

A new Na⁺ sensor based on intramolecular fluorescence energy transfer derived from calix[4]arene

Takashi Jin

Section of Intelligent Materials and Devices, Research Institute for Electronic Science, Hokkaido University, Sapporo 060-0812, Japan. E-mail: jin@imd.es.hokudai.ac.jp

Received (in Liverpool, UK) 14th September 1999, Accepted 1st November 1999

A new calix[4]arene having pyrene (as a donor) and anthroyloxy (as an acceptor) moieties at the lower rim has been synthesized as a fluorescent Na⁺ sensor based on intramolecular energy transfer.

Calixarenes have been shown to be useful building blocks in the design of fluorescent ion sensors for detecting metal ions and anions.^{1–8} There are several designs of calixarene-based fluorescent ion sensor in which ion complexation can be monitored by intramolecular pyrene excimer formation,^{1,2} intramolecular fluorescence quenching³ and photoinduced electron transfer.^{6–8} The objective of this work is to apply fluorescence energy transfer to the metal ion sensing system based on calixarenes. An advantage of the metal ion sensing system using fluorescence energy transfer is that a variety of fluorophore pairs can be chosen for the design of fluorescent ion sensors. Herein we report a new Na⁺ sensor, based on intramolecular fluorescence energy transfer, derived from calix[4]arene.

Fluorescence energy transfer is the transfer of the excited state energy from a donor (d) to an acceptor (a). This transfer occurs as a result of transition dipole–dipole interactions between a d–a pair.⁹ Thus, if a d–a pair is introduced to the appropriate sites of ionophoric calixarenes,¹⁰ it is expected that the ion complexed by the calixarenes can be monitored by the change in the yield of fluorescence energy transfer between the d–a pair. In view of this, we have introduced pyrene (as a donor) and anthroyloxy (as an acceptor) moieties to the terminal positions of the ion binding sites (RCO-) of ionophoric calix[4]arenes.

Fluorescent calix[4]arene **3** was prepared in three steps from the parent calix[4]arene. *p*-*tert*-Butylcalix[4]arene was dialkylated using 2 equiv. ethyl bromoacetate and 2 equiv. of K₂CO₃ in THF. The remaining two phenolic groups were functionalized firstly with 1.5 equiv. 1-pyrenemethyl iodoacetate and 2 equiv. K₂CO₃, and then with 1.5 equiv. *p*-(9-anthroyloxy)phenacyl bromide and 2 equiv. K₂CO₃ in THF. Mono-fluorophore calix[4]arenes **1** and **2** were prepared by the reaction of the tris-ethoxycarbonylmethyl ether¹¹ of *p*-*tert*-butylcalix[4]arene with the fluorescent reagents described above. All compounds were identified by ¹H NMR and field desorption mass spectroscopy.† The ¹H NMR measurements of the ArCH₂Ar protons confirmed that the calixarenes **1–3** have rigid cone conformations in CDCl₃ solution.

Energy transfer from a donor to an acceptor depends on the extent of overlap of the fluorescence spectrum of the donor and the absorption spectrum of the acceptor.⁹ Fig. 1 shows the fluorescence spectrum of **1** and the absorption spectrum of **2** in THF. The fluorescence spectrum of **1** is characterized by the pyrene monomer emission (ca. 385 nm). The absorption spectrum of **2** results from the absorption of the anthroyloxy group (λ_{max} 363 nm). Thus, the overlap between the emission of **1** and the absorption of **2** suggests that intramolecular fluorescence energy transfer from the pyrene to the anthroyloxy group can take place in **3**.

To verify the intramolecular energy transfer from the pyrene to the anthroyloxy group in **3**, we measured the fluorescence spectra of **1**, **2** and **3** at identical concentrations of 5.0 μmol

