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# A general synthetic route to chiral dihydroxy-9,9'-spirobifluorenes

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Abstract— $C_2$ -Symmetric 9,9'-spirobifluorenes with 2,2'-, 3,3'-, and 4,4'-dihydroxyls were conveniently prepared from 1,2-dibromobenzene. The palladium-catalyzed coupling reaction of 1,2-dibromobenzene with methoxyphenylmagnesium bromide or methoxyphenylboronic acid provided methoxy substituted 2-bromobiphenyls. Lithium–bromine exchange with *n*-butyllithium, followed by reaction with dimethyl carbonate afforded di[2-(methoxyphenyl)phenyl]ketones as the key intermediates. A continuous ring-closure induced by a strong Lewis acid and demethylation gave dihydroxy-9,9'-spirobifluorenes. The racemic dihydroxy products were resolved by inclusion crystallization using chiral resolving reagents or separated by chiral HPLC.

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### 1. Introduction

Compounds containing a spirobifluorene backbone have been widely applied in molecular electronics,<sup>1</sup> light-emitting materials,<sup>2</sup> enantioselective molecular recognition,<sup>3</sup> and other areas.<sup>4</sup> In the spirobifluorene family, chiral dihydroxyspirobifluorene was an important branch because the hydroxy group could be easily converted to other groups using well-established protocols.<sup>5</sup> Though the preparation of spirobifluorene itself was realized in 1930 by Gomberg,<sup>6</sup> synthesis of its 2,2'-dihydroxy derivative was not achieved until the 1970s.7 Both procedures used the same strategy; the addition of biphenyl Grignard reagents to 9-fluorenone, followed by a ring-closure to generate the spirobifluorene skeleton. In this procedure, the position of substituents of spirobifluorene depended directly on that in the parent 9-fluorenone, which restricted its use in the synthesis of various spirobifluorene compounds. An alternative strategy used Friedel-Crafts acylation<sup>8</sup> to construct disubstituted spirobifluorene, but it was limited to the preparation of 2,2'-disubstituted spirobifluorenes. In fact, development of a general method for the synthesis of the spirobifluorene compounds with 1,1'-, 2,2'-, 3,3'-, or 4,4'-disubstituents is still a challenge. Recently, we reported the synthesis and resolution of 1,1'-dihydroxy-9,9'-spirobifluorene. Two features of the method are crucial: (1) dimethyl carbonate was employed to condense with 2-bromo-biphenyl to create a diaryl ketone, which was a key intermediate; (2) methanesulfonic acid was used to close both rings of spirobifluorene in one step and the ring-closure proceeded exclusively at the 'bay' position as directed by the methoxy group.<sup>9</sup> Further studies revealed that this method also allowed the synthesis of 9,9'-spirobifluorene structures with disubstituents at the *ortho*, *meta*, and *para* positions. Here we wish to report the synthesis and resolution of 2,2'-, 3,3'-, and 4,4'-dihydroxy-9,9'-spirobifluorenes.

#### 2. Result and discussion

2,2'-Dihydroxy-9,9'-spirobifluorene was prepared with the protocol described below. 2-Bromo-4'-methoxybiphenyl (1) was prepared by the Kumada coupling of 1,2-dibromobenzene with 4-methoxyphenylmagnesium bromide catalyzed by Pd(PPh<sub>3</sub>)<sub>4</sub>. The lithium-bromine exchange, followed by reaction with dimethyl carbonate gave the key intermediate 2 in 60% yield. Owing to the lack of an electron-donating group at the ortho or para position to the 'bay' carbon, the electrophilic ring-closure of compound 2 can only be accomplished at 120 °C. It was found that the demethylation of the methoxy group also took place at this temperature, producing the target molecule 3 directly (Scheme 1). So, the construction of the spirobifluorene skeleton and the deprotection of the diol were realized in one reaction, which shortened the synthesis of 2,2'-dihydroxy-9,9'-spirobifluorene from five steps<sup>9</sup> to only three steps with 21% overall yield. The diol 3 was first resolved by Toda<sup>10</sup> in 1988 and its absolute configuration was determined by Lützen.<sup>11</sup>

3,3'-Dihydroxy-9,9'-spirobifluorene was obtained in a similar procedure by using 3-methoxyphenylmagnesium bromide (Scheme 2). In the ring-closure step, though there were two different 'bay' positions in molecule **5** and two different ring-closure products could be formed, the electrophilic attack occurred at the carbon *para* to the methoxy

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Scheme 1. Reagents and conditions: (a) Pd(PPh<sub>3</sub>)<sub>4</sub>, THF, 40 °C, 50%. (b) (i) n-BuLi, THF, -78 °C; (ii) MeOCOOMe, THF, 60%. (c) MsOH, 120 °C, 70%.



