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Synthesis of Benzoindolines *via* a Copper-Catalyzed Reaction of 1-Bromoethynyl-2-(cyclopropylidenemethyl)arenes with *N*-Allylsulfonamide

Shaoyu Li,[a] Zhiming Li,[a] and Jie Wu[a,b,*]

[a] Department of Chemistry, Fudan University, 220 Handan Road, Shanghai 200433, People's Republic of China
Fax: (+86)-216-564-1740; e-mail: jie_wu@fudan.edu.cn
[b] State Key Laboratory of Organometallic Chemistry, Shanghai Institute of Organic Chemistry, Chinese Academy of Sciences, 354 Fenglin Road, Shanghai 200032, People's Republic of China

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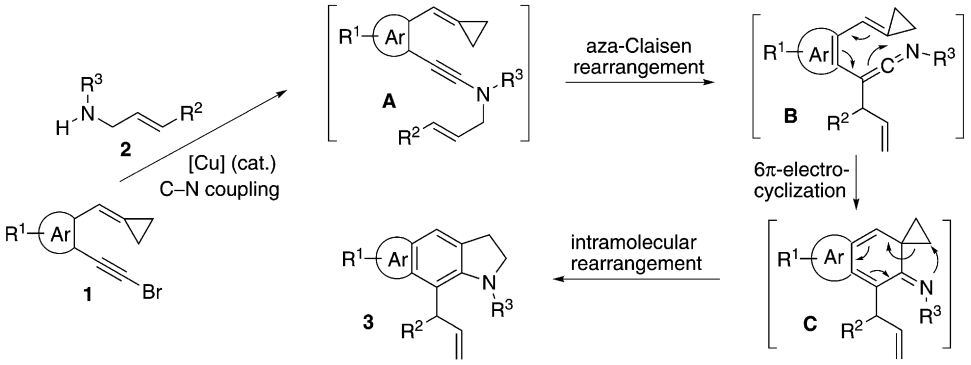
Abstract: A copper-catalyzed tandem reaction of 1-bromoethynyl-2-(cyclopropylidenemethyl)arenes with *N*-allylsulfonamide proceeds smoothly, affording functionalized benzoindolines in moderate to good yields. The transformation is a four-step cascade involving Ullmann coupling, aza-Claisen rearrangement, 6π-electrocyclization, and intramolecular rearrangement.

Keywords: *N*-allylsulfonamide; benzoindolines; 1-bromoethynyl-2-(cyclopropylidenemethyl)arenes; copper(II) acetate; tandem reaction

Introduction

As an important class of heterocyclic compounds, the benzoindoline skeleton is found in many natural products and designed compounds with remarkable biological activities.[1,2] For instance, a structurally distinct class of indoline derivatives has been shown to possess $5HT_{2C/2B}$ receptor antagonist activity, and as such is believed to be of potential use in the treatment of CNS disorders, GI disorders and microvascular disorders.[2a,b] Recently, the National Institutes of Health investigated benzoindoline compounds as Shp2 inhibitors for cancer therapy.[2d] Inspired by their diverse biological activities, continuous efforts have been made to develop methods for the construction of the benzoindoline framework.[3] Among the procedures utilized, efficient pathways for the generation of functionalized benzoindolines with complexity and diversity are in great demand.

The tandem reaction, in which one transformation occurs sequentially after the other in the same reaction vessel, has been widely pursued in the construction of important heterocyclic skeletons.[4] It is well recognized that the strained alkylidenecyclopropanes are useful building blocks for the synthesis of a variety of carbocycles and heterocycles within complex molecules.[5–7] Similarly, 1-haloalkynes are versatile and useful synthons that have been widely applied in syn-



Scheme 1. A proposed synthetic route for the generation of fused benzoindoline derivatives.

thetic organic chemistry.[8,9] Encouraged by the advancement of tandem processes and the reactivities of alkylidenecyclopropanes and 1-haloalkynes, we conceived that 1-bromoethynyl-2-(cyclopropylidenemethyl)arenes, which incorporate alkylidenecyclopropane and 1-haloalkyne in one molecule, would be a good choice for the development of a new tandem methodology to access functionalized benzoindolines.

