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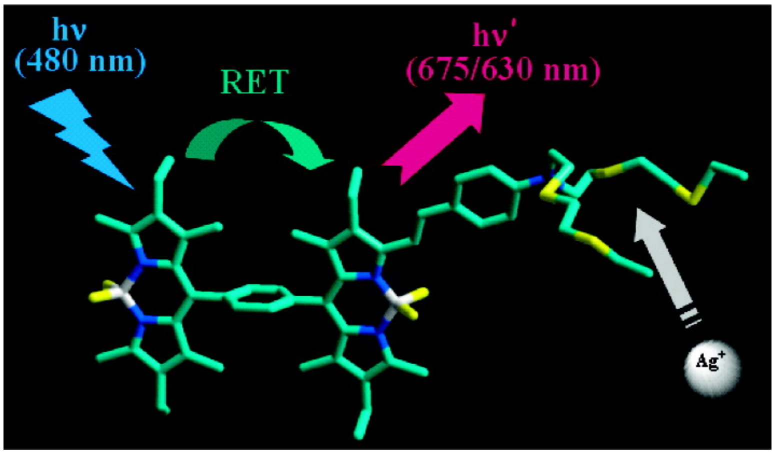

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Ion Sensing Coupled to Resonance Energy Transfer: A Highly Selective and Sensitive Ratiometric Fluorescent Chemosensor for Ag(I) by a Modular Approach

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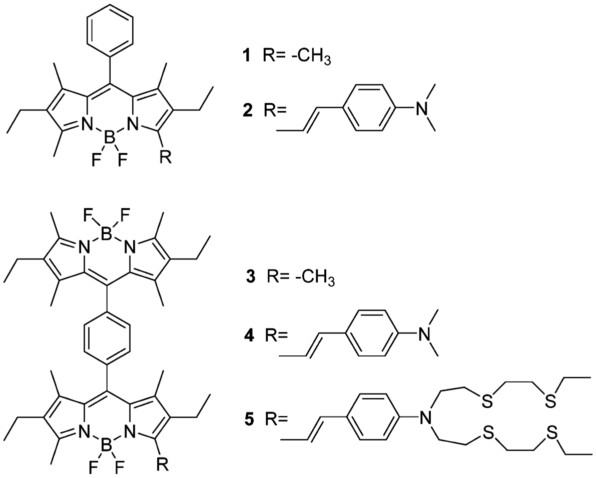
Design and synthesis of fluorescent chemosensors with desirable properties is a vibrant field of supramolecular chemistry.[1] Especially, chemosensors targeting heavy and transition metal cations are very important due to the environmental and biological relevance of such metal ions.[2] Fluorescence sensing of cations, such as Hg(II), Pb(II), Ag(I), and Cu(II), is particularly challenging since these ions generally act as quenchers via the electron transfer and facilitated intersystem crossing (isc) processes. A number of satisfactory chemosensors for these ions have been reported.[3] Most of them display fluorescence intensity changes, but only very few of them result in spectral shifts in either absorption or emission spectra. This would be a highly desirable property as such spectral changes would allow wavelength ratiometric analyses, canceling likely artifacts due to concentration variations in the analysis media.

Boradiazaindacenes (borondipyrromethenes, BODIPYs, BDPs) are very bright fluorophores with high quantum yields and large extinction coefficients. Structural modifications of these compounds are known to generate dyes with emission peaks spanning part of the visible spectrum from green to the red end.[4] A number of fluorescent chemosensors were reported based on modified boradiazaindacene dyes.[5] Recently, a very interesting modification converting a standard green emitting dye to a longer wavelength absorbing and red emitting ICT dye was reported.[6] It was also demonstrated that the emission properties can be switched on upon acid addition, opening possibilities for further interesting cation sensing applications with judiciously designed chemosensors.

To this end, we designed a modular chemosensor composed of two fluorophores and a selective ligand. The design allows a facile attachment and derivatization of boradiazaindacene fluorophores geared for efficient energy transfer and modulation of the emission signal. Thus, we synthesized compound **3** by the reaction of terephthaloyl chloride with 3-ethyl-2,4-dimethylpyrrole, following established procedures. Energy minimized (MM+, Hyperchem v. 7.5) structure of this compound shows two coplanar boradiazaindacene units with a nearly perpendicular 1,4-phenylene ring as a spacer. Methyl groups on the pyrrole units ensure the perpendicular orientation. Absorption spectrum of **3** (see Supporting Information) correlates well with two noninteracting chromophores with no evidence of excitonic interactions. The methyl groups neighboring the BF_2 bridge are slightly acidic, and this property was exploited in the synthesis of compounds **4** and **5**. The condensation reactions between compound **3** and corresponding aldehydes were carried out in toluene, with azeotropic removal of water. Slight modifications in the literature procedure resulted in improved yields, facilitating the synthesis of our target compounds and also accentuating the modularity of our approach.

