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COMMUNICATION

Fluoride-selective optical sensor based on the dipyrrolyl-tetrathiafulvalene chromophore†

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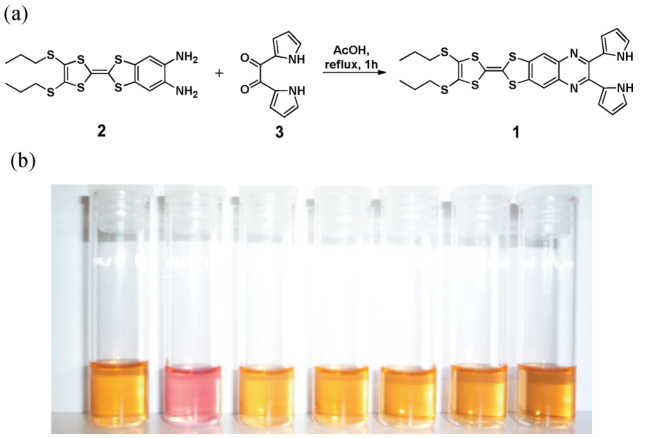
A chemosensor bearing dipyrrolyl motifs as recognition sites and a tetrathiafulvalene redox tag has been evaluated as an optical and redox sensor for a series of anions (F^-, Cl^-, Br^-, HSO_4^-, CH_3COO^-, and $H_2PO_4^-$) in DCM solution. The receptor shows specific optical signaling for fluoride but little electrochemical effect in solution. The solid-state performance of the sensor leads to measurable changes in water. Design implications towards better systems based on these results and other examples are discussed.

Luminescent and colorimetric sensors for various chemically, biologically, medically, and environmentally significant anions is currently an area of great interest.[1] The ubiquity of anions and their importance in biology, as agricultural fertilizers and industrial raw materials necessitates the development of highly sensitive anion sensors.[2] Nature provides us with many great examples of anion recognition motifs.[3] Chemistry has developed a number of alternative synthetic chemosensors, generally involving the covalent linking of an optical-signaling fragment to an anion receptor.[4–8] A widely used approach to the synthesis of colorimetric anion sensors utilizes chromophores such as indoles,[9] carbazole,[10] quinone,[11] and naphthalene diimide,[12] and other electron-withdrawing moieties covalently or non-covalently attached to an anion receptor.[13] Two approaches to anion binding are plausible. The first relates to a reversible non-covalent interaction between the sensor and anion, and this method has led to a significant amount of literature. The second is to induce an irreversible, or pseudo reversible chemical event that leads to the formation of a permanent or semi-permanent change. Both methods are pragmatic methods.

Fluoride recognition is an area of immense research interest to the scientific community due to its role in chemical, industrial, food, hygiene and toxicity.[14] Fluoride is one of the most challenging targets for anion recognition because of its high hydration enthalpy. For practical application, probes that can detect F^- by both colorimetric and fluorometric[15] analyses are favored, with several dual-mode F^- probes having being proposed so far.[16] Indeed, the colorimetric sensor based on the deprotonation of the binding moiety by F^- is very efficient and highly sensitive. Unfortunately, only a few colorimetric anion sensors are able to differentiate selectively between anionic substrates of similar basicity and surface charge density.[17] An additional problem is the compatibility of most of the anion sensors with water and electrolytes. Despite considerable effort, the need for good anion sensors remains.

Tetrathiafulvalene (TTF) and its derivatives have recently appeared as key constituents for new applications, exploiting the remarkably well behaved redox properties and high π-donating ability.[18] There are however only a few reports of TTF-based anion sensors, primarily towards $H_2PO_4^-$ and Cl^- anions utilizing anthracene disulfonamide-TTF, calix[4]arene-TTF platform and amide TTF derivatives, respectively.[19] Recently, a diindolylquinoxaline receptor bearing a TTF redox probe was prepared and found to be selective for dihydrogen phosphate over other small anions in dichloromethane using electrochemical and fluorescence quenching methods.[20] Here, we report on a very close analogue **1** (Scheme 1) bearing pyrrole groups and report on how this minor change affects both the selectivity as well as the nature of the optical readout in both absorption and emission.



