# Colorimetric and Fluorescent Recognition of Fluoride by a Binaphthol Thioureido Derivative

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A new thiourea based receptor (**1**) was synthesized and applied to fluoride ion recognition in acetonitrile solution. Receptor **1** displayed dual changes in absorption and fluorescence emission intensities selectively for fluoride ions. The interaction of **1** with fluoride undergoes a deprotonation process that is confirmed by ^{1}H NMR titration.

## Introduction

Anion recognition using artificial receptors is currently an increasingly important research area due to their fundamental roles in many biological and chemical processes.[1-4] Particularly, fluoride ion sensing is more important and has attracted considerable attention due to its vital roles in unique biology and chemistry properties. For instance, fluoride plays crucial roles in dental care[5] and the treatment of osteoporosis.[6] A high intake of fluoride can leads to the most widespread side effect of fluoride, namely, fluorosis,[7] and also leads to nephrotoxic changes[8] and urolithiasis.[9] In addition, with the development of industry and the increase in the number and the scale of enterprises on fluorine products, the contamination of fluorine becomes more serious. For these reasons, selective recognition of fluorine ion is of realistic significance.

Anion recognition by colorimetric and fluorescent dual responsive sensors have attracted much attention, because they have two significant advantages, namely the high sensitivity of fluorescence and the naked-eye detectable feature of color changes. During the past decade, a great number of synthetic sensors have been developed for fluoride ion detection,[10-15] however, very few of them have the advantage of dual mode of detection.[16-24] Among the detection mechanisms employed, the N-H deprotonation was widely used, which can induce the N-H proton transfer from the donor unit to fluoride ion. We report herein a new binaphthol based thiourea type receptor (**1**) for the colorimetric and fluorescent recognition of fluoride ion in acetonitrile solution.

## Experimental Section

**General Methods and Materials.** All the solvents were of analytic grade from commercial sources and used without further purification. Column chromatography was performed on silica gel (200-300 mesh). NMR spectra were recorded on an AVANCE-600 MHz NMR spectrometer. MALDI-TOF-MS was carried out on a MALDI AXIMA-CFR (PLUS) mass spectrometer. UV-vis spectra were measured on a SP-1900 spectrophotometer. Fluorescence measurements were performed on a 970 CRT spectrofluorometer (Shanghai Sanco, China).

**Synthesis of Receptor 1.** To a stirred solution of **2**[25] (0.5 g, 2.8 mmol) in 30 mL absolute ethanol was added **3** (0.25 g, 1.16 mmol), then the mixture was heated to reflux for 12 h. The formed yellow precipitate was collected by filtration and purified by recrystallization from absolute ethanol to give a pale yellow solid (0.54 g, yield 80%). mp > 250 °C. ^{1}H NMR (600 MHz, DMSO-$d_6$) δ 11.70 (s, 2H), 8.98 (s, 2H), 8.50 (s, 2H), 8.35 (s, 2H), 8.17 (s, 2H), 8.02 (d, $J$ = 7.2 Hz, 2H), 7.49 (t, $J$ = 7.2 Hz, 2H), 7.34 (t, $J$ = 7.2 Hz, 2H), 7.02 (d, $J$ = 8.4 Hz, 2H), 4.56 (d, $J$ = 6.0 Hz, 2H), 4.50 (d, $J$ = 6.0 Hz, 2H), 2.75 (s, 6H). ^{13}C NMR (150 MHz, DMSO-$d_6$) 178.6, 152.1, 138.7, 134.4, 130.8, 129.2, 127.9, 127.6, 126.1, 126.0, 125.3, 99.5, 56.9, 56.5, 19.5. MALDI-TOF-MS: [M+H]$^+$ 577.4.

