

Visible Colorimetric Fluoride Ion
Sensors

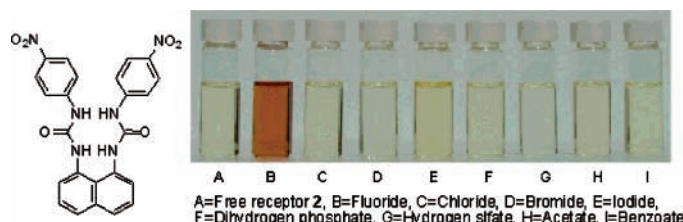
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ABSTRACT



Five new urea derivative naphthalene compounds were synthesized by a reaction of 1,8-diaminonaphthalene and the corresponding isocyanates and showed a distinct color change only when treated with fluoride ions.

Anions play an important role in a wide range of chemical and biological processes, and considerable attention has been focused on the design of host molecules that can recognize and sense anion species selectively through visible, electrochemical, and optical responses.^{1,2} Color changes, as signaling an event detected by the naked eye, are widely used owing to the low cost or lack of equipment required. Those chemosensors are constructed according to the receptor–chromophore general binomial, which involves the binding of a specific anion substrate with receptor sites and a chromophore responsible for translating the receptor–anion association into an optical signal. This color variation can be related to either structural or conformational changes in the receptor structure when a complex is formed or to the formation of a charge-transfer complex.^{3–6}

Among the range of biologically important anions, fluoride is of particular interest owing to its established role in preventing dental caries.⁷ The fluoride ion has also been examined extensively as a treatment for osteoporosis.⁸

However, excess fluoride can lead to fluorosis,⁹ which is a type of fluoride toxicity that generally manifests itself clinically in terms of increases in bone density. This diversity of its function, both beneficial and otherwise, makes the detection of fluoride ion important. Even though some receptor compounds for fluoride ions have been reported,¹⁰ there is a paucity of reports on a selective visible chemosensor for fluoride ions.¹¹ Naphthalene urea receptors for carboxylate and dihydrogen phosphate have been reported as fluorogenic and chromogenic chemosensors,¹² but the

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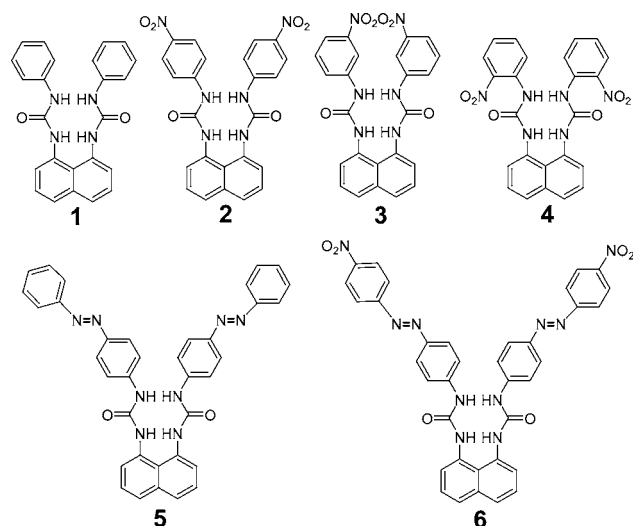
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previous studies introduced one urea group at the 1-position of naphthalene and combined two or three naphthalene urea units together with spanners. However, we introduced two urea groups into the 1,8-positions of naphthalene, which can provide selective fluoride binding sites. In pursuit of fluorescent fluoride ion chemosensors, a naphthalene urea derivative **1** was synthesized, and its spectral characteristics with fluoride ions were investigated.¹³ Five new naphthalene urea derivatives that were selective, visible fluoride ion sensors were synthesized by introducing a nitro group and an azo unit into an aromatic moiety, and their anion binding properties were investigated by UV-vis spectroscopy and color changes. All of the naphthalene urea derivatives showed significant bathochromic shifts in the presence of fluoride. However, ligands **2**, **4**, **5**, and **6** could be utilized as visible chemosensors owing to the noticeable color changes in the presence of fluoride ion.



Ligands **1**–**4** were prepared using the one-step reaction¹³ of 1,8-diaminonaphthalene and appropriate isocyanates in a tetrahydrofuran solution in high yield. Two azo naphthalene urea derivatives **5** and **6** were prepared from 1,8-diaminonaphthalene and the corresponding azo isocyanates. The azo isocyanates were obtained easily by treating 4-phenylazobenzene and disperse orange with triphosgene.

The UV-vis experiments were carried out in a DMSO solution. A receptor solution (3×10^{-5} M) was treated with the representative anions such as tetrabutylammonium (TBA) fluoride, chloride, bromide, iodide, dihydrogen phosphate, hydrogen sulfate, benzoate, and acetate. When compound **1** forms a complex with F^- , the absorption peak at 318 nm

disappears and a new peak appears at 384 nm, red-shifted by a $\Delta\lambda_{\max}$ of 66 nm. However, a bathochromic shift of other ions was also observed with a small change.

