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Effective signal control (off-on-off action) by metal ionic inputs on a new chromoionophore-based calix[4]crown

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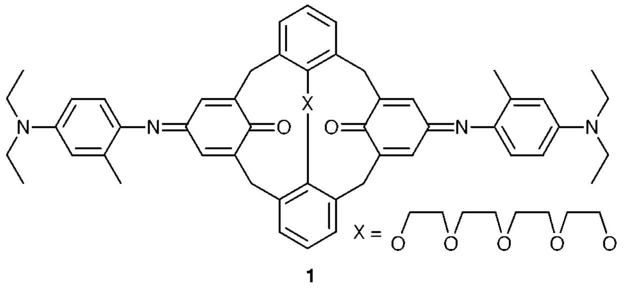
A new chromoionophore-based calix[4]crown 1 possessing an effective 'off-on-off' signalling for metal cationic inputs has been developed, the controllable signal function of which may not only be welcome for molecular information processing but also contribute to the design of new sensory materials.

The design and construction of devices miniaturized to the molecular level would not only contribute to the development of nanotechnology, but would also be of scientific interest.[1] Such progress may have important implications for biomimetic engineering.[2] Ionically-controlled optical signalling is a particularly attractive approach to switchable molecular devices for the use in information processing. In order to achieve such processing, effective ionic signal control is no doubt of importance. So far, de Silva *et al*. have reported pioneering work on developing molecular logic devices based on photo-induced electron transfer (PET) characteristics.[3] In many instances, it is of particular interest that a tailored PET system possessing two different proton binding sites forms a pH-dependant 'off-on-off' photoionic switch[4] that is a molecular emulator of an electronic device. However, the more intricate switches have only dealt with the simplest ion: H^+.[5] 'Off-on-off' switchable systems induced by ionic guests other than H^+ are as yet unknown. Thus, as an alternative approach, we have found it worthwhile to design a simplified receptor system based on competitive cation-induced 'off-on-off' colorimetric signal control:[6] it is in principle required that this system should show a colorimetric effect ('off-on' step) with the first ion, and then, if the second ion can not only bind to the system with greater affinity than the first but also induce no colorimetric effect, the second ion would release the first ion efficiently to bring about an active 'on-off' signal switch. Here we report that calix[4]crown-5[7] **1** does in fact serve as such a photoionic system.



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The system **1** contains paired indoaniline chromophores that allow a color change to be induced when a cation becomes encapsulated within the cavity. A critical design feature of this system is the use of the crown-strapped cavity. This means that an alkali metal ion can be bound with high affinity, as it is known that calix[4]crown-5 derivatives possess high K^+ selectivity.[8] However, it occurred to us that the carbonyl groups of the chromophores, being more polar donor groups than the ethers, strongly favor Ca^{2+} over either Na^+ or K^+.[9] Indeed, we reported that a bis(ethyl acetate)-derived calix[4]arene–indoaniline conjugate efficiently encapsulated Ca^{2+} with a remarkable bathochromic absorbance shift, making it of potential use as an optical sensor for Ca^{2+} detection.[10] Taken together, if an alkali metal ion such as K^+, which is bound by the macroring crown oxygens, forms a more favorable complex with **1** than Ca^{2+}, the Ca^{2+}-induced signal response could be efficiently switched off by the cation. As a consequence, it is expected that system **1** will define a rather unique chromogenic system capable of effective 'off-on-off' signal control. As detailed below, this does indeed occur.

System **1**† was synthesized from calix[4]arene[11] *via* a set of straightforward steps involving a Williamson synthesis with 3,6,9-trioxaundecane-1,11-diyl ditosylate in the presence of a base, and condensation with 2-amino-5-(diethylamino)toluene monohydrochloride under alkaline conditions in the presence of $KMnO_4$. Based on our previous work,[10] system **1** was expected to complex Ca^{2+} with high efficiency within its cavity. Indeed, an EtOH solution of **1** showed a remarkable bathochromic shift ($\Delta\lambda$ = 112 nm) and an increase in absorption intensity upon addition of Ca^{2+}, resulting in an immediate color change from blue to green. At a $[Ca^{2+}]$ to [**1**] ratio of 1.5 : 1, a new absorption band at 734 nm was observed ('off-on' switch; Fig. 1). Independent Job plot analysis[11] was consistent with the formation of a 1 : 1 stoichiometric complex. This then allowed an association constant (K_a) of 1.8×10^6 M^{-1} to be calculated using a nonlinear least-squares curve fitting procedure. The Ca^{2+}-induced colorimetric effect is mainly attributed to efficient ion–dipole interactions between the encapsulated Ca^{2+} and the quinone carbonyl groups of the indoaniline chromophores. In contrast, upon interaction with K^+ under similar conditions, no evidence of significant interaction between this cation and the chromophores was obtained. However, of particular interest is

