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A Fluorescence Turn-on Sensor for Cyanide Anion Based on Exciplex Signaling Mechanism

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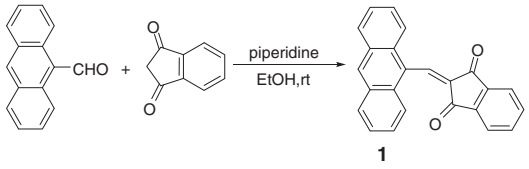
A new fluorescent chemosensor comprising anthracene and indanedione-based Michael receptor, which recognizes cyanide anion with high selectivity was designed and synthesized. The Michael addition of cyanide to the chemosensor elicits a fluorescence enhancement at a longer wavelength, which constituted the signature for cyanide detection. The mechanism of exciplex formation was proposed for the interesting observation.

Anion recognition is an area of growing interest in supramolecular chemistry due to its important role in a wide range of environmental, clinical, chemical, and biological applications.[1] Among various anions, cyanide is one of the anions of most concern because of its being widely used in synthetic fibers, resins, herbicide, and the gold-extraction process.[2] However, cyanide anion is extremely detrimental and could be absorbed through lungs, gastrointestinal track, and skin, leading to vomiting, convulsion, loss of consciousness, and eventual death.[3] Thus, there is a need for an efficient sensing system to monitor cyanide concentration from contaminant sources. A variety of colorimetric and fluorescent probes for cyanide have been developed over the past ten years by making use of the coordination ability and the nucleophilic reactivity of cyanide,[4] which involve addition with Zn^{2+}–porphyrin, Ru^{2+}–pyridine, Co^{2+}–salen,[5] displacement,[6] as well as bond-forming reaction between the cyanide and either an electrophilic carbon[7] or a boron center.[8] However, many of them have delayed response time and require high equivalents (100 or higher) of cyanide to reach a maximal fluorescent signal.

Recently, Lin reported a coumarin-containing 2-formylacrylonitrile conjugate as doubly activated Michael receptor for ratiometric fluorescent detection of cyanide.[7t] The 2-formylacrylonitrile moiety in the molecule is highly reactive to cyanide, and only 5 equiv of cyanide was used in the assay. Intrigued by these, herein, we introduced an anthracene–indanedione Michael receptor **1**, with two strong electron-withdrawing groups, to increase the electrophilicity of the β-carbon of the probe. The results obtained showed that the probe exhibited higher reactivity toward CN^- with a fast response, and only 3 equiv of cyanide was required to reach spectral saturation. Interestingly, the fluorescence turn-on response of **1** toward cyanide is due to the exciplex formation[9] between indanedione anion and anthracene moiety in the **1**–CN adduct. To the best of our knowledge, only one example that used exciplex formation as signaling mechanism for anion recognition was reported.[9c]

Probe **1** could be conveniently synthesized via the condensation of 9-anthracenecarboxaldehyde with 1,3-indanedione in ethanol (Scheme 1 and Supporting Information; SI[11]). Structural identification of the compound was confirmed by ^{1}H NMR, ^{13}C NMR, and HRMS spectroscopy. We first examined the time-dependent changes in the absorption spectra of probe **1** (50 μM) upon reaction with CN^- (2 equiv) (Figure 1). The addition of CN^- elicits not only a significant absorption increase around 359 nm but also a dramatic absorption decrease around 466 nm. Notably, in the presence of 2 equiv of cyanide, the nucleophilic CN^- addition to the probe **1** occurs very rapidly (within 1 min). Thus, high reactivity is the unique feature of probe **1** when compared to some known fluorescent cyanide probes.



Scheme 1. Synthesis of probe **1**.

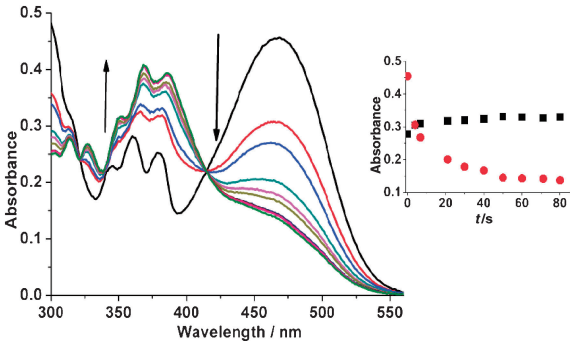


Figure 1. Time-dependent changes in the absorption spectra of probe **1** (50 μM) upon reaction with CN^- (2 equiv) in CH_3CN. The arrows indicate the change of incubation time from 0 to 80 s. Inset: Time-dependent absorption intensity of probe **1** at 466 (● in red) and 359 nm (■) in the presence of CN^- (2 equiv).

