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Fluorescent photoinduced electron transfer (PET) sensing of anions using charge neutral chemosensors†

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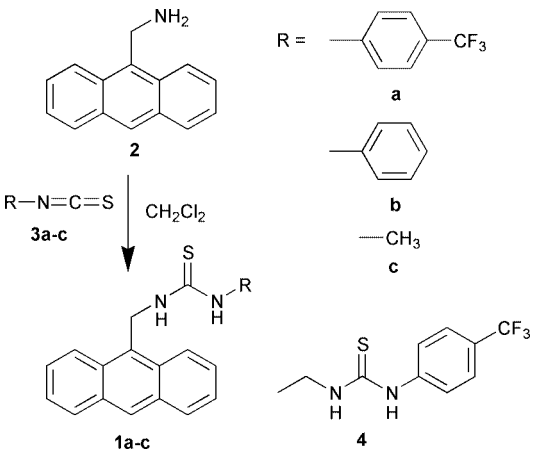
We demonstrate for the first time that the charge neutral anthracene based fluorescent sensors 1a–c, having an aromatic or aliphatic thiourea moiety as an anion receptor, show *ideal* PET sensor behaviour where the anthracene fluorescence emission is selectively quenched upon titration with AcO^-, $H_2PO_4^-$ and F^- but not by Cl^- and Br^- in DMSO.

There is great interest in the design and synthesis of luminescent based chemosensors for on-line and real time detection of physiologically important ions and molecules,[1] and for environmental monitoring of harmful pollutants.[2] While numerous fluorescent and metal based delayed luminescent sensors for cations and organic molecules have emerged from the fields of supramolecular and coordination chemistry,[3] sensors for selective detection of anions are still relatively rare, despite the fact that several elegant examples of anion receptors have been reported over the years.[4] These, however, often involve the synthesis of complex and challenging organic hosts from scaffolds such as cholic acid,[5] calixarenes and peptides.[6] Luminescent anion sensing has recently been achieved[4] through the use of anion receptors composed, for example, from metal based Lewis acid centres,[7] calix[4]pyrroles,[8] thiouronium[9] and protonated quinoxaline,[10] amine[11] or polyamine moieties,[12] but the use of simple and easily synthesised electroneutral anion receptors for such sensing has been less investigated.[13] Intrigued by this fact, we set out to develop the charge neutral chemosensors **1a–c**, employing the criteria of PET sensing using the *fluorophore–spacer–receptor* model developed by de Silva for the detection of cations.[14] A few research groups have attempted to develop PET anion sensors.[11–13,15] But, to the best of our knowledge no such systems, employing neutral anion receptors, have yet been reported that show *ideal* PET behaviour, *i.e.* (*i*) only the quantum yield (intensity) and lifetime of the fluorescence emission should be modulated upon ion recognition due to (*ii*) changes in the free energy of electron transfer (ΔG_{PET}) between the excited state of the fluorophore and the receptor upon ion recognition, and (*iii*) no changes should be observed in the absorption spectra of the fluorophore.[14]

The three PET chemosensors **1a–c**, were easily made in good yield from readily available starting materials, Scheme 1. The 9-aminomethyl anthracene **2**, synthesised by reducing 9-cyanoanthracene using B_2H_6 in THF, was reacted in dry CH_2Cl_2 at room temperature, under an inert atmosphere with an equimolar amount of 4-(trifluoromethyl)phenyl-, phenyl- and methyl isothiocyanate respectively, **3a–c**, yielding **1a–c** as off-white solids that were purified by crystallisation from CH_2Cl_2. For comparable UV-Vis binding studies, the thiourea receptor **4** was prepared in an analogous way from ethylamine. All products were analysed by conventional methods.† The three different isothiocyanates **3a–c**, were chosen with the aim of being able to modulate or tune the acidity of the thiourea receptor moiety, which would lead to different *receptor–analyte* complex stability and hence different binding constants. Of the three chemosensors, **1a** was expected to show the strongest binding due to this effect, and **1c** the least. We initially investigated the binding of **1a** using $(C_4H_9)_4N(O_2CCH_3)$, since AcO^- is known to form strong directional hydrogen bonding with thiourea, as well as having a functional group of great biological relevance.[16] The ^1H NMR of **1a** in DMSO-d_6, showed two sharp signals at 9.62 ppm and 8.36 ppm for the thiourea hydrogens. These were substantially shifted downfield upon addition of $0.1 \rightarrow 2$ equivalents of $(C_4H_9)_4N(O_2CCH_3)$ ($\Delta\delta$ = 1.92 and 1.66 ppm respectively after 1 eq.) signifying the formation of a 1 : 1 binding through hydrogen bonding with a log β = 3.2.†

