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Barium ion sensing by a 2,2′-binaphthalene derivative bearing two monoaza-15-crown-5 ethers

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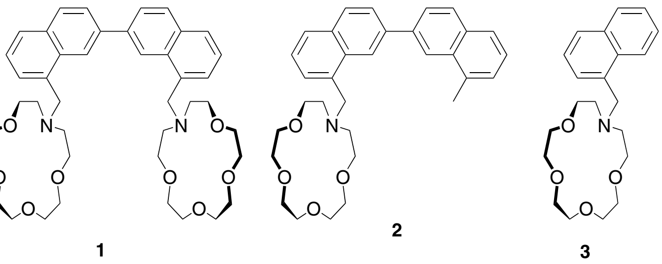
Abstract—A novel fluoroionophore **1** based on 2,2′-binaphthalene bearing two monoaza-15-crown-5 ethers at 8- and 8′-positions was prepared. UV–vis and fluorescence responses of **1** upon the addition of alkali and alkaline earth metal cations were evaluated in 15% MeOH–MeCN. Receptor **1** showed unique response for Ba^{2+} due to the formation of an intramolecular sandwich complex.

Construction of effective fluoroionophores and chromoionophores, which convert the signal on molecular recognition into fluorescence and absorbance changes, has been of importance due to practical applications.[1,2] (Aza)crown ether moieties have been accepted as the most common functional groups in the recognition site of metal ions and ammonium groups in host–guest chemistry.[3] Azacrown ethers bearing fluorometric sensing site such as anthracene through a methylene spacer show fluorescence quenching by photoinduced electron transfer (PET) from the nitrogen atom of the azacrown group and the quenching is diminished by coordination of metal ions in its cavity.[4] In general, sensitivity and selectivity for cation recognition by azacrown ether derivatives are insufficient. To enhance affinity, selectivity, and sensitivity of cationic species by (aza)crown ether derivatives, a sandwich complex formation by bis-((aza)crown ether)s is one of the versatile strategies.[5–7] However, fluoro- or chromoionophores bearing plural azacrown ether moieties as cation binding sites to form an intramolecular sandwich complex have been scarcely reported.[8,9]

Recently, we have reported that a 2,2′-binaphthalene derivative bearing two thiourea groups at 8- and 8′-positions is an effective host for anionic species in MeCN and a 2,2′-binaphthalene derivative bearing two dimethylaminomethyl groups at 8- and 8′-positions shows remarkable DNA intercalation ability in aqueous media.[10] The skeleton of 2,2′-binaphthalene consists of rigid two naphthalene moieties connected with a flexible single bond and complexation of 2,2′-binaphthalene derivatives bearing recognition sites at 8- and 8′-positions with a target guest causes restriction of rotation around the 2,2′-bond. In this communication, we show the unique response to a large alkaline earth metal ion such as Ba^{2+} with a novel 2,2′-binaphthalene bearing two aza-15-crown-5 moieties at 8- and 8′positions (**1**) by formation of the intramolecular sandwich complex (Scheme 1).



Scheme 1.

Keywords: 2,2′-Binaphthalene; Molecular recognition; Host–guest chemistry; Azacrown ether; Fluoroionophore.

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Monoaza-15-crown-5 (1,4,7,10-tetraoxa-13-azacyclopentadecane) groups were introduced into 8,8′-bis(bromomethyl)-2,2′-binaphthalene[10b] in the presence of potassium carbonate in MeCN giving **1** in 34% yield. Monobromination of 8,8′-dimethyl-2,2′-binaphthalene was performed with 1 equiv of NBS in the presence of catalytic amount of AIBN in CCl_4 (27%) and the bromo group was substituted with monoaza-15-crown-5 to give **2** in 72%. A reference compound **3** based on naphthyl moiety was also prepared from commercially available 1-chloromethylnaphthalene. The products were characterized by ^{1}H NMR, elemental analysis, and ESI-MS.[11]