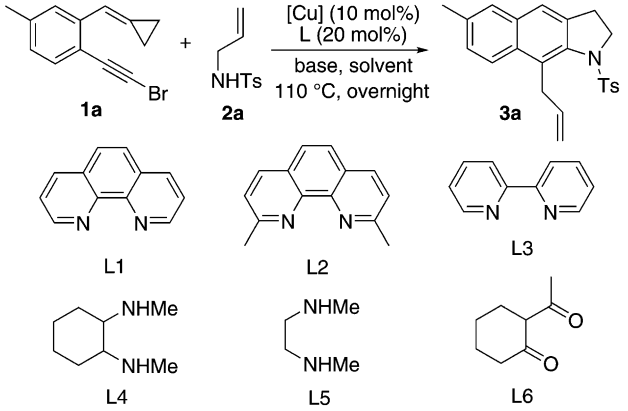
Our strategy is illustrated in Scheme 1. Beginning with readily accessible starting materials, we envisioned that the reactive ketenimine **B** could be obtained as well *via* an aza-Claisen rearrangement[10] of the ynamine[11] intermediate **A** (Scheme 1). Retrosynthetically, the intermediate **A** could be generated *via* a copper-catalyzed Ullmann reaction[12] of 1-bromoethynyl-2-(cyclopropylidenemethyl)arene **1** with allylic amine **2.** If the ketenimine **B** could be formed as expected, a consecutive 6π-electrocyclization[13] would then occur to form intermediate **C**, which would subsequently undergo an intramolecular rearrangement to produce the fused benzoindoline **3**. Although there are several competing pathways in the proposed process, the attractiveness of indoline **3** and the challenge of the tandem synthetic route described in Scheme 1 prompted us to investigate the feasibility of this proposed conversion.

Results and Discussion

The initial experiment evaluated the reaction of 1-(bromoethynyl)-2-(cyclopropylidenemethyl)-4-methylbenzene **1a** with *N*-allyl-4-methylbenzenesulfonamide **2a** catalyzed by copper sulfate (10 mol%) with 1,10-phenanthroline (20 mol%) as ligand in the presence of K_3PO_4 in toluene at 80 °C (Table 1, entry 1). Unfortunately, only a trace amount of the desired product **3a** was detected and most of the observed species were the Ullman coupling products (intermediate **A**). However, when the reaction temperature was increased to 110 °C, the expected indoline **3a** was isolated as the major product, albeit in low yield (20%, Table 1, entry 2). Encouraged by this promising result, we tried to further optimize the reaction conditions. Various bases were examined in this tandem process, and the results indicated that K_2CO_3 was the best choice (Table 1, entries 3–9). Only a trace amount of product was observed when a strong base such as NaO-*t*-Bu was used. The outcome could not be improved when the ratio of substrates was increased to 1.5:1 (Table 1, entry 10). The yield was increased to 54% when copper sulfate was replaced by copper acetate as catalyst (Table 1, entry 11). However, inferior results were obtained when other copper(I) or copper(II) salts were employed (Table 1, entries 12–17). The yield decreased dramatically when the amount of copper acetate was reduced to 5 mol% (Table 1, entry 18). In contrast to 1,10-phenanthroline, other Ullmann coupling ligands gave rise to inferior results (Table 1, entries 19–23). Solvent screening revealed that polar solvents favor the reaction process. In particular, use of DMF improved the yield to 73% (Table 1, entries 24–26).

With the optimized reaction conditions in hand (as highlighted in Table 1, entry 25), we set out to explore

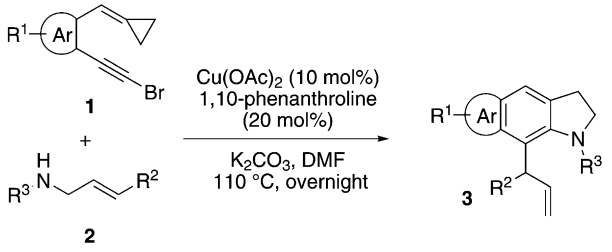
Table 1. Initial studies for the copper-catalyzed reaction of 1-bromoethynyl-2-(cyclopropylidenemethyl)-4-methylbenzene **1a** with *N*-allyl-4-methylbenzenesulfonamide **2a**.

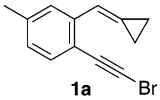
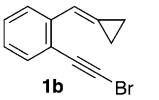
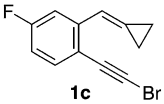
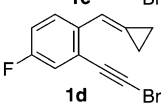
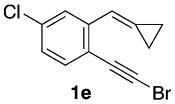
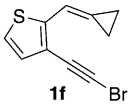


