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An anthracene based bispyridinium amide receptor for selective sensing of anions

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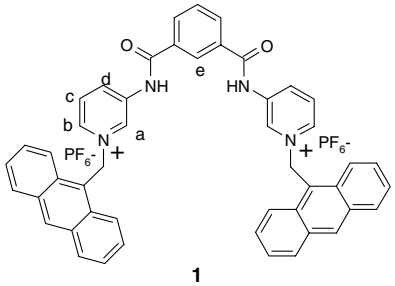
Abstract—A new receptor has been designed and synthesized for selective recognition of anions through hydrogen bonding and electrostatic interactions. The recognition ability has been studied by fluorescence, UV–vis and ^{1}H NMR spectroscopic methods. The results demonstrate that the receptor exhibits good recognition ability towards anions and shows strong binding to AcO^-, $H_2PO_4^-$ and F^-.

The development of chemosensors for the selective recognition of important anions is of great interest in host–guest chemistry due to their biological and environmental significance.[1] In this context, the search for new hydrogen bonding motifs and their judicious placement onto a suitable spacer for selective binding of anionic species is a challenging problem. Hydrogen bonds are used as recognition elements due to their directional nature. The orientation of the hydrogen bonds can differentiate anionic guests with different geometries. Anion binding by various hydrogen bonding receptors has been demonstrated.[2] In general, most of these receptors consist of urea,[3] thiourea,[4] imidazolium,[5] guanidinium,[6] etc, as the hydrogen bonding synthons attached to the fluorophores. In this connection, pyridinium amide as a binding motif is less explored. To investigate the significance of C–H–O hydrogen bonds in highly polar solvents for carboxylate ion recognition, Jeong and Cho reported the use of a pyridinium salt.[7] Later on, Steed and co-workers[8] described the synthesis, anion binding and conformational properties of a series of 3-aminopyridinium based tripodal, tricationic hosts for anions. In contrast to these known receptors for anion recognition, we herein present a new designed receptor **1**, which shows effective selectivity in the recognition of AcO^-, $H_2PO_4^-$ and F^- over other anions such as $C_6H_5COO^-$, Cl^-, Br^-, I^- and HSO_4^-. On addition of F^- and AcO^- anions, receptor **1** undergoes a selective fluorescence quenching effect, while the fluorescence emission of **1** in the presence of $H_2PO_4^-$ ions is strongly enhanced.



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Receptor **1** was synthesized according to the Scheme 1. The symmetrical bis amide **2** was obtained by coupling 3-aminopyridine with isophthaloyl chloride. This was treated with 9-chloromethylanthracene in dry CH_3CN and refluxed for 48 h to afford the salt **3**. Anion exchange using NH_4PF_6 gave the receptor **1** in 88% yield as a light yellow solid. Compound **1** was fully characterized by ^{1}H NMR, ^{13}C NMR and mass spectroscopy.[9]

The ability of receptor **1** to recognize anions was evaluated by ^{1}H NMR, fluorescence and UV–vis spectroscopic methods. Figure 1 shows the fluorescence changes of receptor **1** ($c = 5.65 \times 10^{-5}$ M, excitation of the anthracene fluorophore at 365 nm) upon the addition of F^-, AcO^-, $CH_3CH_2COO^-$, $(CH_3)_2CHCH_2$-$C_6H_4CH(CH_3)COO^-$, $C_6H_5COO^-$, Cl^-, Br^- and I^- (10 equiv as their tetrabutylammonium salt). As shown

