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Signalling Mechanisms in Anion-Responsive Push-Pull Chromophores: The Hydrogen-Bonding, Deprotonation and Anion-Exchange Chemistry of Functionalized Azo Dyes

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A family of azo dyes containing amide (**1**), urea (**2**), thiourea (**3**), carbamate (**4**) or amino (**5**) hydrogen-bond donating groups were synthesized and their response toward anions was studied. Acetonitrile solutions of **1**–**5** show bright yellow colours, due to charge-transfer bands in the 375–400 nm region, slightly modulated by the electron donor strength of the group attached to the 4′ end of the 4-nitroazobenzene scaffold. Anions of different shape and size (i.e., spherical F^-, Cl^-, Br^- and I^-, planar and tetrahedral oxoanions such as NO_3^-, $H_2PO_4^-$ and HSO_4^-, carboxylates such as acetate and benzoate and the linear anions cyanide and thiocyanate) were employed in the recognition studies. Two different effects were distinguished: (i) bathochromic shifts of <40 nm to pale orange, due to anion coordination, and (ii) strong red shifts of ca. 200 nm with a concomitant colour change to blue, due to deprotonation. This behaviour was explained as a balance between the deprotonation tendency of the binding sites in the different receptors and the proton affinities of the anions. Semiempirical calculations were carried out to evaluate the hydrogen bond-donating abilities of the anions and the dyes and a good correlation with the experimentally found values was observed. Stability constants for the receptor–anion complexes were determined spectrophotometrically and the different responses toward fluoride and acetate were assessed by NMR titration experiments. Finally, as a special case, we also report the use of this family of compounds as colorimetric carbon dioxide sensors through reaction with the unprotonated forms of the azo dyes.
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Introduction

The recognition and signalling of ionic and neutral species of varying complexity is one of the most intensively studied areas of contemporary supramolecular chemistry.[1] The host molecules are commonly designed in such a way that the presence of a guest is transformed into a change in colour, fluorescence or redox potential.[2] Because of the multifold possibilities of system design and development, researchers from many chemical subdisciplines have taken an interest in developing and investigating these host–guest interactions from both pure and applied chemistry points of view.[3] In general, the supramolecular signalling process comprises two steps: (i) the selective coordination of a target guest by suitable coordinating groups, and (ii) a transduction of the coordination event through modulation of optical or electrochemical properties. In addition to indication formats such as chemical displacement[4] or molecular chemodosimetry,[5] this two-step process usually requires an architecture in which the two chemical entities responsible for the key actions of coordination and transduction (i.e., the binding site and the signalling subunit) are integrated into a superstructure.[6] Optical outputs are especially attractive with respect to the transduction of a modulated signal, because detection can then use cheap, easy-to-handle and widely used instrumentation. Besides fluorescence-based systems, colorimetric recognition has gained popularity in recent years because a shift of an absorption band is often intrinsically ratiometric and avoids the necessity for an internal reference and also offers the possibility of so-called "naked eye detection" for semiquantitative determinations.[7]

As well as optically responsive hosts for metal ions, which have been investigated for more than 25 years,[8] anionic guests have recently shifted into focus[9] since the pioneering work of Czarnik and co-workers.[10] This is basically due to the fact that the host–guest chemistry of inorganic anions is already more challenging than for metal ions because of their more complex shapes, common pH-dependence and the competition of water in hydrogen

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bonding interactions.[11] Moreover, the literature on anion indication shows that the goal is traditionally approached from two complementary directions. One type of approach, stressing analytical applications, is materials chemistry-related and often uses simple and commercially available optical or redox probes, places them in a matrix (e.g., a polymer matrix) or develops ion-responsive membranes. Selectivity and sensitivity for the target guests in realistic samples is then achieved by, for instance, searching for an appropriate matrix and by adapting suitable instrumentation.[12] The second, supramolecular, approach often starts with the design of the recognition and transduction processes at the molecular scale and studies the relationship between host–guest interactions and the photophysical or electrochemical outcomes. A disadvantage of many of these systems is the fact that they are often not applicable in real media. However, the wealth of knowledge on matrices generated by the first approach, as well as recent developments in the design of organic-inorganic hybrid materials,[13] suggest that the performance of such probes should be improved for real environments in a simple manner.

In this paper we have centred our attention on the supramolecular approach, toward the colorimetric recognition of small anions. Being aware of the fact that most publications dealing with chromogenic anion signalling focus on single receptors and the colour modulations observed with certain anions, we have synthesized a series of azo dye derivatives functionalized with hydrogen-bonding moieties and investigated them in the presence of different anions to elucidate the impact on the optical response of receptor topology, gradual modulation of the hydrogen and electron donor abilities of the binding sites and anion basicity. Furthermore, we were able to show that anion-exchange reactions offer potential for the development of gas-sensing protocols.