Scheme 2. Reagents and conditions: (a) (i) Pd(PPh<sub>3</sub>)<sub>4</sub>, THF, 40 °C, 60%. (b) (i) *n*-BuLi, THF, -78 °C; (ii) MeOCOOMe, THF, 75%. (c) MsOH, 35 °C, 4 h, 96%. (d) BBr<sub>3</sub>, added at -78 °C, and reacted at rt 8 h, 90%.

group to give the spirobifluorene compound **6** with 100% selectivity at 35 °C. Using boron tribromide, the protecting methyl group was removed smoothly at room temperature, affording the product 3,3'-dihydroxy-9,9'-spirobifluorene (7). The overall yield from 1,2-dibromobenzene was 39%.

In order to prepare the pure enantiomer of diol 7, (R,R)-2,3-dimethoxy-N,N,N',N'-tetracyclohexylsuccinamide (8), which has successfully resolved 1,1'- and 2,2'-dihydroxy-9,9'-spirobifluorene, was chosen as inclusion resolving reagent to recrystallize with racemic 7. As expected, (R,R)-8 could selectively recognize (–)-7 in the solution of acetone and formed a white inclusion precipitate, which decomposed in aqueous NaOH to release (–)-7 in 60% ee (Scheme 3). The enantiomerically pure (–)-7 was obtained after repeating the resolution procedure two more times. Elementary analysis of inclusion complex showed that (R,R)-8 and (–)-7 assembled in a 1:1 manner. Unfortunately, the crystal structure of the inclusion complex of [(R,R)-8/(–)-7] was too complicated to determine the absolute configuration of (–)-7. The enantiomerically pure (+)-7 was gained by resolution with (*S*,*S*)-8.



Scheme 3.

For the synthesis of 4,4'-dihydroxy-9,9'-spirobifluorene (**12**), the Kumada coupling of 2-methoxyphenylmagnesium bromide with 1,2-dibromobenzene was first attempted to prepare

the intermediate 2-bromo-2'-methoxy-biphenyl (9), but no reaction took place. Fortunately, the Suzuki coupling reaction of 2-bromophenylboronic acid with 1,2-dibromobenzene catalyzed by Pd(PPh<sub>3</sub>)<sub>4</sub> was found to be an efficient method to give the desired coupling product 9 in 71% yield. Following the procedure used in the synthesis of the dihydroxy-9,9'-spirobifluorenes described above, the diaryl ketone 10 was prepared from biphenyl 9 in 65% yield. However, the ring-closure of biphenyl 9 prompted by MsOH was sluggish at room temperature and 80 °C. When the reaction temperature was increased to 120 °C, the reaction became complicated. Alternatively, the 4,4'-dimethoxy-9,9'-spirobifluorene (11) was successfully achieved in 79% yield when PPA (polyphosphoric acid) was used to replace the MsOH as ring-close reagent. Finally, the treatment of compound 11 with boron tribromide afforded 4,4'-dihydroxy-9,9'-spirobifluorene (12) in high yield (Scheme 4).

The resolution of racemic 12 was unsuccessful by inclusion recrystallization with chiral host molecules such as (R,R)-2,3-dimethoxy-*N*,*N*,*N*',*N*'-tetracyclohexylsuccinamide (8) and N-benzylcinchonidinium chloride. We therefore turned to the direct separation of racemic 12 in preparative chiral HPLC. By using chiral column AD-H two enantiomers of 12 were separated. The absolute configuration of 4,4'dihydroxy-9,9'-spirobifluorene (12) was determined by chemical correlation with (S)-(-)-1,1'-dihydroxy-9,9'-spirobifluorene as illustrated in Scheme 5. The optically pure (S)-(-)-1,1'dihydroxy-9,9'-spirobifluorene  $(13)^9$  was methylated with iodomethane to yield 14, which was brominated in the presence of sodium bromide and hydroperoxide, followed by demethylation to give the (S)-4,4'-dibromo-1,1'-dihydroxy-9,9'-spirobifluorene (16) in 73% yield in three steps. The diol 16 was converted to (S)-1,1'-dihydroxy-4,4'dimethoxy-9,9'-spirobifluorene (17) by reaction with sodium



