Synthesis of biphenylenes and tetraphenylenes using copper-catalyzed coupling of arylzinc intermediates

S. M. Humayun Kabir, Masashi Hasegawa, Yoshiyuki Kuwatani, Masato Yoshida, Haruo Matsuyama and Masahiko Iyoda *

Department of Chemistry, Graduate School of Science, Tokyo Metropolitan University, Hachioji, Tokyo 192-0397, Japan

Biphenylene and some of its 2,3,6,7- and 1,8-substituted derivatives were synthesized using the $CuCl_2$-mediated intramolecular coupling of an organozinc species prepared from 2,2′-dilithiobiaryls with one or two molar equiv. of $ZnCl_2$ or $ZnBr_2$ in THF. Although most of the reactions of 2,2′-dilithiobiaryls with $CuCl_2$ in THF in the absence of $ZnCl_2$ or $ZnBr_2$ led to biphenylenes as a major product, similar reactions of the organozinc species with $CuCl_2$ in THF produced biphenylenes in much better yields, due to smooth transmetallation and reductive elimination reactions. In particular, the copper-mediated cyclization of benzannelated organozinc intermediates, prepared from equimolar proportions of 2,2′-dilithiobiaryls with $ZnCl_2$, proceeded smoothly and selectively to afford the desired biphenylenes in 46–81% yield except for the reaction of the zinc intermediate derived from 4,4′,5,5′-tetramethoxy-2,2′-dilithiobiphenyl with $ZnCl_2$ (1.0 molar equiv.). The reaction of the tetramethoxy-substituted organozinc species with $CuCl_2$ produced 2,3,6,7,10,11,14,15-octamethoxytetraphenylene as a major product in 67% yield.

Introduction

Since the first synthesis of biphenylene **1** in 1941,[1] considerable attention has been devoted to designing and constructing new analogues of this benzannelated cyclobutadiene system.[2] Graphite, diamond, and fullerenes are well documented carbon allotropes, having fundamental significance in science and technology.[3] The new all-carbon allotropes **2** and **3** containing biphenylene **1** as a unit (see Fig. 1) have been claimed to be materials with attractive properties,[4] and the syntheses of sub-units of **2** and **3** have been reported recently.[5] In addition, **1** and its derivatives can be widely used as starting materials for organic synthesis[6] and as spacers and building blocks for functionalized organic materials.[7] Many synthetic methods, such as dimerization of benzyne,[8a] the Ullmann cyclization of 2,2′-diiodobiphenyl with Cu_2O or Cu,[1,8b] the pyrolytic extrusion method,[8c–j] and the Vollhardt method using cobalt-catalyzed cyclization,[9] have been employed for the preparation of **1** and [*n*]phenylenes. However, only a few limited methods are known for the construction of functionalized biphenylenes with methyl, fluoro, and other functional groups, due to the difficulty in obtaining appropriate starting materials.[10]

It is known that the $CuCl_2$-catalyzed coupling of 2,2′-dilithiobiphenyl **6** in diethyl ether leads to tetraphenylene **7** (53%) with a small amount of **1** (3%).[11] Since the yield of **1** can be improved by changing the solvent from Et_2O to an Et_2O–THF mixture,[11a] the yields of **1** and **7** might depend on the structure of **6** in solution and/or a copper-intermediate derived from **6** and $CuCl_2$. Recently, we reported that the copper-catalyzed cyclization of organozinc compounds gave dithienothiophenes, cyclopentadithiophenes, silacyclopenta-dithiophenes, and cyclooctatetrathiophenes in moderate to good yields.[12] This method can be applied advantageously to synthesize biphenylene **1** and its derivatives **5**, **8** and **9** but not the tetramethoxy derivative (R = OCH_3) (Scheme 1). In preliminary form, we reported the synthesis of biphenylenes and proposed the synthetic utility of this type of reaction for construction of the biphenylene framework.[13] In this paper we describe the details of the successful syntheses of the title compounds, together with some mechanistic features and the scope and limitations of this synthetic methodology.

Results and discussion

Biphenylene synthesis was carried out using the copper(II)-mediated oxidative coupling, *i.e.*, by a reaction sequence of halogen–lithium exchange, transmetallation, and then reductive elimination. Since the direct transmetallation reaction may not proceed smoothly,[14a] two-step reactions *via* arylzinc intermediates[14b] were employed for the coupling (Scheme 2). Thus, the reaction of 2,2′-dihalogenobiphenyls **10** and **11** with Bu^{n}Li (2.1–2.2 mol equiv.) at −78 °C in THF, followed by treatment with $ZnCl_2$ (1.1–2.4 mol equiv.) at −50 °C, gave a solution which contained an arylzinc species (**12** and **13**).[15a] The reaction of **12** or **13** with $CuCl_2$ (3 mol equiv.) produced biphenylene **1** in 70–81% yield, together with a trace of tetraphenylene **7**. The results are summarized in Table 1. The arylzinc chloride derivative **12**, prepared from dilithiobiphenyl **6** with 2.2 mol equiv. of $ZnCl_2$, was treated with $CuCl_2$ (3 mol equiv.), and biphenylene **1** was isolated in 70–71% yield, together with a small amount of tetraphenylene **7** (entries 1 and 3). Interestingly, the zinc species **13**, prepared from dilithiobiphenyl **6** with 1.1 mol equiv. of $ZnCl_2$,[15a] reacted with $CuCl_2$ (3 mol equiv.) to produce **1** in 80–81% yield, together with tetraphenylene **7** in 5–6% yield (entries 2 and 4). Thus, **1** can be prepared in good yield, when the zincafluorene **13** is employed as intermediate. The zinc species

Table 1 Synthesis of biphenylene using organozinc reagents

Entry	Compd	Bu^{n}Li (mol equiv.)	$ZnCl_2$ (mol equiv.)	Yield (%)	
				1	**7**
1	**10**	2.2	2.4	70	Trace
2	**10**	2.1	1.1	80	6
3	**11**	2.2	2.4	71	Trace
4	**11**	2.1	1.1	81	5

1: R = H

2

3

Fig. 1

10: X = Br
11: X = I

ZnCl
12

13

CuCl₂ (3 equiv)

CuCl₂ (3 equiv)

