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Enantioselective fluorescent sensors for amino acid derivatives based on BINOL bearing benzoyl unit

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ABSTRACT

The derivatives of BINOL, (*S*)-**1** and (*R*)-**1**, and their analogues have been prepared and the structures of these compounds have been characterized by IR, MS, ^{1}H, and ^{13}C NMR spectroscopy and elemental analysis. The enantioselective recognition of these receptors has been studied by fluorescence titration and ^{1}H NMR spectroscopy. The receptors exhibited different chiral recognition abilities toward some enantiomers of chiral materials and formed 1:1 complexes between host and guest. Receptor (*S*)-**1** or (*R*)-**1** exhibits excellent enantioselective fluorescent recognition abilities toward amino acid derivatives.

1. Introduction

The chiral recognition of chiral compounds is an important subject not only in the field of supramolecular chemistry, but also in the field of medicinal and biomedical applications. In particular, supramolecular approaches to quickly determine the absolute configurations of chiral compounds are receiving increasing interest.[1] The basis of any chiral recognition event is the formation of diastereomeric complexes composed of a chiral receptor and a chiral substrate possessing different stabilities.[2] The crucial points in the molecular design of chemosensors are how to achieve the specific recognition of a certain molecule and how to transduce the recognition event into a signal.[3] Many efforts are involved in the covalent linking of an optical signaling unit (a chromophore or a fluorophore) to a specific receptor for the chiral molecules.[4] Compared with other detection methods, such as NMR, HPLC, CD, and capillary electrophoresis, fluorescence techniques have often been used to study the interaction between enantiomers and receptors because of their sensitivity, selectivity, and versatility.[5] On the basis of their respective advantages, we attempted to design some receptors with an optical response to the enantiomers in the recognition interaction, which may offer a simple method to explore the recognition process for more information. The binaphthyl unit was especially eye-catching because of its stable chiral configuration and tunable dihedral angle between the two naphthalene rings. Over the last two decades, binaphthyl derivatives have been shown to exhibit excellent enantioselectivities and turnovers in several types of asymmetric reactions, often matching the enantioselectivities traditionally regarded as being reserved for enzymes.[6] The enantioselective detection of amino acids and their derivatives has received attention because of the importance of this class of compounds in biological processes as well as in organic synthesis.[7] Herein, we report the development of 1,1′-bi-2-naphthol (BINOL) derivatives bearing a benzoyl unit; their chiral recognition ability toward two amino acid anions and two amino alcohols has been explored by a fluorimetric titration and a ^{1}H NMR study. Obvious changes in fluorescence and in NMR chemical shifts highlight the fact that compounds based on BINOL have excellent chiral recognition abilities toward the enantiomers of the *N*-Boc-protected alanine or phenylalanine anion.

2. Results and discussion

2.1. Synthesis

The starting material 2,2′-bis-methoxymethoxy-1,1′-binaphthyl, (*S*)-**2**, was prepared from 1,1′-bi-2-naphthol (BINOL).[8] The addition of benzoyl chloride led to the formation of (*S*)-**3** in 84% yield which upon hydrolysis under acidic conditions gave the enantiomerically pure (*S*)-**1** in 86% yield. In order to understand the functions of the aryl hydroxyl groups in the chiral recognition of (*S*)-**1**, we synthesized compound (*S*)-**4** where the hydroxyls were selectively protected with methyl groups (Scheme 1). The *ortho*-metalation of (*S*)-2,2′-dimethoxy-1,1′-binaphthalenyl,[9] (*S*)-**5**, with *n*-BuLi in the presence of TMEDA, followed by the addition of benzoyl chloride, gave (*S*)-**4** in 72% yield. In this compound, the two aryl hydroxyls are protected. In order to study how the aryl hydroxyls and BINOL groups in (*S*)-**1** and (*S*)-**4** influenced enantioselective fluorescent recognition, compounds (*R*)-**1** and (*R*)-**4**, the enantiomeric compounds of (*S*)-**1** and (*S*)-**4**, were also prepared. These are readily soluble in common organic solvents such as

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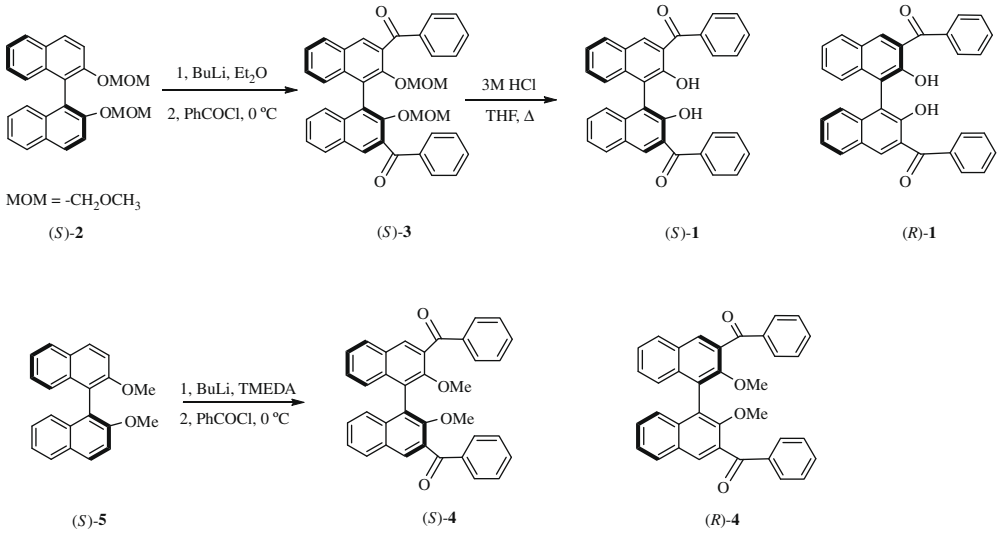

Scheme 1. Synthesis of the receptors (*S*)-**1**, (*R*)-**1**, (*S*)-**4**, and (*R*)-**4**.

