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Enantiopure Double-Helical Phenylene Ethynylene Cyclophynes with the 2,2′-Binaphthyl Template

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Abstract: New types of enantiopure compounds were synthesized to gain better insight into the structural features of phenylene ethynylene cyclophynes. Besides the previously obtained *meta*-substituted arylene ethynylenes, **1**, *ortho*-connected phenylene ethynylene units were incorporated to give cyclophynes with *ortho*/*meta* and *ortho*/*ortho* connection modes, **2** and **3**. Furthermore, a diphenylethyne component was also accommodated in **4**. Both ab initio calculations and NMR spectra suggest a large amount of strain for **2** but less strain for **3** and **1a**, the latter having the smallest ring size among cyclophynes with the *meta/meta* connection mode. The CD spectra of **2** and **3** showed a characteristic shoulder at around 340 nm, similar to the case of **1a**. This implies that the aromatic acetylene bonds cross over each other in the double-helical structure. These results indicate that chirality information is useful for probing the persistency of molecular shape.

Keywords: acetylenes · chirality · cyclophanes · cyclophynes · helical structures

Introduction

Modern cyclophane chemistry has witnessed great advances in its acetylenic family, cyclophynes, in the context of growing interest in carbon-rich materials and shape-persistent macrocyclic molecules.[1] In particular, numerous aromatic cyclophynes have appeared owing to rapidly developed technology for the synthesis of aromatic acetylenes. Some of these molecules are chiral but, unfortunately, obtained as racemates except for only a few.[2] Previously, we synthesized double-helical cyclophynes composed of *meta*-connected phenylene ethynylene frameworks with 2,2′-binaphthyl templates such as (*R*,*P*)-**1a** and -**1b**.[3] The CD spectra of these molecules displayed dramatic variations of the Cotton effect that depended on ring size, thus implying that molecular chirality, once enantiopure materials have been acquired, can provide a probe for the persistency of molecular shape. Accordingly, we were intrigued by the design of other cyclophynes with double helicity in enantiopure form. In phenylene ethynylene cyclophynes, the substitution pattern of the aromatic rings directs the orientation of the acetylenic bonds, thereby defining the molecular structure and its persistency. In this study, the *ortho* connection of the ethynyl groups on the phenylene ring was newly taken into account to give (*R*,*P*)-**2** and -**3**. Furthermore, a diphenylethyne component was also accommodated to provide (*R*,*P*)- and (*S*,*M*)-**4**. The shape persistency of these compounds, together with **1** for comparison, will be discussed on the basis of the NMR and CD spectra.

Resuls and Discussion

The synthesis of (*R*,*P*)-**2** and -**3** is shown in Scheme 1. *meta*-Substituted phenylethynyl compounds **8a** and **9a** were prepared according to our previous method.[3] The corresponding *ortho*-substituted derivatives, **8b** and **9b**, were obtained analogously. Desilylation of **8a** and **8b** afforded *meta*- and *ortho*-triazenes **10a** and **10b**, respectively. Next, coupling of **9a** or **9b** with **10b** afforded **11a** or **11b**. Conversion of tri-

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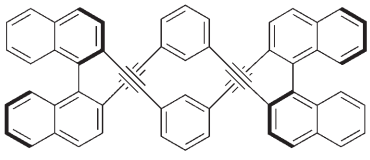
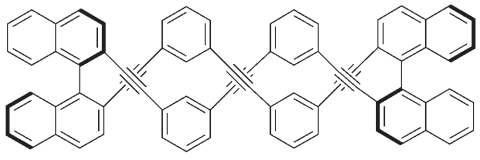


(*R*,*P*)-**1a**



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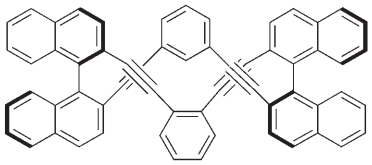
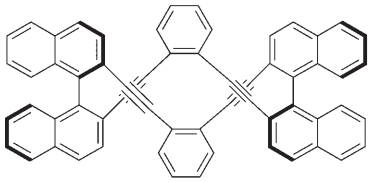
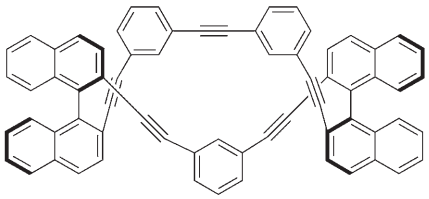


