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Selective fluoride sensing using colorimetric reagents containing anthraquinone and urea or thiourea binding sites

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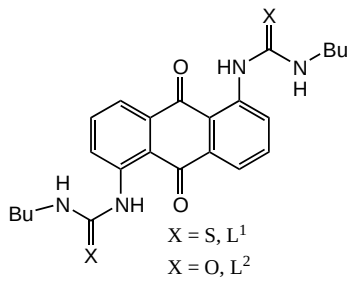
Abstract—Novel colorimetric reagents for fluoride sensing containing anthraquinone as chromogenic signalling subunit and thiourea (L^1) and urea (L^2) binding sites have been characterised. A selective colour change from orange to brown was observed upon addition of fluoride to CH_3CN solutions of L^1 and to DMSO solutions of L^1 or L^2. © 2002 Published by Elsevier Science Ltd.

The development of selective and sensitive chemosensors for anion sensing is a topic of current attention.[1] The reason for this interest is the importance that detection and quantification of anions have in fields such as biology and environmental chemistry as a consequence of the role played by anions in environmental or chemical processes. Among sensing systems for anions, those displaying an optical signal upon anion coordination are of special interest.[2] These systems can be built by combination of anion binding-parts, able to interact with anions, and signalling subunits that transform receptor–anion interactions into optical signals. These units can be fluorescent groups[3] (the output signal is a fluorescence change) or dyes[4] (the output signal is a colour change). We have been involved in the synthesis of chemosensors for anions and are currently interested in those than can act as chromogenic reagents.[5] We report here a new chromogenic and selective fluoride chemosensor having urea and thiourea groups able to bind fluoride via anion–receptor hydrogen-bonding interactions and an anthraquinone group as chromogenic signalling subunit.

The synthesis of the receptors 1,5-bis-*N*-(9,10-dioxo-9,10-dihydroanthracen-1-yl)-*N'*-butylthiourea (L^1) and 1,5-bis-*N*-(9,10-dioxo-9,10-dihydroanthracen-1-yl)-*N'*-butylurea (L^2) was carried out by condensation of 1,5-diaminoanthraquinone with butylisothiocyanate and butylisocyanate, respectively, in DMF or DMSO at room temperature for L^2 and heating to 70°C for L^1. The reaction mixture was dropped into water, extracted with ethyl acetate and the solid obtained was chromatographed on silica gel with hexane:ethyl acetate (1:1) as eluent.[6]



^1H, ^{13}C NMR, and mass spectra are consistent with the proposed formulation of L^1 and L^2. Some unsuccessful attempts were carried out in order to obtain *N'*-phenylurea and *N'*-phenylthiourea derivatives by reaction of 1,5-diaminoanthraquinone and phenylisocyanate or phenylisothiocyanate. As stated above, L^1 and L^2 are potential chromogenic receptors for anion sensing as they contain hydrogen-bonding sites and an anthraquinone signalling subunit.[7]

Changes in colour were studied in a first step in acetonitrile by addition of 10 equiv. of the corresponding anion (F^-, Cl^-, Br^-, I^-, NO_3^-, HSO_4^-, $H_2PO_4^-$, CN^-, SCN^-, acetate or benzoate added as their tetrabutylammonium salts) to solutions of receptor L^1 (1×10^{-3} mol dm^{-3}). The most remarkable effect is the selective colour change in the presence of fluoride from

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orange to brown, due to the appearance of a broad new band centred at ca. 670 nm. For L^2, addition of 100 equiv. of the corresponding anion in acetonitrile resulted in significant colour changes for fluoride, dihydrogenophosphate, cyanide, acetate and benzoate (see Fig. 1). Colour changes are most probably due to formation of hydrogen bonds between the urea or thiourea groups and the corresponding anion[8]. The formation of these hydrogen bonds most likely affects the electronic properties of the chromophore, resulting in a colour change. In acetonitrile colour variations on L^2 are observed upon addition of strong basic anions (derived form weak acids) such as CN^-, acetate, benzoate, fluoride and dihydrogenophosphate, whereas there is no colour variation upon addition of other anions. Colour changes on L^1 are observed only in the presence of fluoride, which is one of the anions expected to give stronger hydrogen bonds due to its comparatively smaller size. Changes in colour in L^1 are observed upon addition of a few equiv. of the corresponding anion (typically 10 equiv.), whereas a much larger excess of ca. 100 equiv. of anion is necessary to observe colour variations on L^2 in acetonitrile. Additionally, the thiourea-functionalised receptor L^1 shows a very remarkable selectivity against fluoride that was not found for L^2. This is in agreement with reported data indicating that usually larger stability constants are observed for thiourea derivatives than for urea ones.[9] Unfortunately, in our case attempts to calculate complex stability constants from titration curves were unsuccessful. This may be due to the coexistence of different anion-to-ligand stoichiometries, to the formation of very weak complexes or to the existence of slow reactions as suggested by the fact that complete colour changes were observed for some anions after several minutes. However competitive assays indicated that the system is selective to fluoride. Thus, addition of a mixture of CN^-, acetate, benzoate, F^-, and $H_2PO_4^-$ to acetonitrile solutions of L^1 or L^2 in CH_3CN resulted in a UV–vis spectrum similar to that obtained for the F^- anion.