Keywords: Aminopyridine; Anthracene; Anion recognition; PET sensor; Fluoride detection; Acetate detection.
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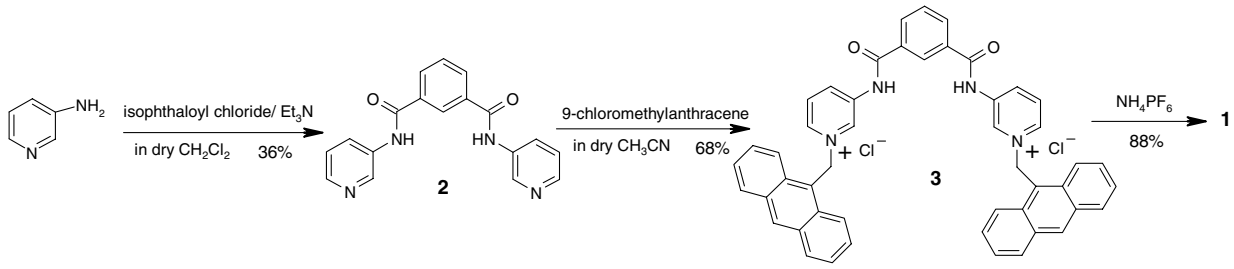

Scheme 1. Synthesis of receptor **1**.

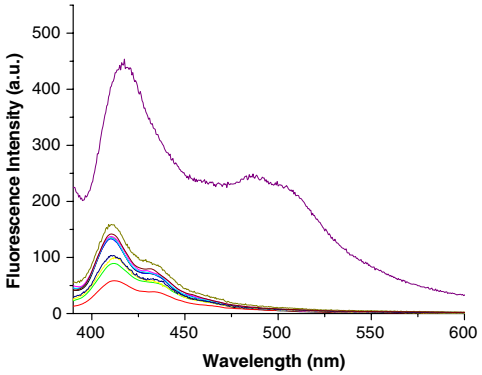

Figure 1. Fluorescent emission changes of **1** ($c = 6.56 \times 10^{-5}$ M) upon the addition of various anions (10 equiv) in CH_3CN. (**1** only, F^-, AcO^-, Cl^-, Br^-, I^-, propanoate, SO_4^-, ibuprofen, benzoate, $H_2PO_4^-$).

in Figure 1, the intensity of the monomer emission was quenched significantly in the cases of F^- and AcO^- ions and no other observable changes such as excimer formation were noticed. Interestingly, in the presence of $H_2PO_4^-$ ions, the monomer emission of **1** was greatly increased along with the appearance of a new peak at 500 nm, ascribed to excimer formation between the closely spaced anthracene moieties. This excimer formation allows $H_2PO_4^-$ ions to be distinguished from the other anions studied in the present case. The greater quenching in the presence of F^- (Fig. 2) is ascribed to the strong interactions in the open cleft initially through N–H---F^- and C–H---F^- hydrogen bonds to give the F^-·**1** complex, followed by deprotonation of the amide protons in a manner previously explained by us.[4e] Such interactions were less with larger sized and less basic ions such as Cl^-, Br^- and I^- as reflected from the negligible change in fluorescence of **1** upon their addition. In a similar way, the cavity of **1** exhibits preferential binding of AcO^- over $C_6H_5COO^-$ and shows appreciable quenching upon complexation (Fig. 3). This can be explained by the steric features of the phenyl group in the binding site. This steric role in the binding of the guest was further proved using the tetrabutylammonium salt of ibuprofen. The presence of a Me group at the carboxylate end of the salt of ibuprofen reduces the binding leading to less quenching compared to AcO^- and $CH_3CH_2COO^-$ (propanoate) (Fig. 1). The different extents of fluorescence quenching of **1** in the presence of different anions are explained by the Stern–Volmer plot (Fig. 4) and this quenching effect is attributed to a photo-induced electron transfer (PET) mechanism.