**Scheme 4.** Reagents and conditions: (a) Pd(PPh<sub>3</sub>)<sub>4</sub>, dioxane, 50 °C, 71%. (b) (i) *n*-BuLi, THF, -78 °C; (ii) MeOCOOMe, THF, 70%. (c) PPA, 150 °C, 79%. (d) BBr<sub>3</sub>, CH<sub>2</sub>Cl<sub>2</sub>, -78 °C to rt, 89%.



Scheme 5. Reagents and conditions: (a) KOH, MeI, water, rt, 4 h, 97%. (b) NaBr, H<sub>2</sub>O<sub>2</sub>, HAc, rt, 10 h, 88%. (c) BBr<sub>3</sub>, CH<sub>2</sub>Cl<sub>2</sub>, -78 °C to rt, 8 h, 85%. (d) NaOMe, CuCl, DMF, 120 °C, 10 h, 59%. (e) Tf<sub>2</sub>O, Py, CH<sub>2</sub>Cl<sub>2</sub>, 0 °C, 70%. (f) Pd/C/H<sub>2</sub>, K<sub>2</sub>CO<sub>3</sub>, *i*-PrOH, 45%. (g) BBr<sub>3</sub>, CH<sub>2</sub>Cl<sub>2</sub>, -78 °C to rt, 73%.

methoxide catalyzed by copper(I) chloride with 59% yield.<sup>12</sup> The esterification of compound **17** with Tf<sub>2</sub>O, followed by palladium-catalyzed hydrogenation and demethylation with BBr<sub>3</sub> finally gave (*S*)-(+)-**12** with 23% yield in three steps (Scheme 5).

### 3. Experimental

### 3.1. General

All reactions and manipulations were performed using standard Schlenk techniques. THF was distilled from sodium benzophenone ketyl. CH<sub>2</sub>Cl<sub>2</sub> was distilled from CaH<sub>2</sub>. Melting points were measured on a RY-I apparatus and uncorrected. <sup>1</sup>H, <sup>13</sup>C and <sup>31</sup>P NMR spectra were recorded on Varian Mercury Vx-300 or Bruker 300 MHz spectrometers. Chemical shifts were reported in parts per million down field from internal Me<sub>4</sub>Si. Optical rotations were determined using a Perkin–Elmer 341 MC polarimeter. Elemental analyses were performed on Yanaca CDRDER MT-3 instrument. Mass spectra were recorded on a VG-7070E spectrometer. HPLC analyses were performed on a Hewlett–Packard Model HP 1100 Series or a Waters 600E.

# **3.2.** Synthesis of racemic 2,2'-dihydroxy-9,9'-spirobifluorene

**3.2.1. Preparation of 2-bromo-4'-methoxybiphenyl (1).** A solution of 4-methoxy-1-bromobenzene (16.6 g, 89 mmol)

in 40 mL of THF was added dropwise to the magnesium scraps under nitrogen atmosphere at 40 °C over 30 min. The reaction mixture was refluxed for 1 h and transferred into a nitrogen flushed flask charged with 1,2-dibromobenzene (20.0 g, 92 mmol) and tetrakis(triphenylphosphine)palladium (1.5 g, 1.3 mmol) in 100 mL of THF. The mixture was stirred for 30 h at 40 °C and quenched with saturated NH<sub>4</sub>Cl solution, diluted with Et<sub>2</sub>O, washed with 3 M HCl and brine, dried over MgSO<sub>4</sub>. Evaporation of the solvent under reduced pressure yielded the crude product that was purified by chromatography on silica gel with PE/EA (30:1, v/v). The product 1 was obtained as a colorless liquid (11.8 g, 50%), which solidified after standing at room temperature. Mp 53–54 °C (lit. 55 °C);<sup>13</sup> <sup>1</sup>H NMR (CDCl<sub>3</sub>)  $\delta$  3.85 (s, 3H, Ar-OCH<sub>3</sub>), 6.96 (d, 2H, J=9 Hz, Ar-H), 7.13-7.19 (m, 1H, Ar-H), 7.31-7.36 (m, 4H, Ar-H), 7.65 (d, 1H, J=7.5 Hz, Ar-H).

