A New Metal Sensory System Based on Intramolecular Fluorescence Quenching on the Ionophoric Calix[4]arene Ring

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To design a new metal sensory system, calix[4]arene bearing pyrene (as a fluorophore) and nitrobenzene (as a quencher) near the ionophoric cavity is synthesized: in response to the metal-binding event the fluorescence intensity is dramatically enhanced.

Calixarenes are cyclic oligomers made up of phenol units linked by methylene bridges. Owing to their cavity-shaped architecture, they are useful building blocks in the design of novel host molecules.[1,2] Calixarene derivatives incorporating ionophoric functional groups such as ester and amide linkages on the phenolic oxygen atoms exhibit some excellent properties as neutral receptors for metal ions: they form stable complexes and show sharp size selectivity because of their well preorganized ionophoric groups.[3,4] We thus considered that they would provide a potential sensory system for metal ions if one could modify their molecular structures so as to transduce a chemical signal (*e.g.* metal concentration) to a physical signal (*e.g.* light).

Sensory systems which employ cation-controlled photo-induced electron transfer and conformational changes are known.[5] In order to design such a calixarene-based sensory system, we applied fluorescence quenching which is frequently observed for the photoinduced electron transfer system.[6–8] It is well known that nitrobenzene is capable of quenching the fluorescence of aromatic hydrocarbons very effectively under appropriate conditions.[9] This suggests that if the quenching efficiency is disturbed through the metal-binding event, a large change in the emission intensity can be expected. We thus introduced pyrene (as a fluorophore) and nitrobenzene (as a quencher) near the ionophoric cavity composed of four esters on the calix[4]arene ring (compound 1). Fluorescence recovery by disconnecting fluorophore–nitrobenzene systems is known.[7,8]

Compound 1 (m.p. 73 °C) was synthesized by the method shown in Scheme 1. Compound 2 (m.p. 69 °C) was synthesized by the method similar to that described for 1. The structures and the purities of 1, 2 and 3 (m.p. 94 °C: used as a reference compound) were identified by IR, ^{1}H NMR spectroscopy and elemental analysis. Compounds 1 and 2 adopted the rigid cone conformation, which was confirmed from the $ArCH_2Ar$ splitting pattern in their ^{1}H NMR spectra.† Typical fluorescence spectra of 1, 2 and 3 are illustrated in Fig. 1. Although the spectrum of 1 was very similar to those of 2 and 3, the intensity of 1 was smaller by a factor of 50 than those of 2 and 3 ([1, 2 or 3] = 1.00 × 10^{-6} mol dm^{-3}). The ratio of the fluorescence intensities of 1 *vs.* 2 (I_1/I_2) increased with increasing solvent viscosity: I_1/I_2 = 0.026 in diethyl ether (0.22 mPa s at 30 °C), 0.034 in 1,4-dioxane (1.20 mPa s at 25 °C) and 0.081 in polyethylene glycol (the average molecular mass: 400, 95 mPa s at 25 °C). The spectral shape of 1 was scarcely affected in these solvents. These findings suggest that the fluorescence quenching in 1 involves the intramolecular dynamic quenching between the nitrobenzene quencher and the excited pyrene fluorophore.‡

When alkali metal ions were added to 1 in a diethyl ether–acetonitrile mixed solvent (97:3, v/v%),§ the fluorescence intensity increased sensitively (*at least 6.3 times of that in the absence of the metal ion*). In contrast, such a fluorescence

1

2

3

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† ^{1}H NMR data (CDCl₃, 25 °C, δ from SiMe₄). δ (ArCH₂Ar) 3.20, 3.21, 4.83, and 4.89 (d each, 2H each, *J* 13.8 Hz each) for 1. δ(ArCH₂Ar) 3.12, 3.17, 4.88, and 4.90 (d each, 2H each, *J* 13.8 Hz each) for 2.

