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A Core-Substituted Naphthalene Diimide Fluoride Sensor

Sheshanath V. Bhosale,*,† Sidhanath V. Bhosale,‡ Mohan B. Kalyankar,†,‡ and Steven J. Langford*,†

School of Chemistry, Monash University, Clayton, Victoria, Australia 3800, and
Department of Organic Chemistry, North Maharashtra University, Jalgaon-425 001, India

sheshanath.bhosale@sci.monash.edu.au; s.langford@sci.monash.edu.au

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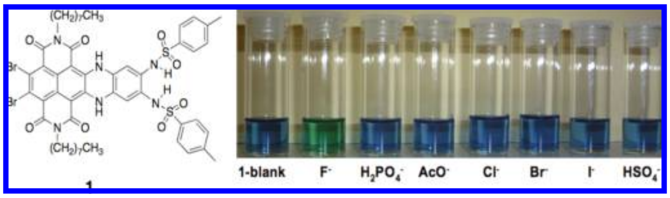
ABSTRACT



The synthesis and characterization of a highly fluorescent core-substituted naphthalene diimide sensor ($\phi = 0.34$) bearing a bis-sulfonamide group is described. The compound shows a unique selectivity and reactivity for the fluoride ion over other anions in $CHCl_3$ by a two-stage deprotonation process leading to a colorimetric response. In DMSO solution, the sensor is shown to be highly selective for fluoride ($K_a \sim 10^6$ M^{-1}) over other anions with more pronounced changes in absorption characteristics.

Anions play an important role in many biological processes and pathological events and also in bulk materials such as fertilizers and industrial raw materials, all of which necessitate the development of sensitive anion sensors that use either optical or electrochemical outputs.[1] In recent years, anion sensing and recognition has grown into an area of great interest in supramolecular and biological chemistry.[2] As anion−receptor interactions, mainly of a hydrogen bonding and electrostatic nature,[2e,3] are different than the metal−ligand coordination for cation−receptor interactions, the design of anion receptors differs substantially from that of cation receptors.[4] Most synthetic anion chemosensors generally involve the covalent linking of an optical-signaling chromophoric fragment to a neutral anion receptor containing urea, thiourea, amide, phenol, or pyrrole subunits, which can provide one or more H-bond donor sites for selective binding and sensing of some anions, especially for F^-, AcO^-, and $H_2PO_4^-$.[1−3] Unfortunately, few colorimetric anion sensors are able to differentiate selectively between anionic substrates of similar basicity and surface charge density.[2] A widely used approach to the synthesis of colorimetric anion sensors utilizes chromophores such as indoles,[5] bisindole,[6] carbazole,[7] nitrophenyl,[8] quinone,[9] and nitrobenzene/azo groups[10] and other electron-withdrawing moieties[11] covalently attached to an anion receptor. The selectivity of an anion sensor

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* To whom correspondence should be addressed. Phone: +61-3-99054569. Fax: +61-3-99054597.

† Monash University.

‡ North Maharashtra University.

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is related to the structure of the hydrogen bond complex and the basicity of the anions. Among anions, F^- is the most electronegative atom and, as such, usually forms the strongest H-bond interaction with an NH or OH groups. Of particular interest to our work is the early studies of Crabtree and Stranes in using a sulfonamide moiety for the recognition of anionic species.[12]

Among other aromatic molecules that have found utility in the design of chromophoric supramolecular materials, naphthalene diimide (NDI) derivatives have attracted particular attention.[13,14] NDIs are compact, highly colored, and functionalizable materials. Considering their rich spectroscopic and electrochemical properties, core-substituted NDI derivatives, in particular, are ideally suited to sensor design.[13] As yet though, core-substituted NDIs have not been explored in a receptor or sensor capacity. Here, we report the use of core-substituted NDI chromophores for anion sensing purposes through the synthesis and evaluation of a β,β'-bis-sulfonamide-quinoxaline derivative **1** (Figure 1) and compare its sensing ability to a model system **2** which does not contain the sulfonamide groups.

