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Hydrazone-palladium catalyzed annulation of 1-allyl-2-bromobenzene derivatives with internal alkynes

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Annulation of 1-allyl-2-bromobenzene derivatives with internal alkynes using a hydrazone-palladium catalyst system proceeded smoothly and gave the corresponding polysubstituted naphthalene derivatives in good to high yields.

Introduction

Polysubstituted naphthalene derivatives have become interestingly important because of their potential utility as π-conjugated functional materials, such as organic semiconductors and luminescent materials.[1] Furthermore, they are also basic skeletons of many biologically active compounds and pharmaceuticals such as an inhibitor of glycogen synthase kinase-3 (GSK-3).[2] Therefore, the synthetic methodologies for such structures have attracted significant attention and been developed.[3] Among modern potential strategies to prepare polysubstituted naphthalene derivatives are the metal catalyzed coupling of aromatic compound with two internal alkynes.[4] In 2014, Pham and co-workers reported Rh-catalyzed annulation of directing group-free monocyclic arenes with two internal alkynes *via* C-H activation for synthesis of polysubstituted naphthalenes.[4p] However, the products of these methods are very restricted in terms of substituents of product because they are derived from two internal alkynes. On the other hand, there are some examples of the intramolecular annulation without internal alkyne for polysubstituted naphthalene derivatives, but these protocol required installing substituent in design of starting materials for selective synthesis.[5] In 2002, Larock and co-workers reported that polysubstituted naphthalene can be prepared by annulation of *o*-alkenylaryl halides with internal alkynes using a triphenylphosphine-palladium catalyst system.[6] This protocol *via* intramolecular Heck reaction is very effective for a selective approach to trisubstituted naphthalenes with the object of installing various substituents. However, this protocol is strongly limited in terms of substrates. For instance, the main starting materials of annulation are aryl iodides, which are reactive but expensive. Furthermore, all starting materials aside from one have electron-deficient olefin. When 1-allyl-2-iodebenzene, whose olefin has no substituent, reacted with diphenylacetylene, the corresponding naphthalene product was obtained in only 32% yield.[6b] On the other hand, Chen and co-workers reported similar reaction which was achieved by C-H bond activation.[7] However, this protocol was also tolerated only electron-deficient olefin bearing a phenyl group and required $Cu(OAc)_2$ as a co-catalyst in the presence of excess amount of TFA.

1 **2**

1a: R^1 = Ph, R^2 = Me
1b: R^1 = 2-Pyridyl, R^2 = Me
1c: R^1, R^2 = -$(CH_2)_4$-
1d: R^1, R^2 = -$(CH_2)_5$-
1e: R^1, R^2 = -$(CH_2)_6$-

Figure 1 Hydrazones **1** and **2**.

We recently demonstrated phosphine free hydrazone compounds (Figure 1) as an effective ligands for palladium-catalyzed C-C bond formations such as the Mizoroki-Heck,[8] Suzuki-Miyaura,[9] Sonogashira[10] and Hiyama[10] cross-coupling reactions of aryl halides. Herein, we report how limitation of substrates on palladium-catalyzed annulation of aryl bromides with internal alkynes for synthesis of polysubstituted naphthalene derivatives would be solved by using hydrazone as a ligand.

Results and discussion

Initially, we sought the optimal reaction conditions for a palladium-catalyzed synthesis of polysubstituted naphthalenes using hydrazone ligands. The reaction using 1-allyl-2-

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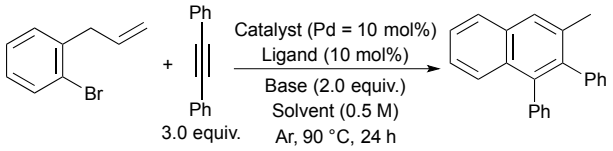
bromobenzene and diphenylacetylene as model substrates was performed under an argon atmosphere at 90 °C for 24 h (Table 1). Using $Pd(OAc)_2$ and bishydrazone **1a** as a ligand, we observed that the reaction in the presence of Cs_2CO_3 in DMF as a solvent gave corresponding product **5aa** in 41% yield (Table 1, entry 1). Several palladium sources were tested (Table 1, entries 2-8). When we used $Pd(TFA)_2$, product **5aa** was obtained in 67% yield (Table 1, entry 6). On the other hand, palladium(0) sources, such as $Pd_2(dba)_3$ and $Pd(PPh_3)_4$ were not effective for this reaction (Table 1, entries 7 and 8). Next, we tested hydrazone ligands **1a**-**e** and **2** (Table 1, entries 6 and 9-14). While phenyl-methyl-type bishydrazone ligand **1a** afforded the corresponding product in high yield (Table 1, entry 6), 2-pyridyl-methyl-type bishydrazone ligand **1b** afforded slightly lower yield of product (Table 1, entry 9).

