ORGANIC
LETTERS

2012
Vol. 14, No. 1
130–133

A Selective, Colorimetric, and Fluorescent Chemodosimeter for Relay Recognition of Fluoride and Cyanide Anions Based on 1,1′-Binaphthyl Scaffold

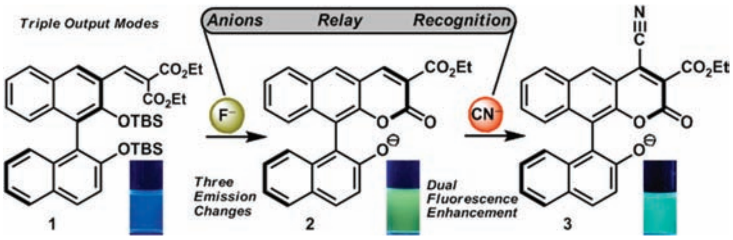
Ming Dong, Yu Peng, Yu-Man Dong, Ning Tang, and Ya-Wen Wang*

State Key Laboratory of Applied Organic Chemistry, Key Laboratory of Nonferrous Metals Chemistry and Resources Utilization of Gansu Province and College of Chemistry and Chemical Engineering, Lanzhou University, Lanzhou 730000, China

ywwang@lzu.edu.cn

Received October 30, 2011

ABSTRACT



The reaction-based relay recognition of fluoride and cyanide anions was demonstrated for the first time, with rapid response and unique triple (fluorescence color, intensity and absorption band) output modes in either of two sequential sensing events. Ratiometric determination of these two anions by fluorescence and/or absorbance spectra is also achieved.

There are two main pathways to anion sensing: displacement of a metal complex[1] (Scheme 1, path a in left block) and employment of an ion-pair receptor[2] (path b) through cooperative interactions among cobound ions and a heteroditopic host, except for a fundamental binding site–signaling subunit approach.[3] Thus, when choosing a host for the target anion, the shape and geometry of this anion should be taken into account carefully and the best match between the host and the anion must be obtained to get high selectivity. Compared to the above traditional chemosensor method, an alternative chemodosimeter approach[4] (Scheme 1, path c in right dashed block) based on an irreversible specific chemical reaction has emerged as an active research area of significant importance recently. However, considerable efforts have been devoted to the development of a chemodosimeter for *single* anions, and sequential recognition of *two* anions has not been developed so far. Inspired by relay catalysis[5] from synthetic organic chemistry, we envisioned the feasibility of relay recognition through the intermediacy product $\mathbf{P}^1$, which will be generated by the first recognition to anion $\mathbf{A}^1$ with

---

[1] For a review, see: (a) Nguyen, B. T.; Anslyn, E. V. *Coord. Chem. Rev.* **2006**, *250*, 3118. For recent examples, see: (b) ($Cu^{2+} \rightarrow CN^-$) Chung, S.-Y.; Nam, S.-W.; Lim, J.; Park, S.; Yoon, J. *Chem. Commun.* **2009**, 2866. (c) ($Ca^{2+} \rightarrow F^-$) Rochat, S.; Severin, K. *Chem. Commun.* **2011**, *47*, 4391. (d) ($Zn^{2+} \rightarrow CN^-$) Su, X.; Robbins, T. F.; Aprahamian, I. *Angew. Chem., Int. Ed.* **2011**, *50*, 1841.

[2] For a review, see: (a) Kim, S.-K.; Sessler, J. L. *Chem. Soc. Rev.* **2010**, *39*, 3784. For recent examples, see: (b) (Na^+ and F^-) Reeske, G.; Bradtmöller, G.; Schürmann, M.; Jurkschat, K. *Chem.—Eur. J.* **2007**, *13*, 10239. (c) (Cs^+ and F^-) Sessler, J. L.; Kim, S. K.; Gross, D. E.; Lee, C.-H.; Kim, J. S.; Lynch, V. M. *J. Am. Chem. Soc.* **2008**, *130*, 13162. (d) (Zn^{2+} and F^-) Chen, Y.; Wang, D.-X.; Huang, Z.-T.; Wang, M.-X. *Chem. Commun.* **2011**, *47*, 8112.

