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Fluorescence Turn-On Sensor for Cyanide Based on a Cobalt(II)−Coumarinylsalen Complex

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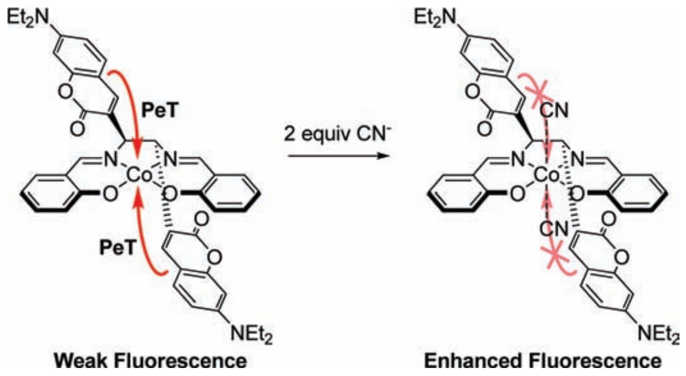
ABSTRACT



A Co(II)−salen based fluorescent sensor (1·Co) that can selectively recognize cyanide anions in 1:2 binding stoichiometry over other anions has been developed. 1·Co displayed fluorescence enhancement upon the addition of cyanide owing to the interruption of photoinduced electron transfer from the coumarin fluorophore to the cobalt(II) ion. A general regression method was developed to calculate the binding constants in the 1:2 binding system, through which the 1:2 binding between 1·Co and cyanide anions was estimated to be in the range of micromolar dissociation constants.

Optical sensors for anions have gained considerable attention due to their applicability to the detection of toxic anions, monitoring of enzyme reactions related to anions, and bioimaging of anions.[1] Cyanide anions are known to inhibit the process of cellular respiration in mammals by interacting strongly with a heme unit in the active site of cytochrome a_3.[2] The high level of intracellular calcium ion concentration is caused by the uptake of cyanide anions and triggers a cascade of enzymatic reactions to increase the level of reactive oxygen species, which finally inhibits the antioxidant defense system.[3] The widespread use of cyanide anions in industrial settings (1.5 million tons per year) and potential threats for terrorism[4] also increase the significance to sense cyanide anions by a simple and fast luminescence method. Most cyanide sensors operate on the basis of a 1:1 binding

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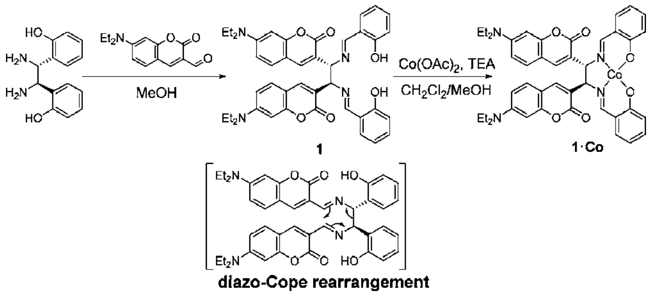
mode whether they are transition metal complexes[5] or nonmetal probes.[6] The 1:2 binding system, however, does closely resemble nature's binding or recognition systems like antibody−antigen[7] and protein−metal ion binding.[8] We thought that 1:2 binding between a metal complex and a cyanide anion would provide a useful sensing mechanism. Herein, we report a Co(II)−salen based fluorescent sensor (**1·Co**) bearing coumarin derivatives on the 1,2-positions of the ethylenediamine part of the salen ligand and cobalt(II) ion as a fluorescence quencher. The cobalt(II)−salen complex exhibited selective and tight binding toward cyanide anions on the basis of a 1:2 host−guest binding mode.

In addition, we developed a general method to determine the binding constants for a 1:2 binding system using a C program. Generally, a 1:2 binding system usually involves difficulties in quantifying binding properties such as binding constant and stoichiometry compared with a 1:1 binding system. We expected that the calculation method developed for the current 1:2 binding system will establish a general solution for quantification of the binding properties in multiple binding systems.

