Colorimetric ‘naked-eye’ and fluorescent sensors for anions based on amidourea functionalised 1,8-naphthalimide structures: anion recognition via either deprotonation or hydrogen bonding in DMSO

Haslin Dato Paduka Ali, Paul E. Kruger and Thorfinn Gunnlaugsson

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Introduction

Anion recognition and sensing has become a fast growing field of research in the last few years. In particular the study of anion sensing using fluorescent or colorimetric sensors has been actively studied. In the latter, anion recognition gives rise to changes in the absorption spectra with associated colour changes. The use of charge neutral anion receptors such as imidazoles, pyrroles, calixpyrroles, amides, cabamides, phenols, ureas, thioureas and amidoureas to achieve such sensing has been demonstrated. For these receptors, the anion is recognized through hydrogen bonding or by deprotonation of labile protons by the basic anions (such as fluoride) in organic solvents. Such sensors can also operate within supporting matrices or polymers as recently demonstrated by Anzenbacher or by simply adsorbing anion sensors onto cellulose, or filter paper. The recognition moiety often forms part of a chromophore possessing a push–pull character based on electron-donor–acceptors, which often make them non or weakly luminescent. We have been active in developing sensors for anions. Herein we present three new anion sensors 1–3, based on the 4-amino-1,8-naphthalimide structure, which has an internal charge transfer excited state, and which has been extensively used for sensing cations such as Na⁺, K⁺ and transition metal ions. We and others have previously shown that such amidoureas are particularly effective hydrogen bonding donors capable of anion recognition. Indeed, by simply changing the 4-amino moiety for a hydrazine and reacting the ‘free amine’ with isocyanates gave the desirable 4-amidourea-1,8-naphthalimide based sensors. By incorporating electron withdrawing substituents such as CF₃, as part of the amidourea moiety we were also able to ‘tune’ both the selectivity and sensitivity of the anion recognition. These anion sensors were all strongly coloured, absorbing in the visible region with a λmax of 450 nm, and we demonstrate that the ICT fluorescence of 1–3 is significantly modulated upon excitation of the ICT band, as well as upon excitation of the newly formed long wavelength absorption band at 540 nm, which gives rise to long wavelength emission. These colour changes were clearly visible to the naked eye even at low concentrations.
washed with H₂O, giving ethyl-benzo[...]

Experimental); by, for instance, their characteristic urea pro-

duction needed. All the compounds were fully characterised (see

41, 52 and 45% yields, respectively, with no further purifica-

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cia.

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8

isocyanate (1–3

sensors

anion binding.

The three anion sensors differ only in the nature of the ‘urea’

part of their receptors. Where 1 is a simple aryl urea, 2 has an
electron donating substituent making the receptor more elec-

tron rich whilst 3, in contrast, has a strongly electron with-
drawing substituent, making its urea protons better hydrogen

bonding donors. 34 It was hoped that these simple structural

differences could be used to fine-tune the sensitivity of the

anion binding.

The synthesis of 1–3 is shown in Scheme 1. 6-Bromo-2-
ethyl-benzolo[de]isoquinoline-1,3-dione 4 was formed in 89%
yield using a literature procedure6 from the corresponding
4-bromo-1,8-naphthale anhydride, which was then reacted
with hydrazine monohydrate at 130 °C for one hour. 6 Upon
cooling to room temperature, the solution was added to H₂O,

which gave a yellow precipitate which was collected and

washed with H₂O, giving 5 in 95% yield. Finally, the anion

sensors 1–3 were formed by reacting 5 with phenyl isocyanate

(6), para-tolyl isocyanate (7) and 4-trifluoromethylphenyl

isocyanate (8), respectively, under reflux in anhydrous

MeCN. This gave rise to the formation of precipitates after

ca. 30 min, which were collected and purified by washing with

hot CH₂Cl₂ : MeOH (1 : 4) solvent mixture. This gave 1–3 in

41, 52 and 45% yields, respectively, with no further purification

needed. All the compounds were fully characterised (see

Experimental); by, for instance, their characteristic urea pro-
tons as observed in the 1H NMR spectrum (400 MHz, DMSO-
d₆). For instance, for 3, the characteristic resonances for

the urea protons were observed in the 1H NMR (400 MHz,

DMSO-d₆) at 9.64 and 9.45 ppm, respectively (Fig. 1). The

4-amino proton occurred at 8.90 ppm, and the five naphtha-

limide protons as well as the two resonances for the aryl urea

based receptors were all clearly visible. All the compounds

were highly coloured and gave rise to strong green fluores-
cence typical for such naphthalimide derivatives.