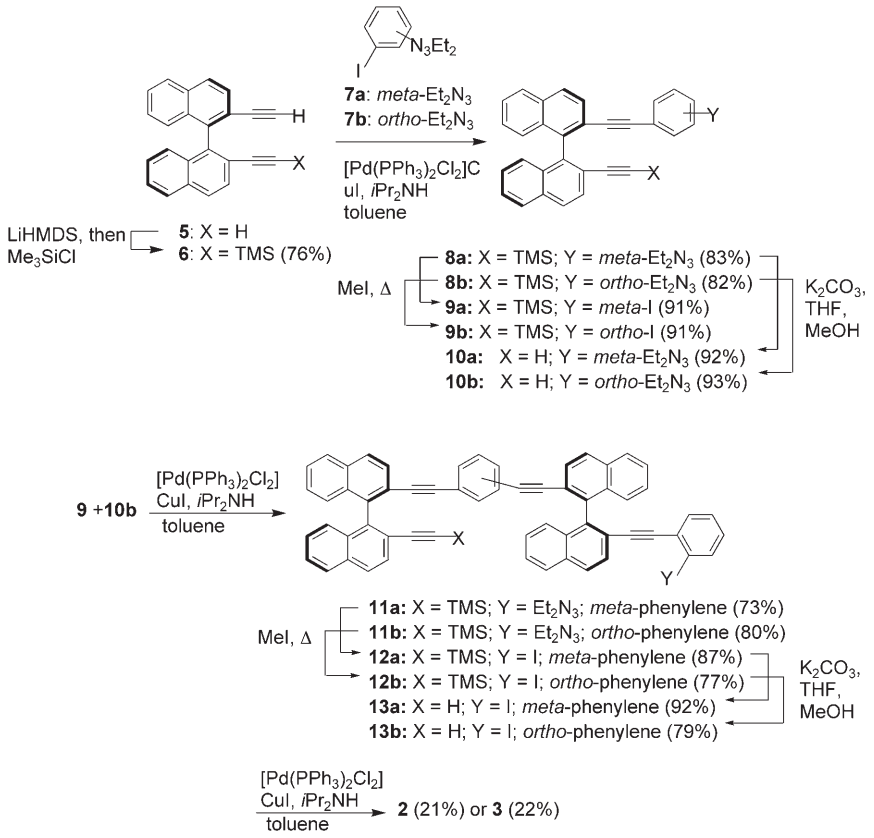
(*R*,*P*)-**2**



(*R*,*P*)-**3**



(*R*,*P*)-**4**



Scheme 1. Synthesis of (*R*,*P*)-**2** and -**3**. LiHMDS = lithium hexamethyldisilazide, TMS = trimethylsilyl.

azenes **11a** and **11b** into iodides **12a** and **12b** followed by desilyation afforded precursors **13a** and **13b**, respectively. Subjection of these compounds to intramolecular cyclization afforded (*R*,*P*)-**2** and (*R*,*P*)-**3**.

Diphenylethyne-containing (*R*,*P*)- and (*S*,*M*)-**4** were prepared according to the procedures shown in Scheme 2. Reaction of **6** with building block **15** afforded **16**, which was then converted into iodide **17**. Coupling between **10a** and **17** followed by the usual transformations via **18** and **19** afforded precursor **20**. Subjection of (*R*)- and (*S*)-**20** to intramolecular coupling afforded (*R*,*P*)- and (*S*,*M*)-**4**, respectively.

The molecular structures of **1a**, **2**, and **3** were calculated at the HF/6-31G* level.[4] The results are summarized in Table 1, and the space-filling models are shown in Figure 1. Corey–Pauling–Koltun (CPK) models of these compounds suggest very slight flexibility arising from fluttering of the dihedral angle between the biphenyl faces, although **2** is more rigid than the others. This is in accord with the smaller enthalpy of formation of **2** relative to **1a** and **3**. Apparently, **2** is more strained because of unsymmetrical *ortho*/*meta* mixed connecting modes; this is reflected in the bond angles of the C(sp) atoms, which are smaller for **2** (169.7–174.5°) than for **1a** and **3** (174.0–177.8°). At first glance, it seemed to us that the conformation of **3** with *ortho*/*ortho* connections might be tightest, but this is not the case because of the high molecular symmetry. This indicates clearly that the persistency of molecular shape is not only governed by the connectivity; the symmetry of the whole molecule plays a more important role. Accordingly, it is quite natural that **1a**, which bears symmetrical *meta*/*meta* connections, has the most relaxed conformation of the three compounds.

The NMR spectral data are in good agreement with the above calculations. As summarized in Table 2, the ^{13}C NMR spectra showed acetylenic carbon signals between 89.6 and

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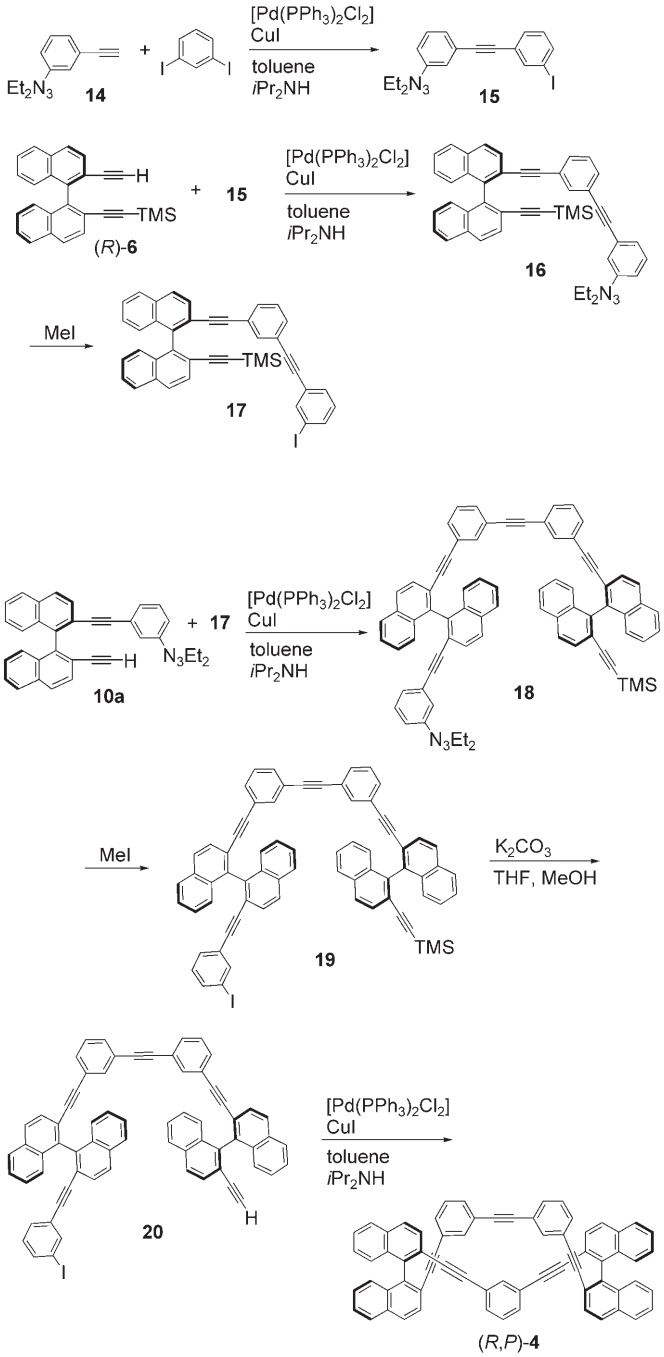

Scheme 2. Synthesis of (*R*,*P*)- and (*S*,*M*)-**4**.

Table 1. Differences in enthalpy of formation and bond angles calculated at the HF/6-31G* level.

