

Visual sensing of fluoride ions by dipyrrolyl derivatives bearing electron-withdrawing groups

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Abstract. Two new, easy-to-prepare dipyrrolyl derivatives endowed with electron-withdrawing quinone or dicyano functionalities in their architecture permit the detection of fluoride ions under visual (naked-eye) as well as optical (absorption and fluorescence) and electrochemical conditions in organic solvents.

Keywords. Fluoride ion sensors; dipyrrolyl derivatives; binding constants.

1. Introduction

The coordination chemistry of anions is a relatively new area of research as opposed to that of cations. Indeed, sensing anions can, often, be quite challenging.^{1–5} Among the many inorganic anions, fluoride is drawing a special attention due to its beneficial (e.g. prevention of dental caries and treatment of osteoporosis) as well as detrimental (e.g. fluorosis) roles.^{6–8} Recently, calix[4]pyrrole^{9,10} and dipyrrolylquinoxaline (DPQ) based receptors^{11–14} have been reported to be efficient sensors for F^- and other inorganic anions. Herein, we report two new dipyrrolyl receptors **1** and **2** (figure 1), both of which are avid binders of F^- . Structurally, while receptor **1** can be considered as a DPQ derivative having the quinone moiety as part of its extended *p*-framework, compound **2** is a newly introduced receptor motif, viz. dipyrrolylpyrazine (DPP), that is substituted with two cyano groups directly on its skeleton.

2. Results and discussion

Reaction of the easily synthesizable 1,2-di(1H-2-pyrrolyl)-1,2-ethanedione^{11,16} with commercially available 1,2-diaminoanthraquinone or 1,2-diaminomaleonitrile readily furnished receptors **1** and **2** respectively, in ~80% yield in each case. These new compounds were sufficiently characterized for their

purity and structural integrity by elemental analysis, FAB-MS, IR, UV/Vis and 1H (1D and $^1H-^1H$ COSY) and ^{13}C NMR methods.[†]

In the room temperature 1H NMR spectra, while the two *b*-pyrrole protons of **1** (2.56×10^{-2} M in $(CD_3)_2SO$) resonated as two distinct signals at 6.52 and 6.65 ppm (see figure 2, trace A), the corresponding protons of **2** (3.84×10^{-2} M in $CDCl_3$) appeared at 7.37 ppm. We reasoned that close proximity of the symmetrically disposed and highly electron withdrawing cyano groups was responsible for the observed deshielding of the peak due to the *b*-pyrrole protons of **2** compared to the corresponding peaks of receptor **1**. On the other hand, an 'unsymmetric' juxtaposition of the quinone subunit with respect to the DPQ framework seems to rationalize the dissimilar nature of the two pyrrole rings of **1**.

During the NMR titration with F^- (tetrabutylammonium salt, [TBAF] = $0-12 \times 10^{-2}$ M) both the

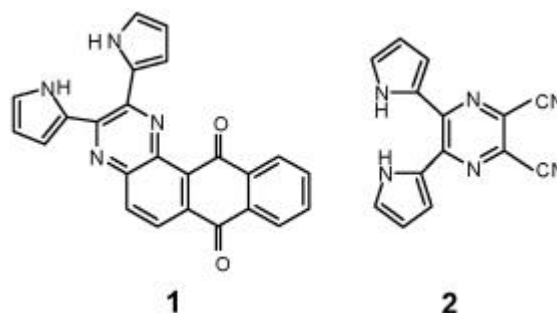


Figure 1. Molecular structures of receptors **1** and **2**.

*For correspondence

b-pyrrole resonances of **1** initially merged and finally appeared as a broad band centred at ~ 6.9 ppm (see figure 2, trace B). The **b**-pyrrole resonance of **2** was also shifted during the titration with TBAF and was found to locate within a broad band centred at 7.10 ppm at the end of the titration. Similar broadening of the peaks as well as shifts in the resonance positions for the **b**-pyrrole protons have been noticed earlier in the ^1H NMR spectra of various DPQ derivatives in the presence of fluoride ion and were interpreted in terms of binding of F^- by the two pyrrolyl subunits.¹¹⁻¹³ We believe that the same interpretation holds good for **1** and **2**. Unambiguous evidence that F^- is involved in H-bonding interaction with the two pyrrole $-\text{NH}$ protons comes from the fact that the resonances attributed to the $-\text{NH}$ protons on **1** (11.87 and 11.16 ppm, figure 2) and **2** (9.61 ppm) were initially broadened and finally disappeared from the spectrum upon successive addition of TBAF. Thus, the ^1H NMR data of **1** and **2** in the presence of F^- are consistent with a structural model which suggests that binding of F^- is facilitated by the rotation of the pyrrole rings of these receptors in such a way that the $-\text{NH}$ protons direct