$CHCl_3$, CH_2Cl_2, CH_3OH, DMSO, and DMF. The structures of all these compounds were characterized by IR, MS, ^1H, and ^{13}C NMR spectroscopy and elemental analysis.

2.2. Fluorescence spectra study

In order to investigate the properties of the enantioselectivity recognition of (*S*)-**1** and (*R*)-**1** various chiral carboxylates, such as mandelate, *N*-Boc-protected alanine anion (Ala), and *N*-Boc-protected phenylalanine anion (Phe) were also examined as the guests, which could increase the reaction between the receptor and guest by hydrogen bondings. The amino groups were protected by the *tert*-butyloxycarbonyl functionality. In each case tetrabutylammonium was used as the counter cation. We also chose two amino alcohols, namely alaninol and phenylalaninol, as guests to compare the associated abilities of the hosts to bind with neutral molecules (see Fig. 1).

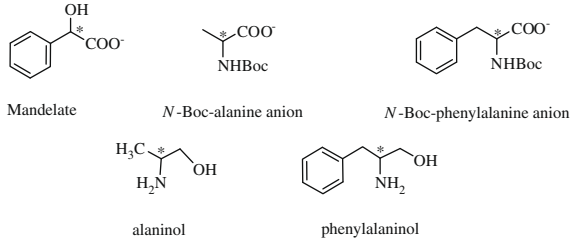

Figure 1. Structures of the guests.

The fluorescence spectra of receptor (*S*)-**1** were studied from a solution (2.24×10^{-6} mol L^{-1}) of $CHCl_3$ in the absence and presence of various enantiomers, (*S*)- or (*R*)-Ala, Phe, mandelate, alaninol, and phenylalaninol. Upon addition of (*S*)- or (*R*)-amino acid anions, a different fluorescent quenching degree of (*S*)-**1** was observed. The quenching efficiency of (*S*)-amino acid anions was much higher than that of the (*R*)-amino acid anions. Figures 2 and 3 show the fluorescence emission spectra of a mixture of (*S*)-**1** and different concentrations of the (*S*)- or (*R*)-Ala anion in $CHCl_3$ (λ_{ex} = 290 nm), respectively. The graphs in the top right corner of Figures 2 and 3 show the fluorescence intensity change of receptor (*S*)-**1** upon addition of (*S*)- and (*R*)-Ala anions, respectively. Figure 4 shows the different fluorescence intensity changes when the same equivalent of (*S*)- or (*R*)-Ala anion was added to the host (*S*)-**1**, the quenching efficiency was 51.6% when 11.4 equiv of (*S*)-Ala anion was added to the solution of (*S*)-**1**, while the quenching efficiency was only 84.5% when 11.4 equiv of (*R*)-Ala anion was added. The quenching efficiencies ($\Delta I_S/\Delta I_R$ = 3.12) indicated that the host (*S*)-**1** has a good enantioselective recognition ability between the (*S*)- and (*R*)-Ala anions, respectively.

Satisfactory non-linear curve fitting (the correlation coefficient is over 0.99) confirmed that (*S*)-**1** and the (*S*)- or (*R*)-Ala formed a 1:1 complex. For a complex of 1:1 stoichiometry, the association constant (K_{ass}) can be calculated by using Eq. 1 from the Origin 7.0 software package,[10,11] where I represents the fluorescence intensity, C_H and C_G are the host and guest concentrations, and C_0 is the initial concentration of the host. The association constants (K_{ass}) and correlation coefficients (R) obtained by a non-linear least squares analysis of I versus C_H and C_G are listed out in Table 1.

$$X = X_0 + (X_{lim} - X_0)/2C_0C_H + C_G + 1/K_{ass} - [(C_H + C_G + 1/K_{ass})^2 - 4C_HC_G]^{1/2}. \quad (1)$$

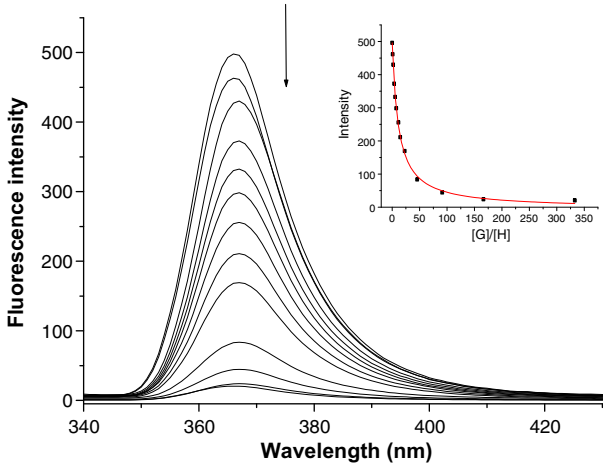

Figure 2. Fluorescence spectra of receptor (*S*)-**1** (2.24×10^{-6} mol L^{-1}) with (*S*)-Ala anion in $CHCl_3$. The anion equivalents are: 0, 0.92, 1.84, 3.68, 5.52, 7.36, 11.4, 14.72, 22.8, 45.6, 91.2, 166.4, and 332.8. λ_{ex} = 290 nm (EX: 5; EM: 5). Inset: changes in the fluorescence intensity of (*S*)-**1** at 367 nm upon addition of S-Ala anion. The line shown is a line-fitted curve. The correlation coefficient (R) of the non-linear curve fitting is 0.9994.