Compound	$\Delta\Delta H$[a] [kcal mol^{-1}]	C(sp) bond angles [°]
1a	0	173.9, 173.9, 174.9, 174.9, 175.5, 175.5, 174.9, 175.0
2	+4.69	169.7, 169.7, 171.5, 171.5, 172.9, 173.0, 174.4, 174.5
3	+0.80	175.2, 175.2, 175.8, 175.8, 175.9, 175.9, 177.8, 177.8

[a] Relative to **1a**.

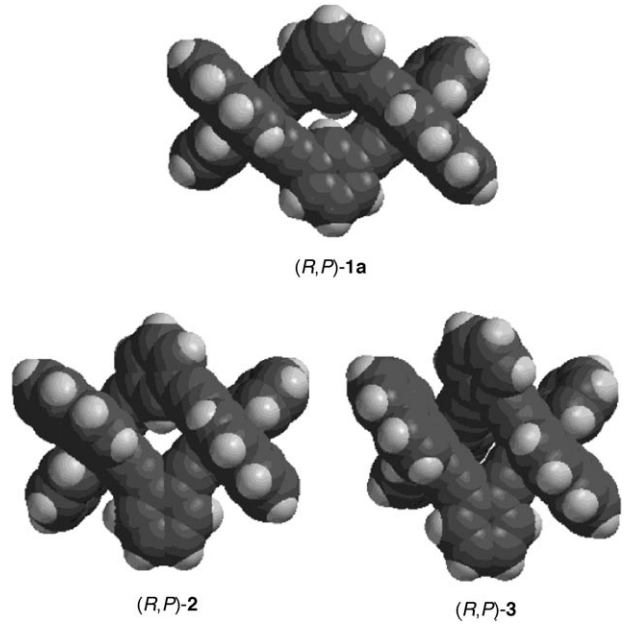

Figure 1. Space-filling models of **1a**, **2**, and **3**.

Table 2. Representative ^{1}H NMR chemical shifts (ppm) of **1a**, **1b**, **2**, **3**, and **4**.

Compound	*ortho*-H	Acetylenic carbon atoms
1a	7.92[3a]	90.4, 92.1[3a]
1b	7.49[3b]	89.1, 89.7, 92.1[3b]
2	7.51	92.1, 92.2, 93.2, 94.2
3		91.4, 92.3
4	7.64	89.6, 89.7, 89.9, 91.7, 91.8

92.3 ppm for **3** and **4**. Moreover, **1a** and **1b** also gave similar results (89.1–92.1 ppm). On the other hand, the acetylenic carbon nuclei of **2** resonated at higher frequency (92.1–94.2 ppm). This is reminiscent of bent atomic arrangements around acetylenic carbon atoms induced by the strained structure.[5] The ^{1}H NMR signal of the proton located at the double-*ortho* position in the *meta*-connected phenylene is also diagnostic of the molecular structures. A singlet appeared at 7.51 and 7.64 ppm in **2** and **4**, respectively, whereas **1a** exhibited this signal at 7.92 ppm. Clearly, the proton in **1a** is situated closer to the phenyl ring of another chain, thus undergoing paramagnetic deshielding effectively. X-ray crystallography[3a] as well as the above molecular modeling show that the central benzene rings in **1** are somewhat tilted from planarity due to the close contact of the protons at the double-*ortho* position.

The CD spectra of the relevant compounds are illustrated in Figure 2. A strong positive band appeared at around 300 nm for the *R*,*P* enantiomers of **1a**, **2**, and **3**. Furthermore, a shoulder can also be seen in the longer-wavelength region (330–340 nm). Previously, we disclosed that the positive band in this region is attributable to aromatic acetylenic bonds that cross each other in the *P* helicity.[6]

In contrast, a negative band appeared at around 340 nm for (*R*,*P*)-**4**, as was also observed for (*R*,*P*)-**1b**.[3b] We also

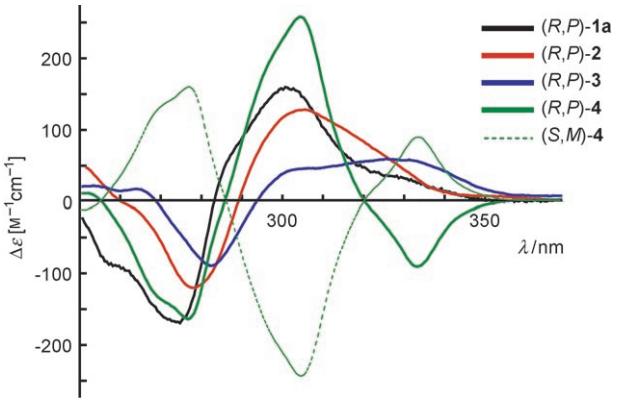

Figure 2. CD spectra of (*R*,*P*)-**1a**, -**2**, and -**3**, as well as (*R*,*P*)- and (*S*,*M*)-**4**.

disclosed that such alteration is a result of loose arylene ethynylene macrocycles that do not bear fixed crossing aromatic acetylenic bonds.[3b] As the magnitude of the negative band of (*R*,*P*)-**4** is comparable to that of (*R*,*P*)-**1b** and is much smaller than those of the higher homologues with 52- and 62-membered cycles,[3b] the structure of (*R*,*P*)-**4** is not completely flexible but strained to some degree. Of further note is the perfect reversal of the CD spectrum of (*S*,*M*)-**4**, which is indicative of the enantiopurity of the compounds obtained here.

Conclusions

We have synthesized novel phenylene ethynylene cyclophynes in enantiopure form. On the basis of ab initio calculations, the *ortho* connection of ethynyl groups on the benzene ring has proved, as expected, to induce a more rigid structure than *meta* connection. However, it was found that molecular symmetry contributes a greater extent to the structure and causes the unsymmetrical *ortho/meta* mixed connecting modes to be most strained. The strained sp-hybridized carbon atoms were explicitly detected by means of ^{13}C NMR spectra. More interestingly, a slight difference in shape persistency between these molecules was detected by CD spectroscopy. In other words, the high sensitivity of CD spectroscopy is promising for probing molecular persistency.

