6.69 (s, 1H), 7.18 (t, 1H, J = 6.8 Hz), 7.28 (ddd, 1H, J = 1, 6.8, 7.8 Hz), 7.51 (d, 1H, J = 8.3 Hz), 7.63 (d, 1H, J = 7.8 Hz), 7.71 (d, 2H, J = 8.3 Hz), 8.13 (d, 2H, J = 8.3 Hz); ^{13}C nmr (deuteriochloroform): δ 14.3, 55.9, 61.0, 74.7, 104.5, 110.2, 120.8, 120.9, 122.9, 128.2, 129.0, 129.8, 136.7, 138.8, 140.6, 166.3; hrms: Calcd. for $C_{19}H_{19}NO_3$: 309.1360. Found: 309.1351.

1-Methyl-2-(2-pyridyl)indole **4i**.

This compound was obtained as colorless crystals (recrystallized from ethyl acetate-hexane) and had mp 92-93° (lit [12] mp 90-91°); ^{1}H nmr (deuteriochloroform): δ 4.07 (s, 3H), 6.85 (s, 1H), 7.13 (t, 1H, J = 6.8 Hz), 7.21 (ddd, 1H, J = 2, 4.8, 6.8 Hz), 7.27 (ddd, 1H, J = 1, 6.8, 7.8 Hz), 7.40 (d, 1H, J = 8.3 Hz), 7.65 (d, 1H, J = 7.8 Hz), 7.68-7.78 (m, 2H), 8.69 (d, 1H, J = 4.8 Hz); ^{13}C nmr (deuteriochloroform): δ 31.9, 103.5, 109.9, 119.9, 121.0, 121.6, 122.5, 123.4, 127.6, 139.0, 139.4, 149.0, 152.5.

Anal. Calcd. for $C_{14}H_{12}N_2$: C, 80.74; H, 5.81; N, 13.45. Found: C, 80.68; H, 5.98; N, 13.50.

1-Methoxy-2-(2-pyridyl)indole **4j**.

This compound was obtained as a syrup and had ^{1}H nmr (deuteriochloroform): δ 3.96 (s, 3H), 6.99 (s, 1H), 7.15 (dt, 1H, J = 1, 6.8 Hz), 7.23 (dd, 1H, J = 4, 7.8 Hz), 7.30 (t, 1H, J = 6.8 Hz), 7.50 (d, 1H, J = 8.3 Hz), 7.63 (d, 1H, J = 7.8 Hz), 7.77 (dt, 1H, J = 2, 7.8 Hz), 7.94 (d, 1H, J = 7.8 Hz), 8.71 (d, 1H, J = 4 Hz); ^{13}C nmr (deuteriochloroform): δ 64.7, 101.2, 109.0, 120.9, 121.6, 121.8, 122.2, 123.4, 123.9, 134.6, 135.4, 136.6, 149.7, 149.8; hrms: Calcd. for $C_{14}H_{12}NO$: 224.0947. Found: 224.0941.

tert-Butyl 2-(2-Pyridyl)indole-1-carboxylate **4k**.

This compound was obtained as a syrup and had ir (film): 1730 cm^{-1}; ^1H nmr (deuteriochloroform): δ 1.33 (s, 9H), 6.77 (s, 1H), 7.20-7.30 (m, 2H), 7.35 (dt, 1H, J = 1.5, 7.8 Hz), 7.50 (d, 1H, J = 7.8 Hz), 7.58 (d, 1H, J = 7.8 Hz), 7.73 (dt, 1H, J = 1.5, 7.8 Hz), 8.19 (d, 1H, J = 8.3 Hz), 8.67 (d, 1H, J = 5 Hz); ^{13}C nmr (deuteriochloroform): δ 27.5, 83.3, 110.9, 114.9, 120.9, 122.1, 122.8, 123.2, 124.9, 128.8, 135.9, 137.7, 139.3, 148.9, 149.9, 153.3; hrms: Calcd. for $C_{18}H_{18}N_2O_2$: 294.1367. Found: 294.1378.