## Results and Discussion

The interaction of receptor **1** with anions were examined by both UV-vis absorption and fluorescence spectroscopy in
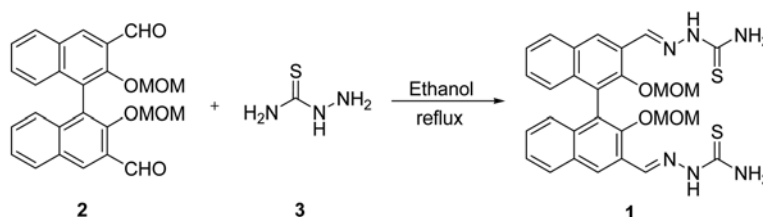


**Scheme 1.** Synthesis of receptor **1**.

acetonitrile, tetrabutyl ammonium (TBA) salt of various anions ($F^-$, $Cl^-$, $Br^-$, $I^-$, $NO_3^-$, $HSO_4^-$, $AcO^-$ and $H_2PO_4^-$) were used in the experiment. Upon addition 200 equiv. of $F^-$, the solution color changes instantaneously from colorless to yellow, and the absorption maximum of the **1** solution was red-shifted from 340 nm to 414 nm. Whereas, when 200 equiv. of other anions were subjected to this experiment, only rather small absorption spectra changes could be observed (Figure 1). These results indicate that receptor **1** has a good selectivity to fluoride ions.

Subsequently, absorption titration experiment was carried out and the results were shown in Figure 2. Free receptor **1** exhibited a major absorption band centered at 340 nm. Upon incremental addition of $F^-$ to **1** solution, the absorption band centered at 340 nm gradually decreased, concomitantly, a new absorption band centered at 414 nm developed. A well-defined isosbestic point at 368 nm was observed, indicating the formation of a new species upon treatment of receptor **1** with $F^-$. The absorption intensity ratio, $A_{414}/A_{340}$, increases with the increase of fluoride concentrations (Figure 2, inset), which indicates the potential application of receptor **1** as a
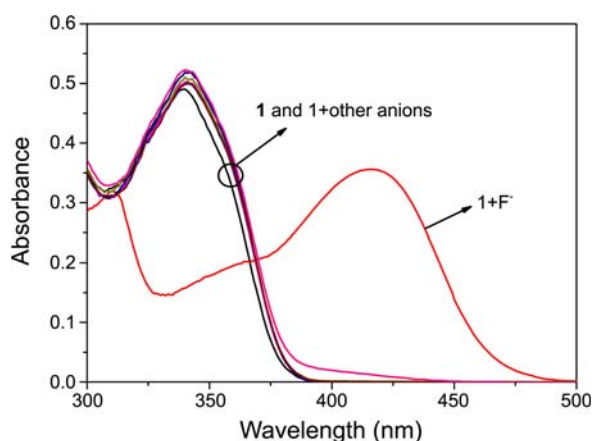
ratiometric colorimetric sensor for the fluoride detection. The perceived color variation and spectral response upon the addition of $F^-$ would be useful not only for the ratiometric method of detection but also for rapid visual sensing.

The sensing property of **1** toward $F^-$ was further investigated by emission spectroscopy titration experiment and the results were shown in Figure 3. Upon progressive addition of $F^-$ (0 to 200 equiv.) to the $CH_3CN$ solution of **1**, a gradual enhancement of the fluorescence at 338 nm can be observed. Linear fitting of the titration profiles using Benesi-Hildebrand plot based on a 1:2 binding mode results in a good linearity (correlation coefficient is over 0.99) (Figure 4), which strongly support the 1:2 binding stoichiometry of **1** and $F^-$, and the binding constant is calculated to be $3.02 \times 10^4 \, M^{-2}$. The equation used is as follow:

$$\frac{1}{F-F_0} = \frac{1}{K(F_{max}-F_0)[F^-]^2} + \frac{1}{F_{max}-F_0}$$

Where $F_0$ is the fluorescence intensity of **1**, $F$ is the fluorescence intensity obtained with $F^-$, $F_{max}$ is the fluorescence