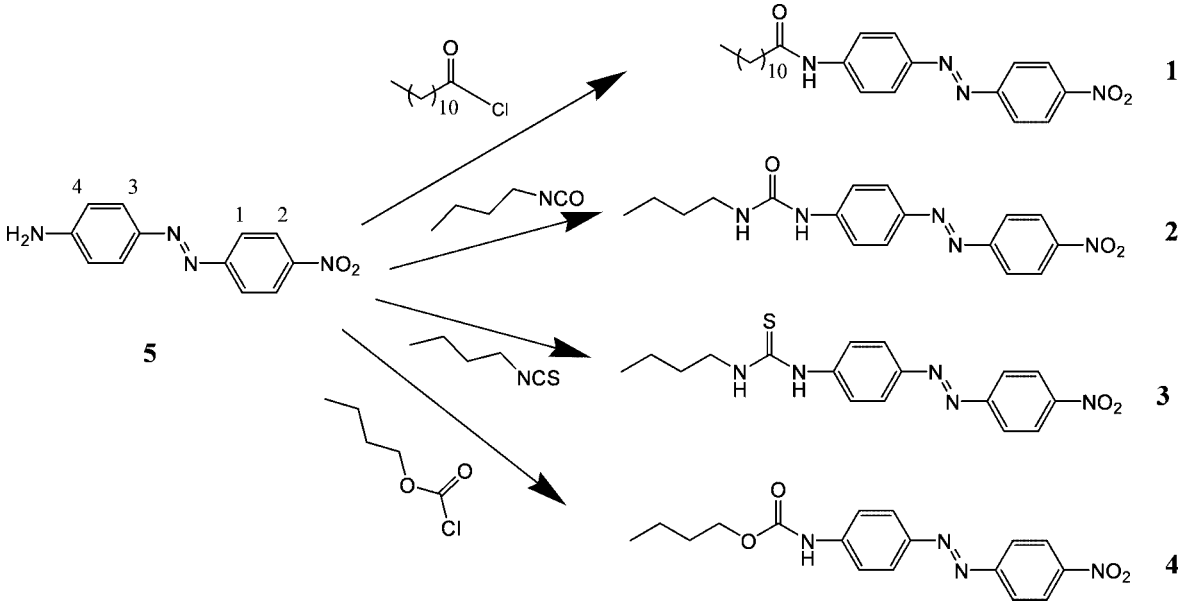
Results and Discussion

One of the goals of this work is the study of structure–property relationships of hosts capable of signalling the presence of particular anions through a colorimetric response due to hydrogen-bonding association between host and guest. An azo dye skeleton was chosen as the signalling unit and hydrogen bond donor groups of different topology, number of heteroatoms and electron-donating capability – namely amine, amide, urea, thiourea and carbamate moieties – were covalently attached to the chromophoric π system in the "binding site signalling subunit" fashion.[14,15] The receptors were synthesised by treatment of 4-(4-nitrophenylazo)aniline (**5**) with lauroyl chloride, butyl isocyanate, butyl isothiocyanate and propyl chloroformate to yield **1**–**4**, respectively (Scheme 1). Compound **5** was also used in the studies as a model compound lacking an anion receptor. Compounds **1**–**5** display absorption spectra typical of azo dyes, each with an intense absorption band ($\log\varepsilon > 4$) at ca. 400 nm.[16] This yellow band has a charge-transfer character as a consequence of the presence of the various electron donor groups and the nitro group, acting as the electron acceptor.

The influence of the different electron-donating properties of **1**–**5** on the colours of the dyes is directly obvious from Table 1. As the electron-donor strength decreases from amino (**5**) > urea (**2**) > thiourea (**3**) > amide (**1**) ≈

Table 1. Spectroscopic data for **1**–**5**.

	λ_{max} (nm)	$\log\varepsilon$	$\lambda_n - \lambda_5$ (nm)
1	378	4.38	–49
2	395	4.38	–32
3	389	4.29	–38
4	378	4.42	–49
5	427	4.33	0



Scheme 1. Synthetic procedure for the preparation of **1**–**4**.

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carbamate (**4**), the spectral bands shift to shorter wavelengths. Since the anion-responsive motif represents the donor side, coordination of anions would be expected to increase its character and to produce bathochromic shifts (vide infra) through modulation of the dipole moments of ground and excited state and thus the energetic positions of HOMO and LUMO.[17]

Responses to Anions

The responses of **1**–**5** were studied with anions of various shapes and sizes (i.e., spherical F^-, Cl^-, Br^- and I^-, planar and tetrahedral oxoanions such as NO_3^-, $H_2PO_4^-$ and HSO_4^-, carboxylates such as acetate (AcO^-), benzoate (BzO^-) and the linear anions cyanide and thiocyanate) in acetonitrile solutions. Figure 1 shows a set of photographs of **1**–**5** (from top to bottom) in the presence of 10 equivalents of the anionic guests. It is obvious that the response toward anions depends strongly on the chemical nature of the binding site; Table 2 lists the spectral shifts observed for the visible absorption bands of **1**–**5** upon addition of 100 equiv. of the corresponding anions. For **1**–**4** and F^-, a pronounced bathochromic displacement of the absorption band to 550–630 nm is already observable at a 10-fold excess of the anion, the colours of the solutions turning to blue. Compound **5** shows a qualitatively similar response, manifested in a colour change from pale orange to green. Cyanide yielded minor changes in colour for **1**, **2**, **4** and **5**, but on **3** it had an effect similar to that of F^- (Table 2). The addition of AcO^-, BzO^- and $H_2PO_4^-$ induced colour changes from yellow to pale orange, their magnitudes depending on the combination of host and guest. In contrast, the presence of Cl^-, Br^-, I^-, NO_3^-, HSO_4^- and SCN^- gave only negligible shifts in the UV/Vis profiles.

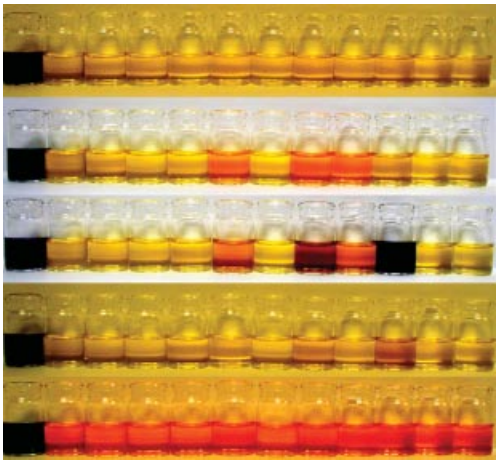

Figure 1. Photographs of acetonitrile solutions of **1**–**5** (from top to bottom; 1.0×10^{-4} M) in the presence of 10 equiv. of F^-, Cl^-, Br^-, I^-, NO_3^-, $H_2PO_4^-$, HSO_4^-, AcO^-, BzO^-, CN^-, SCN^- and no anion (from left to right).

Table 2. Shifts (in nm) of the visible absorption band of **1**–**5** upon addition of 100 equiv. of the corresponding anion.

	F^-	CN^-	AcO^-	BzO^-	$H_2PO_4^-$	Cl^-
1	185	2	5	5	5	3
2	230	12	32	30	29	15
3	182	182	36	34	34	21
4	183	4	4	3	3	1
5	200	1	3	3	2	0

In general, the results reflect the expectation that the interaction between an electron-rich partner and a donor group in a push–pull system will produce a bathochromic shift. However, it is also evident from Figure 1 and Table 2 that two entirely different effects can be distinguished: (i) bathochromic shifts of <40 nm, corresponding to changes in colour from yellow to pale orange, and (ii) distinctly more pronounced modulations of ca. 200 nm with concomitant colour changes from yellow to blue. Such unusually large colour shifts, mainly in the presence of fluoride, have also been observed with other amide, urea, thiourea or pyrrole-containing hosts for several years and have been attributed to the formation of strong hydrogen-bonded complexes between F^- and the ionophores. Only in recent years have we and others furnished evidence of an alternative mechanism for several types of anion-responsive hosts in which large colour modulations induced by fluoride in organic solvents were found to originate from the deprotonation of the binding site of the host by the highly basic fluoride anion.[18] However, there is often controversy still today as to whether a hydrogen-bonded complex is formed or whether fluoride deprotonates the ligand. More interestingly, some detailed studies have even suggested that mixed processes might occur (i.e., initial complex formation at low fluoride-to-receptor ratios, this then being followed by deprotonation at higher fluoride-to-receptor ratios).[19]

