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Tune Metal Ion Selectivity by Changing Working Solvent: Fluorescent and Colorimetric Recognition of Cu^{2+} by a Known Hg^{2+} Selective Probe

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A known Hg^{2+} selective rhodamine B derivatised probe **1** was reinvestigated as a colorimetric and fluorescent probe for Cu^{2+} through changing the applied solvent media. Probe **1** exhibited good selectivity and sensitivity to Cu^{2+} in CH_3CN-H_2O (7:3, v/v, HEPES 10 mM, pH 7.0) solution with a detection limit of 9.74×10^{-7} M. The Cu^{2+} sensing event was proved to be irreversible through hydrolysis of **1** to release rhodamine B.

Key Words : Cu^{2+} recognition, Fluorescence, Colorimetric, Rhodamine

Introduction

Copper ion, as the third-most abundant transition metal in human body, plays vital roles in the fundamental physiological processes of organisms ranging from bacteria to mammals.[1] However, overloading of copper in the neuronal cytoplasm can lead to Alzheimer's[2] or Parkinson's disease.[3] Designing probes for Cu^{2+} have recently drawn considerable attention.[4] On the other hand, Rhodamine derived probes have been widely used due to their excellent photophysical properties including long absorption wavelength, high molar extinction coefficient and high quatum yields.[5] Recently, tremendous efforts have been focused on the development of rhodamine based chemical probes for the detection of heavy and transition metal (HTM) ions.[5,6]

Currently, the most popular strategy to realize specific metal ion selectivity of a certain fluorophore/chromophore is by fine-tuning of the binding group structure of receptor-reporter coupling probes.[7] In fact, the overwhelming majority of the reported HTM probes are based on this approach. Another method for tuning the metal ion binding selectivity of a given probe is by altering the working solvent system. Different working solvent can affect not only the emission wavelength of a fluorophore,[8] but also the ion selectivity of a given probe.[9] In some cases, altering solvent media can completely change the target metal ion.[10] For instance, a recently developed benzimidazole-based probe **HL[1]** behaved Fe^{2+} and Fe^{3+} selectivity in CH_3CN-H_2O solution,[11] whereas, **HL[1]** exhibited Hg^{2+} selectivity in CH_3OH-H_2O solution.[12] To date, reports on changing the metal ion selectivity of a certain small molecular weight probe by altering solvent system are still rare.

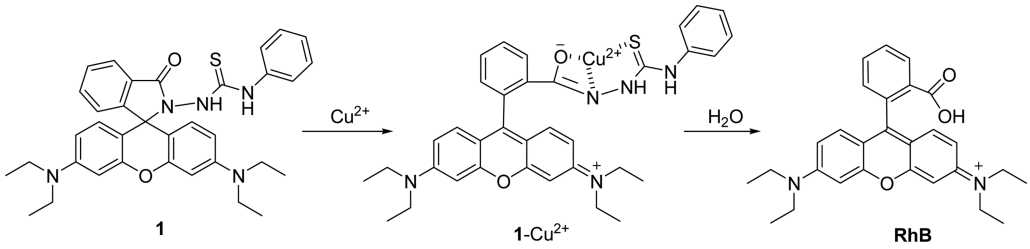
Tuning metal ion selectivity by altering the solvent system is in keep with the newly emerged chemosensor design concept of "single sensor for multiple analytes", namely, analysis of more than one analyte by one receptor using a single or an array of detection method.[13] Due to avoiding of tedious receptor synthesis, the ability of screening samples for multiple targets with a single probe leads to faster analytical processing and potential cost reductions. Herein we report the Cu^{2+} ion selective recognition by a known Hg^{2+} selective probe (**1**, Scheme 1) through changing the working solvent media. The results showed that the recognition of **1** to Cu^{2+} underwent a Cu^{2+} promoted hydrolysis process.

