Generation of arylzinc reagents through an iodine–zinc exchange reaction promoted by a non-metallic organic superbase†

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Received (in Montpellier, France) 16th March 2010, Accepted 28th April 2010
DOI: 10.1039/c0nj00202j

Functionalized aryl and heteroaryl zinc reagents were prepared from aryl iodides and diethylzinc through *t*-Bu-P_4 base-promoted iodine–zinc exchange reactions. The scope and limitations of this protocol, and several applications for the synthesis of oligoaryls and fused aromatics, are presented.

Introduction

Arylzinc compounds are important reagents for the synthesis of the functionalized aromatic compounds that are important constituents of biologically-active compounds.[1] Compared to sister aryllithium or arylmagnesium compounds, arylzinc compounds display less but chemoselective reactivity. Accordingly, arylzinc reagents have been widely used for chemoselective reactions, such as Negishi cross-couplings with unsaturated organic halides and asymmetric additions to carbonyl compounds.[1,2] The preparation of arylzinc compounds has been accomplished through transmetalation from aryllithium or arylmagnesium compounds, but this method suffers from the limited compatibility of the aryllithium or arylmagnesium reagent towards functional groups on the aromatic ring.[3] Recently, several improved methods have been developed to enable the generation of variously-functionalized aromatic zinc compounds.[4–6] For instance, the use of lithium dialkylamidozincates [R_2Zn(tmp)Li] and related zincate complexes,[4,5] or simple amidozinc reagents,[6] has allowed the direct zincation of aromatic rings. The LiCl-promoted direct metal insertion of Zn(0) dust to aryl halides,[7] or the halogen–zinc exchange of aryl halides[8] mediated either by lithium zincates (R_3ZnLi[8b] or R_4ZnLi_2[8c–e]) or by *i*-Pr_2Zn and 0.1 equiv. Li(acac)[8f,g] give the corresponding functionalized organozinc regents. However, these methods often require extra metallic compounds other than zinc, such as alkali or transition metals, which, in some cases, can cause problematic side reactions.[9]

We have recently reported that phosphazene base *t*-Bu-P_4[10] dramatically promoted the generation of arylzinc compounds from aryl iodides **1** through iodine–zinc exchange reactions (Fig. 1 and Scheme 1).[11,12] This method utilizes commercially available diethylzinc as a zincation reagent. Although diethylzinc is pyrophoric, this protocol does not require any other metallic promoters. The resulting salt-free arylzinc reagents can be functionalized by various electrophiles. In this paper, we detail the scope and limitations of this arylzinc generation, and several applications for the synthesis of structurally-defined, multi-functionalized aromatic compounds.

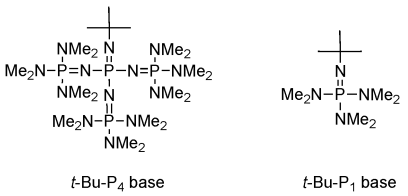
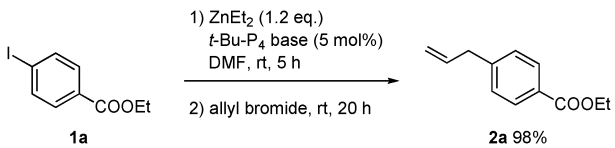


Fig. 1 Phosphazene bases.



1a **2a** 98%

Scheme 1 Zincation of aryl iodide **1a** in the presence of a phosphazene base.[11]

Results and discussion

Chemoselective generation of 2-iodoarylzinc reagents

In our previous conditions (Scheme 1), the reactivity in the zincation of complex substrates was rather limited. For instance, the mono-zincation of 1,2-diiodobenzene (**1b**) proceeded slowly under the typical reaction conditions and hydrolysis yielded iodobenzene (**2b**) in only 54% yield, with the recovery of **1b** in 46% yield (Table 1, entry 1). The selective preparation of 2-iodoarylzinc species is considered difficult because of competitive bis-zincation or benzyne generation through 1,2-elimination.[7,13] After re-investigating the reaction conditions, we found that the use of a polar aprotic solvent significantly accelerated the reaction rate (Table 1, entries 2–5). Although benzene (**3b**) was also observed in 3–13% yield, the yield of **2b** was increased up to 72–93%. Dimethylacetamide (DMA) proved to be the best solvent, allowing mono-zincation at room temperature to yield **2b** in 93% selectively after a methanol quench. Surprisingly, the reaction

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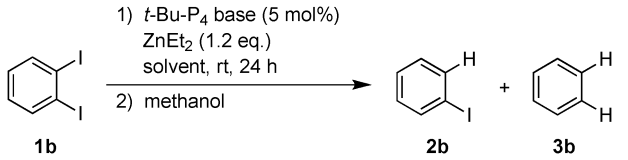
† This paper is dedicated to the memory of Professor Pascal Le Floch and is part of a themed issue on Main Group chemistry.