2-(2-Phenylvinyl)-1-methylindole **4l**.

This compound was obtained as colorless crystals (recrystallized from ethyl acetate-hexane) and had mp 119-121°; ^1H nmr (deuteriochloroform): δ 3.82 (s, 3H), 6.80 (s, 1H), 7.11 (t, 1H, J = 6.8 Hz), 7.16-7.22 (m, 3H), 7.26-7.32 (m, 2H), 7.38 (t, 2H, J = 7.8 Hz), 7.53 (d, 2H, J = 7.8 Hz), 7.58 (d, 1H, J = 7.8 Hz); ^{13}C nmr (deuteriochloroform): δ 29.9, 99.2, 109.2, 117.2, 119.9, 120.5, 121.8, 126.4, 127.8, 128.1, 128.8, 131.0, 137.2, 138.3, 138.5.

Anal. Calcd. for $C_{17}H_{15}N$: C, 87.57; H, 6.48, N, 6.00. Found: C, 87.52; H, 6.42; N, 5.94.

1-Methoxy-2-styrylindole **4m**.

This compound was obtained as colorless crystals (recrystallized from ethyl acetate-hexane) and had mp 90-91°; ^1H nmr (deuteriochloroform): δ 4.01 (s, 3H), 6.56 (s, 1H), 7.10 (dt, 1H, J = 1, 6.8 Hz), 7.17 (d, 1H, J = 11 Hz), 7.20-7.45 (m, 6H), 7.54 (d, 3H, J = 8.3 Hz); ^{13}C nmr (deuteriochloroform): δ 64.7, 96.9, 108.1, 115.7, 120.5, 120.8, 122.6, 124.1, 126.5, 127.9, 128.7, 130.9, 133.1, 134.1, 137.2.

Anal. Calcd. for $C_{17}H_{15}NO$: C, 81.90; H, 6.06; N, 5.61. Found: C, 81.98; H, 6.21; N, 5.57.

tert-Butyl 2-Styrylindole-1-carboxylate **4n**.

This compound was obtained as colorless crystals (recrystallized from ethyl acetate-hexane) and had mp 81-82°; ir (chloroform) 1726 cm^{-1}; ^1H nmr (deuteriochloroform): δ 1.69 (s, 9H), 6.84 (s, 1H), 7.04 (d, 1H, J = 16 Hz), 7.17-7.30 (m, 3H), 7.30-7.40 (m, 2H), 7.50-7.55 (m, 3H), 7.73 (d, 1H, J = 16 Hz), 8.11 (d, 1H, J = 8.3 Hz); ^{13}C nmr (deuteriochloroform): δ 28.2, 84.0, 106.7, 115.7, 120.3, 120.7, 122.9, 124.1, 126.6, 127.8, 128.6, 129.4, 130.6, 136.9, 137.2, 139.5, 150.6.

Anal. Calcd. for $C_{21}H_{21}NO_2$: C, 78.96; H, 6.62; N, 4.38. Found: C, 78.86; H, 6.77; N, 4.37.

1-(Phenylsulfonyl)-2-styrylindole **4o**.

This compound was obtained as a syrup and had ^1H nmr (deuteriochloroform): δ 6.83 (s, 1H), 7.01 (d, 1H, J = 7 Hz), 7.20-7.50 (m, 9H), 7.56 (d, 2H, J = 7.8 Hz), 7.73 (d, 2H, J = 8.3 Hz), 7.83 (d, 1H, J = 7 Hz), 8.22 (d, 1H, J = 8.3 Hz); ^{13}C nmr (deuteriochloroform): δ 108.6, 115.2, 118.5, 120.6, 124.1, 124.7, 126.6, 126.9, 128.3, 128.8, 129.0, 130.1, 132.4, 133.6, 136.7, 137.4, 138.3, 139.7; hrms: Calcd. for $C_{22}H_{17}NO_2S$: 359.0979. Found: 359.0986.