To get insight into the binding of CN^- with **1**, the absorption spectra of **1** upon titration with CN^- were recorded. As shown in Figure 2, free **1** exhibits a main absorption peak at 466 nm and the absorption bands of anthracene moieties centered at $\lambda = 359$ nm. Upon addition of increasing amounts of CN^- to a solution of **1**, the absorbance at 466 nm decreased gradually, whereas the absorbance of the anthracene moiety increased gradually. An obvious color change from yellow to colorless was clearly observed. In fact, only 3 equiv of cyanide

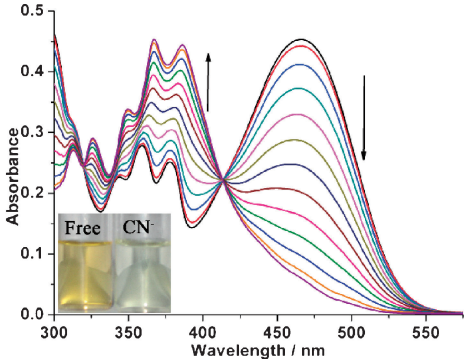


Figure 2. Concentration-dependent changes in absorption spectra of probe **1** (50 μM) upon gradual addition of CN^- (0–3 equiv) for 1 min in CH_3CN.

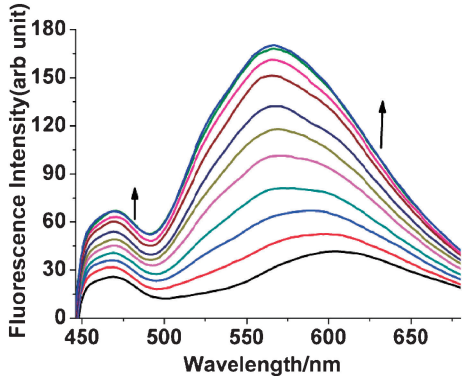


Figure 3. Concentration-dependent changes in fluorescence spectra of probe **1** (50 μM) upon gradual addition of CN^- (0–2 equiv) for 1 min in CH_3CN with excitation at 413 nm.

used in the assay within 1 min is impressive as many reported cyanide probes require high equivalents of cyanide to reach a maximal spectral signal. In addition, two clear isosbestic points at 319 and 413 nm were observed during the spectral titration, indicating the formation of a well-defined **1**–CN adduct. The Job plot analysis of the absorbance titrations revealed a maximum at about 0.5 mol fraction (Figure S1[11]), in line with the proposed 1:1 binding stoichiometry.

Next, we investigated the concentration-dependent changes in the fluorescence spectra upon incubation of **1** (50 μM) with CN^- (Figure 3). When excited at 413 nm, the free probe **1** features a wide fluorescence band at 603 nm (Φ for **1**: 0.005) and a weaker band at 467 nm. The band at 603 nm arises from the ICT band of **1**, whereas the band at 467 nm is a typical emission of anthracene moiety probably due to the steric hindrance-induced slight deconjugation of **1**.[7t] Interestingly, with the addition of CN^-, the emission at 603 nm did not decrease, but significantly increased with a blue shift of 38 nm (Φ for **1**–CN: 0.02). Because Michael addition of CN^- with **1** really interrupts the π-conjugation of the molecule and blocks the ICT process, the fluorescence enhancement at long wavelength of **1** upon addition of CN^- is abnormal. In fact, the case can be rationalized by exciplex formation.[9] As shown in Figure 4, in the absence of cyanide anion, compound **1** contains a conjugated Michael receptor and possesses a rigid structure that is difficult to fold.

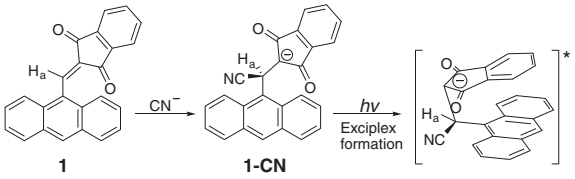


Figure 4. The propose sensing mechanism of **1** for CN^-.

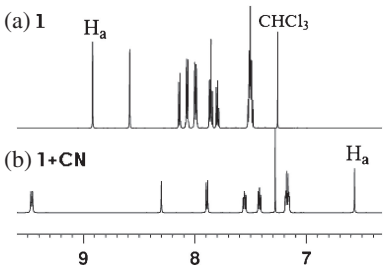


Figure 5. ^1H NMR spectral changes for probe **1** (10 mM in $CDCl_3$) upon addition of CN^- (2 equiv). (a) Probe **1** only; (b) probe **1** + CN^-.

