JOC The Journal of Organic Chemistry

Article

pubs.acs.org/joc

Synthesis, Structures, and Photophysical Properties of Optically Stable 1,16-Diphenyl-3,14-diaryl-Substituted Tetrahydrobenzo[5]helicenediol Derivatives: Enantioselective Recognition toward Tryptophan Methyl Esters

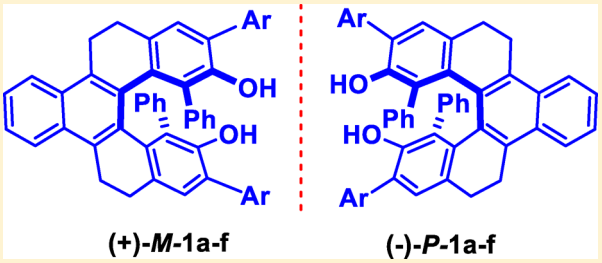
Lei Fang,[†,‡] Meng Li,[†] Wei-Bin Lin,[†,‡] Yun Shen,[†] and Chuan-Feng Chen*[,†,‡]

[†]Beijing National Laboratory for Molecular Sciences, CAS Key Laboratory of Molecular Recognition and Function, Institute of Chemistry, Chinese Academy of Sciences, Beijing 100190, China

[‡]University of Chinese Academy of Sciences, Beijing 100049, China

Supporting Information

ABSTRACT: Starting from commercially available 7-methoxytetralone, 1,16-diphenyl-3,14-dibromotetrahydrobenzo[5]helicenediol (Br-H[5]HOL) was conveniently prepared, which underwent efficient resolution to give the optically stable enantiomeric diols in gram scale by HPLC with semipreparative chiral columns. The absolute configurations of the diols were determined by the circular dichroism (CD) spectra and X-ray crystal structure. By Suzuki–Miyaura cross-coupling reactions, a series of enantiopure π-extended 1,16-diphenyl-3,14-diaryltetrahydrobenzo[5]helicenediol derivatives (Ar-H[5]HOL) were further synthesized in high yields. The enantiomeric Ar-H[5]HOL exhibited almost identical absorption and emission spectra but showed mirror-image CD spectra and mirror-image circularly polarized luminescence properties. Moreover, it was also found that aryl substituents at the 3,14-positions could extend the chiral environment of the helical skeletons, which led to efficient enantioselective recognition of the enantiomers of tryptophan methyl esters.



INTRODUCTION

Helicenes are aromatic compounds that perfectly combine π-conjugated structure and helical chirality, and they have been widely utilized in fields including molecular machines, dye materials, asymmetric catalysis, and chiral recognition.[1] Compared with helicenes, hydrohelicenes[2] have not only π-conjugated structure and helical chirality but also flexible skeletons, which can result in their specific photophysical and chiroptical properties.[3] Although these properties could make the hydrohelicenes show wide potential applications in fluorescent sensing,[4] cell fluorescent imaging,[5] organic optical waveguides,[6] full-color emission dyes,[5] and switchable organic dyes,[7] to our knowledge, none of their applications in chiral recognition has been reported so far.

1,1′-Bi-2-naphthol (BINOL)[8] and analogues have been utilized as one kind of typical chiral fluorescent receptors for the enantioselective recognition of various chiral organic enantiotopic molecules,[9] such as chiral amines,[10] amino alcohols,[10,11] carboxylic acids,[12] amino acids,[13] and others.[14] Similar to BINOL, hydro[5]helicenediols combine fluorescent emission, hydroxyl groups, and helical chirality; meanwhile, skeletons of hydro[5]helicenediols are more flexible to adjust the torsional angles compared to helicenediols. As a result, they could also become an important kind of chiral molecule and find wide potential applications in chiral recognition.[15] However, optically stable hydro[5]helicenediols have never been reported to date.

Recently, we[3,16] reported an efficient route for the synthesis of enantiopure benzo[5]helicene derivatives functionalized on the interior side of the helix. In particular, we found that introducing aryl groups at the 1,16-positions could greatly increase the racemization barrier of the helical skeletons and prevent the racemization of the helical structures.[16b] It was feasible to design and obtain optically stable hydro[5]-helicenediols by the similar method. Herein, we report the convenient synthesis of a couple of enantiopure Br-H[5]HOL in gram scale, which resulted in a series of π-extended Ar-H[5]HOL (−)-*P*-**1a**–**f** and (+)-*M*-**1a**–**f** (Figure 1). The Ar-H[5]HOL exhibited clear mirror-image circular dichroism (CD) spectra and mirror-image circularly polarized luminescence (CPL) properties. Moreover, it was also found that the diols (−)-*P*-**1a**–**f** and (+)-*M*-**1a**–**f** combining the π-conjugated system, chiral pocket, and hydroxyl groups could be used as new kinds of chiral fluorescent receptors and exhibited efficient enantioselective recognition toward the enantiomer of tryptophan methyl esters.

Received: May 5, 2017
Published: June 27, 2017

DOI: 10.1021/acs.joc.7b01087
J. Org. Chem. 2017, 82, 7402–7409

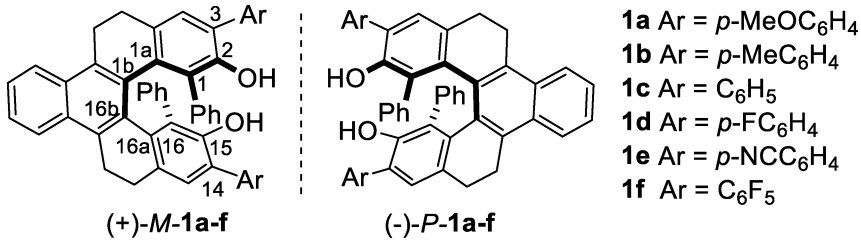
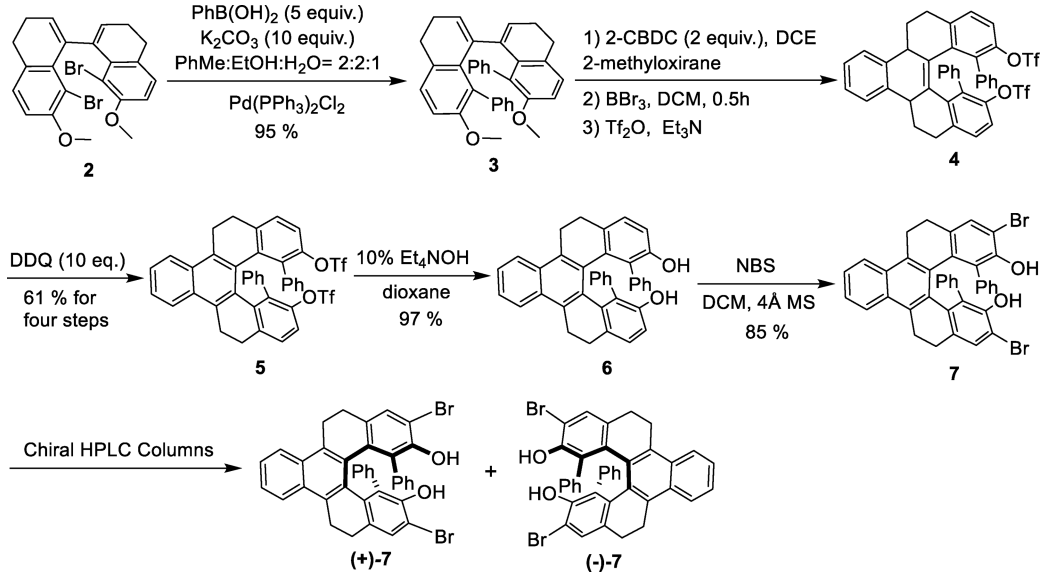


Figure 1. Structures of the enantiomers (−)-*P*-**1a**−**f** and (+)-*M*-**1a**−**f**.