Entry	[Cu]	Ligand	Base	Solvent	Yield [%][a]
1[b]	$CuSO_4$	L1	K_3PO_4	toluene	trace
2	$CuSO_4$	L1	K_3PO_4	toluene	20
3	$CuSO_4$	L1	K_2CO_3	toluene	39
4	$CuSO_4$	L1	Cs_2CO_3	toluene	7
5	$CuSO_4$	L1	Na_2CO_3	toluene	N.D.
6	$CuSO_4$	L1	NaO-*t*-Bu	toluene	trace
7	$CuSO_4$	L1	LiOH	toluene	21
8	$CuSO_4$	L1	$KHCO_3$	toluene	22
9	$CuSO_4$	L1	KOAc	toluene	trace
10[c]	$CuSO_4$	L1	K_2CO_3	toluene	38
11	$Cu(OAc)_2$	L1	K_2CO_3	toluene	54
12	CuI	L1	K_2CO_3	toluene	30
13	CuBr	L1	K_2CO_3	toluene	43
14	CuCl	L1	K_2CO_3	toluene	38
15	$CuCl_2$	L1	K_2CO_3	toluene	39
16	$CuBr_2$	L1	K_2CO_3	toluene	22
17	$Cu(OTf)_2$	L1	K_2CO_3	toluene	38
18[d]	$Cu(OAc)_2$	L1	K_2CO_3	toluene	36
19	$Cu(OAc)_2$	L2	K_2CO_3	toluene	32
20	$Cu(OAc)_2$	L3	K_2CO_3	toluene	15
21	$Cu(OAc)_2$	L4	K_2CO_3	toluene	25
22	$Cu(OAc)_2$	L5	K_2CO_3	toluene	trace
23	$Cu(OAc)_2$	L6	K_2CO_3	toluene	trace
24	$Cu(OAc)_2$	L1	K_2CO_3	dioxane	65
25	$Cu(OAc)_2$	L1	K_2CO_3	DMF	73
26	$Cu(OAc)_2$	L1	K_2CO_3	DMSO	60

[a] Isolated yield based on *N*-allyl-4-methylbenzenesulfonamide **2a**.
[b] The reaction was performed at 80 °C.
[c] The ratio of **1a**/**2a** was 1.5.
[d] In the presence of $Cu(OAc)_2$ (5 mol%).

Table 2. Copper-catalyzed reaction of 1-2-bromoethynyl-2-(cyclopropylidenemethyl)arene **1** with *N*-allylsulfonamide **2**.



Entry	Substrate **1**	R^2, R^3	Yield [%][a]
1	 **1a**	H, Ts (**2a**)	73 (**3a**)
2	 **1b**	H, Ts (**2a**)	66 (**3b**)
3	 **1c**	H, Ts (**2a**)	65 (**3c**)
4	 **1d**	H, Ts (**2a**)	70 (**3d**)
5	 **1e**	H, Ts (**2a**)	66 (**3e**)
6	 **1f**	H, Ts (**2a**)	30 (**3f**)
7	**1a**	CH_3, Ts (**2b**)	60 (**3g**)
8	**1a**	C_6H_5, Ts (**2c**)	75 (**3h**)
9	**1a**	H, $PhSO_2$ (**2d**)	68 (**3i**)
10	**1a**	H, 4-$BrC_6H_4SO_2$ (**2e**)	65 (**3j**)
11	**1a**	H, 4-$NO_2C_6H_4SO_2$ (**2f**)	trace
12	**1a**	H, Ms (**2g**)	77 (**3k**)
13	**1a**	H, Ph_2PO (**2h**)	35 (**3l**)
14	**1a**	H, PhCO (**2i**)	NR
15	**1d**	C_6H_5, Ts (**2c**)	65 (**3m**)
16	**1f**	C_6H_5, Ts (**2c**)	55 (**3n**)

[a] Isolated yield *N*-allylsulfonamide **2**.

the scope of this tandem reaction. The reaction proceeded smoothly when 1-(bromoethynyl)-2-(cyclopropylidenemethyl)benzene **1b** was reacted with *N*-allyl-4-methylbenzenesulfonamide **2a** under the standard conditions, affording the desired product **3b** in 66% yield (Table 2, entry 2). The structure of compound **3b** was unambiguously confirmed by X-ray crystallography analysis (Figure 1, see also the Supporting Information). Reactions of *N*-allyl-4-methylbenzenesulfonamide **2a** and substrates **1** with electron-withdrawing groups attached to the aromatic ring gave satisfactory results (Table 2, entries 3–5). However, the reaction of thiophenyl-incorporated substrate **1f** with *N*-allyl-4-methylbenzenesulfonamide **2a** provided the corresponding product in relatively low 30% yield (Table 2, entry 6). With respect to the scope of the R^2 group in substrate **2**, but-2-en-1-amide **2b** reacted effectively with substrate **1a**, generating the expected product **3g** in 60% yield (Table 2, entry 7). A better yield was observed when 3-phenylprop-2-en-1-amide **2c** was employed as a replacement (**3h**, 75%; Table 2, entry 8). With respect to the R^3 group in substrate **2**, the reaction of *N*-allyl amide **2d** or **2e** with 1-(bromoethynyl)-2-(cyclopropylidenemethyl)-4-methylbenzene **1a** afforded the corresponding products **3i** and **3j** in good yields, respectively (Table 2, entries 9 and 10). In contrast, only a trace amount of desired product was detected when amide **2f** was used in the reaction (R^3 = 4-nitrobenzenesulfonyl group, Table 2, entry 11). Interestingly, a good yield was obtained when methylsulfonyl-substituted amide **2g** was employed as a partner in the reaction of substrate **1a** (77% yield, Table 2, entry 12). The yield was decreased significantly for the reaction of substrate **1a** with *N*-allyl-*P*,*P*-diphenylphosphinic amide **2h** (35%, Table 2, entry 13). No reaction occurred between compound **1a** and *N*-allylbenzamide **2i** under the standard conditions (Table 2, entry 14). Substrates **1d** and **1f** reacted smoothly with 3-phenylprop-2-en-1-amide **2c** to furnish the expected indolines (Table 2, entries 15 and 16).

