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Chiral Fluorescent Receptors based on Amino Acid Unit: Synthesis and Their Enantioselective Recognition

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Three chiral fluorescent receptors (1, 2 and 3) were synthesized and their structures were characterized by IR, ^{1}H NMR, ^{13}C NMR, MS spectra and elemental analysis. The enantioselective recognition of receptors 1, 2 and 3 were studied by fluorescence spectra and ^{1}H NMR spectra. The results demonstrate that receptors 1, 2 and 3 with the N-Boc-protected phenylalanine anion formed a 1:1 complex. The receptor 3 exhibits good enantioselective recognition ability toward the enantiomers of the N-Boc-protected phenylalanine anion.

Keywords: Chiral receptor; Synthesis; Fluorescent sensor; Enantioselective recognition

INTRODUCTION

Enantioselective recognition is one of the essential reaction processes occurring in living systems. The development of enantioselective receptors is receiving growing research attention because such receptors can potentially provide a real time technique to determine the enantiomertic composition of chiral molecules [1–4]. Fluorescent sensors based on molecular recognition are of particular interest, on account of their high sensitivity and selectivity [5], being able to detect metal ions [6,7], anions [8] and organic bioactive molecules [9,10]. The enantioselective fluorescence sensor is more important because of their potential application in a rapid detection of enantiomer purity and bioactive molecules, and has an important significance for promoting development of medicament, chiral catalyst and biochemistry [11]. However, very few examples of enantioselective fluorescence sensors have been reported so far [12–17]. Amide and amino group is all good H-bonding donor, which are used widely to design and synthesize artificial receptors for anions [18–25]. We have previously utilized amide or amino as binding sites for the chiral anions, such as mandelate and tartaric acid derivatives [26]. Herein we designed and synthesized three new chiral fluorescence sensors (**1**, **2** and **3**) which have two chiral centers in close proximity to the binding sites of the sensors and their enantioselective recognition for D- and L-N-Boc-protected phenylalanine anions was studied by fluorescence and ^{1}H NMR spectra. The synthetic route of sensors is shown in Scheme 1.

RESULTS AND DISCUSSION

Synthesis

The chiral fluorescent receptors (**1, 2** and **3**) were efficiently synthesized by the reaction of intermediates **10**, **11** or **12** and 9-anthraldehyde, and then reduced by $NaBH_4$ (Scheme 1). To avoid a cyclic product, the intermediates **10**, **11** or **12** were prepared with good yields by the reaction of compound **7**, **8** or **9** and excess of ethylenediamine. The structures of these compounds were characterized by IR, ^{1}H NMR and ^{13}C NMR spectra. Because the stereogenic centers of receptors **1**, **2** and **3** disturb the symmetry of the molecule, the ^{13}C NMR spectra of receptors **1**, **2** and **3** produced more carbon signals. This pattern is similar to that which has been observed previously [27,28].

Receptors **1**, **2** and **3** are easily soluble in common organic solvents, such as $CHCl_3$, CH_3OH, DMSO, and DMF.

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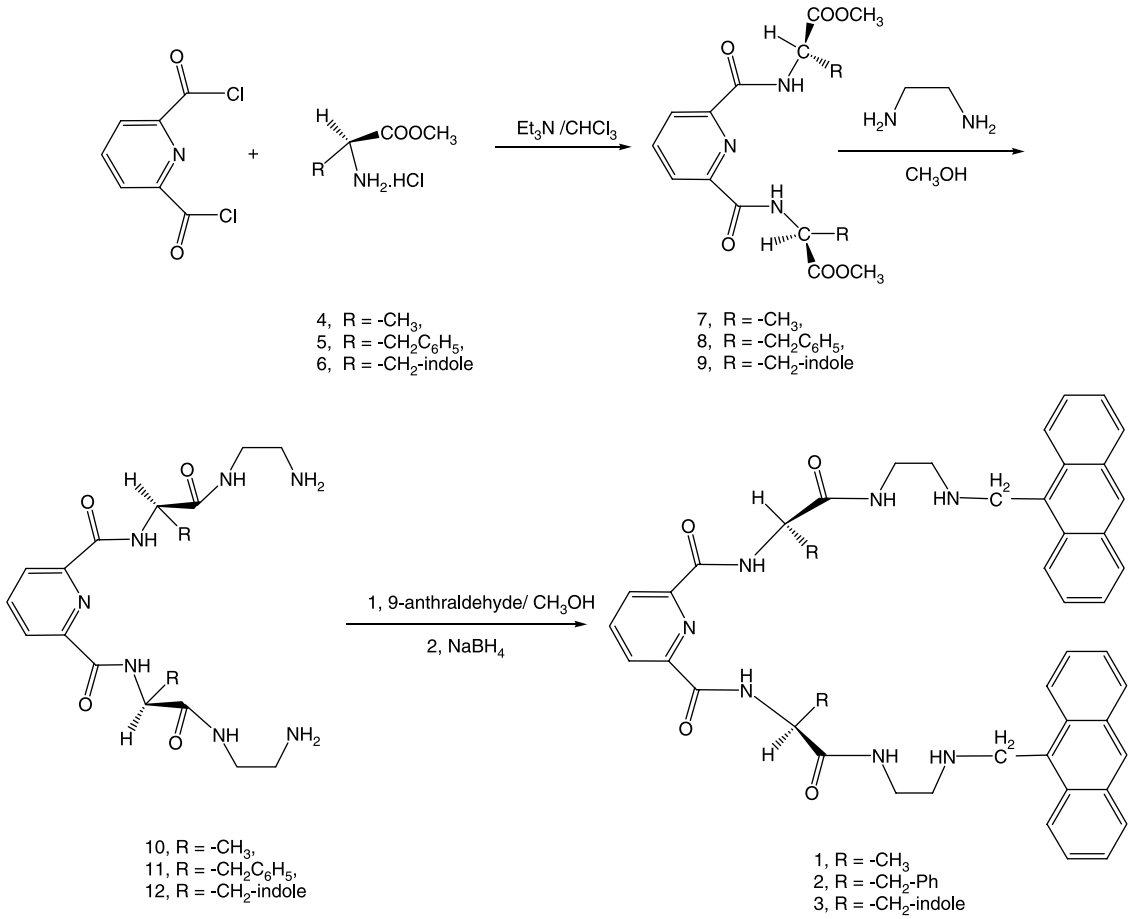