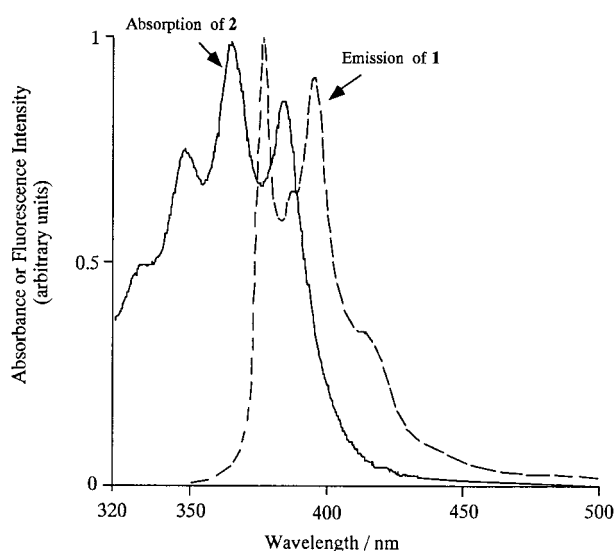
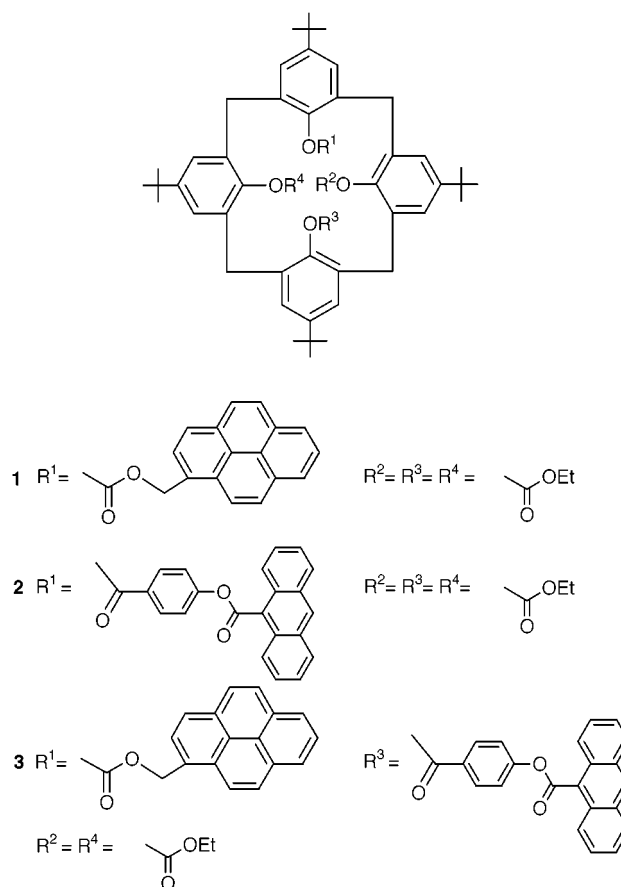


Fig. 1 Spectral overlap between the fluorescence spectrum of **1** and the absorption spectrum of **2**.

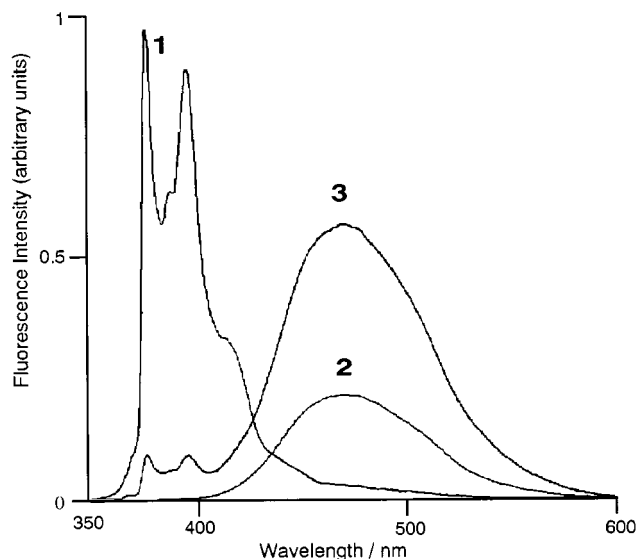


Fig. 2 Fluorescence spectra (ex. 330 nm) of **1**, **2** and **3** in THF at 25 °C.