Experimental Section

General

All reactions were carried out under an atmosphere of nitrogen with freshly distilled solvents, unless otherwise noted. Melting points were determined with a Taike XT-4 micromelting-point apparatus and are uncorrected. THF was distilled from sodium/benzophenone. Other solvents such as toluene and diisopropylamine were distilled from CaH_2. A solution of BuLi in hexane was purchased from Aldrich and titrated before use by the Gilman method. $[Pd(PPh_3)_2Cl_2]$ was purchased from Merck. NMR spectra were recorded on Varian INOVA-400 or JEOL Lambda 500 instruments with tetramethylsilane as an internal reference. Mass spectra were recorded on an LCQ-Advantage LC/MS^n (atmospheric pressure chemical ionization (APCI), Thermo-Finnigan) mass spectrometer. Optical rotations were obtained on a JASO P-1010 polarimeter. UV/Vis and CD spectra were recorded on LabTech UV-2000/2100 and JASO J-820 spectrometers, respectively. IR spectra were recorded on a WQF-410 spectrometer.

Syntheses

Compounds **5**, **6**, **7**, **8a**, and **9a** were prepared according to the previously published procedures.[3] The synthetic procedures for **11b**, **12b**, **13b**, and **15**–**20** are given in the Supporting Information.

8b: A 100-mL flask was charged with **6** (743 mg, 1.98 mmol), **7b** (500 mg, 1.65 mmol), $[(Ph_3P)_2PdCl_2]$ (42 mg, 0.06 mmol), CuI (11 mg, 0.06 mmol), diisopropylamine (8 mL), and toluene (30 mL). After the mixture was stirred at 80 °C for 11 h, it was cooled to room temperature and filtered. The filtrate was poured into aqueous NH_4Cl and extracted with ethyl acetate. The extract was then washed with brine, dried over $MgSO_4$, and filtered. The solvent was evaporated in vacuo, and the residue was subjected to chromatography (SiO_2, hexane/CH_2Cl_2 = 2:1) to give **8b** (743 mg, 82 %) as a yellow solid. M.p.: 132–133 °C; $[\alpha]_D^{26.7} = +498.7$ (c = 0.1 M, $CHCl_3$) for *R* enantiomer; IR (KBr): $\tilde{\nu}$ = 2927 (C_{arom}–H), 2145 (C≡C), 1398, 1086, 849, 750 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz): $\delta = -0.30$ (s, 9H, TMS), 1.32 (t, J = 7.2 Hz, 6H), 3.77 (q, J = 7.2 Hz, 4H), 6.13 (d, J = 7.2 Hz, 1H), 6.76 (t, J = 7.2 Hz, 1H), 7.07 (t, J = 8.0 Hz, 1H), 7.23 (d, J = 8.0 Hz, 1H), 7.28–7.31 (m, 3H), 7.40 (d, J = 8.4 Hz, 1H), 7.44–7.49 (m, 2H), 7.67 (d, J = 8.4 Hz, 1H), 7.69 (d, J = 7.6 Hz, 1H), 7.90 (d, J = 8.4 Hz, 2H), 7.93 ppm (d, J = 8.4 Hz, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz): $\delta = -0.71$ (TMS), 10.2 (CH_3), 14.4 (CH_3), 41.0 (CH_2), 48.4 (CH_2), 92.4 (C≡), 93.2 (C≡), 98.5 (C≡), 104.9 (C≡), 116.5 (CH), 118.2 (C), 121.5 (C), 122.3 (C), 124.3 (CH), 126.0 (CH), 126.4 (CH), 126.5 (CH), 126.5 (CH), 126.6 (CH), 126.9 (CH), 127.6 (CH), 127.7 (CH), 127.8 (CH), 127.9 (CH), 128.0 (CH), 128.3 (CH), 128.4 (CH), 132.5 (C), 132.7 (C), 132.8 (C), 133.0 (CCH), 139.6 (C), 141.4 (C), 151.5 ppm (C); MS (APCI): m/z (%) = 550.0 $[M+1]^+$ (100), 551.0 $[M+2]^+$ (42), 552.0 $[M+3]^+$ (16).

9b: A 50-mL sealed tube was charged with **8b** (319 mg, 0.58 mmol) and methyl iodide (30 mL). The solution was kept at 120 °C for 20 h. The reaction mixture was filtered and then evaporated. The residue was subjected to chromatography (SiO_2, hexane/CH_2Cl_2 = 5:1) to give **9b** (304 mg, 91 %) as a pale-yellow solid. M.p.: 48–49 °C; $[\alpha]_D^{26.2} = +510.6$ (c = 0.1 M, $CHCl_3$) for *R* enantiomer; IR (KBr): $\tilde{\nu}$ = 3055 (C_{arom}–H), 2954, 2146 (C≡C), 1587 (C_{arom}–C), 1248, 845, 748 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz): $\delta = -0.26$ (s, 9H, TMS), 6.79 (d, J = 8.0 Hz, 1H), 6.82 (t, J = 8.0 Hz, 1H), 7.09 (t, J = 7.6 Hz, 1H), 7.24 (d, J = 8.8 Hz, 1H), 7.30 (d, J = 7.6 Hz, 1H), 7.35 (t, J = 8.0 Hz, 2H), 7.46 (t, J = 8.4 Hz, 1H), 7.48 (t, J = 8.4 Hz, 1H), 7.63 (d, J = 8.0 Hz, 1H), 7.67 (d, J = 8.4 Hz, 1H), 7.82 (d, J = 8.4 Hz, 1H), 7.90 (d, J = 7.6 Hz, 2H), 7.94 ppm (d, J = 8.8 Hz, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz): $\delta = -0.65$ (TMS), 92.9 (C≡), 94.6 (C≡), 98.9 (C≡), 99.8 (C≡), 104.7 (C), 121.1 (2C), 121.7 (C), 126.5 (CH), 126.6 (CH), 126.6 (CH), 126.6 (CH), 126.8 (CH), 126.8 (CH), 127.3 (CH), 127.8 (CH), 127.9 (CH), 127.9 (CH), 127.9 (CH), 128.2 (CH), 128.6 (CH), 128.9 (CH), 130.0 (C), 132.6 (CH), 132.8 (C), 133.2 (C), 133.3 (C), 138.3 (CH), 140.0 (C), 141.1 ppm (C); MS (APCI): m/z (%) = 577.0 $[M+1]^+$ (100), 578.0 $[M+2]^+$ (37), 579.1 $[M+3]^+$ (14).