SCHEME 1 The synthesis of receptors.

Fluorescence Spectra

In order to investigate the properties of the chiral recognition of receptors **1**, **2** and **3**, N-Boc-protected-alanine and phenylalanine tetrabutylammonium salts (D- and L-Ala anions, D- and L-Phe anions) were chosen as the guests. The fluorescence spectra were recorded from the solution of receptors **1**, **2** or **3** in DMSO in the absence and presence of various anions. Figures 1 and 2 show the fluorescence spectra of a mixture of receptor **3** (2.0×10^{-5} mol·L^{-1}) with different concentration of D- or L-Phe anion in DMSO. With a gradual increase of the concentration of D- or L-Phe anion, the fluorescent quenching phenomena of **3** at 396 nm, 418 nm and 435 nm (λ_{ex} = 372 nm) were observed, which indicated that the complexation happened between receptor **3** and D- or L-Phe anion, respectively. Figure 3 showed the fluorescence intensity change of receptor **3** at 418 nm upon the addition of L- or D-Phe anion. While on the addition of D- or L-Ala anion to the solution of receptor **3** (2.0×10^{-5} mol·L^{-1}) in DMSO, the fluorescence spectra of **3** were almost unchanged as shown in Fig. 4, which indicates that there were no effective complexation between the receptor **3** and D- or L-Ala anion, respectively. When D- or L-Ala anion was added to the solution (2.0×10^{-5} mol·L^{-1}) of receptor **1** or **2** (λ_{ex} = 372 nm), similar phenomena were observed, which indicated that the π-π stack interactions between aromatic-rings of host and guest were the important factor in the complexation process [22,29,30].

In the presence of amino acid anions, the fluorescence quenching of receptors **1**, **2** and **3** most

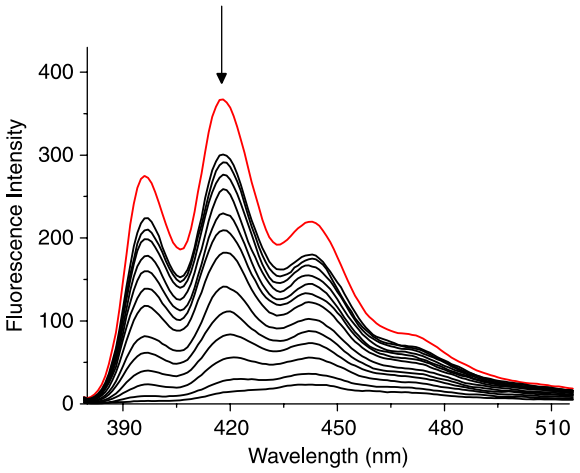

FIGURE 1 Fluorescence spectra of receptor **3** (2.0×10^{-5} mol L^{-1}) with D-Phe anion in DMSO. The equivalents of anion are: 0, 1.9, 4.2, 6.7, 9.7, 13.9, 20.3, 25.4, 40.7, 65.3, 95.5, 154.2, 227.1 and 350.0. λ_{ex} = 372 nm.

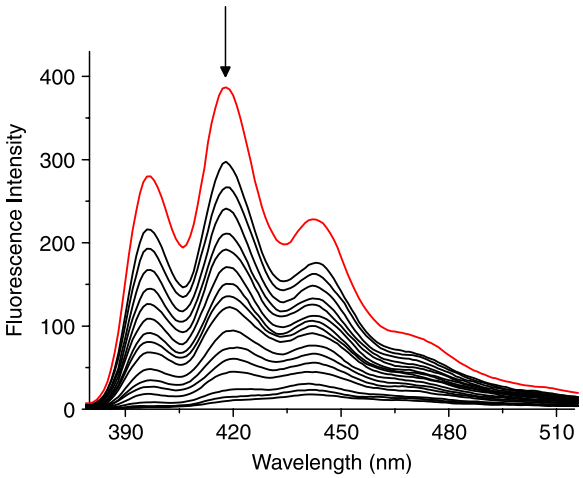

FIGURE 2 Fluorescence spectra of receptor **3** (2.0×10^{-5} mol L^{-1}) with L-Phe anion in DMSO. The equivalents of anion are: 0, 5.8, 11.7, 17.5, 23.3, 29.2, 35.0, 40.8, 46.7, 52.5, 64.2, 87.5, 99.2, 128.3, 157.5 and 186.7. λ_{ex} = 372 nm.

