Potassium Ion Selective Signaling Based on Intramolecular Dimer Formation of Biscrown Ether Azochromophore
—Chemosensor Exhibiting Forceps Function—

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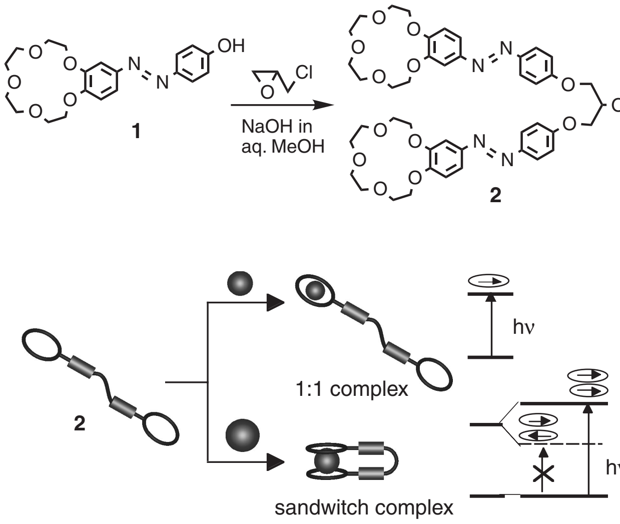
A novel bisbenzo-15-crown-5 azochromophore, **2**, which exhibits forceps function, has been designed. **2** shows selective UV–vis spectral response for K^+ in acetonitrile, which is based on the exciton interaction of the two azochromophores upon forming an intramolecular sandwich complex with K^+.

The control of dynamic molecular recognition events is a key concept in the design of supramolecular chemosensors.[1] In the development of chemosensors for metal ion, the metal-ion-induced conformational folding of binding sites is used for realizing efficient photosignal transduction systems.[2] In this type of chemosensors, donor and acceptor chromophores are generally introduced at the two ends of the acyclic binding site. The binding of metal ions to the ionophoric moiety within the spacer chain brings the chromophoric donor sufficiently close to the chromophoric acceptor to produce a new UV–vis absorption or fluorescence emission through a charge transfer,[3] an electron transfer,[4] or an energy transfer.[5] Ajayaghosh et al. have recently reported a unique Ca^{2+}-selective chemosensor, the principle of which is based on exciton interaction in a rigid-flexible-rigid bichromophoric "H" foldamer, in which the Ca^{2+} binding induces the formation of an "H" aggregate of two chromophores, resulting in the Ca^{2+}-selective optical response.[6]

The concept of bichromophoric "H" foldamer has inspired us to design a novel alkali metal ion selective chemosensor that utilizes the forceps function of biscrown ethers. As shown in Scheme 1, we have designed a bisbenzo-15-crown-5 azochromophore, **2**, which exhibits exciton interaction response by forming a selective intramolecular sandwich complex with K^+.



Scheme 1. Synthesis and response mechanism of biscrown ether azochromophore **2**.

On the basis of Kasha's theory, the excited-state energy level of the monomeric azochromophore is split into two states upon intramolecular dimer formation (Scheme 1).[7] In the case of "H" aggregate dimer (face-to-face stacking structure of the two azochromophores), UV–vis absorption at the shorter wavelength is allowed, whereas that absorption at the longer wavelength is forbidden. Thus, a blue shift of the UV–vis spectra is expected for the intramolecular dimer formation. Although the benzo-15-crown-5 (B15C5) binding sites in **2** can form a 1:1 complex with alkali metal cations, the 1:1 binding events exhibit optically no response. By contrast, the intramolecular 2:1 complex formation of the B15C5 binding sites with alkali metal cations induces the formation of the "H" aggregate structure (forceps function), resulting in a blue shift of the UV–vis spectra. Consequently, an amplified response selectivity for recognition of alkali metal ion is expected for **2**.

B15C5-azophenol **1** was synthesized by the azo coupling of 4′-aminobenzo-15-crown-5 with phenol in a conventional manner.[8] Biscrown ether azochromophore **2** was prepared by reacting **1** with epichlorohydrin in 97% water–3% methanol (v/v) containing NaOH, followed by recrystallization from aqueous methanol. The structure of **2** was fully confirmed by ^1H NMR and combution analyses.[9]

Figure 1 shows the UV–vis spectra of **2** (0.020 mM; $1\,M = 1\,mol\,dm^{-3}$) in acetonitrile. In the absence of alkali metal ions, the maximum absorption of the π–π^* transition is noted at 366.5 nm.[10] A linear increase in absorbance at 366.5 nm is confirmed for **2** in the concentration range of 0.00 to 0.03 mM ($\varepsilon = 3.7 \times 10^4\,cm^{-1}\,mol^{-1}\,dm^3$), indicating that no aggregation

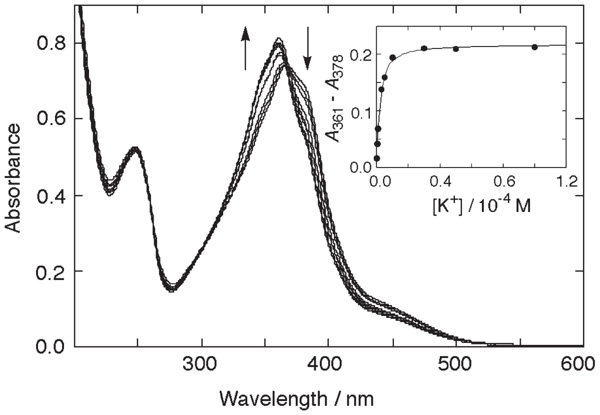


Figure 1. Change in UV–vis spectra of **2** upon addition of K^+ (as perchlorate salt). [**2**] = 0.020 mM in CH_3CN. Inset: dependence of ($A_{361} - A_{378}$) on the concentration of K^+.