Scheme 1. Synthesis and Resolution of the Dibromo-Substituted Diol 7



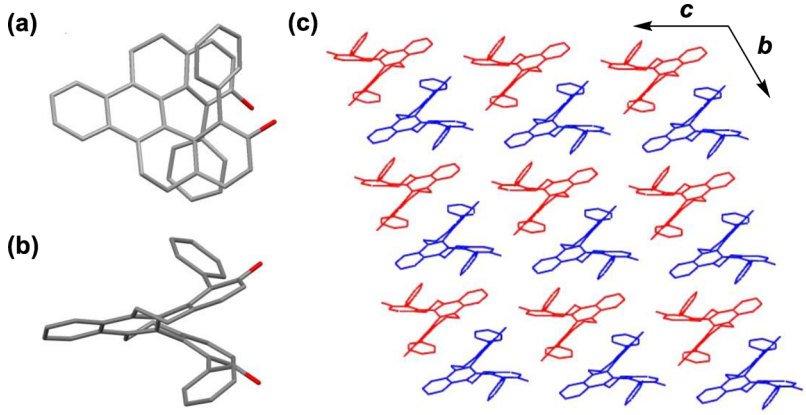


Figure 2. Top view (a) and side view (b) of crystal structure of **6**. (c) Packing of **6** along the *b* and *c* axes. Hydrogen atoms are omitted for clarity.

RESULTS AND DISCUSSION

Synthesis of Br-H[5]HOL. According to the previously reported method,[16b] we first prepared diene **2**, which was transferred into diene **3** in 95% yield by the Suzuki−Miyaura cross-coupling reaction (Scheme 1). By the Diels−Alder addition of **3** with 2-carboxybenzene diazonium chloride (2-CBDC) in dichloroethane and 2-methyloxirane, demethylation with BBr_3 in dichloromethane (DCM), and subsequent esterification reaction of the diol with trifluoromethanesulfonic anhydride, we obtained compound **4**, which was followed by oxidative dearomatization to give tetrahydro[5]helicene derivative **5** in a total 61% yield for the four steps. The ester hydrolysis reaction of triflate **5** with Et_4NOH in dioxane gave tetrahydrobenzo[5]helicenediols **6** in 97% yield, which was then followed by bromination with *N*-bromosuccinimide (NBS) in DCM to give 3,3′-dibromotetrahydrobenzo[5]-helicenediol **7** in 85% yield as yellow powder.

The single crystal of diol **6** was obtained by slow evaporation of its solution in hexane/DCM. As shown in Figure 2a,b, the crystal structure[17] of **6** showed that the torsional angles for C1−C1a−C1b−C16b, C1a−C1b−C16b−C16a, and C1b−C16b−C16a−C16 were 37.70, 18.11, and 40.33°, respectively, which were larger than those of benzo[5]helicene derivatives[16] due to the release of strain of the helical scaffold by the two ethylidene chains. As a result, the distance between the two oxygen atoms of hydroxyl groups was 5.42 Å, which was also

DOI: 10.1021/acs.joc.7b01087
J. Org. Chem. 2017, 82, 7402−7409

larger than that in benzo[5]helicene derivatives.[16] Moreover, it was found that the heterochiral molecules could pack alternately along the *b* axis by the intermolecular C−H···O hydrogen bonding between adjacent heterochiral molecules with the distance of 2.01 Å, whereas homochiral molecules packed along the *c* axis (Figure 2c).

Optical Resolution, Absolute Configuration, and Optical Stability of Br-H[5]HOL. An efficient optical resolution of Br-H[5]HOL 7 was then achieved by HPLC with semipreparative chiral columns and *n*-hexane/DCM (30:70, v/v) as the mobile phase, which provided a couple of enantiopure diols 7 (ee >99%, Figures S38 and S39) in gram scale. The specific rotations ($[\alpha]_D^{25}$ in DCM, c = 1.0 mg mL^{-1}) of (−)-7 and (+)-7 were determined to be −456 and +435, respectively. The enantiomers (−)-7 and (+)-7 showed identical UV−vis spectra and fluorescence spectra, but their CD spectra displayed perfect mirror symmetry (Figure 3). For

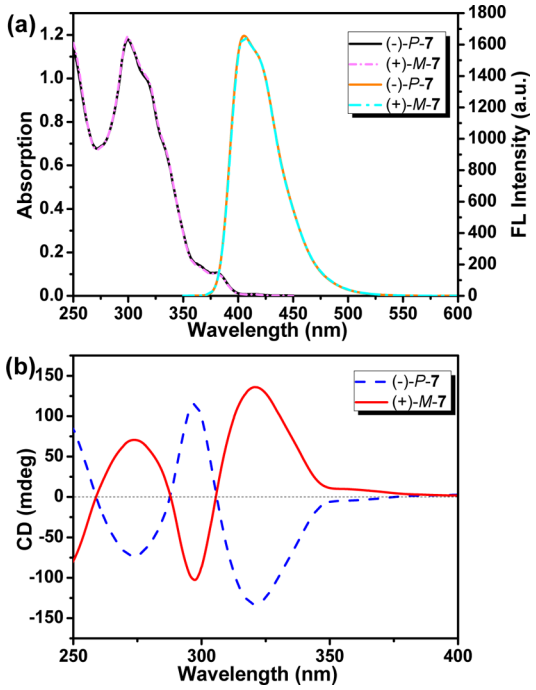


Figure 3. (a) UV−vis and fluorescence spectra (excited at corresponding $\lambda_{abs,max}$) of (−)-*P*-7 and (+)-*M*-7 in DCM (c = 1.0 × 10^{-5} M). (b) Mirror-image CD spectra of (−)-*P*-7 and (+)-*M*-7 in DCM (c = 1.0 × 10^{-4} M).

the reported [5]helicenes,[16a,18] the negative Cotton effects at the maximum absorption peak were found for *P* helicenes, whereas the positive Cotton effects at the maximum absorption peak were observed for *M* helicenes. Thus, according to the empirical law, the absolute configuration of (−)-7 was assigned to *P* helicity, and (+)-7 was assigned to be *M* helicity.

To determine the absolute configurations of the enantiomers unambiguously, we also obtained the single crystal of the enantiomer (−)-7 by slow evaporation of its solution in hexane/DCM. Based on the crystal structure,[17] (−)-7 possessed *P* helicity (Figure 4a,b), which was consistent with the result of the empirical law. The distance between the two oxygen atoms of hydroxyl groups was 5.65 Å, comparable to that of its precursor **6**. As shown in Figure 4c, it was also found that (−)-*P*-7 could self-assemble into a one-dimensional ladder-like structure along the *c* axis by *π*−*π* stacking interactions

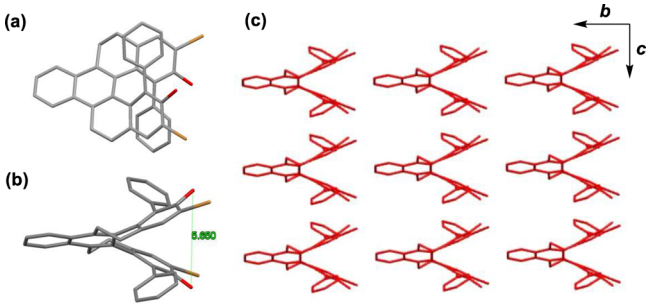


Figure 4. Top view (a) and side view (b) of crystal structure of (−)-*P*-7. (c) Packing of (−)-*P*-7. Hydrogen atoms are omitted for clarity.

between the phenyl groups at the 1,16-position and the terminal benzene rings in the helical scaffold of the adjacent molecules, which further packed into a two-dimensional layer structure.

To investigate the optical stability of the H[5]HOL core, we dissolved *M*-7 in diethylene glycol dibutyl ether, kept the sample under 423 K for 12 h, and then monitored by HPLC (Figure S52). The results showed that *M*-7 did not undergo racemization or dearomatization. So it can be concluded that the H[5]HOL skeleton exhibited excellent optical stability at temperatures below 423 K and could be performed in the majority of applications such as asymmetric catalysis, enantioselective recognition, and chiral optical materials without loss of the optical purity.