Hydrogen Bond-Donating and -Accepting Properties of Receptors and Anions

The extents of the colorimetric shifts in the series **1**–**5** represent delicate balances between the deprotonation tendencies of the different binding sites and the proton affinities of the anions. For instance, a comparison of **2** and **3** in Figure 1 reveals how small variations in the binding sites and the corresponding anions can result in different colour modulations due to hydrogen bond formation or deprotonation. Hydrogen bonding can thus be seen as a "frozen" intermediate between the pre-association state and the dissociation state after proton relocation (deprotonation) has taken place [Equation (1)].[20]

$$BH + A^- \leftrightarrows B\text{-}H\cdots A^- \leftrightarrows B^- + AH \quad (1)$$

Since the relation between deprotonation and hydrogen bonding reflects the intrinsic acidity/basicity of a system, a convenient, simplified way of describing the hydrogen bond- donating or -accepting ability of a molecule at a particular site can be assessed through the gas-phase deprotonation energy by quantum chemical calculations.[21] We thus determined the proton affinities for the anions used in this study at semiempirical level, employing the PM3 model by

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subtracting the energy of the anion from the energy of the protonated molecule. From the results shown in Table 3, anion basicity follows the order $F^- > CN^- > AcO^- > H_2PO_4^- > BzO^- > Cl^- > HSO_4^- > SCN^- > NO_3^- > Br^- > I^-$, which is in general agreement with the Hofmeister series.[22] This sequence is expected not to differ significantly from the real behaviour in acetonitrile because this is a solvent with a weak Lewis acid character (i.e., has low anion coordination ability) and all the anions tested have the same charge. In fact, this order also agrees with available experimental data for several of the naked anions in DMSO.[23] Fluoride is the most basic anion, with a considerable energy gap between it and the following one (cyanide).

Table 3. Stabilization energies ($E_{anion-H} - E_{anion}$) of the different anions calculated at semiempirical level; the more negative the value the stronger the hydrogen-bond acceptor ability and the more basic the character.

Anion	$E_{anion-H} - E_{anion}$ (kcal mol^{-1})
F^-	–83.63
CN^-	–46.87
Ac^-	–34.37
$H_2PO_4^-$	–31.95
Bz^-	–28.62
Cl^-	–21.36
HSO_4^-	–9.17
SCN^-	2.04
NO_3^-	3.19
Br^-	9.44
I^-	41.31

Similar calculations were carried out to evaluate the hydrogen bond donor abilities of **1**–**5**, expressed as the difference in energy between the deprotonated and the neutral species. For **2** and **3**, with two NH sites, deprotonation most probably occurs at the NH group attached to the azo benzene core, which shows a more acidic character than the outer NH (Table 4). The theoretical results support the experimental spectroscopic (vide ante) and NMR (vide infra) findings. Whereas fluoride – as the most basic anion – deprotonates all dyes, cyanide as the second most basic anion is only capable of deprotonating **3**, the dye that is the best hydrogen-bond donor. Furthermore, the hydrogen bond-accepting characters of acetate, dihydrogen phosphate, benzoate and chloride are not strong enough to abstract protons, yet formation of hydrogen-bonded complexes is clearly indicated by spectral or resonance shifts.

Stability Constants

UV/Vis spectrophotometric titrations were performed to determine the stability constants for complex formation between the receptors and the anions AcO^-, BzO^-, $H_2PO_4^-$ and Cl^-. Fluoride was excluded because of its special behaviour, as discussed above. In all cases the titration profiles for **1**–**5** and the corresponding anion showed clear isosbestic points and the experimental data could be satisfactorily fitted to the formation of a complex with 1:1 stoichiometry. The stability constants are shown in Table 5 and reveal that

Table 4. Stabilization energy of the deprotonation reaction for **1**–**5**; the more negative the value the stronger the hydrogen-bond donor character (i.e., the more acidic the receptor).

Receptor	$E_{(n)}^- - E_{(n)H}$ (kcal mol^{-1})
1	7.25
2	9.83
3	–7.59
4	4.87
5	13.03

the primary factor governing complex formation is the topology of the ligand. The K_S values of **2** and **3**, which are capable of forming two directed hydrogen bonds, distinctly exceed the K_S values of **1**, **4** and **5** for all anions by orders of magnitude. In comparison of **2** and **3**, however, the strength of the host–guest interaction is related to the intrinsic acidity of the protons of the binding site and the basicity of the target anion.[24] The reversal of the order between BzO^- and $H_2PO_4^-$, which possess close stabilization energies, is presumably due to the fact that urea and thiourea sites are excellent receptors for Y-shaped anions such as carboxylates.[25] For **1**, **4** and **5**, with monodentate binding sites, no clear pattern was found, suggesting that steric factors prevail over electronic properties in the weak host–guest associates. Comparison of our data with the literature shows that the stability constants of the thiourea-containing **3** ($\log K$ of 4.8, 3.9 and 3.1 for AcO^-, $H_2PO_4^-$ and Cl^- in acetonitrile) agree very well with those measured by Teramae's group for *N*-methyl-*N*-(*p*-nitrophenyl)thiourea ($\log K$ of 5.7, 4.3 and 3.5 for AcO^-, $H_2PO_4^-$ and Cl^- in DMSO, respectively).[26] Hong et al. also found fairly similar values for an azophenol-bis-thiourea host, though with a difference in the order of selectivity, the bis(thiourea) receptor binding $H_2PO_4^-$ more strongly than it did AcO^-.[27] In the cases of **3** and the *p*-nitrophenyl derivative, the presence of the nitro group induces an electron density deshielding of the hydrogens in the urea moiety, enhancing acidity and enabling the formation of strong hydrogen-bonded complexes. On exchanging an alkyl chain at a thiourea moiety with a second *p*-nitrophenyl group, as in *N*,*N*′-bis(*p*-nitrophenyl)thiourea, Teramae et al. found that the stability constant increased substantially ($\log K$ 6.23 for AcO^-).[28] Very recently, Fabbrizzi et al. have demonstrated that deprotonation can be triggered not only with F^- but also with the less basic AcO^-, BzO^- and $H_2PO_4^-$ anions by functionalisation of both nitrogen atoms of a urea or thiourea moiety with several aromatic heterocycles containing nitro

Table 5. Binding constants (M^{-1}) for **1**–**5** with AcO^-, BzO^-, $H_2PO_4^-$ and Cl^- measured by UV/Vis titrations.