From the fluorescence titrations, the association constants[10] of the complexes of **1** with the anions are accumulated in Table 1. As shown in Table 1, receptor **1** shows higher binding constant values with $H_2PO_4^-$ and AcO^- compared to other anions. The selectivity in binding AcO^- and $CH_3CH_2COO^-$ anions over $C_6H_5COO^-$ has strong relevance in the distinction between aliphatic and aromatic carboxylates. The isophthaloyl moiety in **1**, as a spacer, introduces the binding selectivity, which was found to be greater with the tetrahedral shaped $H_2PO_4^-$ ion. In this context, the role of basicity of the anions in their selection by receptor **1**

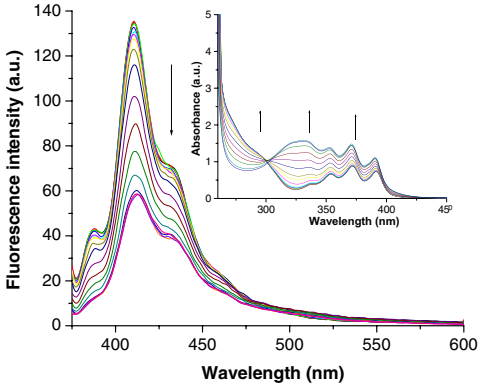

Figure 2. Fluorescent titrations of **1** with F^- in CH_3CN (excitation at 365 nm) and the change in the UV–vis spectra of **1** ($c = 6.06 \times 10^{-5}$ M) upon the addition of F^- (inset).

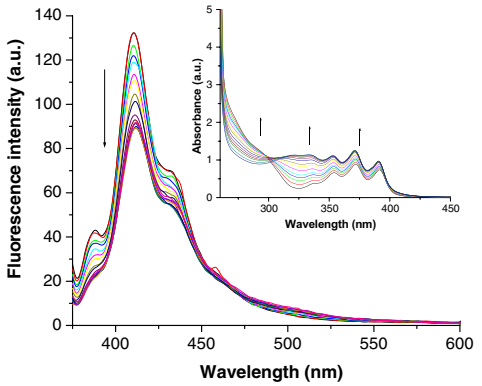

Figure 3. Fluorescent titration of **1** with AcO^- in CH_3CN (excitation at 365 nm) and change in the UV–vis spectra of **1** ($c = 6.06 \times 10^{-5}$ M) upon the addition of AcO^- (inset).

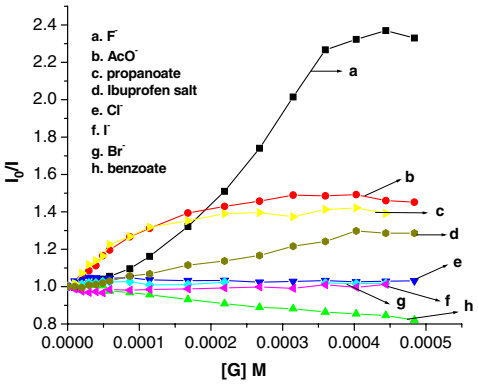

Figure 4. Stern–Volmer plot of **1** at 410 nm.

Table 1. Binding constants (K_a) based on fluorescence and UV–vis methods

Guest anion	K_a (M^{-1})[a]	K_a (M^{-1})[b]
F^-	1.85×10^3	2.0×10^3
Cl^-	—[c]	—[c]
Br^-	—[c]	—[c]
I^-	—[c]	—[c]
HSO_4^-	—[c]	—[c]
$H_2PO_4^-$	1.03×10^4	2.14×10^4
AcO^-	6.99×10^3	1.29×10^4
$CH_3CH_2COO^-$	5.07×10^3	4.08×10^3
$(CH_3)_2CHCH_2C_6H_4CH(CH_3)COO^-$	3.34×10^3	3.37×10^3
$C_6H_5COO^-$	4.12×10^2	3.63×10^2

[a] Determined by fluorescence in CH_3CN.
[b] Determined by UV–vis in CH_3CN.
[c] Binding constant values were not determined due to minimal change.

cannot be excluded. The change in fluorescence of **1** in the presence of $H_2PO_4^-$ in this regard is shown in Figure 5. The gradual increase in the fluorescence intensity of **1** upon addition of the tetrabutylammonium salt of $H_2PO_4^-$ is due to the inhibition of PET from the binding site to the excited anthracene unit.