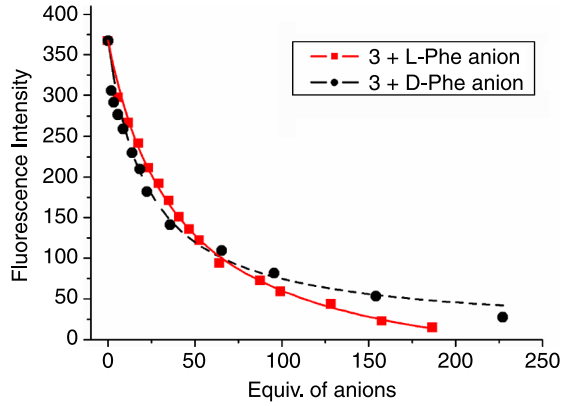

FIGURE 3 Fluorescence intensity change of receptor **3** (2.0×10^{-5} mol L^{-1}) at 418 nm upon addition of L- or D-Phe anion in DMSO. λ_{ex} = 372 nm. The line is fitting curve. The correlation coefficient (R) of non-linear curve fitting is 0.9949 (**3** with D-Phe anion) and 0.9917 (**3** with L-Phe anion).

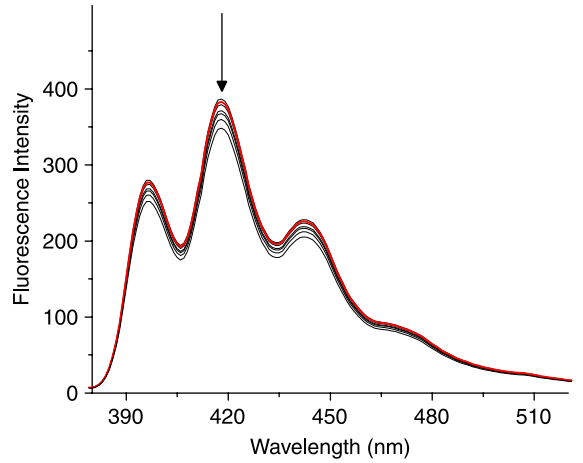

FIGURE 4 Fluorescence spectra of receptor **3** (2.0×10^{-5} mol L^{-1}) with D-Ala anion in DMSO. The equivalents of anion are from 0 to 350. λ_{ex} = 372 nm.

likely arises from the change of the free energy (ΔG_{PET}) of electron transfer between the excited fluorophore and the receptor [31,32]. When the anion was introduced into a solution of either receptor **1**, **2** or **3**, the reductive potential of the amide group increased along with the ratio of the electron transfer from the HOMO orbit of the receptors to the excited anthryl group, which in turn leads to the intramolecular PET (photo-induced electron transfer) process being easier [32–34]. Therefore fluorescence quenching was observed. The satisfactory result (the correlation coefficient is over 0.99) of non-linear curve fitting (fluorescence intensity at 418 nm versus equivalent of Phe anion) confirmed that receptor **1**, **2** or **3** and D- or L-Phe anion formed a 1:1 complex (see the Fig. 3) [35]. For the complex of 1:1 stoichiometry, an association constant K_{ass} can be calculated by using the following equation [35–37]:

$$X = X_0 + (X_{lim} - X_0)/2C_0\{C_H + C_G + 1/K_{ass} - [(C_H + C_G + 1/K_{ass})^2 - 4C_H C_G]^{1/2}\}$$

Where X represents the fluorescence intensity, and C_H and C_G are the corresponding concentrations of host and anion guest. The association constants (K_{ass}) and correlation coefficients (R) obtained by a non-linear least-squares analysis of X versus C_H and C_G are listed in Table I. The fluorescence emission intensities of receptor **1** or **2** (λ_{ex} = 372 nm) were also quenched when anions were added. The results of non-linear curve fitting (at 418 nm) also indicate that a 1:1 complex was formed between receptor **1** or **2** with D- or L-Phe anion, respectively. The association constants (K_{ass}) and correlation coefficients (R) obtained by a non-linear least-squares analysis of X versus C_H and C_G are also listed in Table I.

The data in Table I illustrated that the association constants of **1**, **2** or **3** with D-Phe anion were much higher than that of receptors **1**, **2** or **3** with L-Phe anion, which was probably due to the D-Phe anion having a more complementary structure with the receptors **1**, **2** or **3**. Receptor **3** has a good enantioselective recognition ability to the enantiomers of Phe anion, the enantioselectivity $K_{ass(D\text{-}Phe)}/K_{ass(L\text{-}Phe)}$ is about 5, which may be due to the NH of indole participating in the complexation with the anion guests.