[3] Martínez-Máñez, R.; Sancenón, F. *Chem. Rev.* **2003**, *103*, 4419.

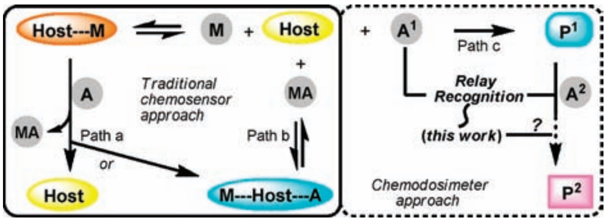
[4] For recent reviews about reaction-based sensing approach, see: (a) Cho, D.-G.; Sessler, J. L. *Chem. Soc. Rev.* **2009**, *38*, 1647. (b) Quang, D. T.; Kim, J. S. *Chem. Rev.* **2010**, *110*, 6280. (c) Jun, M. E.; Roy, B.; Ahn, K. H. *Chem. Commun.* **2011**, *47*, 7583.

[5] For a leading review, see: (a) Ambrosini, L. M.; Lambert, T. H. *ChemCatChem* **2010**, *2*, 1373. For selected examples, see: (b) Vora, H. U.; Rovis, T. *J. Am. Chem. Soc.* **2007**, *129*, 13796. (c) Nicewicz, D. A.; MacMillan, D. W. C. *Science* **2008**, *322*, 77. (d) Cernak, T. A.; Lambert, T. H. *J. Am. Chem. Soc.* **2009**, *131*, 3124. (e) Jones, S. B.; Simmons, B.; Mastracchio, A.; MacMillan, D. W. C. *Nature* **2011**, *475*, 183.

10.1021/ol202926e

the initial host and, in turn, trigger the second recognition to anion $\mathbf{A^2}$ as a relay host. Thus, the differences of spectra properties among the resulting products ($\mathbf{P^2}$, $\mathbf{P^1}$), host, and the specificity of two step reactions to two anions, respectively, are keys to the success of this novel concept.

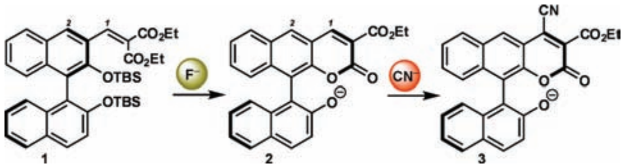
Scheme 1. Illustration of Approaches for Sensing Anions[a]



[a] A, A^1, A^2 = anions, M = metal ions, P^1, P^2 = products, MA = ion pair.

First, we chose F$^-$ and CN$^-$ as a combination to investigate the feasibility of the above new sensing fashion considering their impact on human beings: fluoride is used for prevention of dental caries and clinical treatment for osteoporosis,[6] and cyanide salts are also widely used in industrial settings such as gold mining and electroplating. However, even very small amounts of CN$^-$ are extremely toxic to living creatures; any accidental release can result in serious environmental disaster.[7] In connection with our continuing research of chemosensors (-dosimeters) based on an efficient 1,1′-binaphthyl fluorophore,[8,9] herein we report a highly selective, colorimetric, and fluorescent chemodosimeter **1** for F$^-$ and CN$^-$ (Scheme 2) as a preliminary demonstration of this interesting strategy (**A**nion **R**elay **R**ecognition, **ARR**). The designed **1** was easily prepared by double silylation of free phenol hydroxyl groups of 2,2′-dihydroxy-1,1′-binaphthyl-3-carbaldehyde[8b] with *tert*-butyldimethylsilyl chloride (TBSCl) and subsequent Knoevenagel condensation with diethylmalonate (see Supporting Information). Its structure was identified by ^{1}H, ^{13}C NMR, IR, and ESI mass spectrometry (Figures S1−S4).