1-Methoxymethyl-2-styrylindole **4p**.

This compound was obtained as colorless crystals (recrystallized from ethyl acetate-hexane) and had mp 73-74°; ^1H nmr (deuteriochloroform): δ 3.30 (s, 3H), 5.56 (s, 2H), 6.84 (s, 1H), 7.13 (dt, 1H, J = 1, 6.8 Hz), 7.17-7.46 (m, 7H), 7.53 (dd, 2H, J = 1, 8 Hz), 7.59 (d, 1H, J = 7.8 Hz); ^{13}C nmr (deuteriochloroform): δ 55.8, 73.9, 101.0, 109.3, 116.9, 120.5, 120.7, 122.4, 126.5, 127.9, 128.3, 128.7, 131.5, 137.0, 138.4, 138.6.

Anal. Calcd. for $C_{18}H_{17}NO$: C, 82.09; H, 6.50; N, 5.31. Found: C, 82.02; H, 6.45; N, 5.25.

2-(4-*tert*-Butylcyclohex-1-enyl)-1-methylindole **4q**.

This compound was obtained as colorless crystals (recrystallized from ethyl acetate-hexane) and had mp 138-139°; ^1H nmr (deuteriochloroform): δ 0.93 (s, 9H), 1.30-1.50 (m, 2H), 1.90-2.10 (m, 2H), 2.23-2.55 (m, 3H), 3.70 (s, 3H), 5.90-5.95 (m, 1H), 6.34 (s, 1H), 7.07 (dt, 1H, J = 1, 6.8 Hz), 7.18 (ddd, 1H, J = 1, 6.8, 7.8 Hz), 7.27 (d, 1H, J = 7.8 Hz), 7.55 (d, 1H, J = 7.8 Hz); ^{13}C nmr (deuteriochloroform): δ 24.4, 27.3, 27.5, 31.1, 32.4, 43.9, 99.5, 109.3, 119.5, 120.2, 121.2, 127.9, 129.6, 129.8, 138.2, 143.3.

Anal. Calcd. for $C_{19}H_{25}N$: C, 85.33; H, 9.42; N, 5.24. Found: C, 85.25; H, 9.55; N, 5.18.

2-(4-*tert*-Butylcyclohex-1-enyl)-1-methoxyindole **4r**.

This compound was obtained as colorless crystals (recrystallized from ethyl acetate-hexane) and had mp 83-84°; ^1H nmr (deuteriochloroform): δ 0.93 (s, 9H), 1.30-1.45 (m, 2H), 1.95-2.10 (m, 2H), 2.28-2.38 (m, 1H), 2.57-2.67 (m, 1H), 3.83 (s, 3H), 6.26 (s, 1H), 6.58-6.63 (m, 1H), 7.07 (dt, 1H, J = 1, 6.8 Hz), 7.19 (dt, 1H, J = 1, 6.8 Hz), 7.37 (dd, 1H, J = 1, 7.8 Hz), 7.50 (d, 1H, J = 8.3 Hz); ^{13}C nmr (deuteriochloroform): δ 24.2, 27.2, 27.6, 28.7, 32.2, 43.7, 63.4, 96.7, 108.3, 120.2, 120.5, 122.1, 123.9, 127.2, 127.4, 133.8, 137.3.

Anal. Calcd. for $C_{19}H_{25}N$: C, 80.52; H, 8.89; N, 4.94. Found: C, 80.47; H, 8.99, N, 4.91.

tert-Butyl 2-(4-*tert*-Butylcyclohex-1-enyl)indole-1-carboxylate **4s**.