UV–vis spectral changes of **3** upon the addition of Na^+, K^+, Mg^{2+}, Ca^{2+}, Sr^{2+}, and Ba^{2+} perchlorate salts in 15% MeOH–MeCN (v/v) were only small (Fig. S1b). In general, when a crown ether and a chromophore which has no interaction site with guest cation are connected with a methylene spacer, there are only minor spectral changes upon the complexation with a guest. The UV–vis spectra of **1** also showed small spectral changes upon the addition of Na^+, K^+, Mg^{2+}, Ca^{2+}, and Sr^{2+} (Fig. S1a) in a similar manner of that of **3**, however, a significant hypsochromic shift around 310 nm was observed upon the addition of Ba^{2+} through isosbestic points at 291 and 334 nm as shown in Figure 1. Figure 2 shows the changes of absorbance at 310 nm of **1** upon the addition of alkali and alkaline earth metal ions. It is clear that the large absorption response of **1** to Ba^{2+} is unique. The stoichiometry of the complexation of **1** with $Ba(ClO_4)_2$ was determined to be 1:1 by Job's analysis (Fig. S3), and the apparent association constant ($\log K_{app}$) for the complexation of **1** with $Ba(ClO_4)_2$ in 15% MeOH–MeCN was determined to be 5.20 ± 0.06 by nonlinear least square curve-fitting of the titration data. These results suggest that the complexation of **1** with Ba^{2+} causes dramatic structural change of the 2,2′-binaphthalene skeleton.

The receptor **3** showed increase in the fluorescence intensity upon the addition of alkaline earth metal ions such as Mg^{2+}, Ca^{2+}, Sr^{2+}, and Ba^{2+} in 15% MeOH–MeCN (v/v) due to inhibition of PET process by the complexation with the metal ions as reported previously in a similar fluoroionophore bearing azacrown ether by a methylene spacer.[4] The chelation-enhanced fluorescence (CHEF) of **3** is in the order of Ca^{2+} ($\log K_{11} = 4.56 \pm 0.04$) > Mg^{2+}(4.34 ± 0.01) > Sr^{2+}(4.25 ± 0.04) > Ba^{2+}(4.25 ± 0.01) as shown in Figure 3b. The receptor **1** shows weak fluorescence emission (λ_{ex} = 291 nm, which is one of the isosbestic points for the

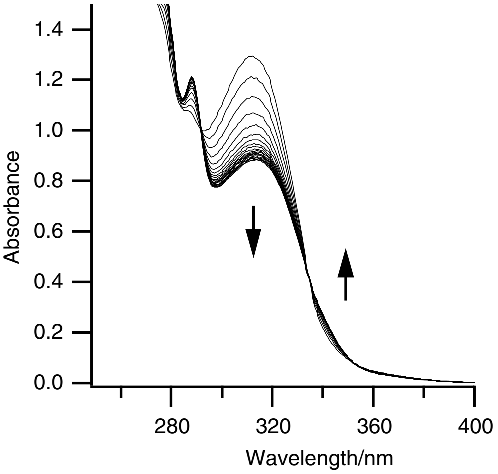


Figure 1. UV–vis spectral change of **1** upon the addition of $Ba(ClO_4)_2$ in 15% MeOH–MeCN (v/v) at 298 K. [**1**] = 6.67×10^{-5} M.

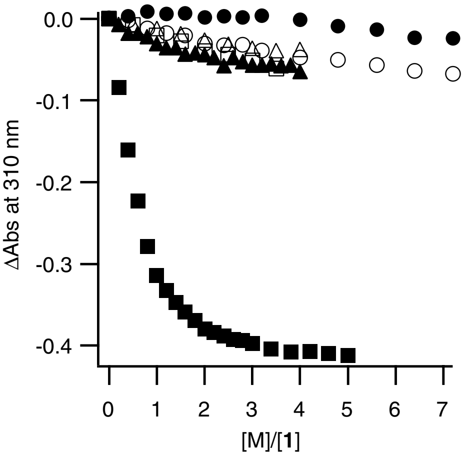


Figure 2. ΔAbs at 310 nm versus [M]/[**1**] in 15% MeOH–MeCN (v/v) at 298 K: Ba^{2+} (■), Sr^{2+} (▲), Ca^{2+} (●), Mg^{2+} (○), K^+ (□), and Na^+ (△). [**1**] = 6.67×10^{-5} M.