Experimental

Apparatus and Reagents. Probe **1** was synthesized and characterized according to the previously reported method.[14] Unless otherwise stated, all the solvents were of analytical grade from commercial sources and used as received. UV-vis spectra were measured on a SP-1900 spectrophotometer (Shanghai, China). Fluorescence measurements were performed on a Sanco 970-CRT spectrofluorometer (Shanghai, China). The pH measurements were made with a Model PHS-25B meter (Shanghai, China).

Results and Discussion

Probe **1** has been used as a Hg^{2+} selective probe in CH_3OH-



Scheme 1. The proposed mechanism for Cu^{2+} induced hydrolysis of **1**.

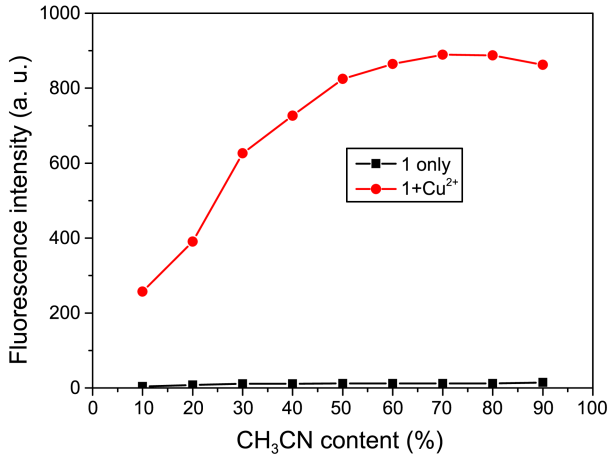


Figure 1. Fluorescence intensity of **1** and **1**+5.0 equiv of Cu^{2+} in CH_3CN-H_2O solution (pH = 7.0) with different CH_3CN content.

H_2O (3/7, v/v, pH 7.0) solution based on desulfonation reaction.[15] We found that probe **1** performed Cu^{2+} selectivity when it was applied in CH_3CN-H_2O (7:3, v/v, HEPES 10 mM, pH 7.0) solution. This phenomenon promoted us to further investigate the Cu^{2+} recognition behavior of **1**. The fluorescence intensity of **1** solution with and without Cu^{2+} against acetonitrile content was examined. The results reveal that **1** solution (10 μM) containing 5 equiv. Cu^{2+} exhibited strong emission intensity when CH_3CN and H_2O with a 7:3 volume ratio (Fig. 1). Time-dependent absorption changes revealed that the response of **1** to Cu^{2+} could complete within 1 minute (Fig. 2). Thus, the solvent CH_3CN-H_2O (7:3, v/v, HEPES 10 mM, pH 7.0) was selected as the working moiety in the following spectroscopic studies, and the spectra were checked 1 minute after the metal ion addition.

Fluorescence and UV-vis absorption spectral changes of **1** solution (10 μM) to miscellaneous metal ions were explored. As depicted in Figure 3, addition of 5.0 equiv. of Cu^{2+} to **1** solution led to a strong fluorescence enhancement at 582 nm. Nevertheless, addition of metal ions such as Ag^{+}, Pb^{2+},

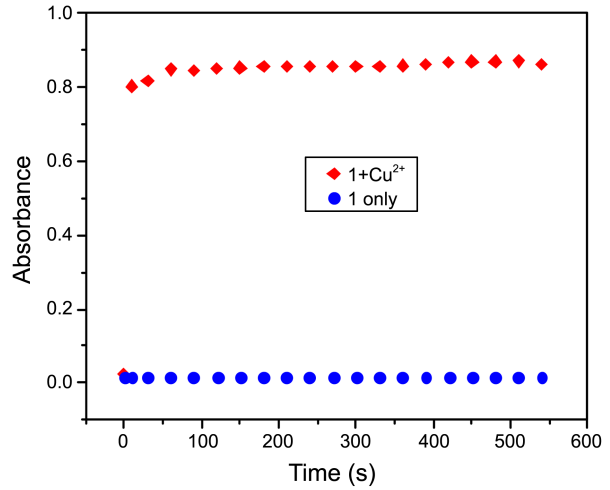


Figure 2. Time–dependent absorbance (at 547 nm) of **1** and **1**+5.0 equiv of Cu^{2+} in CH_3CN-H_2O (7:3, v/v, HEPES 10 mM, pH 7.0) solution.

