

# Ratiometry of monomer/excimer emissions of dipyranyl calix[4]arene in aqueous media

Hyun Jung Kim,<sup>a</sup> Duong Tuan Quang,<sup>a</sup> Jooyeon Hong,<sup>b</sup> Guipeun Kang,<sup>b</sup>  
 Sihyun Ham<sup>b,\*</sup> and Jong Seung Kim<sup>a,\*</sup>

<sup>a</sup>Department of Chemistry, Korea University, Seoul 136-701, Republic of Korea

<sup>b</sup>Department of Chemistry, Sookmyung Women's University, Seoul 140-742, Republic of Korea

Received 29 April 2007; revised 14 May 2007; accepted 17 May 2007

Available online 20 July 2007

**Abstract**—Variations in the ratio of monomer/excimer emissions from pyrenyl groups bound to a calix[4]arene through facing carboxamidomethyl substituents have been investigated in H<sub>2</sub>O/CH<sub>3</sub>CN mixtures. Above a level of 50% H<sub>2</sub>O, monomer emission declines and the excimer emission concomitantly increases. DFT calculations support the argument that disruption of intramolecular NHO bonds by water results in a geometry, which favors contact of the pyrene units and thus a strong excimer emission. Addition of Fe(III) to a H<sub>2</sub>O/CH<sub>3</sub>CN (4:1, v/v) solution of **1** at pH 6.1 quenches both monomer and excimer emissions through electron transfer (eT) from excited pyrene to the metal ion. © 2007 Elsevier Ltd. All rights reserved.

## 1. Introduction

Calix[4]arene-based fluorogenic chemosensors are good candidates as cation and anion probes because of their high selectivity toward specific metal ions.<sup>1–4</sup> For such species, the sensing mechanisms include photoinduced electron/energy transfer (PET),<sup>5–7</sup> fluorescence resonance energy transfer (FRET),<sup>8</sup> photoinduced charge transfer (PCT),<sup>9</sup> and excimer/excimer formation.<sup>10</sup> Pyrene is an extremely useful fluorescent substituent because it can display not only a well-defined monomer emission at 370–430 nm but also an excimer emission at around 480 nm.<sup>11,12</sup> Where excimer formation is intramolecular, the ratio of excimer to monomer emission intensity, ( $I_E/I_M$ ), can be sensitive to conformational changes of the pyrene-appended receptors, and thus can be an informative parameter in regard to changes induced by metal ion binding.<sup>12,13</sup>

A variety of fluorescent probes based on molecules having a pyrene moiety as the basic signaling function have been reported.<sup>14,15</sup> Excimer emissions have been the basis of several molecular probes for alkaline earth metal ions,<sup>16</sup> Cu<sup>2+</sup> ion,<sup>17,18</sup> phosphate,<sup>6</sup> and of molecular logic circuits.<sup>19</sup> We recently found evidence that the ratio of monomer/excimer emissions from **1** depends on the extent of the intramolecular NHO-bonding between the pyrenyl amide group and a phenolic-O atom of the calixarene lower rim. We now report a study of the fluorescence changes of **1** in different mixtures

of H<sub>2</sub>O/CH<sub>3</sub>CN, which verifies that excimer formation is determined by this factor, a conclusion supported by DFT calculations. In addition, we report on the sensitivity of the fluorescence of **1** to Fe(III) ion (Fig. 1).