The absorption spectra of compounds **4** and **5** (Supporting Information) as expected show two distinct peaks centered near 500 and 600 nm. The shorter wavelength absorption corresponds to the unmodified boradiazaindacene unit, whereas the other corresponds to the absorption of extended conjugation ICT chromophore within the same molecule. A comparison of the emission spectra of compounds **1**−**5** (Figure 1) with equal absorbance values at the excitation wavelength (480 nm) for compounds **1** and **3**−**5** was made. For compound **2**, since there is no absorption peak in that region, a comparable concentration of the dye (1.4 μM) was used. The dimeric dye **3** and the monomeric reference compound **1** showed comparable quantum yields (0.73 and 0.76, respectively) with a slight red shift in the emission spectrum of **3**. Most interesting results were obtained on excitation of dyes **2**, **4**, and **5** at 480 nm. Compound **2**, as expected, displays only a very weak and broad emission peak around 680 nm. This is due to very weak absorption of this dye at the excitation wavelength.



However, compounds **4** and **5**, when excited at the same wavelength, show only very weak residual emissions near 550 nm, corresponding to a remarkably decreased quantum yield of this fluorophore from 0.76 in compound **1** to 1.3×10^{-3} in **4** and 4.1×10^{-3} in **5**. However, as a result of the excitation energy transfer, strong emission peaks centered around 700 and 680 nm, respectively, were obtained from the red emitting dye. Highly diminished emission from the green emitting boradiazaindacene dye clearly demonstrates the efficiency of energy transfer (near 100%) from this dye to the red emitting extended conjugation boradiazaindacene derivative. This result encouraged us in developing this system further by attaching a selective soft metal binding ligand. The ligand we chose for further modification of the dimeric dye, *N*-phenyl-9-aza-3,6,12,15-tetrathiaheptadecane, is reportedly a highly selective ligand for Ag(I).[7] Absorption spectra of compound **5** in response to changing Ag(I) concentrations are shown in Figure 2. The binding of Ag(I), in accordance with our design expectations, resulted in a blue shift of the long wavelength peak, which corresponds to the modified boradiazaindacene dye, whereas no significant change takes place in the absorption peak corresponding to the unmodified

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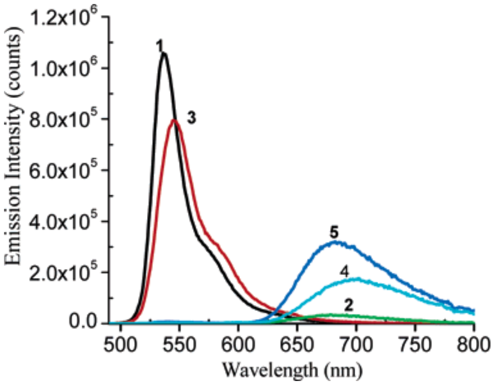

Figure 1. Emission spectra of compounds **1**−**5** in THF. Excitation was at 480 nm with 5 nm slit widths.

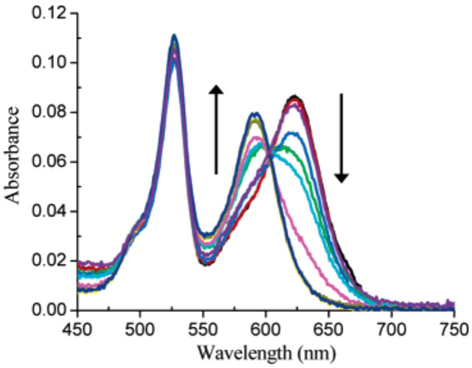

Figure 2. Absorption spectra of compound **5** in the presence of increasing Ag(I) concentrations (0, 0.5, 0.75, 1.0, 1.5, 2.0, 2.5, 4.0, 5.0, 7.5, 10 μM). The concentration of the chemosensor was 1.4 μM.

dye. This creates multiple opportunities for ratiometric cation analysis. Excitation can be done either at the unmodified boradiazaindacene absorption or at any one of the longer wavelength peaks corresponding to the free and metal-bound form of the chemosensor. To take advantage of larger pseudo-Stokes' shift generated by resonance energy transfer, we chose to excite the dye close to the absorption peak of the unmodified boradiazaindacene unit. The emission spectra obtained by excitation at 480 nm demonstrate that we have a very efficient emission ratiometric chemosensor working in the long wavelength end of the visible spectrum (Figure 3). Ag(I) binding causes a 41 nm hypsochromic shift. Remarkably, all the other metal ions studied caused only insignificant changes in the emission spectrum, not enough for an accurate assessment of the binding constant. It is also remarkable that cations, such as Pb(II), Mn(II), Fe(II), Hg(II), and Co(II), have practically no effect on the emission spectrum, although they are known to be effective HTM (heavy or transition metal) quenchers. As a ratiometric chemosensor, compound **5** is outstanding; emission ratio of intensities at 630 and 671 nm (I_{630}/I_{671}) changes from 0.25 to 1.42 for the free and Ag(I)-bound chemosensor, respectively. The binding constant of silver in THF was determined to be 1.7×10^5 M^{-1}.