	AcO^-	BzO^-	$H_2PO_4^-$	Cl^-
1	194 ± 7	149 ± 5	258 ± 15	–
2	27100 ± 600	13200 ± 200	3900 ± 300	370 ± 110
3	60000 ± 4000	41000 ± 2000	7400 ± 600	1250 ± 50
4	142 ± 12	108 ± 6	134 ± 2	–
5	125 ± 8	151 ± 4	167 ± 14	–

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groups (7-nitrobenzo[1,2,5]oxadiazole) or imide groups (naphthalimides and phthalimides).[19]

A good empirical relationship between the binding constant and the shift in the absorption maximum was found for AcO^-, BzO^-, Cl^- and $H_2PO_4^-$ and **1**–**5** (Figure 2). This correlation reflects the weakening of the N–H bond upon anion coordination and an increase in the electronic density, resulting in stabilization of the excited state and a bathochromic shift of the absorption band. It is also evident from Figure 2 that the slopes for AcO^- and BzO^- are steeper than that for $H_2PO_4^-$, which has also been found in other cases.[18c] However, the fact that chloride (not shown) shows a slope similar to those of the carboxylates but is distinctly less basic disfavours an explanation based on the proton-accepting ability of the anions. We tentatively assume that these differences stem from geometrical features. The two oxygen atoms of carboxylates are commonly separated by 2.20 Å, which fits well with the distance between the two hydrogen atoms of the urea or thiourea moieties. In contrast, the distance between two oxygen atoms in $H_2PO_4^-$ amounts to ca. 2.70 Å.[29] This mismatch in size most probably governs the special behaviour often found for $H_2PO_4^-$ and such type of receptors.

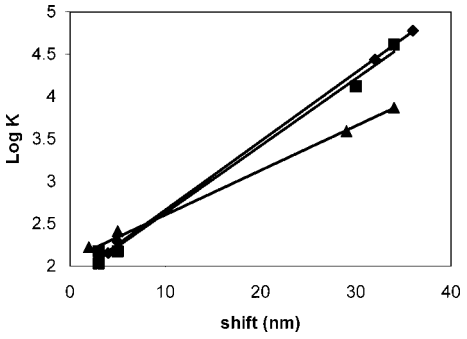

Figure 2. Plots of $\log K_S$ vs. absorption band shift upon coordination with BzO^- (■), $H_2PO_4^-$ (▲) and AcO^- (♦); for data see Table 2.

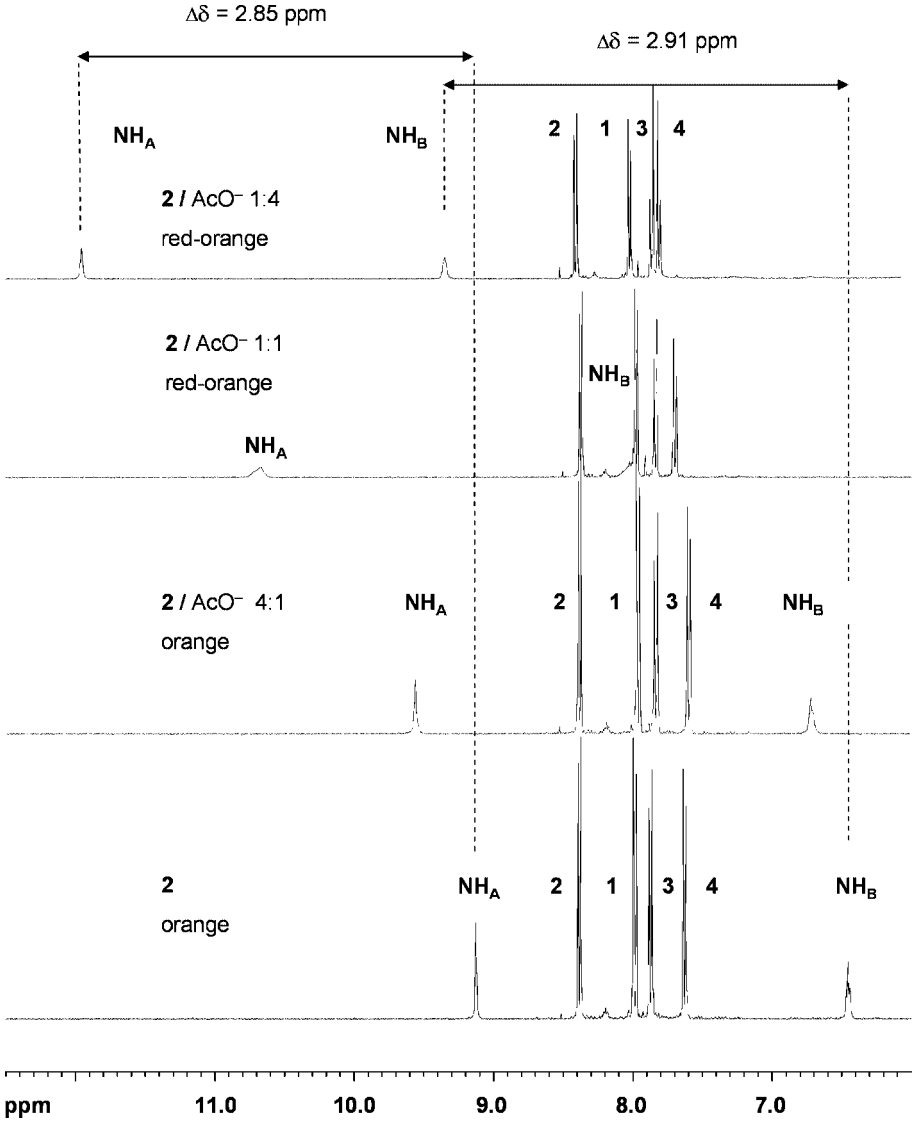

Figure 3. ^1H NMR titration spectra for **2** with [TBA][AcO] in $[D_6]$DMSO.

