Study on host–guest complexation of anions based on a tripodal naphthylurea derivative

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In this paper, we report the synthesis of tripodal naphthylurea tri(2-aminoethyl)amine (**1**) designed for the recognition of anions (*e.g.*, $H_2PO_4^-$ and HSO_4^-) by complexation-enhanced changes of fluorescence in DMF solution. The effect of protonation and addition of anions upon the photophysical properties of **1** was investigated for comparison with those of analogous receptors, **1**·HCl and the di(2-aminoethyl)amine (**2**) and *n*-amylamine (**3**) naphthylurea derivatives. The fluorescent chemosensor **1** shows obvious changes in its fluorescence spectrum upon addition of $H_2PO_4^-$ and HSO_4^- anions. The association constants for the complexes of **1** with anions were measured by fluorometric titration and show a higher specific selectivity for the $H_2PO_4^-$ anion with a 1 : 1 stoichiometry of the complex. These effects, which strongly depend on the interaction of hydrogen-containing oxoanions with the receptor, can be interpreted in terms of anion-induced reduction of the efficiency of photoinduced electron transfer (PET). The results were also confirmed by ^{1}H NMR spectra and a plausible structure for the complex of **1**·H^+ with HPO_4^{2-} is proposed.

In nature, the selective complexation and transportation of anions is regulated by anion-binding proteins that act as anion carriers and channels across the cell membrane.[1] The origin of the discrimination between the simple tetrahedral oxoanions phosphate and sulfate by their respective binding proteins was traced back to the ability of the former to act as a hydrogen-bond donor deeply buried in the interior of the protein.[2] The design and synthesis of artificial organic host molecules for anions has attracted much attention over the last decades.[3] Progress in the construction of anion hosts has been made in systems such as guanidinium hosts,[4] polypyrroles,[5] hosts based on multi-site metal complexes,[6] cyclodextrins,[7] calix[6]arenes,[8] covalently-bonded poly-Lewis acids,[9] and polyazonia compounds.[10] Reinhoudt and coworkers[11] introduced a tri(2-aminoethyl)amine moiety into the framework of hosts and produced host molecules capable of binding anions by the formation of multiple hydrogen bonds in three-dimensional arrangements. Morán and coworkers[12] have used triangular-shaped spacers to prepare receptors for binding anions and the urea group is often used as it can form more hydrogen bonds with tetrahedral anions such as phosphate and sulfate.[11,12] From the most recent literature, it can be noted that the discussion of the interaction between host and guest is mainly based on guest-induced ^{1}H NMR shifts. It should be pointed out that the utility of these guest-induced ^{1}H NMR shifts to determine quantitatively the complexation constants is limited,[11] because of the high association of the host and guest species and the relatively high concentrations (usually 10^{-2}–10^{-3} M) required to obtain the NMR signals.

Another kind of host, called fluorescent chemosensors (FCS), has been developed for metal ions and neutral organic molecules during the last two decades.[13] This is based on complexation by guests that can induce large changes in the photophysical properties of the host fluorophores. This kind of study is also of great interest for the photoinduced electron transfer (PET) strategy,[13,14] which is distinguished by its intrinsically supramolecular nature since distinct components perform each one or more of the necessary functions. However, the near absence of fluorophores responsive to small anionic spaces is an embarrassing fact and thus the number of fluorescent hosts for anions for this study is very limited.[15]

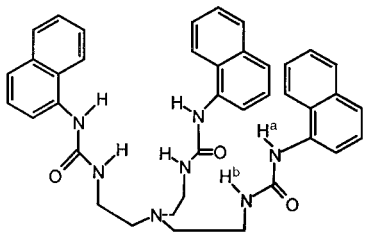
In the present paper, we report on the results obtained with tri(2-aminoethyl)amine (**1**), di(2-aminoethyl)amine (**2**) and mono *n*-amylamine (**3**) derivatives, in which the primary amino group is functionalized with three, two or one naphthyl urea moieties, respectively (Scheme 1). The urea moieties of receptor **1** can function as neutral receptors for selective binding of anions, and the anion recognition can easily be monitored by guest-complexation-induced variation of the photophysical properties of the naphthyl groups. The effects on the PET strategy are carefully examined. The binding mode between host and anion guest is also investigated.