1 + **7**

Scheme 2

CuCl₂
Ether

7: R = H

6: R = H

1) ZnCl₂
2) CuCl₂
THF

1: R = H
4: R = Me
5: R = F

8

9

Scheme 1

14: R,R = Me
15: R,R = F
16: R,R = -(CH=CH)₂-

i, ii

17: R,R = Me
18: R,R = F
19: R,R = -(CH=CH)₂-

or

23: R,R = Me
24: R,R = F
25: R,R = -(CH=CH)₂-

iii

4: R,R = Me
5: R,R = F
9: R,R = -(CH=CH)₂-

20: R,R = Me
21: R,R = F
22: R,R = -(CH=CH)₂-

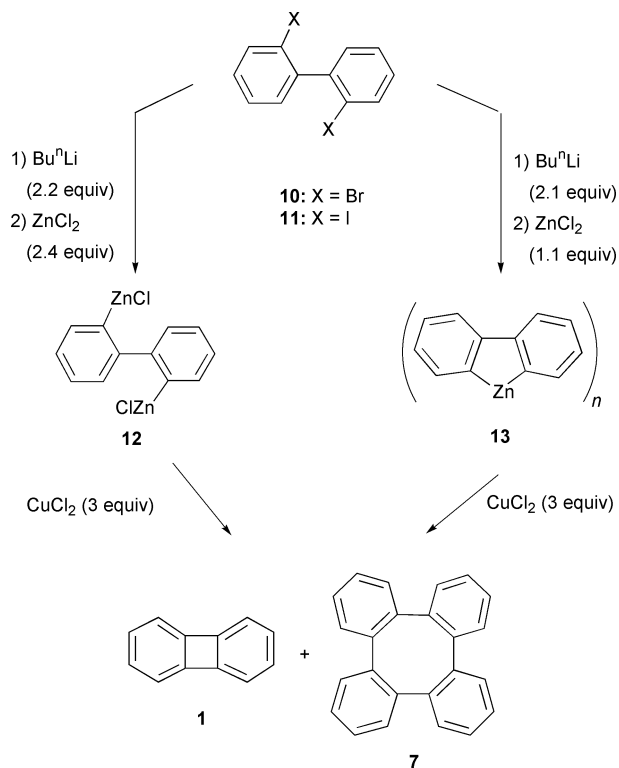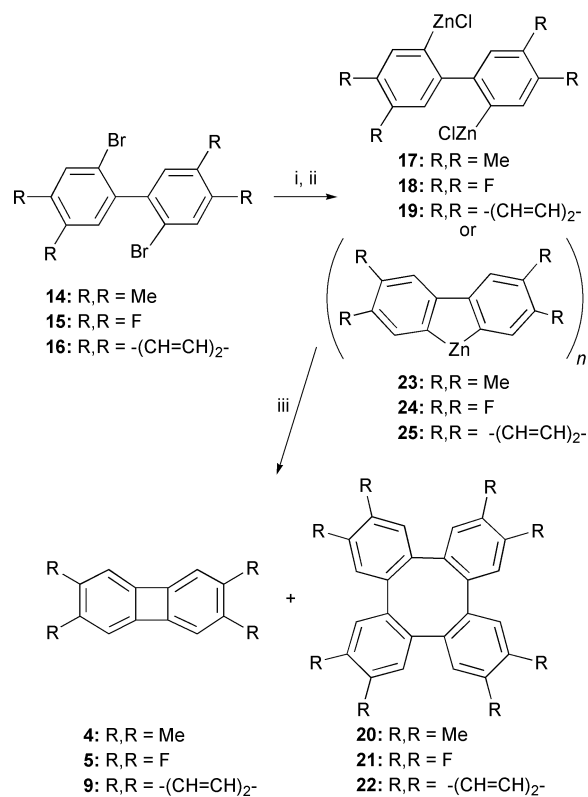**Scheme 3** *Reagents*: i, Bu″Li (2.1–2.2 mol equiv.); ii, ZnCl₂ (2.4 or 1.1 mol equiv.); iii, CuCl₂ (3 mol equiv.).
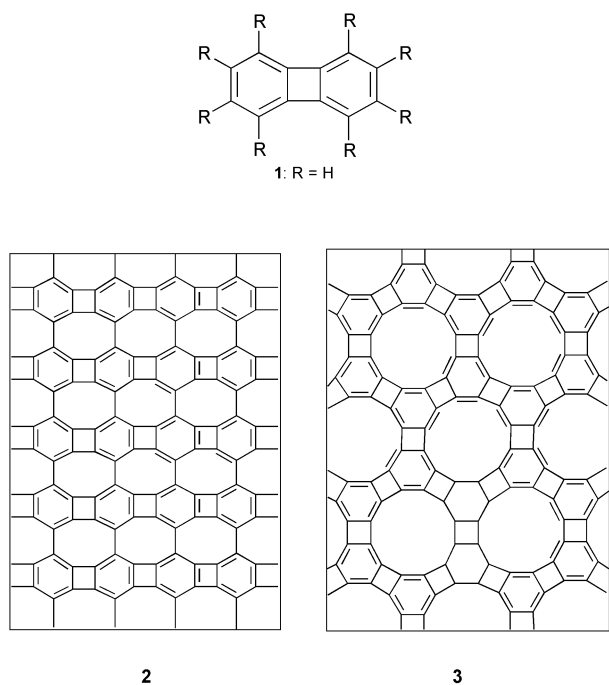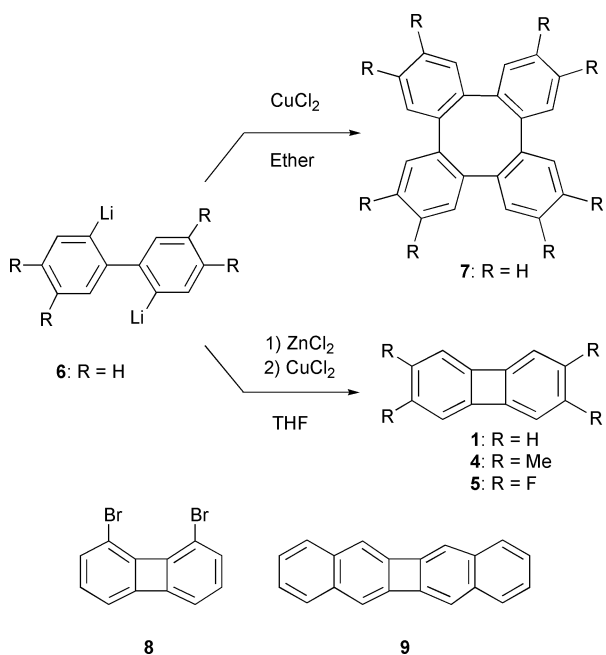
13 may exist in a monomer–dimer equilibrium,[15b] although the structures of organozinc species in solution are still not completely elucidated.[15c] On the basis of these results, this reaction was extended to the synthesis of substituted biphenylenes.