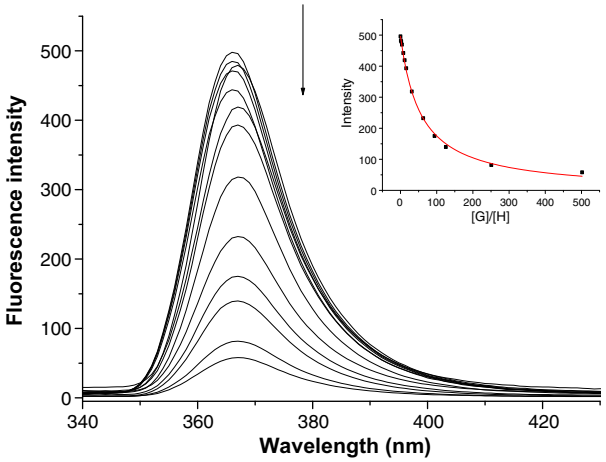

Figure 3. Fluorescence spectra of receptor (*S*)-**1** (2.24×10^{-6} mol L^{-1}) with (*R*)-Ala anion in $CHCl_3$. The anion equivalents are: 0, 0.98, 1.96, 3.92, 7.84, 11.4, 15.68, 31.36, 62.72, 94.08, 125.44, 250.88, and 501.76. λ_{ex} = 290 nm (EX: 5; EM: 5). Inset: changes in the fluorescence intensity of (*S*)-**1** at 367 nm upon addition of (*R*)-Ala anion. The line shown is a line-fitted curve. The correlation coefficient (*R*) of the non-linear curve fitting is 0.9922.

The continuous variation methods were also employed to determine the stoichiometric ratio of the receptor (*S*)-**1** with the guest (*S*)- and (*R*)-Ala anions. The total concentration of the host and guest was constant (1.0×10^{-6} mol L^{-1}) in $CHCl_3$, with a continuously variable molar fraction of host ([H]/([H]+[G])). Figure 5 shows the Job plots of receptor (*S*)-**1** with (*S*)- and (*R*)-Ala anions (at 367 nm, λ_{ex} = 290 nm). When the molar fraction of the host was 0.50, the fluorescence intensity reached a maximum, which demonstrated that receptor (*S*)-**1** formed a 1:1 complex with (*S*)- and (*R*)-Ala anions, respectively.[12]

Similar phenomena were observed when (*S*)- or (*R*)-Phe anions were added into a solution of (*S*)-**1**. The result of the non-linear curve fitting (at 367 nm) indicates that a 1:1 complex was formed between receptor (*S*)-**1** and (*S*)- or (*R*)-Phe (see Table 1). In addition, the association constants (K_{ass}) were different (see Table 1) ($K_{ass(S)} = (3.24 \pm 0.04) \times 10^4$ M^{-1}, $\Delta G_0 = -25.75$ kJ mol^{-1}; $K_{ass(R)} = (4.39 \pm 0.12) \times 10^4$ M^{-1}, $\Delta G_0 = -20.79$ kJ mol^{-1}), yielding an *S*/*R* selectivity [$K_{ass(S)}/K_{ass(R)}$] of 7.38 for the Phe anions and a $\Delta\Delta G_0$ value of −4.96 kJ mol^{-1}, demonstrating that (*S*)-**1** has good chiral recognition ability toward the enantiomers of Phe anions.

The decrease in the fluorescence intensity of the excimer upon addition of the anion is similar to the anion-induced fluorescence decrease reported previously.[13] In the binding with (*S*)- and (*R*)-Ala or Phe anions, the large fluorescence decrease can be attributed to the photoinduced electron transfer (PET) mechanism. When the guest anion binds with the host, an electron of anion transfers to the SOMO of the excited fluorophore, which in turn decreases the excited-state binaphthyl electron transferring to the LUMO. Therefore an anion-induced fluorescence decrease was observed.[14]

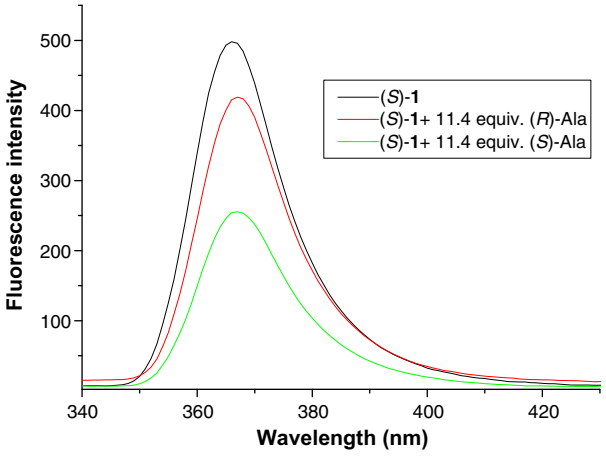

Figure 4. Fluorescence spectra of receptor (*S*)-**1** (2.24×10^{-6} mol L^{-1}) with 11.4 equiv of (*S*)- and (*R*)-Ala anions in $CHCl_3$.