Table 1 Optimization of palladium-catalyzed annulation of 1-allyl-2-bromobenzene (**3a**) with diphenylacetylene (**4a**) using hydrazone ligand.[a]



3a **4a** **5aa**

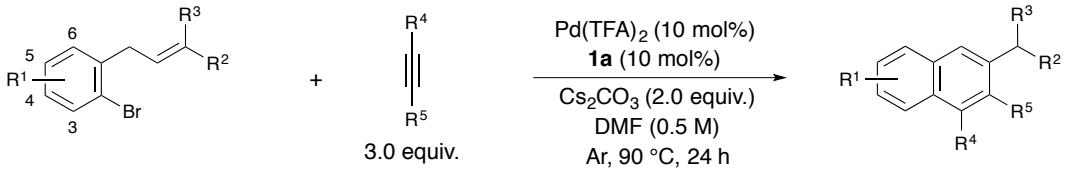
Entry	Catalyst	Ligand	Base	Solvent	Yield of **5aa** [%]
1	$Pd(OAc)_2$	**1a**	Cs_2CO_3	DMF	41
2	$PdCl_2$	**1a**	Cs_2CO_3	DMF	57
3	$[Pd(\eta^3\text{-allyl})]_2$	**1a**	Cs_2CO_3	DMF	14
4	$Pd(acac)_2$	**1a**	Cs_2CO_3	DMF	55
5	$PdCl_2(MeCN)_2$	**1a**	Cs_2CO_3	DMF	47
6	$Pd(TFA)_2$	**1a**	Cs_2CO_3	DMF	67
7	$Pd_2(dba)_3$	**1a**	Cs_2CO_3	DMF	8
8	$Pd(PPh)_4$	-	Cs_2CO_3	DMF	24
9	$Pd(TFA)_2$	**1b**	Cs_2CO_3	DMF	50
10	$Pd(TFA)_2$	**1c**	Cs_2CO_3	DMF	42
11	$Pd(TFA)_2$	**1d**	Cs_2CO_3	DMF	58
12	$Pd(TFA)_2$	**1e**	Cs_2CO_3	DMF	29
13	$Pd(TFA)_2$	**2**	Cs_2CO_3	DMF	45
14	$Pd(TFA)_2$	PPh_3[b]	Cs_2CO_3	DMF	17
15	$Pd(TFA)_2$	**1a**	K_2CO_3	DMF	15
16	$Pd(TFA)_2$	**1a**	K_3PO_4	DMF	25
17	$Pd(TFA)_2$	**1a**	$Ca(OH)_2$	DMF	Trace
18	$Pd(TFA)_2$	**1a**	NaOAc	DMF	Trace
19	$Pd(TFA)_2$	**1a**	Et_3N	DMF	Trace
20	$Pd(TFA)_2$	**1a**	Cs_2CO_3	DMA	28
21	$Pd(TFA)_2$	**1a**	Cs_2CO_3	NMP	42
22	$Pd(TFA)_2$	**1a**	Cs_2CO_3	DMSO	29
23	$Pd(TFA)_2$	**1a**	Cs_2CO_3	1,4-Dioxane	41
24	$Pd(TFA)_2$	**1a**	Cs_2CO_3	PhMe	39

[a] Reaction conditions: **3a**, **4a** (3.0 equiv.), catalyst (Pd = 10 mol%), ligand (10 mol%), base (2.0 equiv.), solvent (0.5 M) at 90 °C for 24 h under Ar. [b] 20 mol% of PPh_3 was added.

Using hydrazone ligands **1c**-**e** bearing 5-7 member rings gave the corresponding product in 42%, 58% and 29% yields, respectively (Table 1, entries 10-12). In the case of using pyridine-type monohydrazone ligand **2**, the desired product was obtained in 45% yield (Table 1, entry 13). On the other hand, the reaction proceeded inefficiently using triphenylphosphine as a ligand and gave the desired product in a low yield (Table 1, entry 14). As a result, we found phenyl-methyl-type bishydrazone ligand **1a** was the most suitable for this annulation (Table 1, entry 6). Next, the effects of various bases were investigated (Table 1, entries 6 and 15-19). Using Cs_2CO_3 led to the highest yield in this reaction (Table 1, entry 6). Various solvents were also tested (Table 1, entries 6 and 20-24). DMF was the most suitable solvent for this reaction (Table 1, entry 6).