towards the lone pairs of the anion.¹¹ Such a rotation is expected to aid the pyrrole rings to assume a 'bite angle' suitable for the size of F^- and to position them atop the quinoxaline/pyrazine chromophores in such a way that orbital overlap between the pyrrole and quinoxaline/pyrazine subunits are perturbed and the optical and electrochemical properties of these chromophores are altered. As will be discussed below, this is indeed the case.

In the naked-eye colorimetric experiments, receptors **1** and **2** (1×10^{-4} M in CH_2Cl_2 or DMSO) showed dramatic colour changes from red to green and from yellow to orange-red, respectively, in the presence of TBAF (3×10^{-3} M), figure 3. Both the receptors were found to be insensitive to the addition of Cl^- , Br^- , I^- or ClO_4^- (up to ~ 1000 mole equivalents excess; see figure 3). Interestingly, the addition of F^- (3×10^{-3} M) to those solutions of **1/2** (1×10^{-4} M) containing excess of these latter anions also generated the expected green/orange-red colour suggesting that these receptors are selective binders of F^- .

During the titrations with F^- in CH_2Cl_2 , the UV/Vis bands seen at 508 nm for **1** (figure 4) and

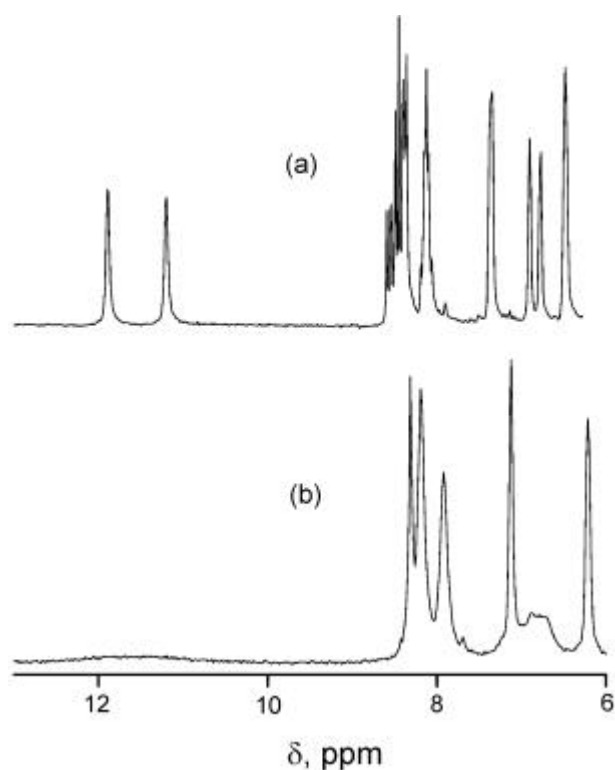


Figure 2. ^1H NMR spectra ($(\text{CD}_3)_2\text{SO}$) of (a) receptor **1** (2.56×10^{-2} M) and (b) a solution containing equimolar concentrations of **1** and TBAF (2.56×10^{-2} M each).