^{1}H NMR Study

^{1}H NMR experiments were undertaken to assess the enantioselective recognition properties between host and guest because it can provide direct structural and dynamic information [38,39]. Studies on the enantioselective recognition were carried out on a 300 MHz NMR spectrometer using the compounds **1**, **2** or **3** as chiral solvating agents in $CDCl_3$ at room temperature.

TABLE I Association constants (K_{ass}), correlation coefficients (R) and enantioselectivities K_D/K_L of receptor **1**, **2** and **3** with D- or L-Phe anions in DMSO

	Receptor **1**			Receptor **2**			Receptor **3**		
Anion[a]	K_{ass} (M^{-1})[b]	R	K_D/K_L	K_{ass} (M^{-1})[b]	R	K_D/K_L	K_{ass}(M^{-1})[b]	R	K_D/K_L
D-Phe	$(5.94 \pm 0.45) \times 10^3$	0.9966	3.19	$(7.64 \pm 0.45) \times 10^3$	0.9962	2.55	$(1.24 \pm 0.10) \times 10^4$	0.9949	4.98
L-Phe	$(1.86 \pm 0.13) \times 10^3$	0.9967		$(3.00 \pm 0.24) \times 10^3$	0.9939		$(2.49 \pm 0.23) \times 10^3$	0.9917	

[a]The anions were used as their tetrabutylammonium salts; [b]All error values were obtained by the results of nonlinear curve fitting.

The Phe anion was chosen as the probe. Figure 5A shows the ^{1}H NMR spectrum of the racemic Phe anion, the peaks at 4.17 ppm for the CH proton resonance of racemic Phe anion were observed in the absence of host. The ^{1}H NMR spectra of the receptor **3** (2×10^{-3} M) and its complex with equimolar amounts (2×10^{-3} M) of racemic, D- or L-Phe anion are shown in Fig. 5. When treated with equimolar amounts of receptor **3**, the CH proton signal of the racemic Phe anion cleaved into two triplet peaks