Scheme 2. Relay Recognition of Fluoride and Cyanide



Next, the fluorescence properties of **1** were studied in THF solution.[10] As shown in Figures 1a and 2d (top), **1** exhibits unusual blue fluorescence,[11] corresponding to the emission band at 480 nm for intermolecular excimer formation of the binaphthyl fluorophore.[12] The other emission band for monomer formation is also observed at about 360 nm. Subsequently, F$^-$, Cl$^-$, Br$^-$, I$^-$, CN$^-$, AcO$^-$, ClO$_4{}^-$, CF$_3$SO$_3{}^-$, NO$_3{}^-$, HSO$_4{}^-$, H$_2$PO$_4{}^-$, BF$_4{}^-$, N$_3{}^-$, SCN$^-$, and HSCH$_2$COOH were used to measure the selectivity of probe **1** (50 μM, $\Phi = 0.9\%$), and fluorescence spectra were recorded after 3 min upon addition of 2.0 equiv of each of these anions. Compared to other anions examined, only F$^-$ generated a prominent fluorescence quench at 360 nm and a new peak at 460 nm assigned as a characteristic monomer peak of coumarin derivative **2** ($\Phi = 1.0\%$), appearing at the same time (Figures 1a and S12). And the change of the fluorescence emission band from 480 nm to a new shoulder peak at 550 nm was also observed. Thus, two emission peaks of **1** exhibit dramatic 100 and 70 nm bathochromic shifts, respectively, once upon the recognition of F$^-$. Moreover, with the addition of CN$^-$ (50 μM) to the **1** + F$^-$ system (**2**), fluorescence emission bands with intensity enhancement were observed at 470 and 550 nm, respectively (Figure 1a). In contrast, no significant fluorescence changes were observed, even at longer times, when other anions including N$_3{}^-$ and SCN$^-$ with strong nucleophilicity were added (Figure S13). To validate the selectivity of **1** in practice, the competition experiments were also examined by addition of 2.0 equiv of F$^-$ to the solution of **1** in the presence of 2.0 equiv of other anions, and then addition of 1.0 equiv of CN$^-$ to in situ generated (**1** + other anions + F$^-$) solution (Figure 1b). These competitive anions had no obvious interference with the detection of F$^-$ ion. These results suggested that probe **1** displayed an excellent selectivity toward F$^-$ in THF and the resulting **1** + F$^-$ system (**2**) showed high selectivity of CN$^-$ as well. To this end, the designed relay recognition of these two anions has been realized with sequence specificity (F$^-$ → CN$^-$).

The fluorescence titrations were also conducted using a 50 μM solution of **1** in THF. Upon the addition of F$^-$ to the solution of **1**, a significant decrease of the fluorescence intensity at 360 nm was observed (Figure 2a). The total fluorescence intensity at 360 nm of **1** decreased to 15% when 1.0 equiv of F$^-$ was present. The corresponding detection limit[13] was determined to be 1.86 μM (35.3 ppb) (Figure S14). Importantly, there was a linear fluorescence response to F$^-$ concentration ranging from 5.0 to 45.0 μM (Figure 2a, inset), indicating that probe **1** is potentially

---

[6] (a) Farley, J. R.; Wergedal, J. E.; Baylink, D. J. *Science* **1983**, *222*, 330. (b) Kleerekoper, M. *Endocrinol. Metab. Clin. North Am.* **1998**, *27*, 441.

[7] (a) Kulig, K. W. *Cyanide Toxicity*; U.S. Department of Health and Human Services: Atlanta, GA, 1991. (b) Koenig, R. *Science* **2000**, *287*, 1737.