Ground state investigations of anion recognition

The anion sensors 1–3 are soluble in a variety of solvents such

as EtOH, DMSO, CH₃CN and 50 : 50 H₂O-EtOH mixtures.

However, preliminary studies of these amidourea sensors

showed that they were only able to successfully bind anions

in aprotic solvents. 7 Therefore, anion recognition of 1–3 was

conducted in DMSO at room temperature. In DMSO their

extinction coefficients were determined to be 14 586, 14 507

and 13 748 M⁻¹ cm⁻¹, respectively, for the ICT transition,

which for 3 had a λmax at 420 nm. Upon the addition of acetate

(AcO⁻), dihydrogenphosphate (H₂PO₄⁻) or fluoride (F⁻) to 3,

the 420 nm band decreased in intensity in response to each

anion (Fig. 2 for AcO⁻). Indeed, binding of AcO⁻ also gave

rise to the concomitant formation of two new absorption

bands, one at longer wavelength (ca. 569 nm) and one at

shorter wavelength (ca. 360 nm). These changes were also

accompanied by the formation of two clear isosbestic points at

385 and 470 nm, respectively. The ICT band was significantly

reduced in absorbance after the titration, appearing as a broad

shoulder at ca. 430 nm. These overall changes are consistent

with anion binding, through hydrogen bonding at the ami-
dourea moiety, which enhances the ICT character of the

chromophore by placing a highly electron rich moiety adjacent
to the donating amine. This gives rise to a stronger ‘push–pull’
effect and consequently, shifts the long wavelength absorption

towards the red. This feature was characteristic of all the anion

titrations carried out on 1–3.

Further analysis of these spectral changes (Fig. 2) clearly

shows that the long wavelength absorption band has the

appearance of ‘fine structure’, while the short wavelength

absorption increased in intensity to ca. 80% of the band for

the free (unbound) sensor at 420 nm. Similar features were

also observed for the titrations against 1 or 2. For 1 a λmax at

415 nm was recorded for the free sensor and upon titration

with AcO⁻ two new bands arose centred at 353 and 556 nm,

respectively, with associated isosbestic points at 384 and

464 nm, respectively. Similarly for 2, a λmax at 419 nm was

observed for the free sensor whilst after titration with AcO⁻
two new bands appeared centred at 353 and 558 nm, respec-
tively. Again, two clear isosbestic points were observed at 382

and 466 nm, respectively. The reversibility of this sensing

action was also confirmed by adding a polar protic solvent

(EtOH) to the above sample. This fully reversed the changes

seen in the absorption spectra in Fig. 2. Such changes were not

seen in the thiourea analogue of 1, 8 which allowed for the

sensing of AcO⁻ in aqueous media.

When titrations were carried out on 3 using either H₂PO₄⁻
or F⁻, similar overall results were observed as seen in Fig. 3

and Fig. 4, respectively. However, the absorption spectra of
each displayed some subtle differences from that observed for

the titration with AcO⁻. In the case of H₂PO₄⁻, the formation of a

long wavelength absorption band at 565 nm was accompa-

nied by the formation of a short wavelength absorption

band at 353 nm and two isosbestic points at 356 and 459 nm,

respectively. However, the latter of these was shifted slightly to

9 This is in contrast to their thioureaamido analogues that we have

also investigated and shown to sense anions in both organic and

aqueous solutions (see ref. 6).
the red at high anion concentration. We also noted that the short wavelength absorption band was not as ‘broad’ as that seen for AcO⁻ in Fig. 2, and that the long wavelength absorption band was slightly more structured. Again, we assign these changes to the recognition of the anion at the amidourea moiety, occurring through hydrogen bonding.