However, when cyanide anion is added, the original π conjugation of the molecule is interrupted. As a result, the whole molecular structure becomes flexible, which makes it easy for the two parts of compound **1** to fold. Consequently, light excitation may induce the interaction of 1,3-indanedione anion with anthracene, leading to exciplex formation. In addition, the fluorescence enhancement at short wavelength (467 nm) is probably a result of the inhibition of PET (photoinduced electron transfer) quenching from the anthracene to the indanedione-containing Michael receptor upon addition of cyanide.

The binding pattern between **1** and CN^- was also examined by ^1H NMR titration experiment (Figure 5). Upon addition of 2 equiv of n-Bu_4NCN to a $CDCl_3$ solution of **1**, the signals attributed to **1** disappeared with the appearance of a set of new signals. Moreover, the fact that resonance signal of the vinylic proton (H_a) at around 8.84 ppm was shifted to 6.56 ppm upon the addition of cyanide and no signal corresponding to the α-proton of the indanedione group was observed, suggests the formation of the stabilized anionic species **1**–CN. In addition, this formation of **1**–CN adduct was also characterized by mass spectrometry, in which peaks at m/z 360.1025 (calcd: 360.1030) corresponding to [**1**–CN] $^-$ were clearly observed (Figure S2[11]).

The detection limit of probe **1** for CN^- (Figure S3[11]) was calculated based on the fluorescence titration data according to a reported method.[10] Under the present conditions, a good linear relationship between the intensity and the cyanide concentration could be obtained with the concentration of cyanide between 0 and 10 μM, and the detection limit for CN^- was determined as 0.35 μM based on S/N = 3.

Another important feature of probe **1** is its high selectivity toward the CN^- over other competitive anions. Changes of fluorescence spectra of **1** (50 μM) caused by CN^- (5 equiv) and miscellaneous competing species (5 equiv), including F^-, Cl^-, Br^-, I^-, AcO^-, N_3^-, NO_3^-, SO_4^{2-}, and $H_2PO_4^-$, as n-Bu_4N salts, are recorded in Figure 6. As can be seen, these competitive species, including F^-, AcO^-, and $H_2PO_4^-$ which often show the strong interference to cyanide detection, did not lead to any

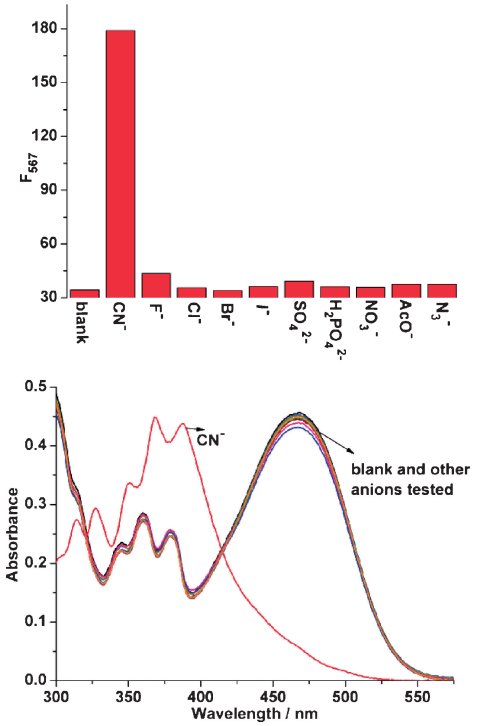


Figure 6. Emission intensities (F_{567}) of probe **1** (50 μM) in the absence or presence of various anions (5 equiv) as *n*-Bu_4N salts in CH_3CN (top). Absorption spectra of probe **1** (10 μM) in the presence of 5 equiv of various anion (below). Anions: CN^-, F^-, Cl^-, Br^-, I^-, N_3^-, NO_3^-, AcO^-, SO_4^{2-}, and $H_2PO_4^-$ as *n*-Bu_4N salts.

significant fluorescence changes at all, and the fluorescence emission spectrum of **1** remained almost undisturbed. The selective experiment was also performed by using UV–vis titration, and the high selectivity was also confirmed (Figure 6).

In addition, we also evaluated the effect of water on the reaction of **1** to CN^-. As found in most cyanide probes, the improvement of water content would result in longer reaction time due to big solvation. However, in 9:1 CH_3CN–water solution, the reaction of **1** and cyanide could be completed within 2 min at an elevated temperature of 50 °C (Figure S4[11]), but 10 equiv of cyanide was required to reach the spectral saturation (Figure S5[11]).

In summary, we have developed a new fluorescent chemosensor based on an anthracene-containing Michael receptor. The molecule exhibits excellent selectivity and sensitivity for cyanide detection. Exciplex formation was responsible for the recognition process. We hope that this report can provide a new concept for development of other novel chemosensors.

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