[8] (a) Dong, Y.-M.; Peng, Y.; Dong, M.; Wang, Y.-W. *J. Org. Chem.* **2011**, *76*, 6962. (b) Ma, T.-H.; Dong, M.; Dong, Y.-M.; Wang, Y.-W.; Peng, Y. *Chem.—Eur. J.* **2010**, *16*, 10313. (c) Dong, M.; Ma, T.-H.; Zhang, A.-J.; Dong, Y.-M.; Wang, Y.-W.; Peng, Y. *Dyes Pigm.* **2010**, *87*, 164.

[9] For the leading reviews, see: (a) Pu, L. *Chem. Rev.* **2004**, *104*, 1687. (b) Pu, L. *Acc. Chem. Res.* **2011**10.1021/ar200048d.

[10] The fluorescence behaviors of **1** in other solvents or mixed aqueous solution were not very good. For details, see Figures S5−S10.

[11] The blue fluorescence corresponds to the emission band at 480 nm. For a similar emission, see: (a) Li, Z.-B.; Lin, J.; Sabat, M.; Hyacinth, M.; Pu, L. *J. Org. Chem.* **2007**, *72*, 4905. (b) Li, Z.-B.; Pu, L. *J. Mater. Chem.* **2005**, *15*, 2860.

[12] The concentration effect on the probe **1** in THF was studied; see Figure S11. The details can be found in ref 11 and Li, Z.-B.; Lin, J.; Pu, L. *Angew. Chem., Int. Ed.* **2005**, *44*, 1690.

[13] For the method employed, see: Lin, W.; Yuan, L.; Cao, Z.; Feng, Y.; Long, L. *Chem.—Eur. J* **2009**, *15*, 5096.

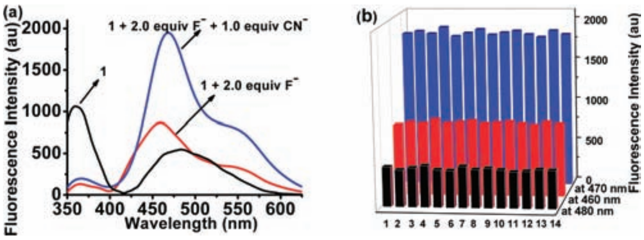


Figure 1. (a) Fluorescence responses of **1** (50 μM) in THF (λ_{ex} = 330 nm). (b) Anions selectivity of **1** (50 μM). The black bars represent the emission intensity of **1** in the presence of other anions (100 μM), respectively. The red bars represent the emission intensity that occurs upon the subsequent addition of 100 μM of F^- to the above solution (**1** + other anions). The blue bars represent the emission intensity that occurs upon the subsequent addition of 50 μM of CN^- to the solution (**1** + other anions + F^-). From 1 to 14: none, Cl^-, Br^-, I^-, AcO^-, ClO_4^-, $CF_3SO_3^-$, NO_3^-, HSO_4^-, $H_2PO_4^-$, BF_4^-, N_3^-, SCN^- (as n-Bu_4N salt, respectively), and $HSCH_2COOH$.