With the optimized reaction conditions in hand (Table 1, Entry 6), we reacted 1-allyl-2-bromobenzene derivatives **3** with internal alkynes **4** at 80-110 °C to investigate the scope and limitation of this annulation (Table 2). The reactions of 1-allyl-2-bromobenzenes with an electron-donating or withdrawing group at the 5-position of the aromatic ring and diphenylacetylene **4a** proceeded and gave corresponding products in good to high yields respectively (Table 2, entries 2-5). Furthermore, 4-methyl-substituted aryl bromide **3f** was also tolerated (Table 2, entry 6). Aryl bromide **3g** bearing two methoxy groups on the aromatic ring reacted with **4a** at 110 °C to afford the desired product **5ga** in good yield (Table 2, entry 7). Moreover, we also succeeded in synthesizing polysubstituted phenanthrene derivative **5ha** in 66% yield (Table 2, entry 8). The reaction of bromide **3i**, whose olefin has a phenyl group, gave the corresponding product **5ia** in high yield (Table 2, entry 9). On the other hand, the annulation of **3j**, which has a prenyl group, did not afford the desired product (Table 2, entry 10). Presumably, this result indicated that bulky olefin bearing no electron-withdrawing group did not undergo an intramolecular Heck reaction because of steric and electronic effects. Next, we tested the reaction of 1-allyl-2-bromobenzene (**3a**) with various symmetrical internal alkynes **4**. When we employed diaryl acetylenes bearing electron-donating or withdrawing substituents on the aryl ring, the corresponding products were also obtained in good yields (Table 2, entries 11-14). However, the product was not observed in the case of using di-*p*-cyanophenyl acetylene (**4f**). This result indicated that internal alkyne bearing strong electron-withdrawing groups does not have enough coodination force to palladium complex because of the lack of electron density on the triple bond of the internal alkyne (Table 2, entry 15). Aliphatic internal alkyne such as 4-octyne (**4g**) was tolerated and afforded the desired product **5ag** in 65% yield. Unfortunately, the desired product was not obtained from the reaction of 1-allyl-2-bromobenzene (**3a**) with diethyl acetylenedicarboxylate (**4h**) because of the same reason in the cace of **4f** (Table 2, entry 17). On the other hand, the use of an acetyl-protected 2-butyne-1,4-diol resulted in obtaining a naphthalene product **5ai** in 56% yield (Table 2, entry 18). In the case of using unsymmetric internal alkyne **4j,** the reaction gave

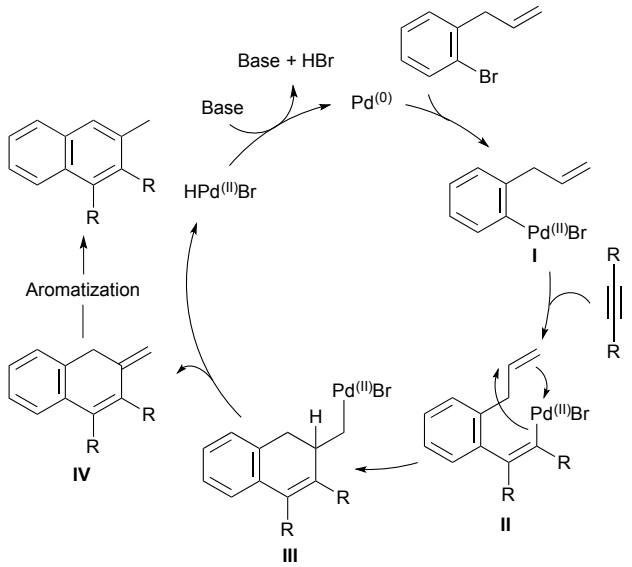
Table 2 Scope and limitation of annulation of aryl bromide **3** with internal alkynes **4** using hydrazone ligand.[a]