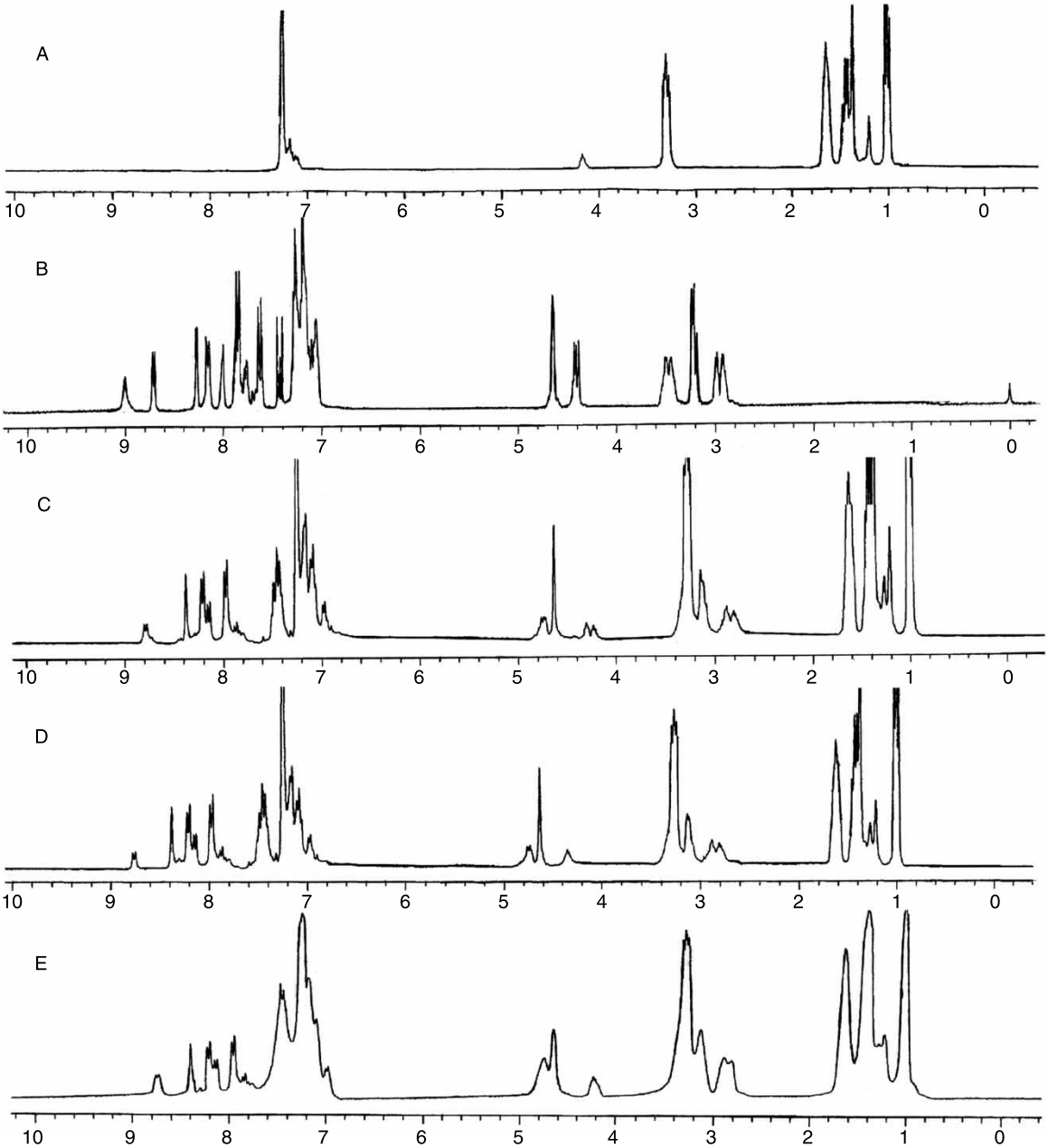

FIGURE 5 ^{1}H NMR spectra of receptor **3** and their complexes with Phe anion at 25°C in $CDCl_3$ at 300 MHz. (A) [racemic Phe anion] $= 2.0 \times 10^{-3}$ mol·L^{-1}; (B) [receptor **3**] $= 2.0 \times 10^{-3}$ mol·L^{-1}; (C) [receptor **3**] = [racemic Phe anion] $= 2.0 \times 10^{-3}$ mol·L^{-1}; (D) [receptor **3**] = [D-Phe anion] $= 2.0 \times 10^{-3}$ mol·L^{-1}; (E) [receptor **3**] = [L-Phe anion] $= 2.0 \times 10^{-3}$ mol·L^{-1}.

(Fig. 5C) with a downfield shift (from δ 4.17 ppm to 4.31 ppm and 4.24 ppm), and their intensity ratio is about 1:1. This indicateed that the interactions of receptor **3** with the D and L forms of Phe anion were different, resulting in the different chemical shift for the racemic CH proton. The CH proton singles of D- and L-Phe anion were shifted downfield about 0.14 ppm and 0.07 ppm in the presence of the receptor **3** (Fig. 5D, 5E), respectively. The larger downfield shift of the CH proton toward D-enantiomer revealed that the receptor **3** had stronger enantioselective recognition ability toward D-Phe anion than its L-enantiomer.

The similar phenomena were observed when adding equimolar amounts of the racemic Phe anion to a solution of **1** or **2**. The signals of the CH proton of racemic Phe anion were observed with $\Delta\delta$ 0.09 ppm and 0.05 ppm for receptor **1** and 0.09 ppm and 0.04 ppm for receptor **2** downfield shifts, respectively.

The ^{1}H NMR spectra of receptors **1**, **2** and **3** showed dramatic changes in the presence of the guest anion. Upon the addition of equimolar amount of D-Phe anion to the solution of receptor **3**, the peaks of anthracene proton signals were downfield shifted from 8.26–7.26 ppm to 8.38–7.36 ppm, one characteristic peak of amine (N**H**) at 8.97 ppm disappeared, one peak of amide (N**H**) was upfield shifted from 7.05 ppm to 6.90 ppm ($\Delta\delta$ 0.15 ppm), the other peak of amide (N**H**) at 8.77 ppm and 8.74 ppm had a little downfiled shifed. Upon the addition of equimolar amounts of L-Phe anion to the solution of **3**, the peaks of anthracene proton signals were also downfield shifted to 8.39–7.38 ppm, the peaks of amide (N**H**) also happened different chemical shift changes.

The above results illustrated that the enantioselective recognition of receptors **1**, **2** and **3** for D- or L-Phe anion were mainly through multiple hydrogen bonding interactions [40,41] and the π-π stack interaction between anthryl-ring of the host and phenyl-ring of the guest [22,29,30].

CONCLUSION

In summary, three chiral fluorescent receptors (**1**, **2** and **3**) were synthesized. The enantioselective recognition abilities of receptors was studied by ^{1}H NMR and fluorescence spectra. Receptors (**1**, **2** and **3**) exhibit different enantioselective recognition abilities toward the enantiomers of N-Boc-protected-phenylalanine anion, and formed 1:1 complex between host and guest, and receptor **3** has better enantioselective recognition ability than the receptors **1** and **2**. The steric effect, multiple hydrogen bondings and π—π stacking between host and guest may be responsible for the chiral recognition of receptors. Receptor **3** is promising in its use as a fluorescent sensor for chiral anions.

EXPERIMENTAL

Materials and Methods

Ethylenediamine and triethylamine were distilled before use; chloroform was washed with water and dried from $CaCl_2$. All other commercially available regents were used without further purification. The anions were used as their tetrabutylammonium salts. Fluorescence spectra were obtained on a Shimadzu RF–5301. Melting points were measured on Reichert 7905 melting-point apparatus (uncorrected). The IR spectra were performed on a Nicolet 670 FT–IR spectrophotometer. Mass spectra were recorded on a Finnigan LCQ advantage mass spectrometer. ^{1}H NMR spectra were recorded on a Varian Mercury VX–300 MHz spectrometer. ^{13}C NMR spectra were recorded on a Varian Inova unity–600 MHz spectrometer. Elemental analysis was determined with a FlashEA1112 instrument.

Intermediates **4**, **5**, **6** and 9-anthraldehyde were prepared according to the literature method. [42–44].