The simultaneous UV–vis experiments in CH_3CN upon addition of the aforementioned anions showed minor changes in the absorbance of the anthracene peaks. This

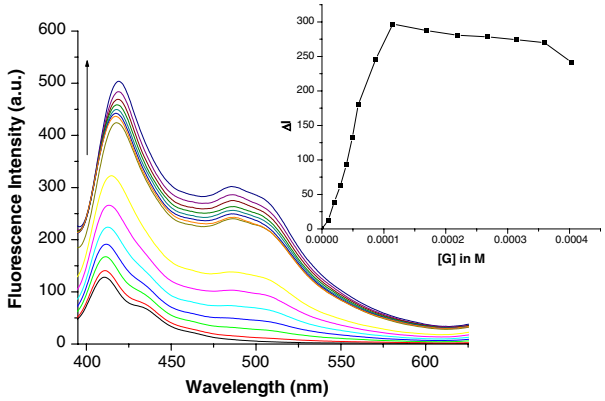

Figure 5. Fluorescent titrations of **1** ($c = 6.56 \times 10^{-5}$ M) with $H_2PO_4^-$ in CH_3CN (excitation at 365 nm) and the change in fluorescence intensity of **1** with [$H_2PO_4^-$] (inset).

indicates the insulating role of the –CH_2– group, which minimizes the ground state interaction between anthracene and the binding site. In the presence of $H_2PO_4^-$, the absorption peaks of anthracene were red shifted ($\Delta\lambda = 7$ nm) indicating a strong hydrogen bonding interaction in the cleft of **1**. From the UV–vis titration in CH_3CN, the minor change in absorbance of the anthracene peak at 371 nm was used to determine the binding constant[10] values (Table 1), which were found to follow a similar trend to the fluorescence. However, in the present case, both in the ground and excited states, receptor **1** showed 1:1 binding stoichiometries with F^- and AcO^-. The Job plots (Figs. 6a and b) as well as the break of the titration curve (ΔI vs [G]/[H]) confirmed the 1:1 stoichiometry. Moreover, during the course of the UV–vis titration experiments with both F^- and AcO^-, the appearance of clear isosbestic points at 300 nm (Figs. 2 and 3 insets) also revealed the 1:1 stoichiometries. In the case of $H_2PO_4^-$, the stoichiometry was found to be complicated. In Figure 6c, two inflections close to 1:1 and 1:2 (host:guest) bindings were observed, respectively. From these results, we suggest the different possible hydrogen bonded modes of **1** with the anions, shown in Figure 7. In the case of $H_2PO_4^-$, the forms **C** and **D** may remain in equilibrium (Fig. 7) and the initially formed complex **C** of 1:1 stoichiometry is transformed into **D** of 2:1 stoichiometry in the presence of excess $H_2PO_4^-$ ions. The break in the titration curve (ΔI vs [G]/[H]) for $H_2PO_4^-$ also demonstrated these features.

The expected strong interactions between **1** with F^- and AcO^- in the modes **A** and **B** (Fig. 7) were further confirmed by ^{1}H NMR (Fig. 8a). As shown in Figure 8a, the pyridinium H_a of **1** displayed a significant downfield shift of $\Delta\delta = 0.03$ ppm in the 1:1 complexes with F^- and AcO^- ions and $\Delta\delta = 0.09$ ppm for benzoate. The isophthaloyl *peri* proton (H_e) underwent a downfield shift ($\Delta\delta = 0.10$–0.16 ppm) with F^-, AcO^- and $C_6H_5COO^-$ ions. During complexation, the H_d and H_b protons of the pyridine ring showed upfield shifts ($\Delta\delta = 0.20$–0.28 ppm), presumably due to a complexation induced conformational change in the receptor. A similar type of conformational change of an isophthaloyl spacer based receptor in the presence of F^- is well documented in a recent publication by Gale and co-workers.[11] In all the cases, the amide proton resonances at 11.15 ppm were too broad to be noted accurately during complexation and this is attributed to the strong hydrogen bonding interactions. As shown in Figure 8b, in the presence of $H_2PO_4^-$, protons H_a and H_b moved downfield significantly ($\Delta\delta = 0.79$ ppm) indicating the involvement of C–H---O bonds for strong complexation. At [G]/[H] = 2, protons H_d underwent a downfield shift ($\Delta\delta = 0.30$ ppm). This observation further confirmed our proposition on the possible structure **D** in Figure 7.