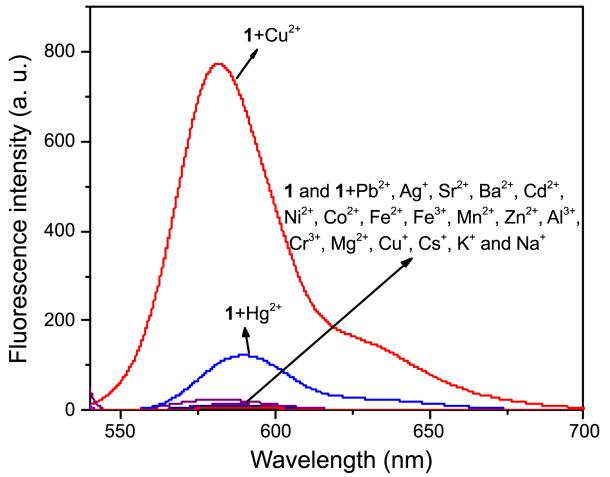


Figure 3. Fluorescence spectral changes of **1** solution (1.0×10^{-5} M) in the presence of different metal ions (5.0 equiv of each). Excited at 530 nm.

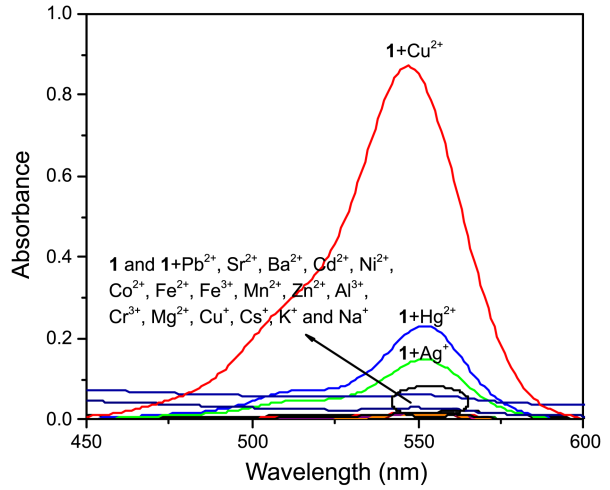


Figure 4. Absorption spectral changes of **1** solution (1.0×10^{-5} M) in the presence of different metal ions (5.0 equiv of each).

Sr^{2+}, Ba^{2+}, Cd^{2+}, Ni^{2+}, Co^{2+}, Fe^{2+}, Mn^{2+}, Fe^{3+}, Zn^{2+}, Al^{3+}, Cr^{3+}, Mg^{2+}, Cs^{+}, Cu^{+}, K^{+} and Na^{+} (5.0 equiv of each) induced negligible fluorescence spectra changes. The introduction of Hg^{2+} ions only induced a small emission enhancement at 590 nm. However, the Hg^{2+} induced fluorescence intensity enhancement is far below that caused by Cu^{2+} (F_{Cu}/F_{Hg} = 6.22) under the identical conditions, which indicating the lower affinity of Hg^{2+} to **1**. The UV-vis absorption spectra changes of **1** solution in the presence of different metal ions (Fig. 4) were then conducted. Free **1** solution is colorless and has no absorption in the visible region. Upon addition of 5 equiv. of Cu^{2+} ion, the colorless solution turned to pink red immediately with a distinct absorption band at 547 nm. Other tested metal ions including Pb^{2+}, Sr^{2+}, Ba^{2+}, Cd^{2+}, Ni^{2+}, Co^{2+}, Fe^{2+}, Mn^{2+}, Fe^{3+}, Zn^{2+}, Al^{3+}, Cr^{3+}, Mg^{2+}, Cs^{+}, Cu^{+}, K^{+} and Na^{+} (5.0 equiv of each) did not induce significant absorption increase, except Hg^{2+} and Ag^{+} caused slight absorption increase at 552 nm. These observations indicate that probe **1** has a high selectivity to Cu^{2+} ion.

