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KCN sensor: unique chromogenic and 'turn-on' fluorescent chemodosimeter: rapid response and high selectivity†

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An indole conjugated coumarin 1 for KCN chemodosimeter has been prepared and displayed considerable dual changes in both absorption (blue-shift) and emission (turn-on) bands exclusively for KCN. DFT/TDDFT calculations support that the fluorescence enhancement of 1-KCN is mainly due to blocking of the ICT process.

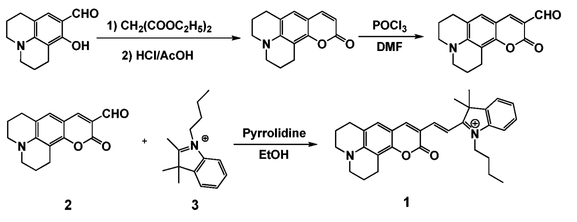
The recognition and sensing of anions have received considerable attention because of their important roles in biological, industrial, and environmental processes.[1] Cyanide is especially known to be a detrimental anion causing poisoning in biology and in the environment.[2] Cyanide exists in numerous forms including gaseous hydrogen cyanide (HCN), water-soluble potassium or sodium cyanide salts. Its poisoning may occur in industry, particularly in the metal trades, mining, electroplating, jewellery manufacturing, and X-ray film recovery.[3] In particular, KCN has been known to be one of the most lethal chemical reagents and even used as a terror material.[4]

Taking these considerations into account, several receptors as optical sensors have been proposed for cyanide ion detection.[5,6] However, many of these sensors rely on a hydrogen-bonding motif and have generally displayed moderate selectivity over other anions.[6] To overcome these limitations, reaction based CN^- receptors have been recently developed; these include oxazines,[7] cationic borane derivatives,[8] acridinium salts,[9] and β-turn motif.[10] Most of them display either color changes or fluorescence changes, individually, but there are only a few cases showing simultaneous changes in both absorption and emission spectra.[6–12] Moreover, those dual spectral change-based sensors showed fluorescence quenching (On-Off) after the addition of CN^-.[9,12] In the other aspect, in order to exclude the cation effect in sensing system for the CN^- detection, tetrabutylammonium (TBA) cation has been usually used as a counter cation. However, since KCN is known to be very toxic and therefore limited to 0.8 mg L^{-1} in drinking water by EPA standard, detection of KCN rather than that of $(n\text{-Bu})_4N^+CN^-$ should be more meaningful in aspect of a practical application in CN^- detection. The corresponding response time for the CN^- detection has also remained problematic.

In light of these considerable drawbacks in CN^- sensing reported so far, we have been preparing a promising CN^- (particularly KCN) sensor, new indole conjugated coumarin **1** able to function as a selective and sensitive dual chromogenic and 'turn-on' fluorogenic sensing as well as naked-eye detector for the KCN with a rapid response time (<1.0 s). In addition, upon reaction of CN^- ion, we have clearly elucidated the fluorescence enhancement (turn-on) of **1** by DFT/TDDFT calculation.

The choice of indole moiety conjugated to coumarin[13] as a chromogenic sensory molecule was mainly based on the fact that the conjugated indole skeleton could function as a color-reporting group. Conjugation of indole with coumarin moiety as seen in **1** (synthetic Scheme 1) might modulate the internal charge transfer (ICT) state and give rise to large dual color and fluorescence changes in the presence of CN^-. Compound **1** was synthesized in 41% yield *via* base-mediated condensation of coumarin-aldehyde **2**[14] with indolium derivative **3**[15] in absolute ethanol in the presence of pyrrolidine. Structural identification of each synthetic compound was confirmed by ^{1}H-NMR, ^{13}C-NMR, FT-IR, and FAB-MS spectroscopy (Supporting Information†).

The spectral changes of **1** towards various anions were explored by UV-vis absorption and fluorescence spectrophotometry. Among 12 anions (K^+ salts of F^-, Cl^-, Br^-, I^-, $CH_3CO_2^-$, HSO_4^-, HPO_4^{2-}, HCO_3^-, NO_3^-, ClO_4^-, CN^-, and SCN^-) tested in a solution of H_2O–CH_3CN (5 : 95, v/v), only CN^- ion responded to **1** with a remarked color change from dark blue to yellow and a fluorescence change from weak



Scheme 1 Synthetic pathway of **1**.