Scheme 1 (a) General synthetic route for the synthesis of 2,3-dipyrrol-2′-yl-TTF-quinoxaline **1**, and (b) change in colour observed for **1** only upon the addition of 3 equiv of fluoride. All anions were introduced as their tetrabutylammonium salts respectively. [**1**] = 1.0 × 10^{-5} M.

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The target compound 2,3-dipyrrol-2′-yl-TTF-quinoxaline **1** was obtained *via* the direct condensation reaction of diamino-TTF **2**[21] with the 2,3-dipyrrol-2′-yl ethanedione **3**[17c] in the presence of acetic acid under an argon atmosphere at reflux, leading to the formation of the yellow crystalline solid in excellent yield (Scheme 1). Among the six anions tested in solution (DCM), namely, F^-, $H_2PO_4^-$, AcO^-, Cl^-, Br^-, and HSO_4^-, **1** responded positively to only F^-, resulting in a marked color change (Scheme 1b). This qualitative analysis was further explored using UV–vis absorption and fluorescence spectroscopy.

The UV–visible spectrum of **1** in CH_2Cl_2 (Fig. 1) shows three strong absorption bands at 288, 311 and 484 nm with a shoulder at 374 nm. The addition of TBAF to **1** causes significant changes in the absorption spectra with bands at 288, 311 and 484 nm decreasing in intensity while three new bands at 290, 323 and 503 nm appeared with a shoulder at 384 nm. Three clear isosbestic points at 326, 418, and 492 nm indicated a clean conversion throughout the titration process. The resultant Job plot indicated a 1 : 1 interaction stoichiometry. No significant changes in the absorption spectra of **1** were observed upon addition of AcO^-, $H_2PO_4^-$, Cl^-, Br^-, and HSO_4^- (at 0–50 equiv) in the same solvent (see ESI†) indicating very weak binding at best. Association constants were obtained by fitting the changes in the emission to a 1 : 1 binding stoichiometry.[22] The association constants for 1 : 1 complexes between **1** and F^- were calculated to be $6 \times 10^4\ M^{-1}$.‡

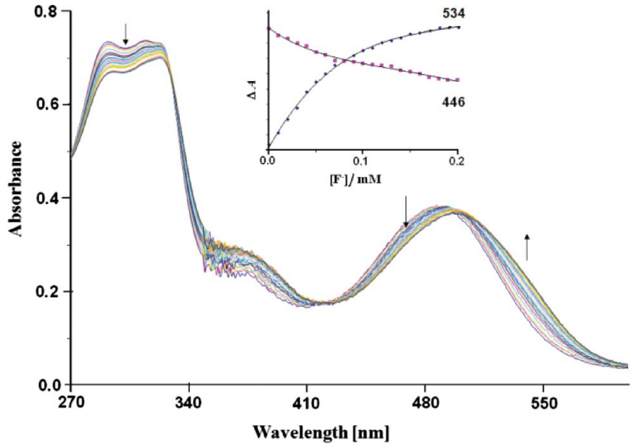

Fig. 1 UV–vis spectral changes of complex **1** upon the addition of fluoride anion; $[\mathbf{1}] = 1.0 \times 10^{-5}$ M, [TBAF] = $0–5 \times 10^{-4}$ M, DCM, 25 °C. The inset shows the fit of the experimental data to a 1 : 1 binding profile.

The emission spectrum of **1** in DCM at room temperature shows a strong band at 662 nm with a shoulder 703 nm ($\lambda_{ex} = 446$ nm) with a calculated quantum yield $\Phi_{em} = 0.22$ against Rhodamine (Fig. 2). Importantly, an emission intensity enhancement was observed with slight red shift (~4 nm) for **1** only upon addition of F^- (0–5 equivalents). Under the same conditions, no significant spectra changes were observed in the presence of large excesses (10–100 equiv) of other anions (AcO^-, $H_2PO_4^-$, Cl^-, Br^-, and HSO_4^-, as their tetrabutylammonium anion salts). The results suggest that sensor **1** has a high selectivity for the fluoride anion over the anions under common forms of spectroscopy.