Results

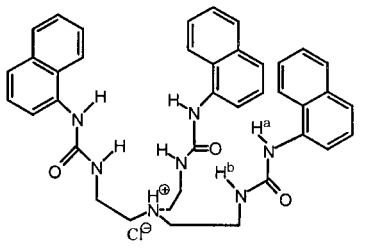
Anion-induced changes in fluorescence spectra

Compounds **1**–**3** display strong fluorescence emission in DMF, as shown in Fig. 1(*a*), but the fluorescence intensity of **1** is much lower than that of **2** and **3**. We also checked the concentration effects of these compounds. For dilute solutions, the fluorescence intensities of **1**–**3** and **1**·HCl are all linear as a function of their concentration (from 2×10^{-6} to 2×10^{-5} M). The fluorescence intensities of **1** and **1**·HCl deviate from straight lines at concentrations higher than 2×10^{-5} M. At the same time, the fluorescence emission spectra of **1** and **1**·HCl revealed not only the expected monomer emission at 377.2 nm, but also a broad band at 410 nm that is typical of the structureless emission of a naphthyl excimer [Fig. 1(*b*)].

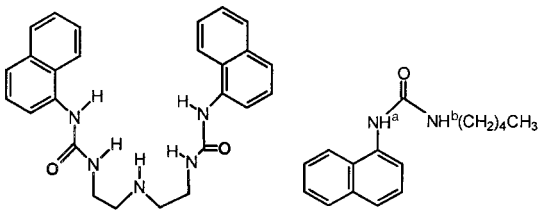
The effect of protonation on the fluorescence intensities (I_f) of **1**–**3** was investigated by gradual addition of CF_3COOH to the solutions of these compounds in DMF (Fig. 2). It can be seen that there is a sharp change in I_f for compound **1** in the range of pH 7.0–7.5, but no change is observed for the **1**·HCl salt and very slight change for **2** after adding CF_3COOH. Although pH values in DMF are obviously different from



1



1·HCl



2 3

Scheme 1

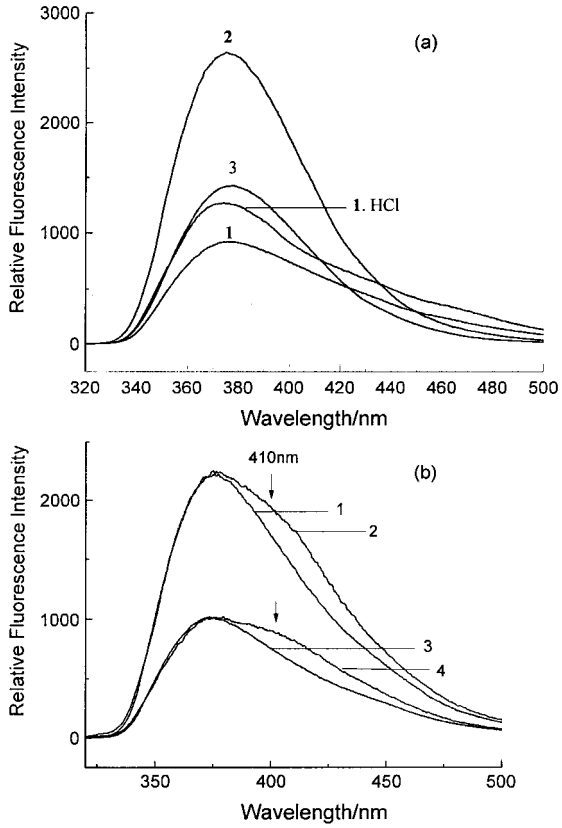


Fig. 1 (*a*) Fluorescence spectra of compounds **1**, **2**, **3** and **1**·HCl (1.0×10^{-5} M) in DMF. $\lambda_{ex} = 310$ nm. (*b*) The normalized fluorescence spectra of compounds **1** and **1**·HCl in DMF at various concentrations (curve 1) **1** (2.0×10^{-6} M); (curve 2) **1** (8.0×10^{-6} M); (curve 3) **1**·HCl (2.0×10^{-6} M); (curve 4) **1**·HCl (6.0×10^{-6} M).