Compound **1** was prepared by the treatment of 2,2′-dihydroxyphenylene ethylenediamine with 2 equiv of 7-diethylaminocoumarin-3-carboxaldehyde through a diaza-Cope rearrangement reaction.[9] The metal complex, **1·Co**, was obtained by mixing **1** with cobalt(II) acetate in the presence of triethylamine (TEA), followed by recrystallization of the complex in methanol and dichloromethane (Scheme 1).[10]

Scheme 1. Synthetic Strategy of **1·Co**



The effect of the metal coordination on the emission spectra was measured by fluorescence spectroscopy: the cobalt−salen complex (**1·Co**) showed weak fluorescence emission compared with ligand **1** because there seems to exist an intramolecular photoinduced electron transfer (PeT) from the coumarin moiety to the cobalt cation of **1·Co**. We expected that the addition of cyanide anions would cause an alteration in HOMO and LUMO energy levels and lead to a significant change in the fluorescence intensity of **1·Co** by blocking the PeT pathway (Figure 1).

As expected, we found that the fluorescence of the **1·Co** complex was significantly enhanced upon the addition of cyanide anions. 1:2 Complexation between **1·Co** and the cyanide anion was confirmed by high-resolution mass spectral analysis: observed *m/z* 803.2341, calculated 803.2341 for [**1·Co·(CN$^-$)$_2$**]. The effect of anions on the emission spectra of **1·Co** was examined by adding various anions to the cobalt−salen complex in acetonitrile. **1·Co** exhibited a significant fluorescence enhancement upon the addition of cyanide, whereas other anions showed no detectable fluorescence changes (Figure 2). Compared to cyanide, fluoride showed a little fluorescence increase even though fluoride is a much more basic anion.[11] The nucleophilic azide anion also did not show any significant fluorescence change. These

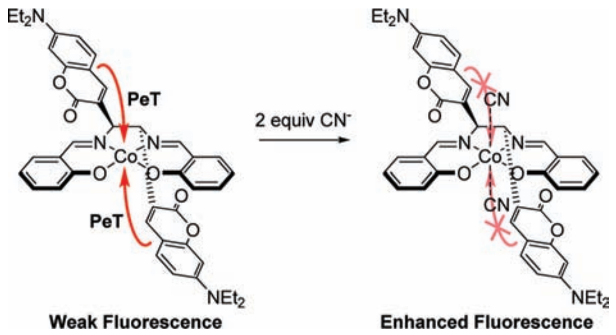


Figure 1. Complexation of the cyanide ion with **1·Co**.

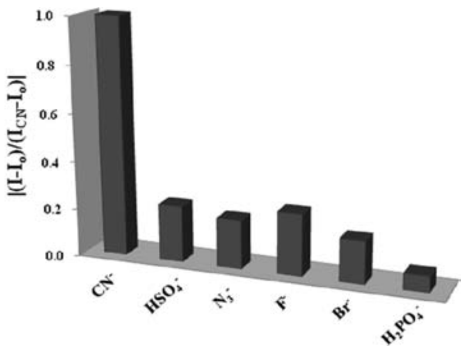


Figure 2. Relative fluorescence emission of **1·Co** (5 μM, CH_3CN) in the presence of various anions (10 μM). I_O = emission of **1·Co**. I_{CN} = fluorescence emission intensity of **1·Co** in the presence of 2 equiv of CN^-. All the anions were used as tetrabutylammonium salts.

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results suggest that **1·Co** has a high selectivity for cyanide over other anions.

To address the origin of the fluorescence enhancement of **1·Co** by the coordination of cyanide anions, the HOMO and LUMO energy levels of the cobalt−salen complex in the absence and in the prescence of cyanide anions were measured through cyclic voltammetric and UV−vis spectroscopic measurements by using the method of Nagano and co-workers.[12] The energy diagrams indicate that a donor-excited PeT could occur in the absence of cyanide anions, and therefore an electron transfer takes place from the excited coumarin fluorophore to the LUMO of the cobalt−salen complex. The PeT is, however, prohibited in the presence of cyanide anions by the raised LUMO level of the cobalt−salen complex, which can enhance the fluorescence of **1·Co** upon the addition of cyanide (Figure 3). The fluorescence enhancement possibly comes from the strong coordination ability of the cyanide anion to **1·Co**.[5] This strong coordination of cyanide will alter the energy levels in the cobalt(II)−salen complex, especially raising the LUMO level of the cobalt(II)−salen moiety enough to block the donor-excited PeT and enhance the fluorescence of **1·Co**. However, weak or noncoordinating anions do not complex with the cobalt ion and thus cannot block the donor-excited PeT pathway in **1·Co**. Therefore, the selectivity of **1·Co** plausibly comes from the stronger coordination ability of the cyanide anion over other anions.