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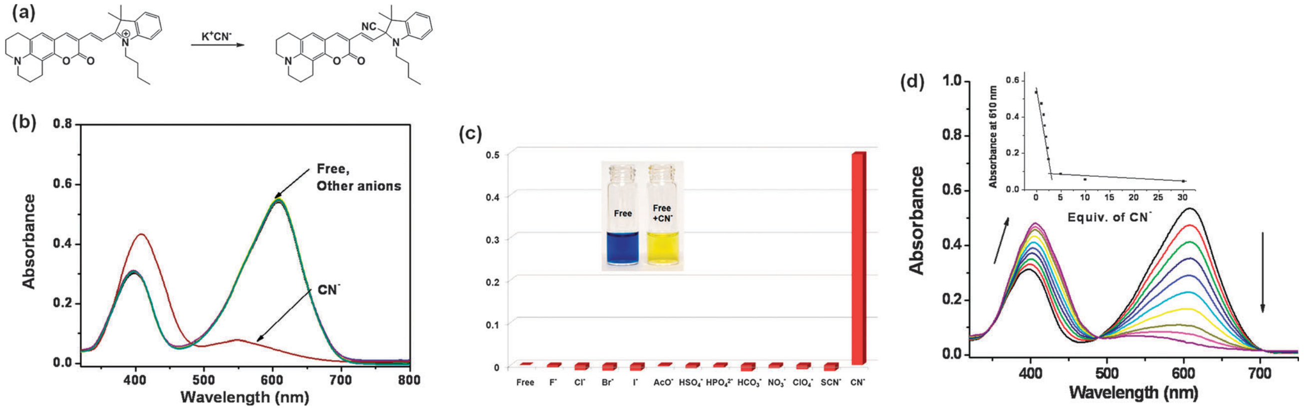

Fig. 1 (a) Reaction mechanism of **1** for the CN^- addition. (b) Absorption spectra and (c) relative responses of **1** (20.0 μM) at 610 nm with addition of K^+ salts of F^-, Cl^-, Br^-, I^-, $CH_3CO_2^-$, HSO_4^-, HPO_4^{2-}, HCO_3^-, NO_3^-, ClO_4^-, CN^-, and SCN^- (10 equiv, respectively) in H_2O–CH_3CN (5 : 95, v/v). (d) Absorption titration profile of **1** (20.0 μM) in H_2O–CH_3CN (5 : 95, v/v) solution upon addition of KCN (0, 1, 1.5, 1.7, 2, 2.3, 2.5, 3, and 10 eq). (Inset) Changes in absorbance at 610 nm.

blue to intense green. Compound **1** showed two characteristic UV-vis absorbance bands centered at 398 and 609 nm in a solution of H_2O–CH_3CN (5 : 95, v/v). In the presence of CN^- ion, the absorption band at 398 nm was red-shifted to 409 nm and a band at 610 nm completely disappeared (Fig. 1b). It is obviously thoughtful that in **1** an ICT takes place from the coumarin N atom to the positive charged indole group through the double bond conjugated spacer. This ICT is, however, disrupted by CN^- reaction with **1** simply because the nucleophilic addition of the cyanide anion toward the $-C{=}N\oplus-$ of **1** induces breaking of the indole conjugation as depicted in Fig. 1b. Thus, the reaction weakens its ITC to give an apparent color change of **1** from deep blue to pale yellow. Fig. 1d shows the absorption spectral changes of **1** upon the gradual addition of CN^-. The isosbestic point at 490 nm obviously suggests that reaction of **1** with CN^- produces a single component. More interestingly, we observed a remarkable fluorescence increase of **1** at 484 nm upon addition of CN^- ion, whereas no meaningful fluorescence changes were noticed with other potassium salt anions (Fig. 2).

To understand the absorption and fluorescence changes of **1** by KCN reaction, we carried out density functional theory (DFT) calculations with 6-31G* basis sets using a suite of Gaussian 03 programs.[16] The optimized structures of **1** and **1**-CN were shown in Fig. 3. Compound **1** has a conjugated sp^2 hybridized carbon bond between coumarin and indole groups.

Reaction product **1**-CN has, however, almost 90° (dihedral angle = 85°) tilted conformation and has a sp^3 hybridized carbon bond in the perpendicular direction to the coumarin ring. This structural difference gives rise to a significant difference in π-conjugation between **1** and **1**-CN, hence no ICT was observed in **1**-CN. The calculated HOMO–LUMO energy gaps of **1** and **1**-CN are 2.41 and 3.37 eV, respectively (Table S1†). As a result, experimental λ_{max} absorption peak changes of **1** (2.03 eV/610 nm) and **1**-CN (3.03 eV/409 nm) could be explained by the delocalization changes.

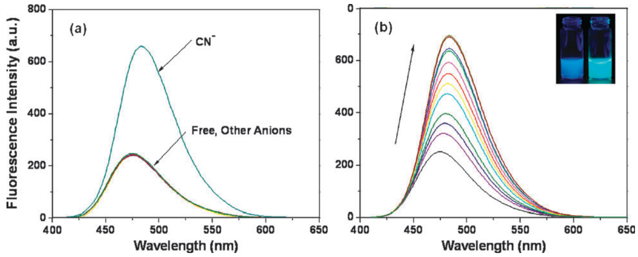

Fig. 2 Fluorescence spectra (a) and fluorescence titration spectra (b) of **1** (5.0 μM) in H_2O–CH_3CN (5 : 95, v/v) solution upon addition of KCN (0, 0.1, 0.2, 0.3, 0.5, 1.0, 1.1, 1.3, 2.0, and 3.0 eq). Excitation at 410 nm (slit 1.5/3).