10a: A 50-mL flask was charged with **8a** (250 mg, 0.5 mmol), K_2CO_3 (632 mg, 5 mol), THF (10 mL), and methanol (10 mL). The resulting mixture was stirred at room temperature for 5 h. The reaction mixture was poured into water and extracted with ethyl acetate, and the organic layer was dried over $MgSO_4$ and filtered. The solvent was evaporated, and the residue was subjected to chromatography (SiO_2, hexane/CH_2Cl_2 = 5: 1) to give **10a** (200 mg, 92 %) as a pale-yellow oil. ^{1}H NMR ($CDCl_3$ 500 MHz): δ = 1.25 (br s, 6H, 2×CH_3), 2.77 (s, 1H, C≡CH), 3.73 (q, J = 7.02 Hz, 4H, 2×CH_2), 6.53 (d, J = 7.65 Hz, 1H), 6.94 (s, 1H), 7.05 (t, J = 7.80 Hz, 1H), 7.19–7.32 (m, 5H), 7.45–7.49 (m, 2H), 7.74–7.77 (m, 2H), 7.90–7.95 ppm (m, 4H); ^{13}C NMR ($CDCl_3$ 125 MHz): δ = 11.7 (CH_3), 13.7 (CH_3), 41.0 (CH_2), 48.4 (CH_2), 80.7 (CH≡), 82.8 (C≡), 88.6 (C≡), 94.0 (C≡), 120.4 (C), 120.5 (CH), 121.6 (C), 122.9 (CH), 123.3 (C), 126.1 (CH), 126.3 (CH), 126.4 (CH), 126.5(8) (CH), 126.6(5) (CH), 126.7 (CH), 127.8 (CH), 127.9 (CH), 127.9 (CH), 128.0 (CH), 128.0 (CH),

128.1 (CH), 128.3 (CH), 128.8 (CH), 132.4 (2 C), 132.7 (C), 133.0 (C), 139.6 (C), 140.7 (C), 150.7 ppm (C).

10b: A round-bottomed flask was charged with **8b** (682 mg, 1.24 mmol), K_2CO_3 (497 mg, 3.6 mmol), THF (30 mL), and methanol (30 mL). The resulting mixture was stirred at room temperature for 1.5 h. The reaction mixture was poured into water and extracted with ethyl acetate, and the organic layer was dried over $MgSO_4$ and filtered. The solvent was evaporated, and the residue was subjected to chromatography (SiO_2, hexane/CH_2Cl_2=3:1) to give **10b** (550 mg, 93%) as a yellow powder. M.p.: 178–180°C; $[\alpha]_D^{26.6}=+456.7$ ($c=0.1$ M, $CHCl_3$) for *R* enantiomer; IR (KBr): $\tilde{\nu}=3309$ (C≡C–H), 2970 (C_{arom}–H), 2198 (C≡C), 1398, 1090, 822, 752 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz): $\delta=1.32$ (t, $J=7.2$ Hz, 6H), 3.77 (q, $J=7.2$ Hz, 4H), 6.30 (d, $J=7.6$ Hz, 1H), 6.79 (t, $J=7.6$ Hz, 1H), 7.09 (t, $J=7.6$ Hz, 1H), 7.24 (d, $J=7.6$ Hz, 1H), 7.24 (d, $J=8.8$ Hz, 2H), 7.29 (t, $J=7.6$ Hz, 1H), 7.31 (t, $J=7.2$ Hz, 1H), 7.47 (t, $J=8.0$ Hz, 2H), 7.72 (d, $J=8.8$ Hz, 1H), 7.75 (d, $J=8.4$ Hz, 1H), 7.91 (d, $J=8.0$ Hz, 1H), 7.91 ppm (d, $J=8.4$ Hz, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz) $\delta=10.2$ (CH_3), 14.4 (CH_3), 41.0 (CH_2), 48.4 (CH_2), 80.5 (CH≡), 83.0 (C≡), 92.6 (C≡), 92.9 (C≡), 116.6 (CH), 118.1 (C), 120.6 (C), 122.5 (C), 124.4 (CH), 126.2 (CH), 126.3 (CH), 126.6 (CH), 126.7 (CH), 126.7 (CH), 126.8 (CH), 127.9 (CH), 127.9 (CH), 127.9 (CH), 128.0 (CH), 128.4 (CH), 128.6 (CH), 128.9 (CH), 132.6 (2×C), 132.7 (C), 133.1 (CH), 133.1 (C), 139.2 (C), 141.0 (C), 151.6 ppm (C); MS (APCI): *m/z* (%)=377.3 $[M-N_3Et_2]^+$ (100), 478.1 $[M+1]^+$ (72), 479.1 $[M+2]^+$ (23).