Table 1 The mono-zincation of 1,2-diiodobenzene in the presence of phosphazene base[a]



Entry	Solvent	Yield of **2b** (%)	Yield of **3b** (%)	Recovery of **1b** (%)
1	DMF	54	<1	46
2	NMP	72	7	21
3	DMA	93	3	4
4	DMI	77	5	18
5	DMPU	85	13	2
6[b]	DMA	73	11	16
7[c]	DMA	59	18	23

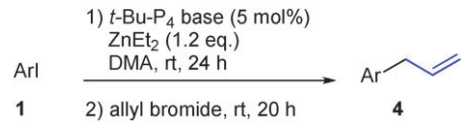
[a] NMR yield. DMF = *N*,*N*-dimethylformamide, NMP = *N*-methylpyrrolidone, DMA = *N*,*N*-dimethylacetamide, DMI = *N*,*N*′-dimethylimidazolidinone, DMPU = *N*,*N*′-dimethylpropyleneurea. [b] *t*-Bu-P$_1$ (5 mol%) was used instead of *t*-Bu-P$_4$. [c] Without *t*-Bu-P$_4$.

proceeded in DMA using *t*-Bu-P$_1$ base (5 mol%), or even without any base, but the product yield and selectivity were lower than the *t*-Bu-P$_4$ base-promoted system (Table 1, entries 6 and 7).

The trapping of functionalized arylzinc reagents

With the improved conditions in hand, we tested the phosphazene base-promoted zincation–allylation sequence for various aromatic iodides (Table 2). The selective zincation of **1b** at room temperature for 24 h, followed by trapping of the arylzinc intermediate with allyl bromide at room temperature, yielded 2-allyl-iodobenzene (**4b**) in 91% yield (Table 2, entry 1). This protocol transformed dihaloaromatics **1c–e** to mono-allylated products **4c–d** in 65–95% yields (Table 2, entries 2–4). Zincation of *p*-cyanoiodobenzene (**1f**) and allylation proceeded without the loss of the cyano group (Table 2, entry 5; 76%). *O*-Allyl-2-iodophenyl ether (**1g**) resisted cyclization and yielded allylated product **4g**, excluding the formation of radical intermediates (Table 2, entry 6; 83%). Zincation at the 3-position of protected indole **1h** proceeded at room temperature without thermal migration to the 2-position (Table 2, entry 7).[14] Pyrazine **1i** also underwent zincation–allylation to yield allylated product **4i** in 97% yield (Table 2, entry 8). Aryl and heteroaryl iodides with perfluoroalkyl groups **1j–l** also underwent the reaction to yield the corresponding allylated products **4j–l** in 76–98% yield (Table 2, entries 9–11). These products can be easily separated from non-fluorous compounds using so-called fluorous technology.[15] The 2-pyridylzinc intermediate was trapped with benzaldehyde instead of allyl bromide because 2-allylpyridine is highly volatile, and the corresponding alcohol, **5m**, was obtained in 81% yield (Table 2, entry 12). Overall, the *t*-Bu-P$_4$ base-promoted zincation in DMA proved to be a powerful method for the chemoselective preparation of multi-functionalized aromatic and heteroaromatic zinc reagents.

Table 2 Phosphazene base-promoted zincation–allylation sequences[a]



Entry	Substrate	Product	Yield (%)
1	**1b**	**4b**	91
2[b]	**1c**	**4c**	65
3	**1d**	**4d**	71
4	**1e**	**4e**	95
5	**1f**	**4f**	76
6	**1g**	**4g**	83
7	**1h**	**4h**	90
8	**1i**	**4i**	97
9	**1j**	**4j**	76
10	**1k**	**4k**	98
11	**1l**	**4l**	77
12[c]	**1m**	**5m**	81

[a] NMR yield. [b] 0.6 eq. ZnEt$_2$ was used. [c] Quenched with benzaldehyde instead of allyl bromide.

Biaryl synthesis through the oxidative coupling of arylzinc reagents

Oxidative homo-coupling[16] of arylzinc intermediates is a powerful method for the preparation of synthetically useful biphenyls, as demonstrated in the pioneering reports by Knochel and co-workers.[6b,16e] Thus, we next tested the application of this transformation to the arylzinc compounds prepared by the phosphazene-promoted iodine–zinc exchange

reaction (Table 3). As a typical example, aryl iodide **1n** was treated with diethylzinc (0.6 eq.) in the presence of *t*-Bu-P_4 base (5 mol%), followed by the addition of chloranil. As a result, the corresponding biaryl, **6n**, was obtained in 57% yield (Table 3, entry 1). The homo-coupling of indole **1h** provided bisindole **6h** in 72% yield (Table 3, entry 2). Selective mono-zincation of iodothiophenes **1o–q**, followed by the homo-coupling, gave the corresponding bisthiophenes **6o–q** in 85–92% yield (Table 3, entries 3–5).