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NMR Spectroscopic Studies in the Presence of Anions

In view of the diverse reports on fluoride binding vs. fluoride-assisted deprotonation reactions of chromo- and fluorogenic chemosensor molecules in highly polar organic solvents, the response of the title compounds toward fluoride and acetate was investigated by means of NMR titration experiments in deuterated acetonitrile and DMSO. The results of the NMR studies support the interpretation of the deprotonation/coordination dualism given in the preceding paragraphs. The different behaviour patterns encountered are illustrated in Figure 3, Figure 4, and Figure 5 with the example of **2**. The ^{1}H NMR spectra of **2** show the expected signals of the azo-phenyl moieties in the aromatic range. In addition, two broad singlets appear at δ = 6.45 and 9.12 ppm and were assigned to the urea protons. Compound **2** shows strong interaction with AcO^-, discernible through a neat colour change (see above) and a remarkable displacement of the urea H–N protons (Figure 3). Both signals are shifted downfield by ca. 2.4 ppm upon addition of one equivalent of AcO^- and remain downfield by ca. 2.9 ppm at full complexation, suggesting that binding occurs through hydrogen-bonding interactions. Moreover, only minor shifts were observed for all the other protons, indicating the absence of other interactions. Similar Δ-shifts ($\Delta\delta = \delta_{\mathbf{2}/\text{anion}} - \delta_2$) of 2.85 and 2.91 ppm found for the HN-aryl and HN-alkyl protons, respectively, indicate that both NH sites are equally involved in the hydrogen-bonding interaction.[19]

Studies of **3** with acetate in CD_3CN yielded qualitatively identical results, with the net Δ-shifts of 4.9 and 4.6 ppm being higher for the thiourea binding site. This is consistent with the stability constants as determined by UV/Vis ti-

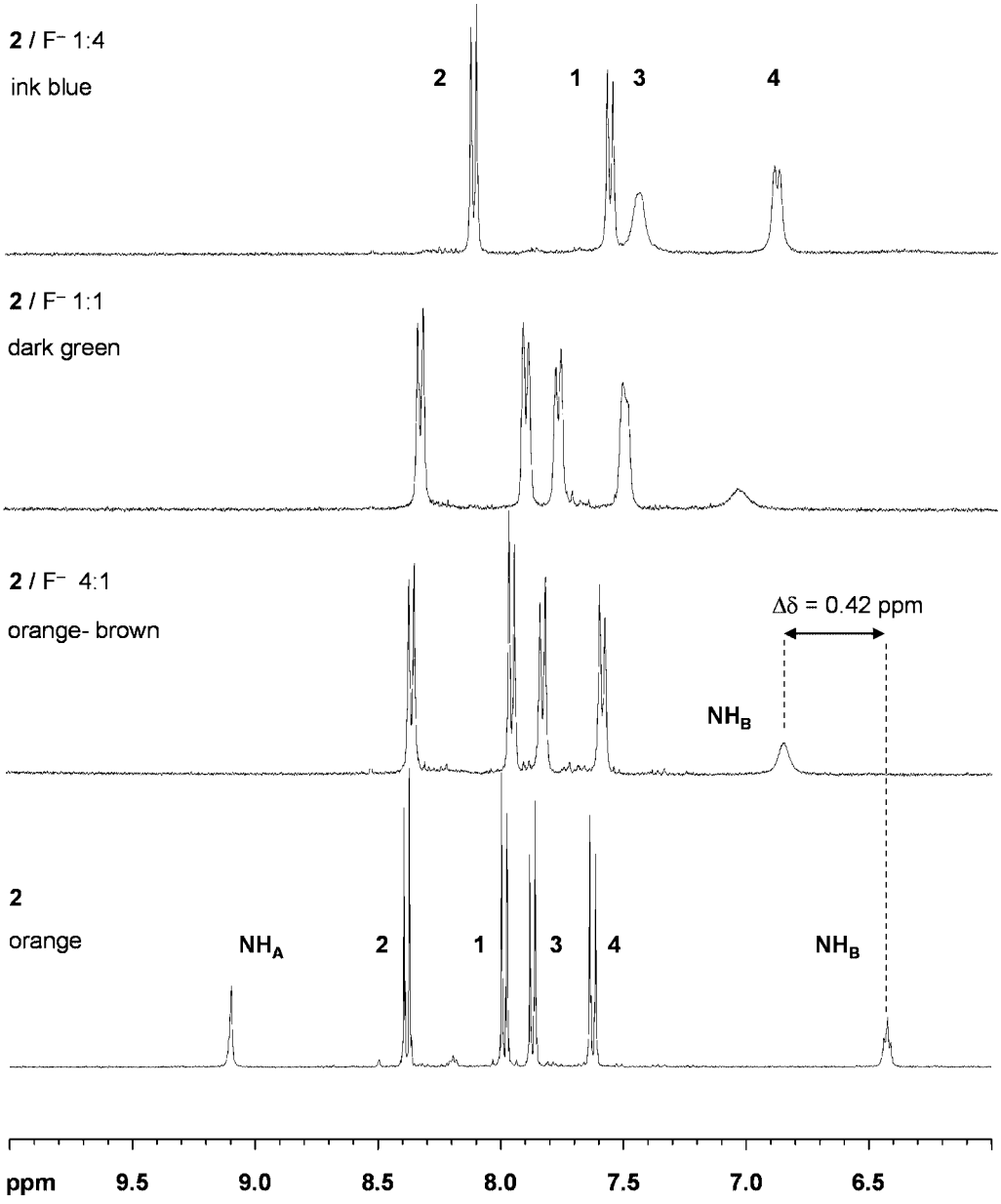

Figure 4. ^{1}H NMR titration spectra for **2** with [TBA][F] in [D_6]DMSO.