The binding of (*S*)-**1** and mandelate was also carried out; the association constants of the host (*S*)-**1** and mandelate are listed out in Table 1. Receptor (*S*)-**1** exhibits weak enantioselective recognition ability toward mandelate we have tested (see Table 1). Upon the addition of alaninol or phenylalaninol into a solution of (*S*)-**1** in $CHCl_3$, the fluorescence intensity of (*S*)-**1** was slightly quenched by both (*S*)- and (*R*)-enantiomers (see Table 1). This indicates that hydrogen bonding plays an important role in the interaction between the host and guest and leads to easier signal transductions of chiral recognition by fluorescence method. The fluorescence responses of (*S*)-**4** in the presence of both enantiomers of Ala and Phe were investigated. When (*S*)-**4** was treated with them, no fluorescence quenching was observed, this demonstrates that the interaction of the hydroxyl protons with the amino acid anion is essential for the fluorescence quenching of (*S*)-**1**. This also indicates that hydrogen bonding plays an important role in the interaction between the host and guest and leads to the easier signal transductions of chiral recognition by the fluorescence method.

We also prepared (*R*)-**1**, the enantiomer of (*S*)-**1**, and studied its interaction with mandelate, (*S*)- or (*R*)-Ala, Phe anions, alaninol, and phenylalaninol which showed the opposite enantioselectivity, that is, the enantiomer of (*R*)-Ala, Phe anion, alaninol, and phenylalaninol quenched the fluorescence of (*R*)-**1** more efficiently than the (*S*)-guest. The result of fluorescence titrations indicated that the enantiomers of guest anions interacted with (*R*)-**1**, (*R*)-**2** and (*S*)-**1**, (*S*)-**2** in a similar fashion.

From Table 1, it can be seen that the interaction of (*S*)-**1** with the (*S*)-Ala and (*S*)-Phe anions is better than that with the (*R*)-Ala and (*R*)-Phe anions, which is probably due to the (*S*)-amino acid anions having a more complementary structure with receptor (*S*)-**1**. Both receptors (*S*)-**1** and (*R*)-**1** exhibited good chiral recognition ability toward the enantiomers of the Ala and Phe anions, which indicates that the preorganized structure of the chiral center of the binaphthyl unit plays important roles in the enantioselective recognition process. The Phe anion has a structure similar to that of the Ala anion, but the association constants for the association of the receptors with the Phe anion are smaller than those for the Ala anion, which could be attributed to the greater steric hindrance of the phenyl ring relative to the methyl group.

2.3. ^{1}H NMR study

^{1}H NMR experiments were carried out in order to assess the chiral recognition properties between receptor (*S*)-**1** and chiral anionic guest because NMR spectroscopy can provide structural and dynamic information directly[15]. Chiral recognition studies were carried out with a 400-MHz NMR spectrometer using receptor (*S*)-**1** by ^{1}H NMR in $CDCl_3$ at room temperature. The spectra of receptor (*S*)-**1** and its complex with equimolar amounts of racemic Ala anions are shown in Figure 6. When treated with equimolar amounts of receptor (*S*)-**1**, the signal of the CH proton of the racemic Ala anion cleaved into a more complicated signal pattern (Fig. 6C) with a downfield shift (from δ = 3.83 to 4.18 ppm, $\Delta\delta$ = 0.35 ppm). The interaction of receptor (*S*)-**1** with the (*S*)-enantiomer shows that the CH proton has a larger downfield shift (from δ = 3.83 to 4.24 ppm, $\Delta\delta$ = 0.41 ppm, Fig. 6D) than the CH proton of the (*R*)-enantiomer (from δ = 3.83 to 4.13 ppm, $\Delta\delta$ = 0.30 ppm, Fig. 6E). Moreover, the signals of the –OH proton in the ^{1}H NMR spectra of receptor (*S*)-**1** almost disappeared while

Table 1
Association constants (K_{ass}), correlation coefficients (R), enantioselectivities ($K_{ass(S)}/K_{ass(R)}$), Gibbs free energy changes ($-\Delta G_0$), and $\Delta\Delta G_0$ calculated from ΔG_0 for the complexation of receptors (*S*)-**1** and (*R*)-**1** with (*S*)-/(*R*)-guests in $CHCl_3$ at 25 °C