Syntheses

The Synthesis of Intermediates 7, 8 and 9

To a solution of L-amino acid methyl hydrochloride (**4**, **5** or **6**, 2.1 mmol) and triethylamine (4 equiv. for each amino acid methyl hydrochloride) in anhydrous chloroform (20 mL), pyridine-2,6-dicarboyl dichloride (0.5 equiv. for each amino acid methyl hydrochloride) in anhydrous chloroform (10 mL) was dropwise added in an ice brine bath under nitrogen atmosphere. After addition, the reaction mixture was stirred at 0°C for 1 h and then stirred for 12 h at room temperature. The reaction solution was washed with H_2O (3 × 20 mL) the organic layer was dried over anhydrous Na_2SO_4. After filtration the solvent was evaporated under reduced pressure. The crude product was purified by column chromatography on silica gel using $CHCl_3/C_2H_5OH$ (100/1) as eluant to obtain pure products **7**, **8** and **9**, respectively.

Compound **7**: Yield 87%; m.p. 74–76°C; IR(KBr): 3341, 2992, 2953, 1743, 1680, 1536, 1450, 1215, 1171, 672 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ: 8.38 (br, 2H, amide), 8.36 (d, J = 7.9 Hz, 2H, Py-H), 8.03 (t, J = 8.9 Hz, 1H, Py-H), 4.86–4.77 (m, 2H, *CH), 3.83 (s, 6H, CH_3), 1.60 (d, J = 7.2 Hz, 6H, CH_3); ^{13}C NMR (150 MHz, $CDCl_3$): δ (ppm) 171.6, 167.8, 148.5, 138.8, 127.5, 52.1, 50.9, 17.2, 16.9; Elemental analysis calcd. (%) for $C_{15}H_{19}N_3O_6$: C, 53.39; H, 5.68; N, 12.46; found: C, 53.42; H, 5.71; N, 12.45.

Compound **8**: Yield 90%; m.p. 88–90°C; IR(KBr): 3335, 3027, 294, 1750, 1679, 1516, 1443, 1249, 1193, 757, 702 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ: 8.34 (br, 2H, amide), 8.06–8.00 (m, 3H, Py-H), 7.16–7.33 (m, 10H, Ar-H), 5.10–5.04 (m, 2H, *CH), 3.82 (s, 6H, CH_3),

3.36–3.17 (m, 4H, CH_2); ^{13}C NMR (150 MHz, $CDCl_3$): δ(ppm) 172.9, 168.5, 148.2, 139.4, 138.8, 128.1, 125.9, 124.9, 53.8, 50.6, 37.1, 36.9; Elemental analysis calcd. (%) for $C_{27}H_{27}N_3O_6$: C, 66.23; H, 5.56; N, 8.59; found: C, 66.27; H, 5.58; N, 8.60.

Compound **9**: Yield 91%; m.p. 112–114°C; IR (KBr): 3403, 2953, 2926, 1740, 1668, 1525, 1439, 1213, 1099, 744 cm^{-1}; ^1H NMR ($CDCl_3$) δ: 8.41 (b, 2H, Ind-NH), 8.36 (d, $J = 7.2$ Hz, 2H, Py-H), 8.11 (t, $J = 8.9$ Hz, 1H, Py-H), 8.04 (d, $J = 8.1$ Hz, 2H, Ind-7-H), 7.50 (d, $J = 8.2$ Hz, 2H, Ind-4-H), 7.35–7.24 (m, 4H, Ind-5,6-H), 6.97 (d, $J = 8.7$ Hz, 2H, Ind-2-H), 5.27–5.21 (m, 2H, *CH), 3.85 (s, 6H, CH_3), 3.41–3.32 (m, 4H, CH_2); ^{13}C NMR (150 MHz, $CDCl_3$): δ(ppm) 173.5, 168.5, 149.2, 139.4, 137.8, 128.1, 125.9, 123.0, 120.3, 119.4, 112.7, 109.0, 53.8, 50.6, 30.9; Elemental analysis calcd. (%) for $C_{31}H_{29}N_5O_6$: C, 65.58; H, 5.15; N, 12.34; found: C, 65.57; H, 5.23; N, 12.31.

The Synthesis of Intermediates 10, 11 and 12

The solution of **7, 8** or **9** (1 mmol) in methanol (30 mL) was added dropwise to the stirred solution of ethylenediamine (0.6 g, 10 mmol) in methanol (10 mL). The mixture was stirred for 48 h under N_2 protection at room temperature. The solvent and excess ethylenediamine were removed under reduced pressure, and the residue was dried in vacuum to give the products **10, 11** and **12** as a slightly hygroscopic solid.

Compound **10**: Yield: 94%; IR(KBr): 3424, 2989, 2947, 1655, 1533, 1442, 1382 cm^{-1}; ^1H NMR (DMSO-d_6) δ: 9.10 (br, 2H, amide), 7.66 (d, $J = 7.5$ Hz, 2H, Py-H), 7.23 (t, $J = 7.5$ Hz, 1H, Py-H), 6.99 (br, 2H, amide), 4.38–4.24 (m, 2H, *CH), 2.64–2.60 (m, 4H, C**H**$_2$$CH_2$-$NH_2$), 3.17–3.11 (m, 4H, CH_2C**H**$_2$$NH_2$), 2.34–2.19 (m, 4H, CH_2CH_2N**H**$_2$), 1.40 (d, $J = 7.2$ Hz, 6H, CH_3); ^{13}C NMR (150 MHz, $CDCl_3$): δ (ppm) 171.5, 168.1, 148.1, 138.9, 124.9, 52.9, 42.1, 40.9, 17.9, 17.5; Elemental analysis calcd. (%) for $C_{17}H_{27}N_7O_4$: C, 51.88; H, 6.92; N, 24.93; found: C, 51.83; H, 7.01; N, 24.88.