3 **4** **5**

Entry	R^1	R^2	R^3	R^4	R^5	Yield of **5** (%)
1	H	H	H (**3a**)	Ph	Ph (**4a**)	67 (**5aa**)
2	5-MeO	H	H (**3b**)	Ph	Ph (**4a**)	57 (**5ba**)
3[b]	5-Me	H	H (**3c**)	Ph	Ph (**4a**)	60 (**5ca**)
4	5-Cl	H	H (**3d**)	Ph	Ph (**4a**)	47 (**5da**)
5[c]	5-F	H	H (**3e**)	Ph	Ph (**4a**)	50 (**5ea**)
6[d]	4-Me	H	H (**3f**)	Ph	Ph (**4a**)	58 (**5fa**)
7[d]	4,5-diMeO	H	H (**3g**)	Ph	Ph (**4a**)	71 (**5ga**)
8	-(CH=CH)$_2$- (3,4)	H	H (**3h**)	Ph	Ph (**4a**)	66 (**5ha**)
9	H	Ph	H (**3i**)	Ph	Ph (**4a**)	81 (**5ia**)
10	5-MeO	Me	Me (**3j**)	Ph	Ph (**4a**)	N.D.[e] (**5ja**)
11[b]	H	H	H (**3a**)	*p*-MeOC$_6$H$_4$	*p*-MeOC$_6$H$_4$ (**4b**)	60 (**5ab**)
12	H	H	H (**3a**)	*p*-MeC$_6$H$_4$	*p*-MeC$_6$H$_4$ (**4c**)	50 (**5ac**)
13[b]	H	H	H (**3a**)	*p*-ClC$_6$H$_4$	*p*-ClC$_6$H$_4$ (**4d**)	64 (**5ad**)
14[b]	H	H	H (**3a**)	*p*-FC$_6$H$_4$	*p*-FC$_6$H$_4$ (**4e**)	65 (**5ae**)
15	H	H	H (**3a**)	*p*-NCC$_6$H$_4$	*p*-NCC$_6$H$_4$ (**4f**)	N.D.[e] (**5af**)
16[b]	H	H	H (**3a**)	*n*-Pr	*n*-Pr (**4g**)	65 (**5ag**)
17	H	H	H (**3a**)	COOEt	COOEt (**4h**)	N.D.[e] (**5ah**)
18[b]	H	H	H (**3a**)	CH$_2$OAc	CH$_2$OAc (**4i**)	56 (**5ai**)
19[d]	H	H	H (**3a**)	Me	Ph (**4j**)	62[f] (**5aj**+**5aj'**)

[a] Reaction conditions: Aryl bromide **3**, internal alkyne 4 (3.0 equiv.), Pd(TFA)$_2$ (10 mol%), **1a** (10 mol%), Cs_2CO_3 (2.0 equiv.), DMF (0.5 M) at 90 °C for 24 h under Ar. [b] This reaction was carried out at 100 °C. [c] This reaction was carried out at 80 °C. [d] This reaction was carried out at 110 °C. [e] Not detected. [f] The ratio of **5aj**/**5aj'** was 9/1 by ^{1}H NMR analysis.



Scheme 1 Plausible reaction mechanism

1,3-dimethyl-2-phenylnaphthalene (**5aj**) and 1,2-dimethyl-3-phenylnaphthalene (**5aj'**) (**5aj**/**5aj'** = 9/1) (Table 2, entry 19).

A plausible mechanism of annulation of 1-allyl-2-bromobenzene derivatives with internal alkynes is illustrated in Scheme 1. At first, oxidative addition of aryl bromide occurs and hydrazone-palladium(0) species inserts into carbon-bromide bond of 1-allyl-2-bromobenzene to generate aryl-palladium(II) complex **I**. Next, a triple bond of internal alkynes coordinates to palladium complex **I** and inserts into a carbon-palladium bond of complex **I** to generate intermediate **II**. Subsequently, Intramolecular Heck reaction of intermediate **II** forms alkyl palladium(II) species **III**. alkyl-palladium(II) species **III** undergoes *β*-hydride elimination to generate intermediate **IV** and hydride-palladium(II) species. Intermediate **IV** easily transforms to the aromatic product *via* aromatization. On the other hand, after the reductive elimination of HBr from hydride-palladium(II) species by base, hydrazone-palladium(0) species is regenerated and the catalytic cycle is completed. We thought these palladium complexes were stabilized by hydrazone ligand, and this reaction proceeded smoothly in spite of the use of aryl bromides without electron-deficient olefin.

Conclusions

In summary, we found that palladium-catalyzed annulation of 1-allyl-2-bromobenzene derivatives **3** with internal alkynes **4** using hydrazone **1a** as a ligand proceeded smoothly and gave the corresponding polysubstituted naphthalene derivatives **5** in good to high yields even though low reactive aryl bromides without electron-deficient olefin were employed as starting materials.

Experimetal section

Representative procedure for hydrazone-Pd catalyzed annulation.