Entry	Host	Guest	K_{ass}[a,b] (M^{-1})	R	$K_{ass(S)}/K_{ass(R)}$	$-\Delta G_0$ (kJ mol^{-1})	$\Delta\Delta G_0$ (kJ mol^{-1})
1	(*S*)-**1**	(*S*)-Ala[c]	$(3.90 \pm 0.12) \times 10^4$	0.9994		26.20	
2	(*S*)-**1**	(*R*)-Ala[c]	$(5.43 \pm 0.03) \times 10^3$	0.9922	7.18	21.32	4.88
3	(*S*)-**1**	(*S*)-Phe[c]	$(3.24 \pm 0.04) \times 10^4$	0.9937		25.75	
4	(*S*)-**1**	(*R*)-Phe[c]	$(4.39 \pm 0.12) \times 10^3$	0.9917	7.38	20.79	4.96
5	(*S*)-**1**	(*S*)-mandelate	$(4.26 \pm 0.44) \times 10^4$	0.9974		26.43	
6	(*S*)-**1**	(*R*)-mandelate	$(4.06 \pm 0.13) \times 10^4$	0.9957	1.05	26.31	0.12
7	(*S*)-**1**	(*S*)-alaninol	$(7.94 \pm 0.31) \times 10^2$	0.9917		16.55	
8	(*S*)-**1**	(*R*)-alaninol	$(1.50 \pm 0.05) \times 10^2$	0.9909	5.29	12.42	4.13
9	(*S*)-**1**	(*S*)-phenylalaninol	$(6.13 \pm 0.11) \times 10^2$	0.9929		15.91	
10	(*S*)-**1**	(*R*)-phenylalaninol	$(1.02 \pm 0.04) \times 10^2$	0.9911	6.01	11.47	4.44
11	(*R*)-**1**	(*S*)-Ala[c]	$(5.38 \pm 0.10) \times 10^3$	0.9986		21.30	
12	(*R*)-**1**	(*R*)-Ala[c]	$(3.79 \pm 0.21) \times 10^4$	0.9943	1/7.04	26.14	−4.84
13	(*R*)-**1**	(*S*)-Phe[c]	$(4.52 \pm 0.12) \times 10^3$	0.9962		20.87	
14	(*R*)-**1**	(*R*)-Phe[c]	$(3.49 \pm 0.07) \times 10^4$	0.9974	1/7.72	25.93	−5.06
15	(*R*)-**1**	(*S*)-mandelate	$(4.41 \pm 0.08) \times 10^4$	0.9938		26.51	
16	(*R*)-**1**	(*R*)-mandelate	$(4.69 \pm 0.14) \times 10^4$	0.9961	1/1.06	26.67	−0.16
17	(*R*)-**1**	(*S*)-alaninol	$(1.74 \pm 0.09) \times 10^2$	0.9927		12.79	
18	(*R*)-**1**	(*R*)-alaninol	$(8.96 \pm 0.29) \times 10^2$	0.9916	1/5.15	16.85	−4.06
19	(*R*)-**1**	(*S*)-phenylalaninol	$(2.08 \pm 0.24) \times 10^2$	0.9907		16.27	
20	(*R*)-**1**	(*R*)-phenylalaninol	$(1.21 \pm 0.11) \times 10^3$	0.9914	1/5.82	11.89	−4.38

[a] The data were calculated from results of fluorescence titrations in $CHCl_3$.
[b] All error values were obtained from non-linear curve fitting.
[c] Ala and Phe tetrabutylammonium salts, the amino group was protected by a *tert*-butyloxycarbonyl function.

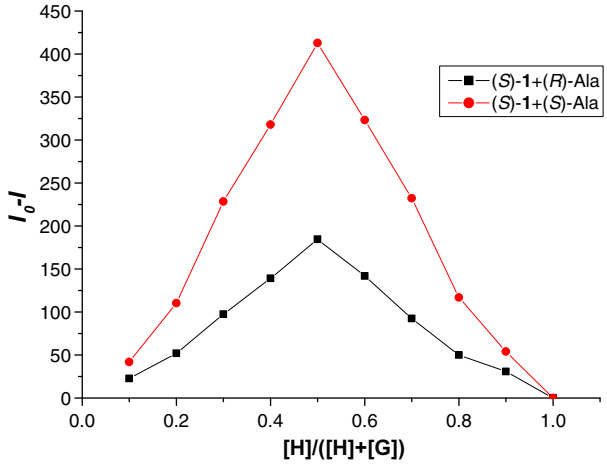

Figure 5. Job plots of receptor (*S*)-**1** with (*S*)- and (*R*)-Ala anions (367 nm, λ_{ex} = 290 nm). The total concentration of the host ([*H*]) and guest ([*G*]) is 1.0×10^{-6} mol L^{-1} in $CHCl_3$. I_0: fluorescence intensity of (*S*)-**1** and *I*: fluorescence intensity of (*S*)-**1** in the presence of the guest.

the signals of the peaks of binaphthyl fragments were shifted downfield and broadened with the addition of the guest. The signal of the amide (N*H*) group linked to the Boc moiety was also shifted clearly upfield from δ = 5.91 to 5.74 ($\Delta\delta$ = 0.17 ppm, Fig. 6D) for the (*S*)-Ala anion, whereas the (*R*)-Ala anion exhibited nearly no change (Fig. 6E), suggesting that the amide group of the (*S*)-Ala anion participated in the association process, while the (*R*)-enantiomer did not participate. Similar phenomena were found when (*S*)-**1** interacted with Phe anion (Table 1). The CH protons signals of (*S*)- and (*R*)-Phe were shifted downfield by about 0.32 and 0.24 ppm in the presence of (*S*)-**1**, respectively. The signal of the amide group linked to the Boc moiety was also shifted upfield by about 0.15 ppm when (*S*)-**1** interacted with (*S*)-Phe while the (*R*)-Phe anion gave nearly no change. The above results indicate that (*S*)-**1** has a stronger interaction with the (*S*)-Ala anion than with its (*R*)-enantiomer. This indicated that the interaction between the host and guest also happened by multiple hydrogen bondings.