dm^{-3} (Fig. 2). At this concentration, **1** shows only the pyrene monomer emission; the intermolecular excimer emission is negligible. The fluorescence spectrum of **2** shows a broad, structureless band (λ_{max} 480 nm), which does not have an anthracene monomer-like structure.¹² It is well known that the 9-anthroyloxy group affords a large Stokes' shift of the broad emission which is a consequence of an excited-state rotation of the carboxyl group into the plane of the anthracene ring.¹² If energy transfer takes place in **3**, the emission of the anthroyloxy group (as an acceptor) should be enhanced compared with that of **2**, and the emission of the pyrene monomer (as a donor) should be depressed compared with that of **1**. As expected, the emission intensity of the anthroyloxy group of **3** increased by a factor of ca. 2.5 compared with **2**, while the emission intensity of the pyrene monomer of **3** decreased by a factor of ca. 10 compared with that of **1**. It should be noted that the emission of the anthroyloxy group of **3** has its maximum at the same wavelength (λ_{max} 480 nm) as that due to this group in **2**. This provides evidence that the anthroyloxy group is not forming an intramolecular exciplex with the pyrene in **3**.

The effects of addition of NaSCN to **1** and **2** were first examined in MeOH–THF (15 : 1 v/v) solution. The emissions of **1** and **2** were only slightly affected by the presence of Na^+ ions. The emission of the pyrene monomer of **1** ($5.0 \mu\text{mol dm}^{-3}$) at 385 nm was enhanced by a factor of 8% in the presence of excess amounts of NaSCN ($454 \mu\text{mol dm}^{-3}$). In the case of **2** ($5.0 \mu\text{mol dm}^{-3}$), the emission of the anthroyloxy group at 480 nm was depressed by a factor of 3% under the same NaSCN concentration. The fluorescence responses of these calix[4]arenes toward Na^+ ions are very poor and they have no potential as Na^+ sensors. In contrast, the fluorescence spectra of **3** showed a significant change in the presence of Na^+ and K^+ ions. Fig. 3 shows Na^+ titrations of the fluorescence spectra of **3** in MeOH–THF (15 : 1 v/v). When NaSCN was added to the solution of **3**, the fluorescence intensity of the anthroyloxy group increased significantly compared with that of the pyrene monomer. Such a fluorescence change was also observed in the case of KSCN. In contrast, the addition of other alkali metal ions such as Li^+ , Rb^+ and Cs^+ did not cause fluorescence changes at concentrations as high as 50 mmol dm^{-3} . From the Na^+ titration data, the dissociation constant of the Na^+ –**3** complex was determined to be $15 \mu\text{mol dm}^{-3}$.[‡] The Na^+/K^+ selectivity evaluated from the dissociation constants was found to be ca. 59. For Li^+ , Rb^+ and Cs^+ , the affinities were too low to be determined accurately and the dissociation constants were estimated to be greater than 100 mmol dm^{-3} .

In conclusion, we have synthesized a first example of a Na^+ sensor based on fluorescence energy transfer. The next step of this investigation will be the synthesis of a fluorescent

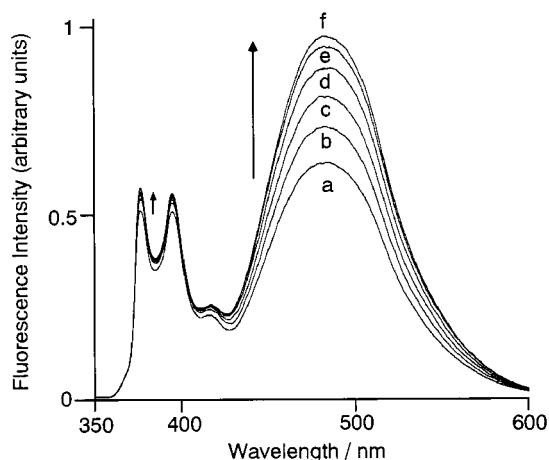


Fig. 3 Na^+ titration of the fluorescence spectra of **3** ($5.0 \mu\text{mol dm}^{-3}$) in MeOH–THF (15 : 1 v/v) at 25 °C: a, $[\text{NaSCN}] = 0$; b, $[\text{NaSCN}] = 5.8$; c, $[\text{NaSCN}] = 17.4$; d, $[\text{NaSCN}] = 46.3$; e, $[\text{NaSCN}] = 104$; f, $[\text{NaSCN}] = 218 \mu\text{mol dm}^{-3}$.

calix[4]arene-based Na^+ sensor which can be excited by visible light along the same design principles. From the standpoint of the practical application of fluorescent ion sensors, the visible-light excitation is desirable to avoid a breaching of fluorescent dyes introduced to sensor compounds. We believe that a variety of donor–acceptor fluorophore pairs can be used for the design of calixarene sensors based on fluorescence energy transfer.