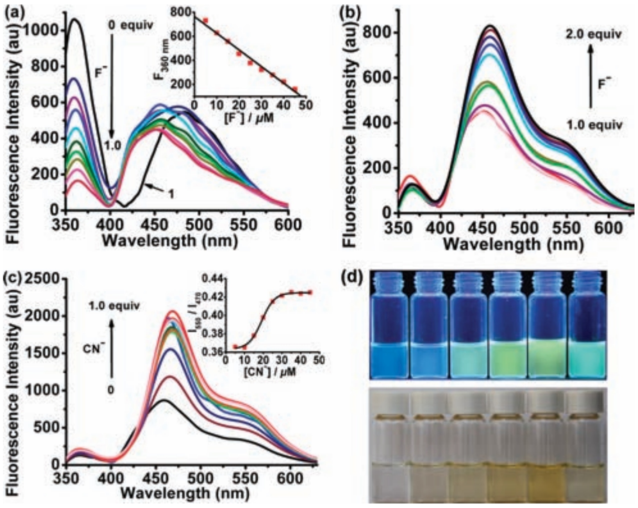


Figure 2. (a, b) Fluorescent spectra of **1** (50 μM) upon addition of F^- (0 to 2.0 equiv) in THF (λ_{ex} = 330 nm). Inset: Plot of the fluorescent intensity of **1** as a function of F^- concentration at 360 nm. (c) Fluorescent spectra of **1** + F^- (50 μM + 100 μM) upon the addition of CN^- in THF (λ_{ex} = 330 nm). Inset: Ratio of fluorescent intensities at 550 and 470 nm as a function of CN^- concentration. (d) Fluorescence change (top) and color change (bottom) of **1** (50 μM). From left to right: **1** only, F^- (0.5 equiv), F^- (1.0 equiv), F^- (1.5 equiv), F^- (2.0 equiv), F^- (2.0 equiv) + CN^- (1.0 equiv). All the images were obtained after 3 min upon the addition of anions.

useful for the quantitative determination of F^-.[14] The addition of more F^- (up to 2.0 equiv) resulted in not only the increase of the emission intensity around 460 nm, owing to a gradual increase of the concentration of **2**, but also a fluorescence enhancement around 550 nm as a result of the promotion of an emissive excimer channel of **2** (Figure 2b vs Figure 2a). When the amount of F^- was increased further, there was no change in the fluorescent spectra. This new excimer signal was also confirmed by the concentration effect (Figure 2b) of the intermediate with the coumarin skeleton. Thus, probe **1** displays striking fluorescence amplification at two emission bands[15] and fluorescence quench at another emission band (360 nm), which can be seen as a unique chemodosimeter with three emission changes.[16] The kinetic behavior of F^- (500.0 μM) to probe **1** (50.0 μM) at 25 °C was measured (Figure S15), and the observed rate constant was estimated to be $k_{obs} = 3.88 \times 10^{-4}\ s^{-1}$ by fitting the initial fluorescent intensity changes according to a pseudo-first-order kinetics equation. In addition, the fluorescence color changed gradually from blue to yellowish green with addition of F^- (Figure 2d, Top). The above results mean that **1** can function as a fluorescent probe for F^-.

Then the generated **1** + F^- system (**2**) was directly used to detect CN^- without separation and purification (Figure 2c). Upon addition of CN^-, a 2.5-fold fluorescence enhancement at 460 nm was observed with a slight bathochromic shift to 470 nm and a 2.5-fold fluorescence enhancement was also observed at ~550 nm simultaneously, which constitutes another example of unusual fluorescence amplification at two emission bands. Notably, the peaks at 470 and 550 nm are monomer and excimer emission bands of the final product **3** (Φ = 5.5%). The corresponding detection limits were analogously determined to be 2.28 μM (59.2 ppb) at 470 nm and 1.41 μM (36.7 ppb) at 550 nm, respectively (Figures S16 and S17). There was also a linear fluorescence response to CN^- concentration ranging from 5.0 to 50.0 μM (Figure S18) at 470 nm; moreover, the ratios of the emission intensities at 550 and 470 nm (F_{550}/F_{470}) showed sigmoid dependence on the CN^- concentration (Figure 2c, inset), indicating that the *in situ* generated **1** + F^- system (**2**) is also potentially useful for the quantitative determination of CN^-. The observed rate constant at 25 °C was analogously estimated to be $k_{obs} = 1.53 \times 10^{-3}\ s^{-1}$ (Figure S19). And the fluorescence color changed from yellowish green to pale green (Figure 2d, top). These results suggested that relay **2** can also function as a fluorescent probe for CN^-. Moreover, upon simultaneous addition of F^- + CN^- (2:1) to the solution of **1**, analogous changes of the fluorescence intensity at 360, 470, and 525 nm were also observed (Figures S20 and S21).

