

Highly Sodium-Selective Fluoroionophore Based on Conformational Restriction of Oligoethyleneglycol-Bridged Biaryl Boron–Dipyrromethene

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Fluoroionophores, by changing their optical properties upon complexation with certain ions, have a great potential for practical applications in the field of analytical chemistry, environmental chemistry, life science, and other fields.¹ Especially, fluoroionophores for sodium ions have been extensively required to sensitively monitor this important and widespread cation in nature. Among the reported Na⁺ sensing molecules, crown ether derivatives² that form a rigid cavity around Na⁺ (e.g., *N*-(*o*-alkoxyphenyl)-aza-15-crown-5 and 16-crown-5) and calix[4]arenes³ that have a flexible cavity with bulky substituents have been used as a receptor. Fluorophores with a fluorescent switching property driven by photoinduced electron transfer (PET) are often employed to signal metal binding.⁴ However, the sensitivity and selectivity of the Na⁺ fluoroionophores with the receptor connected to a PET-type fluorophore are still inadequate due to their poor fluorescent switching and the interference of other ions, such as K⁺. To improve the selectivity and sensitivity to Na⁺ ions, we have been searching for a new binding site with a different spectral change mechanism.

Finney et al. designed and synthesized a series of interesting fluoroionophores consisting of a rotatable biaryl fluorophore and a bridged oligoethyleneglycol chain.⁵ On the basis of the conformational restriction of the rotation triggered by cation recognition at the chain, the fluorescence intensity varies with the ion species and concentration. However, the sensitivity is impractical due to a poor extinction coefficient and fluorescence quantum yield. Assuming that the spectral change mechanism based on the conformational restriction is applied to high-performance fluorophores, the sensitivity would be favorable.

Boron–dipyrromethene derivatives are useful fluorophores because of their advantageous characteristics, such as sharp absorption and fluorescence bands, high extinction coefficients, high fluorescence quantum yields, and high stability against light and chemical reactions.⁶ In addition, they have the advantage that the absorption and emission wavelengths are adjustable by replacing appropriate substituents. However, their wavelengths are not only modulated by the electronegativity of the substituents and the extension of the π -system. Among the various 3,5-substituted boron–dipyrromethene derivatives reported by Burgess et al., we have noted that the absorption maxima of the 3,5-bis(2-methoxyphenyl) and 3,5-bis(1-naphthyl) derivatives are shifted to shorter wavelengths, regardless of the incorporation of electron-donating groups and the extension of the π -system, respectively.⁷ The reason is that the dihedral angles between the dipyrromethene plane and the aryl planes are greater due to steric hindrance so that the orbital interaction becomes weaker. However, as mentioned above, the

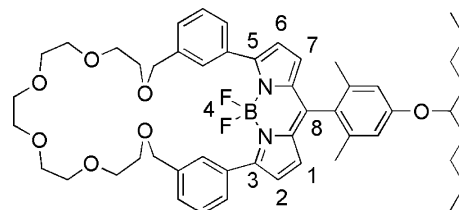


Figure 1. Chemical structure of boron–dipyrromethene fluoroionophore **1**.

absorption wavelength can also be changed by the orientation of the aryl substituent. Utilizing the spectral shift property, 3,5-biaryl boron–dipyrromethene with the dihedral angle controlled by molecular recognition will be used as an optical sensor. As the first step toward the realization of a highly sensitive fluorescent sensor based on a conformational restriction, we have designed and synthesized a fluoroionophore by combining the biaryl boron–dipyrromethene fluorophore with an oligoethyleneglycol bridge acting as a binding site for metal cations.

The chemical structure of the target fluoroionophore **1** is shown in Figure 1. To convert the metal binding event into a change in a dihedral angle, the oligoethyleneglycol bridge is introduced between each of the *m*-position of the 3- and 5-phenyl rings. A branched alkyl chain at the *p*-position of the 8-phenyl group is attached to increase the solubility in organic solvents and the synthetic yield.⁸ Furthermore, methyl groups at the *o*-positions are introduced to enhance the fluorescence quantum yield.⁹