Compound **11**: Yield: 97%; IR(KBr): 3487, 3282, 3025, 2923, 1650, 1528, 1442, 752, 703 cm^{-1}; ^1H NMR (DMSO-d_6) δ: 9.17 (br, 2H, amide), 8.19–8.10 (m, 3H, Py-H), 7.39 (br, 2H, amide), 7.32–7.19 (m, 10H, Ar-H), 4.75–4.71 (m, 2H, *CH), 3.37–3.05 (m, 12H, $CH_2CH_2NH_2$); ^{13}C NMR (150 MHz, $CDCl_3$): δ (ppm) 172.4, 167.2, 148.6, 139.8, 138.0, 128.4, 126.8, 125.1, 52.7, 42.1, 40.9, Elemental analysis calcd. (%) for $C_{29}H_{35}N_7O_4$: C, 63.82; H, 6.47; N, 17.98; found: C, 63.77; H, 6.51; N, 17.95.

Compound **12**: Yield: 95%; IR(KBr): 3399, 2926, 2861, 1653, 1524, 1440, 1101, 745 cm^{-1}; ^1H NMR (DMSO-d_6) δ: 10.79 (b, 2H, amide), 9.29 (b, 2H, Ind-NH), 9.06 (d, $J = 8.7$ Hz, 2H, Py-H), 8.61 (t, $J = 8.7$ Hz, 1H, Py-H), 8.04 (d, $J = 8.1$ Hz, 2H, Ind-7-H), 7.67 (t, $J = 7.2$ Hz, 2H, amide), 7.69 (s, 2H, Ind-2-H), 7.32–7.23 (m, 4H, Ind-5,6-H), 6.97 (d, $J = 10.6$ Hz, 2H, Ind-4-H), 4.76–4.74 (m, 2H, *CH), 3.41–3.32 (m, 4H, CH_2-Ind), 3.37–3.11 (m, 12H, $CH_2CH_2NH_2$); ^{13}C NMR (150 MHz, $CDCl_3$): δ (ppm) 173.8, 168.6, 148.6, 138.4, 137.8, 128.5, 125.2, 123.1, 120.6, 119.6, 112.6, 111.2, 53.4, 42.5, 41.2, 31.7, 30.9; Elemental analysis calcd. (%) for $C_{33}H_{37}N_9O_4$: C, 63.53; H, 5.98; N, 20.22; found: C, 63.49; H, 6.03; N, 20.18.

The Synthesis of Receptors 1, 2 and 3

A mixture of **10, 11** or **12** (1 mmol) and 9-anthraldehyde (2.2 mmol) in CH_3OH (10 mL) was stirred for 24 h at room temperature, and following this $NaBH_4$ (0.2 g) was poured into the solution. The mixture was stirred for 24 h under N_2 protection at ambient temperature. Then the mixture was heated to 50°C and stirred for 2 h. The solvent was removed under reduced pressure, the residue was washed with water. The crude product was purified by column chromatography on silica gel using $CHCl_3/CH_3OH$ (50/1) as eluant to obtain pure products **1**, **2** and **3**, respectively.

Compound **1**: Yield: 79%; m.p.: 182–184°C; $[\alpha]_D^{20} = -9.6°$ (*c* 0.05, $CHCl_3$); IR (KBr): 3302, 3054, 2933, 1653, 1528, 1236, 733 cm^{-1}; ^1H NMR ($CDCl_3$) δ: 9.10 (br, 2H, amide), 8.33 (s, 2H, anthryl), 8.30–8.10 (m, 8H, anthryl), 7.92 (d, $J = 8.1$ Hz, 4H, anthryl), 7.80 (t, $J = 8.7$ Hz, 1H, Py-H), 7.47–7.36 (m, 6H, Py-H, anthryl), 6.76 (b, 2H, amide), 4.79 (s, 2H, anthracene-CH_2), 4.68–4.62 (m, 4H, *CH, anthracene-CH_2), 3.51–3.49 (m, 4H, C**H**$_2$$CH_2$), 3.33–3.22 (m, 4H, CH_2C**H**$_2$), 2.93 (s, 2H, 2ArCH_2N**H**), 1.40 (d, $J = 6.6$ Hz, 6H, CH_3); ^{13}C NMR (150 MHz, $CDCl_3$): δ(ppm) 169.5, 161.3, 156.2, 136.4, 135.7, 129.9, 127.6, 123.4, 122.4, 119.9, 119.0, 116.7, 111.5, 110.6, 107.3, 67.3, 55.7, 40.0, 36.7, 28.5; ESI-MS *m/z* (%): 774 ($M^+ + 1$, 100). Elemental analysis calcd. (%) for $C_{47}H_{47}N_7O_4$: C, 72.94; H, 6.12; N, 12.67; found: C, 72.81; H, 6.19; N, 12.41.