of the chromophore moieties has taken place. Upon addition of K^+, the UV–vis spectra of **2** exhibit a distinct blue shift, and thus the maximum wavelength of **2** is changed from 366.5 nm to 361.0 nm with an enhancement of its molar absorptivity. A clear isosbestic point is noted at 368.0 nm. Based on the intramolecular 2:1 binding mechanism of **2** (L) with alkali metal cations (M^+), the absorbance difference at two wavelength ($A_{361} - A_{378}$) is expressed by the following equations:[11]

$$A_{361} - A_{378} = \frac{2(\varepsilon_{L2} - \varepsilon_{L1}) + (\varepsilon_{ML2} - \varepsilon_{ML1})(B - 1)}{B + 1} L_t \quad (1)$$

$$B = K_{11}(M_t - L_t) + \sqrt{(K_{11}(L_t - M_t) + 1)^2 + 4K_{11}M_t} \quad (2)$$

$$K_{11} = \frac{[ML^+]}{[M^+][L]} \quad (3)$$

where L_t and M_t are the total concentrations of **2** and the alkali metal cation, and ε_{L1} and ε_{L2} are the molar absorptivities for **2** at 378 and 361 nm, respectively. As shown in the inset of Figure 1, the data points are well fitted by the above equations (solid line) and the apparent 1:1 binding constant (K_{11}; intramolecular 2:1 binding constant) of **2** for K^+ is determined to be $(6.29 \pm 1.20) \times 10^4\,M^{-1}$. The K_{11} value of $1.5 \times 10^4\,M^{-1}$ has been reported for the corresponding B15C5 with K^+ in acetonitrile.[12] Thus it is evident that the biscrown ether structure of the binding site in **2** enhances the binding ability for K^+. The K_{11} values of **2** for other alkali metal cations are $(0.66 \pm 0.17) \times 10^4\,M^{-1}$ for Li^+, $(0.37 \pm 0.11) \times 10^4\,M^{-1}$ for Na^+, $(0.48 \pm 0.09) \times 10^4\,M^{-1}$ for Rb^+, and $(0.20 \pm 0.10) \times 10^4\,M^{-1}$ for Cs^+.

To assess the response selectivity, the ratio of the binding constant for K^+ to that for other alkali metal cations $[K_{11}(K^+)/K_{11}(M^+)]$ is plotted against the alkali metal ion radius (Figure 2). It is well known that B15C5 forms a 2:1 (ligand–metal) complex with K^+. Thus, the high selectivity for K^+ shown in Figure 2 indicates the formation of an intramolecular sandwich complex of **2** with K^+, which results in the blue shift of the azochromophores. Although **2** may form an intermolecular 2:2 complex with K^+,[13] the response profile shown in the inset of Figure 1 does not fit with the 2:2 binding mechanism. For the 2:2 complex formation, a sigmoid profile against K^+ concentration should appear based upon the successive binding mechanism.[11,14] The flexible structure of **2** estimated from the CPK space filling model also suggests the difficulty in forming the intermolecular 2:2 complex in bulk solution. In fact, a similar exciton interaction response is noted for the azochromophore **2**/γ-cyclodextrin complex in water.[15] The fact that the B15C5 moiety is too large to penetrate into the γ-cyclodextrin cavity evidences that **2** forms an intramolecular 2:1 sandwich complex with K^+.

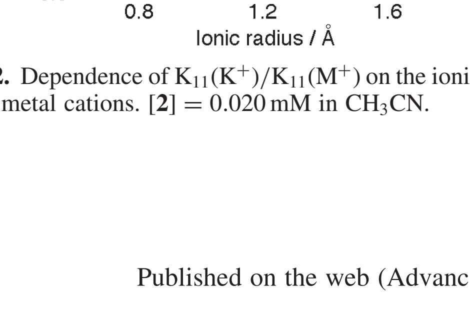


Figure 2. Dependence of $K_{11}(K^+)/K_{11}(M^+)$ on the ionic radius of alkali metal cations. [**2**] = 0.020 mM in CH_3CN.

In conclusion, the biscrown ether azochromophore **2** is found to exhibit high response selectivity for K^+ via the formation of an intramolecular dimer complex, resulting in the exciton interaction of the two azochromophores. This is a novel forceps function of chemosensors for sensing ions and molecules with high selectivity in solution.

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9 ^1H NMR (270 MHz, $CDCl_3$): δ 7.86 (d, 4H, ArH), 7.54 (dd, 2H, ArH), 7.45 (d, 2H, ArH), 7.03 (d, 2H, ArH), 6.94 (d, 4H, ArH), 4.45 (m, 1H, –CH(OH)–), 4.23 (m, 12H, $–OCH_2–$), 3.94 (m, 8H, $–OCH_2–$), 3.77 (m, 16H, $–OCH_2–$). Anal. Calcd for $C_{43}H_{52}O_{13}N_{4}0.4H_2O$: C, 61.48; H, 6.33; N: 6.67%. Found: C, 61.43; H, 6.30; N, 6.54%.
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