These differences were even more pronounced for F⁻ where ‘collapse’ of the \( \lambda_{\text{max}} \) band at 420 nm was initially replaced by the formation of a shoulder similar to that observed for both AcO⁻ and \( \text{H}_2\text{PO}_4^- \) above, and eventually by an absorption band centred at ca. 419 nm. Moreover, the long wavelength absorption was more structured than that seen for either AcO⁻ or \( \text{H}_2\text{PO}_4^- \), with significantly sharper ‘tailing off’ towards the red, and a \( \lambda_{\text{max}} \) at 559 nm. Furthermore, looking at the ratio between the 559 nm and the short wavelength 353 nm transitions, yields an almost 1 : 1 ratio between these two wavelengths, whereas in Fig. 2 and Fig. 3, the short wavelength band was ca. 50% and 40% stronger than the long wavelength absorptions, for AcO⁻ and \( \text{H}_2\text{PO}_4^- \), respectively.

Upon carrying out anion titrations on 1 and 2, similar behaviour was observed for each anion–sensor combination. The changes in the absorption spectra for 1 upon titration with AcO⁻ are shown in Fig. 5 and subtly demonstrate a difference to the absorption spectra of 3. Hence, we propose that these changes are due to the direct interaction of the anion with the receptors in a specific and unique manner, and not due to one common mechanism such as deprotonation of the thiourea protons, as such mechanism would have lead to the formation of the same ‘product’ for all of these anions, and hence an identical absorption spectrum. These titrations were also carried out on 1–3 using ether Cl⁻ or Br⁻, but these titrations did not lead to measurable changes in the absorption spectra.

By plotting the growth of the new long wavelength band of these colorimetric sensors as a function of \(-\log [\text{anion}]\),

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**Fig. 1** \(^1\text{H} \) NMR spectrum (400 MHz, DMSO-\(d_6\)) of 3 with assignments.

**Fig. 2** The changes observed in the absorption spectrum of urea 3 (1.5 \(\times 10^{-5}\) M) upon addition of AcO⁻ (0 M \(\rightarrow\) 3 \(\times 10^{-3}\) M) in DMSO.

**Fig. 3** The changes observed in the absorption spectrum of urea 3 (1.5 \(\times 10^{-5}\) M) upon addition of \(\text{H}_2\text{PO}_4^-\) in DMSO at 25 °C (0 M \(\rightarrow\) 3 \(\times 10^{-3}\) M).
sigmoidal binding curves were observed, which changed over approximately two log units for both AcO\(^-\) and H\(_2\)PO\(_4\)^-, which is indicative of 1:1 binding. This stoichiometry was also confirmed by fitting the changes in the long wavelength band using the nonlinear regression analysis program SPECFIT. Using a number of different binding models with host-to-guest stoichiometries such as 1:1, 1:2 and 1:3, gave log \(\beta\) values as shown in Table 1. However, only the 1:1 binding gave good fits to the experimental data. In contrast to these results it was not possible to accurately calculate the log \(\beta\) values for F\(^-\) binding, as the resulting log \(\beta\) values carried significant errors. This is most likely due to the nature of the binding interactions of F\(^-\) with the amidourea protons. For AcO\(^-\) and H\(_2\)PO\(_4\)^- the sensing is due to hydrogen bonding interactions between the anion and the amidourea protons, however for F\(^-\), initial hydrogen bonding interaction is most likely followed by the formation of the ion pair complex (bifluoride ion) HF\(_2^2^-\), because of the ability of this anion to deprotonate acidic moieties. Similar deprotonation events have been demonstrated previously by our own group as well as those of Gale,\(^19,23\) Fabbrizzi\(^18\) and Pfeffer.\(^7,16\)

Colorimetric responses: naked eye detection of anions

As is clear from the above ground state changes, the absorption spectra of 1–3 were dramatically affected upon interaction with AcO\(^-\), H\(_2\)PO\(_4\)^- or F\(^-\), and each one of these anions gives rise to unique change in the structure of the absorption spectra. However, the ‘colour’ changes seen in the absorption spectra were also clearly visible to the naked eye as demonstrated in Fig. 6, which shows the chromogenic response of 3 (1 \times 10^{-3} M) in DMSO upon the addition of these anions (1 eq.). In general, the colour change was from a bright fluorescent colour to blue or deep purple. However, in the case of F\(^-\), the purple colour change was only observed at low guest concentrations, as at high concentrations the initial colour changed, via purple, to pale orange. This may be ascribed to the deprotonation of the N–H protons of the urea/thiourea moiety of the sensor, resulting in the formation of the HF\(_2^2^-\). No colour change was seen in the presence of either Cl\(^-\) or Br\(^-\).

