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A sensitive fluorescent chemosensor for anions based on a styryl–boradiazaindacene framework

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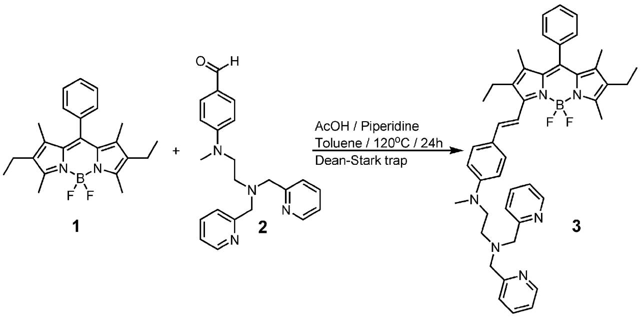
Abstract—Long wavelength emitting, extended conjugation boradiazaindacenes are novel dyes with considerable ICT character. By appending a dipicolylaminylethylamine group, the parent compound was transformed into a fluorescent dye with a strong chelating ability for Zn(II) ions. The zinc complex which has bright orange fluorescence, reversibly signals anions with very large changes in both the absorption and the emission spectra. The remarkable change in the emission intensity is explained in relation to the electron donating capacity of the substituent on the styryl functionality.

Fluorescent chemosensor design for anions is a challenging field in supramolecular chemistry.[1] The challenge at least in part, stems from the highly diverse three dimensional structures of the anions. Thus, shape complementarity between the receptor and the anion can be an important parameter. An alternative scheme, which is based on a receptor providing a metal for the chelation of a multi-dentate anion has been utilized in recent years.[2] The phosphate ion is an appropriate target in such an approach and it also happens to be an important target, due to its biological relevance and role in environmental pollution.[3]

We have been interested in introducing and/or developing novel red emitting chemosensors.[4] In recent years, it became apparent that a particular class of fluorescent compounds known as boradiazaindacenes or BODIPY dyes were highly amenable to chemical modification[5] resulting in dyes with significantly longer wavelength emission[5e,h] than the parent dyes or those modified at the 8-position. Our group has demonstrated that the dyes with 3- and/or 5-methyl substituents can be condensed with aldehydes to yield red emitting fluorophores.[5e,h] This finding was built upon earlier reports in the patent[6] and the primary literature.[7] When both methyl groups were involved in the condensation reaction, the resulting dye had absorption peaks around 650–670 nm. In addition, such boradiazaindacenes retain their typical BODIPY characteristics, namely large extinction coefficients and high quantum yields. Working at the red end of the visible spectrum has well-known advantages, such as much lower background signal and reduced scattering.



For an effective chemosensor for phosphate anions working at the red end of the visible spectrum, we targeted compound **3**. This compound is expected to behave as an internal charge transfer (ICT) dye, and its metal complex should be sensitive to different phosphate concentrations. The synthesis of chemosensor **3** was quite straightforward. First, the parent dye **1** was prepared following literature procedures, that is, by reaction between benzoyl chloride and 2,4-dimethyl-3-ethylpyrrole in dichloromethane and then by treating the dipyrrine intermediate, without isolation or purification with attempt, with Et_3N and $BF_3{\cdot}OEt_2$. The resulting aldehyde **2** was synthesized by analogy to the literature and carries a dipicolylaminylethylamine

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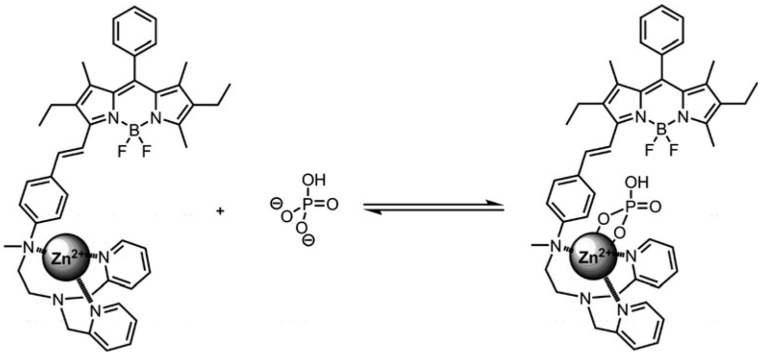