2,2′-Dibromo-4,4′,5,5′-tetramethylbiphenyl **14** was prepared by using the coupling reaction of 4,5-dibromo-*o*-xylene with Bu″Li (0.5 mol equiv.).[16] The successive treatment of **14** with 2.1 mol equiv. of Bu″Li and 1.1 mol equiv. of ZnCl₂ produced the zincaflourene intermediate **23**, which reacted with 3 mol equiv. of CuCl₂ to produce 2,3,6,7-tetramethylbiphenylene[10] **4** in 70% yield, together with 2,3,6,7,10,11,14,15-octamethyltetra-phenylene **20** in 7% yield (Scheme 3). The arylzinc species **17** produced 2,3,6,7-tetramethylbiphenylene **4** in a lower yield (59%) than did the zincafluorene intermediate **23** in a similar manner as for **13**. To obtain 2,3,6,7-tetrafluorobiphenylene **5**, 2,2′-dibromo-4,4′,5,5′-tetrafluorobiphenyl **15** was prepared from 1,2-dibromo-4,5-difluorobenzene in diethyl ether in 25%

yield by successive treatments with Bu″Li, ZnCl₂, and CuCl₂. The reaction of **15** with Bu″Li (2.1 mol equiv.) at −78 °C in THF, followed by treatment with ZnCl₂ (1.1 mol equiv.) at −50 °C, gave the zincafluorene intermediate **24**, which reacted with CuCl₂ (3 mol equiv.) to produce 2,3,6,7-tetrafluoro-biphenylene **5** in 46% yield, together with 2,3,6,7,10,11,14,15-octafluorotetraphenylene **21** in 10% yield (Scheme 3). Unlike the reaction of **13**, the arylzinc species **18** gave an unidentified mixture, which could not be fractionated.

The successful result for the biphenylene synthesis led us to attempt the synthesis of a condensed biphenylene system, dibenzo[b,h]biphenylene[17] 9, starting from 2,2′-dibromobinaphthyl[18] 16 which was itself prepared from 2,3-dibromonaphthalene by reaction with Bu^{n}Li (0.5 mol equiv.). Thus, the reaction of 16 with Bu^{n}Li (2.2 mol equiv.) at −78 °C in THF, followed by treatment with ZnCl$_2$ (2.4 mol equiv.) at −50 °C, gave the arylzinc species 19. Treatment of 19 with CuCl$_2$ (3 mol equiv.) at −78 °C to room temperature produced dibenzo[b,h]-biphenylene 9 in 28% yield and tetranaphthylene[19] 22 in 9% yield. However, on use of 2.1 mol equiv. of Bu^{n}Li and 1.1 mol equiv. of ZnCl$_2$, formation of the zincafluorene species 25 was envisaged, and the reaction of 25 with 3 mol equiv. of CuCl$_2$ gave dibenzobiphenylene 9 in 70% yield, together with tetranaphthylene 22 in 15% yield (Scheme 3). When ZnBr$_2$ (1.1 mol equiv.) was used instead of ZnCl$_2$, dibenzobiphenylene 9 was obtained in 40% yield, together with tetranaphthylene 22 in 22% yield.

Further application utilizing the zincafluorene species to the synthesis of 1,8-dibromobiphenylene[5] 8 is depicted in Scheme 4. The starting tetrabromide 26 was prepared according
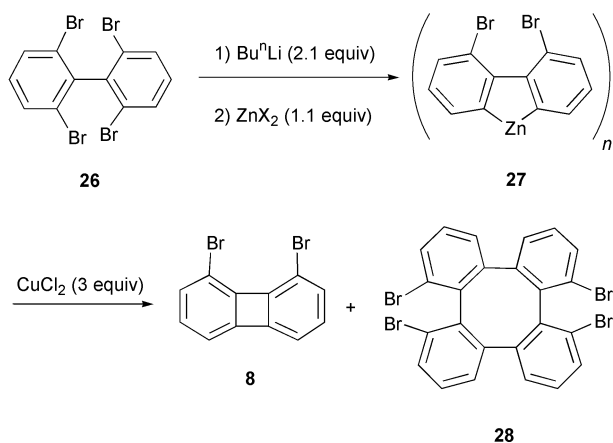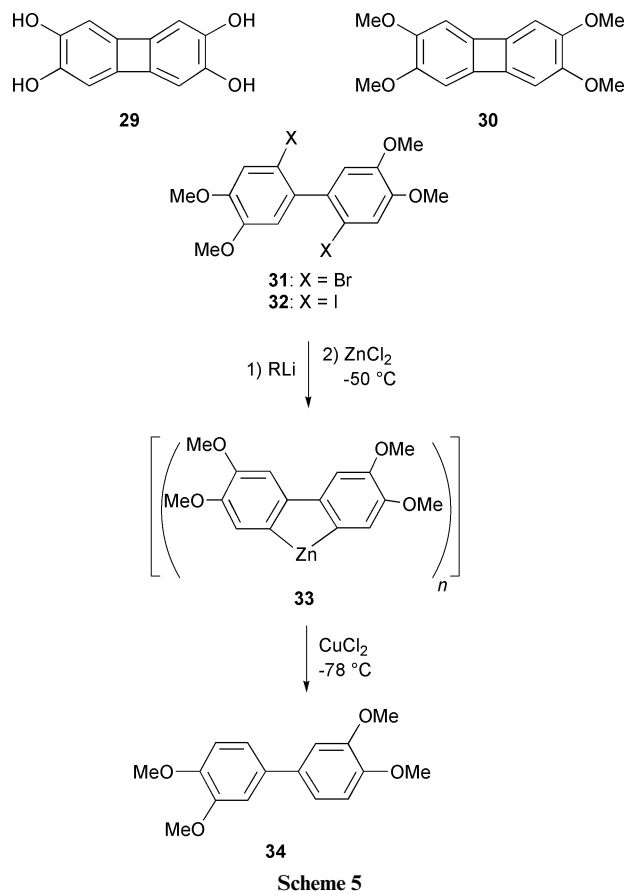
Scheme 4

to the literature procedure,[5] and the successive reactions of 26 with Bu^{n}Li or Bu^{t}Li (2.1 mol equiv.), ZnCl$_2$ (1.1 mol equiv.), and CuCl$_2$ (3 mol equiv.) did not proceed smoothly and produced 1,8-dibromobiphenylene 8 in low (40%) yield, together with 2,2′-dibromobiphenyl 10 (24%) and a trace of 1,8,9,16-tetrabromotetraphenylene 28. However, it was shown that ZnBr$_2$ was effective for the synthesis of 8. Successive treatment of 26 with 2.1 mol equiv. of Bu^{n}Li at −78 °C in THF and 1.1 mol equiv. of ZnBr$_2$ at −50 °C produced the zinc species 27, and the reaction of this zinc species with 3 mol equiv. of CuCl$_2$ produced 1,8-dibromobiphenylene 8 in 72% yield, together with a trace of the tetraphenylene 28. The effectiveness of ZnBr$_2$ over ZnCl$_2$ in this reaction was considered to be due to the higher solubility of ZnBr$_2$ in THF at low temperatures.