A mixture of aryl bromide **3** (0.25 mmol), internal alkyne **4** (0.75 mmol), $Pd(TFA)_2$ (8.31 mg, 0.025 mmol), hydrazone ligand 1a (6.66 mg, 0.025 mmol), and Cs_2CO_3 (0.1630 g, 0.50 mmol) in DMF (0.5 mL) under an Ar atmosphere was stirred for 24 h at 80-110 °C. After the reaction, the reaction was quenched with distilled water. The solution was extracted with ethyl acetate, washed with brine, dried over anhydrous $MgSO_4$, and concentrated under reduced pressure. The residue was purified by silica gel chromatography (hexane, hexane/ethyl acetate (v/v = 100-10/1) or hexane/chloroform (v/v = 1/1)) to afford the product **5**.

3-Methyl-1,2-diphenylnaphthalene (**5aa**)[6b] (Table 1, Entry 6)
Compound **5aa** was obtained according to the general procedure at 90 °C in 67% yield (0.0493 g, 0.17 mmol); White solid; m.p. 149-151 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.84 (d, *J* = 7.9 Hz, 1H), 7.77 (s, 1H), 7.45 (t, *J* = 7.7 Hz, 2H), 7.31 (td, *J* = 6.6, 1.8 Hz, 1H), 7.23-7.08 (m, 8H), 7.03 (dt, *J* = 6.4, 3.6 Hz, 2H), 2.26 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 140.6, 139.8, 139.4, 139.1, 138.6, 134.4, 132.9, 131.3, 131.0, 130.1, 127.5, 127.4, 127.1, 126.8, 126.3, 126.1, 125.7, 125.2, 21.9; EI-MS *m/z* (rel intensity): 294 (M^+, 100).

6-Methoxy-3-methyl-1,2-diphenylnaphthalene (**5ba**) (Table 2, Entry 2)
Compound **5ba** was obtained according to the general procedure at 90 °C in 57% yield (0.0459 g, 0.14 mmol); Yellow solid; m.p. 118-120 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.67 (s, 1H), 7.38 (d, *J* = 9.2 Hz, 1H), 7.22-6.96 (m, 12H), 3.93 (s, 3H), 2.23 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 157.5, 140.6, 139.5, 138.5, 137.7, 135.0, 134.1, 130.9, 130.3, 128.5, 127.44, 127.36, 126.7, 126.4, 126.3, 126.0, 117.7, 105.1, 55.3, 21.9; EI-MS *m/z* (rel intensity): 324 (M^+, 100); HRMS (APPI): calcd for $C_{24}H_{20}O$ $[M]^+$ 324.1509, found 324.1499.

3,6-Dimethyl-1,2-diphenylnaphthalene (**5ca**) (Table 2, Entry 3)
Compound **5ca** was obtained according to the general procedure at 100 °C in 60% yield (0.0464 g, 0.15 mmol); Yellow solid; m.p. 122-124 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.67 (s, 1H), 7.60 (s, 1H), 7.36 (d, *J* = 8.7 Hz, 1H), 7.24-7.00 (m, 11H), 2.49 (s, 3H), 2.23 (d, *J* = 0.6 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 140.7, 139.5, 138.9, 138.3, 135.3, 134.4, 133.1, 131.0, 130.2, 129.5, 127.5, 127.4, 127.3, 126.8, 126.6, 126.2, 126.1, 126.0, 21.9, 21.5; EI-MS *m/z* (rel intensity): 308 (M^+, 100); HRMS (APCI): calcd for $C_{24}H_{21}$ $[M + H]^+$ 309.1638, found 309.1628.

6-Chloro-3-methyl-1,2-diphenylnaphthalene (**5da**) (Table 2, Entry 4)
Compound **5da** was obtained according to the general procedure at 90 °C in 47% yield (0.0385 g, 0.12 mmol); White solid; m.p. 137-138 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.80 (d, *J* = 2.1 Hz, 1H), 7.67 (s, 1H), 7.40 (d, *J* = 9.0 Hz, 1H), 7.24-6.99 (m, 11H), 2.24 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 140.14, 140.11, 138.9, 138.7, 135.9, 133.5, 131.5, 130.9, 130.0, 129.6, 128.6, 127.6, 127.5, 126.53, 126.50, 126.3, 126.0, 125.6, 21.9; EI-MS *m/z* (rel intensity): 328 (M^+, 100); HRMS (APPI): calcd for $C_{23}H_{17}Cl$ $[M]^+$ 328.1013, found 328.1005.