Figure 1. Proposed anion coordination of the **3**–Zn(II) complex resulting in the fluorescence signal.

functionality which is known to be selective for Zn(II) ions.[8] Boradiazaindacene **1** and aldehyde **2** were condensed in the presence of acetic acid and piperidine with concomitant removal of water to yield styryl dye **3**. The product was purified by silica gel column chromatography (95:5, $CHCl_3$–MeOH) with an isolated yield of 30%. Satisfactory analytical data were obtained for compound **3** (see Fig. 1).[9]

Compound **3** had an absorbance peak at 615 nm and a broad emission peak at 660 nm ($\Phi = 0.08$ in acetonitrile, quantum yields were determined using Rhodamine 6G as reference). The extinction coefficient at the absorption maximum was 78,000 $M^{-1}\,cm^{-1}$. In accordance with the literature, the ligand shows the greatest affinity towards Zn(II) ions. Addition of 5 μM Zn(II) to the chemosensor **3** caused a 40 nm hypsochromic shift, and the resulting zinc complex had an absorbance peak at 576 nm (Fig. 2).

The zinc complex of the chemosensor demonstrated a sharp emission peak at 590 nm with a quantum yield of 0.39. The observed blue shift in the emission and the absorbance spectrum upon zinc(II) binding is in agreement with the ICT nature of the fluorophore **3**. Apparently, Zn(II) ions remove electron density from the arylamine group, thus stabilizing the ground state and destabilizing the excited state, thus leading to widening of the HOMO–LUMO gap. When anions were added to a solution of the **3**–Zn(II) complex, those which can effectively chelate to the Zn(II) center should reduce the magnitude of the electron withdrawal by the metal center via partial neutralization of the charge on the metal ion. As we reported earlier,[4c] most anionic species do not form strong enough complexes to remove the Zn(II) ions. To explore the anion selectivity of the **3**–Zn(II) complex, we carried out titration experiments using tetrabutylammonium salts of F^-, Cl^-, Br^-, I^-, CH_3COO^-, PO_4^{3-}, NO_3^-, and HSO_4^-. As expected from the Hofmeister series, among the anions tested, phosphate, acetate and fluoride showed the highest affinity towards the zinc complex of chemosensor **3**. Addition of phosphate anions caused a spectacular change in the emission characteristics. Titration with phosphate quenched the fluorescence, with a 70-fold change in the peak emission intensity. At saturation, it was evident

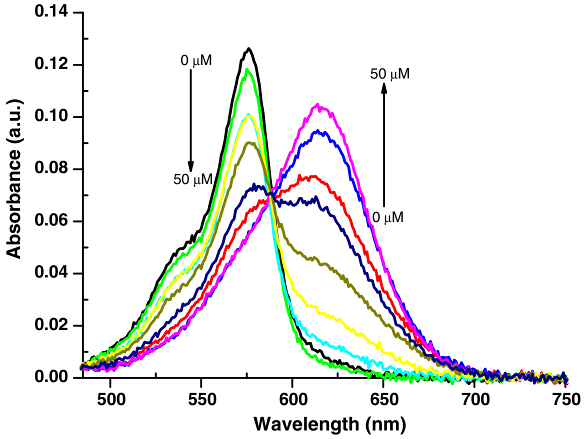

Figure 2. Absorbance spectra of the **3**–Zn(II) complex at increasing phosphate anion concentrations. Measurements were recorded in acetonitrile at 1.35 μM dye concentration. 5 μM of Zn(II) ions was added in the form of perchlorate salt. Phosphate concentrations were 0, 2.5, 5.0, 7.5, 10, 20, 30, 40, and 50 μM, with tetrabutylammonium as the counter-ion.