In addition, the transition metal-free cross-coupling of two aryl iodides, **1r** and **1a**, was also tested (Scheme 2). The zincation of **1r** using 1.2 eq. diethylzinc was followed by the successive treatment of **1a** and chloranil, and the cross-coupling product, **6ra**, was obtained in 43% yield. Although the chemical yield of the cross-coupling product was rather low, transition metal-free biaryl synthesis is characteristic of the presented iodine–zinc exchange method.

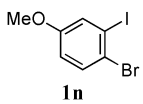
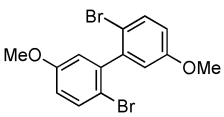
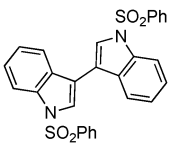
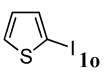
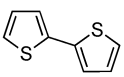
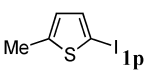
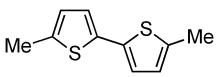
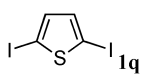
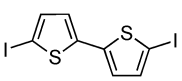
The synthesis of non-symmetrical multi-substituted triphenylenes using functionalized arylzinc reagents

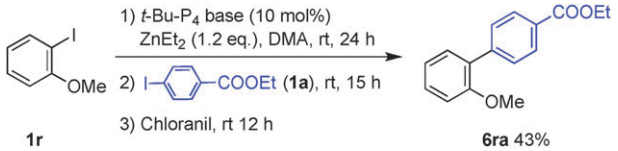
The non-symmetrical substitution of π-conjugated nanocarbon frameworks is an important topic in modern synthetic chemistry, as it often affords higher degrees of functionality than symmetrically-functionalized frameworks.[17] Triphenylene derivatives are one of the simplest two-dimensional π-conjugated nanocarbon frameworks and have been used as core chemical building blocks for functional materials.[18] However, non-symmetrical construction of these frameworks is considered difficult because classical condensation or functionalization methodologies suffer from the formation of regioisomer side-products. Larock *et al*. have reported an efficient method for constructing non-symmetrical triphenylenes using a benzyne annulation strategy, but even this method gave a mixture of isomers when non-symmetrical benzynes were used.[19] Because these isomers are not easy to separate, a reaction that gives only the desired single isomer would be of importance. In addressing this issue, we aimed for the programmed and discrete synthesis of non-symmetrical multi-substituted triphenylenes **7** using the presented zincation–functionalization sequence (Scheme 3).

Scheme 4 shows a phosphazene base-promoted iodine–zinc exchange reaction of **1n** followed by a Negishi cross-coupling with 2-iodo-4′-methylbiphenyl (**1s**).[20] As a result, terphenyl **6ns** was obtained in 78% yield. The Pd-catalyzed annulation

Table 3 Oxidative homo-coupling of arylzinc reagents

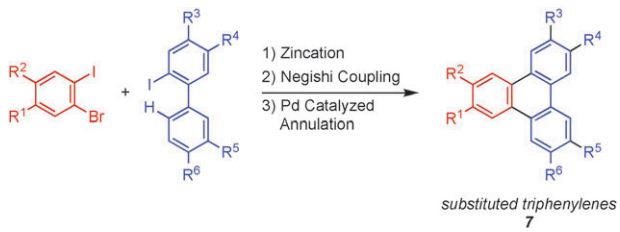
ArI (**1**) → 1) *t*-Bu-P_4 base (5 mol%), $ZnEt_2$ (0.6 eq.), DMA, rt, 16–24 h; 2) chloranil (1.05 eq.), rt, 12–20 h → Ar–Ar (**6**)

Entry	ArI	Ar–Ar		Yield
1	 **1n**		**6n**	57
2	**1h**		**6h**	72
3	 **1o**		**6o**	92
4	 **1p**		**6p**	91
5	 **1q**		**6q**	85

