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Rational Design of a Dual Chemosensor for Cyanide Anion Sensing Based on Dicyanovinyl-Substituted Benzofurazan

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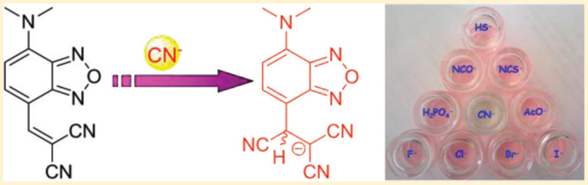
Supporting Information

ABSTRACT: A dicyanovinyl-substituted benzofurazan derivative (**C1**) was prepared as an efficient ratiometric chemosensor for cyanide anion detection in aqueous acetonitrile solution. Mechanism studies suggested that the nucleophilic addition of cyanide to the *α*-position of the dicyanovinyl group blocked the ICT progress of **C1** and induced remarkable emission and absorption shift.

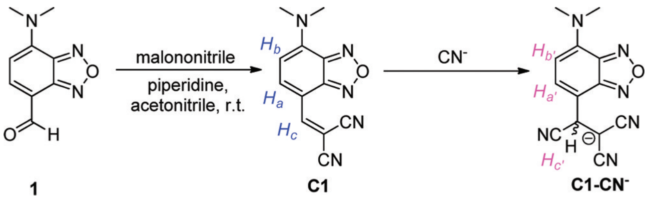


Because of the importance of anions in biological, environmental, and industrial processes, the development of optical chemosensors for anions has recently been an area of great interest.[1] Among anions of interest, because of the extremely high toxicity of cyanide anion in physiological systems, and the continuing environmental concern caused by its widespread industrial use in petrochemical, gold mining, photographic, and steel manufacturing, many researchers have developed selective, sensitive, and easy methods for cyanide anion detection, especially in water and physiological conditions.[2] Recently, optical sensors for cyanide anion have received considerable interest owing to their simple, inexpensive, and rapid implementation.[3] Several sensor systems for cyanide anion detection have been reported to date such as utilization of the coordination of cyanide anion with metal ion,[4] boronic acid derivatives,[5] and CdSe quantum dots.[6] Other strategies including hydrogen-bonding interactions were also involved.[7] For the purpose of minimizing the interference of other anions, many nucleophilic addition reaction mechanism based cyanide anion sensors have been reported.[8] Among these cyanide sensors, vinyl-substituted derivates display both selective and sensitive responses to various concentrations of cyanide anion.[9] However, most of the reported vinyl-substituted cyanide anion sensors only can be operated in pure or mixed organic solvent. For example, Lee and coworkers first reported a *β*-vinyl-substituted calix[4]pyrrole (**sensor 1**) as a ratiometric cyanide sensor.[9a] The nature of its absorbance-based ratiometric response for cyanide anion detection in pure organic solvent restricted its practical use in water-required conditions.

With these considerations in mind, we report here a simple synthesized benzofurazan (2,1,3-benzoxadiazole, **BD**) derivative (**C1**) that exhibits a selective, colometric, and ratiometric response toward cyanide anion in aqueous acetonitrile solution. **BD** derivatives with the electron-donating group (**D**) and the electron-accepting group (**A**) occupying the 4- and 7-positions, respectively, are the typical ICT (intramolecular charge transfer) fluorophores, which are widely used as reporters in chemosensors.[10] The **D**/**A** tuning of **BD** may lead to the different emission nature.[10a] In **C1**, the dicyanovinyl group is conjugated to the 7-position of **BD** both as **A** and a cyanide-dependent reactive subunit, while the *N*,*N*-dimethylamine group at the 4-position acts as **D**. It is expected that cyanide anion can add to the *α*-position of the dicyanovinyl group to generate stabilized anionic species **C1-CN**$^-$. This nucleophilic addition is expected to inhibit the conjugation of the dicyanovinyl group with **BD** and a hypsochromic shift of absorption, and emission should be induced by the decreasing of electron-accepting ability. Then the goal of fluorescence ratiometric and colormetric response to cyanide anion would be achieved.

C1 was synthesized by a one step reaction as depicted in Scheme 1. Condensation of compound **1**[11] with malononitrile in the presence of piperidine in acetonitrile gave rise to **C1** as a red solid in 85% yield. The purity of **C1** was confirmed by ^{1}H, ^{13}C NMR, ESI-MS, and elemental analysis.