In the profile of UV–vis spectra of probe **1** in THF, a new absorption peak emerged at ~335 nm and its intensity gradually increased upon the addition of F^- (Figure 3a). The absorbance at ~303 nm decreased at the same time. Additionally, there was a good linearity between the ratios

---

(14) For the method employed, see: Lin, W.; Cao, X.; Ding, Y.; Yuan, L.; Long, L. *Chem. Commun.* **2010**, *46*, 3529.

(15) There are very rare examples (limited in chemosensor) about this unique *dual* fluorescence enhancement at *two* emission bands, see: (a) Lin, W.; Yuan, L.; Feng, J. *Eur. J. Org. Chem.* **2008**, 3821. (b) Liu, H. L.; Peng, Q.; Wu, Y.-D.; Chen, D.; Hou, X. L.; Sabat, M.; Pu, L. *Angew. Chem., Int. Ed.* **2010**, *49*, 602.

(16) To the best of our knowledge, only an isolated example about F^- chemosensor with this unique property can be found thus so far, see: Kubo, Y.; Yamamoto, M.; Ikeda, M.; Takeuchi, M.; Shinkai, S.; Yamaguchi, S.; Tamao, K. *Angew. Chem., Int. Ed.* **2003**, *42*, 2036.

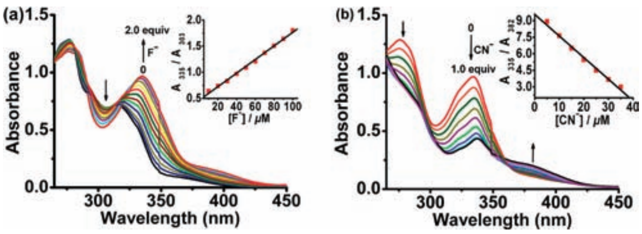


Figure 3. (a) Absorption spectra of **1** (50 μM) upon the addition of F^- (0 to 2.0 equiv) in THF. Inset: Ratios of absorbance at 335 and 303 nm as a function of F^- concentration. (b) Absorption spectra of **1** + F^- (50 μM + 100 μM) upon the addition of CN^- in THF. Inset: Ratio of absorbance at 335 and 382 nm as a function of CN^- concentration.

of the absorbances A_{335}/A_{303} and the concentration of F^- in the range of 10.0 to 100.0 μM (Figure 3a, inset), which also allow quantitative determination of F^- by absorption ratiometry. Upon the addition of CN^- to the solution, the peak at 335 nm decreased prominently and the absorbance at about 382 nm increased moderately (Figure 3b). And the ratios of the absorbances at 335 and 382 nm (A_{335}/A_{382}) increased linearly with increasing CN^- concentration. Moreover, changes of the solution color from colorless to yellow and then to pale yellow were observed by the naked-eye upon the addition of different amounts of F^- and CN^- ions to probe **1** (Figure 2d, bottom). The absorption changes at 335 and 382 nm are in good agreement with these color changes. Furthermore, the UV−vis spectra of probe **1** in THF with different proportions of H_2O were also measured and detailed information is provided in Figures S22−S25. These results indicated that relay recognition of these two anions was also well realized through UV−vis spectroscopy.

The rational explanation of the proposed anion relay recognition (**ARR**) process is given in Scheme 2. Two *O*-TBS groups of **1** could be removed through a fluoride-induced Si−O bond cleavage, and then generated alkoxide could convert to **2** with a coumarin skeleton,[17] which is responsible for the new emission band at 460 nm (Figure 1a). It is noteworthy that this F^- sensing process with triple output modes (fluorescence color, intensity and absorption band) is relatively rare[18] compared to that of previous probes with single[19a,b] or dual[19c−g] output modes. Since the 1-position of intermediate **2** is activated by both electron-withdrawing ester carbonyl groups, nucleophilic cyanide can attack this electron-deficient site. Unlike a usual fluorescence quench,[20a] the transient intermediate resulting from initial Michael addition of CN^- to unusual binaphthyl-coumarin hybrid **2** would proceed with hydride removal[20b] and eventually form cyano-coumarin derivative **3**,[21] which caused a slight red shift[22] (460 nm → 470 nm) and dual enhancement of fluorescence intensity (Figure 2c). The response of probe **1** was also investigated by ^1H NMR spectroscopic analysis (Figure S26a). Mass spectrometry analysis also supported the existence of **2** (Figure S27). To verify the hypothesis to the identity of **2** further, a large scale experiment was carried out, and the pure neutral yellow solid [**2** + H] was isolated and characterized by spectrometry (Figures S28−S31). With [**2** + H] in hand, the control experiment to corresponding [**3** + H] was run next (Figure S26b). Spectrometry analysis (Figures S32−S35) confirmed the generation of [**3** + H] as well.