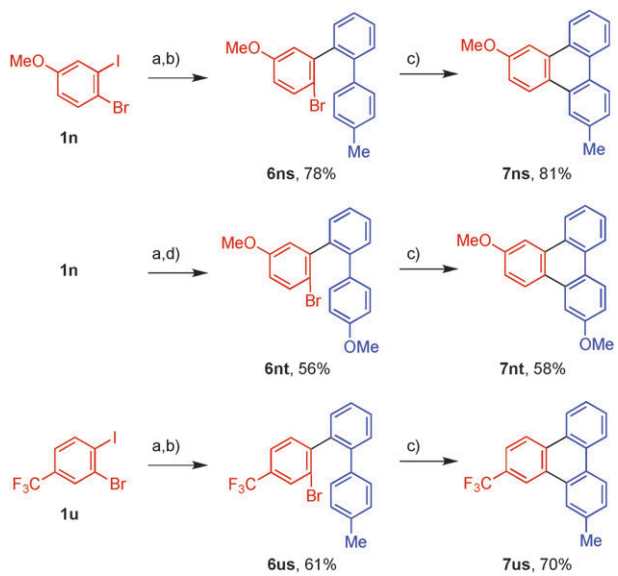


1r — **6ra** 43%

Scheme 2 The oxidative cross-coupling of aryl iodides **1r** and **1a**.



Scheme 3 Programmed synthesis of non-symmetrically substituted triphenylenes.



Scheme 4 The regiocontrolled synthesis of substituted triphenylenes **7**. (a) 0.6 eq. $ZnEt_2$, 5 mol% *t*-Bu-P_4, DMA, rt, 24 h; (b) 2-iodo-4′-methylbiphenyl (**1s**), 2.5 mol% Pd_2dba_3, 5 mol% P(2-furyl)$_3$, rt, 24 h; (c) 10 mol% $Pd(OAc)_2$, 20 mol% PCy_3, 2 eq. K_2CO_3, DMF, MW 300 W, 100 °C, 3 h; (d) 2-iodo-4′-methoxylbiphenyl (**1t**), 2.5 mol% Pd_2dba_3, 5 mol% P(2-furyl)$_3$, rt, 24 h.

of **6ns** under microwave irradiation afforded non-symmetrical triphenylene **7ns** in 81% yield. The same protocol using 2-iodo-4′-methoxybiphenyl (**1t**) instead of **1s** gave terphenyl **6nt** in 56% yield and triphenylene **7nt** in 58% yield. Aryl iodide-bearing trifluoromethyl compound **1u** afforded terphenyl **6us** in 61% yield and triphenylene **7us** in 70% yield. In all cases, no other regioisomer was formed, and **6** and **7** were easily separated from the minor hydrolyzed side products using silica gel chromatography. To summarize, the zincation–coupling protocol proved to be an efficient and reliable method for constructing terphenyls and non-symmetrical functionalized triphenylenes in a programmed and discrete manner.

Conclusions

The scope and limitations of the phosphazene base-promoted iodine–zinc reaction on aromatic and heteroaromatic iodides were investigated. Chemoselective zincation of various aromatics and heteroaromatics generated functionalized aryl- and heteroarylzinc compounds without using alkali or transition metal promoters. These arylzinc intermediates underwent allylation and oxidative coupling. Furthermore, the present protocol was found to be a powerful method for the regio- and chemoselective synthesis of complex aromatic compounds.

Experimental

General comments

Reactions were carried out under an Ar atmosphere using dry solvents. Melting points (mp) were determined with a Yazawa micro melting point apparatus and are uncorrected. Infrared (IR) data were recorded on a SensIR ATR (attenuated total reflectance) FT-IR. The spectra were acquired as 32 scans per spectrum at a resolution of four using system ReactIRTM 2.20 software. Absorbance frequencies are reported in reciprocal centimetres (cm^{-1}). NMR data were recorded on a JEOL AL400 spectrometer (395.75 MHz for ^1H, 99.50 MHz for ^{13}C). Chemical shifts are expressed in δ (parts per million, ppm) values, and coupling constants are expressed in Hertz (Hz). ^1H NMR spectra were referenced to a tetramethylsilane internal standard or to a solvent signal ($CDCl_3$: 7.26 ppm). ^{13}C NMR spectra were referenced to a tetramethylsilane internal standard or to a solvent signal ($CDCl_3$: 77.0 ppm). The following abbreviations are used: s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, dd = double doublet, dt = double triplet and br = broad. Low and high resolution mass spectra (LRMS and HRMS) were obtained from Mass Spectrometry Resource, Graduate School of Pharmaceutical Sciences, Tohoku University, on JEOL JMS-DX303 and JMS-700 spectrometers, respectively. Microwave irradiation was performed on CEM's DiscoverTM.

Iodine–zinc exchange reaction using Et_2Zn/*t*-Bu-P_4

1,2-Diiodobenzene (**1b**, 0.50 mmol), a diethylzinc 1.0 M solution in n-hexane (0.60 mL, 0.60 mmol) and dry solvents noted in the text (0.50 mL) were added to a test tube sealed with a septum equipped with a magnetic stirring bar under an argon atmosphere. A *t*-Bu-P_4 1.0 M solution in n-hexane (0.025 mL, 0.025 mmol) was added to the solution at room temperature and the mixture stirred for 24 h. The mixture was then treated with methanol. The yields of **2b** and **3b** were determined by ^1H NMR.