Synthesis of Enantiomers of Ar-H[5]HOL. With the enantiopure *P*-7 and *M*-7 in hand, we then conveniently synthesized five pairs of Ar-H[5]HOL *P*-**1a−e** and *M*-**1a−e** in high yields by Suzuki−Miyaura cross-coupling reactions (Scheme 2 and Table 1). According to the same reaction

Scheme 2. Synthesis of Enantiomers *P*-1a−e and *M*-1a−e

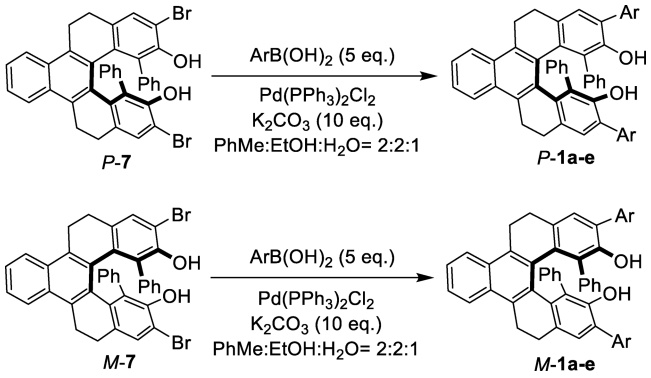


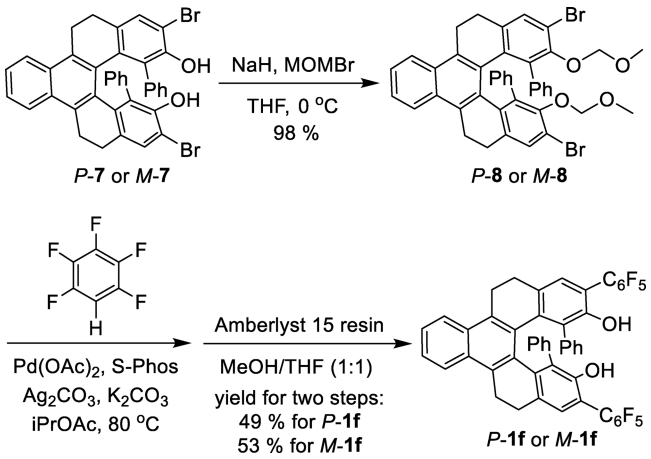
Table 1. Synthesis of Enantiomers *P*-1a−e and *M*-1a−e

entry	Ar	product	yield (%)
1	4-methoxyphenyl	*P*-**1a**	92
2	4-methylphenyl	*P*-**1b**	91
3	phenyl	*P*-**1c**	94
4	4-fluorophenyl	*P*-**1d**	91
5	4-cyanophenyl	*P*-**1e**	90
6	4-methoxyphenyl	*M*-**1a**	90
7	4-methylphenyl	*M*-**1b**	92
8	phenyl	*M*-**1c**	93
9	4-fluorophenyl	*M*-**1d**	89
10	4-cyanophenyl	*M*-**1e**	90

DOI: 10.1021/acs.joc.7b01087
J. Org. Chem. 2017, 82, 7402−7409

conditions, we could not obtain diol *P*-**1f** or *M*-**1f** by direct Suzuki–Miyaura cross-coupling between *P*-7 or *M*-7 with 2,3,4,5,6-pentafluorobenzeneboronic acid, probably due to the electron deficiency of perfluorophenyl. However, *P*-**1f** and *M*-**1f** could be synthesized by the coupling reaction between MOM-protected tetrahydrobenzo[5]helicenes *P*-**8** and *M*-**8** with pentafluorobenzene, followed by the deprotected reactions (Scheme 3). The specific rotations ($[\alpha]_D^{25}$ in DCM, c = 1.0 mg mL^{-1}) of enantiopure compounds (−)-*P*-**1a–f** and (+)-*M*-**1a–f** were determined, and the negative values of −426 to −512 for (−)-*P*-**1a–1** and the positive values of +432 to +528 for (+)-*M*-**1a–f** were found.

Scheme 3. Synthesis of 3,14-Diperfluorophenyl-H[5]HOL *P*-1f and *M*-1f



Photophysical and Chiroptical Properties of (−)-*P*-1a–f and (+)-*M*-1a–f. Similar to those of the enantiomers (−)-*P*-7 and (+)-*M*-7, the UV–vis spectra and fluorescence spectra of enantiomers (−)-*P*-**1a–f** and (+)-*M*-**1a–f** should also be identical. Therefore, the *P* configurations of **1a–f** were then employed as examples to investigate their photophysical properties, and the results are summarized in Table 2. As shown in Figure 5 and Table 2, no obvious changes of the maximum absorption wavelength for (−)-*P*-**1a–f** in DCM were observed. It was also found that there was no obvious substituent effect on the fluorescence emission of Ar-H[5]HOL with different substituent groups on the aromatic rings at the 3,14-positions. Moreover, the (−)-*P*-**1a–f** all exhibited large Stokes shifts of about 102–104 nm and showed blue fluorescence with the maximum emission at about 407–416 nm. It was further found that the enantiomers all exhibited strong fluorescence with the absolute fluorescence quantum yields of 22.37 to 35.35% in DCM.

Table 2. Photophysical Properties of (−)-*P*-1a–f

compound[a]	λ_{abs}[b] (nm)	log ε (M^{-1} cm^{-1})	λ_{em}[c] (nm)	Φ_f[d] (%)	$\Delta\lambda_{Stokes}$[e] (nm)
(−)-*P*-**1a**	306	4.82	409	23.01	103
(−)-*P*-**1b**	305	4.57	407	32.71	102
(−)-*P*-**1c**	304	4.77	408	27.34	103
(−)-*P*-**1d**	302	4.99	406	35.35	104
(−)-*P*-**1e**	313	4.56	416	22.37	104
(−)-*P*-**1f**	305	4.74	408	27.33	103

[a]All spectra were recorded in DCM (c = 1.0 × 10^{-5} M). [b]The maximum absorption bands. [c]Excited at the maxima absorption. [d]Absolute fluorescence quantum yield. [e]Stokes shift = $\lambda_{em} - \lambda_{max,abs}$.

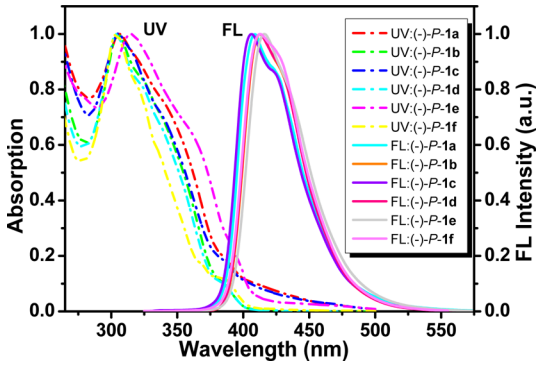


Figure 5. UV–vis and fluorescence spectra (excited at corresponding $\lambda_{abs,max}$) of (−)-*P*-**1a–f** (c = 1.0 × 10^{-5} M).

Chiroptical properties of the enantiomers (−)-*P*-**1a–f** and (+)-*M*-**1a–f** were also investigated. It was found that similar to (−)-*P*-7 and (+)-*M*-7, the enantiomers (−)-*P*-**1a–f** and (+)-*M*-**1a–f** all exhibited notable mirror-image CD spectra in DCM (Figure 6a), which was consistent with the general principle of Cotton effect and absolute configuration. Moreover, the enantiomers also showed clear mirror-image CPL signals in DCM (Figure 6b) with the luminescence dissymmetry factor g_{lum} values of −5.5 × 10^{-4} to −10.0 × 10^{-4} for the *P* configuration enantiomers and +6.6 × 10^{-4} to +9.7 × 10^{-4} for the *M* configuration enantiomers (Table S2).

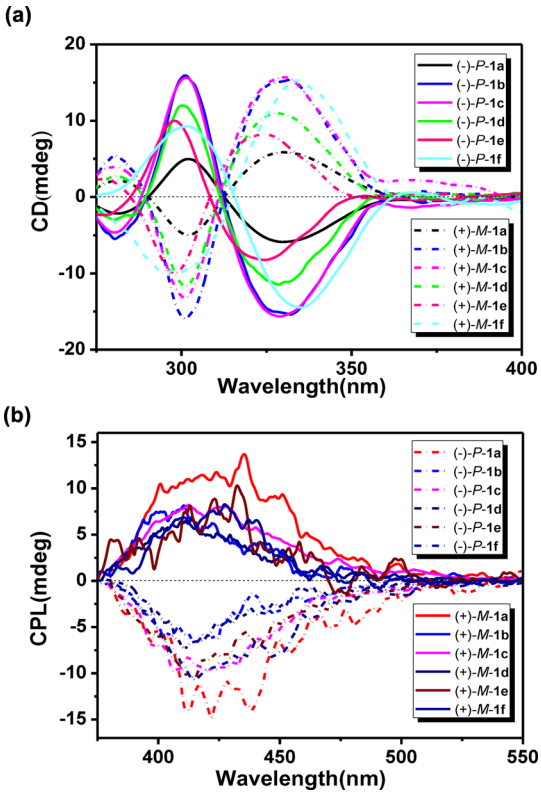


Figure 6. Mirror-image CD (a) and CPL (b) spectra of (−)-*P*-**1a–f** and (+)-*M*-**1a–f** in DCM (c = 1.0 × 10^{-5} M).