**Fig. 4** Changes observed in the absorption spectrum of urea 3 (1.5 \times 10^{-5} M) upon addition of F\(^-\) in DMSO at 25 °C (0 M \rightarrow 3 \times 10^{-3} M).

**Fig. 5** The changes observed in the absorption spectrum of urea 1 (1.5 \times 10^{-5} M) upon addition of AcO\(^-\) (0 M \rightarrow 3 \times 10^{-3} M) in DMSO.

Excited state spectroscopic investigation of anion recognition

In parallel with the absorption binding experiments discussed above, the changes in the fluorescence emission spectra of 1–3 were also monitored in DMSO upon anion sensing. The changes in the fluorescence emission of 1 upon excitation \(\lambda_{\text{max}}\) at 420 nm, is shown in Fig. 7. The emission spectrum of the free sensor gave rise to the formation of a broad band with a maximum intensity at 520 nm upon excitation of the ICT band at 420 nm. Following titration with AcO\(^-\) fluorescence quenching was observed for this band and the emission was significantly “switched off”. However, it is clear from Fig. 7 that the \(\lambda_{\text{Fmax}}\) was also shifted to a longer wavelength. When the changes in emission intensity at the 520 nm band are plotted as a function of \(-\log [\text{AcO}^-]\) (Fig. 7, insert) a sigmoidal profile results, indicative of 1:1 binding between the anion and the sensor. From these changes, we estimated the binding constant log \(\beta\) to be \(\sim 5.0 \pm 0.2\), which correlates well with that observed in the ground state (Table 1). The emission spectra was also monitored by exciting at the two isosbestic points shown in Fig. 1, as well as at the anion induced long wavelength absorption band. Upon excitation of the isosbestic point at 360 nm, similar changes were observed, with \(\lambda_{\text{max}}\) at 510 nm. However, here the emission was fully quenched, or fully “switched off”, with concomitant formation of a new weakly emitting band at longer wavelength centred at ca. 625 nm. On the other hand, when exciting at the 470 nm isosbestic point, an emission band with \(\lambda_{\text{max}}\) at 545 nm was observed that tailed into the 760 nm region. This emission was much less modulated upon titration with AcO\(^-\), with only

**Fig. 6** Chromogenic response of solutions of sensor 3 (1 \times 10^{-3} M) upon interaction with various anions: (a) Free host 3; (b) 3 + 1 eq. AcO\(^-\); (c) 3 + 1 eq. H\(_2\)PO\(_4\)^-; (d) 3 + 1 eq. F\(^-\); (e) 3 + F\(^-\) (excess).
The changes in the fluorescence emission of $3.99$ with $\lambda_{\text{max}}$ was observed at ca. 610 nm, with a smaller shoulder at 690 nm, which was enhanced upon increasing the concentration of AcO$^-$. Both 2 and 3 also gave rise to long wavelength emission bands upon excitation at the ICT bands and at their isosbestic points, which was again modulated upon titration with AcO$^-$. These changes were however, followed by a significant “switching on” effect (after the addition ca. $50$ equivalents of the anion) which also gave rise to a red shift from a maximum intensity at 520 nm to 530 nm, Fig. 8. Similarly, the effect of the addition of either $\text{H}_2\text{PO}_4^-$ or $\text{F}^-$ following excitation at 360 nm gave rise to an initial decrease in the fluorescence emission ($\lambda_{\text{max}} 510$ nm) by ca. $25\%$, followed by an increase in the same band with the appearance of two new bands at 440 and 615 nm, respectively. Fig. 9 shows these changes for 1 in the presence of $\text{F}^-$. Similar behaviour was also observed for 2 and 3 when titrated with $\text{H}_2\text{PO}_4^-$ or $\text{F}^-$. One rationale for these changes is that the hydrazine proton directly attached to the 4-position of the naphthalimide ring is also involved in the binding of these anions. In the case of $\text{H}_2\text{PO}_4^-$ it may be due to hydrogen-bonding interactions with this moiety as demonstrated by Pfeffer et al. for related

![Fig. 7](image1)

**Fig. 7** Changes observed (quenching) in the fluorescence of 1 ($1.5 \times 10^{-3}$ M) upon addition of AcO$^-$ in DMSO at 25 °C (excited at 420 nm; 0 M $\rightarrow$ $3 \times 10^{-3}$ M). Insert: the changes at 520 nm as a function of $-\log \left[ \text{AcO}^- \right]$. See Fig. 5 for the corresponding ground state changes.