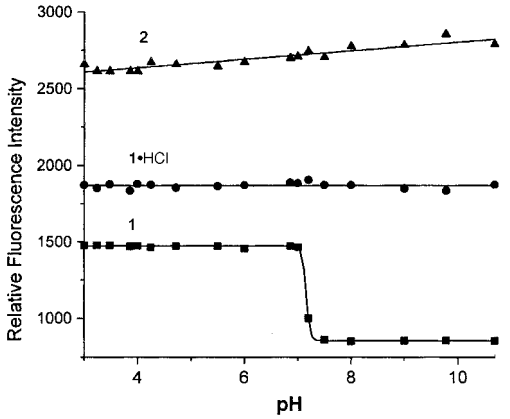


Fig. 2 Fluorescence intensities of compounds **1**, **2** and **1**·HCl in DMF as a function of the pH value, varied by adding CF_3COOH. Excitation was at 310 nm; emission was measured at 378 nm.

those in aqueous solution, they indicate the same quantity ($-\log[H^+]$) in non-aqueous solution.[16]

The fluorescence spectrum of receptor **1** shows an obvious enhancement in intensity upon addition of $H_2PO_4^-$ anions (Fig. 3), but only a small increase with HSO_4^- and no change with halide anions such as Br^- or I^- (Fig. 4). On the other hand, at a molar ratio of receptor **1** to anion of about 1 : 1 (stoichiometry of the complex), the fluorescence intensity of **1** reaches a plateau (for $H_2PO_4^-$ and HSO_4^-).

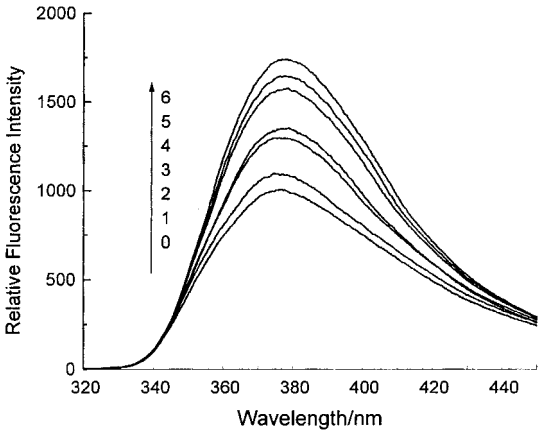


Fig. 3 Effect of the addition of $H_2PO_4^-$ anion (as $Bu_4N^+ \cdot H_2PO_4^-$ salt) upon the fluorescence spectra of **1** (1.0×10^{-5} M) in DMF: excitation wavelength, 310 nm; 25 °C; the concentrations of $H_2PO_4^-$ are 0, 2, 4, 6, 8, 10, and 12×10^{-6} M for curves 0–6, respectively.

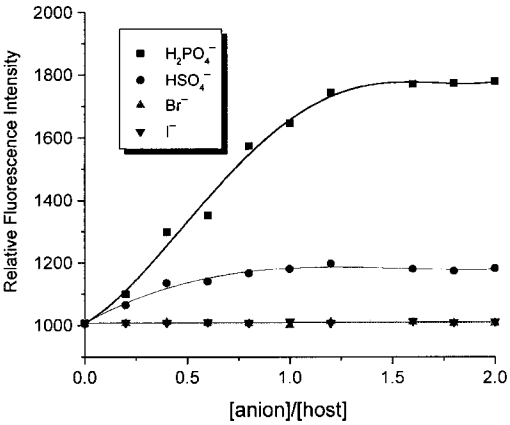


Fig. 4 Fluorescence intensity of **1** in DMF (1.0×10^{-5} M) *vs.* the anion concentration (all anions are added as tetrabutylammonium salts). Excitation at 310 nm; emission recorded at 377 nm.

Table 1 The fluorescence quantum yield (Φ_f) of compounds **1**, **2**, **3** and **1**·HCl in DMF with or without guests[a]

Compound	Guest						
	None	F_3CCOOH	CH_3COOH	$H_2PO_4^-$	HSO_4^-	Br^-	I^-
1	0.215	0.297	0.293	0.299	0.222	0.215	0.216
2	0.493	0.495	0.485	0.491	0.486	0.493	0.493
3	0.333	0.313	0.306	0.322	0.314	0.311	0.313
1·HCl	0.306	0.306	0.305	0.305	0.305	0.302	0.302

[a] All solutions of host compounds were 1×10^{-5} M in DMF with the same concentration of guest ([host] : [guest] = 1 : 1) where applicable; $\lambda_{ex} = 310$ nm, $slit_{ex} = 5$ nm, $slit_{em} = 2.5$ nm.

