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Novel fluorescent chemosensor for anions via modulation of oxidative PET: a remarkable 25-fold enhancement of emission

Ali Coskun, Bilge T. Baytekin and Engin U. Akkaya*

Department of Chemistry, Middle East Technical University, TR-06531, Ankara, Turkey

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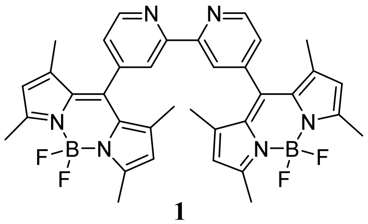
Abstract—The fluorescence emission intensity of the 1:1 Zn(II) complex of a doubly boradiazaindacene (BODIPY) substituted bipyridyl ligand is highly sensitive to anion coordination to the metal center. Oxidative PET, which is responsible for the quenching of the fluorescence in the complex is effectively inhibited by anion coordination, leading to a 25-fold enhancement of the emission intensity.

Effective signalling of anions remains to be a challenging target[1] of chemosensor designs. Anions in general, play important roles in biological processes and anomalies in regulation and intake of certain anions are implicated in disease states. Moreover, anions like phosphate, arsenate, technetate, etc., are important pollutants and selective recognition and/or signalling of these species is of prime importance. The progress in the field has been reviewed recently.[2] Fluorescence signalling is preferable considering a multitude of practical issues, including sensitivity and inherent selectivity.

As part of our research program[3] in exploring photophysical phenomena for fluorescent chemosensor[4,5] applications, we recently reported[3d] a bis-BODIPY(4,4-difluoro-4-bora-3a,4a-diaza-*s*-indacene)-substituted bipyridyl ligand **1**. The ligand has a very high quantum yield in organic solvents (in acetonitrile, $\phi_f = 0.39$), but metal chelation quenches the fluorescence. One of the most effective quenchers of the fluorescence of compound **1** is Zn(II), thus eliminating the possibility of a simple paramagnetic/HTM related quenching. In fact, we proposed that the quenching was due to oxidative[6] photoinduced electron transfer (PET); from the excited BODIPY units to the metal complexed bipyridyl group. Thermodynamic feasibility of this process depends on the availability of lower energy LUMO orbital in the electron deficient "acceptor" part of the molecular system. Metal ion complexation apparently lowers the LUMO energy of the bipyridyl unit at least just enough to allow such an oxidative electron transfer from the excited fluorophore, resulting an effective quenching. Considering the magnitude and effectiveness of this quenching, we explored processes which could restore the BODIPY emission, thereby signalling the causative analyte. There have been recent examples[7] of target analytes chelating to a metal complex and thus signalling the analyte anion concentration. However, the observed effects are only incremental changes in emission intensity. We reasoned that total restoration of the BODIPY emission should be possible with simple chelating anions such as phosphate and acetate.



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The synthesis of **1** has been reported earlier.[3d] To explore the anion response of the metal complex, we have prepared a solution of the complex in acetonitile. To a 2.3×10^{-7} M solution of the ligand, was added 0.1 mM Zn(II) in the form of a perchlorate salt. Given the stoichiometry and the association constant with Zn(II),[3d] it was estimated that more than 99% of the ligand is metal-bound. The metal complex was then titrated with tetrabutylammonium salts; F^-, Cl^-, Br^-, SO_4^{2-}, HPO_4^{2-} and acetate. Among these anions, fluoride, phosphate and acetate displayed the strongest binding effects. The reversible chelation of the anions to the metal center is electrostatic in nature with very little coordination complex character. This is of course

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* Corresponding author. Tel.: +90-312-210-5126; fax: +90-312-210-1280; e-mail: akkayaeu@metu.edu.tr