ca. $15\%$ changes being observed in the emission intensity. This long wavelength emission was also clearly observed when exciting at the newly formed band at 569 nm, where $\lambda_{\text{max}}$ was observed at ca. 610 nm, with a smaller shoulder at 690 nm, which was enhanced upon increasing the concentration of AcO$^-$. Both 2 and 3 also gave rise to long wavelength emission bands upon excitation at the ICT bands and at their isosbestic points, which was again modulated upon titration with AcO$^-$. These changes were however, followed by a significant “switching on” effect (after the addition ca. $50$ equivalents of the anion) which also gave rise to a red shift from a maximum intensity at 520 nm to 530 nm, Fig. 8. Similarly, the effect of the addition of either $\text{H}_2\text{PO}_4^-$ or $\text{F}^-$ following excitation at 360 nm gave rise to an initial decrease in the fluorescence emission ($\lambda_{\text{max}} 510$ nm) by ca. $25\%$, followed by an increase in the same band with the appearance of two new bands at 440 and 615 nm, respectively. Fig. 9 shows these changes for 1 in the presence of $\text{F}^-$. Similar behaviour was also observed for 2 and 3 when titrated with $\text{H}_2\text{PO}_4^-$ or $\text{F}^-$. One rationale for these changes is that the hydrazine proton directly attached to the 4-position of the naphthalimide ring is also involved in the binding of these anions. In the case of $\text{H}_2\text{PO}_4^-$ it may be due to hydrogen-bonding interactions with this moiety as demonstrated by Pfeffer et al. for related

![Fig. 8](image2)

**Fig. 8** Changes observed in the fluorescence of 1 ($1.5 \times 10^{-3}$ M) upon addition of $\text{H}_2\text{PO}_4^-$ in DMSO at 25 °C (excited at 420 nm; 0 M $\rightarrow$ $3 \times 10^{-3}$ M).

systems, which, in our case could result in full proton transfer. $^{16}$ In the case of $\text{F}^-$ it is possible that initially the ion is bound through hydrogen bonding to the urea moiety, followed by either the binding of a second $\text{F}^-$ at the 4-amino moiety or, by deprotonation of a urea NH, or the 4-amino moiety protons, in either case to yield HF$_2^-$ and AcO$^-$. We have recently demonstrated that such deprotonation occurs for similar 4-amino-1,8-naphthimidates at high concentrations of F$^-$ will deprotonate the most acidic proton to form HF$_2^-$. The changes shown in Fig. 9, suggest that such deprotonation is probably occurring here. Analysis of the emission spectra by plotting the changes at 440, 510 and 615 nm, respectively, as a function of $-\log \left[ \text{F}^- \right]$, clearly revealed the complexity of the anion recognition–deprotonation process for both $\text{H}_2\text{PO}_4^-$ or $\text{F}^-$, supporting our explanation. Unfortunately, we were unable to determine accurate binding constants from these changes by fitting the emission changes by using the nonlinear regression analysis program SPECFIT.

### 1H NMR spectroscopic investigation of anion recognition

Having established above that anion recognition was either through ‘pure’ hydrogen bonding interactions, or as a combination of hydrogen bonding and/or deprotonation, we carried out detailed 1H NMR spectroscopic titrations on 1–3 in DMSO-$d_6$ using $1.0 \times 10^{-2}$ M of the above anions at 25 °C. The naked eye effect discussed above was also quite striking in these studies due to the relatively high concentration of the sensors, and the yellow to purple colour change began to occur immediately after the addition of 0.1 equivalent of anion. The naphthalimide protons of these sensors were primarily monitored as the chemical shifts of the NH protons of the urea moiety broadened significantly early on in the titration. Nevertheless, it was also possible to observe the changes in the chemical shift of the 4-amino-naphthalimide proton in 1 and 2, while that of sensor 3 became too broad to monitor upon anion interaction, most likely due to the electron-withdrawing effect of the 4-(trifluoromethyl)-phenyl substituents which would be expected to increase in the acidity of the urea N–H protons.