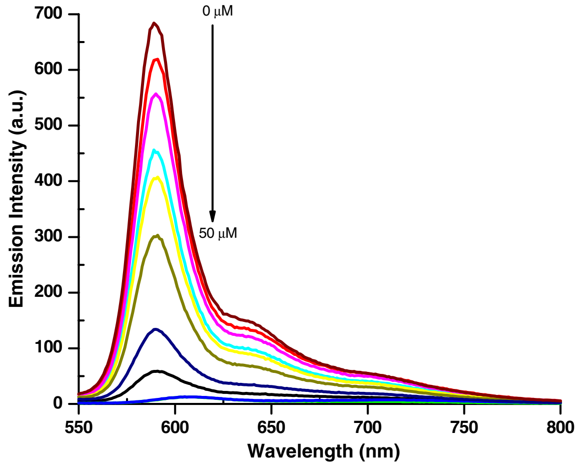

Figure 3. Emission spectra of the Zn(II) complex at increasing phosphate anion concentrations were obtained by excitation at 535 nm at 25 °C. Slit widths 5 nm. Measurements were recorded in acetonitrile at 1.35 μM dye concentration. 5 μM of Zn(II) ions was added in the form of perchlorate salt. Phosphate concentrations were 0, 2.5, 5.0, 7.5, 10, 20, 30, 40, and 50 μM, with tetrabutylammonium as the counter-ion.

that the original red-shifted and weaker emission of the chemosensor **3**–Zn(II) complex was restored. Benesi-Hildebrand analysis of the binding data revealed strong association constants; $4.1 \times 10^4\ M^{-1}$ for phosphate ions, and almost identical values for acetate and fluoride (4.6×10^4 and $4.2 \times 10^4\ M^{-1}$, respectively). These results are in agreement with a previous report.[4c] An attempt was made to investigate sensing ability in aqueous solution, however, even small amounts of water resulted in quenching of the emission, most likely due to the formation of dye aggregates (see Fig. 3).

Thus, we have reported an excitation ratiometric fluorescent chemosensor, which signals anion concentrations at the red end of the visible spectrum. The changes in both the absorbance and the emission spectra of the Zn(II)–**3** complex in the presence of phosphate anions are especially promising. In addition, this approach can easily be extended to aqueous media with appropriate structural modifications. Work towards these ends is in progress.

Acknowledgments

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9. *Analytical data for compound* **3**: ^{1}H NMR ($CDCl_3$, 400 MHz, 298 K) δ; 8.45 (d, 2H, $J = 4.5$ Hz), 7.61–7.06 (m, 15H), 6.51 (d, 2H, $J = 8.5$ Hz), 3.84 (s, 4H), 3.45 (t, 2H, $J = 6.8$ Hz), 2.83 (s, 3H), 2.73 (t, 2H, $J = 6.8$ Hz), 2.55–2.45 (m, 5H), 2.26 (q, 2H, $J = 7.5$ Hz), 1.23 (s, 3H), 1.21 (s, 3H), 1.07 (t, 3H, $J = 7.5$ Hz), 0.92 (t, 3H, $J = 7.5$ Hz). ^{13}C NMR ($CDCl_3$, 100 MHz, 298 K) 156.2, 153.2, 148.7, 137.7, 137.4, 136.6, 136.2, 135.2, 134.7, 132.1, 131.8, 131.0, 130.5, 128.0, 127.9, 127.6, 125.3, 124.1, 120.9, 115.6, 114.9, 111.7, 65.2, 57.6, 50.4, 30.4, 17.4, 16.3, 13.6, 13.0, 11.6, 10.6, 10.3. MS (EI) *m*/*e* 722.4 (M^+). Elemental analysis: Found: C, 74.63; H, 6.89; N, 11.39. $C_{45}H_{49}BF_2N_6$ requires C, 74.78; H, 6.83; N, 11.63.