We thank Mr E. Yamada for the measurement of ^1H NMR spectra.

Notes and references

[†] Selected data for **3**: ^1H NMR (400 MHz, CDCl_3), δ 0.98 (s, 18H, CMe_3), 1.08 (t, 6H, CH_2CH_3), 1.17 and 1.19 (s, 9H, CMe_3), 3.14, 3.26, 4.85 and 5.02 (d, 2H, ArCH_2Ar , J 13.0 Hz), 4.05 (m, 4H, CH_2CH_3), 4.73 (s, 4H, OCH_2O), 5.09 (s, 2H, $\text{OCH}_2\text{OCH}_2\text{Py}$), 5.83 (s, 2H, CH_2COPh), 5.87 (s, 2H, CH_2Py), 6.62 and 6.69 (d, 2H each, ArH , J 2.4 Hz), 6.86 and 6.95 (s, 2H, ArH), 7.45–8.62 (m, 18H, anthracene and pyrene); field desorption mass spectrum, m/z 1431 (M^+).

[‡] Since the absorption spectrum of **3** did not change upon addition of Na^+ and K^+ ions, a simple relationship between the intensity change (ΔF) in the anthroyloxy emission after complexation with metal ions and the concentration ($[\text{M}^+]$) of the metal ion can be derived as follows: $1/\Delta F = c + cK_d/[\text{M}^+]$, where K_d and c represent the dissociation constants of the metal ion complexes and a constant including terms of the quantum yields of free and complexing species, respectively.

- T. Jin, PhD Thesis, Hokkaido University, 1990, p. 89; T. Jin, K. Ichikawa and T. Koyama, *J. Chem. Soc., Chem. Commun.*, 1992, 499.
- I. Aoki, H. Kawabata, K. Nakashima and S. Shinkai, *J. Chem. Soc., Chem. Commun.*, 1991, 1771.
- I. Aoki, T. Sakaki and S. Shinkai, *J. Chem. Soc., Chem. Commun.*, 1992, 730.
- C. Pérez-Jiménez, S. J. Harris and D. Diamond, *J. Chem. Soc., Chem. Commun.*, 1993, 480.
- F. Unob, Z. Asfari and J. Vicens, *Tetrahedron Lett.*, 1998, **39**, 2951.
- H.-F. Ji, G. M. Brown and R. Dabestani, *Chem. Commun.*, 1999, 609.
- I. Larey, F. O'Reilly, J.-L. Habib Jiawan, J.-Ph. Soumilion and B. Valeur, *Chem. Commun.*, 1999, 795.
- P. D. Beer, V. Timoshenko, M. Maestri, P. Passaniti and V. Balzani, *Chem. Commun.*, 1999, 1755.
- J. R. Lakowicz, *Principles of Fluorescence Spectroscopy*, Plenum, New York, 1983.
- A. Arduini, A. Pochini, S. Reverberi, R. Ungaro, G. D. Andreotti and F. Ugozzoli, *Tetrahedron*, 1986, **42**, 2089; F. Arnaud-Neu, E. M. Collins, M. Deasy, G. Ferguson, S. J. Harris, B. Kaitner, A. J. Lough, M. A. McKervey, E. Marques, B. L. Ruhl, M. J. Schwing-Weill and E. M. Seward, *J. Am. Chem. Soc.*, 1989, **111**, 8681; T. Jin and K. Ichikawa, *J. Phys. Chem.*, 1991, **95**, 2601.
- K. Iwamoto and S. Shinkai, *J. Org. Chem.*, 1992, **57**, 7066.
- T. C. Werner and D. M. Hercules, *J. Phys. Chem.*, 1969, **73**, 2005; T. C. Werner and R. M. Hoffman, *J. Phys. Chem.*, 1973, **77**, 1611; T. C. Werner, T. Matthews and B. Soller, *J. Phys. Chem.*, 1976, **80**, 533; M. N. Berberan-Santos, M. J. E. Prieto and A. G. Szabo, *J. Phys. Chem.*, 1991, **95**, 5471.