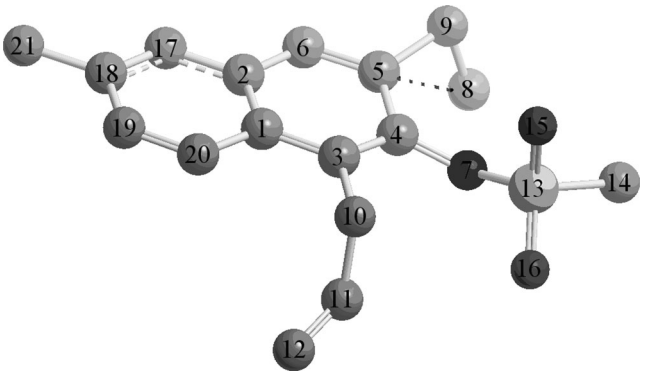
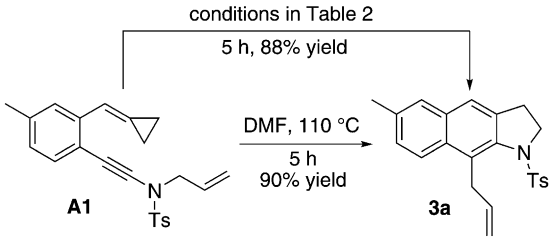


Figure 1. Structure of TS.

To investigate whether the copper catalyst and ligand affect the post-Ullmann aza-Claisen rearrangement and 6π-electrocyclization, a control experiment was performed (Scheme 2). The reaction of compound **A1** (isolated from the Ullmann coupling step) was carried out under the standard conditions shown in Table 2 or in the absence of copper catalyst and ligand. The results of both reactions were similar, indicating that the copper catalyst and ligand are only involved in C–N bond formation.

To get more insight into the experimental results, DFT calculations were performed for the last step



Scheme 2. A control experiment for the reaction of compound **A1**.

(from **C** to **3** in the proposed mechansim) with the *Gaussian 09* program package at B3LYP/6-31+G-(d,p) level.[14,15] The full geometry optimization of all minima and transition states involved was performed at the chosen level of theory. Frequency calculations were carried out at the same level of theory to identify all of the stationary points as minima (zero imaginary frequencies) or first-order saddle points (one imaginary frequency). The intrinsic reaction coordinate (IRC)[16] pathways have been traced to verify two desired minima connected by the transition states.

Solvent effects have been considered at the same DFT level by reoptimizing the structures obtained in the gas-phase using a simple self-consistent reaction field (SCRF) method[17–19] based on the polarizable continuum model (PCM)[20–22] with UFF cavities.[23]

Our computations show that the dihedral angle (C-8–C-9–C-5–C-4) between the 3-membered ring in compound **C** and the adjacent 6-membered ring is 105.5°. While in the TS and product **3**, the corresponding angles are 72.8° and 16.4°, respectively. The structure of TS is more similar with that of **C**. On the other hand, the energy of TS is higher than that of **C** and product **3** by 23.2 and 78.0 kcal mol^{-1}, respectively. The N-7–C-8 distance in **TS** (2.571 Å) is more close to that in **C** (2.793 Å) rather than **3** (1.499 Å). All these data reveal that the TS is an early transition state. At the same time, this process is a concerted intramolecular rearrangement, which can proceed smoothly with the barrier height being 23.2 kcal mol^{-1} in DMF at 110 °C. Moreover, NBO analysis of TS shows that C-8 and C-5 in TS are seen to have approximate valence configuration sp^2 hybridization, and there is a very clear interaction between lone pair (LP) natural bond orbital (NBO) of N atom and anti lone pair (LP*) NBO of C-8, the stabilization energy is 24.3 kcal mol^{-1}. This means that this process is triggered by the initial ring opening of 3-membered ring attacking by lone pair, not π electron of the N atom.

Conclusions

In summary, we have developed a novel route for the generation of fused indolines *via* a copper(II)-catalyzed tandem reaction of 1-bromoethynyl-2-(cyclopropylidenemethyl)arenes with allylic sulfonamides. The transformation is a four-step cascade involving Ullmann coupling, aza-Claisen rearrangement, 6π-electrocyclization, and intramolecular rearrangement. Further exploration of 1-(bromoethynyl)-2-(cyclopropylidenemethyl)arenes for other transformations is ongoing.