The above results illustrate that the nature of the receptor, multiple hydrogen-bonding interactions, and complementary stereogenic center interactions may be responsible for the enantiomeric recognition of amino acid anion.[16]

3. Conclusion

In conclusion, we have demonstrated that, with the introduction of two additional benzoyl groups to BINOL, the resulting compounds (*S*)-**1** and (*R*)-**1** could be synthesized and their enantioselective recognition could be studied by fluorescence titration and ^{1}H NMR spectroscopy. Receptors (*S*)-**1** and (*R*)-**1** exhibit excellent enantioselective fluorescent recognition abilities toward the *N*-Boc-protected alanine anion and *N*-Boc-protected phenylalanine anion and form 1:1 complexes. It is clear that the nature of the receptor, good structural preorganization, multiple hydrogen-bonding interactions and the complementary stereogenic center interactions induced may be responsible for the enantiomeric recognition of anionic guests.[16] Receptors (*S*)-**1** and (*R*)-**1** are promising in their use as fluorescence sensors for amino acid anions.

4. Experimental

4.1. General

The reagents used were of commercial origin and were employed without further purification. Purifications by column chromatography were carried out over silica gel (230–400 mesh). The IR spectra were performed on a Nicolet 670 FT-IR spectrophotometer. ^{1}H NMR and ^{13}C NMR spectra were recorded on a Bruker AV-400 spectrometer. Mass spectra were determined by ESI recorded on an Esquire 3000 LC–MS mass instrument. Optical rotations were taken on a Perkin–Elmer Model 341 polarimeter. Fluorescence spectra were obtained with an F-7000 FL Spectrophotometer. Elemental analyses were performed by the Vario Elemental CHSN-O microanalyzer. All other commercially available reagents were used without further purification. The anions were used as their tetrabutylammonium salts. The N-protected (by the *tert*-butyloxycarbonyl functionality) amino acid derivatives were synthesized according to a literature method.[17]