For the fluorescence quantum yield (Φ_f) determination, the well-known quinine sulfate was chosen as a standard ($\Phi_f = 0.546$[17]) and the corrected emission spectra were used. The variation of quantum yields of **1**–**3** and **1**·HCl in DMF upon addition of anions or organic acids are reported in Table 1. It can be seen that the value of Φ_f of **1** upon addition of an equimolar amount of $H_2PO_4^-$ anion is higher than that of free **1** and is approximately equal to that of **1** with added F_3CCOOH or CH_3COOH and to that of the **1**·HCl salt. With HSO_4^- anions, there is only a slight enhancement in quantum yield and no change when Br^- or I^- are added. The quantum yields of **2**, **3** and **1**·HCl are not changed after adding the same guests.

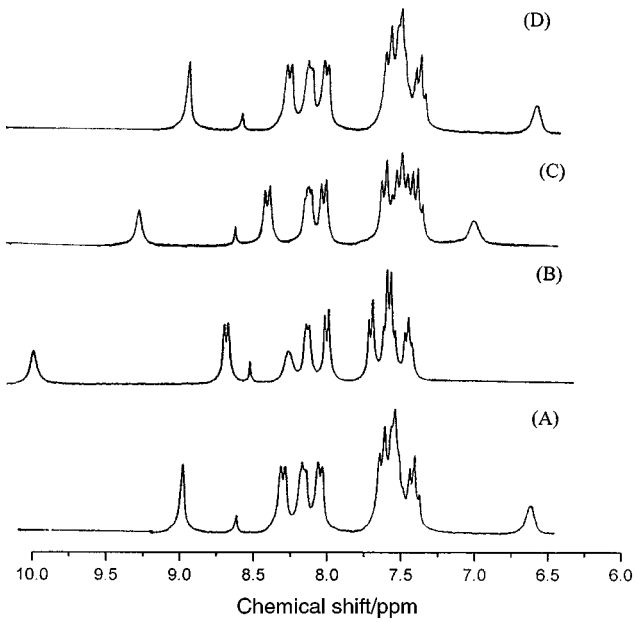


Fig. 5 ^1H NMR spectra of **1** (D_6-DMSO, 1×10^{-3} M, at 25 °C) alone (*A*) and with $H_2PO_4^-$ (*B*), HSO_4^- (*C*) or I^- (*D*) anions (all as tetrabutylammonium salts) in a 1 : 1 molar ratio.

Table 2 ^1H NMR chemical shifts (ppm) of hosts with or without guest anions

Host	Guest	H_a	H_b	H_g
1	None	8.60	6.69	8.06
	$H_2PO_4^-$	9.81	8.04	8.49
	HSO_4^-	8.83	7.02	8.15
	Br^-	8.61	6.70	8.07
	I^-	8.61	6.70	8.07
2	None	8.70	6.79	8.09
	$H_2PO_4^-$	9.20	7.35	8.36

[a] All solutions of host compounds were 1×10^{-3} M in D_6-DMSO with the same concentration of guest ([host] : [guest] = 1 : 1), where applicable, at 25 °C.

Stoichiometry and association constants

The literature[8,18] contains reports that the association constant (K_{ass}) of the 1 : 1 complex of host with anion can be determined from guest-complexation-induced changes in chemical shifts of the host by ^1H NMR titration experiments. Furthermore, it is also reported that cation-induced changes in the photophysical properties of the complex are usually used to determine the stoichiometry and K_{ass}.[19] In the present work, it turned out to be convenient to monitor the anion-induced changes in fluorescence intensity at the wavelength corresponding to the emission maximum of the host compounds. We consider the equilibrium describing the complexation of an anion guest (G) and a host compound (H): H + G $\rightleftharpoons$ HG, in the case of a 1 : 1 stoichiometry, which is controlled by the association constant: $K_{ass} = [HG]/[H][G]$, expressing the degree of binding of the complex under given solvent and temperature conditions. Fluorometric titration experiments (Fig. 4) showed that the stoichiometry of the complex of receptor **1** with anions is 1 : 1.

It is easy to derive the following relation involving the fluorescence emission intensities I_f^0 of the free host and I_f of the complexes at a given emission wavelength.

$$\frac{I_f^0}{I_f^0 - I_f} = \frac{\varepsilon_H \Phi_H}{\varepsilon_H \Phi_H - \varepsilon_{HG} \Phi_{HG}} \left(\frac{1}{K_{ass}[G]} + 1 \right) \quad (1)$$

Φ_H and Φ_{HG} are the fluorescence quantum yields of the host and the complex, respectively.