Fig. 10 and Fig. 11 show the changes observed in the 1H NMR spectrum of 3 upon the addition of AcO$^-$ and $\text{F}^-$, respectively. The data obtained from these titrations was plotted as the cumulative changes in chemical shift ($\Delta\delta$) against the equivalents of anion added and the resulting plots

<table>
<thead>
<tr>
<th>Sensor</th>
<th>AcO$^-$</th>
<th>$\text{H}_2\text{PO}_4^-$</th>
<th>$\text{F}^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.19 ± 0.03</td>
<td>2.86 ± 0.04</td>
<td>—</td>
</tr>
<tr>
<td>2</td>
<td>3.99 ± 0.06</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>3</td>
<td>4.26 ± 0.06</td>
<td>3.49 ± 0.02</td>
<td>—</td>
</tr>
</tbody>
</table>

*a* All measured in DMSO. *b* The binding profile was too complicated to allow for accurate determination of $\log \beta$. 

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were analysed using WinEQN MR. As can be seen from Fig. 10, the amide protons disappeared after ca. 0.1 equivalent of the anion, consequently it should be noted that since the changes were comparably small in magnitude, hence carried larger errors. For all the three sensors, the binding curves obtained for their complex formation with AcO$^-$ reached a plateau after ca. one equivalent, indicating a 1 : 1 host : guest stoichiometry. This supports our finding from the ground and the excited state measurements discussed above that the binding is solely due to hydrogen bonding. On the other hand, the binding of either H$_2$PO$_4^-$ required the addition of two equivalents of the anion in order for the binding process to reach completion. In the case of F$^-$, Fig. 11, the deprotonation process was clearly visible, with the formation of the characteristic triplet for the formation of HF$_2^-$, at ca. 16 ppm. There are many reports of a 1 : 2 host : guest stoichiometry for F$^-$ binding, mostly due to such anion induced protonation. However, there are to the best of our knowledge no known cases of the binding of two equivalents of H$_2$PO$_4^-$ to such a simple mono-urea (or thiourea) receptor. We were however, unable to determine the binding constant for this second interaction accurately (cf. Table 2), which supports that

theory. The binding constants (log $\beta$) for the binding of 1–3 (determined by the WinEQN MR program) are listed in Table 2. On all occasions a good fit was observed. Unfortunately, we were unable to determined binding constants for F$^-$ due to the deprotonation of the urea N–H. However, the results demonstrate the same trend as observed for the ground state changes, and highlight the effect the substituents has on the anion affinity for these sensors.

Conclusions

A family of colorimetric sensors based on the use of 4-amino-1,8-naphthylimide as a chromophore (fluorophore) were developed for the sensing of anions through hydrogen bonding with a few steps synthesis. All the three sensors showed significant changes in the absorption spectra upon binding to anions such as AcO$^-$, H$_2$PO$_4^-$ and F$^-$ in DMSO, where the ICT band of the naphthylimide moiety was shifted to longer wavelength, and a new band was formed at shorter wavelengths and with the formation of several isosbestic points. These changes were fully reversible upon addition of a polar protic solvent. Only minor changes were seen for Cl$^-$ and Br$^-$. The sensitivity of the anion binding could also be tuned by changing the nature of the aryl urea moiety. Importantly, unique differences were seen in the fine structure of the resulting absorption bands as a consequence of the AcO$^-$, H$_2$PO$_4^-$ and F$^-$ binding, which can be considered as being a ‘fingerprint’ identity for each of these anions. Moreover, the anion binding and the changes seen in the absorption spectra were also clearly visible to the naked eye.
Table 2 Stability constants (log \( b \)) obtained from fitting the changes in the \(^1\)H NMR spectra of 1–3 upon titration with various anions\(^a\)

<table>
<thead>
<tr>
<th>Sensor</th>
<th>AcO(^-)</th>
<th>H(_2)PO(_4)(^-)</th>
<th>F(^-)(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.58</td>
<td>2.21(^c)</td>
<td>−</td>
</tr>
<tr>
<td>2</td>
<td>2.85</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>3</td>
<td>3.75</td>
<td>2.33(^a)</td>
<td>−</td>
</tr>
</tbody>
</table>

\(^a\) All measured in DMSO-\(d_6\). \(^b\) The binding process is too complicated for analysis by WinEQN MR.. \(^c\) For the 1 : 1 binding mode. Estimated error: 10%.