Scheme 1. Synthesis of C1



The ability of **C1** to act as a highly selective cyanide anion sensor was first investigated by UV−vis spectroscopy. As shown

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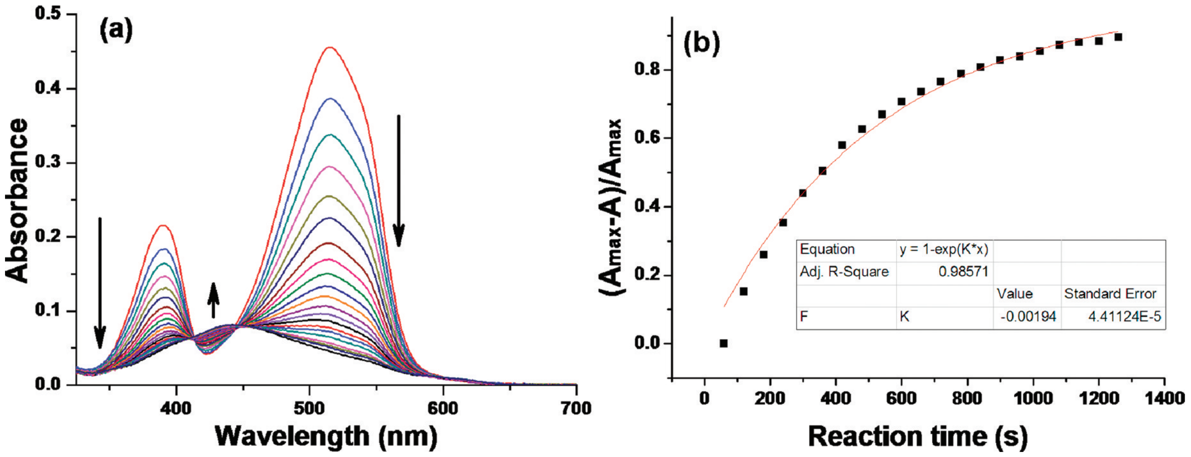


Figure 1. (a) Time-dependent UV−vis spectral changes of **C1** (2×10^{-5} M) seen upon the addition of 5 equiv of cyanide anion in CH_3CN-H_2O (95:5 v/v). The spectra were recorded after incubation of **C1** with cyanide anion for 0 to 1260 s at 25 °C. (b) Time-dependent changes in the absorption at λ_{abs} = 513 nm observed from the reaction between **C1** and cyanide anion. The red curve overlaid on the experimental data points is theoretical fit generated using $k' = (1.94 \pm 0.04) \times 10^{-3}\ s^{-1}$.

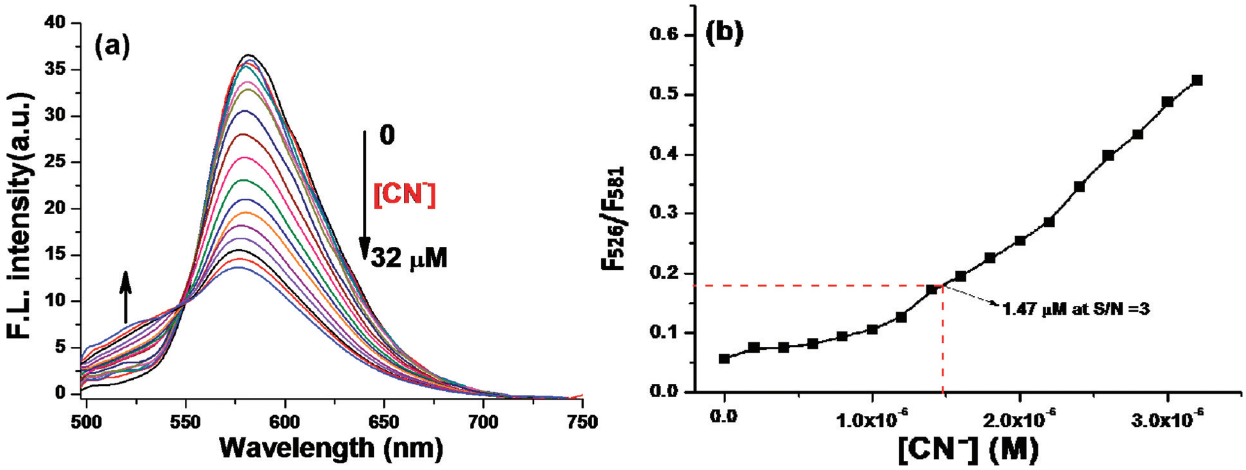


Figure 2. (a) Fluorescence responses of **C1** (2×10^{-5} M) toward different concentrations of cyanide anion in CH_3CN-H_2O (95:5 v/v). Each spectrum was obtained after cyanide anion addition at 25 °C for 2 min. (b) Titration profile based on the emission ratio at 526 and 581 nm, F_{526}/F_{581}.

