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A novel heteroacene, 2-(2,3,4,5-tetrafluorophenyl)-1*H*-imidazo[4,5-*b*]phenazine as a multi-response sensor for F^- detection

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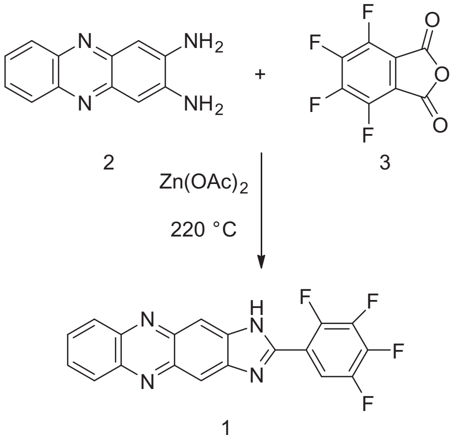
ABSTRACT

A novel heteroacene, 2-(2,3,4,5-tetrafluorophenyl)-1*H*-imidazo[4,5-*b*]phenazine has been successfully synthesized. The heteroacene can selectively detect F^- over Cl^-, Br^-, I^-, NO_3^-, HSO_4^-, ClO_4^-, and BF_4^- in organic solvents through colorimetric and fluorescent responses. The interaction between the heteroacene and F^- was investigated through UV–Vis, fluorescence, and ^1H NMR titration experiments, which suggested that the effects might occur via a combined process including hydrogen bond, deprotonation, and anion–π interactions between the sensor and F^-.

Fluoride plays an important role in the physiology of human beings. Sufficient fluoride is crucial for dental health, while over-exposure of fluoride causes skeletal fluorosis.[1] Thus, quick and efficient analysis of fluoride (F^-) in drinking water and other environments is very important to provide information for fluoride hazard assessment and pollution management. In recent years, the development of colorimetric and luminescent sensors for F^- recognition and concentration monitoring has attracted significant attention.[2] There are many series of sensors reported for detecting F^-, including boron-based Lewis acids,[3] functionalized pyrroles and benzopyrroles,[4] and 1,8-naphthalimide derivatives.[5] However, the application of these sensor systems can be limited by drawbacks such as low sensitivity and difficulties in their preparation. Therefore, developing new, simple, and highly sensitive F^- sensors remains a challenge.

Imidazole is a widely used functional group in F^- detecting sensor systems because it is able to behave as an excellent hydrogen bond donor moiety, and the acidity of the NH group can be easily tuned by adjusting the electronic properties of neighboring substituents so that it can recognize F^- through deprotonation.[6] Currently, the interesting non-covalent binding motif between electron-deficient aromatic rings and anions, namely anion–π interactions, is generating much interest in theoretical and experimental investigations, because anion–π or anion–proton interactions play a crucial role in many chemical and biological processes, and could have potential applications in medicine and in the environment.[7] Since N-substituted heteroacenes are electron-deficient compounds,[8–10] we anticipate that they should be good candidates for F^- recognition through combined processes.

Herein, we report a new heteroacene based sensor, 2-(2,3,4,5-tetrafluorophenyl)-1*H*-imidazo[4,5-*b*]phenazine (**1**), which can recognize selectively F^- with multiple responses. As shown in Scheme 1, compound **1** was obtained as an orange powder in 19% yield through a one-pot, solid-state reaction between 2,3-phenazinediamine, zinc acetate, and 3,4,5,6-tetrafluorophthalic anhydride at



Scheme 1. Synthesis of compound **1**.

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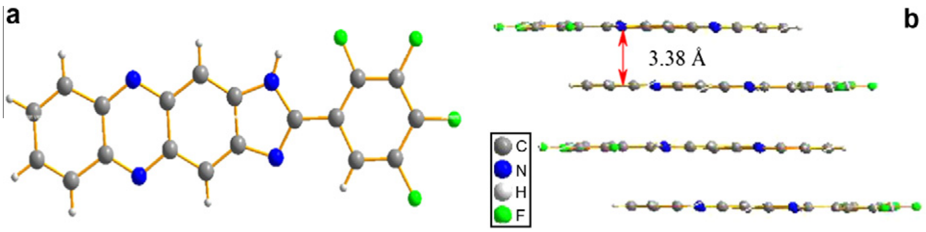

Figure 1. (a) Single crystal structure and (b) molecular packing diagram of **1**. Carbon, nitrogen, hydrogen, and fluoride are colored in gray, blue, white gray and green, respectively.