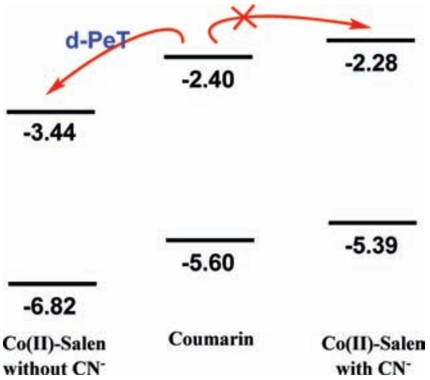

Figure 3. Energy diagrams (in eV) of coumarin and Co(II)−salen without and with cyanide anion, which was measured from cyclovoltametry and UV−vis spectroscopy.

As expected, a Job's plot for binding between **1·Co** and cyanide has shown a 1:2 binding stoichiometry (Supporting Information).[13] To calculate the binding constants for the 1:2 binding system from the spectral data without assumptions,[14] we have introduced a simple regression program using C language, which is generally applicable to any "one-to-two" binding system (Supporting Information).

Using the program, K_1 and K_2 for cyanide binding to **1·Co** were determined to be $K_1 \geq 10^7$ M^{-1} and $K_2 = 4.0 \times 10^5$ M^{-1} by fluorescence titration in acetonitrile.[15] It is remarkable that the simple cobalt(II)−salen complex shows such a tight binding toward cyanide anions with micromolar dissociation constants. The calculation program shows satisfactory results. The fluorescence intensity constants for HG and HG_2 were calculated to be 166 and 235, respectively, which are very similar to the observed intensities (Figure 4).

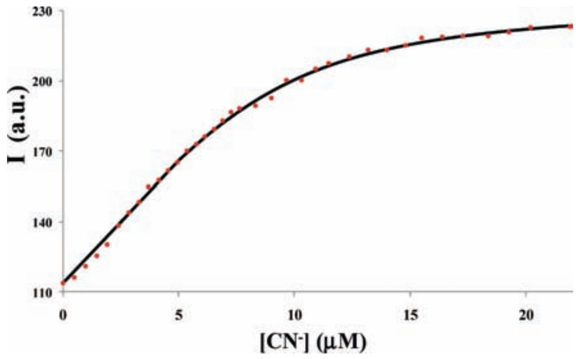

Figure 4. Fluorescence titration curve by the addition of cyanide (0−21.9 μM) to **1·Co** (5 μM) in acetonitrile. Calculated (line) and observed data (dot).

In summary, we have developed a Co(II)−salen complex (**1·Co**) which exhibited selective and tight binding to a cyanide anion. **1·Co** displayed a significant fluorescence enhancement upon the addition of cyanide owing to the interruption of photoinduced electron transfer from the coumarin fluorophore to the cobalt(II)−salen moiety. We also developed a general regression method to estimate

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(15) Using the program, K_1 was calculated over 10^7 M^{-1} in acetonitrile, which is above the limit of detection. Detailed programming for the calculation of K_1 and K_2 is described in the Supporting Information.

the binding constants in the 1:2 binding system and found the dissociation constants of **1·Co** to be in the range of micromolar concentrations for cyanide anions.

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Supporting Information Available: Synthetic procedure and selected spectral data for compounds **1** and **1·Co**, fluorescence spectra, Job's plots, electrochemical data, and a regression program for the determination of binding constants. This material is available free of charge via the Internet at http://pubs.acs.org.

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