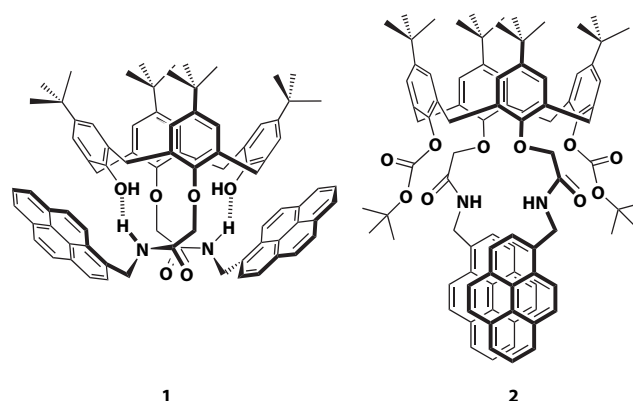
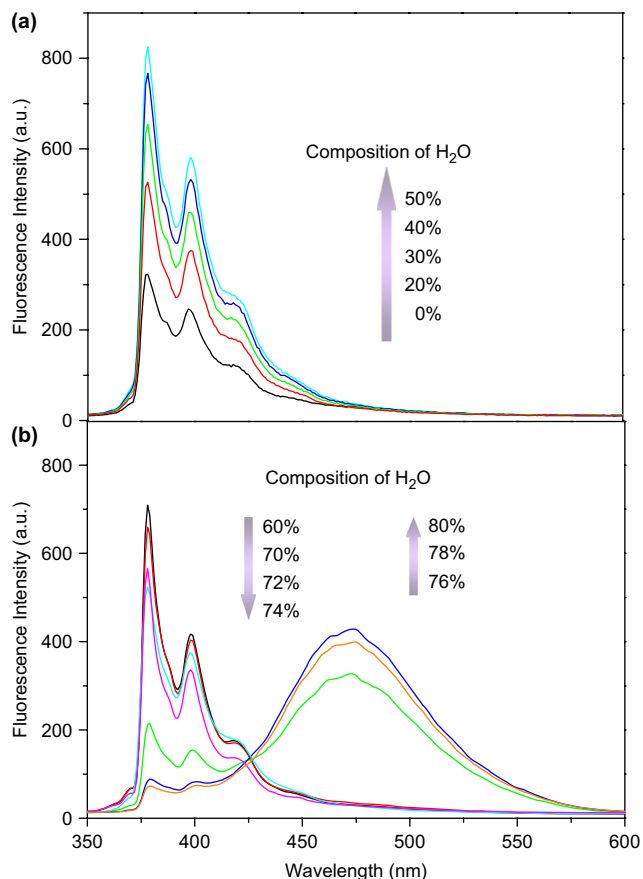


Figure 1. Structures of fluorescent chemosensors **1** and **2**.

## 2. Results and discussion

Previously, we demonstrated that free **1** in CH<sub>3</sub>CN exhibited only a monomer emission at around 398 nm without an excimer emission.<sup>20</sup> This is completely unlike the behavior of a very similar calix[4]arene derivative **2**,<sup>21</sup> which differs only in that the pyrene units are appended through ester and not amide groups. In this case, a strong intramolecular

\* Corresponding authors. E-mail addresses: sihyun@sookmyung.ac.kr; jongskim99@paran.com



**Figure 2.** Fluorescence spectra of **1** (5.0  $\mu$ M) in water/ $\text{CH}_3\text{CN}$  mixtures (pH 6.1,  $\lambda_{\text{exc}}=343$  nm).

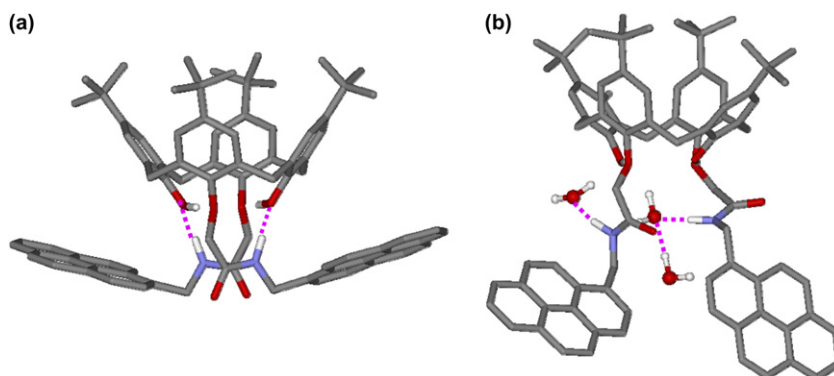
excimer band (along with weak monomer emission) is observed. The fluorescence behavior of **1** can be rationalized on the basis of its crystal structure.<sup>20</sup> This shows the formation of intramolecular H bonds between the phenolic OH groups and the amide H atoms, which are believed to preclude face-to-face  $\pi$ -stacking of the pyrene units and hence any excimer formation. Consistent with this, **2** contains no phenolic H-bond donors, so that it is possible that pyrene stacking is the dominant force.