**Figure 1.** The absorption spectra of **1** ($1.0 \times 10^{-5}$ M) upon addition of various anions (200 equiv. of each).
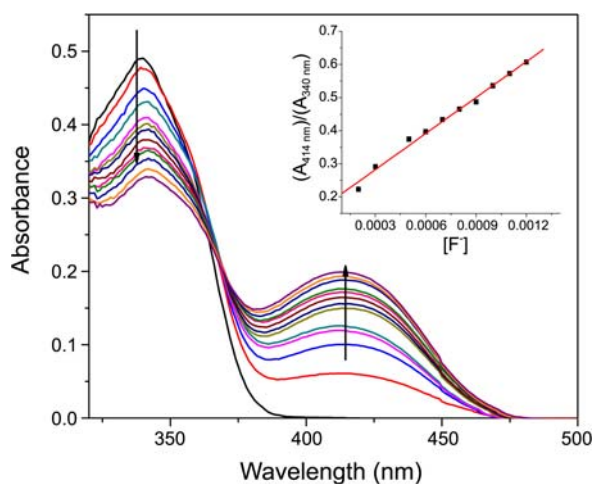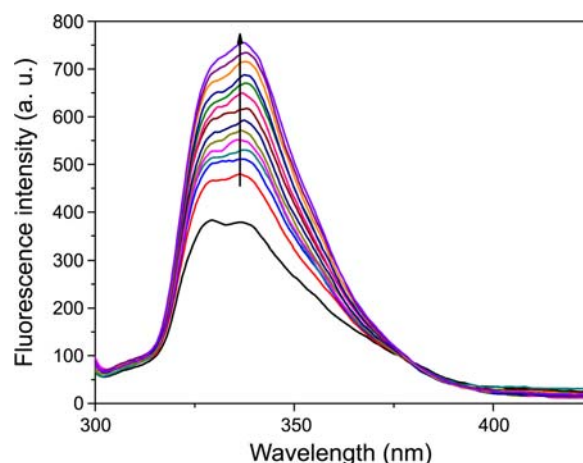


**Figure 2.** Changes in absorption spectra of **1** ($1.0 \times 10^{-5}$ M) in $CH_3CN$ solution with various amounts of $F^-$ anions (0 to 120 equiv.). Inset: The absorption intensity ratio $A_{414}/A_{340}$ *versus* the fluoride concentration.



**Figure 3.** Changes in fluorescence emission spectra of **1** ($1.0 \times 10^{-5}$ M) in $CH_3CN$ solution with various amounts of $F^-$ anions (0 to 200 equiv.).
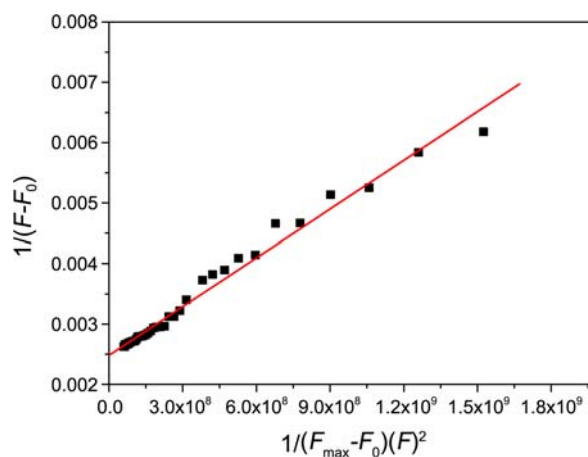


**Figure 4.** Benesi-Hildebrand plot (emission at 338 nm) of **1** ($1.0 \times 10^{-5}$ M) using 1:2 stoichiometry for association between **1** and $F^-$.
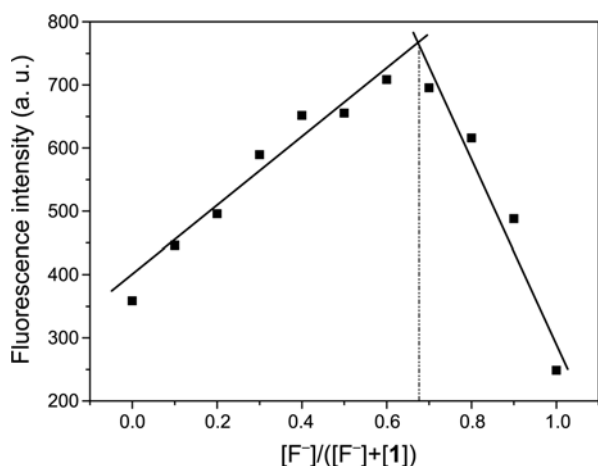
**Figure 5.** Job plot curve for **1**-F$^-$ complex in acetonitrile, the total concentration of F$^-$ and **1** was $1.0 \times 10^{-5}$ M.