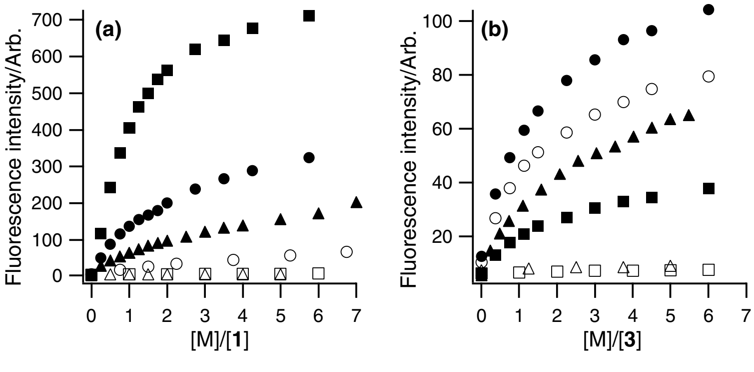


Figure 3. Fluorescence intensity versus [M]/[**1**] (a, λ_{ex} = 291 nm, λ_{em} = 373 nm) and [M]/[**3**] (b, λ_{ex} = 270 nm, λ_{em} = 328 nm) in 15% MeOH–MeCN (v/v) at 298 K: Ba^{2+} (■), Sr^{2+} (▲), Ca^{2+} (●), Mg^{2+} (○), K^+ (□), and Na^+ (△). [**1**] = [**3**] = 2.67×10^{-5} M.

complexation of **1** with Ba^{2+}) in the absence of metal ion. The fluorescence quantum yields of 8,8′-dimethyl-2,2′-binaphthalene and **1** were determined to be 0.33 and 0.0033, respectively, in 15% MeOH–MeCN[12] indicating that the PET from the nitrogen atoms in the azacrown ethers causes effective quenching of **1** in the excited state. The addition of Na^+ and K^+ induces no fluorescence change, meanwhile, the addition of alkaline earth metal ions induces substantial increases in fluorescence as shown in Figure 4. Interestingly, CHEF of **1** is in the order of $Ba^{2+} > Ca^{2+} > Sr^{2+} > Mg^{2+}$ and the order is a different trend from that of **3** as described above (Fig. 3). A Job plot analysis of the fluorescence responses indicates the formation of 1:1 complex with Ba^{2+} as shown in Figure 5. In the case of the complexation with Ca^{2+} and Sr^{2+}, the complex approaches a maximum when the mole fraction of guest ca. 0.4, suggesting 1:2 host–guest complexation. The apparent association constant ($\log K_{app}$) for the complexation of **1** with $Ba(ClO_4)_2$ by fluorescence titration was determined to be 4.89 ± 0.01, which are in fairly good agreement with that calculated from the UV–vis titration.

Plausible equilibria are illustrated in Scheme 2. For a 1:1 complex of **1**, two possible structures are formed, that is, a complex in which one azacrown is occupied with a metal ion and the other is unoccupied (**1**M) and an

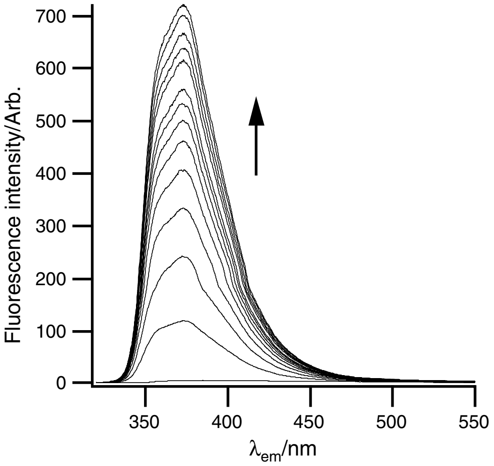


Figure 4. Fluorescence spectral changes of **1** upon the addition of $Ba(ClO_4)_2$ excited at 291 nm in 15% MeOH–MeCN (v/v) at 298 K. $[\mathbf{1}] = 2.67 \times 10^{-5}$ M.