To explore the influence of H-bonding interactions on the fluorescence of **1**, the emission spectrum was measured in various mixtures of water and acetonitrile (Fig. 2).

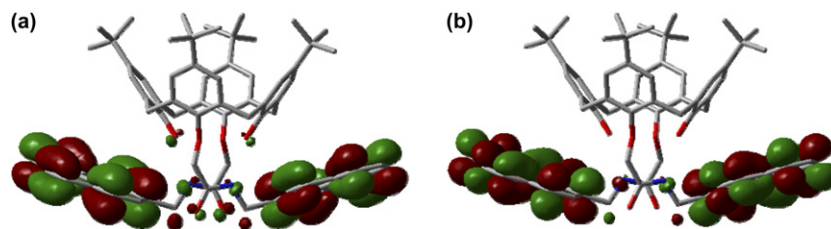
Excitation of free **1** at 343 nm produces only monomer emission at 398 nm in 100%  $\text{CH}_3\text{CN}$  and addition of water up to the point of 50% (v/v) composition leads to enhancement of this monomer emission. This we attribute to suppression of PET to the solvent, water being less reducible than acetonitrile. Interestingly, we found that further addition of water induces a weakening of the monomer emission and a simultaneous increase in excimer emission at 472 nm (Fig. 2b). This we attribute to an ultimate disruption of the intramolecular amide-NH $\cdots$ phenolic-O bond by the separate hydration of the two centers, which allows a new conformation to be adopted where the pyrene units can come into proximity and thus readily form an excimer.

To support this interpretation, we have performed calculations using density functional theory (DFT).<sup>22</sup> Ground state geometry optimization for the global minimum structure of free **1** in vacuo was executed using the B3LYP hybrid functional with a 3-21G basis set.<sup>23</sup> Several different starting geometries were used for the geometry optimization to ensure that the optimized structure corresponded to a global minimum. The lowest-energy structure at this level for free **1** was found to be a cone conformer. As shown in Figure 3a, two H bonds are found between the phenolic OH groups and the amide H atoms (1.70 Å) and two H bonds are between the hydrogens of OH groups and the phenolic oxygen (1.57 Å) in the lower rim. In total, four H bonds contribute to the stability of the cone conformer and the molecular shape is in good agreement with that found by X-ray crystallography.<sup>20</sup>

A time-dependent density functional theory (TDDFT) calculation<sup>24</sup> was executed to characterize the nature of the fluorescence behavior. The molecular orbital energies and the associated singlet–singlet electronic transitions were calculated from the optimized geometry of the  $S_0$  state by TDDFT/B3LYP/3-21G. Several studies have shown that hybrid functionals give the best performance for evaluating electronic transitions in organic molecules.<sup>25</sup> As well, we have recently reported electronic transition properties calculated by TDDFT in good agreement with experimental fluorescence spectra.<sup>4d</sup> From TD-B3LYP/3-21G calculations on free **1** in vacuo, the lowest-energy electronic transition involves the promotion of an electron from the HOMO to the LUMO (see Fig. 4) of each pyrene independently. No appreciable probability was found for a HOMO–LUMO excitation from one pyrene to the other pyrene (Py–Py\*)



**Figure 3.** Computed geometry for (a) free **1** in vacuo and (b) **1** with three water molecules.

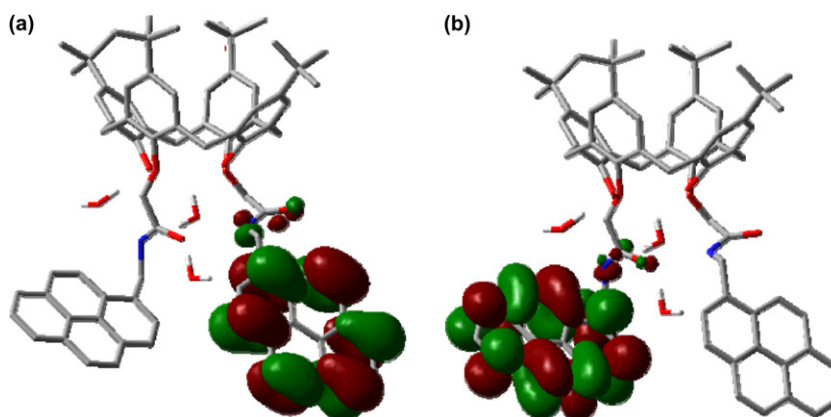


**Figure 4.** HOMO and LUMO for free **1** in vacuo computed at the TDDFT/B3LYP/3-21G level.

interaction), which would produce an excimer band. The conformation induced by the intramolecular H-bonding is thus unsuited to pyrene–pyrene interactions.