Changes in the properties of the binding sites are not the only modifications one can make to control anion binding; it is known that solvent effects can also play a fundamental role in governing anion binding and selectivity. Because of that, the behaviour of L^1 and L^2 in the presence of anions has been studied in different solvents and we show here preliminary results obtained in DMSO. In this case, both L^1 and L^2 gave, after addition of a few equiv. of fluoride (typically 2 equiv. for L^1 and 20 equiv. for L^2), a colour change from orange to brown (see Fig. 2). In DMSO the colour variation is highly specific and other anions such as chloride, bromide, iodide, hydrogenosulfate, dihydrogenophosphate, acetate, benzoate, cyanide and nitrate do not induce any colour change. The origin of the dramatic colour change observed in the presence of fluoride and the appearance of a new absorption peak might be ascribed to a new charge-transfer process between electron-rich, thiourea-bound fluoride and the electron deficient anthraquinone moiety.[10] (Scheme 1) The slightly larger dipole and dielectric constant of DMSO than those of CH_3CN might account for the different behaviour observed for L^2 in the presence of anions.

In conclusion it has been shown that thiourea and urea binding sites anchored to anthraquinone signalling subunits are suitable chromogenic reagents for anion sensing. The effect that subtle changes in the structure of the receptor (from urea to thiourea) and changes in the properties of the solvent (CH_3CN or DMSO) have been studied in order to get a selective response. A highly specific colorimetric reaction in the presence of fluoride has been found in DMSO.

Figure 1. Colour changes induced on L^2 (1×10^{-3} mol dm^{-3}) in CH_3CN: from left to right: no anion, fluoride, dihydrogenophosphate, acetate, cyanide, benzoate.

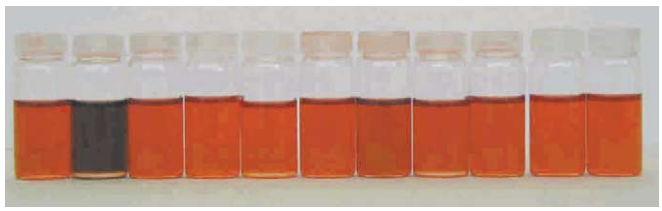
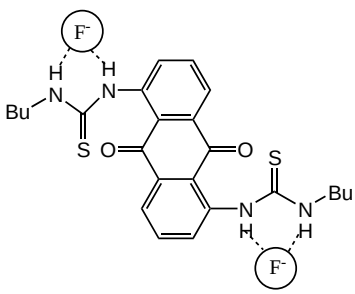


Figure 2. Colour changes induced on L^1 (1×10^{-3} mol dm^{-3}) in DMSO: from left to right: no anion, fluoride, chloride, bromide, iodide, hydrogenosulfate, dihydrogenophosphate, acetate, benzoate, cyanide and nitrate. A similar colour change in the presence of anions was found for this ligand in CH_3CN.



Scheme 1. Proposed hydrogen bond formation between fluoride and receptor L^1.

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6. Receptor L^1: ^{1}H NMR (300 MHz, DMSO-d_6): δ 0.85 (t, 3H, $J=6.3$ Hz), 1.14–1.42 (m, 4H), 2.95 (t, 2H, $J=6.3$ Hz), 7.09 (d, 2H, $J=8.0$ Hz), 7.37 (d, 2H, $J=8.0$ Hz), 7.47 (t, 2H, $J=8.0$ Hz), 7.85 (s, 2H), 8.51 (s, 2H). ^{13}C NMR (300 MHz, DMSO-d_6): δ 14.07, 19.90, 32.57, 40.14, 112.24, 115.11, 122.40, 134.95, 135.49, 152.22, 158.48, 184.68. Receptor L^2: ^{1}H NMR (300 MHz, DMSO-d_6): δ 0.85 (t, 6H, $J=6$ Hz), 1.24–1.37 (m, 8H), 2.94 (t, 4H, $J=6$ Hz), 7.09 (d, 2H, $J=12$ Hz), 7.37 (d, 2H, $J=12$ Hz), 7.48 (t, 2H, $J=12$ Hz), 7.80 (s, 2H), 9.02 (s, 2H). ^{13}C NMR (300 MHz, DMSO-d_6): δ 14.11, 19.89, 32.25, 39.25, 112.26, 115.13, 122.41, 134.98, 135.51, 152.22, 158.46, 184.70.
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