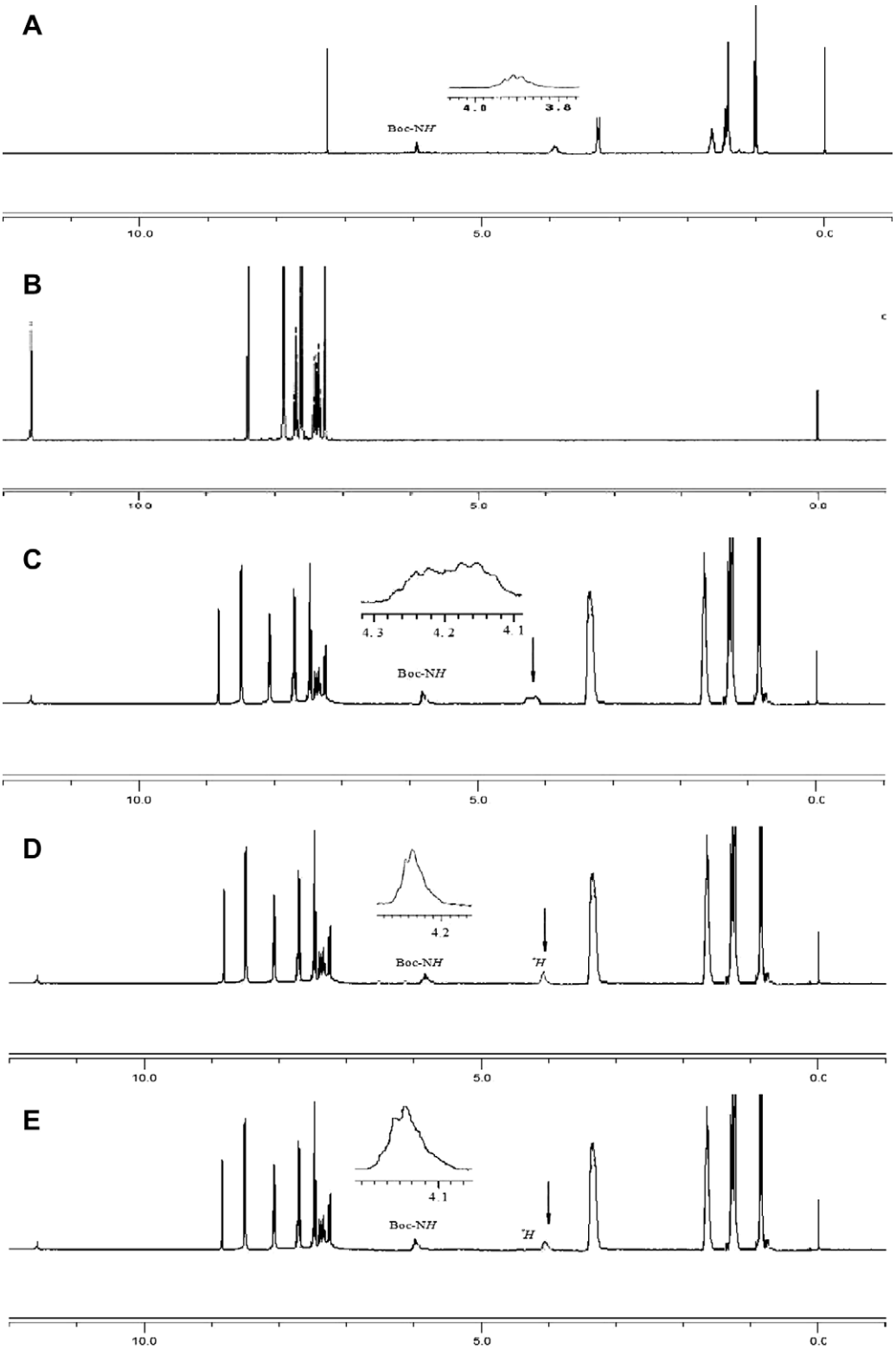

Figure 6. The ^{1}H NMR spectra of (*S*)-**1** and its guest complexes at 25 °C ([(*S*)-**1**] = [guest] = 4.0×10^{-3} mol L^{-1}) in $CDCl_3$ at 400 MHz. (A) Racemic Ala anion; (B) receptor **S-1**; (C) receptor (*S*)-**1** + racemic Ala anion; (D) receptor (*S*)-**1** + (*S*)-Ala anion; and (E) receptor (*S*)-**1** + (*R*)-Ala anion.

4.1.1. Synthesis of compound 3,3′-bis-benzoyl-2,2′-bis-methoxymethyl-1,1′-binaphthyl, (*S*)-3 and (*R*)-3

Under nitrogen, 2,2′-bis-methoxymethyl-1,1′-binaphthyl, (*S*)-**2** (5.0 mmol, 1.87 g) was dissolved in ether (100 mL) in a flask equipped with a side arm and a magnetic stirring bar. The solution was cooled to 0 °C, and *n*-BuLi (25.0 mmol, 2.5 M in hexane, 10 mL) was added dropwise. The reaction mixture was stirred for 3 h at 0 °C, and then benzoyl chloride (25.0 mmol, 3.50 g) was added slowly. The reaction mixture was allowed to warm to room temperature overnight to afford a cream-like mixture. A saturated aqueous NH_4Cl solution was added to quench the reaction. The organic layer was separated, and the aqueous layer was extracted

with ethyl acetate (20 mL × 3). The combined organic extracts were washed with brine, and dried over Na_2SO_4. After removal of the solvent, the residue was purified by column chromatography on silica gel. Elution with hexane/ethyl acetate (5:1) gave compound (*S*)-**3** as a yellow solid in 84% yield (2.44 g): R_f = 0.4 (hexane/ethyl acetate = 5:1); (*R*)-**3** was also prepared from (*R*)-**2** via the same procedure. The specific rotation of (*S*)-**3**, $[\alpha]_D^{20} = -124.2$ (*c* 1.00, $CHCl_3$), and that of (*R*)-**3**, $[\alpha]_D^{20} = +117.8$ (*c* 1.00, $CHCl_3$). IR (KBr, cm^{-1}): 3446, 3059, 2930, 1632, 1392, 751, 621 cm^{-1}. ^1H NMR ($CDCl_3$): δ 8.41(s, 2H), 8.14 (d, *J* = 7.2 Hz, 4H), 7.88 (d, *J* = 9.2 Hz, 2H) 7.62 (d, *J* = 11.6 Hz, 4H), 7.47 (d, *J* = 7.8 Hz, 4H), 7.44-7.34 (m, 4H), 5.07(d, *J* = 6.4 Hz, 2 H), 4.97(d, *J* = 5.2 Hz, 2 H), 3.13 (s, 6H) ppm. ^{13}C NMR ($CDCl_3$): 200.2, 154.5, 136.3, 135.4, 136.1, 132.2, 130.2, 129.4, 128.7, 128.8, 127.0, 124.9, 124.3, 121.1, 117.5, 100.4, 57.1 ppm, ESI-MS *m*/*z*: 605 (M+Na^+, 100). Anal. Calcd for $C_{38}H_{30}O_6$: C, 78.33; H, 5.19. Found: C, 78.01; H, 5.22.

4.1.2. Synthesis of compound 3,3′-bis-benzoyl-2,2′-bis-dihydroxy-1,1′-binaphthyl, (*S*)-1 and (*R*)-1

After compound (*S*)-**3** (0.58 g, 1.0 mmol) was dissolved in a minimum amount of CH_2Cl_2, ethanol (10 mL) and HCl (3 N, 10 mL) were added successively, and the mixture was heated at reflux overnight. The resulting yellow solution was concentrated with a rotary evaporator. Water (10 mL) was then added, and the solution was extracted with CH_2Cl_2 (20 mL × 3). The combined extract was dried over Na_2SO_4. After removal of the solvent, the residue was purified by column chromatography on silica gel eluted with $CHCl_3/C_2H_5OH$ (20:1) to give (*S*)-**1** as yellow needle crystals in 86% yield (0.40 g): R_f = 0.26, (hexane/ethyl acetate = 6:1). Compound (*R*)-**1** was also prepared from (*R*)-**3** via the same procedure. The enantiomeric purity of (*S*)-**1** was 95% ee as determined by using HPLC-Chiralcel OD column (solvent: hexane/^{i}PrOH) 20/80, flow rate: 0.3 mL/min). The specific optical rotation of (*S*)-**1**, $[\alpha]_D^{20} = -94.2$ (*c* 1.00, $CHCl_3$), and that of (*R*)-**1**, $[\alpha]_D^{20} = +91.8$ (*c* 1.00, $CHCl_3$). IR (KBr, cm^{-1}): 3442, 3059, 2957, 1631, 1504, 1447, 1323, 1284, 1205, 750, 699 cm^{-1}. ^1H NMR ($CDCl_3$): δ 11.60 (s, 2H), 8.40 (s, 2H), 7.88 (s, 2H), 7.86 (d, *J* = 8.0 Hz, 4H), 7.69 (t, *J* = 7.6 Hz, 2H), 7.61 (t, *J* = 7.6 Hz, 4H), 7.41 (t, *J* = 7.6 Hz, 2H), 7.35 (t, *J* = 8.0 Hz, 2H), 7.27 (s, 2H) ppm.