Since 2,3,6,7-tetrahydroxybiphenylene 29 can be expected to show interesting properties in organic and organometallic chemistry,[20] the synthesis of 29 was planned by using the copper(II)-mediated cyclization of an organozinc species. The preparation of 2,3,6,7-tetramethoxybiphenylene[10,21] 30 as a precursor of 29 was first attempted. The reaction of 4,5-dibromoveratrole with Bu^{n}Li (0.5 mol equiv.) gave 2,2′-dibromo-4,4′,5,5′-tetramethoxybiphenyl 31 in 65% yield.[10,21–23] Treatment of 31 with Bu^{n}Li or Bu^{t}Li (2.1–2.2 mol equiv.) at −78 °C in THF, followed by reaction with 1.1–1.2 mol equiv. of ZnCl$_2$ or ZnBr$_2$ at −50 °C, produced what we thought was the zinc species 33, and the product was treated with CuCl$_2$ (3 mol equiv.). However, methoxy-substituted biphenyl 34[21] was isolated as the major compound instead of the expected biphenylene. The reaction of the zinc species derived from

2,2′-diiodo-4,4′,5,5′-tetramethoxybiphenyl[21] 32 gave almost the same results (Scheme 5).

Scheme 5

After several attempts to modify the reaction conditions, the methoxy-substituted tetraphenylene 35 was obtained as the major product. The reaction of 2,2′-diiodo-4,4′,5,5′-tetramethoxybiphenyl 32 with Bu^{n}Li (2.2 mol equiv.) at −78 °C in THF, followed by treatment with ZnBr$_2$ (1.2 mol equiv.) at −50 to 0 °C, gave the organozinc species 33 (Scheme 6). The reaction
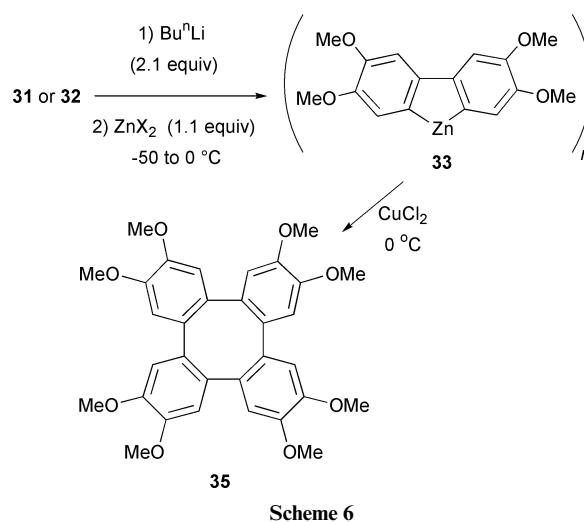
Scheme 6

of zinc species 33 with CuCl$_2$ (3 mol equiv.) at 0 °C to room temperature produced 2,3,6,7,10,11,14,15-octamethoxytetraphenylene 35 in 67% yield. When ZnCl$_2$ and ZnI$_2$ were used instead of ZnBr$_2$, the methoxy-substituted tetraphenylene 35 was isolated in 35 and 43% yield, respectively. As ZnBr$_2$ proved to be an effective reagent for the synthesis of 35, a similar reaction of 2,2′-dibromo-4,4′,5,5′-tetramethoxybiphenyl 31 was carried out to form 35 in 52% yield. The formation of
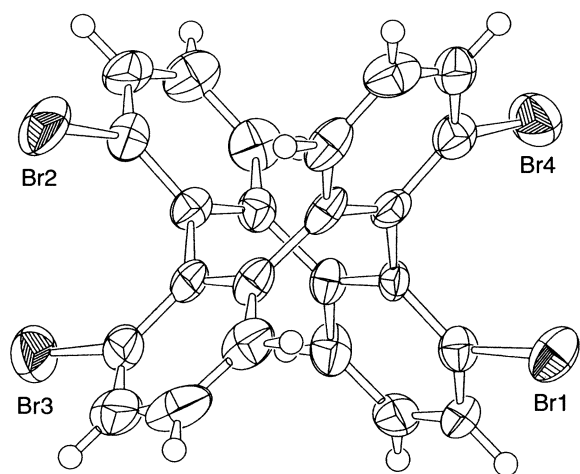
Fig. 2 ORTEP drawing of **28**.

tetramethoxybiphenyl **34** shown in Scheme 5 suggests the difficulty in the construction of the metallacycle **33** and the facility of hydrogen-capture *via* carbon–metal bond cleavage after the addition of CuCl$_2$ at −78 °C.

In order to clarify the reason(s) why the copper-mediated oxidation of an organozinc species produces biphenylenes and tetraphenylenes selectively depending on the substituents, we examined the following experiments. It was reported that the reaction of 2,2′-dilithiobiphenyl **6** with CuCl$_2$ at 0 °C in diethyl ether produced tetraphenylene **7** as the major component (53%), together with a small amount (3%) of biphenylene **1**.[11,15,24] However, when this reaction was conducted in THF at −78 °C to room temperature, biphenylene **1** was the major product (65%), together with a trace amount of tetraphenylene **7**. In a similar manner, the reaction of **15** or **16** with Bu^{n}Li (2.2 mol equiv.), followed by treatment with CuCl$_2$ (3 mol equiv.), afforded biphenylenes **5** (30%) from **15** or **9** (58%) from **16**, together with **21** (15%) from **15** or **22** (7%) from **16**. These results suggest that THF is favoured for biphenylene synthesis, whereas diethyl ether is favoured for tetraphenylene synthesis (Scheme 7). In the reaction of the dibromo zincafluorene or
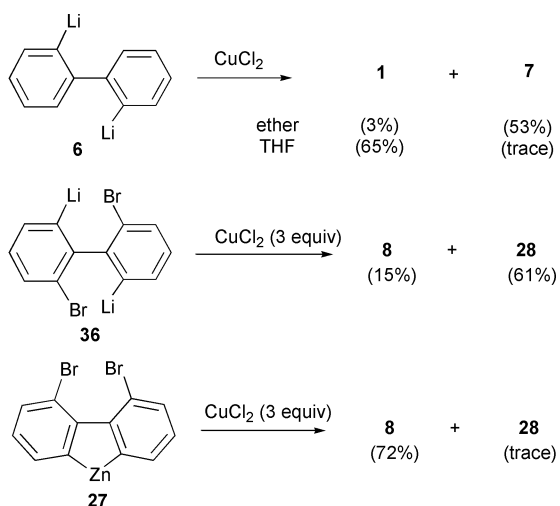
Scheme 7