Allylation reactions of arylzinc compounds prepared from aryl iodides using Et_2Zn/*t*-Bu-P_4

Aryl iodide **1** (0.50 mmol), a diethylzinc 1.0 M solution in n-hexane (0.60 mL, 0.60 mmol) and dry DMA (0.50 mL) were added to a test tube sealed with a septum equipped with a magnetic stirring bar under an argon atmosphere. A *t*-Bu-P_4 1.0 M solution in n-hexane (0.025 mL, 0.025 mmol) was added to the solution at room temperature and the mixture stirred for 24 h. Allyl bromide (72 mg, 0.60 mmol) was added to the reaction mixture and stirred for 24 h at room temperature. The mixture was treated with saturated aq. NH_4Cl and the mixture extracted with EtOAc. The extract was washed with brine and dried over $MgSO_4$. The solvent was removed under reduced pressure and the crude product purified by silica gel column chromatography (gradient elution; 0–10% EtOAc or $CHCl_3$ in hexane) to give **4**. Spectral data for **4b**,[21] **4d**,[22] **4e**,[21] **4f**,[23] **4g**,[24] **4h**[8g] and **5m**[25] were identical to those in the literature.

4c. The reaction was carried out using 0.6 eq. diethylzinc. Yield: 71%, colorless oil. ^1H NMR (400 MHz, $CDCl_3$/TMS) δ (ppm): 3.33 (d, J = 6.9 Hz, 2H), 5.07–5.11 (m, 2H), 5.89–5.95 (m, 1H), 7.02 (t, J = 7.8 Hz, 1H), 7.15 (d, J = 7.3 Hz, 1H), 7.53–7.55 (m, 2H) $^{13}C\{^1H\}$NMR (100 MHz, $CDCl_3$) δ (ppm): 39.7, 94.5, 116.5, 127.9, 130.1, 135.2, 136.5, 137.6, 142.5. LRMS (EI) m/z: 244 (M^+). HRMS: calc. for C_9H_9I: 243.9749; found: 243.9751. IR(neat): 3076, 2922, 2360, 1639, 1596, 1562, 1469, 1427, 1290, 1063, 914.5, 770.8 cm^{-1}.

4i. Yield: 97%, brown oil. ^1H NMR (400 MHz, $CDCl_3$/TMS) δ (ppm): 3.40–3.43 (m, 2H), 4.00 (s, 3H), 5.12–5.18 (m, 2H), 5.97–6.07 (m, 1H), 8.15 (s, 1H). $^{13}C\{^1H\}$NMR (100 MHz, $CDCl_3$) δ (ppm): 36.4, 54.5, 117.3, 133.0, 133.6, 137.0, 143.7, 157.3. LRMS (EI) m/z: 227 (M^+). HRMS: calc. for $C_8H_9N_2BrO$: 227.9898; found: 227.9863. IR(neat): 2950, 1638, 1536, 1459, 1414, 1362, 1169, 1127, 1007, 899.2 cm^{-1}.

4j. Yield: 76%, colorless oil. ^1H NMR (400 MHz, $CDCl_3$/TMS) δ (ppm): 2.30 (m, 2H), 3.45 (d, J = 6.6 Hz, 2H), 4.62 (t, J = 6.5 Hz, 2H), 5.07–5.12 (m, 1H), 5.91–5.96 (m, 1H), 7.27 (d, J = 8.3 Hz, 2H), 7.96 (d, J = 8.3 Hz, 2H). LRMS (EI) m/z: 608 (M^+). HRMS: calc. for $C_{20}H_{13}F_{17}O_2$: 608.0644; found: 608.0623. IR(neat): 2360, 1725, 1612, 1273, 1199, 1178, 1133, 1021, 919.3, 756.3, 703.2 cm^{-1}.

4k. Yield: 98%, recrystallized from hexane, colorless crystals, mp 66–70 °C. Anal. calc. for $C_{23}H_{17}O_3S$: C, 39.90; H, 1.89; F, 46.65; O, 6.93; S, 4.63; found: C, 39.67; H, 1.93%; ^1H NMR (400 MHz, $CDCl_3$/TMS) δ (ppm): 3.33 (d, J = 6.3 Hz, 2H), 5.01–5.08 (m, 2H), 5.84–5.90 (m, 1H), 6.87 (d, J = 8.3 Hz, 2H), 7.09 (d, J = 8.3 Hz, 2H), 7.72 (t, J = 7.9 Hz, 1H), 7.88 (d, J = 7.8 Hz, 1H), 8.08 (d, J = 7.6 Hz, 1H) LRMS (EI) m/z: 692 (M^+). HRMS: calc. for $C_{23}H_{13}F_{17}O_3S$: 692.0314; found: 692.0300. IR(neat): 2357, 2311, 1501, 1382, 1196, 1148, 956.9, 880.7, 709.0 cm^{-1}.