6-Fluoro-3-methyl-1,2-diphenylnaphthalene (**5ea**) (Table 2, Entry 5)
Compound **5ea** was obtained according to the general procedure at 80 °C in 50% yield (0.0386 g, 0.12 mmol); White solid; m.p. 147-149 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.70 (s, 1H), 7.48-7.41 (m, 2H), 7.23-7.00 (m, 11H), 2.24 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 162.3, 159.0, 140.3, 139.2, 139.1, 138.7, 135.8, 133.7 (d, *J* = 9.3 Hz), 130.9, 130.1, 129.5 (d, *J* = 8.8 Hz), 128.4, 127.5 (d, *J* = 5.0 Hz), 126.7 (d, *J* = 5.3 Hz), 126.3 (d, *J* = 21.8 Hz), 115.3 (d, *J* = 24.9 Hz), 109.9 (d, *J* = 20.2 Hz), 21.9; EI-MS *m/z* (rel intensity): 312 (M^+, 100); HRMS (APPI): calcd for $C_{23}H_{17}F$ $[M]^+$ 312.1309, found 312.1302.

3,7-Dimethyl-1,2-diphenylnaphthalene (**5fa**) (Table 2, Entry 6)
Compound **5fa** was obtained according to the general procedure at 110 °C in 58% yield (0.0447 g, 0.15 mmol); White solid; m.p. 134-135 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.74 (d, *J* = 8.5 Hz, 1H), 7.72 (s, 1H), 7.30 (dd, *J* = 8.3, 1.6 Hz, 1H), 7.22-7.07 (m, 9H), 7.03-7.00 (m, 2H), 2.36 (s, 3H), 2.23 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 140.7, 139.9, 139.5, 137.9, 134.8, 133.3, 131.3, 131.1, 131.0, 130.1, 128.0, 127.43, 127.36, 127.1, 127.0, 126.2, 126.0, 125.6, 21.9, 21.8; EI-MS *m/z* (rel intensity): 308 (M^+, 100); HRMS (APCI): calcd for $C_{24}H_{21}$ $[M + H]^+$ 309.1638, found 309.1628.

3-Methyl-6,7-dimethoxy-1,2-diphenylnaphthalene (**5ga**) (Table 2, Entry 7)
Compound **5ga** was obtained according to the general procedure at 110 °C in 71% yield (0.0624 g, 0.18 mmol); Yellow solid; m.p. 203-205 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.63 (s, 1H), 7.23-7.08 (m, 9H), 7.04-7.01 (m, 2H), 6.76 (s, 1H), 4.02 (s, 3H), 3.69 (s, 3H), 2.22 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 149.3, 148.8, 140.8, 140.0, 138.1, 137.4, 132.6, 130.8, 130.2, 128.7, 127.5, 127.4, 126.6, 126.3, 126.0, 125.9, 105.61, 105.56, 55.9, 55.5, 21.7; EI-MS *m/z* (rel intensity): 354 (M^+, 100); HRMS (APCI): calcd for $C_{25}H_{23}O_2$ $[M + H]^+$ 355.1693, found 355.1681.

2-Methyl-3,4-diphenylphenanthlene (**5ha**) (Table 2, Entry 8)
Compound **5ha** was obtained according to the general procedure at 90 °C in 66% yield (0.0571 g, 0.17 mmol); Yellow solid; m.p. 137-140 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.81-7.69 (m, 4H), 7.38-7.33 (m, 2H), 7.20-6.94 (m, 11H), 2.23 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 143.1, 142.1, 141.0, 138.9, 134.9, 133.5, 132.8, 131.0, 130.7, 130.2, 129.0, 128.5, 128.2, 127.8, 127.7, 127.4, 127.1, 127.0, 126.3, 125.8, 125.4, 124.9, 21.6; EI-MS *m/z* (rel intensity): 344 (M^+, 100); HRMS (APPI): calcd for $C_{27}H_{20}$ $[M]^+$ 344.1560, found 344.1549.

3-Cinnamyl-1,2-diphenylnaphthalene (**5ia**) (Table 2, Entry 9)
Compound **5ha** was obtained according to the general procedure at 90 °C in 81% yield (0.0752 g, 0.20 mmol); Yellow solid; m.p. 153-155 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.82 (d, *J* = 8.0 Hz, 1H), 7.68 (s, 1H), 7.48-7.42 (m, 2H), 7.35-7.30 (m, 1H), 7.22-7.07 (m, 11H), 6.97-6.89 (m, 4H), 3.93 (s, 2H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 140.8, 139.9, 139.7, 139.3, 139.1, 137.4, 132.7, 131.5, 130.9, 130.4, 129.1, 128.1, 127.9, 127.5, 127.4, 127.3 (2C), 126.8, 126.3, 126.1, 125.8, 125.6, 40.5; EI-MS *m/z* (rel intensity): 370 (M^+, 100); HRMS (APCI): calcd for $C_{29}H_{22}$ $[M]^+$ 370.1716, found 370.1705.