11a: A 100-mL flask was charged with **9a** (242 mg, 0.42 mmol), **10b** (229 mg, 0.48 mmol), $[(Ph_3P)_2PdCl_2]$ (11 mg, 0.016 mmol), CuI (3 mg, 0.016 mmol), diisopropylamine (5 mL), and toluene (20 mL). After the mixture was stirred at 80°C for 15 h, it was cooled to room temperature and filtered. The filtrate was poured into aqueous NH_4Cl and extracted with ethyl acetate. The extract was then washed with brine, dried over $MgSO_4$, and filtered. The solvent was evaporated in vacuo, and the residue was subjected to chromatography (SiO_2, hexane/CH_2Cl_2=3:1) to give **11a** (287 mg, 73%) as a yellow solid. M.p.: 101–102°C; $[\alpha]_D^{269.5}=+104.5$ ($c=0.1$ M, $CHCl_3$) for *R* enantiomer; IR (KBr): $\tilde{\nu}=3442$, 3057 (C_{arom}–H), 2960, 2204, 2146 (C≡C), 1593 (C_{arom}–C), 1408, 1248, 818, 750, 688 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz): $\delta=-0.28$ (s, 9H), 1.27 (t, $J=7.6$ Hz, 6H), 3.73 (q, $J=7.6$ Hz, 4H), 6.23 (d, $J=7.6$ Hz, 1H), 6.28 (s, 1H), 6.40 (d, $J=8.0$ Hz, 1H), 6.43 (d, $J=7.2$ Hz, 1H), 6.78 (t, $J=7.6$ Hz, 2H), 7.08 (t, $J=7.6$ Hz, 1H), 7.24 (d, $J=7.6$ Hz, 1H), 7.25–7.34 (m, 8H), 7.39–7.50 (m, 4H), 7.65 (d, $J=8.0$ Hz, 1H), 7.70–7.77 (m, 3H), 7.82–8.00 ppm (m, 8H); ^{13}C NMR ($CDCl_3$, 100 MHz): $\delta=11.1$ (CH_3), 14.8 (CH_3), 41.9 (CH_2), 48.8 (CH_2), 89.7 (C≡), 89.9 (C≡), 92.6 (C≡), 92.6 (C≡), 92.7 (C≡), 93.1 (C≡), 98.7 (C≡), 104.8 (C≡), 116.7 (CH), 118.2 (C), 121.3 (C), 121.4 (C), 121.5 (C), 122.6 (C), 123.0 (C), 123.2 (C), 124.3 (CH), 126.2 (CH), 126.4 (CH), 126.5 (4×CH), 126.6 (3×CH), 126.7(CH), 126.9 (CH), 127.5 (CH), 127.6 (CH), 127.8 (2CH), 127.9 (2CH), 127.9 (2CH), 128.0 (2×CH), 128.0 (2CH), 128.2 (CH), 128.4 (CH), 128.5 (CH), 130.4 (CH), 130.7 (CH), 132.4 (C), 132.6 (C), 132.7 (C), 132.7 (C), 132.8 (C), 133.0 (CH, 2×C), 133.6 (CH), 133.7 (C), 139.6 (C), 140.3 (C), 140.4 (C), 141.1 (C), 151.7 ppm (C); MS (APCI): *m/z* (%)=926.3 $[M+1]^+$ (79), 927.4 $[M+2]^+$ (100), 928.4 $[M+3]^+$ (52), 929.4 $[M+4]^+$ (27), 930.4 $[M+5]^+$ (16).

12a: A 50-mL sealed tube was charged with **11a** (259 mg, 0.28 mmol) and methyl iodide (30 mL). The solution was kept at 120°C for 20 h. The reaction mixture was filtered and then evaporated. The residue was subjected to chromatography (SiO_2, hexane/CH_2Cl_2=5:1) to give **12a** (230 mg, 87%) as a pale-yellow solid. M.p.: 119–120°C; $[\alpha]_D^{25.0}=+349.0$ ($c=0.1$ M, $CHCl_3$) for *R* enantiomer; IR (KBr): $\tilde{\nu}=3437$, 3057 (C_{arom}–H), 2956, 2146 (C≡C), 1593 (C_{arom}–C), 1502, 1250, 818, 748, 685 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz): $\delta=10.28$ (s, 3H, TMS), 6.33 (s, 1H), 6.41 (d, $J=8.0$ Hz, 1H), 6.47 (d, $J=7.6$ Hz, 1H), 6.79 (t, $J=7.6$ Hz, 1H), 6.81 (t, $J=7.6$ Hz, 1H), 6.84 (d, $J=8.0$ Hz, 1H), 7.09 (t, $J=7.6$ Hz, 1H), 7.24–7.37 (m, 8H), 7.41–7.49 (m, 4H), 7.62 (d, $J=8.0$ Hz, 1H), 7.65 (d, $J=8.4$ Hz, 1H), 7.71 (d, $J=8.4$ Hz, 1H), 7.75 (d, $J=8.8$ Hz, 1H), 7.84 (d, $J=8.4$ Hz, 1H), 7.87 (d, $J=8.4$ Hz, 2H), 7.90–7.97 (m, 5H); ^{13}C NMR ($CDCl_3$, 100 MHz): $\delta=-0.66$ (TMS), 89.7 (C≡), 89.8 (C≡), 91.1 (C≡), 92.6 (C≡), 92.9 (C≡), 94.9 (C≡), 98.8 (C≡), 99.8 (C≡), 104.8 (C), 121.3 (C), 121.3 (C), 121.5 (C), 121.7 (C), 123.1 (C), 123.1(2) (C), 126.4 (CH), 126.5 (2×CH), 126.6 (2×CH), 126.6 (2×CH), 126.6(7) (2×CH), 126.7(7) (CH), 126.8 (CH), 126.9 (CH), 127.4 (CH), 127.6 (CH), 127.8 (CH), 127.9 (2×CH), 128.0 (CH), 128.0 (3×CH), 128.1 (4×CH), 128.5 (CH), 128.7 (CH), 128.9 (CH), 130.6 (CH), 130.6 (CH), 132.5 (C), 132.7 (C), 132.7 (2×C), 133.0 (C), 133.0 (C), 133.1 (C), 133.2 (C), 133.3 (C), 133.7 (CH), 138.4 (CH, C), 139.9 (C), 140.3 (C), 140.4 (C), 141.1 (C); MS (APCI): *m/z* (%)=952.2 $[M]^+$ (31), 953.1 $[M+1]^+$ (100), 954.1 $[M+2]^+$ (60), 955.1 $[M+3]^+$ (21).