The fluorescence emission spectra of **1a** when titrated with AcO^- in DMSO displayed typical PET behaviour. In the absence of AcO^- the fluorescence emission spectra consisted of three sharp bands at 443, 419 and 397 nm, with a shoulder at 473 nm, when excited at 370 nm with Φ_F = 0.1037.‡ Upon addition of the AcO^- ($0 \rightarrow 32$ mM), the intensity of these bands gradually decreased with no other spectral changes being observed (*i.e.* no spectral shifts or formation of new emission bands), Fig. 1a. Using PET nomenclature, the emission can be said to being *ca.* 70% (at 443 nm) '*switched off*', with Φ_F = 0.0070. Concurrently, the absorption spectra of **1a**, consisting of bands at 390, 370, 352 and 336 nm, was hardly affected by the addition of AcO^-.† This confirms the insulating role of the methylene spacer, which minimises any ground state interactions between the fluorophore and the anion receptor. Similar emission and absorption effects were observed for **1b** and **1c**. When the fluorescence titrations of **1a–c** were carried out in CH_3CN, CH_3CO_2Et or THF, the emission was also quenched upon addition of AcO^- but the degree of quenching was somewhat smaller. In EtOH, which is a highly competitive hydrogen bonding solvent, no binding was observed between **1a** and AcO^-. Furthermore, *no* exciplex emission was observed in any of these solvents; in contrast, Teramae *et al.* have recently shown that a pyrene analogue of **1c**, is a ratiometric anion



Scheme 1 The synthesis of **1a–c**. **4** was made in a similar way.

† Electronic supplementary data (ESI) available: ^1H, ^{13}C NMR for **1a–c** and UV-Vis and NMR titration results for **1a** are available as electronic supplementary information (ESI). See http://www.rsc.org/suppdata/cc/b1/b107608f/

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indicator based on the control of intramolecular exciplex emission.[13]

To investigate the selectivity and the sensitivity of the sensor towards biologically important anions, we carried out a series of titrations using $N(C_4H_9)_4^+$ salts of F^-, Cl^-, Br^- and $H_2PO_4^-$ in DMSO. In the case of $H_2PO_4^-$ and F^- the fluorescence emission was quenched by *ca.* 50 (Φ_F = 0.0156) and 90% Φ_F = 0.0011) respectively (at 443 nm), but only minor quenching (<7%) was observed when titrated with Cl^- (Φ_F = 0.108) or Br^- (Φ_F = 0.088), ruling out a quenching by heavy atom effect. We propose that the quenching is likely to be due to the modulations of ΔG_{PET} upon anion sensing. This can be regarded as an enhancement in the rate of electron transfer from the HOMO of the thiourea–anion complex to the anthracene excited state, upon anion recognition *i.e*, the reduction potential of the thiourea is increased causing PET to become competitively more viable, which causes the fluorescence emission to be quenched or *'switched off'*.§ Plotting the fluorescence intensity changes (at 443 nm) as a function of log [anion] further supports this view. Fig. 1b, shows several features commonly seen for PET cation sensors *e.g.* the profiles for AcO^-, $H_2PO_4^-$ and F^- are all sigmoidal, the quenching occurs over two log concentration units, which is consistent with 1 : 1 binding and simple equilibrium. From these changes the binding constant log β for **1a** was measured to be 3.35 (±0.05) for F^-, 2.55 (±0.05) for AcO^- and 2.05 (±0.05) for $H_2PO_4^-$.‡ Similar binding constants were found for **4a** by measuring the changes in its absorption spectra at 286 nm. Importantly, **1a** shows good anion selectivity with AcO^- being recognised over $H_2PO_4^-$, but both represent families of biological important anions. The fact that **1a** shows higher affinity and more efficient quenching for F^- than AcO^- is not surprising, since its high charge density and small size enables it to form strong hydrogen bonding with the thiourea receptor. Measurements using **1b** and **1c** and the same anions showed similar results. For **1b**, the same selectivity trend was observed as for **1a**, with smaller binding constants due to the reduced acidity of the thiourea protons. For **1c** the order of selectivity and the sensitivity was somewhat different with $H_2PO_4^-$ (log β = 2.05 (±0.05)) being selectively detected over AcO^- (log β = 1.75 (±0.05)). These results show that the anion sensor's affinity can be controlled by simple design.[16]