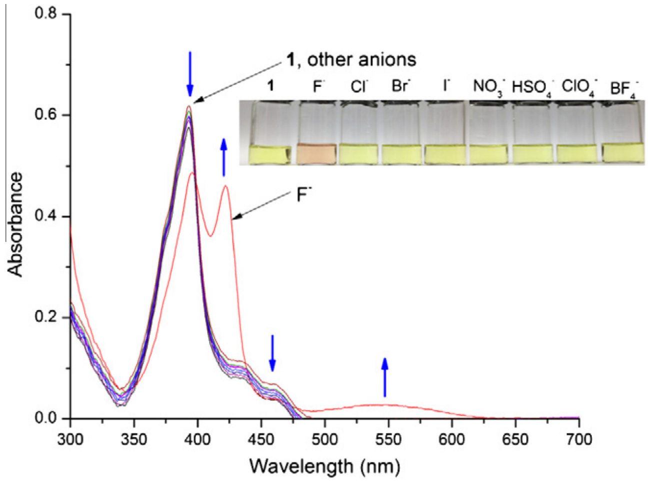

Figure 2. Changes in the UV–Vis spectra of **1** (2×10^{-5} M) in CH_3CN upon addition of 2 equiv of different anions as TBA salts. Inset: the corresponding color changes.

220 °C under an argon atmosphere for 12 h.[11] The novel compound **1** was fully characterized by MALDI-TOF and HR-TOF, and ^1H NMR, ^{19}F NMR and FT-IR spectroscopy (see Fig. S1–S5, Supplementary data).

Needle-like single crystals of compound **1**, which were suitable for single-crystal X-ray diffraction, were obtained in DMSO. As shown in Figure 1a, the single crystal structure (CCDC number: 922629, ORTEP plot see Fig. S10, Supplementary data) analysis indicated that the 2,3,4,5-tetrafluorophenyl unit and 1*H*-imidazo[4,5-*b*]phenazine moiety were in the same plane, which demonstrates the existence of strong intramolecular hydrogen bonds. Figure 1b presents a packing diagram for compound **1**, which shows that it adopts interlayer face-to-face stacking with a neighboring interplanar distance of 3.38 Å, suggesting the existence of strong π–π stacking.[12]

As shown in the UV–Vis spectrum (Fig. 2), compound **1** has three UV–Vis absorption peaks at 392 nm (strongest), 438 nm, and 465 nm. The last two broad peaks might result from intramolecular charge transfer. The anion sensing properties of **1** were investigated by addition of different anions [all as tetrabutylammonium (TBA) salts] in CH_3CN. Figure 2 shows the changes in the UV–Vis spectra of **1** (2×10^{-5} M) in CH_3CN after adding 2 equiv of the anion. The inset shows the corresponding color response of compound **1** with eight different anions (Cl^-, Br^-, I^-, NO_3^-, HSO_4^-, ClO_4^-, BF_4^-, and F^-). Clearly, compound **1** showed no response to Cl^-, Br^-, I^-, NO_3^-, HSO_4^-, ClO_4^-, or BF_4^-. When F^- was added to the solution of **1**, the absorbance was red shifted, leading to a color change from yellow to red, which could be detected by the ‘naked-eye’.

Figure 3 shows the fluorescence spectra of **1** (2×10^{-5} M, excited at 392 nm) in CH_3CN with 2 equiv of various anions, and the inset shows the corresponding fluorescence changes under a UV lamp. On addition of F^- to a CH_3CN solution of **1**, the original emission at 512 nm was quenched, and a new emission centered at 637 nm appeared, which resulted in a change in the fluorescence from green to orange. In comparison, there was almost no fluorescence change on the addition of Cl^-, Br^-, I^-, NO_3^-, HSO_4^-, ClO_4^-, and BF_4^-. Analysis of the Job plot revealed that the binding stoichiometry between **1** and F^- was 1:1 in CH_3CN (Fig. S6, Supplementary data).[5b,13] Based on the changes in the UV–Vis and fluorescence spectra, compound **1** showed high sensitivity and selectivity for F^- over other anions, indicating that **1** represents a robust multi-response sensor for detecting F^-.

The interaction between **1** and F^- was further investigated through spectrophotometric titration methods by adding a standard solution of F^- to a CH_3CN solution of **1** (2×10^{-5} M). Figure 4 shows the UV–Vis spectral changes of **1** on treatment with F^-. Upon addition of 0.5 equiv of F^-, little change was observed. As the amount of F^- increased from 0.5 to 10 equiv, the initial maximum absorbance at 392 nm progressively decreased, and the band at 422 nm gradually increased. At the same time, the broad band in the range from 438 to 491 nm decreased and a new broad peak centered at 540 nm appeared, which indicated stronger intermolecular charge transfer between compound **1** and the F^- anions. The three well-defined isosbestic points demonstrated neat interconversion in the equilibria.[14] These results suggested that the interaction between **1** and F^- might be a combined process including hydrogen bond, deprotonation of the NH group, and anion–π interactions between **1** and F^-.[15] The inset to Figure 4 shows the near-linear correlation curves of **1** at 422 and 392 nm (vs fluoride equiv concentration in CH_3CN), which indicates the potential