‡ The intermolecular quenching was effectively negligible under the present condition ([1] = 1.00 × 10^{-6} mol dm^{-3}).
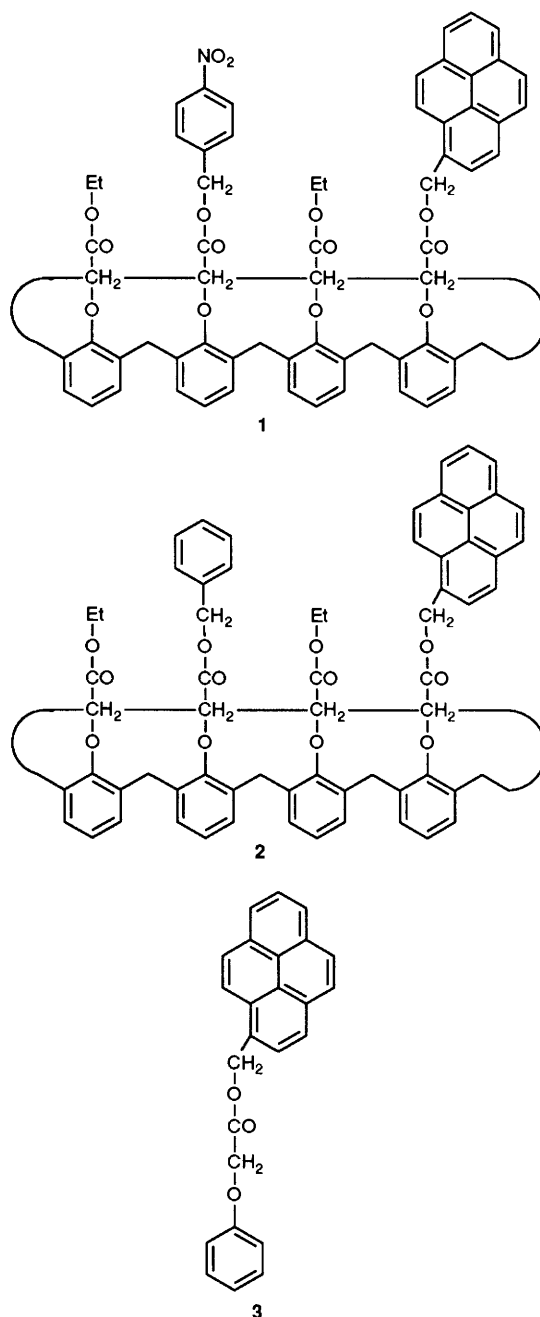
§ The metal-induced fluorescence increase in 1 was also observed in 1,4-dioxane and benzene but not so significant in methanol and acetonitrile.
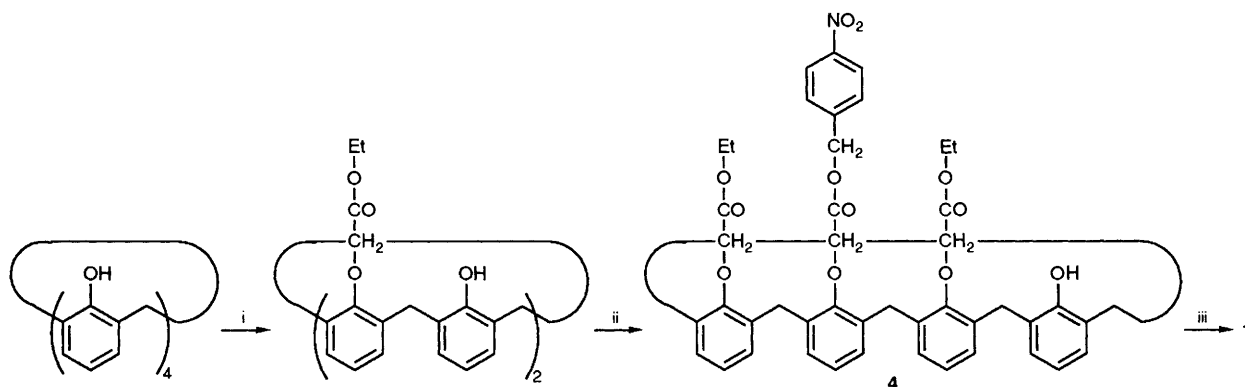
Scheme 1 *Reagents*: i, BrCH$_2$CO$_2$Et, K$_2$CO$_3$ in acetone; ii, *p*-NO$_2$C$_6$H$_4$CH$_2$OCOCH$_2$Br, CaH$_2$ in *N,N*-dimethylformamide; iii, C$_{16}$H$_9$CH$_2$OCOCH$_2$Br, K$_2$CO$_3$ in acetone
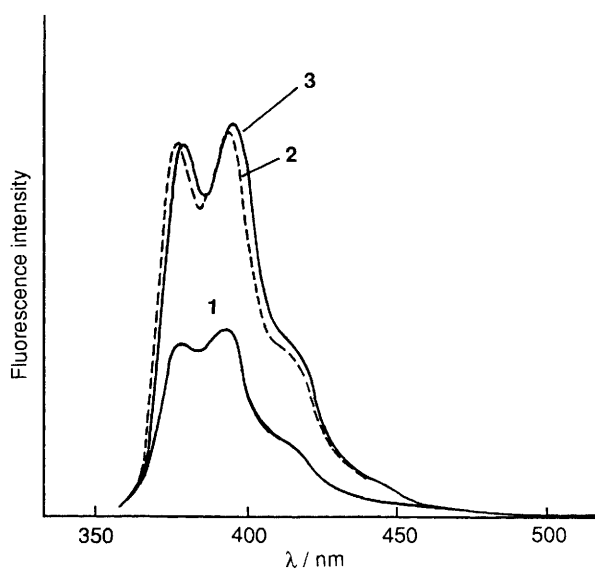

Fig. 1 Typical fluorescence spectra of **1**, **2** and **3** in methanol at 25 °C. The ordinate scale for **1** was expanded by a factor of 25. [**1**, **2** or **3**] = 1.00 × 10^{-6} mol dm^{-3}. Excitation wavelength: 342 nm for **1** and **2**, and 340 nm for **3**.