3.2.2. Preparation of bis(4'-methoxybiphenyl-2-yl)methanone (2). To a solution of 1 (5.9 g, 22.4 mmol) in 40 mL of THF at -78 °C was added n-BuLi (13.5 mL, 27 mmol, 2.0 M in hexane), and the yellow solution was stirred for another 0.5 h. After slow addition of dimethyl carbonate (0.91 g, 10.1 mmol) in 20 mL of THF, this mixture was gradually warmed to -50 to -45 °C and kept at this temperature for 4 h resulting in a yellow slurry. This slurry was warmed to room temperature and quenched with saturated NH<sub>4</sub>Cl solution. The solvent was then removed under reduced pressure. The residue was dissolved in CH<sub>2</sub>Cl<sub>2</sub>, washed with 3 M HCl and brine, dried over MgSO<sub>4</sub>, concentrated under reduced pressure to afford a yellow solid. The solid was washed with petroleum ether, recrystallized with PE/EA (2:1, v/v) to give 2 as a white solid (2.3 g, 60%). Mp 153-154 °C; <sup>1</sup>H NMR (CDCl<sub>3</sub>) δ 3.76 (s, 6H, Ar-OCH<sub>3</sub>), 6.73 (d, 4H, J=8.7 Hz, Ar-H), 7.03 (d, 4H, J= 8.7 Hz, Ar-H), 7.13 (d, 2H, J=7.8 Hz, Ar-H), 7.18 (t, 2H, J=7.5 Hz, Ar-H), 7.32 (t, 2H, J=7.5 Hz, Ar-H), 7.42 (d, 2H, J=7.5 Hz, Ar-H); <sup>13</sup>C NMR (CDCl<sub>3</sub>)  $\delta$  55.3, 113.4, 126.3, 130.1, 130.6, 130.7, 133.0, 139.1, 141.2, 158.8; MS (ESI) (m/z, %): 386 (M+H<sup>+</sup>, 100%); Anal. Calcd for C<sub>27</sub>H<sub>22</sub>O<sub>3</sub>: C, 82.21; H, 5.62. Found: C, 82.47; H, 5.80.

**3.2.3. Preparation of 2,2'-dihyroxy-9,9'-spirobifluorene** (3). Well-powdered **2** (1.05 g, 3.7 mmol) was added to MsOH (7 mL) and heated at 120 °C for 8 h. The reaction mixture was diluted with water, extracted with EA. The organic phase was dried over Na<sub>2</sub>SO<sub>4</sub> and concentrated to give a brown solid that was subjected to chromatography on silica gel with PE/EA (1:1, v/v) to offer **3** as a white solid (0.65 g, yield 70%). Mp 284–287 °C (lit. 286–287 °C);<sup>7b 1</sup>H NMR (CDCl<sub>3</sub>)  $\delta$  4.77 (s, 2H, OH), 6.17 (s, 2H, Ar-H), 6.71 (d, 2H, *J*=7.5 Hz, Ar-H), 7.33 (t, 2H, *J*=7.5 Hz, Ar-H), 7.67 (d, 2H, *J*=8.4 Hz, Ar-H), 7.73 (d, 2H, *J*=7.5 Hz, Ar-H).