In summary, an unprecedented relay recognition of two anions has been achieved and further demonstrated in the highly selective, colorimetric sensing of fluoride and cyanide. This novel concept (**A**nion **R**elay **R**ecognition, **ARR**) opens the way for a new sensing method: detection of two anions does not need to rely on two different probes; ingenious utilization of the innate reactivity of only one probe could achieve a dual recognition purpose in a tandem fashion.

Acknowledgment. This work was supported by NSFC (Nos. 21001058 and 21172096), the "111" Project of MoE, and the Natural Science Foundation of Gansu Province of China (No. 1107RJZA192).

Supporting Information Available. Experimental procedures, spectral data, and copies of $^1H/^{13}C$ NMR and MS. This material is available free of charge via the Internet at http://pubs.acs.org.

---

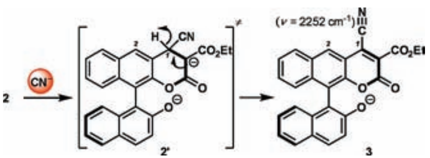
(17) Kim, T.-H.; Swager, T. M. *Angew. Chem., Int. Ed.* **2003**, *42*, 4803.

(18) (Triple output modes): (a) Zhang, J. F.; Lim, C. S.; Bhuniya, S.; Cho, B. R.; Kim, J. S. *Org. Lett.* **2011**, *13*, 1190. (b) Cao, X.; Lin, W.; Yu, Q.; Wang, J. *Org. Lett.* **2011**, *13*, 6098.

(19) (Single output mode): (a) Jiang, X.; Vieweger, M. C.; Bollinger, J. C.; Dragnea, B.; Lee, D. *Org. Lett.* **2007**, *9*, 3579. (b) Kim, S. Y.; Park, J.; Koh, M.; Park, S. B.; Hong, J.-I. *Chem. Commun.* **2009**, 4735. (Dual output modes): (c) Kim, S. Y.; Hong, J.-I. *Org. Lett.* **2007**, *9*, 3109. (d) Bhalla, V.; Singh, H.; Kumar, M. *Org. Lett.* **2010**, *12*, 628. (e) Altan Bozdemir, O.; Sozmen, F.; Buyukcakir, O.; Guliyev, R.; Cakmak, Y.; Akkaya, E. U. *Org. Lett.* **2010**, *12*, 1400. (f) Hu, R.; Feng, J.; Hu, D.; Wang, S.; Li, S.; Li, Y.; Yang, G. *Angew. Chem., Int. Ed.* **2010**, *49*, 4915. (g) Sokkalingam, P.; Lee, C.-H. *J. Org. Chem.* **2011**, *76*, 3820.

(20) (a) Kim, G.-J.; Kim, H.-J. *Tetrahedron Lett.* **2010**, *51*, 2914. For a similar explanation, see: (b) Kim, G.-J.; Kim, H.-J. *Tetrahedron Lett.* **2010**, *51*, 185; however, no ratiometric sensing of CN^- was observed by either fluorescence or absorption spectra.

(21) The driving force is retrievement of aromaticity, see below:



(22) Signore, G.; Nifosì, R.; Albertazzi, L.; Storti, B.; Bizzarri, R. *J. Am. Chem. Soc.* **2010**, *132*, 1276.