Figure 1 shows the absorption spectra of compound **2** in the presence of the anions. The absorption peak at 350 nm

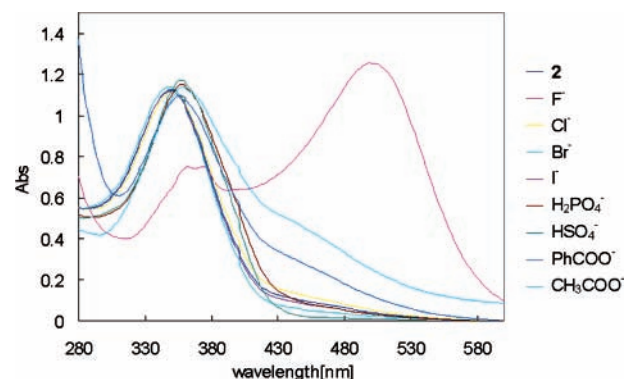


Figure 1. Absorption spectra of compound **2** (3×10^{-5} M) upon addition of tetrabutylammonium fluoride, chloride, bromide, iodide, dihydrogen phosphate, hydrogen sulfate, benzoate, and acetate (3×10^{-3} M) in DMSO.

was shifted to 498 nm ($\Delta\lambda_{\max}$ 148 nm) when fluoride was added to compound **2** in the DMSO solution. On the other hand, the absorption peaks at 319 and 415 nm of *m*- and *o*-nitrophenyl derivatives **3** and **4** were shifted to 379 and 502 nm ($\Delta\lambda_{\max} = 60$ and 87 nm), respectively, with a similar concentration of added fluoride as summarized in Table 1.

Table 1. Absorption Peak (λ_{\max}) Change in Ligands **1**–**6** in the Presence of Fluoride Ion

ligands	λ_{\max} (ligand) ^a	λ_{\max} (ligand + F^-) ^b	$\Delta\lambda_{\max}$
1	318 nm	384 nm	66
2	350 nm	498 nm	148
3	319 nm	379 nm	60
4	415 nm	502 nm	87
5	361 nm	542 nm	181
6	404 nm	662 nm	258

^a Absorption spectra were taken at a concentration of 3×10^{-5} M in DMSO. ^b Tetrabutylammonium fluoride (3×10^{-3} M) was added.

As predicted from the ab initio calculation,¹⁴ it is obvious that the ligand (L) exists as L^- when treated with fluoride, which can be visualized by the large red shift. The largest red shift (258 nm) was observed when ligand **6** was complexed with fluoride ion. This was attributed to the elongated conjugation by the nitro group at the para position of the azo phenyl derivative.

A color change could be observed easily by mixing the ligand and anion as shown in Figure 2. A receptor solution

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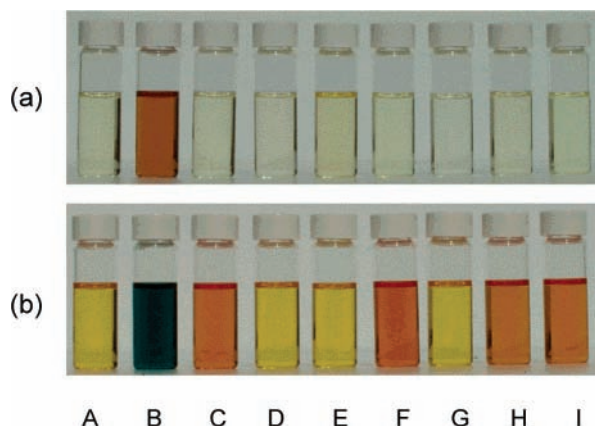


Figure 2. Color changes of ligands **2** (a) and **6** (b) (2×10^{-5} M) in DMSO with the addition of tetrabutylammonium anions (2×10^{-3} M). A = free receptor, B = fluoride, C = chloride, D = bromide, E = iodide, F = dihydrogen phosphate, G = hydrogen sulfate, H = acetate, I = benzoate.

was simply treated with various anions such as F^- , Cl^- , Br^- , I^- , $H_2PO_4^-$, HSO_4^- , CH_3COO^- , and $C_6H_5COO^-$. Noticeable color changes were observed when ligands **2**, **4**, **5**, and **6** were treated with the anions. In particular, it was remarkable that a pale yellow ligand solution became red when fluoride ions were added to compound **2** in DMSO, but no color changes were observed when the other anions were added. A similar red color was observed when the azo phenyl ligand **5** was treated with fluoride ions. However, a blue color was observed in the case of ligand **6** with fluoride ion, and the yellow color was deepened when chloride, dihydrogen phosphate, benzoate, and acetate were added.

The origin of the color change in the host solution could be ascribed to the charge-transfer interactions between the electron-rich donor units and the electron-deficient *p*-nitrophenyl and azo phenyl moieties.

As the receptor bound the fluoride ions, hydrogen bonds were constructed to form stable complexes, and the electron density in the supramolecular system was increased, which enhanced the charge-transfer interactions between the electron-rich and electron-deficient moieties, resulting in a visible color change (Figure 3).

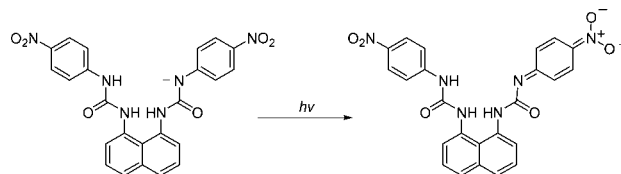


Figure 3. Charge-transfer transition occurring in the deprotonation form of compound **2**

In conclusion, five new urea derivatives were synthesized by a reaction of 1,8-diaminonaphthalene and the corresponding isocyanates. A distinct color change was observed when ligands **2**, **4**, **5**, and **6** were treated with fluoride ions by extending the conjugated system of the ligand anion, which is formed only when complexed with a fluoride ion. Due to the poor solubility of receptors, we are unable to study the ion binding properties in the aqueous solution as well as other organic solvents except in DMSO.

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Supporting Information Available: Spectroscopic data for ligands **2–6**, UV–vis spectra and color change of ligands **1**, **3**, **4**, and **5** upon addition of tetrabutylammonium anions, and 1H NMR titration spectra of ligand **3**. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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