Experimental Section

General Experimental Procedure for the Copper-Catalyzed Tandem Reaction of 1-(Bromoethynyl)-2-(cyclopropylidenemethyl)arene 1 with *N*-Allylsulfonamide 2

N-Allylsulfonamide **2** (0.3 mmol) was added to a solution of 1-(bromoethynyl)-2-(cyclopropylidenemethyl)arene (0.36 mmol, 1.2 equiv.), $Cu(OAc)_2$ (5.4 mg, 0.03 mmol), 1,10-phenanthroline (11.0 mg, 0.06 mmol), and K_2CO_3 (83.0 mg, 0.6 mmol) in DMF (1.5 mL). The mixture was stirred at 110 °C overnight under N_2. After completion of reaction as indicated by TLC, the reaction mixture was cooled to room temperature. The mixture was filtered through Celite, and diluted with ethyl acetate (30 mL). The organic solution was washed with water (20 mL × 3), brine (30 mL), and dried over Na_2SO_4. The solvent was evaporated and the residue was purified by column chromatography on silica gel (eluted with *n*-hexane/EtOAc = 30:1 to 10:1) to provide the corresponding product **3**.

9-Allyl-6-methyl-1-tosyl-2,3-dihydro-1*H*-benzo[*f*]indole (3a): yield: 73%; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.23 (t, J = 7.2 Hz, 2H), 2.36 (s, 3H), 2.49 (s, 3H), 4.01 (t, J = 7.2 Hz, 2H), 4.28 (d, J = 4.8 Hz, 2H), 5.05–5.12 (m, 2H), 6.03–6.13 (m, 1H), 7.09 (d, J = 8.0 Hz, 2H), 7.16–7.25 (m, 1H), 7.23–7.36 (m, 4H), 7.47 (s, 1H), 8.06 (d, J = 8.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.5, 21.6, 28.9, 33.8, 52.9, 115.4, 121.5, 125.8, 127.2, 127.8, 127.8, 128.3, 129.1, 129.4, 129.5, 131.0, 133.5, 135.0, 135.3, 136.2, 138.0, 138.7, 144.1; HR-MS (ESI); m/z = 400.1320, calcd. for $C_{23}H_{23}NO_2S$ (M + Na^+): 400.1347.

9-Allyl-1-tosyl-2,3-dihydro-1*H*-benzo[*f*]indole (3b): yield: 66%; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.25 (t, J = 6.8 Hz, 2H), 2.36 (s, 3H), 4.01 (t, J = 6.8 Hz, 2H), 4.30 (d, J = 4.0 Hz, 2H), 5.06–5.12 (m, 2H), 6.06–6.09 (m, 1H), 7.10 (d, J = 8.0 Hz, 2H), 7.34–7.36 (m, 3H), 7.41–7.48 (m, 2H), 7.70 (d, J = 7.2 Hz, 1H), 8.17 (d, J = 8.0 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.7, 28.9, 33.9, 52.9, 115.5, 122.2, 125.6, 125.7, 125.9, 127.7, 128.1, 129.6, 132.8, 133.2, 135.0, 136.1, 137.9, 139.5, 144.2; HRMS (ESI): m/z = 386.1175, calcd. for $C_{22}H_{21}NO_2S$ (M + Na^+): 386.1191.

9-Allyl-6-fluoro-1-tosyl-2,3-dihydro-1*H*-benzo[*f*]indole (3c): yield: 65%; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.25 (t, J = 6.8 Hz, 2H), 2.36 (s, 3H), 4.00 (t, J = 6.8 Hz, 2H), 4.25 (s, 2H), 5.05–5.09 (m, 2H), 6.01–6.06 (m, 1H), 7.11 (d, J = 7.2 Hz, 2H), 7.21–7.35 (m, 5H), 8.12–8.16 (m, 1H);

^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.6, 28.9, 34.0, 52.9, 111.2 (d, $^2J_{C,F}$ = 20.1 Hz), 115.5 (d, $^2J_{C,F}$ = 23.8 Hz), 115.7, 121.5 (d, $^4J_{C,F}$ = 4.8 Hz), 127.7, 128.4 (d, $^3J_{C,F}$ = 8.6 Hz), 129.6, 129.8, 134.2 (d, $^3J_{C,F}$ = 8.6 Hz), 134.8, 137.6, 137.7, 139.1, 139.1, 144.3, 160.6 (d, $^1J_{C,F}$ = 244.0 Hz); HR-MS (ESI): *m/z* = 404.1105, calcd. for $C_{22}H_{20}FNO_2S$ (M + Na^+): 404.1096.