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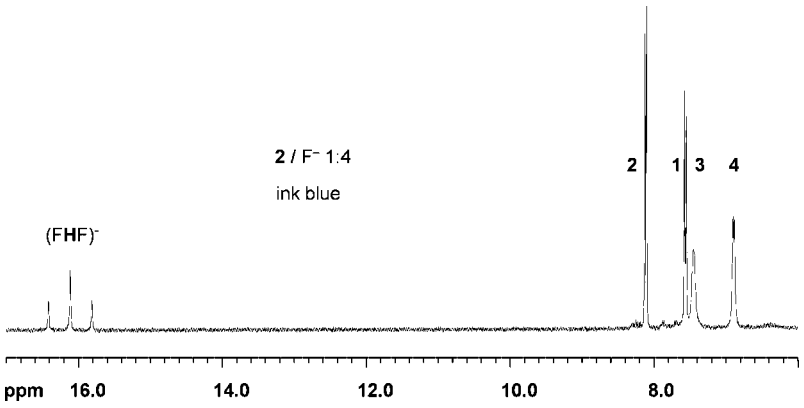

Figure 5. ^{1}H NMR spectrum of **2** in the presence of 0.25 equiv. F^- in [D_6]DMSO.

trations for the pairs **2**/AcO^- and **3**/AcO^- (Table 5). In the presence of F^-, the NMR titration spectra look entirely different (Figure 4). Only at low F^--to-**2** ratios is the behaviour similar to that found for **2** and AcO^-, whereas at higher F^--to-**2** ratios the HN signals are broadened and decreased. In accordance with our recent investigations on the fluoride binding of phenoxazinone derivatives with similar receptor units in DMSO, the disappearance of the NH signals at higher anion concentrations are accompanied by the appearance of a new 1:2:1 triplet signal at δ = 16.1 ppm, attributed to the bifluoride ion (HF_2^-, Figure 5).[18a]

Additionally, the ^{19}F NMR spectrum also shows the F–H–F signal. The broadened and shifted signals at low F^- concentrations thus indicate hydrogen bonding, while the occurrence of the new species points to deprotonation of either ligand or solvent. Indications of both were found, yet the concomitant high-field shift of all proton signals of the phenylazobenzene moiety is a clear sign of the deprotonation of the NH group of **2**, accompanied by an overall change of the electron distribution.[19] Very similar behaviour was observed for **2** in the presence of fluoride in CD_3CN, with deprotonation occurring upon approaching equimolarity. Moreover, as would be expected on the basis of the above, **3** shows very similar behaviour to **2** in the presence of F^- in organic solvents. Finally, for **1** and **4**, deprotonation was also observed in the NMR titrations, but only at higher fluoride-to-dye rations.

Carbon Dioxide Sensing

During the course of our studies on deprotonation of this family of receptors we observed an intriguing phenomenon. As outlined above, fluoride deprotonates **3** in acetonitrile, accompanied by a colour change to blue. Under argon the solution remains blue for hours, but after opening of the cell the band centred at 600 nm immediately starts to decrease, resulting in the loss of the blue colour. Similar behaviour was also found for the other title dyes. Additional studies carried out with different gases demonstrated that the blue-to-yellow transformation occurs only in the presence of carbon dioxide,[12,30] and this was confirmed by bubbling CO_2 into the blue **3**/F^- solutions or by adding dry ice (in both cases an almost instant colour modulation to yellow was observed). This reaction was found to be selective for CO_2: other gases such as oxygen, nitrogen, carbon monoxide or organic gases induced no colour change. Furthermore, it was also found that the reaction occurred only in the presence of fluoride and was not observed in the presence of the other anions studied. To characterize the response toward carbon dioxide better we carried out kinetic studies for the series of compounds in the presence of one equivalent of fluoride. As can be seen in Figure 6, the bleaching of the visible band at ca. 600 nm proceeds more rapidly for **1**, **2** and **5** than for **4** and, especially, **3**. The order of reaction rates (**5** > **1** ≈ **2** > **4** > **3**) correlates with the proton acceptor character (basicity) of the deprotonated form of the receptors ($\mathbf{5}^- > \mathbf{2}^- \approx \mathbf{1}^- > \mathbf{4}^- > \mathbf{3}^-$; i.e., the inverse of the proton-donating ability displayed in Table 4). Consequently, the unprotonated forms of the dyes seem to be involved in the rate-limiting step of the reaction (i.e., acting as strong hydrogen acceptors).

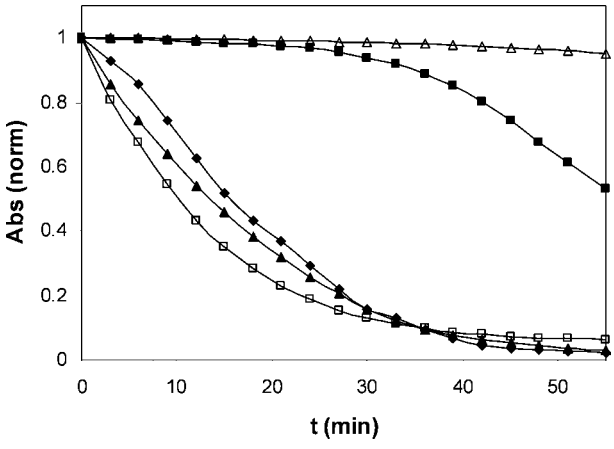

Figure 6. Evolution of the visible band at 600 nm for the systems **n**/F^- (**n** = **1**–**5**, $c_n = 3.0 \times 10^{-5}$ M, 50 equiv. F^-) upon air exposure: **1** (♦), **2** (▲), **3** (Δ), **4** (■), **5** (□).

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Additional ^{1}H NMR studies were carried out with the **3**/F^-/CO_2 system in CD_3CN (Figure 7). The two first spectra of **3** and **3**/F^- show features similar to those shown in Figure 4 for **2** and F^- (i.e., a disappearance of the NH signals and a high-field displacement of the protons of the azo chromophore, both features indicating deprotonation). Upon addition of carbon dioxide, the spectrum again changes to give a signal pattern similar to that observed for the hydrogen-bonded complex **3**–AcO^- (cf. the two upper spectra in Figure 7). This suggests that the end result is the formation of a complex in which the thiourea moiety of **3** hydrogen-bonds a Y-shaped anion. A coherent interpretation of these data involves the production of HCO_3^- through a reaction between the deprotonated form of **3** and traces of water and carbon dioxide and finally the formation of a complex **3**···HCO_3^- [see Equations (2) and (3)]. Although we have been unable to obtain crystals of the complex, several examples of similar structures have been reported in the literature recently.[18c]