1,2-Bis(4-methoxyphenyl)-3-methylnaphthalene (**5ab**)[3a] (Table 2, Entry 11)
Compound **5ab** was obtained according to the general procedure at 100 °C in 69% yield (0.0603 g, 0.17 mmol); Cream solid; m.p. 201-202 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.82 (d, *J* = 8.1 Hz, 1H), 7.74 (s, 1H), 7.50 (d, *J* = 8.5 Hz, 1H), 7.44 (td, *J* = 8.0, 1.1 Hz, 1H), 7.30 (ddd, *J* = 8.2, 7.6, 1.1 Hz, 1H), 7.02 (dt, *J* = 8.7, 2.0 Hz, 2H), 6.93 (dt, *J* = 8.7, 2.8 Hz, 2H), 6.75 (tt, *J* = 8.9, 2.8 Hz, 4H), 3.78 (s, 3H), 3.76 (s, 3H), 2.25 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 157.8, 157.6, 139.8, 138.5, 134.9, 133.1, 132.8, 132.0, 131.8, 131.7, 131.1,

127.2, 127.0, 126.8, 125.6, 125.1, 113.0, 112.9, 55.1, 55.0, 22.0; EI-MS *m/z* (rel intensity): 354 (M^+, 100); HRMS (APCI): calcd for $C_{25}H_{22}O_2$ $[M]^+$ 354.1614, found 354.1614.

3-Methyl-1,2-di-*p*-tolylnaphthalene (**5ac**)[3a] (Table 2, Entry 12)
Compound **5ac** was obtained according to the general procedure at 90 °C in 50% yield (0.0404 g, 0.13 mmol); White solid; m.p. 159-160 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.81 (d, *J* = 8.1 Hz, 1H), 7.74 (s, 1H), 7.44 (q, *J* = 7.0 Hz, 2H), 7.28 (t, *J* = 7.1 Hz, 1H), 7.03-6.90 (m, 8H), 2.30 (s, 3H), 2.27 (s, 3H), 2.23 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 139.8, 138.6, 137.6, 136.4, 135.6, 135.4, 134.7, 132.8, 131.5, 130.8, 129.9, 128.2, 128.1, 127.2, 127.0, 126.8, 125.5, 125.1, 22.0, 21.21, 21.18; EI-MS *m/z* (rel intensity): 322 (M^+, 100); HRMS (ESI): calcd for $C_{25}H_{22}Na$ $[M + Na]^+$ 345.1614, found 345.1610.

1,2-Bis(4-chlorophenyl)-3-methylnaphthalene (**5ad**) (Table 2, Entry 13)
Compound **5ad** was obtained according to the general procedure at 100 °C in 64% yield (0.0587 g, 0.16 mmol); White solid; m.p. 166 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.84 (d, *J* = 8.2 Hz, 1H), 7.77 (s, 1H), 7.50-7.31 (m, 3H), 7.20 (t, *J* = 6.4 Hz, 4H), 7.01 (d, *J* = 4.6 Hz, 2H), 6.95 (d, *J* = 4.6 Hz, 2H), 2.23 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 138.7, 138.6, 137.5, 137.3, 134.1, 132.9, 132.5, 132.3, 132.2, 131.3, 131.0, 128.0, 127.93, 127.89, 127.2, 126.4, 126.1, 125.6, 21.8; EI-MS *m/z* (rel intensity): 362 (M^+, 88); HRMS (APPI): calcd for $C_{23}H_{16}Cl_2$ $[M]^+$ 362.0624, found 362.0623.

1,2-Bis(4-fluorophenyl)-3-methylnaphthalene (**5ae**) (Table 2, Entry 14)
Compound **5ae** was obtained according to the general procedure at 100 °C in 65% yield (0.0537 g, 0.16 mmol); White solid; m.p. 210 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.84 (d, *J* = 8.1 Hz, 1H), 7.77 (s, 1H), 7.50-7.42 (m, 2H), 7.33 (t, *J* = 7.9 Hz, 1H), 7.06-6.86 (m, 8H), 2.24 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 161.5 (d, *J* = 245.5 Hz), 161.3 (d, *J* = 245.2 Hz), 139.1, 137.8, 136.3 (d, *J* = 3.3 Hz), 135.1 (d, *J* = 3.3 Hz), 134.4, 133.0, 132.4 (d, *J* = 7.8 Hz), 131.5 (d, *J* = 7.8 Hz), 131.3, 127.7, 127.2, 126.5, 125.9, 125.5, 114.8 (d, *J* = 5.7 Hz), 114.5 (d, *J* = 5.8 Hz), 21.8; EI-MS *m/z* (rel intensity): 330 (M^+, 100); HRMS (APPI): calcd for $C_{23}H_{16}F_2$ $[M]^+$ 330.1215, found 330.1211.