9-Allyl-7-fluoro-1-tosyl-2,3-dihydro-1*H*-benzo[*f*]indole (3d): yield: 70%; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.26 (t, *J* = 6.4 Hz, 2H), 2.36 (s, 3H), 4.00 (t, *J* = 6.4 Hz, 2H), 4.21 (d, *J* = 4.0 Hz, 2H), 5.08–5.12 (m, 2H), 6.03–6.06 (m, 1H), 7.11 (d, *J* = 7.6 Hz, 2H), 7.17–7.21 (m, 1H), 7.34–7.36 (m, 3H), 7.65–7.68 (m, 1H), 7.78 (d, *J* = 11.6 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.6, 28.8, 34.0, 52.9, 109.9 (d, $^2J_{C,F}$ = 21.9 Hz), 115.7 (d, $^2J_{C,F}$ = 24.8 Hz), 115.9, 122.1, 127.7, 128.9 (d, $^4J_{C,F}$ = 5.7 Hz), 129.6, 130.1, 130.2 (d, $^3J_{C,F}$ = 8.6 Hz), 134.1 (d, $^3J_{C,F}$ = 8.7 Hz), 134.9, 135.5 (d, $^4J_{C,F}$ = 1.9 Hz), 137.4, 140.5, 144.3, 160.6 (d, $^1J_{C,F}$ = 243.1 Hz); HR-MS (ESI): *m/z* = 404.1115, calcd. for $C_{22}H_{20}FNO_2S$ (M + Na^+): 404.1096.

9-Allyl-6-chloro-1-tosyl-2,3-dihydro-1*H*-benzo[*f*]indole (3e): yield: 66%; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.25 (t, *J* = 6.8 Hz, 2H), 2.36 (s, 3H), 4.00 (t, *J* = 6.8 Hz, 2H), 4.24 (s, 2H), 5.04–5.07 (m, 2H), 6.00–6.04 (m, 1H), 7.10 (d, *J* = 7.2 Hz, 2H), 7.26 (s, 1H), 7.33 (d, *J* = 7.2 Hz, 2H), 7.39 (d, *J* = 8.8 Hz, 1H), 7.65 (s, 1H), 8.08 (d, *J* = 8.8 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.6, 28.9, 33.8, 52.8, 115.8, 121.3, 126.3, 126.7, 127.6, 127.7, 129.6, 129.7, 131.2, 131.6, 134.0, 134.8, 137.6, 139.8, 144.4; HR-MS (ESI): *m/z* = 420.0779, calcd. for $C_{22}H_{20}ClNO_2S$ (M + Na^+): 420.0801.

4-Allyl-5-tosyl-6,7-dihydro-5*H*-thieno[2,3-*f*]indole (3f): yield: 30%; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.19 (t, *J* = 6.4 Hz, 2H), 2.37 (s, 3H), 4.01 (t, *J* = 6.4 Hz, 2H), 4.13 (d, *J* = 5.2 Hz, 2H), 5.08–5.12 (m, 2H), 6.05–6.09 (m, 1H), 7.12 (d, *J* = 7.2 Hz, 2H), 7.34–7.41 (m, 4H), 7.53 (d, *J* = 5.2 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.6, 29.0, 35.3, 53.3, 115.7, 116.4, 123.5, 126.0, 127.8, 128.9, 129.5, 134.7, 135.1, 137.4, 138.5, 138.9, 139.7, 144.1; HR-MS (ESI): *m/z* = 392.0730, calcd. for $C_{20}H_{19}NO_2S_2$ (M + Na^+): 392.0755.

9-(But-3-en-2-yl)-6-methyl-1-tosyl-2,3-dihydro-1*H*-benzo-[*f*]indole (3g): yield: 60%; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.65 (d, *J* = 6.8 Hz, 3H), 2.14–2.32 (m, 2H), 2.36 (s, 3H), 2.47 (s, 3H), 3.94–4.06 (m, 2H), 4.91 (s, 1H), 5.21–5.28 (m, 2H), 6.47–6.54 (m, 1H), 7.10 (d, *J* = 7.2 Hz, 2H), 7.23–7.26 (m, 2H), 7.36 (d, *J* = 7.2 Hz, 2H), 7.46 (s, 1H), 8.29 (d, *J* = 8.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 18.7, 21.4, 21.7, 29.0, 37.9, 53.0, 112.8, 121.8, 127.0, 127.0, 127.5, 127.8, 129.5, 130.2, 134.2, 135.0, 135.0, 135.1, 136.1, 138.5, 144.0, 144.1; HR-MS (ESI): *m/z* = 414.1474, calcd. for $C_{24}H_{25}NO_2S$ (M + Na^+): 414.1504.