its oligomer **27** with CuCl$_2$, the selectivity changed significantly and showed a marked difference. Thus, the reaction of 2,2′,6,6′-tetrabromobiphenyl **26** with Bu^{n}Li (2.1 mol equiv.) at −78 °C in THF gave the dilithio derivative **36**, which was treated with CuCl$_2$ (3 mol equiv.) to produce tetrabromotetraphenylene **28** in 61% yield, together with 1,8-dibromobiphenylene **8** in 15% yield, whereas a similar reaction of **27** led to 1,8-dibromobiphenylene **8** in 72% yield. The twisted structure of **28** was determined by X-ray analysis (Fig. 2).

The plausible pathways for the formation of biphenylene, tetraphenylene and polyphenylenes *via* an organozinc species are depicted in Scheme 8. The organozinc intermediate **13** can
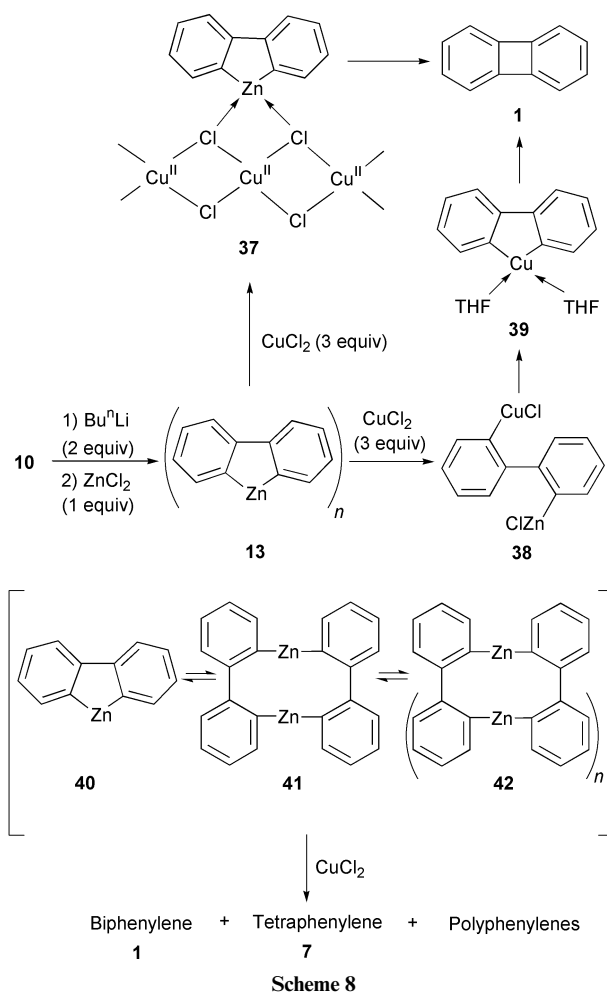
Scheme 8

react with CuCl$_2$ in three different ways, *i.e.*, path A: a cluster-like complex **37** is formed,[25] which undergoes reductive elimination to yield biphenylene **1**; or path B: an aryl radical is generated *via* one-electron oxidation, followed by radical cyclization to afford **1**; or path C: transmetallation *via* ring cleavage occurs to form **38**, from which elimination of ZnCl$_2$ produces copper(II) species **39**, which may be stabilized by THF.[11] Reductive elimination of Cu^0 from **39** produces biphenylene **1**. The zincafluorene intermediate **40** (**13**, $n = 1$) can exist in equilibrium with a dimeric form **41** and a polymeric form **42**. The equilibrium may favour **40**, from which biphenylene **1** is formed in good yield, whereas **41** and **42** probably lead to tetraphenylene **7** and polyphenylenes, respectively. In the reaction of **27** with CuCl$_2$, the selective formation of **8** may suggest the cluster-like intermediate (path A), because the conversion of **37** into **1** decreases the steric repulsion suffered between the 4- and 5-position in **37**, and because the cyclization of **38** to **39** in path B is sterically unfavourable. The reaction of **36** with CuCl$_2$ produces selectively the tetraphenylene derivative **28**. In the case of the methoxy derivative, we presume the difficulty lies in the formation of the metallacycle **33** or its copper analogue equivalent to **39**, presumably due to the electronic effect of the methoxy groups. The sequential reactions of **31** or **32** with Bu^{n}Li, ZnCl$_2$, and CuCl$_2$ produced only the tetraphenylene derivative **35**, and no biphenylene derivative was isolated.

In summary, an efficient and flexible synthetic route to biphenylenes has been developed, and biphenylene and its

derivatives have been produced selectively with a few exceptions. Further studies on the mechanism of the biphenylene synthesis are under way.

Experimental

Mps were determined with a Yanaco MP-500D melting point apparatus and are uncorrected. IR spectra were recorded on a Perkin-Elmer 1600 series FT-IR spectrometer. NMR spectra were recorded on a JEOL JNM-LAMBDA 400 or 500 spectrometer using tetramethylsilane as internal standard. Unless otherwise specified, CDCl$_3$ was used as solvent. The mass and high-resolution mass spectra were determined with a JEOL AX 505 mass spectrometer with a JMA 5000 mass data system at an ionizing voltage of 70 eV. Gel-permeation liquid chromatography (GPLC) was performed on JAI LC-08 and LC-908 liquid chromatography instruments with a JAIGEL-1H column, and chloroform and toluene were used as eluents. TLC was performed with Merck 60 F$_{254}$ silica gel or Merck 60 F$_{254}$ alumina. Column chromatography was performed with Daisogel IR-60 (60/210 nm) or Merck aluminium oxide 90. All solvents were dried and purified by the usual techniques.