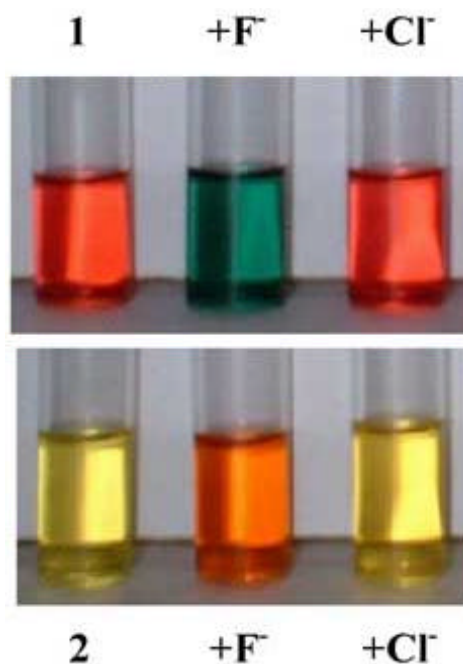


Figure 3. Colour changes observed for **1** and **2** in CH_2Cl_2 upon the addition of anions as tetrabutylammonium salts. Similar colour changes were also noticed when DMSO was used as the solvent. Concentrations employed: $[\mathbf{1}]/[\mathbf{2}] = 1 \times 10^{-4}$ M; $[\text{F}^-] = 3 \times 10^{-3}$ M and $[\text{Cl}^-] = 9 \times 10^{-2}$ M.

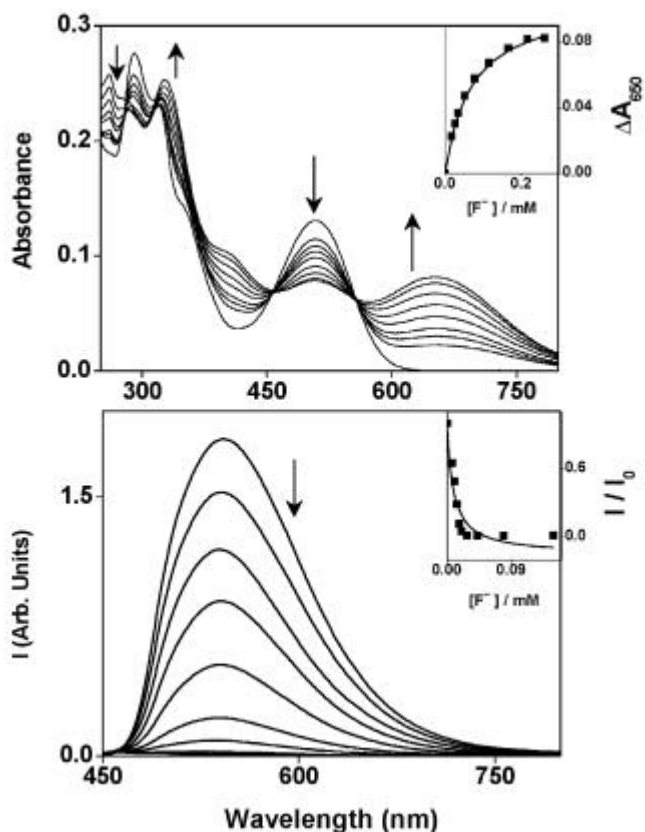


Figure 4. Top panel: UV/Vis spectral changes seen for 1.0×10^{-5} M **1** upon the addition of successive amounts of TBAF ($0-3 \times 10^{-4}$ M) in CH_2Cl_2 . Bottom panel: Fluorescence spectral changes seen for **2** ($I_{\text{exc}} = 430$ nm; OD = 0.18) upon the addition of TBAF ($0-3 \times 10^{-4}$ M) in CH_2Cl_2 . The inset in each case shows fit of the experimental data to a 1 : 1 binding profile.¹⁷

427 nm for **2** disappeared with a concomitant appearance of new bands at 652 and 469 nm, respectively. Upon the addition a drop of water, the original band and the solution colour reappeared in each case. Thus, the complexation between F^- and **1/2** is reversible in nature. The binding constants (K_a) obtained by UV/Vis titration experiments are 1.62×10^4 and $1.65 \times 10^5 \text{ M}^{-1}$ ($\pm 10\%$) for **1** and **2** respectively.¹⁷ The fact that K_a for **2** is an order of magnitude higher probably indicates the greater electron deficiency and enhanced hydrogen bond-donating character of this receptor. It should be noted here that addition of Cl^- , Br^- , I^- or ClO_4^- to solutions containing **1** or **2** produced only marginal spectral changes; the K_a values, being too low, could not be estimated by this method in these cases.