6-Methyl-9-(1-phenylallyl)-1-tosyl-2,3-dihydro-1*H*-benzo-[*f*]indole (3h): yield: 75%; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.21–2.35 (m, 2H), 2.39 (s, 3H), 2.42 (s, 3H), 3.98–4.16 (m, 2H), 5.25–5.34 (m, 2H), 6.26 (d, *J* = 7.2 Hz, 1H), 6.53–6.60 (m, 1H), 7.06 (d, *J* = 8.4 Hz, 1H), 7.11–7.21 (m, 3H), 7.23–7.30 (m, 2H), 7.36–7.40 (m, 3H), 7.43–7.50 (m, 3H), 7.71 (d, *J* = 8.8 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.4, 21.7, 29.2, 50.2, 53.2, 117.7, 122.5, 125.8, 127.1, 127.5, 127.8, 127.9, 128.1, 128.2, 129.6, 129.7, 132.4, 134.3, 135.1, 135.2, 136.4, 139.6, 140.0, 143.0, 144.2; HR-MS (ESI): *m/z* = 476.1663, calcd. for $C_{29}H_{27}NO_2S$ (M + Na^+): 476.1660.

9-Allyl-6-methyl-1-(phenylsulfonyl)-2,3-dihydro-1*H*-benzo[*f*]indole (3i): yield: 68%; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.21 (t, *J* = 6.8 Hz, 2H), 2.48 (s, 3H), 4.02 (t, *J* = 6.8 Hz, 2H), 4.27 (d, *J* = 4.0 Hz, 2H), 5.06–5.12 (m, 2H), 6.06–6.09 (m, 1H), 7.27–7.32 (m, 4H), 7.46–7.54 (m, 4H), 8.06 (d, *J* = 8.8 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.5, 28.8, 33.8, 52.9, 115.5, 121.6, 125.8, 127.2, 127.7, 127.8, 128.9, 129.4, 131.0, 133.2, 133.5, 135.4, 136.0, 137.8, 138.0, 138.6; HR-MS (ESI): *m/z* = 386.1163, calcd. for $C_{22}H_{21}NO_2S$ (M + Na^+): 386.1191.

9-Allyl-1-(4-bromophenylsulfonyl)-6-methyl-2,3-dihydro-1*H*-benzo[*f*]indole (3j): yield: 65%; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.29 (t, *J* = 6.8 Hz, 2H), 2.49 (s, 3H), 4.02 (t, *J* = 6.8 Hz, 2H), 4.24 (s, 2H), 5.06–5.10 (m, 2H), 6.04–6.07 (m, 1H), 7.24–7.32 (m, 4H), 7.43–7.48 (m, 3H), 8.05 (d, *J* = 8.0 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.5, 28.9, 33.8, 52.9, 115.6, 121.8, 125.8, 127.3, 128.0, 128.4, 129.2, 129.5, 131.0, 132.2, 133.5, 135.6, 135.6, 136.9, 137.8, 138.3; HR-MS (ESI): *m/z* = 464.0275, calcd. for $C_{22}H_{20}BrNO_2S$ (M + Na^+): 464.0296.

9-Allyl-6-methyl-1-(methylsulfonyl)-2,3-dihydro-1*H*-benzo[*f*]indole (3k): yield: 77%; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.48 (s, 3H), 2.78 (s, 3H), 3.17 (t, *J* = 6.4 Hz, 2H), 4.09 (d, *J* = 4.0 Hz, 2H), 4.14 (t, *J* = 6.8 Hz, 2H), 5.01–5.04 (m, 2H), 5.95–5.99 (m, 1H), 7.29 (d, *J* = 8.4 Hz, 1H), 7.52–7.53 (m, 2H), 7.98 (d, *J* = 8.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.4, 30.0, 33.5, 37.4, 53.3, 115.5, 122.2, 125.6, 127.2, 128.0, 128.9, 131.0, 133.5, 135.1, 135.5, 137.7, 138.2; HR-MS (ESI): *m/z* = 324.1039, calcd. for $C_{17}H_{19}NO_2S$ (M + Na^+): 324.1034.

9-Allyl-1-(diphenylphosphoryl)-6-methyl-2,3-dihydro-1*H*-benzo[*f*]indole (3l): yield: 35%; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.43 (s, 3H), 2.84 (t, *J* = 6.8 Hz, 2H), 3.66–3.72 (m, 2H), 3.80 (d, *J* = 4.8 Hz, 2H), 4.73–4.80 (m, 2H), 5.58–5.65 (m, 1H), 7.18 (d, *J* = 8.4 Hz, 1H), 7.40–7.41 (m, 8H), 7.70–7.76 (m, 5H); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.3, 30.6, 33.4, 53.0 (d, $J_{P,C}$ = 3.8 Hz), 114.9, 121.5, 122.4, 124.9, 127.0, 127.4, 128.6 (d, $J_{P,C}$ = 12.4 Hz), 131.0, 132.1 (d, $J_{P,C}$ = 125.8 Hz), 132.2 (d, $J_{P,C}$ = 22.8 Hz), 132.2, 133.7, 135.7 (d, $J_{P,C}$ = 3.8 Hz), 137.3, 141.8; ^{31}P NMR (100 MHz, $CDCl_3$): δ = 28.7; HR-MS (ESI): *m/z* = 446.1661, calcd for $C_{28}H_{26}NOP$ (M + Na^+): 446.1650.