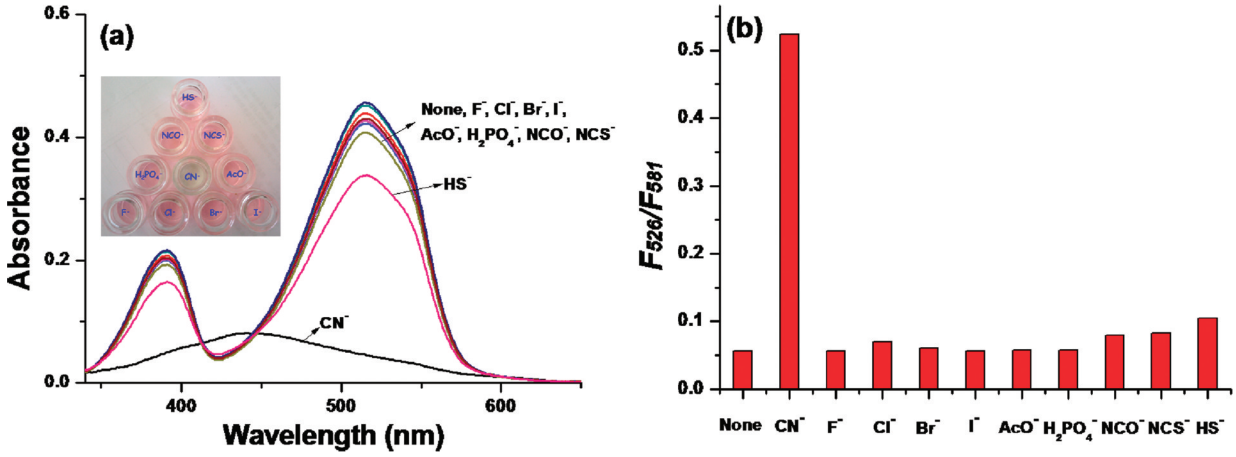


Figure 3. (a) UV−vis spectral changes of the free **C1** (2×10^{-5} M) seen upon the addition of 5 equiv of various anions in CH_3CN-H_2O (95:5 v/v). Each spectrum was obtained after addition of various analytes at 25 °C for 2 min (inset: color changes of **C1** (2×10^{-5} M) seen in the presence of 5 equiv of CN^-, F^-, Cl^-, Br^-, I^-, AcO^-, $H_2PO_4^-$, SCN^-, OCN^-, and HS^-). (b) Fluorescence responses of (2×10^{-5} M) toward various analytes (5 equiv in CH_3CN-H_2O (95: 5, v: v). All data represent the fluorescence intensity ratio F_{526}/F_{581}.

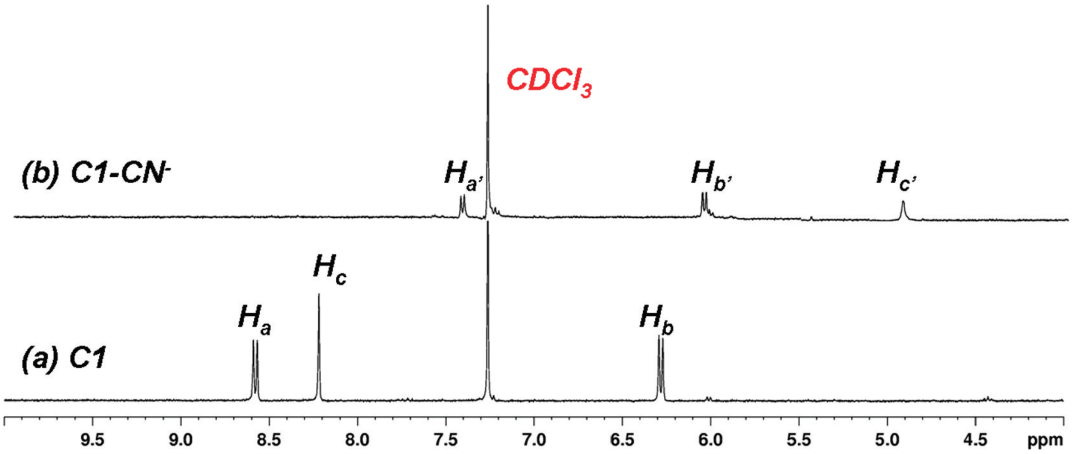


Figure 4. ^{1}H NMR spectral changes seen upon the addition of cyanide anion (as its tetrabutylammonium salts) to **C1** (2.4 mM) in $CDCl_3$ at 25 °C.