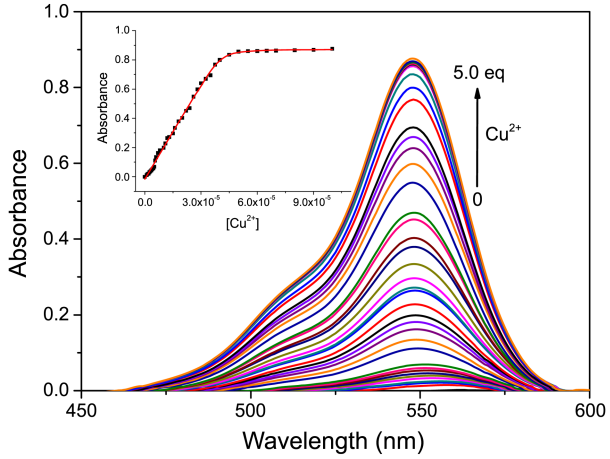


Figure 5. Changes of absorption spectra of **1** solution (1.0×10^{-5} M) in the presence of different concentration of Cu^{2+} (0-5 equiv). Inset: Non-linear least squares fitting plot (absorption at 547 nm) of **1** based on 1:1 binding stoichiometry.

To get further insight into the sensing behavior of **1** toward Cu^{2+} ions, UV-vis and fluorescence titration of **1** solution (1.0×10^{-5} M) with different amounts of Cu^{2+} were conducted. Upon incremental addition of Cu^{2+} (0 to 5.0 equiv) to **1** solution, the fluorescence emission band centered at 582 nm progressively increased and reached saturation when 5.0 equiv. of Cu^{2+} was added (Fig. 5). Nonlinear least-squares fitting of the UV-vis titration data based on a 1:1 binding mode results in a nice smooth curve ($R^2 > 0.998$, Figure 5, inset), which strongly support the 1:1 binding stoichiometry of **1** and Cu^{2+}, and the binding constant was evaluated to be 3.57×10^6 M^{-1}. Fluorescence intensity of **1** solution also displayed gradual enhancement upon incremental increasing the Cu^{2+} concentration (Fig. 6). Based on the fluorescence titration profile, the detection limit of **1** for Cu^{2+} was calculated to be 9.74×10^{-7} M (Fig. 6, inset),[16] which is quite lower than the limit of copper in drinking water (~20 μM) and the typical concentration of blood copper (15.7-23.6 μM) in normal individuals defined by the U.S. Environmental Protection Agency.[4c] These results indicate that probe

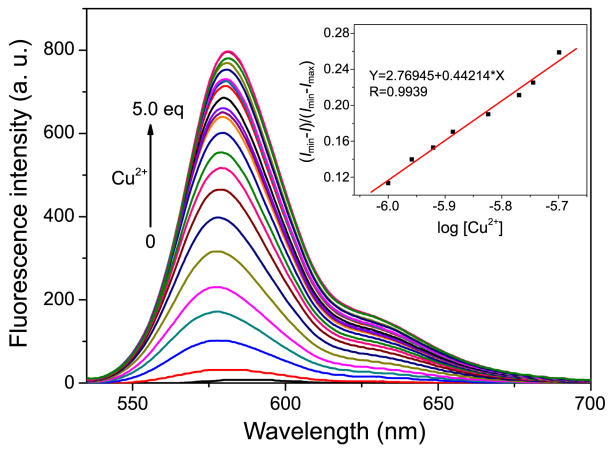


Figure 6. Fluorescence spectra change of **1** solution (1.0×10^{-5} M) in the presence of different concentration of Cu^{2+} (0-5 equiv). Inset: Normalized response of the fluorescence signal to log[Cu^{2+}].