Enantioselective Recognition of Tryptophan Methyl Esters by Enantiomers (−)-*P*-1a–f and (+)-*M*-1a–f. The

DOI: 10.1021/acs.joc.7b01087
J. Org. Chem. 2017, 82, 7402–7409

enantioselective recognition abilities of (−)-*P*-**1a**−**f** and (+)-*M*-**1a**−**f** (c = 1.0 × 10^{-5} M) toward tryptophan methyl esters D-**9** and L-**9** were further investigated by the fluorescence method, and the results are summarized in Table 3. It was found that all

Table 3. Fluorescence Quenching Rates of (−)-*P*-1a−f and (+)-*M*-1a−f by Tryptophan Methyl Esters D-9 and L-9

enantiomers	K_{Dsv}/K_{Lsv}	enantiomers	K_{Lsv}/K_{Dsv}
(−)-*P*-**1a**	1.29	(+)-*M*-**1a**	1.19
(−)-*P*-**1b**	1.23	(+)-*M*-**1b**	1.32
(−)-*P*-**1c**	1.60	(+)-*M*-**1c**	1.52
(−)-*P*-**1d**	1.67	(+)-*M*-**1d**	1.67
(−)-*P*-**1e**	1.64	(+)-*M*-**1e**	1.67
(−)-*P*-**1f**	2.99	(+)-*M*-**1f**	2.97

of the enantiomers (−)-*P*-**1a**−**f** and (+)-*M*-**1a**−**f** showed obvious different fluorescence spectral changes upon the addition of D-**9** or L-**9** on the same tested conditions (Figures S1−S24), which implied that the enantiomers (−)-*P*-**1a**−**f** and (+)-*M*-**1a**−**f** exhibited enantioselective recognition toward tryptophan methyl esters D-**9** and L-**9**. Moreover, it was also found that with the increase of the electron-deficient ability of the substituents at the 3,14-position of the receptors, the obvious high enantioselectivities of (−)-*P*-**1a**−**f** and (+)-*M*-**1a**−**f** toward D-**9** or L-**9**, respectively, were observed, and the highest one was found to be the enantiomers of **1f** containing two pentafluorobenzene groups at the 3,14-position (Table 3). According to the Stern−Volmer plots of (−)-*P*-**1f** and (+)-*M*-**1f** in the presence of D-**9** or L-**9** (Figure 7), we determined the Stern−Volmer constants for (−)-*P*-**1f**/D-**9** and (−)-*P*-**1f**/L-**9** to be 3595 M^{-1} (K_{Dsv}) and 1203 M^{-1} (K_{Lsv}), respectively. Therefore, the enantioselectivity factor K_{Dsv}/K_{Lsv} was 2.99 for (−)-*P*-**1f**. Similarly, in the case of (+)-*M*-**1f**, the Stern−Volmer constant was 3379 M^{-1} (K_{Lsv}) for L-**9** and 1139 M^{-1} (K_{Dsv}) for D-**9**, which resulted in the enantioselectivity factor K_{Lsv}/K_{Dsv} of 2.97. Under the same tested conditions as above, the MOM-protected **1f** as a control experiment showed no chiral recognition abilities (Figures S35 and S36) toward tryptophan methyl esters D-**9** and L-**9**, suggesting that the phenolic hydroxy groups of **1** were involved in their enantioselective recognition toward the tryptophan methyl esters, which could be similar to those results reported by Reetz[15] and Mattay.[19] The opposite enantioselective trend of enantiomers **1a**−**f** toward D-**9** or L-**9** might offer a new prospect for designing chiral fluorescent receptors.

CONCLUSION

In conclusion, we have conveniently synthesized Br-H[5]HOL starting from the commercial available 7-methoxytetralone, obtained the optically stable enantiomeric diols in gram scale by HPLC resolution with semipreparative chiral columns, and determined their absolute configurations by the CD spectra and X-ray crystal structure analysis. By Suzuki−Miyaura cross-coupling reactions, we have also synthesized a series of enantiopure Ar-H[5]HOL in high yields and found that the enantiomers exhibited almost identical absorption and emission spectra but showed mirror-image CD spectra and mirror-image CPL signals. Moreover, it was also found that the Ar-H[5]HOL showed significant enantioselective recognition toward the enantiomers of tryptophan methyl esters. Further investigation on the applications of the enantiomeric Ar-H[5]HOL in asymmetric catalysis is currently underway in our laboratory.

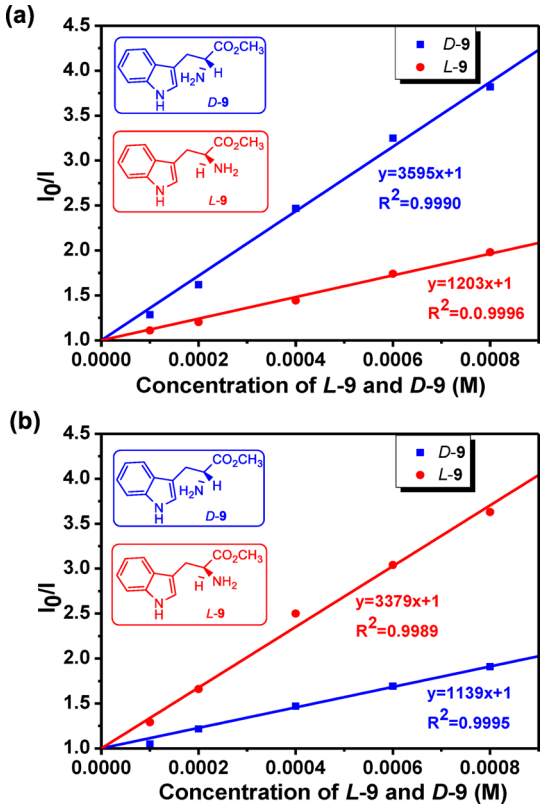


Figure 7. (a) Stern−Volmer plot of (−)-*P*-**1f** (1.0 × 10^{-5} M) in DCM in the presence of L-**9** and D-**9** (λ_{ex} = 305 nm). (b) Stern−Volmer plot of (+)-*M*-**1f** (1.0 × 10^{-5} M) in DCM in the presence of L-**9** and D-**9** (λ_{ex} = 305 nm).

EXPERIMENTAL SECTION

General Information. All the reagents and solvents were commercially available and used without further purification. Reactions were carried out under inert and anhydrous conditions unless otherwise noted. ^{1}H and ^{13}C NMR spectra were recorded at 298 K, and the chemical shifts were reported relative to internal standard with TMS (0 ppm). CD spectra were recorded at room temperature in DCM, using 10 mm cells. During the measurement, the instrument was thoroughly purged with nitrogen. All the melting points were not calibrated. The mass analyzer type is Orbitrap, and the ionization methods used in mass spectrometry include atmospheric pressure chemical ionization (APCI) and electrospray ionization (ESI). APCI utilizes gas-phase ion−molecule reactions at atmospheric pressure (10^5 Pa), whereas ESI used an electrospray in which a high voltage is applied to a liquid to produce ions. Optical resolutions were carried out by HPLC using the column (Chiralpak IE, 10 mm × 250 mm). Analytical injections were performed on a chiral stationary phase using the column (Chiralpak ID 5 μm, 4.6 mm × 250 mm, Chiralpak IE 5 μm, 4.6 mm × 250 mm and Chiralpak IG 5 μm, 4.6 mm × 250 mm). Diene **2** was synthesized according to the reported method.[16b]

Compound 5. To the solution of diene **3** (4.7 g, 10 mmol) in DCE (100 mL) and 2-methyloxirane (10 mL) was added 2-CBDC (3.7 g, 20 mmol). The mixture was refluxed for 2 h and then concentrated to give the crude product, which was dissolved in DCM (100 mL), and BBr_3 (10 mL, 100 mmol) was added dropwise at 0 °C. The reaction mixture was stirred for about 30 min, water added (40 mL), stirred for another 5 min, and washed by water. The organic layer was concentrated, and the crude product was purified by flash column chromatography with DCM and petroleum ether (1:1, v/v) as eluent. To the above product in DCM (50 mL) at 0 °C were added Tf_2O (8.5 g, 30 mmol) and Et_3N (3.0 g, 30 mmol). The mixture was stirred for 4 h at room temperature and then concentrated to give the crude product, which was purified by flash column chromatography with