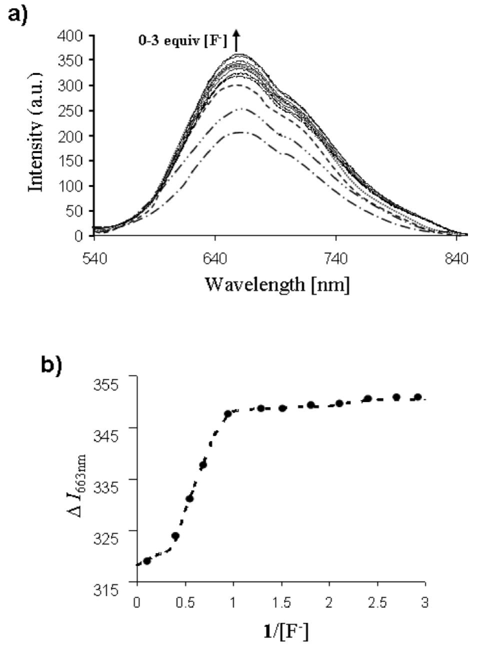

Fig. 2 (a) Fluorescence emission spectral changes of complex **1** upon the addition of TBAF; $[\mathbf{1}] = 1.0 \times 10^{-5}$ M, [TBAF] = 0–5 equivalents in DCM at 25 °C ($\lambda_{ex} = 446$ nm). (b) The changes observed at emission wavelength at 663 nm of **1** upon titration with TBAF.

Cyclic voltammetry was used to probe the changes in redox properties of the TTF containing dipyrrole receptor upon complexation with the fluoride anion. The TTF unit is a strong π-electron donor and has two sequential, and reversible oxidation couples corresponding to the radical cation $TTF^{+\bullet}$ and dication TTF^{2+}.[23] Table 1 in the ESI† displays the changes in electrochemical behaviour with the progressive addition of F^- ions to a 1 mM solution of the dipyrrole in DCM at 298 K. The results are shown graphically in Fig. 3.

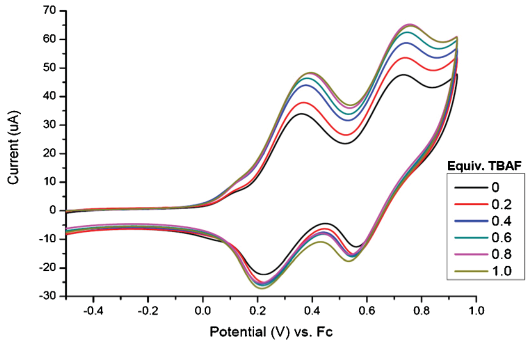

Fig. 3 Cyclic voltammogram of 1mM TTF-dipyrrole obtained by adding increasing quantities of 0.5 M TBAF solution (0 to 1.0 equiv). (Reference electrode: Fc^+/Fc, supporting electrolyte, *n*-Bu_4NPF_6 (0.1 M) in DCM.)

Overall, changes were consistent for both redox couples. Although a slight positive shift of the first and second oxidation potentials was observed, the characteristic potential $E_{1/2}$ (= E_p^{ox} + E_p^{red}/2) did not change significantly. An increase in current is also evident, however this proved *not* to be associated with F^- concentration. Control experiments showed the same effect with successive scans in the absence of the fluoride anion.

This increase in peak current, in combination with the somewhat Gaussian nature of the first peak couple, suggested surface effects. Continuous cycling experiments confirmed layer formation at the

Table 1 EC data—addition of NaF to aqueous solution contacting glassy carbon electrode containing electrodeposited TFF-dipyrrole layer

PEAK COUPLE I

Equiv. F^- added	$i_{p\ ox\ (uA)}$	$i_{p\ red\ (uA)}$	$E_{1/2}$/mV	$E_{p\ ox\ (mV)}$	$E_{p\ red\ (mV)}$	$\Delta E_{p\ (mV)}$
0	26.7	−18.5	581	664	498	166
0.2	28.5	−15.2	591	686	496	190
0.4	27.5	−12.6	609	705	513	192
0.6	26.7	−10.3	634	722	546	176
0.8	27.7	−9.2	637	725	549	176
1.0	27.0	−8.3	638	735	541	194
Overall change	NO TREND	DECREASE		Positive SHIFT	Positive SHIFT	

surface of the working electrode by electrochemical deposition (see ESI†). When the switching potential was altered so that the scan was reversed after the first oxidation, deposition ceased and the voltametric peak no longer grew in magnitude. This suggests that layer deposition is associated only with the doubly oxidised TTF species. As scanning to the potential of the second oxidation process resulted in electrochemical deposition, further solution phase electrochemical experiments were conducted without scanning past the first oxidation peak couple. In organic media, the first oxidation peak, corresponding to the radical cation $TTF^{\bullet+}$, was stable over >50 successive scans with no change in E_p or i_p, and no evidence of deposition or other surface effects. The effect of adding increasing quantities of TBAF solution (0 to 1.0 equiv) leads to only minor changes to the voltammogram, certainly not significant enough to ascribe to anion binding.