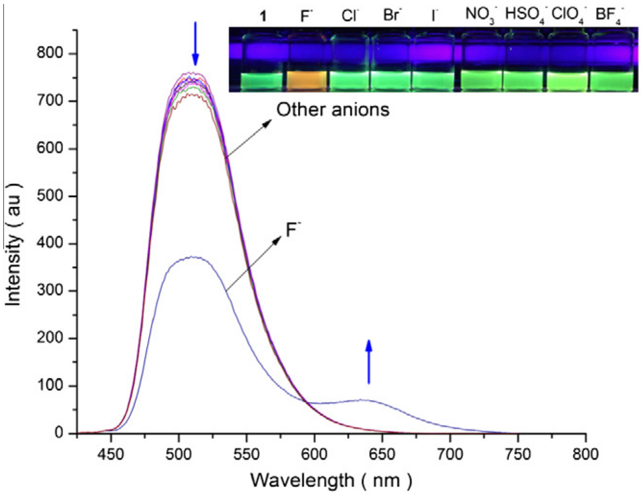

Figure 3. Changes in the fluorescence spectra of **1** (2×10^{-5} M) in CH_3CN upon addition of 2 equiv of different anions as TBA salts excited at 392 nm. Inset: the corresponding fluorescence changes under a UV lamp.

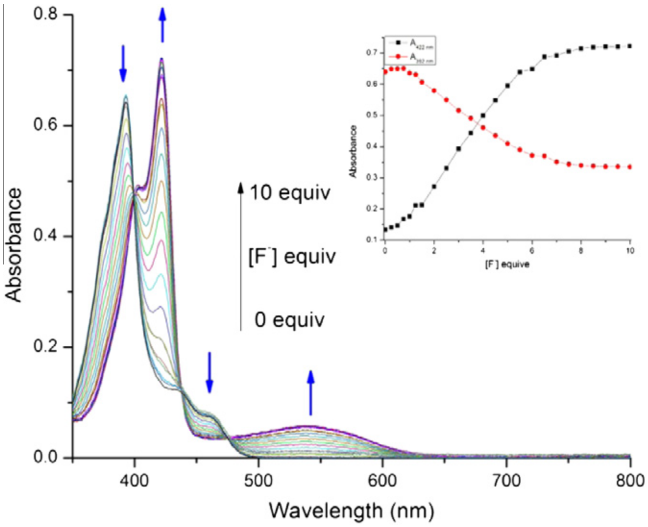

Figure 4. UV–Vis titration of **1** (2×10^{-5} M) with F^- (as the TBAF salt from 0 to 10 equiv) in CH_3CN. Inset: near-linear correlation curve of **1** monitored at 422 nm (black) and 392 nm (red) versus fluoride equiv concentration in CH_3CN.

utility of sensor **1** for calibrating and determining the F^- concentration in CH_3CN. The detection limitation was determined to be 8.6298×10^{-5} M under the experimental conditions using a reported method (Fig. S7, Supplementary data).[16] The overall association constant cannot be calculated because of the small absorbance changes upon addition of 0.5 equiv of F^-.[17]

The results of the fluorescence titrations of **1** with F^- are shown in Figure 5. The fluorescence spectra changed little upon the addition of 0.5 equiv of F^-. On further increasing the concentration of F^- (0.5–10 equiv), the original fluorescent emission peak at 512 nm decreased progressively and a new fluorescence emission centered at 637 nm appeared, that is, the same trend to that found for the UV–Vis changes. The inset shows the near-linear correlation curves of **1** at 512 and 637 nm (vs fluoride equiv concentration in CH_3CN), which demonstrated the potential utility of compound **1** for quantitative determination of F^- in CH_3CN.

Next, we examined whether compound **1** could retain its sensing properties for F^- in the presence of potential competing anions. Thus, **1** was treated with F^- in the presence of Cl^-, Br^-, I^-, NO_3^-, HSO_4^-, BF_4^-, ClO_4^-, and BF_4^- in CH_3CN, respectively. As displayed in Figures S8 and S9 (Supplementary data), all the tested competing anions had virtually no influence on the response of **1** to the detection of F^-. Thus, compound **1** shows potential to be useful for selectively sensing F^- in the presence of competing anions.