^{13}C NMR ($CDCl_3$): 202.5, 155.6, 138.5, 137.9, 137.8, 137.7, 132.8, 130.7, 130.1, 129.0, 127.4, 125.2, 124.7, 121.3, 118.0 ppm, ESI-MS *m*/*z*: 517 (M+Na^+, 100). Anal. Calcd for $C_{34}H_{22}O_4$ (517): C, 82.58; H, 4.48. Found: C, 82.37; H, 4.51.

4.1.3. Synthesis of 3,3′-bis-benzoyl-2,2′-dimethoxy-1,1′-binaphthyl, (*S*)-4 and (*R*)-4

Under nitrogen, diethyl ether (50 mL, dried) and TMEDA (7.5 mmol, 0.88 g) were placed in a 250-mL three-necked round-bottomed flask equipped with a side arm and a magnetic stirring bar. To this solution was added *n*-BuLi (12.5 mmol, 2.5 M in hexane, 5 mL) dropwise. It was then stirred at room temperature for 30 min. (*S*)-2,2′-Dimethoxy-1,1′-binaphthalenyl, (*S*)-**5** (2.5 mmol, 0.79 g) was added in one portion, and the reaction mixture was stirred for 3 h. Benzoyl chloride (12.5 mmol, 1.75 g) in diethyl ether (10 mL) was added to the resulting light brown suspension via syringe over 10 min. The reaction mixture was stirred overnight and quenched with saturated aqueous NH_4Cl solution. The volatile solvent was removed in vacuum, and the remaining aqueous solution was extracted with CH_2Cl_2 (20 mL × 3). The organic phase was dried over $MgSO_4$ and evaporated to dryness. The residue was passed through a silica gel column eluted with $CHCl_3/C_2H_5OH$/(50/1) to afford (*S*)-**4** (0.94 g) as a yellow solid in 72% yield. R_f = 0.32, (hexane/ethyl acetate = 6:1). (*R*)-**4** was also prepared from (*R*)-**5** with the same procedure. The specific optical rotation of (*S*)-**4**, $[\alpha]_D^{20} = -93.6$ (*c* 1.00, $CHCl_3$), and that of (*R*)-**4**, $[\alpha]_D^{20} = +87.4$ (*c* 1.00, $CHCl_3$). IR (KBr, cm^{-1}): 3050, 2924, 1621, 1596, 1205, 751,698 cm^{-1}. ^1H NMR ($CDCl_3$): δ 8.34 (s, 2H), 7.82 (s, 2H), 7.80 (d, *J* = 1.6 Hz, 4H) 7.63 (t, *J* = 7.6 Hz, 2H), 7.55 (t, *J* = 7.6 Hz, 4H), 7.35 (t, *J* = 8.0 Hz, 2H), 7.29 (t, *J* = 8.0 Hz, 2H), 7.21 (s, 2H), 2.58 (s, 6H) ppm. ^{13}C NMR ($CDCl_3$): 203.0, 155.8, 138.6, 138.0, 137.9, 132.9, 130.7, 130.3, 129.1, 127.4, 125.2, 124.8, 121.3, 118.1, 60.6 ppm, ESI-MS *m*/*z*: 523 (M+1$^+$, 100). Anal. Calcd fpr $C_{36}H_{26}O_4$ (517): C, 82.74; H, 5.01. Found: C, 82.66; H, 5.04.

4.2. Preparation of samples for fluorescence measurement

All solutions were prepared using volumetric syringes, pipettes, and volumetric flasks. The tetrabutylammonium salts were prepared by adding 1 equiv of tetrabutylammonium hydroxide in methanol to a solution of the corresponding carboxylic acid in methanol and stock solutions of the salts were prepared in $CHCl_3$. The resulting syrup was dried under high vacuum for 24 h, analyzed by NMR spectroscopy, and stored in a desiccator. Compounds (*S*)-**1,** (*R*)-**1,** (*S*)-**4**, and (*R*)-**4** were prepared as stock solutions in $CHCl_3$. The test solutions were prepared by adding different volumes of anion solution to a series of test tubes and then the same amount of stock solution of the host compound was added to each of the test tubes and diluted to 3.0 mL with $CHCl_3$. After being shaken for several minutes, the test solutions were analyzed immediately.

4.3. Job plots

Stock solutions of host (*S*)-**1** and the (*S*)-Ala, (*R*)-Ala tetrabutylammonium salts in $CHCl_3$ system (the total concentration of the host and guest is 1.0×10^{-6} M) were freshly prepared. The receptor and Ala solutions were added to the test tubes in ratios of 9:1 and 8:2–0:10, respectively. After being shaken for several minutes, the work solution could be measured immediately.

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