The absorption and emission spectra were recorded in acetonitrile. The ion-free fluoroionophore **1** has sharp absorption and emission bands with a maximum at 551 and 589 nm, respectively. The wavelengths are almost the same as those of the 3,5-diphenyl boron–dipyrromethene derivatives.⁹ It suggests that the electronic effect of the substituent group at the *m*-positions scarcely affects the spectra, and the oligoethyleneglycol bridge hardly alters the dihedral angle. The spectral response to the addition of alkali ions was measured using the corresponding perchlorate salt. The absorption spectra of **1** (5.0×10^{-5} M) with 1000 equiv of added salt are shown in Figure 2. The addition of NaClO₄ leads to a characteristic shift in the absorption maximum (λ_{max}) to a longer wavelength by 12 nm. As for the other alkali ions, the more their ionic radius differs from the one of Na⁺, the lesser the red shift. In titration experiments, the absorption spectra of **1** with various ion concentrations showed an isosbestic point, and their data were linearly fit using Benesi–Hildebrand plots.¹⁰ The results indicate that the fluoroionophore **1** selectively forms a 1:1 complex with the alkali ion. The binding constant of **1** with Na⁺ was estimated to be $1560 \text{ mol}^{-1} \text{ dm}^3$, while that with K⁺, which is the main interference in biological measurements, was found to be $280 \text{ mol}^{-1} \text{ dm}^3$. Although the selectivity of **1** for Na⁺ over K⁺ is low, only

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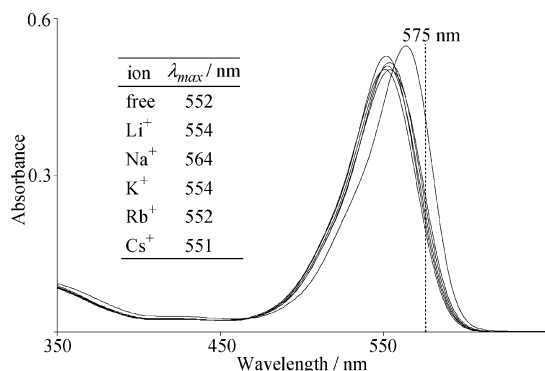


Figure 2. Response of absorption to added alkali salt.

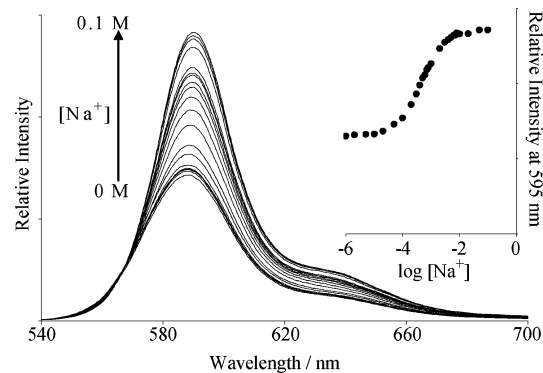


Figure 3. Fluorescence spectra excited at 575 nm. (Inset) Titration curve. The **1**–Na⁺ complex was found to dramatically shift the absorbance to longer wavelengths. It is likely that the two oxygen atoms at the benzyl positions are in close proximity to each other in **1**–Na⁺, inducing a decrease of the dihedral angles between the dipyrromethene plane and the aryl planes. Contrary to Burgess's examples, the decrease may lead to an enhancement of the orbital interaction, giving rise to the observed red shift.

In contrast to the absorption spectra, the emission maximum shifted only slightly even when Na⁺ was added. It appears that the structure of the singlet relaxed excited state of **1**–Na⁺ resembles that of the ion-free **1**. Moreover, the fluorescence quantum yield ($\Phi_f = 0.68$) does not change significantly by adding Na⁺. This is in contrast to fluoroionophores relying on a PET mechanism. It implies that the rates of fluorescence, internal conversion, intersystem crossing, and PET (if present) are hardly changed by the Na⁺ binding. For the purpose of a sensitive detection, titration data in the emission mode were recorded by exciting at 575 nm, where the increase in the absorbance is the highest (Figure 2). Figure 3 shows that the fluorescent intensity increases substantially with increasing concentrations of Na⁺. A plot of relative intensity of the fluorescence against log concentration of Na⁺ can be well fit to a sigmoidal curve, and the Na⁺ concentration of an unknown sample can be accurately determined from it.

In conclusion, we have revealed that the fluoroionophore **1** shows a specific red-shift response for the Na⁺ ion. The photophysical properties of **1**, which are the sharpness of the absorbance band, the high extinction coefficient, and the high fluorescence quantum yield, have been found to be advantageous for quantitative analyses. We believe that the conformational restriction approach can be extended to optical sensors for neutral molecules because the push–pull interactions between the host and guest are unnecessary for signal transduction, unlike that for PET and intramolecular charge transfer (ICT). Unfortunately, the fluoroionophore **1** is hardly soluble in water, as well as most of fluoroionophores, including Finney's molecules. However, a hydrophilic substituent in the place of the branched alkyl chain at the 8-position may render the sensor molecules useful in aqueous solution.¹¹ The next step of this investigation will be to enhance the wavelength shift using rigid recognition sites, as well as the application for anions and neutral molecules.

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Supporting Information Available: Preparative procedures and analytical data for compound **1** and its intermediates; Benesi–Hildebrand plots of **1** with Na⁺ and K⁺ (PDF). This material is available free of charge via the Internet at <http://pubs.acs.org>.

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