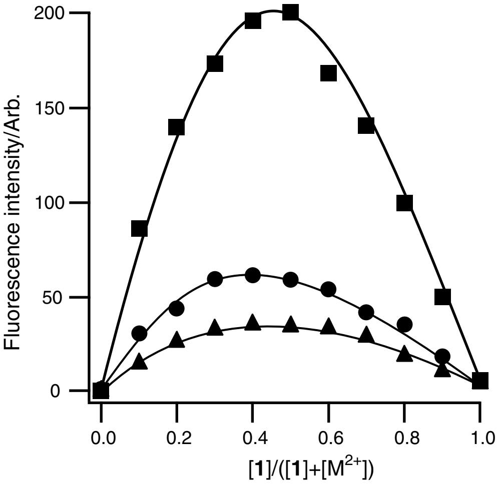
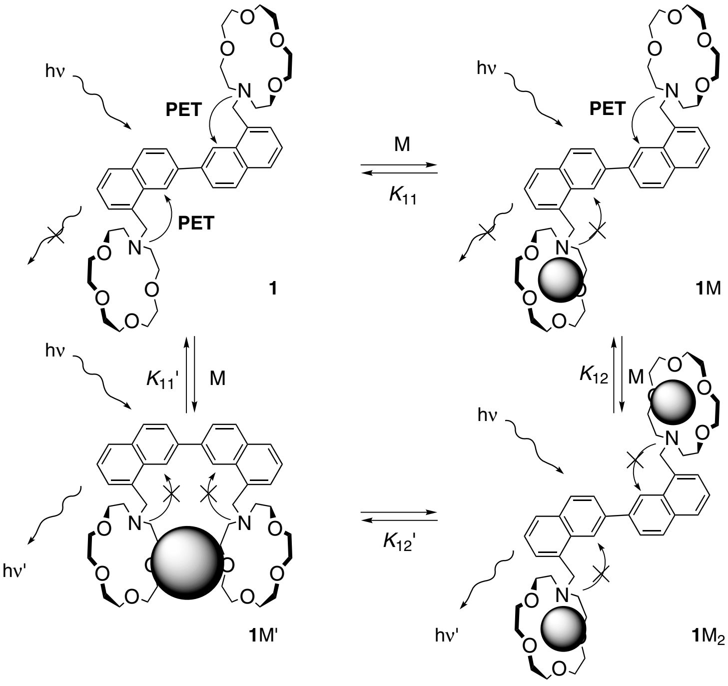


Figure 5. Job plots for the complexations of **1** with Ba^{2+} (■), Sr^{2+} (▲), and Ca^{2+} (●) measured by fluorescence spectroscopy ($\lambda_{ex} = 291$ nm, $\lambda_{em} = 373$ nm) in 15% MeOH–MeCN (v/v) at 298 K. $[\mathbf{1}]+[M(ClO_4)_2] = 2.67 \times 10^{-5}$ M.



Scheme 2.

intramolecular sandwich complex (**1**M′). The fluorescence intensities of **1**M′ and **1**M_2 are expected to be larger than that of free **1** because the PET process is blocked by coordination of the nitrogen atoms to the metal ions. The fluorescence quantum yield of **2** was determined to be 0.0077 in 15% MeOH–MeCN[12] indicating an effective PET quenching was also achieved by the presence of one azacrown ring. This result suggests that the fluorescence intensity of **1**M is expected to be still small. The UV–vis and fluorescence titrations of **1** with Ba^{2+} showed the pronounced spectral changes. The ionic diameter for Ba^{2+} (2.70 Å)[13] is larger than the effective cavity diameter for aza-15-crown-5 (1.7–2.2 Å). Thus **1** forms the intramolecular sandwich complex with Ba^{2+} (**1**$Ba^{2+\prime}$ in Scheme 2) as observed in the crystal structure of (15-crown-5)$_2$$Ba^{2+}$ complex.[14] Formation of a sandwich complex of **1** restricts rotation of two naphthyl rings and affects the electronic property of the 2,2′-binaphthalene skeleton. The slightly larger association constant for **1** with Ba^{2+} than that for **3** from the fluorescence titrations supports the formation of the sandwich complex due to the cooperative effect of the two azacrown moieties. On the 1:1 complexation with the other alkaline earth metal ion, **1**M is predominantly formed, therefore, the small UV–vis spectral changes and the modest fluorescence enhancements were observed.