Fig. 2 Plot of fluorescence intensity *vs.* [NaSCN] (*a*) and its analysis by the equilibrium-shift method (*b*). [**1**] = 1.00 × 10^{-6} mol dm^{-3}, diethyl ether–acetonitrile (97:3, v/v%), at 25 °C.

change was not observed for **2** and **3**. The fluorescence quantum yields (Φ_f) of **1**, **1**·NaSCN, **2** and **3** are 0.0025, 0.016, 0.098 and 0.10, respectively (at 25 °C in non-degassed diethyl ether, λ_{ex} = 342 nm).¶ This shows the Φ_f for **1** is exceptionally small. In Fig. 2, we show a plot of the fluorescence intensity against the added NaSCN concentation. From the analysis of this plot by the equilibrium-shift method, we concluded that **1** forms a 1:1 complex with Na$^+$. We also determined the association constants (K_{ass}) with alkali metal ions from the similar plots of the fluorescence intensity against [M$^+$]: log K_{ass}/mol dm^{-3} = 1.2 for LiSCN, 4.3 for NaSCN, 2.9 for KSCN, 2.2 for CsSCN and 1.9 for NH$_4$SCN [at 25 °C in a mixed solvent of diethyl ether and acetonitrile (97:3, v/v%)].

¶ The Φ_f of **1**·LiSCN, **1**·KSCN, **1**·CsSCN and **1**·NH$_4$SCN are 0.017, 0.015, 0.015 and 0.016, respectively; these Φ_f values contain ±20% errors because the plots of fluorescence intensity *vs.* [MSCN] were not fully saturated because of their poor solubility. The Φ_f values were compared with a quinine H$_2$SO$_4$ (0.1 mol dm^{-3}) solution (λ_{ex} = 366 nm, Φ_f = 0.55). The molar absorptivities of **1**, **1**·NaSCN, **2** and **3** are 4.3 × 10^{-4}, 4.6 × 10^4, 4.6 × 10^4 and 4.6 × 10^4 dm^3 mol^{-1} cm^{-1} (at 342 nm), respectively. We also notice that the pyrenyl ring and the *p*-nitrophenyl ring weakly interact at the ground state (although the distinct charge-transfer band does not appear), which is evidenced by the molar absorptivity for **1** being relatively smaller than those for others.
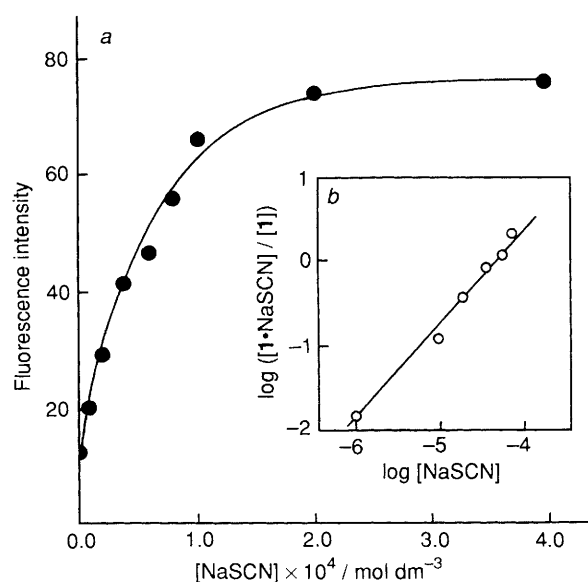
These K_{ass} values are comparable with those estimated for tetraethyl ester derivatives of calix[4]arene in tetrahydrofuran.[10]

Why does the fluorescence intensity of **1** increase so sensitively on the addition of metal ions? To obtain some insights into the conformational change in the pyrene and nitrobenzene moieties, we measured the ^{1}H NMR spectra of **1** in the absence and presence of Na$^+$. As shown in Fig. 3, the chemical shifts (δ/ppm from SiMe$_4$) of the nitrobenzene protons in **4** (compound shown in Scheme 1) appeared at δ 7.6 and 8.2. In **1**, on the other hand, they shifted to higher magnetic field because of a ring-current effect of the pyrene π-system (δ 6.8 and 7.6, respectively).[15] This supports the view that in free **1** the nitrobenzene moiety exists near the pyrene ring. On the other hand, when Na$^+$ was added to **1**, the δ values moved to lower magnetic field (δ 7.6 and 8.3, respectively) and were comparable with those for **4**.‖ This suggests that the nitrobenzene and the pyrene in the **1**·Na$^+$ complex are far separated. On the basis of these ^{1}H NMR data we can expect the following metal-induced conformational change. In free **1**, the ester groups can rotate freely and thus