Modified electrodes are interesting for possible technological applications, therefore the coated electrode was tested in blank aqueous 0.1 M $LiClO_4$ solution. The electrodeposited layer maintained its electrochemical properties when scanned between 0 and 0.8 V. Scanning to the second oxidation potential however, led to desorption of the material (see ESI†). Table 1 displays the changes in electrochemical behaviour with the progressive additions of F^- ions (in the form of NaF), to the blank aqueous electrolyte contacting the coated electrode at 298 K. The corresponding voltammograms can be seen in Fig. 4. The most significant trends were a positive shift (73 mV) in $E_{1/2}$ and a decrease in the magnitude of i_{pred} as the concentration of fluoride was increased. The decrease in peak height of the reductive peak occurred concomitantly with the appearance of a new broad reduction wave at more negative potentials indicating the potential for **1** to be used as a solid-state sensor.

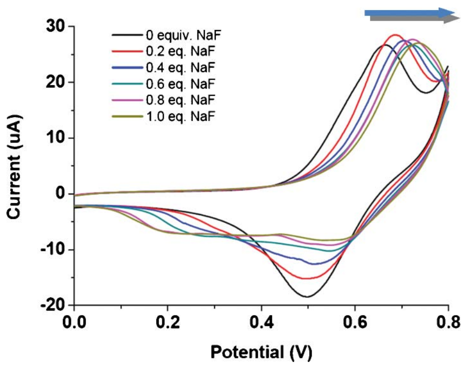

Fig. 4 Glassy Carbon WE drop coated with TTF-dipyrrole, in 0.1 M $LiClO_4$, 0–0.8 V, 0.2 V s^{-1} with varying additions of NaF (0–1.0 equiv).

To elucidate the nature of the intermolecular interactions between **1** and fluoride anion, ^1H NMR titration experiments were also carried out in CD_2Cl_2, primarily by monitoring the changes in signal of pyrrole NH, C–H pyrrole (Fig. 5). Upon the addition of 3 equiv. fluoride anion, dramatic changes occurred in the ^1H NMR spectrum of **1**. In particular the multiplicity and splitting of the pyrrole C–H signals and disappearance of N–H signals consistent with the 1 : 1 stoichiometry of the complex by UV–vis and fluorescence. No change in signal intensity or chemical shift was observed for the TTF protons throughout the addition of anions whereas the proton signal of the pyrrole moiety became broad and shifted upfield. The reason for the upfield shifts is the enhanced resonance of TTF electrons from the anionic character of pyrrole nitrogen upon bifurcation and twisting.[24] Based on these results we suggest a deprotonation mechanism consistent with other sulfonamide and dipyrrole receptors.[17,21] As a consequence, there is an increase in the rigidity of **1** causing the enhancement of fluorescence upon addition of fluoride anion.