Starting materials

2,2′-Dibromobiphenyl[16] **10**, 2,2′-diiodobiphenyl[16] **11**, 1,2-dibromo-4,5-dimethylbenzene,[26] 2,3-dibromonaphthalene,[27] 2,2′,6,6′-tetrabromobiphenyl[5,28,29] **26**, 4,5-dibromoveratrole,[30] and 2,2′-diiodo-4,4′,5,5′-tetramethoxybiphenyl[31] **32** were prepared according to the published procedures.

2,2′-Dibromo-4,4′,5,5′-tetramethylbiphenyl 14

To a stirred solution of 1,2-dibromo-4,5-dimethylbenzene (5.28 g, 20 mmol) in dry THF (80 mL) was added *n*-butyllithium (6.3 mL, 10 mmol; 1.56 M in hexane) at −78 °C. The addition was done below 5 °C (exothermic reaction). After the addition of *n*-butyllithium, the reaction mixture was stirred for another 1 h at −78 °C. The reaction mixture was allowed to warm to room temperature, stirred for 1 h, and then was hydrolyzed with aq. 5% hydrochloric acid. The organic layer was separated and the aqueous layer was extracted with four 20 mL portions of benzene. The extracts were combined with the organic layer and dried over anhydrous MgSO$_4$. The solvent was evaporated *in vacuo* and the product was separated by chromatography on silica gel, using hexane as eluent, to give **14** (2.76 g, 75%) as colourless crystals (from hexane), mp 141–142 °C; ^{1}H NMR (500 MHz) δ 7.41 (s, 2H), 6.98 (s, 2H), 2.27 (s, 6H), 2.22 (s, 6H); ^{13}C NMR (125 MHz) δ 139.3, 138.0, 135.5, 133.0, 132.0, 120.2, 19.3, 19.2; MS (EI) *m/z* 370, 368, 366 (M$^+$), 289, 288, 208. Calc. for C$_{16}$H$_{16}$[79]Br$_2$: *M*, 365.9630. Found: M$^+$, 365.9618. Calc. for C$_{16}$H$_{16}$Br$_2$: C, 52.21; H, 4.38. Found: C, 52.60; H, 4.20%.

2,2′-Dibromo-4,4′,5,5′-tetrafluorobiphenyl 15

To a solution of 1,2-dibromo-4,5-difluorobenzene (1.36 g, 5 mmol) in dry diethyl ether (20 mL) was added *n*-butyllithium (3.3 mL, 5.2 mmol; 1.57 M in hexane) at −78 °C and the mixture was stirred for 2 h at the same temperature. A solution of ZnCl$_2$ (0.736 g, 5.4 mmol) in THF (20 mL) was added at −50 °C and the solution was stirred for 2 h at the same temperature. Then, the reaction mixture was cooled to −78 °C and CuCl$_2$ (1.01 g, 7.5 mmol) was added. After stirring for 2 h at the same temperature, the mixture was allowed to warm to room temperature and was stirred overnight. The mixture was hydrolyzed with aq. 4 M hydrochloric acid. The mixture was extracted with benzene and the extract was dried over anhydrous MgSO$_4$. After removal of the solvent *in vacuo*, the residue was separated by silica gel column chromatography, using hexane as eluent, to give **15**. Pure title compound **15** (240

mg, 25%) was obtained by distillation as a colourless oil, bp 105–107 °C/3 mmHg; ^{1}H NMR (500 MHz) δ 7.51 (dd, 2H, *J* 9.5, 7.3 Hz), 7.09 (dd, 2H, *J* 9.5, 7.3 Hz); ^{13}C NMR (125 MHz) δ 150.1 (dd, *J* 250.0, 13.0 Hz), 149.3 (dd, *J* 250.0, 13.0 Hz), 136.2, 122.9, 117.8, 116.0; ^{19}F NMR (470.4 MHz) δ −138.2 (m, 2F), −134.8 (m, 2F); MS (EI) *m/z* 386, 384, 382 (M$^+$), 304, 303, 224. Calc. for C$_{12}$H$_4$[79]Br[81]BrF$_4$: *M*, 383.8595. Found: M$^+$, 383.8602.

3,3′-Dibromo-2,2′-binaphthyl 16.

Preparation and purification of the product were carried out in a similar manner as for the preparation of **14**. To a solution of 2,3-dibromonaphthalene (2.574 g, 9 mmol) in THF (60 mL) was added *n*-butyllithium (2.94 mL, 4.5 mmol; 1.53 M in hexane) below 5 °C. The mixture was stirred for 0.5 h at −78 °C and then overnight at room temperature. After aqueous work-up, the products were separated by silica gel column chromatography, using hexane–benzene (4 : 1) as eluent, to give **16** (1.11 g, 60%) as colourless crystals (from hexane), mp 161–162 °C (lit.,[16] 162 °C); ^{1}H NMR (500 MHz) δ 8.22 (s, 2H), 7.84 (m, 4H), 7.81 (s, 2H), 7.55 (m, 4H); ^{13}C NMR (125 MHz) δ 139.5, 133.9, 132.0, 131.0, 130.1, 128.0, 127.2, 126.8, 126.7, 121.8; MS (EI) *m/z* 414, 412, 410 (M$^+$), 252, 126.

2,2′-Dibromo-4,4′,5,5′-tetramethoxybiphenyl 31.

In a similar manner as for the preparation of **14**, the reaction of 4,5-dibromoveratrole (5.29 g, 20 mmol) with *n*-butyllithium (10.0 mmol) in THF (45 mL) afforded products which were separated by silica gel column chromatography, using hexane–benzene as eluent, to give **31** in 65% yield as colourless crystals [mp 160–161 °C (lit.,[18,19] 154–158 °C)]; ^{1}H NMR (CDCl$_3$; 500 MHz) δ 7.11 (s, 2H), 6.76 (s, 2H), 3.92 (s, 6H), 3.87 (s, 6H); ^{13}C NMR (CDCl$_3$; 125 MHz) δ 149.1, 148.0, 134.0, 115.1, 113.95, 113.92, 56.20, 56.16; MS (EI) *m/z* 434, 432, 430 (M$^+$), 354, 352.