3-Methyl-1,2-dipropylnaphthalene (**5ag**)[11] (Table 2, Entry 16)
Compound **5ag** was obtained according to the general procedure at 100 °C in 65% yield (0.0366 g, 0.16 mmol); Colorless oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.95 (d, *J* = 8.1 Hz, 1H), 7.67 (d, *J* = 9.3 Hz, 1H), 7.49 (s, 1H), 7.43-7.33 (m, 2H), 3.05-3.00 (m, 2H), 2.78-2.73 (m, 2H), 2.48 (s, 3H), 1.72-1.53 (m, 4H), 1.14-1.06 (m, 6H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 137.4, 135.7, 134.9, 132.4, 131.0, 127.7, 126.8, 124.8, 124.5, 123.9, 32.3, 30.9, 24.5, 23.8, 20.8, 14.9 (2C); EI-MS *m/z* (rel intensity): 226 (M^+, 60).

3-Methyl-1,2-naphthalene dimethanol, 1,2-diacetate (**5ai**) (Table 2, Entry 18)
Compound **5ai** was obtained according to the general procedure at 100 °C in 56% yield (0.0399 g, 0.14 mmol); White solid; m.p. 50-51 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.09-8.05 (m, 1H), 7.79-7.72 (m, 2H), 7.54-7.47 (m, 2H), 5.72 (s, 2H), 5.46 (s, 2H), 2.57 (s, 3H), 2.07 (s, 3H), 2.06 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 170.9, 170.7, 135.2, 133.8, 132.9, 131.5, 131.2, 130.3, 127.8, 126.5, 126.3, 124.1, 60.8, 59.7, 20.93, 20.89, 20.3; EI-MS *m/z* (rel intensity): 286 (M^+, 8); HRMS (APPI): calcd for $C_{17}H_{18}O_4Na$ $[M + Na]^+$ 309.1097, found 309.1097.

1,3-Dimethyl-2-phenylnaphthalene (**5aj**)[12] (including **1,2-dimethyl-3-phenylnaphthalene** (**5aj'**)[13]) (Table 2, Entry 19)
The mixture of **5aj** and **5aj'** was obtained according to the general procedure at 110 °C in 62% yield (0.0536 g, 0.16 mmol) (**5aj**/**5aj'** = 9/1); Colorless oil; ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.02 (m, 1H), 7.81-7.74 (m, 1H), 7.66 (**5aj'** (minor)) and 7.60 (**5aj** (major)) (s, 1H), 7.51-7.35 (m, 5H), 7.27-7.18 (m, 2H), 2.49 (**5aj'** (minor)) and 2.37 (**5aj** (major)) (s, 3H), 2.15 (**5aj** (major)) and 2.13 (**5aj'** (minor)) (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 141.6 (**5aj** (major)), 140.4 (**5aj'** (minor)), 140.2 (**5aj** (major)), 138.3 (**5aj'** (minor)), 135.4 (**5aj'** (minor)), 134.5 (**5aj** (major)), 133.1 (**5aj'** (minor)), 132.9 (**5aj** (major)), 131.9 (**5aj'** (minor)), 131.7 (**5aj'** (minor)), 131.4 (**5aj** (major)), 131.2 (**5aj** (major)), 130.2 (**5aj'** (minor)), 129.3 (**5aj** (major)), 128.3, 127.7 (**5aj** (major)), 127.1 (**5aj'** (minor)), 126.92 (**5aj'** (minor)), 126.86 (**5aj'** (minor)), 126.7 (**5aj** (major)), 126.3 (**5aj'** (minor)), 125.8 (**5aj** (major)), 125.5 (**5aj** (major)), 125.2 (**5aj** (major)), 124.83 (**5aj'** (minor)), 124.78 (**5aj'** (minor)), 124.4 (**5aj** (major)), 22.0 (**5aj** (major)), 21.2 (**5aj'** (minor)), 17.6 (**5aj'** (minor)), 16.5 (**5aj** (major)); EI-MS *m/z* (rel intensity): 232 (M^+, 100).

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