4l. Yield: 77%, recrystallized from hexane–chloroform, colorless needles, mp 83–84 °C. Anal. calc. for $C_{20}H_{16}O_2$: C, 41.97; H, 1.97; F, 45.14; N, 1.96; O, 4.47; S, 4.48; found: C, 41.75; H, 2.17; N, 2.26%. ^{1}H NMR (400 MHz, $CDCl_3$/TMS) δ (ppm): 3.39 (d, J = 6.4 Hz, 2H), 5.07–5.12 (m, 2H), 5.92–5.99 (m, 1H), 7.21 (t, J = 7.7 Hz, 1H), 7.29–7.34 (m, 2H), 7.46 (d, J = 7.7 Hz, 1H), 7.54 (d, J = 7.7 Hz, 1H), 7.71 (d, J = 7.7 Hz, 1H), 7.98–8.04 (m, 2H), 8.10 (s, 1H). LRMS (EI) m/z: 715 (M^+). HRMS: calc. for $C_{25}H_{14}NO_2F_{17}S$: 715.0474; found: 715.0471. IR(neat): 1378, 1197, 1177, 1145, 966.6, 924.1, 745.7, 711.9 cm^{-1}.

Oxidative homo-coupling

Aryl iodide (0.50 mmol), a diethylzinc 1.0 M solution in n-hexane (0.3 mL, 0.6 eq.) and dry DMA (0.50 mL) were added to a test tube sealed with a septum equipped with a magnetic stirring bar under an argon atmosphere. A t-Bu-P_4 1.0 M solution in n-hexane (0.025 mL, 0.025 mmol) was added to the solution at room temperature and the mixture stirred for 24 h. Chloranil (129 mg, 0.525 mmol) in DMA (0.50 mL) was added to the reaction mixture and stirred for 20–24 h at room temperature. The mixture was treated with saturated aq. NH_4Cl and the mixture extracted with EtOAc. The extract was washed with brine and dried over $MgSO_4$. The solvent was removed under reduced pressure and the crude product purified by silica gel column chromatography (gradient elution; 0–10% EtOAc in hexane) to give **6**. Spectral data for **6n**,[26] **6o**,[27] **6p**[28] and **6q**[29] were identical to those in the literature.

6h. Yield: 70%, Recrystallized from chloroform, colorless crystals, mp 273 °C. ^{1}H NMR (400 MHz, $CDCl_3$/TMS) δ (ppm): 7.32 (t, J = 7.6 Hz, 2H), 7.39–7.48 (m, 6H), 7.54–7.58 (m, 2H), 7.67 (d, J = 8.0 Hz, 2H), 7.83 (s, 2H), 7.94 (d, J = 7.5 Hz, 4H), 8.09 (d, J = 8.5 Hz, 2H). ^{13}C{^{1}H}NMR (100 MHz, $CDCl_3$) δ (ppm): 113.9, 115.0, 120.6, 123.6, 125.4, 126.8, 129.4, 129.5, 134.0, 135.2. LRMS (EI) m/z: 512 (M^+). HRMS: calc. for $C_{28}H_{20}N_2O_4S_2$: 512.0864; found: 512.0853. IR(neat): 2969, 2359, 2343, 1745, 1371, 1217, 1130, 1089, 1015, 683.9 cm^{-1}.

Oxidative cross-coupling (6ra)

2-Iodoanisole (117.0 mg, 0.50 mmol), a diethylzinc 1.0 M solution in n-hexane (0.60 mL, 1.2 eq.) and dry DMA (0.50 mL) were added to a test tube sealed with a septum equipped with a magnetic stirring bar under an argon atmosphere. A t-Bu-P_4 1.0 M solution in n-hexane (0.025 mL, 0.025 mmol) was added to the solution at room temperature and the mixture stirred for 24 h. Ethyl 4-iodobenzoate (138.0 mg, 0.50 mmol) was added to the reaction mixture and stirred for 15 h at room temperature. Chloranil (129.0 mg, 0.525 mmol) was added to the reaction mixture at 0 °C and stirred for 12 h at room temperature. The mixture was treated with saturated aq. NH_4Cl and the mixture extracted with EtOAc. The extract was washed with brine and dried over $MgSO_4$. The solvent was removed under reduced pressure and the crude product purified by silica gel column chromatography (3.3% EtOAc–hexane) to give 54.8 mg (yield, 43%) of 2′-methoxy-biphenyl-4-carboxylic acid ethyl ester (**6ra**) as a colorless oil. The spectral data obtained were identical to those in the literature.[30]