In the concentration range 1×10^{-6} to 1×10^{-5} M, the variations in fluorescence intensity as a function of anion concentration permit a determination of the association constants. Following eqn. (1), $I_f^0/(I_f^0 - I_f)$ is plotted *vs.* the reciprocal of the anion concentration [G]. Linear regression of the data leads to good correlation coefficients (>0.998). The association constants K_{ass} were calculated from the ratio intercept/slope and values of 40 650 and 2748 M^{-1} for $H_2PO_4^-$ and HSO_4^- respectively, were found. These values are of the same order of magnitude as those previously determined for tripodal phenylurea derivatives with $H_2PO_4^-$ ($K_{ass} = 1.1 \times 10^4$ M^{-1}) and HSO_4^- ($K_{ass} = 1.0 \times 10^2$ M^{-1}) by ^1H NMR titration experiments.[12] Due to the fact that Br^- and I^- do not induce any change in the absorption and fluorescence spectra or in the ^1H NMR spectra, as will be shown in the following section, it is demonstrated that interaction between host **1** and halide anions is unlikely to occur.

^1H NMR data for interaction of receptors and anions

Previous papers[8,11,12,18] have reported that neutral receptors with hydrogen bond donors selectively bind anions ($H_2PO_4^-$, HSO_4^- and halide anions) exclusively through hydrogen bonding, which can be monitored by the chemical shifts of ^1H NMR spectra. The ^1H NMR spectra of **1**–**3** with or without anion guests were measured in D_6-DMSO at 25 °C. Representative results for the complexes of **1** with various anions are shown in Fig. 5 and Table 2. The urea hydrogens of **1** reson-

ate at 8.60 ppm (NH_a) and 6.69 ppm (NH_b). Fig. 5 shows a downfield shift of the urea hydrogens upon addition of $H_2PO_4^-$ or HSO_4^- and no change upon addition of halide anions such as Br^- or I^-, indicating the formation of hydrogen bonds to the simple tetrahedral oxoanions. In addition, the 8-position protons of the naphthyl substituents on the urea groups show a downfield shift (0.10–0.43 ppm), whereas the positions of the other protons do not change.

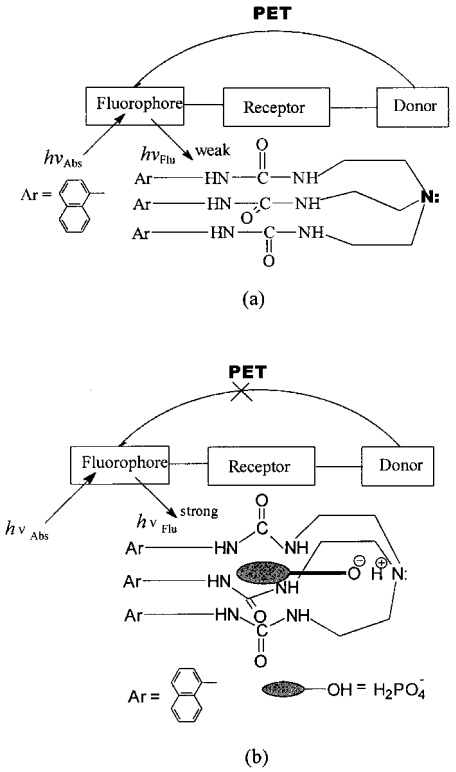
Discussion

The fluorescence quantum yield of compound **1** is much less than that of reference compounds **2** and **3**. The reason can be explained as follows: firstly, the strong intramolecular π–π* interaction among the three naphthyl groups leads to an excimer emission [shown in Fig. 1(*b*)], which reduces the monomer fluorescence of **1**. Furthermore, **1** contains tertiary amine groups, strong electron donors that can quench fluorescence emission through photoinduced electron transfer (PET). In **2**, the group linking the two naphthylurea moieties is a secondary amine that results in a reduction of the PET process. At the same time, no excimer emission was observed in a DMF solution of **2**, indicating that the intramolecular π–π* interaction between the two naphthyl groups of **2** is energetically unfavorable. The above suggestion can be confirmed by the analogous compound **3**, which does not contain an electron-donating substituent and in which no intramolecular π–π* interaction is possible. For this reason, **3** has a stronger fluorescence emission than **1**.

Another fact is the absence of significant changes in the position and shape of the fluorescence spectrum of **1**, whereas the quantum yield can be strongly affected upon addition of CF_3COOH. Protonation of the tertiary amine group in the framework of **1** maybe play an important role in this case. An observed fluorescence dependence on the concentration of the added CF_3COOH acid is coincident with the intramolecular tertiary amine quenching mechanism that has been described previously.[20] This point of view can be used to explain why the fluorescence of the **1**·HCl salt is greater than that of **1**.