Typical procedure for Table 1

Reactions for entries 1 and 3. To a solution of **10** (312 mg, 1 mmol) in dry THF (20 mL) was added *n*-butyllithium (1.44 mL, 2.2 mmol; 1.53 M in hexane) at −78 °C and the solution was stirred for 2 h at −78 °C. A solution of ZnCl$_2$ (327 mg, 2.4 mmol) in THF (10 mL) was added to the reaction mixture at −50 °C and the mixture was stirred for 2 h at the same temperature. The reaction mixture was cooled to −78 °C and CuCl$_2$ (403 mg, 3 mmol) was added. After stirring for 2 h at the same temperature, the mixture was allowed to warm to room temperature and was stirred overnight. The mixture was hydrolyzed with aq. 4 M hydrochloric acid and extracted with benzene. The extracts were dried over anhydrous MgSO$_4$. After removal of the solvent *in vacuo*, the residue was separated by silica gel column chromatography, using hexane as eluent, to give biphenylene in 68–70% yield together with a trace amount of tetraphenylene.

Reactions for entries 2 and 4. To a solution of **10** (312 mg, 1 mmol) in dry THF (20 mL) was added *n*-butyllithium (1.4 mL, 2.1 mmol; 1.53 M in hexane) at −78 °C and the solution was stirred for 2 h at −78 °C. A solution of ZnCl$_2$ (150 mg, 1.1 mmol) in THF (10 mL) was added at −50 °C and the mixture was stirred for 2 h at the same temperature. The mixture was cooled to −78 °C and CuCl$_2$ (403 mg, 3 mmol) was added. After stirring for 2 h at the same temperature, the mixture was allowed to warm to room temperature and was stirred overnight. The mixture was hydrolyzed with aq. 4 M hydrochloric acid and extracted with benzene. The extracts were dried over anhydrous MgSO$_4$. After removal of the solvent *in vacuo*, the residue was separated by silica gel column chromatography, using hexane as eluent, to give **1** (122 mg, 80%) as pale yellow crystals, mp 109.5–110.5 (lit.,[1] 111) °C, together

with **7** (9 mg, 6%) as colourless crystals, mp 237–238 °C (lit.,[11] 233 °C). **1**: ^{1}H NMR (500 MHz) δ 6.73 (m, 4H), 6.62 (m, 4H); ^{13}C NMR (125 MHz) δ 151.2, 128.2, 117.3; MS m/z 152 (M[+]). **7**: ^{1}H NMR (500 MHz) δ 7.29–7.26 (m, 8H), 7.17–7.14 (m, 8H); ^{13}C NMR (125 MHz) δ 141.5, 129.0, 127.2; MS (EI) m/z 304 (M[+]); UV (THF) λ_{max} (log ε) 273sh (3.15), 235 (4.29) nm.

2,3,6,7-Tetramethylbiphenylene 4, 2,3,6,7-tetrafluorobiphenylene 5, and dibenzo[*b,h*]biphenylene 9. To a solution of dibromobiaryl (1 mmol) in THF (20 mL) was added *n*-butyllithium (2.2 mmol) at −78 °C and the mixture was stirred for 2 h. A solution of ZnCl$_2$ (150 mg, 1.1 mmol) in THF (10 mL) was added to the mixture at −50 °C and the whole was stirred for 2 h at −50 °C. The mixture was cooled to −78 °C and CuCl$_2$ (403 mg, 3 mmol) was added. After stirring for 2 h at −78 °C, the mixture was allowed to warm to room temperature and was stirred overnight. After aqueous work-up, the product was separated by silica gel column chromatography, using hexane as eluent, to give the biphenylene derivatives (**4**, 70%; **5**, 46%; **9**, 70%) and tetraphenylene derivatives (**20**, 7%; **21**, 10%; **22**, 15%), respectively. **4**: pale yellow crystals, mp 223–224 °C (lit.,[10] 224–225 °C); ^{1}H NMR (500 MHz) δ 6.40 (s, 4H), 2.07 (s, 12H); ^{13}C NMR (125 MHz) δ 148.9, 134.8, 119.1, 20.1; MS (EI) m/z 208 (M[+]). **20**: colourless crystals, mp > 300 °C (lit.,[32] > 290 °C); ^{1}H NMR (500 MHz) δ 6.91 (s, 8H), 2.21 (s, 24H); ^{13}C NMR (125 MHz) δ 139.3, 135.0, 130.7, 19.3; MS (EI) m/z 416 (M[+]). **5**: colourless crystals, mp 107–108 °C; ^{1}H NMR (500 MHz) δ 6.49 (m, 4H); ^{13}C NMR (125 MHz) δ 150.5 (dd, J 249.9, 13.4 Hz), 144.1, 109.8; ^{19}F NMR (470.4 MHz) δ −138.3 (s, 4F); MS (EI) m/z 224 (M[+]); UV (EtOH) λ_{max} (log ε) 369 (3.93), 350 (3.85), 242 (4.67), 234.5 (4.57) nm; IR (neat) ν_{max} 3102, 1718, 1685, 1654, 1616, 1560, 1534, 1508, 1490, 1458, 1436, 1281, 1008, 854, 753, 612, 573 cm^{-1}. Calc. for C$_{12}$H$_4$F$_4$: M, 224.0288. Found: M[+] 224.0249. **21**: colourless crystals, mp 259–260 °C; ^{1}H NMR (500 MHz) δ 6.97–6.94 (t, 8H, J 9.2 Hz); ^{13}C NMR (125 MHz) δ 149.7 (dd, J 251.9, 14.4 Hz), 135.8, 118.2; ^{19}F NMR (470.4 MHz) δ −97.9 (s, 8F); MS (EI) m/z 448 (M[+]); UV (THF) λ_{max} (log ε) 267 (3.50), 210 (4.67) nm. Calc. for C$_{24}$H$_8$F$_8$: M, 448.0499. Found: M[+], 448.0490. **9**: light yellow crystals, mp 342–348 °C (sublimed) [lit.,[15] 340–345 °C (sublimed)]; ^{1}H NMR (CS$_2$–CDCl$_3$; 500 MHz) δ 7.51 (m, 4H), 7.26 (m, 4H), 7.17 (s, 4H); ^{13}C NMR (CS$_2$–CDCl$_3$; 125 MHz) δ 146.0, 128.6, 128.0, 126.2, 117.0; MS (EI) m/z 252 (M[+]). **22**: colourless crystals, mp 303.5–305 °C (lit.,[17] > 300 °C); ^{1}H NMR (500 MHz) δ 7.79 (m, 8H), 7.76 (s, 8H), 7.43 (m, 8H); ^{13}C NMR (125 MHz) δ 140.2, 132.7, 128.0, 127.6, 126.1; MS (EI) m/z 504 (M[+]); UV (THF) λ_{max} (log ε) 394 (1.40), 380 (1.99), 367 (2.18), 360 (2.19), 325sh (2.57), 287sh (3.81), 251 (4.52), 224 (4.27) nm; IR (neat) ν_{max} 3060, 1495, 1132, 1017, 956, 894, 885, 784, 741 cm^{-1}.