DOI: 10.1021/acs.joc.7b01087
J. Org. Chem. 2017, 82, 7402−7409

DCM and petroleum ether (1:1, v/v) as eluent to give compound **4**. To the solution of **4** in xylene (500 mL) was added 2,3-dichloro-5,6-dicyanobenzoquinone (20.4 g, 90 mmol) in one portion. The reaction mixture was refluxed with stirring overnight, cooled to room temperature, and concentrated by reduced pressure. The crude product was purified by flash column chromatography with DCM and petroleum ether (1:1, v/v) as eluent to give tetrahydrobenzo[5]-helicene triflate **5** (4.8 g, 61% yield for four steps) as pale yellow powder: R_f = 0.46 (PE/DCM, v/v = 1:1); mp 205−207 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.13 (dd, J = 6.5, 3.4 Hz, 2H), 7.56 (dd, J = 6.5, 3.2 Hz, 2H), 7.20−7.04 (m, 8H), 6.77 (td, J = 7.6, 1.7 Hz, 2H), 6.53 (d, J = 7.7 Hz, 2H), 6.02 (d, J = 7.8 Hz, 2H), 3.39−3.31 (m, 2H), 2.43 (dd, J = 13.4, 10.4 Hz, 2H), 1.57−1.51 (m, 2H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 148.0, 136.0, 135.7, 135.6, 135.0, 131.2, 130.4, 130.1, 129.1, 128.2, 128.0, 127.6, 127.1, 125.8, 124.4, 108.1, 53.4, 29.1, 24.8; HRMS (APCI) calcd for $C_{40}H_{27}F_6O_6S_2$ $[M + H]^+$ 781.1148, found 781.1138.

Compound 6. To a solution of **5** (2.3 g, 3 mmol) in dioxane (100 mL) was added 10% Et_4NOH aqueous solution (41 mL) at ambient temperature. The subsequent mixture was stirred for 24 h, and then 1 M aqueous HCl was added dropwise until pH 1. The yellow precipitate was obtained by filtration and thoroughly washed by water to give compound **6** (1.5 g, 97% yield) as pale yellow powder: R_f = 0.75 (DCM); mp 200−202 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.11 (dd, J = 6.3, 3.2 Hz, 2H), 7.50 (dd, J = 6.4, 3.2 Hz, 2H), 7.17−7.12 (m, 4H), 6.90−6.86 (m, 4H), 6.80 (d, J = 8.0 Hz, 2H), 6.56−6.54 (m, 2H), 6.08 (d, J = 7.4 Hz, 2H), 5.05 (s, 2H), 3.30 (d, J = 13.6 Hz, 2H), 2.40 (t, J = 15.1 Hz, 2H), 2.30 (d, J = 15.5 Hz, 2H), 1.41 (t, J = 12.6 Hz, 2H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 151.3, 136.1, 135.5, 135.2, 134.4, 131.7, 131.5, 130.3, 128.9, 128.8, 127.8, 127.7, 126.9, 126.2, 125.4, 124.3, 113.4, 29.3, 25.0; HRMS (ESI) calcd for $C_{38}H_{27}O_2$ $[M - H]^-$ 515.2017, found 515.2005.

Compound 7. To a flame-dried round-bottomed flask containing compound **6** (1.5 g, 3 mmol) were added NBS (1.2 g, 7 mmol), 4 Å molecular sieves (50 mg), and anhydrous DCM (50 mL) in the dark. The reaction mixture was stirred in the dark for 8 h and then quenched with a few drops of saturated NH_4Cl solution. The mixture was extracted with DCM three times and washed with water. The organic layer was combined, dried over $MgSO_4$, and concentrated under reduced pressure. The crude product was separated by flash column chromatography with DCM and petroleum ether (1:1, v/v) as eluent to give compound **7** (1.5 g, 85% yield) as a yellow powder: R_f = 0.66 (PE/DCM, v/v = 1:1); mp 244−246 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.10 (dd, J = 6.4, 3.3 Hz, 2H), 7.52 (dd, J = 6.5, 3.2 Hz, 2H), 7.18 (t, J = 7.4 Hz, 2H), 7.13 (m, 4H), 6.82 (t, J = 7.4 Hz, 2H), 6.72 (d, J = 7.5 Hz, 2H), 6.04 (d, J = 7.7 Hz, 2H), 5.39 (s, 2H), 3.31 (d, J = 15.3 Hz, 2H), 2.39 (td, J = 15.1, 3.7 Hz, 2H), 2.27 (d, J = 12.4 Hz, 2H), 1.44 (td, J = 14.6, 4.1 Hz, 2H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 148.0, 136.0, 135.7, 135.6, 135.0, 131.2, 130.7, 130.4, 130.1, 129.0, 128.2, 128.0, 127.6, 127.1, 125.8, 124.4, 108.1, 29.0, 24.8; HRMS (ESI) calcd for $C_{38}H_{25}Br_2O_2$ $[M - H]^-$ 673.0206, found 673.0227.

General Procedure for the Suzuki−Miyaura Cross-Coupling Reactions. To the mixture of Br-H[5]HOL (−)-*P*-**7** or (+)-*M*-**7** (67 mg, 0.1 mmol), boronic acid (64 mg, 0.5 mmol), and K_2CO_3 (138 mg, 1.0 mmol) in a mixture solution of toluene (15 mL), EtOH (15 mL), and degassed water (7.5 mL) was added $Pd(PPh_3)_2Cl_2$ (0.1 mol). The reaction mixture was refluxed for 12 h, cooled to room temperature, and then EA (30 mL) and water (30 mL) were added. The organic phase was separated, dried over $MgSO_4$, and concentrated by reduced pressure. The crude product was purified by flash column chromatography to give the corresponding pure enantiomers.

Compound (−)-*P*-1a. DCM as eluent; yellow powder (68 mg, 92% yield). $[\alpha]_D^{25}$ = −447 (c = 1.0 mg mL^{-1}, DCM): R_f = 0.68 (DCM); mp 240−242 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.14 (dd, J = 6.2, 3.3 Hz, 2H), 7.59 (d, J = 8.0 Hz, 4H), 7.51 (dd, J = 6.3, 2.9 Hz, 2H), 7.13 (m, 4H), 7.02 (d, J = 8.0 Hz, 4H), 6.95 (s, 2H), 6.88 (t, J = 7.3 Hz, 2H), 6.76 (d, J = 7.1 Hz, 2H), 6.17 (d, J = 7.5 Hz, 2H), 5.23 (s, 2H), 3.87 (s, 6H), 3.35 (d, J = 14.5 Hz, 2H), 2.47 (t, J = 15.0 Hz, 2H), 2.34 (d, J = 13.7 Hz, 2H), 1.51 (t, J = 15.0 Hz, 2H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 158.9, 148.1, 136.5, 135.5, 134.4, 134.2, 131.7, 131.5, 130.8, 130.4, 130.4, 128.9, 128.5, 126.8, 126.5, 126.2, 125.4, 124.4, 113.9, 55.4, 29.3, 25.0; HRMS (APCI) calcd for $C_{52}H_{39}O_4$ $[M - H]^-$ 727.2845, found 727.2848.

Compound (+)-*M*-1a. DCM as eluent; yellow powder (66 mg, 90% yield); $[\alpha]_D^{25}$ = +432 (c = 1.0 mg mL^{-1}, DCM); R_f = 0.68 (DCM); mp 240−242 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.14 (dd, J = 6.5, 3.4 Hz, 2H), 7.59 (d, J = 8.7 Hz, 4H), 7.51 (dd, J = 6.5, 3.2 Hz, 2H), 7.12 (m, 4H), 7.02 (d, J = 8.7 Hz, 4H), 6.95 (s, 2H), 6.88 (t, J = 8.5 Hz, 2H), 6.76 (d, J = 6.9 Hz, 2H), 6.18 (d, J = 7.7 Hz, 2H), 5.23 (s, 2H), 3.87 (s, 6H), 3.35 (d, J = 15.4 Hz, 2H), 2.47 (t, J = 16.3 Hz, 2H), 2.34 (d, J = 18.3 Hz, 2H), 1.52 (t, J = 16.7 Hz, 2H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 158.9, 148.0, 136.5, 135.5, 134.4, 134.2, 131.7, 131.4, 130.7, 130.4, 130.4, 128.6, 128.5, 126.8, 126.5, 126.2, 125.4, 124.4, 113.9, 55.4, 29.3, 25.0; HRMS (APCI) calcd for $C_{52}H_{39}O_4$ $[M - H]^-$ 727.2845, found 727.2843.