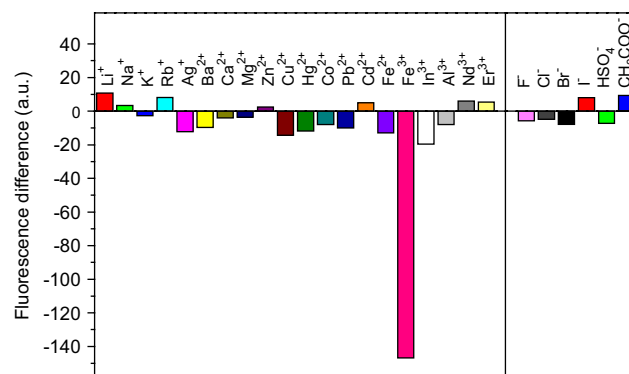
To understand the effect of water addition on the fluorescence spectra of **1**, we performed the DFT calculation for **1** in the presence of explicit water molecules. We placed up to six water molecules around the amide and the hydroxyl groups to allow potential H bonds between the host and solvent H<sub>2</sub>O. Based on the B3LYP/3-21G optimization, three distinct water molecules cause a marked conformational distortion by forming intermolecular H bonds with **1** and the remaining water molecules play a minor role in determining the overall geometry. Thus, we only show three water molecules in Figure 3b. Two water molecules form tight H bonds with two amide hydrogens (1.64 Å and 1.67 Å) and the third H<sub>2</sub>O causes a slight reorientation of one pyrene group. The tightly bound water molecules cause the two pyrenyl moieties to be more remote from the calixarene cavity but to become closer to one another. Calculations for the **1**·(H<sub>2</sub>O)<sub>3</sub> entity indicate delocalization of the LUMO over both pyrene units, consistent with excimer formation in the excited state (Fig. 5).

Based on excimer emission enhancement, we have tested the complexation ability of **1** toward metal cations (Li<sup>+</sup>, Na<sup>+</sup>, K<sup>+</sup>, Rb<sup>+</sup>, Ag<sup>+</sup>, Mg<sup>2+</sup>, Ca<sup>2+</sup>, Ba<sup>2+</sup>, Zn<sup>2+</sup>, Cd<sup>2+</sup>, Fe<sup>2+</sup>, Co<sup>2+</sup>, Cu<sup>2+</sup>, Pb<sup>2+</sup>, Hg<sup>2+</sup>, Al<sup>3+</sup>, Fe<sup>3+</sup>, Nd<sup>3+</sup>, Er<sup>3+</sup>, and In<sup>3+</sup>) in 1:4 (v/v) CH<sub>3</sub>CN/H<sub>2</sub>O at pH 6.1. Alone, **1** shows a characteristic monomer emission at 380 nm and a broad excimer emission centered at 480 nm. The fluorescence of **1** was found to show a remarkable selectivity for Fe<sup>3+</sup> ion, for which the excimer emission is quenched (Fig. 6). In anion tests using HSO<sub>4</sub><sup>-</sup>, CH<sub>3</sub>COO<sup>-</sup>, Br<sup>-</sup>, Cl<sup>-</sup>, F<sup>-</sup>, and I<sup>-</sup>, no changes of fluorescence were observed.