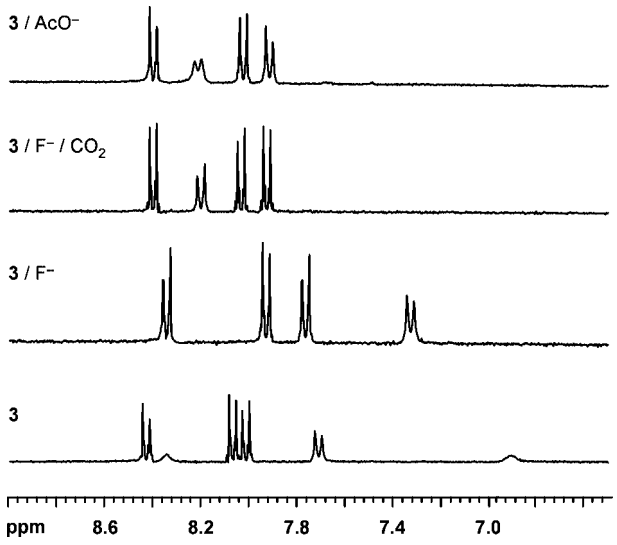


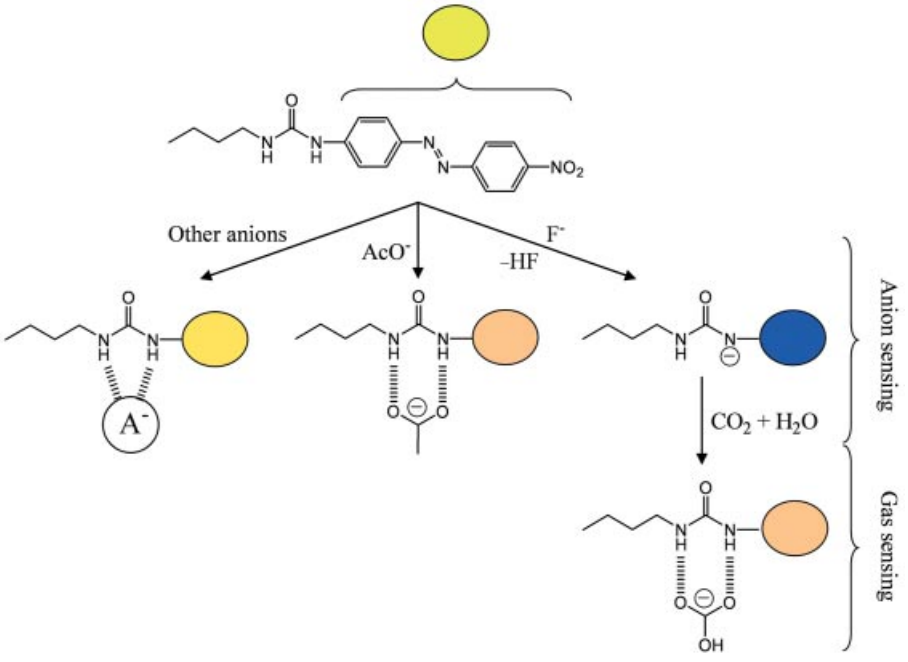
Figure 7. ^{1}H NMR spectra of (from top to bottom) **3**/AcO^-, **3**/F^-/CO_2, **3**/F^-, and **3** in CD_3CN.

$$\mathbf{3} + 2\ F^- \rightarrow \mathbf{3}^- + HF_2^- \quad (2)$$

$$\mathbf{3}^- + CO_2 + H_2O \rightarrow \mathbf{3}\cdots HCO_3^- \quad (3)$$

Conclusions

The differently functionalized azo dyes **1**–**5** show gradual modulation of the hydrogen-bonding and electron-donating capabilities as a function of the chemical group employed and show two different chromogenic responses toward anions in acetonitrile solution. When substituted with bidentate urea or thiourea groups, several oxygen-containing anions are strongly hydrogen-bonded and fluoride induces deprotonation. In contrast, all the anions except for fluoride have negligible effects on the monodentate derivatives **1**, **4** and **5**. Hydrogen bonding is indicated by bathochromic shifts of ca. 40 nm, corresponding to a colour change from yellow to pale orange, whilst deprotonation is visible through the appearance of an absorption band at ca. 580 nm; the solution turns blue. The extent of the colorimetric shift in the series **1**–**5** could be explained on the basis of the deprotonation tendency of the binding sites and the proton affinity of the associated anion. PM3 calculations and ^{1}H NMR studies are in agreement with the proposed processes. Finally, blue-to-yellow colorimetric sensing of CO_2 based on the reactions between the deprotonated



Scheme 2. A schematic representation of the anion- and gas-sensing capabilities of the title dyes.

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forms of the dyes and traces of water and carbon dioxide was observed. Scheme 2 provides a summary of the reactivity patterns of **1**–**5**. In particular, the scheme displays the concept of using dyes containing simple binding sites for the signalling of anions and how, in special cases, this can be transformed into new paradigms for gas sensing (i.e. carbon dioxide colorimetric signalling).

Experimental Section

Materials and Methods: All commercially available reagents were used without further purification. Disperse orange 3 [**5**, 4-(4-nitrophenylazo)aniline], was purified by column chromatography before spectrophotometric studies. Air-/water-sensitive reactions were performed in flame-dried glassware under argon. Acetonitrile was dried with CaH_2 and distilled prior to use. ^1H and ^{13}C NMR spectra were recorded with a Varian Gemini spectrometer. Chemical shifts are reported in ppm downfield from the TMS signal. Spectra taken in $CDCl_3$ were referenced to residual $CHCl_3$.

Syntheses: Compound **1** was obtained under mild conditions by heating a dichloromethane solution of **5**, lauroyl chloride and triethylamine at reflux. The considerably lower reactivity of isocyanates, isothiocyanates and chloroformates, in relation to acid chlorides, obliged us to use stronger conditions (i.e., pyridine at reflux for 72 h) for the preparation of **2**, **3** and **4**. Compounds **1**–**4** were characterized by ^1H NMR, ^{13}C NMR and HRMS and the data obtained were in full agreement with the proposed formulation.