In summary, we have introduced a general strategy for large pseudo-Stokes' shift, ratiometric chemosensors, utilizing efficient energy transfer. Yet, the synthesis is highly straightforward due to the symmetry of the first precursor. In just one step, this symmetric precursor can be transformed into an efficient RET system, where the choice of the ligand carrying aldehyde would also determine the selectivity of the resulting chemosensor. Considering the multitude of choices in ligand selection and the large number of energy transfer casettes operating in aqueous solutions, we are confident that this powerful approach can be extended to polar protic solvents, including water, to yield a new class of chemosensors with practical applications in many sensing fields. Our work toward these ends is in progress.

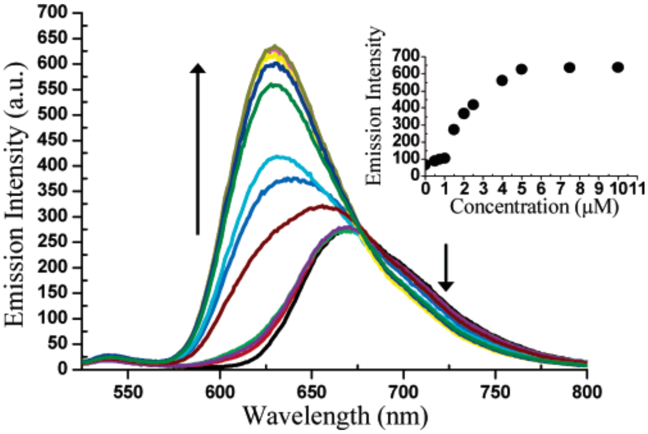

Figure 3. Emission spectra of compound **5** at increasing concentration of Ag(I) (0, 0.5, 0.75, 1.0, 1.5, 2.0, 2.5, 4.0, 5.0, 7.5, 10 μM). Inset: emission change at 630 nm with increasing concentrations of Ag(I). Excitation wavelength was 480 nm with 5 nm slit widths, and spectra were corrected. The concentration of the chemosensor **5** was 1.4 μM.

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Supporting Information Available: Syntheses, experimental details, ^{1}H, ^{13}C NMR spectra, and additional spectroscopic data. This material is available free of charge via the Internet at http://pubs.acs.org.

References

(1) (a) Czarnik, A. W. *Chem. Biol.* **1995**, *2*, 423−428. (b) *Chemosensors of Ion and Molecule Recognition*; Desvergne, J. P., Czarnik, A. W., Eds.; NATO ASI Series C492, 1997. (b) *Molecular Fluorescence*; Valeur, B., Ed.; Wiley-VCH: Weinheim, Germany, 2002. (c) de Silva, A. P.; Gunaratne, H. Q. N.; Gunnlaugsson, T.; Huxley, A. J. M.; McCoy, C. P.; Rademacher, J. T.; Rice, T. E. *Chem. Rev.* **1997**, *97*, 1515−1566. (d) de Silva, A. P.; Fox, D. B.; Huxley, A. J. M. *Coord. Chem. Rev.* **2000**, *205*, 41−57.

(2) (a) Trautwein, A. X. *Bioinorganic Chemistry*; Wiley-VCH: Weinheim, Germany, 1997. (b) Merian, E. *Metals and Their Compounds in the Enviroment*; VCH: Weinheim, Germany, 1991.

(3) Recent reviews: (a) Prodi, L.; Bolletta, F.; Montalti, M.; Zaccheroni, N. *Coord. Chem. Rev.* **2000**, *205*, 59−83. (b) Rurack, K. *Spectrochim. Acta A* **2001**, *57*, 2161−2195.

(4) *Handbook of Fluorescent Probes and Research Products*, 9th ed.; Haugland, R. P., Ed.; Molecular Probes, Inc.: Eugene, OR, 2003. BODIPY is a registered trademark of Molecular Probes, Inc.

(5) Recent examples: (a) Turfan, B.; Akkaya, E. U. *Org. Lett.* **2002**, *4*, 2857−2859. (b) Ulrich, G.; Ziessel, R. *J. Org. Chem.* **2004**, *69*, 2070−2083. (c) Gabe, Y.; Urano, Y.; Kikuchi, K.; Kojima, H.; Nagano, T. *J. Am. Chem. Soc.* **2004**, *126*, 3357−3367. (c) Rurack, K.; Kollmannsberger, M.; Resch-Genger, U.; Daub, J. *J. Am. Chem. Soc.* **2000**, *122*, 968−969.

(6) Rurack, K.; Kollmannsberger, M.; Daub, J. *Angew. Chem., Int. Ed.* **2001**, *40*, 385−387.

(7) (a) Ishikawa J.; Sakamoto, H.; Mizuno, T.; Otomo, M. *Bull. Chem. Soc. Jpn.* **1995**, *68*, 3071−3076. (b) Ishikawa, J.; Sakamoto, H.; Wada, H. *J. Chem. Soc., Perkin Trans. 2* **1999**, 1273−1279.

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