**Figure 7.** The absorbance of **1** ($1.0 \times 10^{-5}$ M) at 414 nm to various anions. The blue bars represent the absorption of **1** in the presence of 200 equiv of miscellaneous anions, the red bars represent the absorption of the above solution upon further addition 200 equiv. of F$^-$.

addition of 1.0 equiv. of fluoride. These signals further shifted to around 8.00 ppm and merged with the aromatic hydrogen signals when 2.0 equiv. of fluoride was added. The occurrence of a broad triplet signal at 16.07 ppm is attributed to the formation of the [FHF]$^-$ species,[18,26-28] which indicating the fluoride induced deprotonation of N-H. These observations demonstrated that the deprotonation process of thiourea N-H was occurred in the interaction of receptor **1** with fluoride anions, the result of this process increased the electron density on the N atom, which is associated with the enhancement in the push-pull effect of the internal charge transfer, thus, a yellow color formation was happened.

The possible interference by other anions was also assessed through competitive experiments and the results are depicted in Figure 7. Except F$^-$, other anions (200 equiv to **1**) do not produce significant absorption changes. Nevertheless, upon addition of F$^-$ (200 equiv to **1**) to the solution containing **1** and other anion, Cl$^-$, Br$^-$, I$^-$, NO$_3^-$ and H$_2$PO$_4^-$, a drastic increase in absorption at 414 nm was induced. It is noteworthy that addition of fluoride ions into the solution containing AcO$^-$ produces a moderate absorbance increase. Addition of fluoride into solution containing HSO$_4^-$ only can causes a small absorption change, this phenomenon can be attributed to the neutralization effect of fluoride by the strong acidic HSO$_4^-$ ions.[23] From these results, it can be inferred that the recognition of F$^-$ by **1** is not significantly
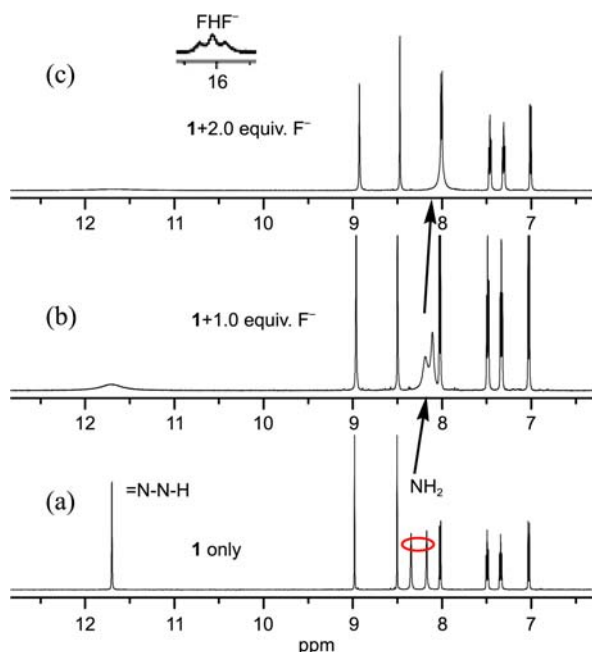


**Figure 6.** $^1$H NMR spectrum of receptor **1** in DMSO-$d_6$ upon addition of TBA$^+$F$^-$: (a) 0, (b) 1.0 and (c) 2.0 equiv.

intensity obtained with excess amount of F$^-$, $K$ is the association constant, and [$F^-$] is the concentration of F$^-$ added.