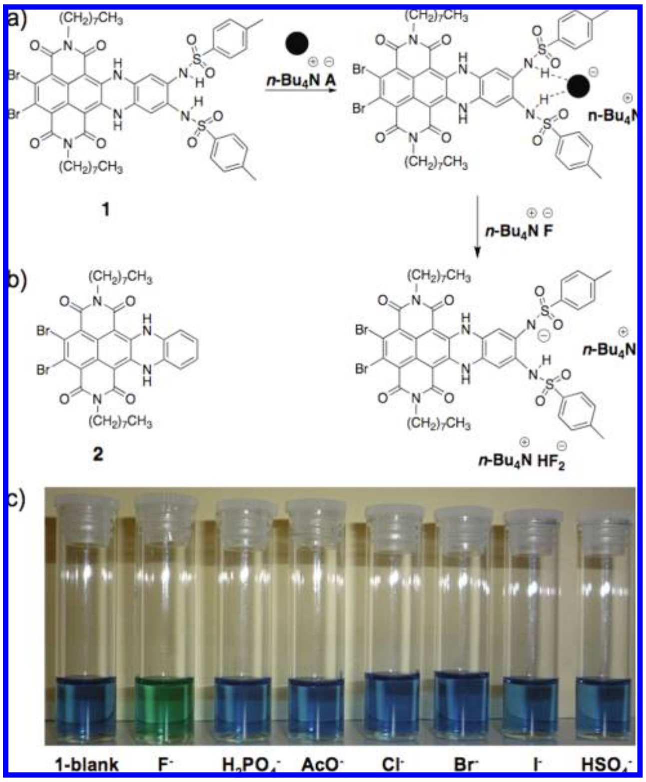

Figure 1. (a) Anion sensor structure illustrating where the anion binds and (b) model NDI **2**. (c) Sensing capability with color changes upon addition of 3 equiv of anions to **1** in chloroform: no anion, F^-, $H_2PO_4^-$, AcO^-, Cl^-, Br^-, I^-, HSO_4^- as their tetrabutylammonium salts; [**1**] = 3.5 × 10^{-6} M.

The core-substituted NDI sensor **1** was synthesized by the condensation of the *ortho*-diamine functionalized disulfonamide **4**[11,15] with tetrabromo-NDI **3**[16] in dry DMF at 135 °C (Scheme 1). Receptor **1** was obtained in 87% yield as a deep blue solid after purification by column chromatography on silica. The fact that monoannulation results in high yield can be attributed to two factors; aniline amines such as **4** are less nucleophilic than the aliphatic amines[17] used in examples where tetrasubstitution takes place.[15] Once the first addition is complete, the deactivating feature of the two amino groups leads to a balance of the two effects that preclude further addition. This result is important as it may allow variation of the structure through the two remaining aryl bromide groups.[18]

The result of adding 3 equiv of various anions (F^-, $H_2PO_4^-$, AcO^-, Cl^-, Br^-, I^-, and HSO_4^-, added as their tetrabutylammonium salts) to **1** in $CHCl_3$ is shown in Figure 1c. Specifically, NDI **1** is a sensor selective for fluoride at micromolar concentration. The dramatic anion-specific re-

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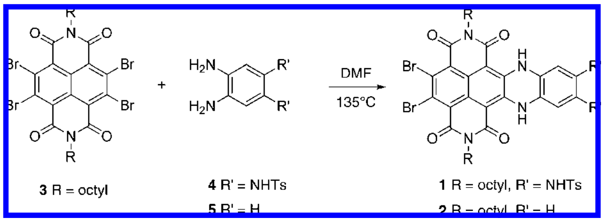
sponse makes **1** an especially effective colorimetric anion sensor under the solution-phase conditions employed. UV−vis spectroscopy was used to quantify the fluoride-induced spectral changes in **1** ([**1**] = 3.5 × 10^{-6} M). Receptor **1** displays four absorption bands, strong bands at 559 and 609 nm, and one weak band at 696 nm in $CHCl_3$ (Figure 2).