In conclusion, a simple pyridinium amide receptor containing two anthracene moieties has been synthesized as a fluorescent chemosensor for $H_2PO_4^-$, F^- and AcO^-. The results show that the cleft of the receptor can distinguish aliphatic carboxylates from aromatic examples

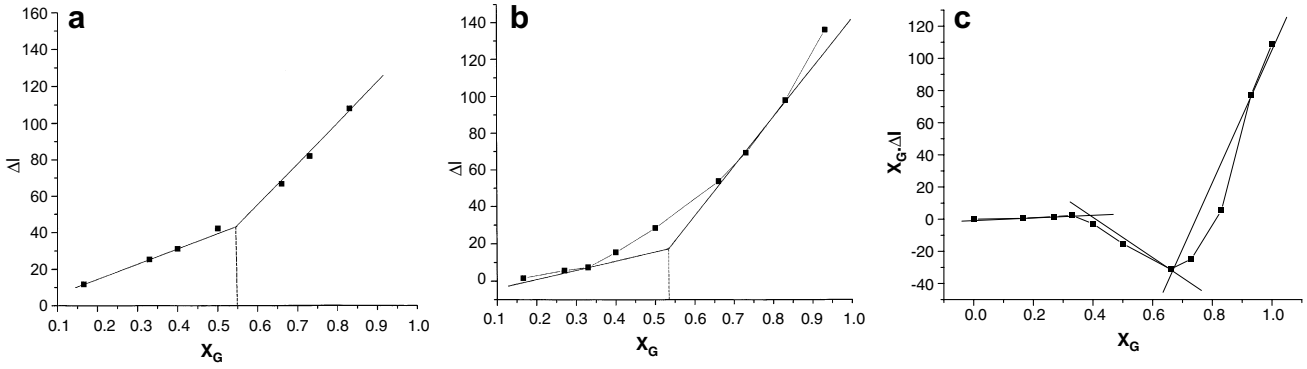

Figure 6. Fluorescence Job plots for complexes $\mathbf{1}\cdot AcO^-$ (a), $\mathbf{1}\cdot F^-$ (b), and $\mathbf{1}\cdot H_2PO_4^-$ (c).