13a: A round-bottomed flask was charged with **12a** (213 mg, 0.22 mmol), K_2CO_3 (230 mg, 2.1 mmol), THF (30 mL), and methanol (30 mL). The resulting mixture was stirred at room temperature for 1 h. The reaction mixture was poured into water and extracted with ethyl acetate, and the organic layer was dried over $MgSO_4$ and filtered. The solvent was evaporated, and the residue was subjected to chromatography (SiO_2, hexane/CH_2Cl_2=4:1) to give **13a** (181 mg, 92%) as a yellow powder. M.p.: 122–123°C; $[\alpha]_D^{25.0}=+295.6$ ($c=0.1$ M, $CHCl_3$) for *R* enantiomer; IR (KBr): $\tilde{\nu}=3464$, 3286 (C≡C–H), 3055 (C_{arom}–H), 2204 (C≡C), 1593 (C_{arom}–C), 1502, 818, 748 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz): $\delta=2.78$ (s, 1H, CH≡), 6.40 (s, 1H), 6.49 (d, $J=7.6$ Hz, 1H), 6.49 (d, $J=8.0$ Hz, 1H), 6.82 (d, $J=8.0$ Hz, 2H), 6.85 (d, $J=8.0$ Hz, 1H), 7.10 (td, $J=7.6$, 1.2 Hz, 1H), 7.18 (d, $J=8.8$ Hz, 1H), 7.24–7.35 (m, 8H), 7.43–7.51 (m, 4H), 7.63 (d, $J=8.0$ Hz, 1H), 7.72 (d, $J=8.4$ Hz, 1H), 7.73 (d, $J=8.8$ Hz, 1H), 7.75 (d, $J=8.4$ Hz, 1H), 7.84 (d, $J=8.4$ Hz, 1H), 7.88–7.98 ppm (m, 7H); ^{13}C NMR ($CDCl_3$, 100 MHz): $\delta=80.6$ (C≡), 80.6 (C≡), 82.8 (C≡), 89.4 (C≡), 89.7 (CH≡), 92.7 (C≡), 92.8 (C≡), 92.8 (C≡), 94.9 (C), 99.8 (C), 120.5 (C), 121.3 (C), 121.4 (C), 121.7 (C), 123.0 (C), 123.1 (C), 126.4 (CH), 126.5 (CH), 126.5 (2×CH), 126.6 (CH), 126.7 (CH), 126.7 (CH), 126.8 (4×CH), 126.9 (CH), 127.4 (CH), 126.7 (CH), 128.0 (CH), 128.1 (5×CH), 128.1 (CH), 128.2 (CH), 128.5 (CH), 128.7 (CH), 128.9 (2×CH), 130.7 (CH), 130.8 (CH), 132.4 (C), 132.5 (C), 132.6 (C), 132.7 (2×C), 133.0 (C), 133.2 (C), 133.3 (C), 133.8 (CH), 138.4 (CH), 140.0 (2×C), 140.3 (C), 140.7 ppm (C); MS (APCI): *m/z* (%)=881.0 $[M+1]^+$ (100), 882.0 $[M+2]^+$ (49).

2: A 100-mL two-necked flask was charged with $[(Ph_3P)_2PdCl_2]$ (14 mg, 0.02 mmol), CuI (4 mg, 0.02 mmol), diisopropylamine (8 mL), and toluene (40 mL). A solution of **13a** (90 mg, 0.10 mmol) in diisopropylamine (5 mL) and toluene (20 mL) was added to the above suspension over a period of 30 h at 80°C by a machine. The reaction mixture was cooled to room temperature and filtered. The filtrate was poured into aqueous NH_4Cl and extracted with ethyl acetate. The extract was then washed with brine, dried over $MgSO_4$, and filtered. The solvent was evaporated in vacuo, and the residue was subjected to chromatography (SiO_2, hexane/CH_2Cl_2=4:1) to give **2** (21 mg, 21%) as a pale-yellow powder. M.p.: 212–214°C; $[\alpha]_D^{32.0}=+682.3$ ($c=0.1$ M, $CHCl_3$) for *R,P* enantiomer; UV/Vis ($CHCl_3$, 1.0×10^{-5} mol L^{-1}): λ_{max} (ε_{max})=242 (9.4×10^4), 252 (9.2×10^4), 276 (6.5×10^4), 306 nm (4.6×10^4 $M^{-1}cm^{-1}$); UV/Vis ($CHCl_3$, 2.7×10^{-6} mol L^{-1}): λ_{max} (ε_{max})=242 (1.1×10^5), 253 (1.1×10^5), 276 (7.8×10^4), 306 nm (5.6×10^4 $M^{-1}cm^{-1}$); IR (KBr): $\tilde{\nu}=3433$, 2924 (C_{arom}–H), 2197 (C≡C), 1588 (C_{arom}–C), 1460, 818, 748 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz): $\delta=6.71$–6.74 (m, 2H), 6.75 (d, $J=7.2$ Hz, 2H), 6.86 (t, $J=7.6$ Hz, 1H), 6.88–6.90 (m, 2H), 7.04 (d, $J=8.4$ Hz, 2H), 7.25 (t, $J=7.6$ Hz, 2H), 7.31 (t, $J=8.4$ Hz, 2H), 7.33 (t, $J=8.8$ Hz, 2H), 7.43 (t, $J=7.6$ Hz, 2H), 7.50 (d, $J=8.4$ Hz, 2H), 7.51 (s, 1H), 7.73 (d, $J=8.4$ Hz, 2H), 7.80 (d, $J=8.0$ Hz, 2H), 7.84 ppm (d, $J=8.8$ Hz, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz): $\delta=92.1$ (C≡), 92.2 (C≡), 93.2 (C≡), 94.2 (C≡), 121.7 (C), 121.8 (C), 123.2 (C), 124.4 (C), 126.3 (CH), 126.4 (CH), 126.5 (CH), 126.5 (CH), 126.7 (CH), 126.8 (CH), 127.2 (2×CH), 127.4 (CH), 127.6 (CH), 127.9 (CH), 128.0 (CH), 128.1 (CH), 128.2 (CH), 130.0 (CH), 132.6 (C), 132.7 (C), 133.0 (C), 133.1 (C), 133.6 (CH), 138.9 (C), 141.1 (C), 141.9 ppm (CH); MS (APCI): *m/z* (%)=753.1 $[M+1]^+$ (100), 754.2 $[M+2]^+$ (56), 755.2 $[M+3]^+$ (18); elemental analysis: calcd (%) for $C_{60}H_{32}$: C 95.72, H 4.28; found: C 95.89, H 4.09.