Compound (−)-*P*-1b. PE/DCM (v/v = 1:1) as eluent; yellow powder (63 mg, 91% yield); $[\alpha]_D^{25}$ = −512 (c = 1.0 mg mL^{-1}, DCM); R_f = 0.42 (PE/DCM, v/v = 1:1); mp 204−206 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.14 (dd, J = 6.3, 3.3 Hz, 2H), 7.57−7.48 (m, 6H), 7.29 (d, J = 7.7 Hz, 4H), 7.12 (m, 4H), 6.96 (s, 2H), 6.87 (t, J = 7.4 Hz, 2H), 6.77 (d, J = 7.2 Hz, 2H), 6.17 (d, J = 8.1 Hz, 2H), 5.23 (s, 2H), 3.35 (d, J = 14.8 Hz, 2H), 2.51−2.42 (m, 8H), 2.34 (d, J = 12.7 Hz, 2H), 1.51 (t, J = 15.4 Hz, 2H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 148.1, 136.9, 136.4, 135.5, 135.4, 134.6, 134.1, 131.6, 131.4, 130.4, 129.2, 129.2, 128.7, 128.5, 128.5, 126.8, 126.5, 125.4, 124.4, 29.3, 25.0, 21.3; HRMS (ESI) calcd for $C_{52}H_{39}O_2$ $[M - H]^-$ 695.2956, found 695.2956.

Compound (+)-*M*-1b. PE/DCM (v/v = 1:1) as eluent; yellow powder (64 mg, 92% yield); $[\alpha]_D^{25}$ = +528 (c = 1.0 mg mL^{-1}, DCM); R_f = 0.42 (PE/DCM, v/v = 1:1); mp 204−206 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.14 (dd, J = 6.5, 3.4 Hz, 2H), 7.55−7.50 (m, 6H), 7.30 (d, J = 7.7 Hz, 4H), 7.18−7.07 (m, 4H), 6.96 (s, 2H), 6.87 (t, J = 13.9 Hz, 2H), 6.77 (d, J = 6.9 Hz, 2H), 6.17 (d, J = 7.1 Hz, 2H), 5.23 (s, 2H), 3.35 (d, J = 15.3 Hz, 2H), 2.49−2.39 (m, 8H), 2.34 (d, J = 12.5 Hz, 2H), 1.52 (t, J = 15.5 Hz, 2H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 148.1, 136.9, 136.4, 135.5, 135.4, 134.6, 134.1, 131.6, 131.5, 130.4, 129.2, 129.2, 128.7, 128.5, 128.5, 126.8, 126.5, 125.4, 124.4, 29.3, 25.0, 21.3; HRMS (APCI) calcd for $C_{52}H_{39}O_2$ $[M - H]^-$ 695.2956, found 695.2948.

Compound (−)-*P*-1c. PE/DCM (v/v = 1:1) as eluent; yellow powder (63 mg, 94% yield); $[\alpha]_D^{25}$ = −165 (c = 1.0 mg mL^{-1}, DCM); R_f = 0.37 (PE/DCM, v/v = 1:1); mp 195−197 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.08 (dd, J = 6.5, 3.1 Hz, 2H), 7.59 (d, J = 3.3 Hz,4H), 7.47−7.37 (m, 6H), 7.30 (t, J = 7.4 Hz, 2H), 7.08−7.05 (m, 4H), 6.91 (s, 2H), 6.82 (t, J = 7.4 Hz, 2H), 6.71 (d, J = 6.2 Hz, 2H), 6.11 (d, J = 6.9 Hz, 2H), 5.19 (s, 2H), 3.29 (d, J = 15.0 Hz, 2H), 2.42 (t, J = 15.0 Hz, 2H), 2.28 (d, J = 13.7 Hz, 2H), 1.46 (t, J = 14.6 Hz, 2H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 147.0, 137.4, 135.3, 134.6, 133.8, 133.1, 130.7, 130.3, 129.4, 128.3, 127.8, 127.6, 127.5, 127.4, 126.1, 125.8, 125.5, 124.5, 123.3, 28.3, 23.9; HRMS (APCI) calcd for $C_{50}H_{35}O_2$ $[M - H]^-$ 667.2643, found 667.2643.

Compound (+)-*M*-1c. PE/DCM (v/v = 1:1) as eluent; yellow powder (62 mg, 93% yield); $[\alpha]_D^{25}$ = +158 (c = 1.0 mg mL^{-1}, DCM); R_f = 0.37 (PE/DCM, v/v = 1:1); mp 195−197 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.08 (dd, J = 6.5, 3.3 Hz, 2H), 7.59 (d, J = 7.1 Hz, 4H), 7.46−7.37 (m, 6H), 7.30 (t, J = 7.4 Hz, 2H), 7.08−7.04 (m, 4H), 6.91 (s, 2H), 6.82 (t, J = 8.2 Hz, 2H), 6.70 (d, J = 7.0 Hz, 2H), 6.11 (d, J = 7.7 Hz, 2H), 5.18 (s, 2H), 3.29 (d, J = 15.3 Hz, 2H), 2.41 (t, J = 17.0 Hz, 2H), 2.28 (d, J = 16.0 Hz, 2H), 1.44 (t, J = 14.7 Hz, 2H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 147.0, 137.4, 135.4, 134.6, 133.8, 133.2, 130.7, 130.4, 129.4, 128.3, 127.7, 127.6, 127.5, 127.4, 126.2, 125.8, 125.5, 124.5, 123.4, 28.3, 24.0; HRMS (APCI) calcd for $C_{50}H_{35}O_2$ $[M - H]^-$ 667.2643, found 667.2637.

Compound (−)-*P*-1d. PE/DCM (v/v = 1:1) as eluent; yellow powder (64 mg, 91% yield); $[\alpha]_D^{25}$ = −426 (c = 1.0 mg mL^{-1}, DCM); R_f = 0.44 (PE/DCM, v/v = 1:1); mp 207−209 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.14 (dd, J = 6.3, 3.2 Hz, 2H), 7.63 (dd, J = 8.1, 5.7 Hz, 4H), 7.52 (dd, J = 6.4, 3.0 Hz, 2H), 7.17−7.14 (m, 8H), 6.96 (s, 2H), 6.91 (t, J = 5.7 Hz, 2H), 6.71 (d, J = 6.8 Hz, 2H), 6.18 (d, J = 7.8 Hz, 2H), 5.24 (s, 2H), 3.36 (d, J = 8.5 Hz, 2H), 2.38 (t, J = 15.3 Hz, 2H), 2.35 (d, J = 9.7 Hz, 2H), 1.43 (t, J = 14.5 Hz, 2H); ^{13}C NMR

DOI: 10.1021/acs.joc.7b01087
J. Org. Chem. 2017, 82, 7402−7409

(126 MHz, $CDCl_3$) δ 148.0, 136.2, 135.7, 134.8, 134.3, 131.8, 131.2, 131.0, 130.9, 130.4, 128.9, 128.8, 128.7, 128.1, 127.1, 125.6, 124.4, 115.3, 115.1, 29.3, 25.0; HRMS (ESI) calcd for $C_{50}H_{33}F_2O_2$ $[M - H]^-$ 703.2454, found 703.2454.

Compound (−)-*M*-1d. PE/DCM (v/v = 1:1) as eluent; yellow powder (63 mg, 89% yield); $[\alpha]_D^{25}$ = +442 (c = 1.0 mg mL^{-1}, DCM); R_f = 0.44 (PE/DCM, v/v = 1:1); mp 207−209 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 8.14 (dd, J = 6.5, 3.4 Hz, 2H), 7.63 (dd, J = 8.6, 5.6 Hz, 4H), 7.52 (dd, J = 6.5, 3.2 Hz, 2H), 7.23−7.10 (m, 8H), 6.94 (s, 2H), 6.90 (t, J = 5.7 Hz, 2H), 6.72 (d, J = 6.8 Hz, 2H), 6.18 (d, J = 7.8 Hz, 2H), 5.24 (s, 2H), 3.36 (d, J = 15.4 Hz, 2H), 2.47 (t, J = 15.3 Hz, 2H), 2.35 (d, J = 11.6 Hz, 2H), 1.50 (t, J = 14.1 Hz, 2H).^{13}C NMR (126 MHz, $CDCl_3$) δ 148.0, 136.2, 135.7, 134.8, 134.3, 131.8, 131.2, 131.0, 130.9, 130.4, 128.9, 128.8, 128.7, 128.1, 127.0, 125.6, 124.4, 115.3, 115.1, 77.3, 77.0, 76.8, 29.3, 25.0; HRMS (APCI) calcd for $C_{50}H_{33}F_2O_2$ $[M - H]^-$ 703.2454, found 703.2447.