‖ The assignment was achieved with the aid of 2D COSY ^{1}H NMR because the signals for the nitrobenzene protons overlapped with those for the phenyl and pyrenyl protons.
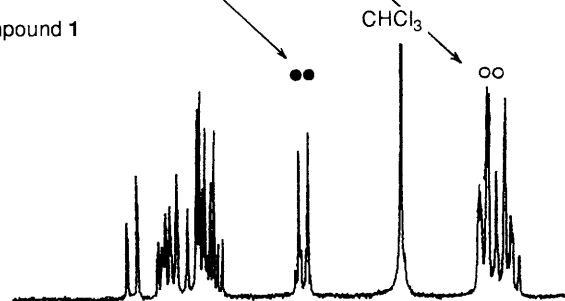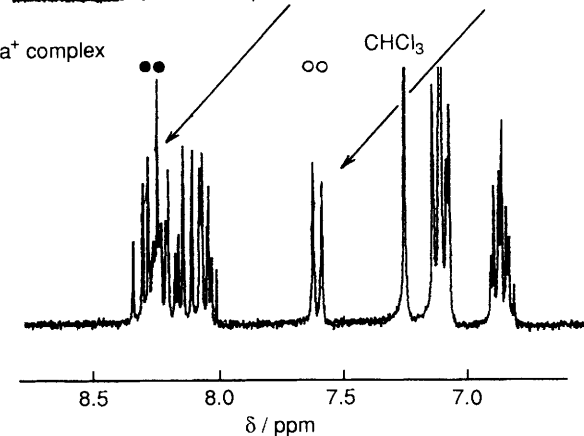
Compound **4**
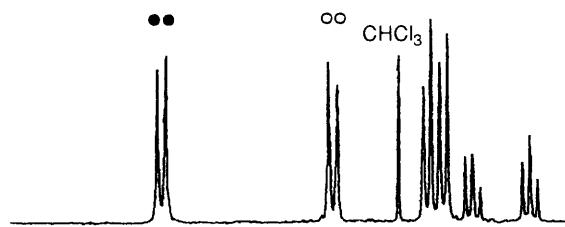
Compound **1**

1· Na⁺ complex

Fig. 3 Partial ¹H NMR spectra (250 MHz) of **4, 1** and **1**·Na⁺ complex in CDCl₃ at 25 °C. [**4, 1** or **1**·Na⁺ complex] = 1.0×10^{-2} mol dm⁻³. ● indicates the signals for *m*-protons and ○ indicates those for *o*-protons in the 4-nitrobenzyl moiety.

the pyrene ring collapses with the nitrobenzene quencher in some probability. In contrast, when Na⁺ is added to **1**, the ester carbonyls orientate inwards so that they may trap Na⁺ in the ionophoric cavity. This metal-induced orientation dramatically reduces the collision probability between the pyrene fluorophore and the nitrobenzene quencher. As a result, metal-induced fluorescence increase was realized in **1**.

'Free **1**'
weakly fluorescent

'**1**· metal complex'
strongly fluorescent
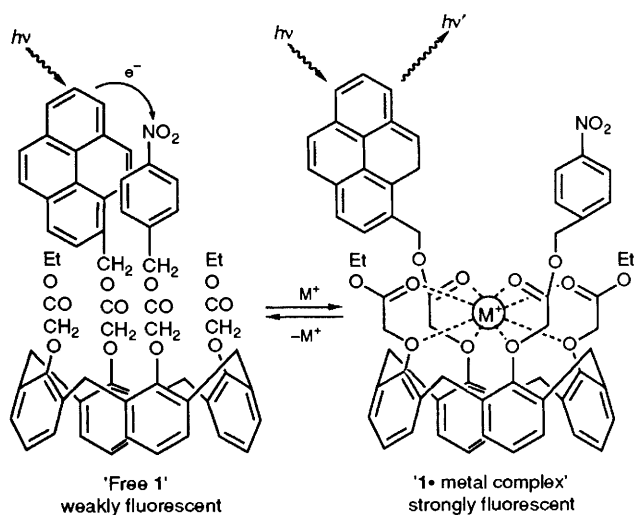
In conclusion, the present paper demonstrated that the basic idea that a metal-induced conformational change would affect the fluorescence quenching process really works and is applicable to a novel calixarene-based host–guest sensory system. A similar conformational change in a similar system has been shown to control excimer–monomer equilibria.[11]

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