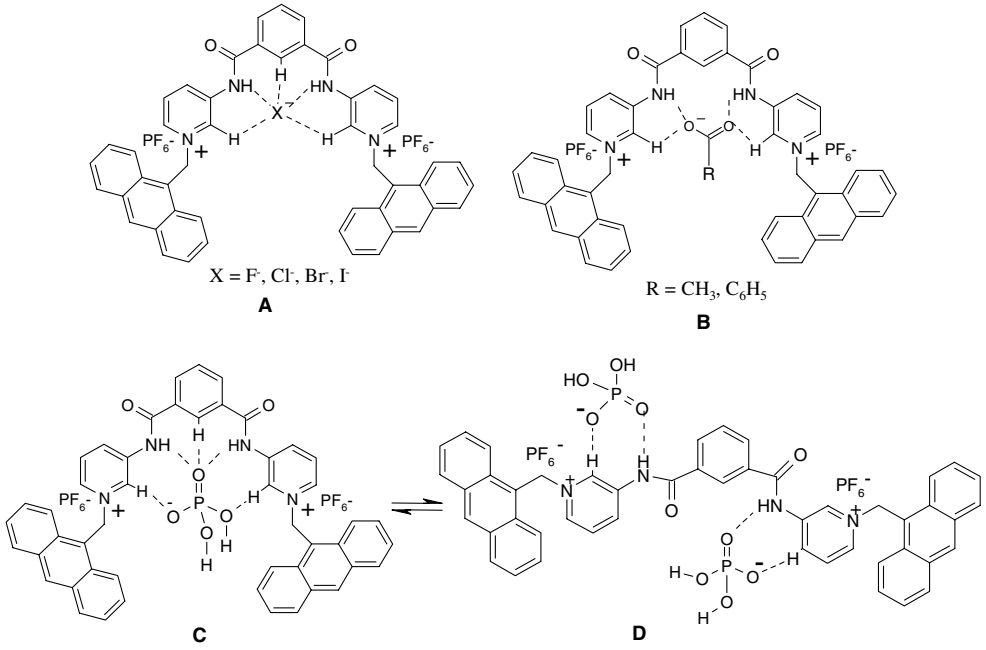

Figure 7. Possible hydrogen bonding modes of complexes of **1** with anions.

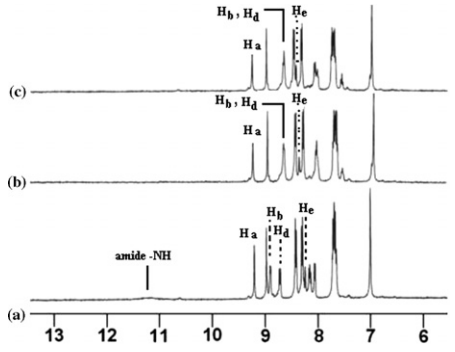

Figure 8a. (a) Partial ^1H NMR spectra (DMSO-d_6, 400 MHz) of **1** only; (b) with F^- (1:1); (c) with AcO^- (1:1).

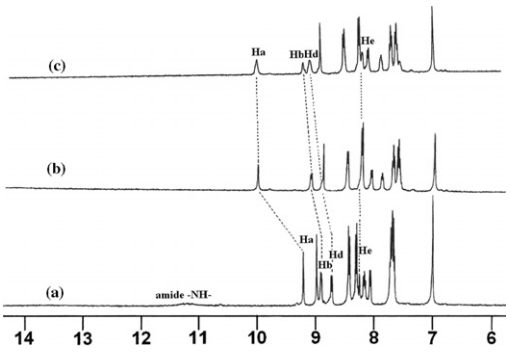

Figure 8b. (a) Partial ^1H NMR spectra (DMSO-d_6, 400 MHz) of **1** only; (b) with $H_2PO_4^-$ ([G]/[H] = 1); (c) with $H_2PO_4^-$ ([G]/[H] = 2).

and is also able to report the selective binding of tetrahedral shaped $H_2PO_4^-$ ions through strong excimer formation. The high affinity and selectivity of such simple fluororeceptors are due to the combined effects of semi-rigid structures, charge–charge interactions, and the involvement of both N–H···O and C–H···O hydrogen bonds. Further work in this direction is underway in our laboratory.

Acknowledgements

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9. Receptor **1**: Mp 216 °C; ^{1}H NMR (DMSO-d_6, 400 MHz): δ 11.15 (s, NH, 2H), 9.19 (s, 2H), 8.97 (s, 2H), 8.89 (d, 2H, $J = 8$ Hz), 8.70 (d, 2H, $J = 8$ Hz), 8.40 (d, 4H, $J = 8$ Hz), 8.28 (d, 4H, $J = 8$ Hz), 8.23 (s, 1H), 8.14 (t, 2H, $J = 8$ Hz), 8.05 (d, 2H, $J = 8$ Hz), 7.71–7.63 (m, 9H), 6.99 (s, 4 H); ^{13}C NMR (DMSO-d_6, 125 MHz): 161.0, 134.9, 130.7, 130.1, 129.6, 129.5, 128.8, 127.3, 126.9, 126.7, 126.5, 125.1, 124.5, 123.9, 122.9, 121.3, 118.7, 117.1, 52.0; FTIR: ν cm^{-1} (KBr): 3444, 1685, 1633, 1522, 1501, 1449. *m/z* (ES^{+}) 845.3 [(M–PF_6)]$^{+}$, 813.3, 735.3, 699.4, 509.2.
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