Compound (−)-*P*-1e. DCM as eluent; yellow powder (64 mg, 90% yield); $[\alpha]_D^{25}$ = −482 (c = 1.0 mg mL^{-1}, DCM); R_f = 0.51 (DCM); mp 220−222 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 8.07 (dd, J = 6.4, 3.3 Hz, 2H), 7.72 (d, J = 8.2 Hz, 4H), 7.66 (d, J = 8.3 Hz, 4H), 7.47 (dd, J = 6.5, 3.1 Hz, 2H), 7.13−7.06 (m, 4H), 6.93 (s, 2H), 6.88 (t, J = 7.6 Hz, 2H), 6.58 (d, J = 7.2 Hz, 2H), 6.12 (d, J = 7.7 Hz, 2H), 5.26 (s, 2H), 3.30 (d, J = 13.6 Hz, 2H), 2.40 (t, J = 16.8 Hz, 2H), 2.31 (d, J = 14.1 Hz, 2H), 1.45 (t, J = 14.6 Hz, 2H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 147.2, 142.4, 135.0, 134.8, 134.7, 133.5, 130.9, 129.7, 129.5, 129.0, 128.3, 128.0, 127.6, 126.6, 126.4, 125.7, 124.9, 123.5, 118.1, 109.4, 28.2, 23.9; HRMS (APCI) calcd for $C_{52}H_{33}O_2N_2$ $[M - H]^-$ 717.2548, found 717.2548.

Compound (+)-*M*-1e. DCM as eluent; yellow powder (64 mg, 90% yield); $[\alpha]_D^{25}$ = +455 (c = 1.0 mg mL^{-1}, DCM); R_f = 0.51 (DCM); mp 220−222 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 8.08 (dd, J = 6.3, 3.1 Hz, 2H), 7.72 (d, J = 7.9 Hz, 4H), 7.66 (d, J = 7.9 Hz, 4H), 7.47 (dd, J = 7.0, 3.2 Hz, 2H), 7.15−7.03 (m, 4H), 6.94 (s, 2H), 6.87 (t, J = 7.9 Hz, 2H), 6.58 (d, J = 7.3 Hz, 2H), 6.12 (d, J = 7.6 Hz, 2H), 5.26 (s, 2H), 3.31 (d, J = 16.4 Hz, 2H), 2.47 (t, J = 16.8 Hz, 2H), 2.31 (d, J = 14.4 Hz, 2H), 1.43 (t, J = 11.3 Hz, 2H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 147.2, 142.4, 135.0, 134.8, 134.7, 133.5, 130.9, 129.7, 129.5, 129.0, 128.3, 128.0, 127.6, 126.6, 126.4, 125.7, 124.9, 123.4, 118.1, 109.4, 28.2, 23.9; HRMS (APCI) calcd for $C_{52}H_{33}O_2N_2$ $[M - H]^-$ 717.2548, found 717.2537.

Compound *P*-8. To a mixture of NaH (60% dispersion in mineral oil, 40 mg, 1 mmol) in THF (30 mL) at 0 °C was added compound *P*-7 (134 mg, 0.2 mmol) as one portion. The reaction mixture was stirred at 0 °C for 1 h, and then MOM-Br (124 mg, 1 mmol) was added dropwise. The mixture was stirred at 0 °C for 10 min, quenched with saturated aqueous NH_4Cl, extracted with DCM, and washed with water. The organic layer was dried over $MgSO_4$, and the solvent was removed by reduced pressure. The crude product was purified by column chromatography on silica gel with 50% DCM in petroleum ether as eluent to give *P*-**8** as a yellow powder (145 mg, 98% yield): R_f = 0.52 (PE/DCM, v/v = 1:1); mp 140−142 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 8.11 (dd, J = 6.5, 3.4 Hz, 2H), 7.52 (dd, J = 6.5, 3.2 Hz, 2H), 7.19 (s, 2H), 7.14−7.00 (m, 4H), 6.82 (d, J = 5.9 Hz, 2H), 6.71 (t, J = 5.3 Hz, 2H)., 6.01 (d, J = 7.8 Hz, 2H), 4.32 (d, J = 5.2 Hz, 2H), 4.01 (d, J = 5.2 Hz, 2H), 3.32 (d, J = 14.6 Hz, 2H), 3.04 (s, 6H), 2.43−2.21 (m, 4H), 1.48 (d, J = 10.5 Hz, 2H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 148.7, 138.9, 135.4, 134.6, 134.4, 134.3, 130.2, 129.8, 129.3, 126.8, 125.8, 125.4, 124.7, 123.4, 114.7, 97.3, 56.7, 28.3, 23.5; HRMS (APCI) calcd for $C_{42}H_{34}Br_2O_4$ $[M]^+$ 762.0803, found 762.0806.

Compound *M*-8. According to the same method as above, compound *M*-**8** (145 mg, 98% yield) was obtained as a yellow powder: R_f = 0.52 (PE/DCM, v/v = 1:1); mp 140−142 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 8.10 (dd, J = 6.5, 3.4 Hz, 2H), 7.51 (dd, J = 6.6, 3.2 Hz, 2H), 7.19 (s, 2H), 7.12−6.98 (m, 4H), 6.83 (d, J = 5.9 Hz, 2H), 6.71 (t, J = 5.3 Hz, 2H)., 4.31 (d, J = 5.2 Hz, 2H), 4.01 (d, J = 5.2 Hz, 2H), 3.31 (d, J = 16.8 Hz, 2H), 3.03 (s, 6H), 2.44−2.26 (m, 4H), 1.53 (t, J = 11.6 Hz, 2H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 148.7, 138.9, 135.4, 134.6, 134.4, 134.3, 130.2, 129.8, 129.3, 126.8, 125.8, 125.4, 124.7, 123.4, 114.7, 97.3, 56.7, 28.3, 23.5; HRMS (ESI) calcd for $C_{42}H_{34}Br_2O_4Na$ $[M + Na]^+$ 785.0696, found 785.0698.

Compound (−)-*P*-1f. To a mixture of K_2CO_3 (210 mg, 1.52 mmol), Ag_2CO_3 (105 mg, 0.38 mmol), *S*-Phos (311.6 mg, 0.76 mmol), and $Pd(OAc)_2$ (4.4 mg, 0.019 mmol) were added 2,3,5,6-tetrafluorobenzotrifluoride (0.21 mL, 1.52 mmol) and *i*-PrOAc (3 mL). The mixture was stirred for 2 min at room temperature, and then MOM-protected compound *P*-**8** (145 mg, 0.19 mmol) was added. The reaction mixture was stirred for another 12 h at 80 °C, cooled to room temperature, passed through a plug of Celite, and then washed with DCM. After the organic layer was concentrated by reduced pressure, the residue was purified by column chromatography on silica gel with DCM and petroleum ether (1:1, v/v) as eluent. To the solution of the above product in MeOH (10 mL) and THF (10 mL) was added Amberlyst 15 resin (200 mg). After the mixture was stirred at 65 °C overnight, the resin was filtered off, and the solvent was removed by reduced pressure. The organic layer was passed through a silica plug with DCM and petroleum ether (2:1, v/v) as eluent to afford the product (79 mg, 49% yield for two steps) as a yellow powder: $[\alpha]_D^{25}$ = −450 (c = 1.0 mg mL^{-1}, DCM); R_f = 0.47 (PE/DCM, v/v = 2:1); mp 206−208 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 8.15 (dd, J = 6.6, 3.4 Hz, 2H), 7.55 (dd, J = 6.5, 3.1 Hz, 2H), 7.22−7.17 (m, 4H), 6.95 (t, J = 7.6 Hz, 2H), 6.88 (s, 2H), 6.72 (d, J = 7.4 Hz, 2H), 6.19 (d, J = 7.8 Hz, 2H), 5.37 (s, 2H), 3.37 (d, J = 14.9 Hz, 2H), 2.47 (t, J = 14.9 Hz, 2H), 2.35 (d, J = 13.9 Hz, 2H), 1.49 (t, J = 14.5 Hz, 2H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 148.2, 144.5, 142.6, 140.5, 138.6, 137.6, 135.6, 135.2, 134.5, 133.0, 130.9, 129.7, 129.5, 128.5, 128.3, 126.4, 126.3, 125.4, 125.0, 123.5, 112.0, 111.8, 110.2, 28.1, 23.9; HRMS (APCI) calcd for $C_{50}H_{25}F_{10}O_2$ $[M - H]^-$ 847.1700, found 847.1698.