Scheme 1. General Synthetic Route to the Core-Substituted NDIs **1** and **2**



On addition of Bu_4NF from 0 to 2.0 equiv, the intensity bands at 559 and 609 nm steadily decrease with the appearance of new bands at 570 and 622 nm. In the presence of 3 equiv of F^-, the bands at 570 and 622 nm predominate with three clear isosbestic points observed. In contrast, the addition of F^- (or other anions) to a $CHCl_3$ solution of the model **2** does not induce change, indicating that neither the core NH protons nor anion−π interactions play a part in sensing.

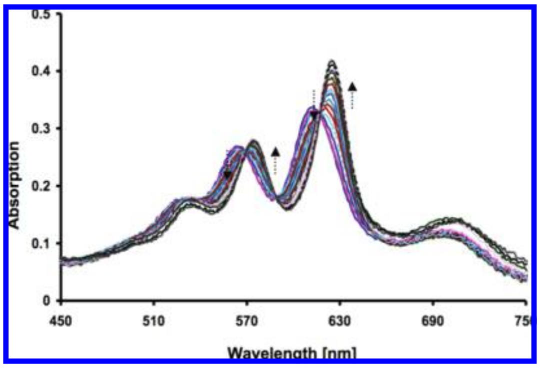


Figure 2. UV/vis titration spectra of receptor **1** upon addition of tetrabutylammonium fluoride ($CHCl_3$, 295 K); [**1**] = 3.5 × 10^{-6} M and [Bu_4NF] = 1 × 10^{-6} to 3.3 × 10^{-5} M.

The association constants of the fluoride complex were calculated using nonlinear least-squares fit of the binding curves. The association constant between **1** and F^- was calculated to be 3.8 × 10^5 M^{-2}. Weak 1:1 complexes (K_a ∼ 10−10^2 M^{-1}) with $H_2PO_4^-$, AcO^-, Cl^-, and Br^- were observed.[19]

Having a chromophore which is colored and emits a strong fluorescence (ϕ = 0.34) means that more than one optical readout is possible, strengthening the sensing capability of the system. The fluorescence emission spectra of **1** (Figure 3) consists of two strong bands at 635 and 696 nm upon photoirradiation at 600 nm. As shown in Figure 3, significant quenching (∼97%) was observed for **1** upon addition of 0−3 equiv of Bu_4NF, due to the fluoride's high charge density. Smaller effects (<15% quenching) were observed for all other anions requiring >25 equiv to achieve this response. These results indicate that **1** has a selective colorimetric and emission response to the presence of fluoride. The 2:1 stoichiometry of the complex was determined by a Job plot. Fluorescence titration experiments determined an association constant[20] between **1** and fluoride to be 4.1 × 10^5 M^{-2}, consistent with the result obtained from absorbance data.

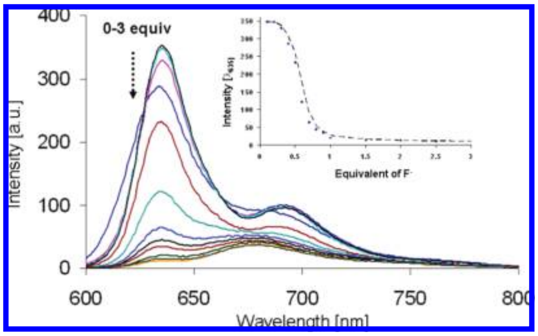


Figure 3. Changes in fluorescence emission for receptor **1** (3.5 μM) upon addition of fluoride (0−3 equiv as their tetrabutylammonium salts) in $CHCl_3$ (λ_{ex} = 600 nm).