Compound **2**: Yield 79%; m.p.: 194–196°C; $[\alpha]_D^{20} = -14.6°$ (*c* 0.05, $CHCl_3$); IR (KBr): 3416, 3060, 2923, 1651, 1524, 1446, 1384, 734, 706 cm^{-1}; ^1H NMR ($CDCl_3$) δ: 8.86 (br, 2H, amide), 8.35 (s, 2H, anthryl), 8.16 (d, $J = 8.7$ Hz, 4H, anthryl), 7.95 (d, 4H, $J = 7.5$ Hz, anthryl), 7.86 (t, $J = 7.5$ Hz, 1H, Py-H), 7.52–7.30 (m, 10H, anthryl, Py-H), 7.12 (d, $J = 7.5$ Hz, 4H, Ar-H), 7.05 (t, $J = 7.2$ Hz, 4H, Ar-H), 6.98–6.94 (m, 2H, Ar-H), 6.32 (br, 2H, amide), 4.76–4.69 (m, 2H, *CH), 4.56 (s, 4H, Ar-CH_2), 3.34–3.26 (m, 4H, C**H**$_2$$CH_2$), 3.15–3.04 (m, 6H, Ar-$CH_2$N**H**, PhC**H**$_2$), 2.86–2.74 (m, 4H, CH_2C**H**$_2$); ^{13}C NMR (150 MHz, $CDCl_3$): δ(ppm) 172.5, 168.7, 156.2, 155.7, 136.4, 135.6, 129.9, 127.7, 125.5, 123.5, 122.3, 119.8, 119.1, 116.7, 111.5, 110.6, 107.3, 80.4, 67.6, 55.9, 36.2, 35.7, 29.7; ESI-MS *m/z* (%): 926 ($M^+ + 1$,100); Elemental analysis calcd. (%) for $C_{59}H_{55}N_7O_4$: C, 76.52; H, 5.99; N, 10.59; found: C, 76.35; H, 6.02; N, 10.73.

Compound **3**: Yield 79%; m.p. 222–224°C; $[\alpha]_D^{20} = -17.2°$ (*c* 0.05, $CHCl_3$); IR (KBr): 3295, 3050,

2926, 1660, 1499, 1447, 735, 708 cm^{-1}; ^1H NMR ($CDCl_3$) δ: 8.97 (b, 2H, Ind-NH), 8.72 (b, 2H, amide), 8.26 (s, 2H, anthryl), 8.15 (d, $J = 8.1$ Hz, 4H, anthryl), 7.99 (b, 2H, Ind-2-H), 7.84 (d, $J = 8.1$ Hz, 6H, anthryl), 7.78 (d, $J = 8.1$ Hz, 2H, anthryl), 7.62 (d, $J = 7.5$ Hz, 4H, Ind-4,7-H), 7.44–7.41 (m, 3H, Py-H), 7.30–7.12 (m, 8H, anthryl, Ind-H), 7.05 (br, 2H, amide), 4.65 (s, 4H, Ar-CH_2), 4.45–4.37 (m, 2H, *CH), 3.53–3.34 (m, 4H, C**H**$_2$$CH_2$), 3.24–3.18 (m, 6H, Ar-$CH_2$N**H**, Ind-C**H**$_2$), 2.94–2.87 (m, 4H, CH_2C**H**$_2$); ^{13}C NMR (150 MHz, $CDCl_3$): δ(ppm) 176.5, 170.8, 158.1, 158.0, 138.5, 137.6, 135.7, 129.9, 127.6, 125.3, 123.5, 122.3, 119.8, 119.1, 116.7, 114.0, 111.5, 110.6, 107.3, 81.3, 68.9, 56.0, 36.4, 36.0, 29.7; ESI-MS *m/z* (%): 1004 ($M^+ + 1$, 100); Elemental analysis calcd. (%) for $C_{63}H_{57}N_9O_4$: C, 75.35; H, 5.72; N, 12.55; found: C, 75.13; H, 5.89; N, 12.29.

Tetrabutylammonium Salts

All tetrabutylammonium salts were prepared by adding 1 equiv of tetrabutylammonium hydroxide in methanol to a solution of the corresponding N-protected (by Boc) amino acid derivatives (1 equiv) in methanol. The mixture was stirred at room temperature for 2 h and evaporated to dryness under reduced pressure. The resulting syrup was dried at high vacuum and 50 °C for 24 h, checked by ^1H NMR and stored in a desiccator.

Binding Studies

The studies on the binding properties of **1**, **2** and **3** were carried out in DMSO or $CDCl_3$. The fluorescence titration was performed with a series of 2.0×10^{-5} mol·L^{-1} solutions of receptor **1**, **2** or **3** containing different amounts of chiral anions (the excited wavelength was 372 nm, the excitation and the emission slit width was 5 nm). ^1H NMR studies were recorded as adding equivalent racemic, D- or L-Phe anion into the receptors (2.0×10^{-3} mol·L^{-1}).

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