(*E*)-*N*-[4-(4-Nitrophenyl)diazenylphenyl]dodecanamide (1): Compound **5** (363 mg, 1.5 mmol) was dissolved in dichloromethane (20 mL), and triethylamine (2 mL, 14 mmol) and lauroyl chloride (1.71 mL, 6 mmol) were then added, followed by heating of the mixture at reflux for 48 h. The crude product was then washed with HCl and Na_2CO_3 solutions, the organic phase was dried with $MgSO_4$, and the solvent was removed by evaporation. The oily residue was purified by column chromatography on silica gel with dichloromethane as eluent. Yield: 85%, ^1H NMR (300 MHz, [D$_6$]-DMSO): δ = 0.84 (t, J = 7.5 Hz, 3 H, CH_2CH_3), 1.23 (m, 16 H, CH_2CH_2), 1.61 (q, J = 7.5 Hz, 2 H, CH_2CH_2), 2.37 (t, J = 7.5 Hz, 2 H, $COCH_2$), 7.86 (d, J = 8.2 Hz, 2 H, ArH), 7.95 (d, J = 8.2 Hz, 2 H, ArH), 8.04 (d, J = 8.2 Hz, 2 H, ArH), 8.43 (d, J = 8.2 Hz, 2 H, ArH), 10.34 (s, 1 H, NH) ppm. ^{13}C {^1H} NMR (75 MHz, $CDCl_3$): δ = 14.4, 22.5, 25.4, 29.1, 29.2, 29.2, 29.4, 29.4, 31.7, 37.0, 119.6, 123.7, 125.0, 125.5, 144.2, 147.8, 148.5, 155.8, 172.5 ppm. HMRS calcd. for $C_{24}H_{32}N_4O_3$: 424.247441; found: 424.244362.

(*E*)-1-Butyl-3-[4-(4-nitrophenyldiazenyl)phenyl]urea (2): Compound **5** (244 mg, 1 mmol) was dissolved in anhydrous pyridine (8 mL) and after addition of butyl isocyanate (136 μL, 1.2 mmol) the mixture was heated at reflux for 72 h. After removal of the solvent by evaporation, the oily residue was purified by column chromatography on silica gel with dichloromethane as eluent. Yield: 47%, ^1H NMR (300 MHz, [D$_6$]DMSO): δ = 0.92 (t, J = 7.3 Hz, 3 H, CH_2CH_3), 1.35 (q, J = 7.3 Hz, 2 H, $CH_2CH_2CH_3$), 1.42 (q, J = 7.3 Hz, 2 H, $CH_2CH_2CH_2$), 3.10 (t, J = 7.3 Hz, 2 H, $NHCH_2CH_2$), 6.35 (t, J = 5 Hz, 1 H, $CONHCH_2$), 7.66 (d, J = 8.2 Hz, 2 H, ArH), 7.88 (d, J = 8.2 Hz, 2 H, ArH), 8.02 (d, J = 8.2 Hz, 2 H, ArH), 8.41 (d, J = 8.2 Hz, 2 H, ArH), 9.02 (s, 1 H, ArNHCO) ppm. ^{13}C {^1H} NMR (75 MHz, $CDCl_3$): δ = 14.1, 19.9, 29.4, 32.1, 117.8, 123.4, 125.2, 125.4, 145.9, 146.1, 148.2, 155.0, 155.9 ppm. HMRS calcd. for $C_{17}H_{19}N_5O_3$: 341.148790; found: 341.146892.

(*E*)-1-Butyl-3-[4-(4-nitrophenyldiazenyl)phenyl]thiourea (3): This compound was prepared analogously to **2**, with use of butyl isothiocyanate (145 μL, 1.2 mmol) instead of butyl isocyanate. Yield: 31%, ^1H NMR (300 MHz, [D$_6$]DMSO): δ = 0.91 (t, J = 7.3 Hz, 3 H, CH_2CH_3), 1.33 (q, J = 7.3 Hz, 2 H, $CH_2CH_2CH_3$), 1.55 (q, J = 7.3 Hz, 2 H, $CH_2CH_2CH_2$), 3.48 (t, J = 7.3 Hz, 2 H, $NHCH_2CH_2$), 7.25 (t, J = 5 Hz, 1 H, $CSNHCH_2$), 7.80 (d, J = 8.2 Hz, 2 H, ArH), 7.94 (d, J = 8.2 Hz, 2 H, ArH), 8.04 (d, J = 8.2 Hz, 2 H, ArH), 8.42 (d, J = 8.2 Hz, 2 H, ArH), 9.91 (s,1 H,ArNHCS) ppm. ^{13}C {^1H} NMR (75 MHz, $CDCl_3$): δ = 14.1, 20.0, 30.6, 43.9, 122.2, 123.6, 124.5, 125.5, 144.7, 147.3, 148.4, 155.8, 180.2 ppm. HMRS calcd. for $C_{17}H_{19}N_5O_2S$: 357.125947; found: 357.123338.

(*E*)-Butyl [4-(4-Nitrophenyl)diazenylphenyl]carbamate (4): This compound was prepared analogously to **2**, from **5** (363 mg, 1.5 mmol) and propyl chloroformate (210 μL, 2 mmol), with purification by column chromatography on silica gel with hexane/acetone 2:1 as eluent. Yield: 68%, ^1H NMR (300 MHz, [D$_6$]DMSO): δ = 0.98 (t, J = 7.2 Hz, 3 H, CH_2CH_3), 1.70 (q, J = 7.2 Hz, 2 H, $CH_2CH_2CH_3$), 4.16 (t, J = 7.2 Hz, 2 H, OCH_2CH_2), 6.84 (s, 1 H,CONHAr), 7.58 (d, J = 8.4 Hz, 2 H, ArH), 7.95 (d, J = 8.4 Hz, 2 H, ArH), 7.98 (d, J = 8.4 Hz, 2 H, ArH), 8.34 (d, J = 8.4 Hz, 2 H, ArH) ppm. ^{13}C {^1H} NMR (75 MHz, $CDCl_3$): δ = 10.6, 22.2, 66.5, 118.5, 123.5, 125.0, 125.4, 144.2, 147.4, 148.4, 153.8, 155.7 ppm. HRMS calcd. for $C_{16}H_{16}N_4O_4$: 328.117155; found: 328.109796.

Physical Measurements: Stock solutions of the anions (F^-, Cl^-, Br^-, I^-, NO_3^-, $H_2PO_4^-$, HSO_4^-, AcO^-, BzO^-, CN^-, SCN^- as tetrabutylammonium [TBA] salts) were prepared at 10^{-3} M in acetonitrile. UV/Vis spectrophotometric studies were carried out with a Perkin–Elmer Lambda 35 spectrometer. The concentrations of ligands used in these measurements were ca. 1×10^{-4} M. The NMR studies were carried out under similar conditions.

Theoretical Studies: Quantum chemical calculations at semiempirical level (PM3, within restricted Hartree–Fock level) were carried out in vacuo with the aid of Hyperchem V6.03. The Polar–Ribiere algorithm was used for the optimization. The convergence limit and the RMS gradient were set to 0.01 kcal mol^{-1}.

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