The anion-induced enhancement of fluorescence can be interpreted as follows. Receptor **1** contains a tertiary amine group. As reported in organic textbooks, tertiary amines usually have basicity constants (pK_a) of *ca.* 8–11 log units in aqueous solution. On the other hand, the hydrogen sulfate anion, HSO_4^-, is a rather strong acid (pK_a 1.94) while dihydrogenphosphate, $H_2PO_4^-$, is a rather weak acid with a pK_a of 7.21 in aqueous solution. Therefore, both $H_2PO_4^-$ and HSO_4^- are stronger acids than the protonated receptor **1** in aqueous solution. Although the study has been carried out in DMF, in this solvent protonation of **1** most likely also takes place, in the presence of $H_2PO_4^-$ and HSO_4^-, to give $\mathbf{1}\cdot H^+$ and HPO_4^{2-} or SO_4^{2-}. Protonation of **1** seems also to be confirmed by the fact that the quantum yield of **1**·HCl is similar to that of **1** upon addition of $H_2PO_4^-$. At least, an equilibrium of the type $\mathbf{1} + H_2PO_4^- \rightleftharpoons \mathbf{1}\cdot H^+\cdot HPO_4^{2-} \rightleftharpoons \mathbf{1}\cdot H^+ + HPO_4^{2-}$ or $\mathbf{1} + HSO_4^- \rightleftharpoons \mathbf{1}\cdot H^+\cdot SO_4^{2-} \rightleftharpoons \mathbf{1}\cdot H^+ + SO_4^{2-}$ should occur. It is also to be noted that the formation of the $\mathbf{1}\cdot H^+\cdot HPO_4^{2-}$ (or SO_4^{2-}) adduct is also favored by charge–charge interactions between the protonated, positively charged receptor and the anions. ^1H NMR data show there is a weak interaction between SO_4^{2-} and the urea groups of **1** in comparison with HPO_4^{2-}. This results in the binding constant of $\mathbf{1}\cdot H^+\cdot HPO_4^{2-}$ being much higher than that of $\mathbf{1}\cdot H^+\cdot SO_4^{2-}$ although HSO_4^- is a stronger acid than $H_2PO_4^-$. These facts also indicate the formation of stable 1 : 1 complexes of $\mathbf{1}\cdot H^+$ with HPO_4^{2-} (or SO_4^{2-}).

Scheme 2 provides a general description of the fluorescence and PET signals and the effect of protonation of the tertiary amine. In (*a*) the tertiary amine as a stronger electronic donor quenches the fluorescence of receptor **1** through the PET

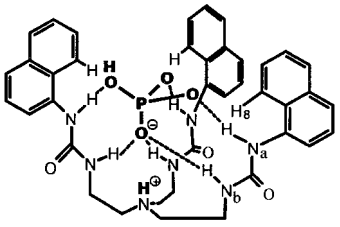


Scheme 2 (*a*) PET exists in the spaced fluorophore-receptor-donor system. (*b*) PET is reduced by protonation of the tertiary amine group in the spaced fluorophore-receptor-donor system.

process. In (*b*) the proton of the complexed anion attracts the lone electron pair of the nitrogen atom of the tertiary amine group and thus reduces its electron-donating character, resulting in an enhancement of fluorescence emission.

The ^1H NMR spectra of **1** show a downfield shift of the urea hydrogen upon addition of $H_2PO_4^-$ or HSO_4^-, indicating the formation of hydrogen bonds to the oxoanion guests. This ^1H NMR experiment coincides with the results on complexation of urea and thiourea with anions reported by Morán *et al.*[12] In addition, a downfield shift of the 8-position protons of the naphthyl groups may be attributed to the deshielding action of the oxygen atom of the oxoanions, indicating that the 8-position protons are much closer to the oxygen atoms of the anions.