## **3.3.** Synthesis and resolution of racemic 3,3'-dihydroxy-9,9'-spirobifluorene (7)

**3.3.1. Preparation of 3,3'-dimethoxy-9,9'-spirobifluorene** (6).<sup>14</sup> The well-powdered **5** (1.0 g, 2.5 mmol) was added to MsOH (30 mL) and warmed at 35 °C for 3 h. The reaction mixture was poured into ice water and extracted twice with EA. The organic phase was washed with aqueous

Na<sub>2</sub>CO<sub>3</sub>, dried over Na<sub>2</sub>SO<sub>4</sub>, and concentrated. The crude product was chromatographed on silica gel with PE/EA (3:1, v/v) to afford **6** as a white solid (0.92 g, 96%). Mp 187–189 °C; <sup>1</sup>H NMR (CDCl<sub>3</sub>)  $\delta$  3.88 (s, 6H, Ar-OCH<sub>3</sub>), 6.66–6.72 (m, 6H, Ar-H), 7.09 (t, 2H, *J*=7.5 Hz, Ar-H), 7.32–7.37 (m, 4H, Ar-H), 7.79 (d, 2H, *J*=7.5 Hz, Ar-H); <sup>13</sup>C NMR (CDCl<sub>3</sub>)  $\delta$  55.5, 64.7, 105.2, 113.9, 119.9, 123.9, 124.6, 127.5, 127.9, 140.8, 141.5, 143.0, 149.9, 159.8; MS (EI) (*m*/*z*, %): 376 (M<sup>+</sup>, 100%); Anal. Calcd for C<sub>27</sub>H<sub>20</sub>O<sub>2</sub>: C, 86.14; H, 5.36. Found: C, 85.98; H, 5.30.

**3.3.2.** Preparation of 3,3'-dihyroxy-9,9'-spirobifluorene

(7). To a flask charged with 6 (2.9 g, 7.7 mmol) in 40 mL of CH<sub>2</sub>Cl<sub>2</sub> at -78 °C under a nitrogen atmosphere, a solution of BBr<sub>3</sub> (3 mL, 32 mmol) in 10 mL of CH<sub>2</sub>Cl<sub>2</sub> was added dropwise with stirring. After addition, the reaction was spontaneously warmed to room temperature and kept at this temperature for 8 h. The dark solution was washed with NaHSO<sub>3</sub> and NaHCO<sub>3</sub>. The organic phase was dried over Na<sub>2</sub>SO<sub>4</sub> and concentrated under reduced pressure. After chromatography on silica gel with PE/EA (2:1, v/v) product 7 was obtained as a white solid (2.4 g, yield 90%). Mp 237-241 °C; <sup>1</sup>H NMR (CDCl<sub>3</sub>) δ 3.30 (s, 2H, Ar-OH), 6.43 (d, 2H, J=8.4 Hz, Ar-H), 6.55 (d, 2H, J=7.6 Hz, Ar-H), 7.03 (t, 2H, J=7.6 Hz, Ar-H), 7.27–7.35 (m, 4H, Ar-H), 7.77 (d, 2H, J=7.6 Hz, Ar-H); <sup>13</sup>C NMR (CD<sub>3</sub>OD)  $\delta$  64.8. 106.4, 114.9, 119.9, 123.6, 124.3, 127.4, 139.9, 141.8, 143.2, 150.3, 157.4, 127.5; MS (ESI) (m/z, %): 347 (M-H<sup>+</sup>, 60%); Anal. Calcd for C<sub>25</sub>H<sub>20</sub>O<sub>2</sub>: C, 86.19; H, 4.63. Found: C, 85.98; H, 5.03.

3.3.3. Resolution of 3,3'-dihydroxy-9,9'-spirobifluorene (7). To a well-powdered mixture of racemic 7 (500 mg, 1.44 mmol) and (R,R)-2,3-dimethoxy-N,N,N',N'-tetracyclohexylsuccinamide (8) (755 mg, 1.50 mmol) was added 1 mL of acetone to give a clear solution. After a white precipitate appeared a further 1 mL of acetone was added to the mixture and stirred at room temperature for 8 h. The mixture was filtrated and the solid was dissolved in Et<sub>2</sub>O and washed with 1 M NaOH three times. The organic phase was dried over Na<sub>2</sub>SO<sub>4</sub> and concentrated to recover the resolving reagent 8. The aqueous phase was acidified with 12 M HCl to pH=3 and extracted with CH<sub>2</sub>Cl<sub>2</sub> twice. The organic phase was dried over  $Na_2SO_4$  and concentrated to give product 7 as a white solid (0.16 g, 30% recovery). The optical purity was determined to be 60% ee by chiral HPLC [AD-H  $(25 \text{ cm} \times 0.46 \text{ cm i.d.})$ , hexane/2-PrOH = 75:25,  $t_{\text{R}}$  of (+)isomer is 8.9 min,  $t_R$  of (-)-isomer is 17.7 min]. A sample of 7 with predominant (-)-configuration was subjected to the resolution procedure twice to give enantiomerically pure (–)-7 in 15% total recovery. Mp 239–241 °C,  $[\alpha]_D^{25}$ -1.82 (c 0.66, acetone).