in Figure 1, free **C1** has two main absorption bands centering at 391 (ε = 1.07 × 10^{-4} $M^{-1}cm^{-1}$) and 513 (ε = 2.3 × 10^{-4} $M^{-1}cm^{-1}$) nm, which can be assigned to the ICT and $\pi-\pi^*$ transition bands, respectively. When 5 equiv of cyanide was added, distinct reduction of these two bands was observed, accompanied by the increase of a new band centered at 441 nm (ε = 4.07 × 10^{-3} M^{-1} cm^{-1}). The evident hypsochromic shift of ICT band from 513 to 441 nm suggests that the decreased electron-accepting ability of the 7-A group was induced by cyanide anion addition to the dicyanovinyl group. The calculated pseudo-first-order rate constant (k') for cyanide anion addition was (1.94 ± 0.04) × 10^{-3} s^{-1} (for details, see the Supporting Information).[12] This result suggests that **C1** is more highly reactive to cyanide anion than the reported dicyanovinyl-based cyanide anion sensors.[9a]

Free **C1** in CH_3CN-H_2O (95:5 v/v) solution exhibits a moderate fluorescence (Φ = 0.7%) with one emission band centered at 581 nm, with λ_{ex} of 485 nm. Upon addition of different concentrations of cyanide anion, the maximum emission peak undergoes a blue shift to 526 nm with an isoemission point at 549 nm (Figure 2). Additionally, the fluorescence intensity ratio of **C1** at 526 and 581 nm (F_{526}/F_{581}) shows a drastic change from 0.05 to 0.55, and the fluorescence detection limit is estimated to be 1.47 × 10^{-6} M at S/N = 3 (for details, see the Supporting Information).[13] Obviously, chemodosimeter C1 is a promising indicator for the cyanide anion of low concentration in samples.

For the purpose of evaluating the cyanide anion selective nature of **C1**, absorption spectral changes upon addition 5 equiv of various anions including F^-, Cl^-, Br^-, I^-, AcO^-, $H_2PO_4^-$, SCN^-, OCN^-, and HS^- were studied. As shown in Figure 3, in all these cases, the two absorption bands of **C1** are slightly decreased. On the other hand, the selectivity observed by UV−vis monitoring is matched when **C1** was employed as a colormetric sensor for cyanide anion. In contrast to the visually observed pink to colorless change associated with the reaction of **C1** with cyanide anion, no significant color changes were promoted by addition of other anions (Figure 3a). The selective fluorescence response of **C1** to cyanide anion was also investigated (Figure 3b). As expected, nearly no emission intensity ratio (F_{526}/F_{581}) changes were observed in the presence of F^-, Cl^-, Br^-, I^-, AcO^-, $H_2PO_4^-$, SCN^-, OCN^-, and HS^-.

The mechanism of **C1** in sensing of cyanide anion was monitored the ^{1}H NMR spectral changes induced via the addition of cyanide anion in $CDCl_3$ at room temperature. As shown in Figure 4, the vinylic proton (H_c) shown at 8.21 ppm completely disappears upon the addition of 1 equiv. of cyanide anion, while a new signal arises at 4.87 ppm ($H_{c'}$). Meanwhile, the protons H_a and H_b at **BD** show a large upfield shift from 8.56 and 6.27 to 7.42 and 6.08 ppm, respectively. These observations obviously indicate that the cyanide anion is added to the vinyl group.

To investigate the mechanism of the colormetric and ratiometric reponse of **C1** to cyanide anion, DFT calculations were carried out for the **C1** and **C1**-**CN**$^-$ adduct with 6-31G* basis sets using a suite of Gaussian 03 programs.[14] The optimized structures of **C1** and **C1**-**CN**$^-$ are shown in Figure 5. **C1** has a conjugated bridge (−C=C−) between the **BD** and dicyano groups, and the dihedral angle between **BD** and dicyano group is 114°. The reaction product **C1**-**CN**$^-$ has a saturated bridge (−C−C−), and the dihedral angle between **BD** and the dicyano group is 137°. This structural difference leads to a significant difference in π-conjunction between **C1** and **C1**-**CN**$^-$.