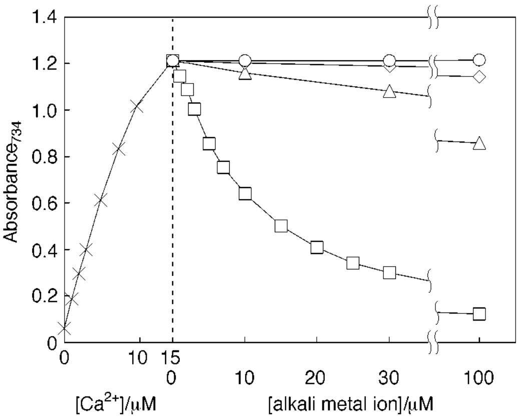

Fig. 1 Absorption intensity change at 734 nm induced by Ca^{2+} addition and subsequent alkali metal ion additions: (○) Ca^{2+}-**1** plus Li^+, (Δ) Ca^{2+}–**1** plus Na^+, (□) Ca^{2+}-**1** plus K^+ and (◇) Ca^{2+}–**1** plus Cs^+. These data were collected in EtOH at 25 °C where the concentration of receptor **1** is 10 μM.

that a competitive titration, involving adding K^+ to a solution of **1** (10 μM) and 1.5 equiv. of Ca^{2+}, exhibited significant reversed spectral changes ('on-off' switch; Fig. 1); when adding 2 equiv. of K^+ to the solution, *ca*. 70% of the absorption intensity at 734 nm was apparently diminished. This phenomenon was readily detected visually, being clearly consistent with the encapsulated Ca^{2+} being released from **1** in an almost stoichiometric reversible and competitive fashion as K^+ was added.‡

Semi-quantitative assessment of the competitive complexation process came from FAB mass spectrometric analyses. The formation of a 1:1 complex between **1** and Ca^{2+} was confirmed by monitoring the peaks at *m/z* 970 ([M+Ca]$^+$) and 1027 ([M − H + Ca + SCN]$^+$) using a *m*-nitrobenzyl alcohol matrix. Upon adding K^+ to the **1**–Ca^{2+} complex, the peak due to the Ca^{2+} complex was almost completely suppressed, whereas a new peak signal at *m/z* 968 ([M−H + K]$^+$) could be detected. These results are consistent with those obtained from the UV–Vis titrations and thus strongly support the notion that reversible competitive complexation takes place between Ca^{2+} and K^+ in the case of receptor **1**. We were interested to know whether or not the effective 'on-off' switch obtained in **1** can be induced by only K^+. Thus, we tested alkali metal ions other than K^+. As depicted in Fig. 1, the Ca^{2+}-induced signal was barely influenced by Li^+, Na^+ and Cs^+. The association constants (K_a) for the complexation of the alkali metal ions to **1** were calculated using a mathematical method that may be applied to competition experiments[13] and **1** was found to have peak affinity with K^+ ($K_a = 7.2 \times 10^6$ M^{-1}); the selectivity of K^+ over Ca^{2+} was 4.0. As K^+ induced almost no color change, and can switch off the Ca^{2+}-induced optical signal with high selectivity over other alkali metal ions, an effective 'off-on-off' switch for system **1** could be achieved by making use of the combination of Ca^{2+} and K^+.

NMR studies were carried out in an effort to understand the detail of the substrate–receptor interactions. Although the ^1H NMR spectra showed that both the Ca^{2+} and K^+ complexes in CD_3OD adopt cone conformations, the binding modes are slightly different, as inferred from 2D COSY and NOESY experiments.§ These different modes in the cavity might suggest that the guest Ca^{2+} is bound by the more polar carbonyl groups of the indoanilines to induce the drastic color change, whereas K^+ interacts with the convergent crown oxygens to switch off the Ca^{2+}-induced signal more efficiently than other alkali metal ions.

In conclusion, the results described here lead us to suggest a new approach to the generation of photochemical 'off-on-off' switching systems. On a different level, the selective 'on-off' switching step described herein could prove useful in terms of generating a molecular sensor in analytical chemistry.[14] We feel that such possibilities warrant future exploration.

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Notes and references

† *Selected data* for **1**: δ_H(400 MHz, DMSO-d_6, 373 K) 1.16 (t, *J* 7.0, 12H), 2.26 (s 6H), 3.19–3.31 (br d, 4H), 3.40 (q, *J* 6.9, 8H), 3.51–3.99 (m, 20H), 6.57–6.84 (m, 12H), 7.08 (2H, s) and 7.14 (2H, s); *m/z* (FAB) 930 [M]$^+$ (Calc. for $C_{58}H_{66}N_4O_7 \cdot 0.5H_2O$: C, 74.10; H, 7.18; N, 5.96. Found: C,73.92; H, 7.22; N, 6.28%); λ_{max}(EtOH)/nm (ε_{max}/dm^3 mol^{-1} cm^{-1}) 622 (47000).

‡ The Ca^{2+}-induced absorption intensity at 734 nm ('on' state) was scarcely influenced by adding 100 μM of H^+.

§ This work will be reported elsewhere.

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