The florescence of these sensors was also modulated upon anion recognition, where the ICT band was either quenched or shifted to longer wavelengths. From these changes we were able to determine binding constants which showed that AcO\(^-\) was bound more strongly than H\(_2\)PO\(_4\)\(^-\) and that the binding of F\(^-\) was most likely due to initial hydrogen bonding to the anion receptor followed by deprotonation and the formation of HF\(_2\)\(^-\). The formation of this species in solution was also confirmed by \(^1\)H NMR measurements; which demonstrated that AcO\(^-\) was recognised through ‘pure’ hydrogen bonding. In contrast, the changes observed upon binding of H\(_2\)PO\(_4\)\(^-\) and F\(^-\) to 1–3 suggest that the initial recognition is more likely due to initial hydrogen bonding interactions, followed by full or partial deprotonation. Hence, we conclude that if the anion is basic enough in the solvent media deprotonation will occur on the most acidic protons of the sensors. However, since the absorption spectrum does not give rise to identical spectra at the endpoint, it strongly suggests that each of AcO\(^-\), H\(_2\)PO\(_4\)\(^-\) and F\(^-\) binds to 1–3 in a unique manner, which can be potentially used to aid in the distinction of these anions. We are currently investigating these and related systems as anion sensors for real time monitoring and sensing of anions in competitive media.

Experimental

Starting materials were obtained from Sigma Aldrich and Fluka. Solvents used were HPLC grade unless otherwise stated. \(^1\)H NMR spectra were recorded at 400 MHz using a Bruker Spectrospin DPX-400, with chemical shifts expressed for C\(_2\)H\(_5\)N\(_2\)O\(_3\): 256.1086 (M + H)\(^+\); found: 256.1077; \(\delta\) \(_{1H}\) (400 MHz, (CD\(_3\)_2)SO) 9.13 (1H, br s, Naph-NH), 8.61 (1H, d, \(J = 8.5\) Hz, Naph-H\(_7\)), 8.41 (1H, d, \(J = 7.0\) Hz, Naph-H\(_5\)), 8.28 (1H, d, \(J = 7.5\) Hz, Naph-H\(_2\)), 7.64 (1H, dd, \(J = 7.8\) Hz, 8.0 Hz, Naph-H\(_6\)), 7.24 (1H, d, \(J = 8.6\) Hz, Naph-H\(_3\)), 4.69 (2H, d, \(J = 10.6\) Hz, Naph-NH-NH\(_2\)), 4.05 (2H, q, \(J = 7.0\) Hz, CH\(_2\)), 1.18 (3H, t, \(J = 7.0\) Hz, CH\(_2\)); \(\delta\) \(_{13C}\) (100 MHz, (CD\(_3\)_2)SO) 163.6, 162.7, 155.8, 152.6, 143.9, 138.9, 136.6, 134.6, 132.7, 127.3, 124.1, 121.7, 118.4, 107.4, 104.0, 32.4, 13.3; IR (KBr) \(\nu\)\(_{max}\) (cm\(^{-1}\)) 3450, 3366, 3316, 1672, 1636, 1614, 1578, 1540, 1439, 1389, 1366, 1346, 1310, 1251, 1114, 1069, 950, 772.

The appropriate isocyanate (1.1 eq.) was added to the amine and this reaction mixture was stirred with heating at reflux for 3 days in dry CH\(_3\)CN. A precipitate formed, which was collected by filtration, washed with water and dried to yield 5 as a yellow solid (0.16 g, 95%). m.p. 252–257 \(^\circ\)C; HRMS (MeOH, ES\(^+\)) calculated for C\(_{14}\)H\(_{12}\)N\(_4\)O\(_3\): 256.1086 (M + H)\(^+\); found: 256.1077; \(\delta\) \(_{1H}\) (400 MHz, (CD\(_3\)_2)SO) 9.13 (1H, br s, Naph-NH), 8.61 (1H, d, \(J = 8.5\) Hz, Naph-H\(_7\)), 8.41 (1H, d, \(J = 7.0\) Hz, Naph-H\(_5\)), 8.28 (1H, d, \(J = 7.5\) Hz, Naph-H\(_2\)), 7.64 (1H, dd, \(J = 7.8\) Hz, 8.0 Hz, Naph-H\(_6\)), 7.24 (1H, d, \(J = 8.6\) Hz, Naph-H\(_3\)), 4.69 (2H, d, \(J = 10.6\) Hz, Naph-NH-NH\(_2\)), 4.05 (2H, q, \(J = 7.0\) Hz, CH\(_2\)), 1.18 (3H, t, \(J = 7.0\) Hz, CH\(_2\)); \(\delta\) \(_{13C}\) (100 MHz, (CD\(_3\)_2)SO) 163.6, 162.7, 155.8, 152.6, 143.9, 138.9, 136.6, 134.6, 1310, 1251, 1114, 1069, 950, 772.