Synthesis of terphenyls (6ns)

2-Bromo-5-methoxy-iodobenzene (**1n**) (156.5 mg, 0.50 mmol), diethylzinc 1.0 M solution in n-hexane (0.30 mL, 0.30 mmol) and dry DMA (0.50 mL) were added to a test tube sealed with a septum equipped with a magnetic stirring bar under argon atmosphere. t-Bu-P_4 base 1.0 M solution in n-hexane (0.025 mL, 0.025 mmol) was added to the solution at room temperature and the mixture was stirred for 24 h. 2-Iodo-4′-methylbiphenyl **1s** (176 mg, 0.60 mmol), Pd_2dba_3 (11.4 mg, 0.0125 mmol) and P(2-furyl)$_3$ (5.8 mg, 0.025 mmol) in DMA (0.50 mL) was added to the reaction mixture and stirred for 24 h at room temperature. The mixture was treated with saturated aq. NH_4Cl and the mixture was extracted with EtOAc. The extract was washed with brine and dried over $MgSO_4$. The solvent was removed under reduced pressure and the crude product was purified by silica gel column chromatography (1% EtOAc–hexane) to give 135.7 mg (yield, 78%) of **6ns** as colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$/TMS) δ (ppm): 2.28 (s, 3H), 3.63 (s, 3H), 6.63–6.66 (m, 2H), 6.99 (d, J = 8.5 Hz, 2H), 7.05 (d, J = 8.5 Hz, 2H), 7.30–7.33 (m, 1H), 7.38–7.44 (m, 4H). ^{13}C{^{1}H}NMR (100 MHz, $CDCl_3$) δ (ppm): 21.2, 55.4, 114.3, 114.7, 117.1, 126.5, 127.9, 128.0, 128.3, 129.0, 129.1, 129.9, 130.5, 132.9, 136.0, 137.8, 139.4, 140.8, 143.0, 158.0. LRMS (EI) m/z: 352 (M^+). HRMS: calc. for $C_{20}H_{17}BrO$: 352.0463; found: 352.0456. IR(neat): 2958 (br), 1590, 1567, 1463, 1216, 1028, 909, 818, 754, 731 cm^{-1}.

6nt. Yield: 56%, colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$/TMS) δ (ppm): 3.64 (s, 3H), 3.76 (s, 3H), 6.63–6.67 (m, 2H), 6.74 (d, J = 6.7 Hz, 2H), 7.09 (d, J = 6.7 Hz, 2H), 7.28–7.47 (m, 5H). ^{13}C{^{1}H}NMR (100 MHz, $CDCl_3$) δ (ppm): 55.1, 55.4, 112.8, 113.1, 114.3, 114.7, 117.1, 126.4, 128.0, 129.9, 130.1, 130.3, 130.5, 133.0, 133.3, 139.4, 140.5, 143.2, 158.1, 158.2. LRMS (EI) m/z: 368 (M^+). HRMS: calc. for $C_{20}H_{17}BrO_2$: 368.0412; found: 368.0381. IR(neat): 3000, 2834, 1735, 1590, 1463, 1437, 1241, 1175, 1027, 831.6, 802.7, 760.2 cm^{-1}.

6us. Yield: 61%, colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$/TMS) δ (ppm): 2.35 (s, 3H), 7.14–7.28 (m, 9H), 7.40–7.48 (m, 2H). ^{13}C{^{1}H}NMR (100 MHz, $CDCl_3$) δ (ppm): 21.2, 121.8, 123.6 (q, J = 4.2 Hz), 124.0, 124.3, 124.5, 125.0, 126.2, 127.3, 128.6, 128.8, 129.0, 129.1, 129.3, 129.5 (q, J = 4.2 Hz), 129.9, 130.2, 130.3, 130.5, 132.3, 136.5, 137.4, 138.2, 138.3, 138.5, 140.8, 142.0 (2C), 145.0, 146.3. LRMS (EI) m/z: 390 (M^+). HRMS: calc. for $C_{20}H_{14}BrF_3$: 390.0231; found: 390.0233. IR(neat): 3058, 2923, 1609, 1472, 1383, 1318, 1272, 1169, 1125, 1079, 1067, 1005, 818.1, 756.4, 700.4 cm^{-1}.