A structure for the complex of host $\mathbf{1}\cdot H^+$ with an HPO_4^{2-} guest is proposed that can account for the various experimental data such as the photophysical properties and ^1H NMR characteristics (Scheme 3). Some general considerations for the interaction of the receptor with anions have been considered, such as a maximal number of H-bonding contacts to the anionic guests results in an optimum condition of thermodynamic stability.[21] The accumulation of H-bonding sites enables a strong binding affinity between receptor **1** and anions. On the other hand, the charge–charge interaction in $\mathbf{1}\cdot H^+\cdot HPO_4^{2-}$ (or SO_4^{2-}) adduct further enhances the binding affinity of the receptor with anions. For this reason, the K_{ass} of $\mathbf{1}\cdot H^+$ with HPO_4^{2-} is much higher than those of other receptors reported in the literature.[11,12] Furthermore, it is important that the three-dimensional cavity of **1**·H exhibits a specific selectivity



Scheme 3

for binding with tetrahedral HPO_4^{2-} and SO_4^{2-} anions rather than the spherical halide anions such as Br^- and I^-, whereas compound **2**, which has a tweezer-shaped structure, cannot complex with tetrahedral oxoanions. These results also suggest that the steric specification factor should be considered first for recognition of anions. Here it ought to be emphasized that only the hydrogen oxoanions are able to induce a change in the fluorescence spectra of **1**. On the other hand, the size and shape of anions also have an effect on the stability of the complex. All of these factors combine such that host $\mathbf{1}\cdot H^+$ has different association constants for HPO_4^{2-} and SO_4^{2-}.

Conclusion

The present study on anion-complexation-induced changes in the fluorescence behavior of receptor **1** with a tridimensional flexible structure, indicates that $\mathbf{1}\cdot H^+$ can be a useful fluorescent chemosensor to distinguish HPO_4^{2-} anions from other anions such as SO_4^{2-}, Br^- and I^-. The protonation of the nitrogen of the tertiary amine group of **1**, charge–charge interactions and H-bonding interactions here play a major role in the formation of host–guest complexes. On the other hand, the ^1H NMR spectra reveal that the HPO_4^{2-} guest is bound tightly into the cavity of host **1** by multiple H-bonding interactions from the three urea groups in the framework of host $\mathbf{1}\cdot H^+$. This means that molecular engineering concepts are involved, the optical, guest-binding and electron donor properties of the moieties of the host compound allow a quantitative prediction of the fluorescent signalling parameters of the supramolecular system. Furthermore, as concerns the anions themselves, their size, shape, H-bonding capability and acid/base properties should also be carefully considered when designing anionic receptors.

Experimental

^1H and ^{13}C NMR spectra were recorded in D_6-DMSO with a Varian Gemana-300 MHz NMR spectrometer using TMS as internal standard. FTIR spectra were recorded on a Biorad FTS spectrometer. Mass spectra were obtained with a Finnigan 4021C mass spectrometer. Elemental analyses were carried out on a Heiaeus CHN-Rapid instrument. Absorption spectra were measured by using a Hitachi 300 spectrophotometer. Fluorescence measurements were made on a Hitachi F-4500 fluorescence spectrophotometer; excitation and emission slit widths were 5.0 and 2.5 nm, respectively. All absorption and fluorescence spectra were recorded on a 10^{-5} M solution of the host in the absence and presence of anion guests at 25 °C. $CHCl_3$ was distilled from CaH_2 and stored over molecular sieves prior to use. Tri(2-aminoethyl)amine, diethylenetriamine and *n*-amylamine were purchased from Aldrich Chemical Co. and distilled prior to use. 1-Naphthyl isocyanate, and tetrabutylammonium salts of $H_2PO_4^-$, HSO_4^-, Br^- and I^- were all purchased from Acros Chemical Co.

The pH measurements in non-aqueous media (DMF) and preparation of standard reference solutions (perchloric acid, Aldrich) were performed according to the literature method.[16] A PHS-2 pH meter and glass electrode were used to measure the pH values by titration experiments using a host concentration of 1×10^{-5} M in DMF with gradual addition of CF_3COOH solution (0.01, 0.1 and 1 M in DMF). Then the fluorescence spectra of the same solutions were recorded.

General procedure for synthesis of compounds 1–3

To a cooled solution of tri(2-aminoethyl)amine (0.5 mL, 3.34 mmol in the case of **1**), diethylenetriamine (0.6 mL, 5.57 mmol, in the case of **2**) or *n*-amylamine (1.4 mL, 11.7 mmol, in the case of **3**) in dried $CHCl_3$ (20 mL) was added a solution of 1-naphthyl isocyanate (2.0 g, 11.7 mmol) in dried $CHCl_3$ (20 mL) at such a rate as to keep the temperature between 0 and 5 °C. The reaction mixture was then stirred at room temperature for 3 h. A white precipitate formed and was collected by suction and washed with $CHCl_3$.