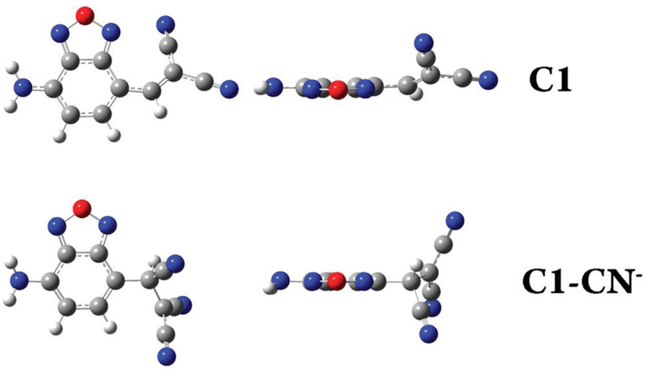
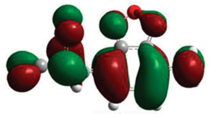
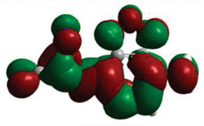
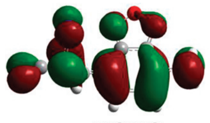
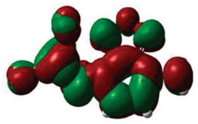
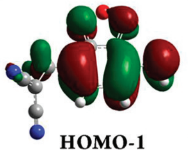
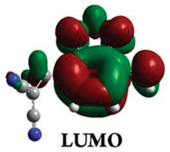


Figure 5. Optimized structures of **C1** and **C1**-**CN**$^-$.

Detailed information regarding the marked absorption and emission blue shift upon the formation of **C1**-**CN**− can be obtained from TDDFT (time-dependent DFT) calculations as well. The calculated excitation wavelengths of **C1** and **C1**-**CN**$^-$ are 2.89 eV/428 nm and 3.06 eV/404 nm, respectively, which are slightly lower but in good agreement with the experiment. Figure S4 shows simulated absorption spectra of **C1** and **C1**-**CN**$^-$. The calculated molecular orbitals and the electronic

Table 1. Calculated HOMOs and LUMOs of C1 and C1-CN$^-$ and Electronic Contributions of the Relevant Excitations for C1 and C1-CN$^-$

	Molecular orbitals		Electronic contribution of transition
C1	 HOMO	 LUMO	Homo ⟶Lumo 28%
	 HOMO	 LUMO+1	Homo ⟶Lumo+1 40%
C1–CN$^-$	 HOMO-1	 LUMO	Homo-1 ⟶Lumo 8.86%

contribution of transition are shown in Table 1. In **C1**, HOMO→LUMO and HOMO→LUMO+1 transitions contribute 28% and 40% to the excitation of **C1**, respectively, while in **C1-CN**$^-$, the HOMO-1→LUMO transition contributes only 8.8%. As expected from the LUMOs of **C1**, it is clear that the ICT takes place through a conjugated bridge between the **BD** and dicyano groups, while this is obviously prohibited in **C1-CN**$^-$ due to the nonconjugated bridge. This result suggests that the marked absorption and emission blue shift from **C1-CN**$^-$ ascribes to its weakened ICT process relative to that in **C1**.

■ CONCLUSIONS

In summary, we have described a new dual functional, dicyano-vinyl substituted benzofurazan chemosensor **C1** for the detection of cyanide, based on the nucleophilic addition of cyanide anion to the α-position of dicyano-vinyl group. **C1** showed remarkable dual changes in absorption and emission bands for cyanide anion over other anions in aqueous acetonitrile solution. From the TDDFT calculations, it was determined that the colormetric and fluorometric sensing behavior of **C1** upon its reaction with cyanide was due to an ICT blocking event.

■ EXPERIMENTAL SECTION

Synthesis of C1. The acetonitrile solution (10 mL) containing compound **1** (0.382 g, 2.0 mmol), malononitrile (0.132 g, 2.0 mmol), and piperidine (0.170 g, 2.0 mmol) was stirred at room temperature for 2 h. After the removal of solvent in vacuo, the residue was purified by column chromatography (silica gel, CH_2Cl_2, $R_f = 0.4$), and pure **C1** was obtained as a red solid in 85% yield: mp 184−185 °C dec; ^1H NMR (400 MHz, $CDCl_3$) $\delta = 3.59$ (s, 6 H), 6.27−6.29 (d, 1 H, $J = 8.4$ Hz), 8.21 (s, 1 H) 8.56−8.58 (d, 1 H, $J = 8.8$ Hz); ^{13}C NMR (400 MHz, $CDCl_3$) $\delta = 8.6$, 104.7, 104.7, 108.8, 114.9, 115.3, 137.3, 144.1, 145.1, 150.1, 150.3; ESI-MS 239.25[M + H]$^+$. Anal. Calcd for $C_{12}H_9N_5O$: C, 60.25; H, 3.79; N, 29.27. Found: C, 60.58; H, 3.78; N, 29.02.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Synthesis of **C1**, experimental details, and **Z**-matrix and total energy of **C1** and **C1-CN**$^-$. This material is available free of charge via the Internet at http://pubs.acs.org.

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