The recognition properties of **1** were also investigated using ^1H NMR spectroscopy in $CDCl_3$, primarily by monitoring the changes in signal of sulfonamide N−H, aryl tosylate, and tosyl methyl hydrogens of **1** as probe protons (Supporting Information). Evident upon 1 equiv of F^- is the development of complications in the δ 7−9 region of the spectrum. In particular, the multiplicity of the tosyl aromatic signals and the apparent splitting of TsNH signals suggest conformational changes within **1**. Further addition of fluoride up to 3 equiv indicates a second process leading to the disappearance of TsNH signals consistent with the 1:2 stoichiometry of the complex by UV/vis and fluorescence. No change in signal intensity or chemical shift was observed for the core NH protons throughout the additions, consistent with our previous statement that they play no part in complexation. On the basis of these results, we suggest a deprotonation mechanism consistent with other sulfonamide receptors.[21,22] The first addition of F^- leads to a H-bonded complex, as shown in Figure 1, while the second F^- induces

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(19) For $H_2PO_4^-$, AcO^-, Cl^-, Br^-, I^-, and HSO_4^-, linear regression analysis of the binding curves cleanly fit a 1:1 binding model. Association constants for 1:1 complexes between **1** and $H_2PO_4^-$, AcO^-, Cl^-, Br^-, I^-, and HSO_4^- were calculated to be 6.2 × 10^4, 2.25 × 10^3, 8.72 × 10^2, 1.23 × 10^2, 8.76 × 10^1, and 6.7 × 10^1 M^{-1}, respectively (error <15%).

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the deprotonation of the bis-sulfonamide, leading to the formation of HF_2^- as the driving force. The fluoride-induced deprotonation process is fully reversible, and the addition of polar protic solvents (CH_3OH or EtOH) results in a reverse color change from green to blue.

A different and dramatic change is seen in more polar and competing DMSO solvent (Figure 4).[23] A significant bathochromic shift of ca. 100 nm was observed upon complexation of **1** with fluoride with a clear isosbestic point at 629 nm. A Job plot in this case indicates a 1:1 complex, and on the basis of titration data, an association constant (K_a) of $1.2 \pm 0.5 \times 10^6$ M^{-1} was calculated. Again, a green solution is achieved. No significant changes in the absorption spectra of **1** were observed upon addition of $H_2PO_4^-$, AcO^-, Cl^-, or Br^- (at 0−50 equiv) in the same solvent (Supporting Information). The distinctive change in stoichiometry and mechanism can be rationalized on the basis of the loss of basicity of the fluoride ion (through solvation) in the more polar DMSO solvent and further indicates that two NH groups act as cooperative binding sites for F^- anion, as suggested in Figure 1. The marked difference in both solvent effect and change in spectroscopic conditions augers well for the development of anion sensors and may suggest a revisiting of some of the original work on colorimetric sensors.

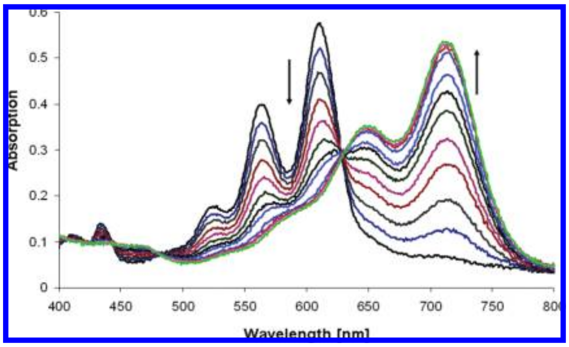

Figure 4. UV/vis titration spectrum of receptor **1** in the presence of fluoride in DMSO solvent. Equivalents of fluoride anion are 0−5; [**1**] = 2.5×10^{-5} M and [Bu_4NF] = 7.5×10^{-6} to 2.5×10^{-4} M.