**Figure 5.** HOMO and LUMO for **1** with three water molecules computed at the TDDFT/B3LYP/3-21G level.

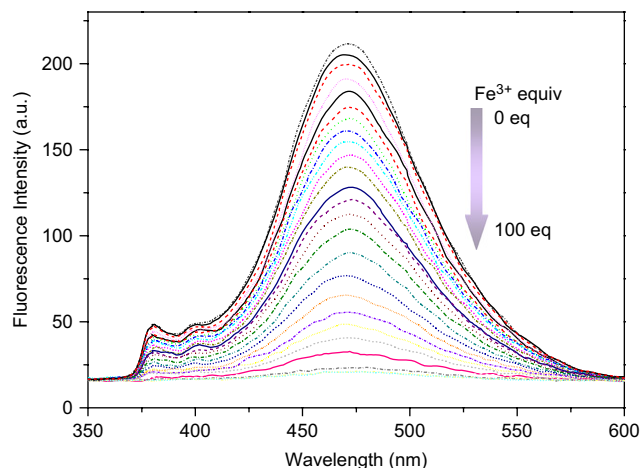
The fluorescence spectra ( $\lambda_{\text{exc}}=343$  nm) of **1** (2.5  $\mu\text{M}$ ) at pH 6.1 in the presence of various concentrations of Fe<sup>3+</sup> are shown in Figure 7. The fluorescence intensity ( $\lambda_{\text{em}}=372$  nm) of **1** continuously decreased upon addition of Fe<sup>3+</sup> without any wavelength change. From the change in excimer band intensity and a Job plot establishing 1:1 stoichiometry, we calculated an association constant value of  $K_a=2.5 \times 10^4 \text{ M}^{-1}$  for **1**·Fe<sup>3+</sup>. We attribute the excimer emission quenching by Fe(III) to be due to electron transfer from the excited pyrene dimer to the oxidizing metal ion, held in proximity by coordination to the amide-O donors.<sup>26</sup>



**Figure 6.** Fluorescence intensity changes of **1** in the presence of various metal ions in 1:4 (v/v) CH<sub>3</sub>CN/H<sub>2</sub>O at pH 6.1.

### 3. Conclusions

The dependence of the fluorescence from the bis(pyrenyl)-functionalized calix[4]arene **1** on the composition of the solvent in which it is dissolved illustrates the sensitivity of



**Figure 7.** Fluorescence spectra of **1** (2.5  $\mu\text{M}$ ) upon addition of  $\text{Fe}^{3+}$  in 1:4 (v/v)  $\text{CH}_3\text{CN}/\text{H}_2\text{O}$  at pH 6.1;  $\lambda_{\text{exc}}=343$  nm.

excimer formation to the molecular conformation. High-level computation indicates that, in the present case, this conformation is determined by H-bonding interactions, which can be converted from intramolecular to intermolecular by the addition of a sufficient quantity of water as an H-bond donor.

## 4. Experimental section

### 4.1. Synthesis

Compounds **1** and **2** were prepared following the literature procedures.<sup>20</sup>

### 4.2. General procedure for fluorescence studies

Fluorescence spectra were recorded with a RF-5301PC spectrofluorimeter. Stock solutions (1.00 mM) of metal perchlorate salts were prepared in  $\text{CH}_3\text{CN}$ . Stock solutions of free **1** (0.050 mM) were prepared in different mixtures of  $\text{CH}_3\text{CN}$  and water. Excitations were carried out at 343 nm with all excitation slit widths at 3 nm and emission slit widths at 1.5 nm. Titration experiments were performed with 2.5  $\mu\text{M}$  solutions of **1** in  $\text{CH}_3\text{CN}/\text{H}_2\text{O}=80:20$  and various concentrations of metal perchlorates in  $\text{CH}_3\text{CN}$ . From the calculated concentrations of the free ligands and complexed forms of **1** in the fluorescence titration experiments, association constants were obtained with the computer program ENZFITTER.<sup>27</sup>

### 4.3. Computational method

Geometry optimizations, vibrational analysis, and molecular orbital calculations were done using the Gaussian 03 package.<sup>28</sup> The geometry optimizations for **1** in vacuo and **1** with explicit water molecules were performed by density functional theory (DFT) with the hybrid functional B3LYP and the 3-21G basis set. Different starting geometries were used for optimization to obtain the global minimum structure for each system. Vibrational frequency analyses were performed to verify the identity of each stationary point as a minimum. The electronic vertical excitation energy and

the oscillator strength of the fluorescent spectra of **1** in vacuo and in explicit water molecules were determined by time-dependent density functional theory (TDDFT) using the same functional and basis set.

## Acknowledgements

This work was supported by the SRC Research centre for Women's Diseases of Sookmyung Women's University.

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