In conclusion, we have synthesized a novel receptor based on 2,2′-binaphthyl moiety for cation recognition. The receptor **1** shows distinctive UV–vis and fluorescence responses for Ba^{2+} due to restriction of the conformational change through the formation of the intramolecular sandwich complex. Selectivity of receptors would be tuned by substitution of aza-15-crown-5 moieties to appropriate functional groups. Further studies on this line are in progress.

Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tetlet.2005.03.054. UV–vis and fluorescence spectral titrations of **1** with $Ca(ClO_4)_2$ and **3** with $Ba(ClO_4)_2$, and a Job plot of **1** with $Ba(ClO_4)_2$ by UV–vis spectroscopy.

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11. Selected data for **1**: Mp 69–71 °C. ^1H NMR (300 MHz, $CDCl_3$) δ 2.92 (t, 8H, $N(CH_2)_2$, *J* = 6.1 Hz), 3.59–3.70 (m, 32H, CH_2), 4.19 (s, 4H, CH_2), 7.41 (dd, 2H, 6- and 6′-CH, J_1 = 6.8, J_2 = 8.1 Hz), 7.53 (d, 2H, 7- and 7′-CH, *J* = 6.8 Hz), 7.80 (d, 2H, 5- and 5′-CH, *J* = 8.1 Hz), 7.94 (s, 4H, 3-, 3′-, 4-, and 4′-CH), 8.67 (s, 2H, 1- and 1′-CH). Anal. Calcd for $C_{42}H_{56}N_2O_8\cdot 1/2H_2O$: C, 69.49; H, 7.91; N, 3.86. Found: C, 69.60; H, 7.76; N, 3.66. ESI-MS (positive ion mode) calcd for $[C_{42}H_{56}N_2O_8+H]^+$: *m*/*z* 717.41; found: 717.7. For **2**: pale yellow oil. ^1H NMR (300 MHz, $CDCl_3$) δ 2.79 (s, 3H, CH_3), 2.91 (t, 4H, $N(CH_2)_2$, *J* = 6.1 Hz), 3.57 (m, 12H, CH_2), 3.66 (t, 4H, CH_2, *J* = 6.1 Hz), 4.18 (s, 2H, CH_2), 7.36 (d, 1H, 7′-CH, *J* = 7.0 Hz), 7.39 (t, 1H, 6′-CH, *J* = 7.0 Hz), 7.41 (t, 1H, 6-CH, *J* = 7.0 Hz), 7.51 (d, 1H, 7-CH, *J* = 7.0 Hz), 7.75 (d, 1H, 5′-CH, *J* = 7.1), 7.80 (d, 1H, 5-CH, *J* = 7.1), 7.88 (dd, 1H, 3′-CH, J_1 = 1.7, J_2 = 8.5 Hz), 7.91 (dd, 1H, 3-CH, J_1 = 1.7, J_2 = 8.5 Hz), 7.95 (d, 1H, 4′-CH, *J* = 8.5), 7.97 (d, 1H, 4-CH, *J* = 8.5), 8.31 (s, 1H, 1′-CH), 8.70 (s, 1H, 1-CH). Anal. Calcd for $C_{32}H_{37}NO_4\cdot 1/2H_2O$: C, 75.56; H, 7.53; N, 2.75. Found: C, 75.21; H, 7.15; N, 2.68. For **3**: pale yellow oil. ^1H NMR (300 MHz, $CDCl_3$) δ 2.88 (t, 4H, $N(CH_2)_2$, *J* = 6.0 Hz), 3.60–3.73 (m, 16H, CH_2), 4.10 (s, 2H, CH_2), 7.39 (t, 1H, 3-CH, *J* = 7.6 Hz), 7.44–7.52 (m, 3H, 2-, 6-, and 7-CH), 7.75 (d, 1H, 4-CH, *J* = 8.3 Hz), 7.83 (d, 1H, 5-CH, *J* = 8.3 Hz), 8.31 (d, 1H, 8-CH, *J* = 8.3 Hz). Anal. Calcd for $C_{21}H_{28}NO_4\cdot 2/3H_2O$: C, 67.90; H, 8.23; N, 3.77. Found: C, 67.99; H, 7.92; N, 3.85.
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