1,8-Dibromobiphenylene 8. Compound **8** was obtained in a similar manner as described for the preparation of **4**, **5**, and **9**. By use of 2,2′,6,6′-tetrabromobiphenyl **26** (470 mg, 1 mmol), *n*-butyllithium (2.1 mmol) in THF (20 mL), ZnBr$_2$ (248 mg, 1.1 mmol), and CuCl$_2$ (403 mg, 3 mmol), compound **8** was obtained in 72% yield, together with a trace of 1,8,9,16-tetrabromotetraphenylene **28**. When ZnCl$_2$ was used instead of ZnBr$_2$, **8** was obtained in 40% yield, together with 2,2′-dibromobiphenyl **10** (24%) and a trace of 1,8,9,16-tetrabromotetraphenylene **28**. Use of *tert*-butyllithium instead of *n*-butyllithium gave almost the the same result. **8**: pale yellow crystals, mp 145.5–146.5 °C (lit.,[5] 145–146 °C); ^{1}H NMR (500 MHz) δ 6.84 (d, 2H, J 8.3 Hz), 6.65 (dd, 2H, J 8.3, 7.0 Hz), 6.58 (d, 2H, J 7.0 Hz); MS (EI) m/z 312, 310, 308 (M[+]). **28**: colourless crystals, mp 306.5–308 °C (sublimed); ^{1}H NMR (500 MHz) δ 7.47 (d, 4H, J 8.3 Hz), 7.28 (dd, 4H, J 8.3, 1.2 Hz), 7.17 (t, 4H, J 8.3 Hz); ^{13}C NMR (125 MHz) δ 142.6, 139.8, 131.8, 129.4, 126.2, 123.8; MS (EI) m/z 620 (M[+]), 460, 300; UV (THF) λ_{max} (log ε) 265 (2.84), 216 (4.56) nm. Calc. for C$_{24}$H$_{12}$[79]Br$_4$: M,

615.7672, Found: M[+], 615.7657. Calc. for C$_{24}$H$_{12}$Br$_4$: C, 46.50; H, 1.95. Found: C, 46.68; H, 2.00%.

2,3,6,7,10,11,14,15-Octamethoxytetraphenylene 35. The preparation of **35** was carried out in a similar manner as described for the preparation of **4**, **5**, **8**, and **9** using 2,2′-diiodo-4,4′,5,5′-tetramethoxybiphenyl **32** (526 mg, 1 mmol), *n*-butyllithium (2.2 mmol) in THF (20 mL), ZnBr$_2$ (270 mg, 1.2 mmol) in THF (10 mL), and CuCl$_2$ (403 mg, 3 mmol). The product was separated by silica gel column chromatography, using benzene–ethyl acetate (10 : 1) as eluent, to give **35** (182 mg, 67%) as colourless crystals. In a similar procedure using 2,2′-dibromo-4,4′,5,5′-tetramethoxybiphenyl **31**, compound **35** was obtained in 52% yield. **35**: mp 258–260 °C (lit.,[33] 260–262 °C); ^{1}H NMR (500 MHz) δ 6.70 (s, 8H), 3.86 (s, 24H); ^{13}C NMR (125 MHz) δ 147.9, 134.1, 112.5, 56.0; MS (EI) m/z 544 (M[+]); UV (EtOH) λ_{max} (log ε) 285 (4.04), 214.5 (4.57) nm; IR (neat) ν_{max} 3001, 2934, 2834, 1602, 1498, 1462, 1438, 1392, 1342, 1304, 1247, 1202, 1165, 1045, 1026, 856, 772 cm^{-1}. Calc. for C$_{32}$H$_{32}$O$_8$: M, 544.2106. Found: M[+], 544.2097. Calc. for C$_{32}$H$_{32}$O$_8$: C, 70.57: H, 5.92. Found: C, 70.77; H, 6.01%.

Preparation of biphenylene 1, dibenzo[*b,h*]biphenylene 9, and 2,3,6,7-tetrafluorobiphenylene 5 in the absence of ZnCl$_2$ in THF

The reaction of 2,2′-dibromobiaryl (1 mmol) with *n*-butyllithium (2.2 mmol) in THF (30 mL) at −78 °C, followed by treatment with CuCl$_2$ (403 mg, 3 mmol) at −78 °C, afforded the products, which were separated by silica gel column chromatography to give the corresponding biphenylenes (**1**: 65%, **5**: 30%, **9**: 58%) and tetraphenylenes (**7**: trace, **21**: 15%, **22**: 7%).

Preparation of 1,8,9,16-tetrabromotetraphenylene 28 in the absence of ZnCl$_2$ in THF

The reaction of 2,2′,6,6′-tetrabromobiphenyl **26** (470 mg, 1 mmol) with *n*-butyllithium (2.2 mmol) in THF (30 mL) at −78 °C, followed by treatment with CuCl$_2$ (403 mg, 3 mmol) at −78 °C, afforded the crude product, which was separated by silica gel column chromatography, using hexane–benzene (10 : 1) as eluent, to give **28** in 61% yield, together with 1,8-dibromobiphenylene **8** in 15% yield.

Crystallographic structural determination of 28 †

Crystals of **28** suitable for X-ray structure analysis were obtained by slow recrystallization of **28** from hexane–benzene (1 : 1); colourless prism of crystal size 0.20 × 0.16 × 0.25 mm. Intensity data were collected using a Rigaku 7R four-circle diffractometer with graphite-monochromated Mo-Kα radiation (λ = 0.710 69 Å); crystal system monoclinic, space group $P2_1/c$ (No. 14); cell parameters: a = 9.148(4), b = 14.796(4), c = 16.223(4) Å, β = 104.75(2)°; V = 2123(1) Å; Z = 4; D_{calc} = 1.939 g cm^{-3}; F(000) = 1184.00; μ(Mo-Kα) = 76.11 cm^{-1}; R = 0.038, R_w = 0.036 using 1689 reflections with I > 3.00$\sigma(I)$. Structural parameters of non-hydrogen atoms were refined anisotropically according to the full-matrix least-squares technique.

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