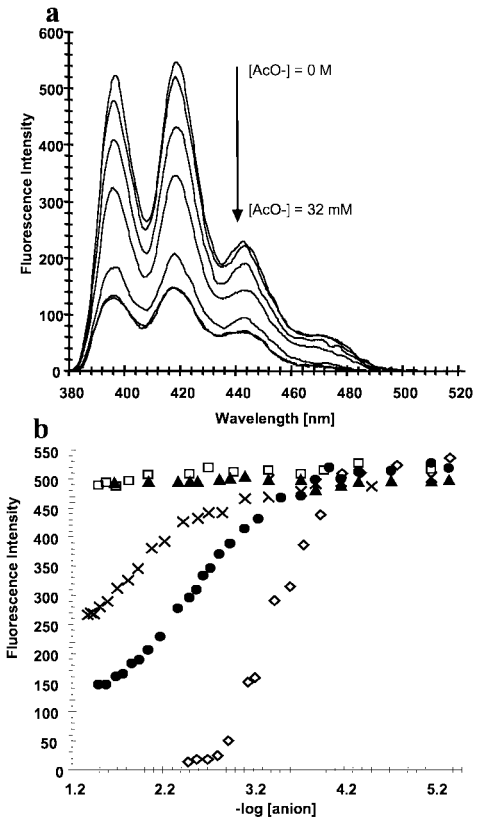

Fig. 1 (a) The changes in the fluorescence spectra of **1a** in DMSO upon addition of acetate. From top: [AcO^-] = 0, 92 μM, 550 μM, 1.8 mM, 8.9 mM, 26 mM, 32 mM. (b) Titration profile for **1a** showing the changes in the fluorescence emission as a function of added anion: ◇ = F^-, ● = AcO^-, × = $H_2PO_4^-$, □ = Cl^-, ▲ = Br^-, when measured at 443 nm. All titrations were repeated two to three times to ensure reproducibility.

In conclusion, the simple fluorescent PET anion chemosensors **1a–c** show *ideal* PET sensing behaviour upon ion recognition, *e.g.* only the fluorescence emission is *'switched off'* in the presence of AcO^-, $H_2PO_4^-$ and F^-. **1a–c** are a very important contribution to the fast growing field of supramolecular anion recognition and sensing.

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Notes and references

‡ **1a–c** Φ_F were measured by comparison with anthracene (Φ_F = 0.27 in EtOH); D. F. Eaton, *Pure Appl. Chem.*, 1988, **60**, 1107. log β was determined from the equation:
$\log [(I_{max} - I_F)/(I_F - I_{min})] = \log [anion] - \log \beta$.
§ CV measurements on **4** showed two irreversible oxidative waves. Accurate ΔG_{ET} could not be determined from these measurements. We investigated the PET dependence of **1a** by comparing the Φ_F of **1a** with that of 9-methylanthracene (9MA), which lacks the anion receptor. In the absence of AcO^- the Φ_F of 9MA was found to be 0.284 in DMSO. This suggests that PET is active in **1a** prior to the anion recognition, but becomes even more efficient after anion recognition. In contrast, the addition of 40 mM of AcO^- to 9MA did not affect the Φ_F.

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