Both the new receptors were found to show fluorescence (CH_2Cl_2 , I_{em} , nm (j_f): **1**, 693 (0.015); **2**, 541

(0.41)), the intensity of which decreased upon binding with F^- in each case. Fluorescence titration experiments followed by standard curve fitting¹⁷ and Job-plot analyses not only provided the K_a values (**1**: $1.32 \times 10^4 \text{ M}^{-1}$ and **2**: $1.38 \times 10^5 \text{ M}^{-1}$), which were comparable to those obtained in the UV/Vis experiments, but also suggested that the binding stoichiometry in each case is 1:1 (see figure 4). Quenching of fluorescence was also observed for **1** and **2** in the presence of Cl^- , Br^- , I^- or ClO_4^- , albeit, only upon the addition of large excess ($> 10^{-3} \text{ M}^{-1}$) of these ions. Rough estimation of the binding constants gave values that vary between ca. $40-500 \text{ M}^{-1}$ for these anions.

Cyclic- and differential pulse (DPV) voltammetric studies revealed that **1** ($5 \times 10^{-4} \text{ M}$) and **2** ($1 \times 10^{-3} \text{ M}$) undergo quasi-reversible reductions at -0.63 and -1.12 V respectively, in CH_2Cl_2 , 0.1 M TBAP. Anodic shifts of the DPV peaks were noticed upon successive addition of TBAF to these solutions, with the shifts in the presence of equimolar concentration of $[F^-]$ being 190 and 220 mV for **1** and **2** respectively. The larger anodic shift observed for receptor **2** in the presence of F^- is consistent with the higher K_a value obtained by the UV/Vis and fluorescence titration methods described above.

3. Conclusion

In conclusion, the new dipyrrolyl derivatives **1** and **2** are easy-to-prepare fluoride ion receptors and allow the detection of F^- under visual as well as optical and electrochemical conditions in organic solvents. Currently, we are engaged in the design and anion-sensing studies of more such dipyrrolyl derivatives endowed with electron-withdrawing substituents.

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† Selected data for **1** and **2**

1: Analysis: Calcd. For $\text{C}_{24}\text{H}_{14}\text{N}_4\text{O}_2$: C, 73.84; H, 3.61; N, 14.35%. Found: C, 73.83; H, 3.71; N, 14.13. FAB-MS (m/z): 392 ($\text{M} + 2\text{H}$)⁺; m.p.: $>250^\circ\text{C}$.

UV/Vis (CH₂Cl₂) I_{\max}/nm (log ϵ): 290 (4.43), 508 (4.09); IR (KBr, cm⁻¹): 3376, 1663, 1657. ¹H NMR (200 MHz, (CD₃)₂SO) δ = 6.22 (2H, *m*), 6.52 (1H, *m*), 6.65 (1H, *m*), 7.13 (2H, *m*), 7.94 (2H, *m*), 8.20 (2H, *m*), 8.25 (1H, *d*, ³J_{H-H} = 10 Hz), 8.40 (1H, *d*, ³J_{H-H} = 10 Hz), 11.16 (1H, *br s*), 11.87 (1H, *br s*); ¹³C NMR (50 MHz, DMSO *d*₆) δ = 114.7, 114.9, 118.4, 119.1, 128.3, 128.8, 130.5, 131.4, 131.7, 133.3, 133.9, 137.1, 138.7, 138.9, 147.3.

2: Analysis: Calcd. For C₁₄H₈N₆: C, 64.61; H, 3.10; N, 32.30. Found: C, 65.11; H, 2.99; N, 33.12. FAB-MS (*m/z*), 260; m.p.: 185 ± 1 °C. UV/Vis (CH₂Cl₂) I_{\max}/nm (log ϵ): 338 (4.27), 427 (4.28); IR (KBr, cm⁻¹): 3314, 2243. ¹H NMR (200 MHz, CDCl₃) δ = 6.33 (2H, *m*), 7.12 (2H, *m*), 7.37 (2H, *m*), 9.61 (2H, *br s*); ¹³C NMR (50 MHz, CDCl₃/CD₃OD, 4:1, *v/v*): 112.0, 115.4, 116.9, 126.6, 126.9, 127.9, 145.4.

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