Compound (+)-*M*-1f. According to the same method as the preparation of (−)-*P*-**1f**, compound (+)-*M*-**1f** (85 mg, 53% yield) was obtained as a yellow powder: $[\alpha]_D^{25}$= +436 (c = 1.0 mg mL^{-1}, DCM); R_f = 0.47 (PE/DCM, v/v = 2:1); mp 206−208 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 8.15 (dd, J = 6.5, 3.4 Hz, 2H), 7.55 (dd, J = 6.5, 3.2 Hz, 2H), 7.22−7.16 (m, 4H), 6.95 (t, J = 7.6 Hz, 2H), 6.88 (s, 2H), 6.72 (d, J = 7.4 Hz, 2H), 6.19 (d, J = 7.8 Hz, 2H), 5.37 (s, 2H), 3.36 (d, J = 18.1 Hz, 2H), 2.51 (t, J = 15.4 Hz, 2H), 2.35 (d, J = 9.6 Hz, 2H), 1.49 (t, J = 10.0 Hz, 2H).^{13}C NMR (126 MHz, $CDCl_3$) δ 148.2, 144.5, 142.5, 140.5, 138.5, 137.6, 135.6, 135.6, 135.2, 134.5, 133.0, 130.9, 129.7, 129.5, 128.5, 128.3, 126.4, 126.3, 125.4, 125.0, 123.5, 111.9, 110.2, 28.1, 23.9; HRMS (APCI) calcd for $C_{50}H_{25}F_{10}O_2$ $[M - H]^-$ 847.1700, found 847.1692.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.7b01087.

Copies of ^1H and ^{13}C NMR spectra for new compounds; fluorescence spectra of *P*-**1a−f** and *M*-**1a−f** in the presence of L-**9** and D-**9**; Stern−Volmer plot of *P*-**1a−e** and *M*-**1a−e** in the presence of L-**9** and D-**9**; HPLC resolution and analysis of enantiomers (PDF)

X-ray data for *rac*-**6** (CIF)

X-ray data for *P*-**7** (CIF)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: cchen@iccas.ac.cn.

ORCID

Chuan-Feng Chen: 0000-0002-4347-1406

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We thank the National Natural Science Foundation of China (21572233, 21332008, 51373180) and the Strategic Priority

DOI: 10.1021/acs.joc.7b01087
J. Org. Chem. 2017, 82, 7402−7409

Research Program of Chinese Academy of Sciences (XDB12010400) for financial support.

REFERENCES

(1) Shen, Y.; Chen, C.-F. *Chem. Rev.* **2012**, *112*, 1463−1535.
(2) (a) Abe, M.; Ohmori, K.; Suzuki, K.; Yamamoto, T. *J. Polym. Sci., Part A: Polym. Chem.* **2010**, *48*, 1844−1848. (b) Rybacek, J.; Huerta-Angeles, G.; Kollarovic, A.; Stara, I. G.; Stary, I.; Rahe, P.; Nimmrich, M.; Kuhnle, A. *Eur. J. Org. Chem.* **2011**, *2011*, 853−860. (c) Stara, I. G.; Stary, I.; Kollarovic, A.; Teply, F.; Saman, D.; Fiedler, P. *Collect. Czech. Chem. Commun.* **2003**, *68*, 917−930. (d) Goedicke, C.; Stegemeyer, H. *Chem. Phys. Lett.* **1972**, *17*, 492−494. (e) Palewska, K.; Ruziewicz, Z. *Chem. Phys. Lett.* **1979**, *64*, 378−382. (f) Borkent, J. H.; Diesveld, J. W.; Laarhoven, W. H. *Recl. Trav. Chim. Pays-Bas* **1981**, *100*, 114−118. (g) Laarhoven, W. H.; Cuppen, T.; Brinkhof, H. H. K. *Tetrahedron* **1982**, *38*, 3179−3182. (h) Prinsen, W. J. C.; Laarhoven, W. H. *J. Org. Chem.* **1989**, *54*, 3689−3694.
(3) (a) Li, M.; Feng, L.-H.; Lu, H.-Y.; Wang, S.; Chen, C.-F. *Adv. Funct. Mater.* **2014**, *24*, 4405−4412. (b) Li, M.; Lu, H.-Y.; Zhang, C.; Shi, L.; Tang, Z.-Y.; Chen, C.-F. *Chem. Commun.* **2016**, *52*, 9921−9924.
(4) Li, M.; Li, X.-J.; Lu, H.-Y.; Chen, C.-F. *Sens. Actuators, B* **2014**, *202*, 583−587.
(5) Li, M.; Niu, Y.-L.; Zhu, X.-Z.; Peng, Q.; Lu, H.-Y.; Xia, A.-D.; Chen, C.-F. *Chem. Commun.* **2014**, *50*, 2993−2995.
(6) Li, M.; Yao, W.; Chen, J.-D.; Lu, H.-Y.; Zhao, Y.; Chen, C.-F. *J. Mater. Chem. C* **2014**, *2*, 8373−8380.
(7) Li, M.; Niu, Y.; Lu, H.-Y.; Chen, C.-F. *Dyes Pigm.* **2015**, *120*, 184−189.
(8) (a) Chen, Y.; Yekta, S.; Yudin, A. K. *Chem. Rev.* **2003**, *103*, 3155−3212. (b) Chen, J.-D.; Fang, L.; Chen, C.-F. *Mini-Rev. Org. Chem.* **2015**, *12*, 310−327.
(9) (a) Pu, L. *Chem. Rev.* **1998**, *98*, 2405−2494. (b) Pu, L. *Acc. Chem. Res.* **2012**, *45*, 150−163. (c) Yu, S.; Pu, L. *Tetrahedron* **2015**, *71*, 745−772.
(10) Jiao, J.-M.; Wei, G.; Li, F.; Mao, X.-R.; Cheng, Y.-X.; Zhu, C.-J. *RSC Adv.* **2014**, *4*, 5887−5892.
(11) Wang, Q.; Chen, X.; Tao, L.; Wang, L.; Xiao, D.; Yu, X.-Q.; Pu, L. *J. Org. Chem.* **2007**, *72*, 97−101.
(12) Lin, J.; Hu, Q.-S.; Xu, M.-H.; Pu, L. *J. Am. Chem. Soc.* **2002**, *124*, 2088−2089.
(13) Wang, F.; Nandhakumar, R.; Hu, Y.; Kim, D.; Kim, K. M.; Yoon, J. *J. Org. Chem.* **2013**, *78*, 11571−11576.
(14) (a) Li, Z.-B.; Lin, J.; Zhang, H.-C.; Sabat, M.; Hyacinth, M.; Pu, L. *J. Org. Chem.* **2004**, *69*, 6284−6293. (b) Liu, H.-L.; Zhu, H.-P.; Hou, X.-L.; Pu, L. *Org. Lett.* **2010**, *12*, 4172−4175.
(15) Reetz, M. T.; Sostmann, S. *Tetrahedron* **2001**, *57*, 2515−2520.
(16) (a) Shen, Y.; Lu, H.-Y.; Chen, C.-F. *Angew. Chem., Int. Ed.* **2014**, *53*, 4648−4651. (b) Lin, W.-B.; Li, M.; Fang, L.; Shen, Y.; Chen, C.-F. *Chem. - Asian J.* **2017**, *12*, 86−94.
(17) CCDC 1500435 (*rac*-**6**) and 1500437 (*P*-**7**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.
(18) Brown, A.; Kemp, C.; Mason, S. F. *J. Chem. Soc. A* **1971**, *5*, 751−755.
(19) Iwanek, W.; Mattay, J. *J. Photochem. Photobiol., A* **1992**, *67*, 209−226.

DOI: 10.1021/acs.joc.7b01087
J. Org. Chem. 2017, 82, 7402−7409