The 1:2 binding stoichiometry of **1** and F$^-$ was further proved by Job's plot according to the continuous variations with a total concentration of [$F^-$] + [**1**] was $1.0 \times 10^{-5}$ M (Figure 5). The maximum fluorescence emission appeared at the 0.67 mole ration of [$F^-$]/([$F^-$] + [**1**]), which further indicating the 2:1 interaction between F$^-$ and **1**.

To get insight into the binding mode of receptor **1** with fluoride, $^1$H NMR titration experiments were subsequently carried out in DMSO-$d_6$ (Figure 6). The signal of thiourea N-H adjacent to C=N bond appears at 11.70 ppm, which is decreased significantly to be a broad peak upon addition of 1.0 equiv. of fluoride, and disappears entirely upon addition of 2.0 equiv. of fluoride. The signals of NH$_2$ at 8.35 and 8.17 ppm all up-shifted to 8.19 and 8.11 ppm respectively upon
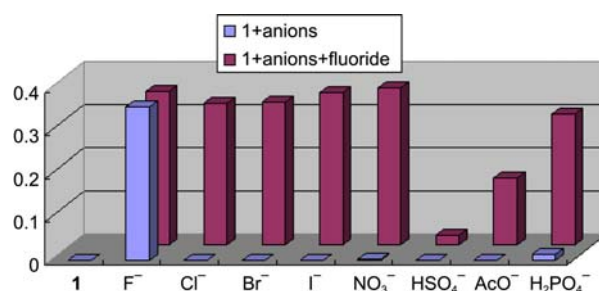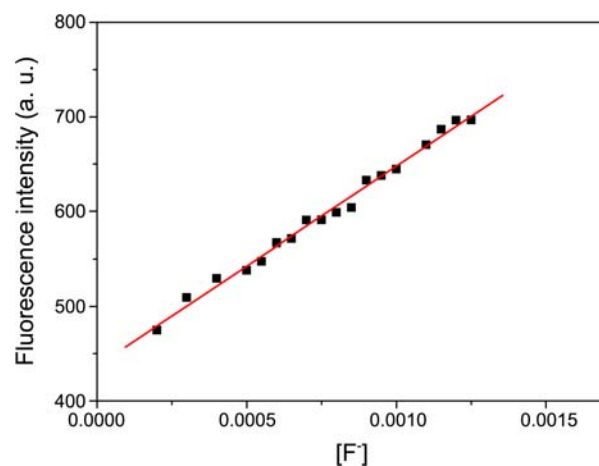


**Figure 8.** Fluorescence Intensity of soiution **1** *versus* the concentration of F$^-$ within the low concentration range ($1.0 \times 10^{-5}$ to $1.1 \times 10^{-3}$ M).

influenced by other coexisting anions except $HSO_4^-$, and therefore **1** exhibits a definite selectivity toward $F^-$.

In addition, to check its practical utility, the colorimetric detection limit of **1** for $F^-$ was evaluated. Under the present conditions, a good linear relationship between the fluorescence intensity and the $F^-$ concentration could be obtained in the $1.0 \times 10^{-5}$ M to $1.1 \times 10^{-3}$ M range (R = 0.9955) (Figure 8). The detection limit is then calculated to be $1.82 \times 10^{-4}$ M with the equation: detection limit = $3S/\rho$, where $S$ is the standard deviation of blank measurements, $\rho$ is the slope between intensity *versus* sample concentration. This result indicates that sensor **1** has a good sensitivity to monitor $F^-$ concentration in $CH_3CN$.

## Conclusion

In summary, a new binaphthol thioureido derivative, receptor **1**, has been synthesized and used as a colorimetric and fluorescent dual responsive sensor for the recognition of fluoride in acetonitrile. The binding stoichiometry of **1** and $F^-$ was proved to be 1:2, the $F^-$ recognition event by **1** is not significantly influenced by other coexisting anions except $HSO_4^-$. ^{1}H NMR studies reveal that the interaction of **1** with $F^-$ undergoes a N-H deprotonation process.

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