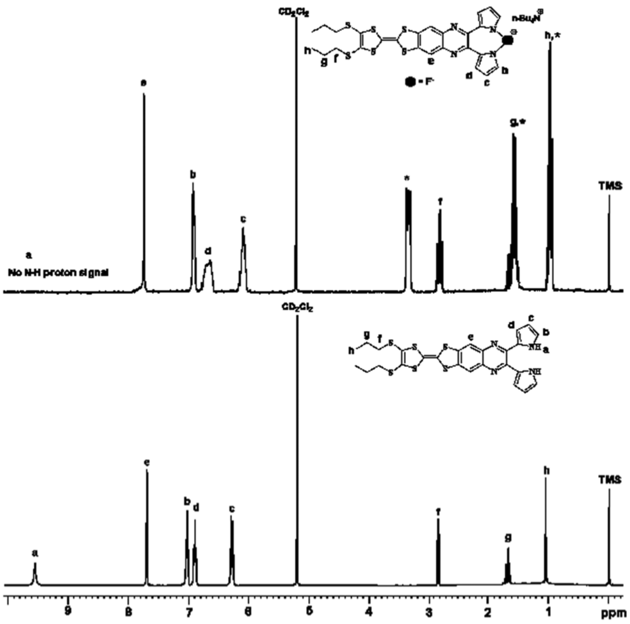

Fig. 5 Changes in the ^1H NMR (400 MHz) spectra of **1** in CD_2Cl_2 upon addition of 3 equiv of F^-. * = TBA peaks.

Crystals of **1** suitable for X-ray analysis were grown by vapour diffusion of MeOH into a $CHCl_3$ solution of **1** (Fig. 6).§ The dark colored crystals have a rod-shaped morphology, with **1** crystallising in the *Pbca* space group.[25] As expected, the crystal

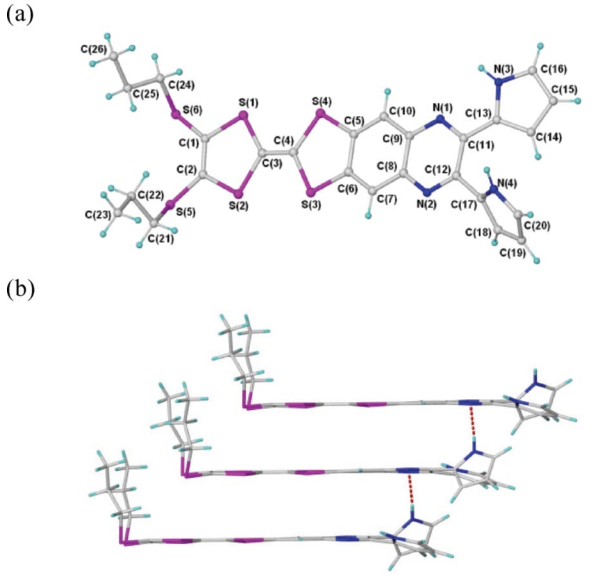

Fig. 6 (a) Ball-and-stick representation of one of two unique TTF-dipyrrolic molecules. (b) Stacking of **1** as viewed down the shorter molecular axes gives rise to a distance of 3.48 Å between each plane.

is stabilised by π–π interactions between TTF units as evidenced by the 3.48 Å separation between aromatic planes. Interestingly, there is a self-organisation of the TTF direction on account of interactions (N–H . . . .N = 2.16 Å) between the pyrrole hydrogen of one molecule with the quinoxaline group of another. The dispersive interactions of the propyl groups on one side of the molecular stack with the same set on an adjacent column lead ultimately to a herringbone structure.

In summary, we report a novel dipyrrolic based fluorescent neutral sensor for fluoride displaying optical changes for both UV/vis-absorption and fluorescence. Although the addition of fluorine causes an intense change in the electronic absorption spectrum of the compound, the electrochemical response remains largely unaffected. This suggests that while the molecular orbital responsible for the colour is close to the anion binding site, the electrochemical orbitals associated with the TTF moiety are sufficiently remote not to be influenced by changes in electron distribution caused by binding. The material may be easily electrodeposited from solution by scanning the potential to the second oxidation process. This produces a stable modified electrode which is electrochemically active in contact with aqueous electrolyte solution. While a polymerization process involving the pyrrole groups can also yield an explanation, we are reluctant to fully discount a mechanism involving TTF^{2+} alone because of the surface effects where no pyrrole groups were present. Further work is clearly required to elucidate the mechanism involved in this intriguing electrodeposition.

Notes and references

‡ Data was obtained using an EXCEL based non-linear regression analysis program, with an estimated error of *ca.* 10%.

§ Crystallographic data for the structure analyses have been deposited with the Cambridge Crystallographic Data Centre, CCDC 834006 for structure of **1**. Copies of this information may be obtained free of charge from the Director, CCDC, 12 Union Road, Cambridge, CB21EZ, UK (fax: +44-1223-336-033; e-mail: deposit@ccdc.cam.ac.uk or http://www.ccdc.cam.ac.uk).

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