The mechanism of the interaction between compound **1** and F^- was further studied by ^{1}H NMR titration experiments. Figure 6 shows the F^- titration ^{1}H NMR spectra of **1** in d_6-DMSO. Clearly, even on addition of only 0.1 equiv of F^-, the proton of the NH group disappeared immediately, which may suggest rapid binding between the NH groups and F^-. With the addition of a further amount of F^-, the protons of the phenazine rings were shifted upfield significantly, which indicates the increase of electron density on the conjugated imidazo[4,5-*b*]phenazine unit, suggesting: (1) deprotonation of the NH group, and (2) F^-–π interactions. At the same time, a downfield shift of H1 was observed, indicating that the electron density of the tetrafluorophenyl group had changed. This phenomenon can be explained by the fact that deprotonation of the NH group prevented intramolecular hydrogen bonding between the tetrafluorophenyl group and the imidazo[4,5-*b*]phenazine unit, leading to the interruption of the coplanar structure. These results corresponded with the spectrophotometric titration results and further suggested that the mechanism of the F^- sensing process was a combination of hydrogen bond, deprotonation of the NH group, and anion–π interactions.

In summary, we have designed and synthesized novel heteroacene **1** as a multi-response sensor for F^- detection with high sensitivity and selectivity. Upon addition of F^-, **1** showed an obvious color change from yellow to red and a change in fluorescence from green to orange on excitation at 392 nm through combined hydrogen bonding, deprotonation, and anion–π interactions. Importantly, the obvious color and fluorescence change of **1** was also observed in the presence of other competing anions. Our strategy should be helpful to develop new multiple response sensors for F^- detection.

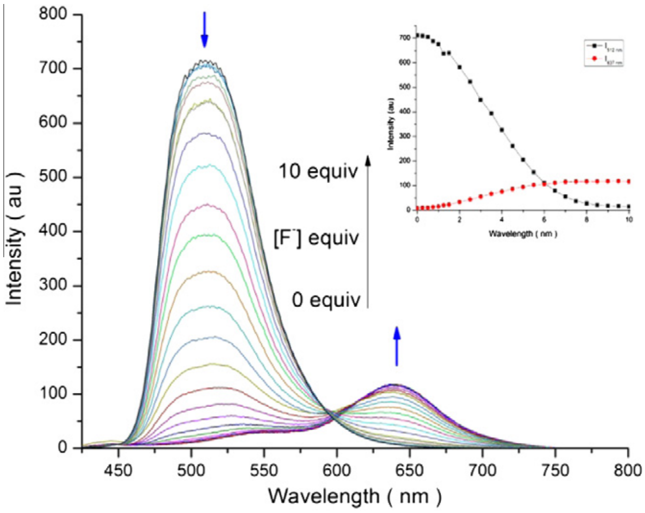

Figure 5. Fluorescence titration of **1** (2×10^{-5} M) with F^- (as the TBAF salt from 0 to 10 equiv) in CH_3CN excited at 392 nm. Inset: near-linear correlation curve of **1** monitored at 512 nm (black) and 637 nm (red) versus fluoride equiv concentration in CH_3CN excited at 392 nm.

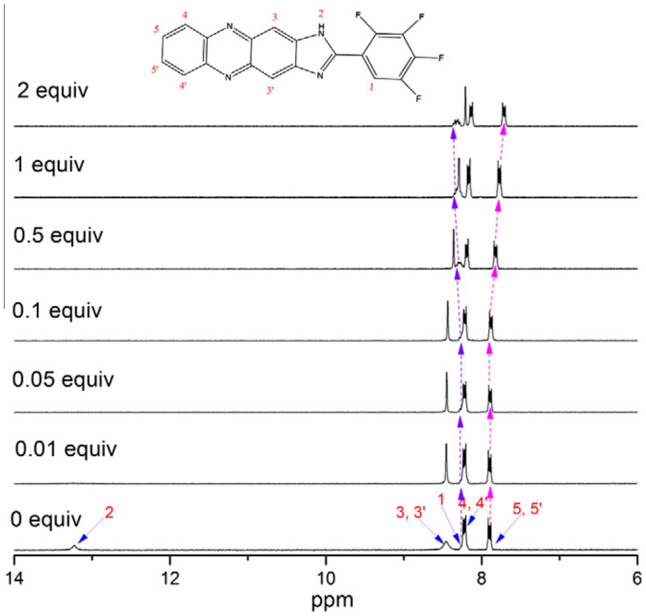

Figure 6. ^{1}H NMR (300 MHz) titration of **1** with F^- (as the TBAF salt from 0 to 2 equiv) in d_6-DMSO.

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Supplementary data

Supplementary data (experimental data, crystallographic data, and the X-ray CIF file for **1** and MALDI-TOF, HR-TOF, NMR, and FT-IR of **1**) associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.tetlet.2013.03.030.

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