This compound was obtained as colorless crystals (recrystallized from ethyl acetate-hexane) and had mp 107-108°; ir (chloroform) 1726 cm^{-1}; ^1H nmr (deuteriochloroform): δ 0.91 (s, 9H), 1.15-1.25 (m, 2H), 1.64 (s, 9H), 1.95-2.05 (m, 2H), 2.10-2.20 (m, 3H), 5.88 (m, 1H), 6.35 (s, 1H), 7.15-7.30 (m, 2H), 7.46 (d, 1H, J = 7.8 Hz), 8.03 (d, 1H, J = 8.3 Hz); ^{13}C nmr (deuteriochloroform): δ 24.1, 27.1, 28.2, 30.5, 32.3, 43.6, 83.4, 107.8, 115.1, 120.1, 122.5, 123.6, 126.8, 129.4, 132.3, 136.8, 143.4, 150.3.

Anal. Calcd. for $C_{23}H_{31}NO_2$: C, 78.14; H, 8.83; N, 3.96. Found: C, 78.25; H, 8.98; N, 4.01.

General Procedure for the Intramolecular Alkyl Migration Reaction of **2f**, **2i** and **2j**.

To a solution of **2f**, **2i** or **2j**, generated *in situ* in tetrahydrofuran (10 ml) from indole **1f** or **1h** (2 mmoles), was added methanol (2 ml) at room temperature. The mixture was stirred for 2 hours. Then the mixture was treated with 10% aqueous sodium hydroxide (10 ml) and 30% aqueous hydrogen peroxide (2 ml) with ice-cooling for 10 minutes. The mixture was diluted with ethyl acetate, washed with brine, and dried over anhydrous magnesium sulfate. The solvent was removed, and the residue was separated by medium pressure liquid chromatography with hexane:ethyl acetate (200:1, v/v) to give **5a**, **5b** or **5d**.

2-Ethyl-1-methylindole **5a**.

This compound was obtained in 65% yield based on **1f** and had bp 145° (15 mmHg) and mp 30-31° (lit [4] mp 29.5-30°); ^1H nmr (deuteriochloroform): δ 1.34 (t, 3H, J = 7.4 Hz), 2.74 (q, 2H,

J = 7.4 Hz), 3.61 (s, 2H), 6.25 (s, 1H), 7.05 (t, 1H, J = 6.8 Hz), 7.12 (t, 1H, J = 6.8 Hz), 7.24 (d, 1H, J = 8.3 Hz), 7.53 (d, 1H, J = 7.8 Hz); ^{13}C nmr (deuteriochloroform): δ 12.7, 20.0, 29.1, 97.8, 108.6, 119.2, 119.7, 120.5, 128.1, 137.5, 142.8.

Anal. Calcd. for $C_{11}H_{13}N$: C, 82.97; H, 8.23; N, 8.80. Found: C, 83.08; H, 8.46; N, 8.70.

1-Methyl-2-(1-methylpropyl)indole **5b**.

This compound was obtained in 61% yield based on **1f** and had bp 153° (15 mmHg); ^{1}H nmr (deuteriochloroform): δ 0.94 (t, 3H, J = 7 Hz), 1.29 (d, 3H, J = 7 Hz), 1.40-2.00 (m, 2H), 2.60-3.00 (m, 1H), 3.66 (s, 3H), 6.24 (s, 1H), 7.05 (dd, 1H, J = 1, 6.8 Hz), 7.14 (dd, 1H, J = 1, 6.8 Hz), 7.27 (d, 1H, J = 8.3 Hz), 7.53 (d, 1H, J = 8.3 Hz); ^{13}C nmr (deuteriochloroform): δ 11.8, 20.3, 29.4, 32.7, 97.1, 108.8, 119.3, 119.9, 120.5, 128.1, 137.4, 146.6.

Anal. Calcd. for $C_{13}H_{17}N$: C, 83.37; H, 9.15; N, 7.48. Found: C, 83.31; H, 9.15; N, 7.42.

2-Ethyl-1,3-dimethylindole **5d**.