7-Fluoro-9-(1-phenylallyl)-1-tosyl-2,3-dihydro-1*H*-benzo-[*f*]indole (3m): yield: 65%; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.26–2.30 (m, 2H), 2.39 (s, 3H), 4.00–4.13 (m, 2H), 5.25–5.27 (m, 2H), 6.24 (d, *J* = 6.4 Hz, 1H), 6.52–6.56 (m, 1H), 7.10–7.20 (m, 4H), 7.26–7.29 (m, 2H), 7.34–7.35 (m, 2H), 7.42–7.46 (m, 4H), 7.63–7.67 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.7, 29.1, 50.0, 53.2, 112.1 (d, $^2J_{C,F}$ = 22.9 Hz), 115.7 (d, $^2J_{C,F}$ = 24.7 Hz), 118.0, 123.0, 126.1, 127.8, 128.1, 128.2, 129.7, 130.3 (d, $^3J_{C,F}$ = 9.5 Hz), 130.9, 132.0 (d, $^4J_{C,F}$ = 5.7 Hz), 132.7(d, $^3J_{C,F}$=9.6 Hz), 135.1, 135.7 (d, $^4J_{C,F}$ = 1.9 Hz), 138.9, 141.7, 142.2, 144.4, 159.7 (d, $^1J_{C,F}$ = 243.1 Hz); HR-MS (ESI): *m/z* = 480.1427, calcd. for $C_{28}H_{24}FNO_2S$ (M + Na^+): 480.1409.

4-(1-Phenylallyl)-5-tosyl-6,7-dihydro-5*H*-thieno[2,3-*f*]-indole (3n): yield: 55%; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.18–2.29 (m, 2H), 2.39 (s, 3H), 4.01–4.11 (m, 2H), 5.24–5.30 (m, 2H), 6.14 (d, *J* = 6.8 Hz, 1H), 6.35–6.42 (m, 1H), 7.01 (d, *J* = 4.8 Hz, 1H), 7.16–7.20 (m, 4H), 7.26–7.29 (m, 2H), 7.36 (d, *J* = 7.2 Hz, 2H), 7.43–7.45 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.7, 29.2, 50.2, 53.5, 117.1, 117.5, 125.0, 125.5, 126.0, 127.9, 128.0, 128.4, 129.6, 132.3, 134.8, 135.3, 138.3, 139.1, 139.3, 140.0, 142.5, 144.2; HR-MS (ESI): *m/z* = 468.1042, calcd. for $C_{26}H_{23}NO_2S_2$ (M + Na^+): 468.1068.

***N*-Allyl-*N*-{[2-(cyclopropylidenemethyl)-4-methylphenyl]-ethynyl}-4-methylbenzenesulfonamide (A1):** yield: 80%; ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 1.17$ (t, $J = 8.0$ Hz, 2H), 1.41 (t, $J = 8.0$ Hz, 2H), 2.32 (s, 3H), 2.43 (s, 3H), 4.07 (d, $J = 6.0$ Hz, 2H), 5.22–5.32 (m, 2H), 5.77–5.82 (m, 1H), 6.93 (d, $J = 7.6$ Hz, 1H), 7.11 (s, 1H), 7.22 (d, $J = 8.0$ Hz, 1H), 7.32 (d, $J = 7.6$ Hz, 2H), 7.59 (s, 1H), 7.85 (d, $J = 7.6$ Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta = 0.6$, 4.3, 21.7, 25.6, 54.5, 69.6, 85.6, 116.4, 118.3, 120.1, 120.2, 125.7, 125.7, 127.4, 127.8, 127.9, 129.8, 131.1, 132.1, 134.8, 137.8, 139.1, 144.7; HR-MS (ESI): $m/z = 400.1367$, calcd. for $C_{23}H_{23}NO_2S$ ($M + Na^+$): 400.1347.

Crystallographic data for the structure **3b** have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC 876411. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre *via* www.ccdc.cam.ac.uk/data_request/cif or on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK [fax (internat.): +44-1223/336-033; e-mail: deposit@ccdc.cam.ac.uk.

Supporting Information

Experimental procedures, characterization data, ^{1}H and ^{13}C NMR spectra of compounds **1** and **3**, and a CIF file of compound **3b** are available in the Supporting Information.

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