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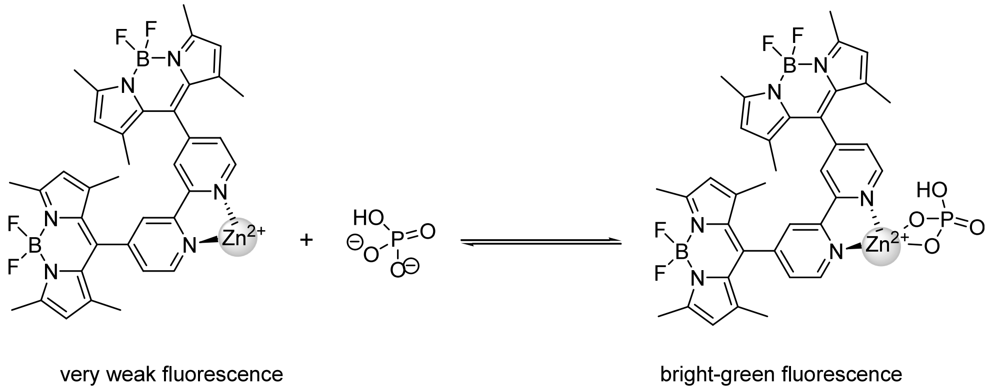

desirable for the signalling of analytes in dynamic systems. As expected, neither the zinc complexation nor the added anion caused a change in the absorption spectrum. The effect of phosphate binding on the emission spectrum is shown in Figure 1. There is a remarkable and to best of our knowledge, unprecedented 25-fold enhancement of the emission intensity at 518 nm on phosphate binding. The fluorescent enhancement factor (FEF) is comparable for all anions at saturation, except for sulfate and fluoride. Sulfate, in agreement with earlier findings,[7c] does not induce any change in the emission intensity. Fluoride, surprisingly, causes a decrease in the emission intensity at the high end of the concentration range studied. Apparent dissociation constants (K_d) were determined by plotting the emission values against the concentration of anions and fitted to the following equation, $F=(F_o+F_{max}[A]/K_d)/(1+[A]/K_d)$, where F_o is the initial F value for the zinc complex in the absence of anions, F_{max} is the maximum F value and [A] is the anion concentration. The dissociation constants (K_d) determined this way were as follows: acetate 0.21 mM; phosphate 0.25 mM; fluoride 0.24 mM; chloride 0.31 mM and bromide 0.40 mM.

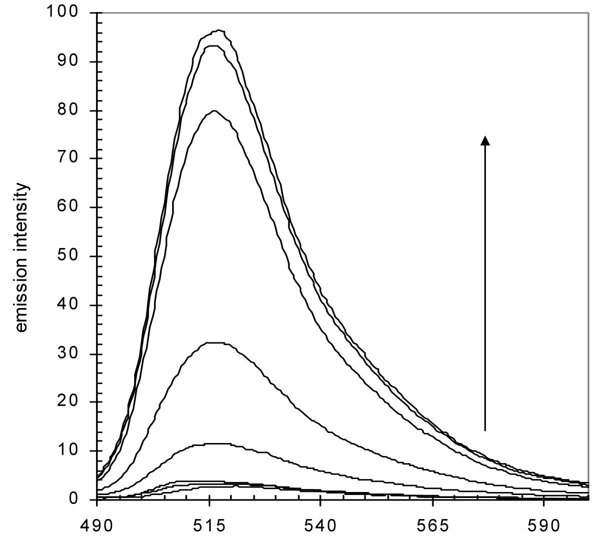

Figure 1. Emission spectrum of the Zn(II) complex in response to increasing phosphate concentrations. Excitation wavelength was 490 nm, both slit widths were set at 5 nm. The acetonitrile solution was 2.3×10^{-7} M in BODIPY **1** and 0.1 mM in $ZnClO_4$. The concentration of tetrabutylammonium hydrogen phosphate was varied from 0 to 2.5×10^{-3} M.

In this novel anion sensing system the enhancement of emission is truly spectacular. BODIPY–Zn(II) complex solution of no visually discernable fluorescence emission becomes bright green fluorescent on the addition of less than one millimolar phosphate. Unlike many other anion sensing systems where only a few-fold change in emission intensity is the norm, here, even in relatively polar acetonitrile solution, a remarkable change is observed. Quantum yields vary between less than 0.002 to 0.39. The origin of this enhancement is the inhibition of oxidative PET. The added anions are not strong chelators that could remove the complexed Zn(II), but through simple electrostatic interactions they can, at least partially, neutralize the charge on the metal center. Thus, the otherwise favorable oxidative PET process becomes thermodynamically unfavorable, hence the full emission intensity of the boradiazaindacene fluorophore is restored. We believe by appropriate selection of the chelator units (i.e.; stronger metal binding ligands) tethered to the fluorophore, this approach can be extended to polar and more competitive media such as water. Work to this end is in progress in our laboratory.

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