# 3.4. Synthesis and resolution of 4,4'-dihydroxy-9,9'-spirobifluorene

**3.4.1. Preparation of 2'-bromo-2-methoxy-biphenyl (9).** To a flask charged with  $Pd(PPh_3)_4$  (0.21 g, 0.19 mmol),  $K_2CO_3$  (2.75 g, 19.9 mmol) was added 6 mL of dioxane and 1,2-dibromobenzene (2.28 g, 9.66 mmol), the mixture was heated at 50 °C and 2-methoxy-1-benzeneboronic acid (1 g, 6.45 mmol, in 6 mL of dioxane) was added over 4 h. The reaction was then quenched with 3 M HCl and extracted

with EA. The organic phase was dried over Na<sub>2</sub>SO<sub>4</sub> and concentrated. After chromatography on silica gel with PE/EA (30:1, v/v), 1.2 g (71% yield) white solid was obtained. Mp 58 °C; <sup>1</sup>H NMR (CDCl<sub>3</sub>)  $\delta$  3.79 (s, 3H, Ar-OCH<sub>3</sub>), 6.97–7.05 (m, 2H, Ar-H), 7.15–7.23 (m, 2H, Ar-H), 7.27– 7.41 (m, 3H, Ar-H), 7.65 (d, 1H, *J*=8.1 Hz, Ar-H); <sup>13</sup>C NMR (CDCl<sub>3</sub>)  $\delta$  55.6, 110.1, 120.3, 124.3, 127.0, 128.6, 129.3, 130.3, 130.8, 131.6, 132.4, 139.8, 156.6; MS (EI) (*m*/*z*, %): 262, 264 (M<sup>+</sup>, 100%); Anal. Calcd for C<sub>13</sub>H<sub>11</sub>BrO: C, 59.34; H, 4.21. Found: C, 59.35; H, 4.10.

3.4.2. Preparation of bis(2'-methoxybiphenyl-2-yl)methanone (10). To a flask charged with 9 (5 g. 19.0 mmol) and 30 mL of THF was added n-BuLi (10 mL, 2.1 M in hexane, 21 mmol) at -78 °C. The mixture was stirred at -78 °C for 20 min, and a solution of dimethyl carbonate (0.727 g, 8.08 mmol) was added dropwise over 5 min. The reaction mixture was allowed to warm to room temperature spontaneously and quenched with aqueous NH<sub>4</sub>Cl. After concentration under reduced pressure the residue was dissolved in CH<sub>2</sub>Cl<sub>2</sub> and washed with 3 M HCl. The organic phase was dried over Na<sub>2</sub>SO<sub>4</sub> and concentrated. The residue was washed with PE/EA (5:1, v/v) to give a pale yellow solid (2.5 g, 70%). Mp 235–237 °C; <sup>1</sup>H NMR (CDCl<sub>3</sub>) δ 3.50 (s, 6H, Ar- $OCH_3$ ), 6.69 (d, 2H, J=7.8 Hz, Ar-H), 6.94 (t, 3H, J=7.5 Hz, Ar-H), 7.14–7.32 (m, 8H, Ar-H), 7.47 (t, 2H, J=7.5 Hz, Ar-H), 7.58 (d, 2H, J=7.2 Hz, Ar-H); <sup>13</sup>C NMR (CDCl<sub>3</sub>) & 54.6, 110.2, 120.8, 126.0, 128.6, 129.9, 130.4, 130.5, 130.7, 131.3, 138.6, 139.3, 155.3; MS (EI) (m/z, %): 394 (M<sup>+</sup>, 35%); Anal. Calcd for C<sub>27</sub>H<sub>22</sub>O<sub>3</sub>: C, 82.21; H, 5.62. Found: C, 82.11; H, 5.57.