Crystals of **1** suitable for X-ray analysis were grown by vapor diffusion of MeOH into a $CHCl_3$ solution of [**1**-H]$^-Bu_4N^+$ (Figure 5).[24] The structure indicates an extended planar orientation of annulated NDI terminated by the two core-substituted bromines on one side and the sulfonamide groups on the other. This structure is one of two unique imide structures solved (see Supporting Information for the second). There appears to be a bifurcation of hydrogen bonding between a methanol solvent molecule and the two sulfonamide groups in **1** (O9⋯N5 = 2.82(1) Å; O9⋯N6 = 2.98(1) Å). Macromolecularly, the structure is ordered through $\pi-\pi$ stacking of the aromatic rings (average distance 3.47 Å; see Supporting Information).

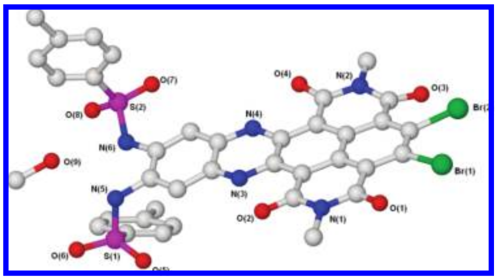

Figure 5. Ball-and-stick representation of one of two unique imide molecules. Hydrogen atoms have been omitted for clarity, and only the first C atom of the octyl chains is shown.

In summary, we reported a novel disulfonamide-based fluorescent, neutral, and selective colorimetric sensor for fluoride in which reversible NDI optical for both UV/vis absorption and fluorescence occurs. The stoichiometry achieved and mode of action are solvent-dependent. Receptor **1** has shown little or no affinity for other anions ($H_2PO_4^-$, AcO^-, Cl^-, Br^-, I^-, and HSO_4^-), especially in DMSO solvent. It is possible to conceive the use of this compound in various sensing applications as well as in other situations such as anion transport and purification, where the availability of cheap and easy-to-make anion receptors would be advantageous. We are currently tailoring these and other core-substituted NDIs as receptors to be specific for the other anion of choice by optical and colorimetric detection.

Acknowledgment. S.V.B. and S.J.L. gratefully acknowledge the Australian Research Council for support under their Discovery project (DP0878220).

Supporting Information Available: Synthesis and characterization of new compounds (**1** and **2**), X-ray data for **1**, and results of titration and Job plot experiments. This material is available free of charge via the Internet at http://pubs.acs.org.

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[23] The DMSO was not pretreated, containing an estimated 0.3% v/v water.

[24] Crystal data for **1**: $C_{129}H_{148}Br_4Cl_3N_{13}O_{18}S_4$, M = 2722.83, 0.20 × 0.08 × 0.02 mm^3, monoclinic, space group $P21/n$, a = 21.116(3), b = 13.8750(16), c = 40.830(6) Å, a = 90, b = 98.026(9), γ = 90°, V = 11845(3) $Å^3$, Z = 4, D_c = 1.527 g/cm^3, F_{000} = 5648, T = 123(2) K, $1.96 < \theta < 25.00°$, 26 359 reflections collected, 16 167 unique (R_{int} = 0.0725). Final GoF = 0.86, $R1$ = 0.1051, $wR2$ = 0.2592, R indices based on 16 167 reflections with $I > 2\sigma(I)$ (refinement on $F2$), 627 parameters. Crystallographic data for **1** have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication No. CCDC-745075. Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB21EZ, UK. Fax: (+44)1223-336-033; E-mail: deposit@ccdc.cam.ac.uk). The current data collection had a significant number of frames in which there was no observable diffraction (although in other scans, the diffraction was strong and well behaved). As a consequence, a portion of the original frames was deleted, resulting in a low overall completeness. Attempts to refine a model including constrained and unrefined octyl chains, allowing limited rotation about each C−C bond, proved unsatisfactory. Therefore, in the current model, only the first−third carbon atoms of each octyl chain were refined, leading to a higher than expected R factor. The structure is intended to give information on the core substitution of the naphthalene ring.