3: A 100-mL two-necked flask was charged with $[(Ph_3P)_2PdCl_2]$ (14 mg, 0.02 mmol), CuI (4 mg, 0.02 mmol), diisopropylamine (8 mL), and toluene (40 mL). A solution of **13b** (90 mg, 0.10 mmol) in diisopropylamine (5 mL) and toluene (20 mL) was added to the above suspension over a period of 30 h at 80°C by a machine. The reaction mixture was cooled to room temperature and filtered. The filtrate was poured into aqueous

NH_4Cl and extracted with ethyl acetate. The extract was then washed with brine, dried over $MgSO_4$, and filtered. The solvent was evaporated in vacuo, and the residue was subjected to chromatography (SiO_2, hexane/CH_2Cl_2 = 4:1) to give **3** (17 mg, 22%) as a pale-yellow powder. M.p.: 239–242 °C; $[\alpha]_D^{30.9} = +479.0$ ($c = 0.1$ M, $CHCl_3$) for *R,P* enantiomer; UV/Vis ($CHCl_3$, 1.0×10^{-5} mol L^{-1}): λ_{max} (ε_{max}) = 242 (1.2×10^5), 250 (1.1×10^5), 270 (7.9×10^4), 305 nm (5.6×10^4 M^{-1}cm^{-1}); UV/Vis ($CHCl_3$, 2.7×10^{-6} mol L^{-1}): λ_{max} (ε_{max}) = 242 (1.5×10^5), 250 (1.4×10^5), 270 (1.1×10^5), 305 nm (7.7×10^4 M^{-1}cm^{-1}); IR (KBr): $\tilde{\nu}$ = 3435, 2925, 2206 (C≡C), 1462, 816, 746 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz): δ = 6.71–6.73 (m, 4H), 6.84–6.86 (m, 4H), 7.19 (d, J = 8.4 Hz, 4H), 7.28 (t, J = 8.0 Hz, 4H), 7.44 (t, J = 7.6 Hz, 4H), 7.69 (d, J = 8.4 Hz, 4H), 7.88 (d, J = 8.4 Hz, 4H), 7.94 ppm (d, J = 8.4 Hz, 4H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 91.4 (C≡), 92.3 (C≡), 121.7 (C), 124.8 (C), 126.2 (CH), 126.4 (CH), 126.4 (CH), 127.1 (CH), 127.5 (CH), 127.9 (CH), 129.6 (CH), 132.4 (CH), 132.5 (C), 133.1 (C), 139.4 ppm (C); MS (APCI): m/z (%) = 753.2 $[M+1]^+$ (100), 754.2 $[M+2]^+$ (65), 755.2 $[M+3]^+$ (33); elemental analysis: calcd (%) for $C_{60}H_{32}$: C 95.72, H 4.28; found: C 95.78, H 4.19.

(*R*)-**4**: A 100-mL flask was charged with $[(Ph_3P)_2PdCl_2]$ (30 mg, 0.03 mmol), CuI (13.4 mg, 0.07 mmol), diisopropylamine (10 mL), and toluene (50 mL). A solution of **20** (161 mg, 0.16 mmol) in toluene (20 mL) was added to the above suspension over a period of 6 h at 75 °C by a syringe machine. The resulting mixture was then stirred at 75 °C for 20 h. The reaction mixture was cooled to room temperature and filtered. The filtrate was poured into aqueous NH_4Cl and extracted with ethyl acetate. The organic layer was dried over $MgSO_4$ and filtered. The solvent was evaporated, and the residue was subjected to chromatography (SiO_2, hexane/CH_2Cl_2 = 3:1) to give (*R*)-**4** (35 mg, 25%) as a pale-yellow solid. M.p: 205.0–206.0 °C; $[\alpha]_D^{19.0} = +17.7°$ ($c = 0.1$ M, $CHCl_3$) for *R,P* enantiomer; UV/Vis (CH_2Cl_3, 1.3×10^{-6} mol L^{-1}): λ_{max} (ε_{max}) 305 (8.3×10^4), 281 (1.2×10^5), 254 (1.0×10^5), 246 nm (9.7×10^4 M^{-1}cm^{-1}); IR (KBr): $\tilde{\nu}$ = 3055, 2924, 1593, 1462, 1377, 893, 818, 746 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz): δ = 6.81 (d, J = 7.6 Hz, 1H), 6.91 (t, J = 8.4 Hz, 1H), 7.04–7.14 (m, 8H), 7.23–7.30 (m, 6H), 7.43–7.50 (m, 5H), 7.64 (s, 2H), 7.79 (d, J = 8.4 Hz, 2H), 7.81 (d, J = 8.8 Hz, 2H), 7.86–7.90 (m, 6H), 7.94 ppm (d, J = 8.4 Hz, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 89.6 (2×C≡), 89.7 (C≡), 89.9 (C≡), 91.7 (C≡), 91.8 (C≡), 121.5 (C), 121.5 (C), 123.1 (C), 123.5 (C), 123.8 (C), 126.4 (CH), 126.5 (CH), 126.6 (CH), 126.6 (CH), 126.6 (CH), 126.7 (CH), 128.0 (CH), 128.1 (CH), 128.1 (CH), 128.2 (CH), 128.3 (CH), 129.0 (CH), 129.5 (CH), 129.8 (CH), 131.4 (CH), 132.5 (C), 132.6 (C), 132.9 (2×C), 133.6 (CH), 137.3 (CH), 139.2 (C), 139.6 ppm (C); MS (APCI): m/z (%) = 851.2 $[M-2]^+$ (29), 852.2 $[M-1]^+$ (44), 853.1 $[M]^+$ (100), 854.1 $[M+1]^+$ (63), 855.1 $[M+2]^+$ (83); elemental analysis: calcd (%) for $C_{60}H_{36}$: C 95.77, H 4.23; found: C 95.66, H 4.31.

(*S,M*)-**4**: Prepared analogously. $[\alpha]_D^{19.0} = -19.2$ ($c = 0.1$ M, $CHCl_3$).

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