3.4.3. Preparation of 4,4'-dimethoxy-9,9'-spirobifluorene (11). To a flask were added PPA (polyphosphoric acid, 20 mL) and bis(2'-methoxybiphenyl-2-yl)methanone (2.0 g, 5.2 mmol). The mixture was heated at 150 °C for 2 h and was poured into ice. The aqueous slurry was extracted with EA. The organic phase was dried over Na<sub>2</sub>SO<sub>4</sub> and concentrated, followed by chromatography on silica gel with PE/EA (4:1, v/v) to afford **11** as a white solid (1.5 g, 79%). Mp 212-213 °C; <sup>1</sup>H NMR (CDCl<sub>3</sub>) δ 4.07 (s, 6H, Ar-OCH<sub>3</sub>), 6.35 (d, 2H, J=7.2 Hz, Ar-H), 6.71 (d, 2H, J=7.5 Hz, Ar-H), 6.87 (d, 2H, J=8.4 Hz, Ar-H), 7.06 (t, 4H, J=7.8 Hz, Ar-H), 7.34 (t, 2H, J=7.5 Hz, Ar-H), 8.18 (d, 2H, J=7.8 Hz, Ar-H); <sup>13</sup>C NMR (CDCl<sub>3</sub>)  $\delta$  55.4, 100.0, 109.6, 116.2, 123.4, 123.7, 126.9, 127.6, 128.8, 141.0, 148.0, 150.6, 155.7; MS (EI) (*m*/*z*, %): 376 (M<sup>+</sup>, 100%); Anal. Calcd for C<sub>27</sub>H<sub>20</sub>O<sub>2</sub>: C, 86.14; H, 5.36. Found: C, 86.08; H, 5.43.

**3.4.4.** Preparation of **4**,4'-dihydroxy-9,9'-spirobifluorene (**12**). To a solution of **11** (1.4 g, 3.8 mmol) in 20 mL of CH<sub>2</sub>Cl<sub>2</sub> at -78 °C under nitrogen atmosphere was added BBr<sub>3</sub> (1.4 mL, 14 mmol) in 10 mL of CH<sub>2</sub>Cl<sub>2</sub>. The mixture was allowed to warm to ambient temperature spontaneously and washed with aqueous NaHSO<sub>3</sub> and NaHCO<sub>3</sub>, dried over Na<sub>2</sub>SO<sub>4</sub>, and concentrated. The residue was subjected to chromatography on silica gel with PE/EA (2:1, v/v) to give **12** as a pale yellow solid (1.2 g, 89%). Mp 125–127 °C; <sup>1</sup>H NMR (CDCl<sub>3</sub>)  $\delta$  5.43 (s, 2H, Ar-OH), 6.34 (d, 2H, *J*=7.5 Hz, Ar-H), 6.71–6.74 (m, 4H, Ar-H), 6.96 (t, 2H, *J*=7.8 Hz, Ar-H), 7.08 (t, 2H, *J*=7.5 Hz, Ar-H); <sup>13</sup>C

NMR (CDCl<sub>3</sub>)  $\delta$  30.9, 114.8, 116.5, 123.5, 123.6, 127.0, 127.7, 128.4, 128.6, 140,7, 148,1, 151.2, 151.1; MS (ESI) (*m*/*z*, %): 347 (M–H<sup>+</sup>, 30%); Anal. Calcd for C<sub>25</sub>H<sub>16</sub>O<sub>2</sub>: C, 86.10; H, 4.63. Found: C, 85.95; H, 4.69.

**3.4.5. Resolution of 4,4'-dihyroxy-9,9'-spirobifluorene** (12). The racemic sample of 11 was directly subjected to HPLC resolution with a preparative Daicel AD-H column [HPLC conditions: hexane/2-PrOH = 85:15 (v/v); fluent rate, 3 mL/min;  $t_{\rm R}$  of (+)-isomer is 12.9 min,  $t_{\rm R}$  of (-)-isomer is 15.5 min]. The first peak corresponded to (+)-11. Mp 125–127 °C,  $[\alpha]_{\rm D}^{25}$  +2.7 (*c* 1.7, acetone).

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#### **References and notes**

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- 14. For the syntheses of compounds **4** and **5**, see Ref. 9 and its supporting information.