Detailed information about marked fluorescence enhancement upon CN^- reaction with **1** can be obtained from time-dependent DFT (TDDFT) calculations as well. As noted in Table S1,† the calculated λ_{max} of **1** and **1**-CN are 2.41 and 3.37 eV, respectively, which are slightly overestimated but in good agreement with experiment. Fig. S7† shows simulated absorption spectra of **1** and **1**-CN, respectively. We noticed that **1** and **1**-CN have apparently separated λ_{max} bands. Thus, it could be expected that the maximum peak of **1** at 511 nm would be gradually decreased upon CN^- reaction whereas that of **1**-CN at 374 nm would be increased.

The molecular orbitals that are relevant to the excitations and the contributions of orbital transitions for **1** and **1**-CN are given in Fig. 4. In **1**, HOMO → LUMO solely contributes to the excitation, while in **1**-CN, the contribution of HOMO → LUMO is only 9.4% and that of HOMO-1 → LUMO is 90.6%. As expected, the electron densities of LUMO of **1**-CN are only distributed over the coumarin moiety, while those of LUMO of **1** are distributed over the entire coumarin through the indole moieties. The ICT blocking in **1**-CN is due to the conjugation breaking between coumarin and indole groups, which can be a main reason for the fluorescence enhancement of **1**-CN.

In addition, we investigated the ^1H NMR spectra of **1** in the presence of cyanide anions (Fig. S8†). The vinyl protons at δ 8.1 (Hd) and δ 7.9 (Hc) were upfield shifted to δ 6.9 (Hd) and δ 6.7 (Hc) upon cyanide addition at room temperature. The 1 : 1 reaction is confirmed by FAB-MS where a peak at m/z 494.30 is assigned to [**1**-CN] ion (Fig. S4†).

In cyanide detection, sensors utilizing an affinity of CN^- to Cu^{2+} to form stable $[Cu(CN)_x]^{n-}$ species have been recently attracting special attention.[17] In most fluorescence chemosensors, the fluorescence was reported quenched with addition of Cu^{2+}

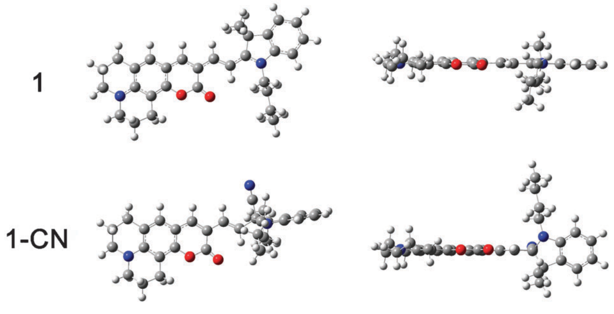

Fig. 3 The optimized structures of **1** and **1**-CN.

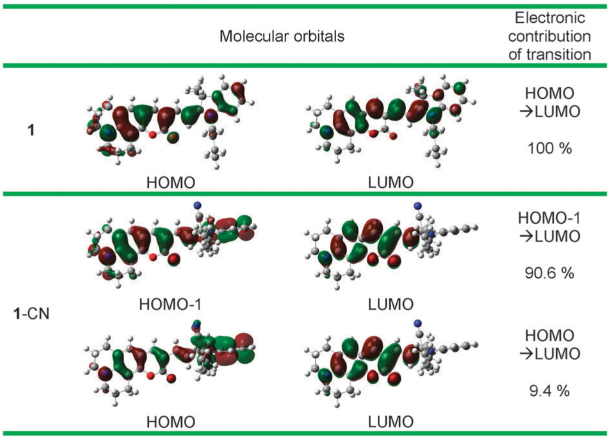

Fig. 4 Molecular orbitals and electronic contributions of the relevant excitations for **1** and **1**-CN.

because of PCT (photo-induced charge transfer) or heavy metal ion effect of the Cu^{2+} ion.[15] Upon the addition of cyanide anion, the quenched fluorescence is immediately recovered (turn-on) caused by a formation of stable $Cu(CN)_2$.[17,18] So, to address any possibility of the Cu^{2+} ion interference toward CN^- detection in our chemodosimetric system, we added KCN to a solution of **1**-Cu^{2+} and *vice versa*, and tested their absorption and emission spectral changes. In both cases, we observed same spectral patterns to those of original **1**-CN (Fig. S9†), strongly implicates that the chemodosimeter **1** implements an irreversible chemical reaction for the CN^- to exert a selective CN^- sensor without any inference with Cu^{2+} ion.

In summary, **1** containing a conjugated indole-coumarin skeleton provides an easy to make, simple, and efficient dual chromogenic and fluorogenic sensing molecule model. The conjugated chemodosimeter **1** showed remarkable dual changes in absorption and emission bands for KCN over other potassium salt anions. DFT/TDDFT calculations indicate that upon the addition of CN^- the fluorescence enhancement of **1** is mainly due to the blocking of conjugation-based ICT process.

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