Tri[*N*′-naphthyl-*N*-(2-amnioethyl)urea]amine (1). Yield 95%; mp 240–242 °C; ^1H NMR (D_6-DMSO): δ 8.60 (3H, s, NH_a), 8.06 (3H, d, $J = 7.6$ Hz, ArH_8), 7.95 (3H, t, $J = 3.5$ Hz, ArH), 7.85 (3H, d, $J = 7.1$ Hz, ArH), 7.72–7.40 (9H, m, ArH), 7.35–7.30 (3H, m, ArH), 6.69 (3H, s, NH_b), 3.30 (6H, t, NCH_{2c}), 2.7 (6H, t, NCH_{2d}); ^{13}C NMR (D_6-DMSO): δ 156.0 (O=C), 135.4, 137.7, 128.0, 125.6, 125.4, 125.0, 121.9, 121.7 and 117.0 (ArC), 54.8 (H_2C_c), 37.8 (H_2C_d). IR ν/cm^{-1}: 3309 (NH), 1635 (C=O). Anal. calcd for $C_{39}H_{39}N_7O_3$: C, 71.65; H, 6.01; N, 15.00. Found: C, 71.35; H, 6.05; N, 14.95%.

Di[*N*′-naphthyl-*N*-(2-amnioethyl)urea]amine (2). Yield 90%; mp 232–234 °C; ^1H NMR (D_6-DMSO): δ 8.07 (2H, s, NH_a), 8.09 (2H, d, $J = 8.0$ Hz, ArH), 7.97 (2H, d, $J = 7.2$ Hz, ArH), 7.86 (2H, d, $J = 4.6$ Hz, ArH), 7.53–7.46 (6H, m, ArH), 7.38–7.35 (2H, m, ArH), 6.79 (2H, s, NH_b), 3.60 (4H, t, NCH_{2c}), 3.35 (4H, t, NCH_{2d}); ^{13}C NMR (D_6-DMSO): δ 155.5 (O=C), 135.8, 135.7, 128.0, 125.6, 125.4, 125.0, 121.8, 121.7 and 117.5 (ArC), 54.5 (H_2C_c), 37.6 (H_2C_d). IR ν/cm^{-1}: 3309 (NH), 1635 (C=O). Anal. calcd for $C_{26}H_{27}N_5O_2$: C, 70.75; H, 6.12; N, 15.87. Found: C, 70.70; H, 6.16; N, 15.66%.

***N*′-Naphthyl-*N*-*n*-amylurea (3).** Yield 90%; mp 130–132 °C; ^1H NMR (D_6-DMSO): δ 8.47 (1H, s, NH_a), 8.08 (1H, d, $J = 7.9$ Hz, ArH), 8.00 (1H, d, $J = 7.2$ Hz, ArH), 7.88 (1H, d, $J = 7.1$ Hz, ArH), 7.54–7.47 (3H, m, ArH), 7.42–7.37 (1H, t, $J = 7.8$ Hz, ArH), 6.57 (1H, s, NH_b), 3.12 (2H, t, NCH_2), 1.46 (2H, m, NCH–CH_2), 1.30 (4H, m, C–CH_2CH_2–C), 0.88 (3H, t, –CH_3); ^{13}C NMR (D_6-DMSO): δ 155.6 (O=C), 135.2, 133.7, 128.3, 125.8, 125.6, 125.5, 125.2, 121.8, 121.3 and 116.4 (ArC), 40.2 (NH_2C), 29.4 (–CH_2C), 28.6 (–CH_2CH_2C), 21.8 (CH_3C), 13.8 (H_3C). IR ν/cm^{-1}: 1635 (C=O).

Preparation of the hydrochloride salt of 1 (1·HCl)

A mixture of hydrochloric acid (36.5%) and **1** in MeOH was stirred for 4 h at room temperature. The solvent was evaporated and the product was dried under vacuum over P_2O_5. Yield: 100%, mp: 180–182 °C (dec); ^1H NMR (D_6-DMSO): δ 9.18 (3H, s, NH_a), 8.31 (3H, m, ArH), 7.95 (3H, d, ArH), 7.85 (3H, d, ArH), 7.53–7.45 (9H, m, ArH), 7.34–7.29 (3H, m, ArH), 3.63 (6H, t, NCH_2), 3.45 (6H, t, N^+CH_2).

Determination of association constants

The measurements were performed by fluorometric titration experiments in DMF at 25 °C using a constant host concentration of 1×10^{-3} M and a varying guest concentration of 2×10^{-6}–2×10^{-4} M. The K_{ass} values were calculated by linear regression as described above.

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