General synthesis of 1–3

The appropriate isocyanate (1.1 eq.) was added to the amine and this reaction mixture was stirred with heating at reflux for 3 days in dry CH\(_3\)CN. A precipitate formed, which was collected and washed with CH\(_3\)CN. The solid was then dried, yielding a yellow solid. Purification of the crude products was carried out by hot filtration using a mixture of DCM : MeOH (1 : 4).

2-Ethyl-6-[[(phenylcarbamoyl)hydrazino]benzo|de|isoquinoline-1,3-dione (1)

1 was synthesised according to above procedure using 5 (0.21 g, 0.82 mmol) and phenyl isocyanate 6 (0.11 g, 0.90 mmol) in dry MeCN (30 mL). The desired product was obtained as a dark yellow solid (0.12 g, 41%). m.p. 252–254 \(^\circ\)C; calculated for C\(_{25}\)H\(_{18}\)N\(_4\)O\(_3\): C, 64.3; H, 5.1; N, 14.3%; found: C, 64.0; H, 4.5; N, 14.5%; \(\delta\) \(_{1H}\) (400 MHz, (CD\(_3\)_2)SO) 9.60 (1H, br s, urea-NH), 9.03 (1H, br s, urea-NH), 8.73 (1H, d, \(J = 8.8\) Hz, Naph-H\(_7\)), 8.67 (1H, br s, Naph-NH), 8.50 (1H, d, \(J = 7.0\) Hz, Naph-H\(_5\)), 8.37 (1H, d, \(J = 7.9\) Hz, Naph-H\(_2\)), 7.78 (1H, t, \(J = 7.9\) Hz, Naph-H\(_6\)), 7.51 (2H, d, \(J = 7.9\) Hz, Ar-H\(_2\), Ar-H\(_6\)), 7.26 (2H, t, \(J = 7.4\) Hz, Ar-H\(_3\), Ar-H\(_5\)), 7.05 (1H, d, \(J = 8.8\) Hz, Naph-H\(_3\)), 6.97 (1H, t, \(J = 7.0\) Hz, Ar-H\(_4\)), 4.07 (2H, q, \(J = 6.7\) Hz, CH\(_2\)), 1.20 (3H, t, \(J = 7.0\) Hz, CH\(_3\)), \(\delta\) \(_{13C}\) (100 MHz, (CD\(_3\)_2)SO) 163.4, 162.7, 155.8, 152.6, 151.3, 139.7, 139.6, 133.7, 130.7, 128.8, 128.6, 124.8, 122.1, 121.8, 119.0, 118.1, 110.7, 105.1, 34.4, 13.3; IR (KBr) \(\nu\)\(_{max}\) (cm\(^{-1}\)) 3285, 1614, 1545, 1498, 1444, 1388, 1369, 1346, 1314, 1251, 1114, 1069, 950, 772.
dry MeCN (30 mL). The desired product was obtained as a dark yellow solid (0.16 g, 51%). m.p. decomposed at 310 °C; calculated for C_{2}H_{3}O_{2}N_{4}O_{2}: C, 66.5; H, 5.0; N, 12.5%; found: C, 66.5; H, 5.0; N, 12.5%.

3 was synthesised according to above procedure using 5 (0.20 g, 88 mmol) and 4-trifluoromethyl-phenyl carbamoyl hydrazino- benzo[d][1,2,3]triazole (1.6 g, 88 mmol) in dry MeCN (30 mL). The desired product was obtained as a dark yellow solid (0.15 g, 45%), m.p. decomposed at 250 °C; calculated for C_{2}H_{12}N_{4}O_{5}: C, 57.4; H, 4.2; N, 12.2%; found: C, 57.7; H, 3.8; N, 12.0%.


3. References


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