Synthesis of non-symmetrically substituted triphenylenes (7ns)

To a test tube equipped with a magnetic stirring bar containing **6ns** (95.4 mg, 0.27 mmol), K_2CO_3 (74.6 mg, 0.54 mmol), $Pd(OAc)_2$ (6.1 mg, 0.027 mmol) and PCy_3 (15.1 mg, 0.054 mmol) was added dry DMF (0.50 mL) under an argon atmosphere. The resulting mixture was stirred at 100 °C under microwave irradiation for 3 h. The mixture was then cooled

down to room temperature, treated with saturated aq. NH_4Cl and extracted with EtOAc. The extract was washed with brine and dried over $MgSO_4$. The solvent was removed under reduced pressure and the crude product purified by silica gel column chromatography (2% EtOAc–hexane) to give 59.4 mg (yield, 81%) of **7ns**. Recrystallized from hexane–chloroform, colorless needles, mp 105 °C. Anal. calc. for $C_{20}H_{16}O$: C, 88.20; H, 5.92; O, 5.87; found: C, 88.24; H, 6.24%. ^{1}H NMR (400 MHz, $CDCl_3$/TMS) δ (ppm): 2.60 (s, 3H), 4.03 (s, 3H), 7.28 (d, J = 2.7 Hz, 1H) 7.42 (d, J = 8.5 Hz, 1H), 7.60–7.66 (m, 2H), 8.05 (d, J = 2.7 Hz, 1H), 8.35 (s, 1H), 8.50–8.63 (m, 4H). ^{13}C{^{1}H}NMR (100 MHz, $CDCl_3$) δ (ppm): 22.0, 55.5, 105.6, 115.6, 122.6, 123.0, 123.1, 123.2 123.5, 124.7, 126.3, 126.4, 127.1, 127.6, 128.9, 129.7, 130.1, 131.2, 136.7, 158.5. LRMS (EI) m/z: 272 (M^+). HRMS: calc. for $C_{20}H_{16}O$: 272.1201; found: 272.1178. IR(neat): 2989, 2912, 1611, 1507, 1422, 1301, 1233, 1206, 1173, 1057, 1034, 850.9, 758.3 cm^{-1}.

7nt. Yield: 58%, recrystallized from hexane–chloroform, colorless needles, mp 126 °C. Anal. calc. for $C_{20}H_{16}O_2$: C, 83.31; H, 5.59; O, 11.10; found: C, 83.19; H, 5.80%. ^{1}H NMR (400 MHz, $CDCl_3$/TMS) δ (ppm): 4.01 (s, 3H), 4.03 (s, 3H), 7.20–7.27 (m, 2H) 7.58–7.65 (m, 2H), 7.94 (d, J = 2.7 Hz, 1H), 8.03 (d, J = 2.7 Hz, 1H), 8.47–8.55 (m, 4H). ^{13}C{^{1}H}NMR (100 MHz, $CDCl_3$) δ (ppm): 55.4, 55.5, 105.2, 105.6, 114.7, 115.6, 122.6, 122.7, 123.1, 123.3, 124.7, 124.8, 125.9, 127.2, 128.3, 130.2, 131.2, 131.5, 158.6, 158.7. LRMS (EI) m/z: 288 (M^+). HRMS: calc. for $C_{20}H_{16}O_2$: 288.1150; found: 288.1129. IR(neat): 2923, 1725, 1613, 1449, 1210, 1181, 1042, 808.5, 746.7, 702.3 cm^{-1}.

7us. Yield: 70%, recrystallized from hexane–chloroform, colorless needles, mp 180–181 °C. Anal. calc. for $C_{20}H_{16}O_2$: C, 77.41; H, 4.22; F, 18.37; found: C, 77.70; H, 4.21%. ^{1}H NMR (400 MHz, $CDCl_3$/TMS) δ (ppm): 2.65 (s, 3H), 7.54 (d, J = 8.5 Hz, 1H), 7.69 (m, 2H), 7.85 (d, J = 8.5 Hz, 1H), 8.42 (s, 1H), 8.55 (d, J = 8.8 Hz, 1H), 8.62–8.64 (m, 2H), 8.73 (d, J = 8.8 Hz, 1H), 8.88 (s, 1H). ^{13}C{^{1}H}NMR (100 MHz, $CDCl_3$) δ (ppm): 21.9, 120.6, 120.9, 123.1 (2C), 123.2, 123.6, 123.9, 126.9, 127.6, 128.1, 128.2, 128.4, 128.8 (2C), 129.4 (2C), 130.4, 132.2, 137.3. LRMS (EI) m/z: 310 (M^+). HRMS: calc. for $C_{20}H_{13}F_3$: 310.0969; found: 310.0979. IR(neat): 2923, 1725, 1320, 1279, 1111, 1081, 812.3, 762.2, 717.8, 698.5 cm^{-1}.

Acknowledgements

This work was partly supported by a Grant-in-Aid for Young Scientists (B) from the Ministry of Education, Culture, Sports, Science and Technology, Japan (to H. N., no. 19790003) and by Grants-in-Aid for Scientific Research on Priority Areas "Advanced Molecular Transformation of Carbon Resources", "Synergistic Effects for Creation of Functional Molecules" (to Y. K.).

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