This compound was obtained in 28% yield based on **1h** and had bp 80° (1 mmHg) (lit [5] bp 65-70° (0.01 mmHg); ^{1}H nmr (deuteriochloroform): δ 1.18 (t, 3H, J = 7.3 Hz), 2.25 (s, 3H), 2.76 (q, 2H, J = 7.3 Hz), 3.64 (s, 3H), 7.06 (dt, 1H, J = 1, 6.8 Hz), 7.14 (dt, 1H, J = 1, 6.8 Hz), 7.22 (d, 1H, J = 8.3 Hz), 7.48 (d, 1H, J = 7.8 Hz); ^{13}C nmr (deuteriochloroform): δ 8.6, 14.3, 17.8, 29.4, 105.6, 108.5, 118.1, 118.6, 120.6, 128.6, 138.4.

Anal. Calcd. for $C_{12}H_{15}N$: C, 83.19; H, 8.73; N, 8.09. Found: C, 83.37; H, 8.75; N, 8.34.

General Procedure for the Intramolecular Alkyl Migration Reaction of **10**.

A solution of 9-bora-9-cyclohexylbicyclo[3.3.1]nonane, generated from cyclohexene (246 mg, 3 mmoles) and 9-borabicyclo-[3.3.1]nonane (0.5 *M* solution in tetrahydrofuran, 6 ml, 3 mmoles) in tetrahydrofuran under an argon atmosphere [13], was added to a solution of 2-lithio-1-methylindole, generated from *tert*-butyllithium (1.6 *M* solution in pentane, 1.5 ml, 2.4 mmoles) and 1-methylindole (262 mg, 2 mmoles) in tetrahydrofuran under an argon atmosphere at room temperature. The mixture was stirred for 1 hour at room temperature. After the addition of methanol (2 ml), the mixture was stirred for 2 hours at room temperature. The reaction mixture was diluted with ethyl acetate, washed with brine, and dried over anhydrous magnesium sulfate. The solvent was removed and the residue was purified by medium pressure liquid chromatography with hexane:ethyl acetate (200:1, v/v).

2-(9-Borabicyclo[3.3.1]non-9-yl)-2-cyclohexyl-1-methylindoline **11a**.

This compound was obtained in 20% yield based on **1a** and had mp 120-121° (recrystallized from methanol); ^{1}H nmr (deuteriochloroform): δ 0.47 (br s, 2H), 0.70-2.10 (m, 23H), 2.80 (d, 1H, J = 16 Hz), 2.93 (s, 3H), 3.29 (d, 1H, J = 16 Hz), 6.80-7.30 (m, 4H); ^{13}C nmr (deuteriochloroform): δ 23.9, 26.2, 26.7, 27.1, 28.4, 31.4, 31.7, 32.5, 35.3, 39.0, 115.3, 124.5, 124.7, 126.4, 137.2, 149.2.

Anal. Calcd. for $C_{23}H_{34}BN$: C, 82.38; H, 10.22; N, 4.17. Found: C, 82.29; H, 10.31; N, 4.19.

2-Cyclohexyl-1-methylindole **13**.

This compound was obtained in 25% yield based on **1f** and had mp 70-71° (recrystallized from ethanol); ^{1}H nmr (deuteriochloroform): δ 1.20-1.60 (m, 5H), 1.75-1.95 (m, 3H), 2.00-2.10 (m, 2H), 2.60-2.75 (m, 1H), 3.68 (s, 3H), 6.23 (s, 1H), 7.05 (t, 1H, J = 6.8 Hz), 7.14 (t, 1H, J = 6.8 Hz), 7.26 (d, 1H, J = 8.3 Hz), 7.53 (d, 1H, J = 8.3 Hz); ^{13}C nmr (deuteriochloroform): δ 26.2, 26.6, 29.4, 33.2, 35.9, 96.5, 198.7, 119.1, 119.8, 120.5, 127.9, 137.2, 146.7.

Anal. Calcd. for $C_{15}H_{19}N$: C, 84.45; H, 8.98; N, 6.57. Found: C, 84.31; H, 9.16; N, 6.55.

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