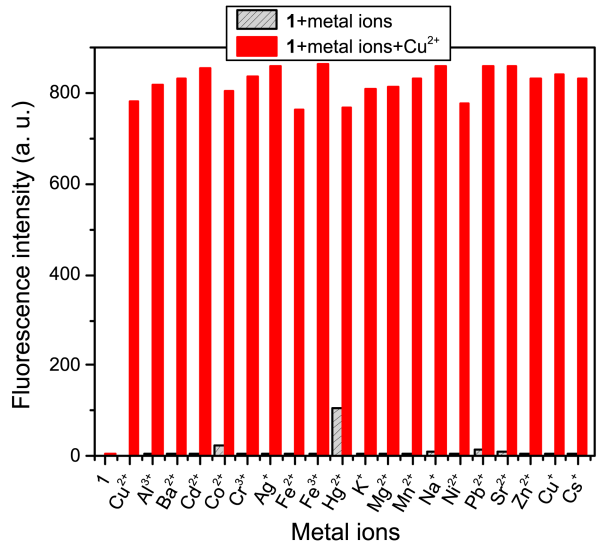


Figure 7. Changes in fluorescence intensity of **1** solution (10 μM) at 582 nm in the presence of different metal ions (50 μM of each) with and without Cu^{2+} (50 μM) addition.

1 has potential utility to monitor Cu^{2+} concentration in water.

Fluorescence and absorption competition experiments were subsequently explored to further evaluate the *anti*-interference ability of probe **1**. The fluorescence (Fig. 7) and UV-vis (Fig. 8) competition studies reveal that the coexistence of equal amount of other metal ions do not induce significant fluorescence and absorption spectral changes, indicating the good anti-interference ability of probe **1**.

To examine whether the Cu^{2+} recognition event is reversible, excess ethylenediamine tetraacetic acid disodium salt ($EDTANa_2$) as Cu^{2+} chelating agent was added to the colored solution of **1**-Cu^{2+}. However, both the color and fluorescence emission of solution **1**-Cu^{2+} were scarcely changed, which indicating the irreversible feature of the Cu^{2+} recognition process. A control experiment using anhydrous CH_3CN

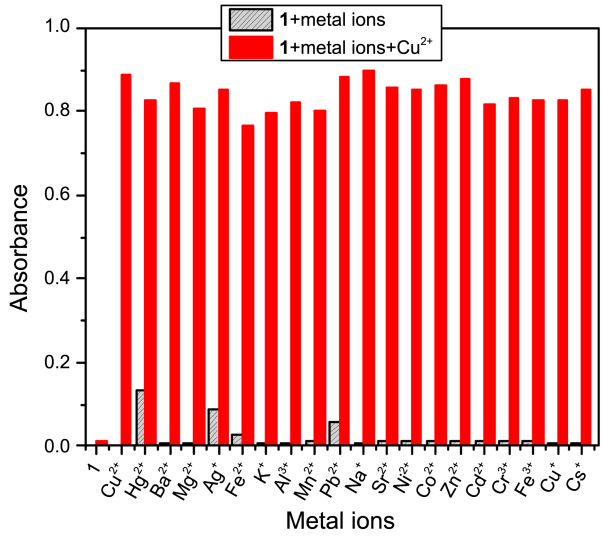


Figure 8. Changes in absorption of **1** solution (10 μM) at 547 nm in the presence of different metal ions (50 μM of each) with and without Cu^{2+} (50 μM) addition.

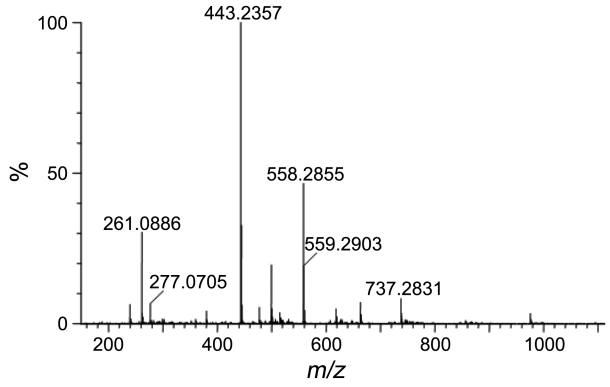


Figure 9. High resolution mass spectrum of the Cu^{2+} detection solution (0.1 mM of **1**+0.5 mM of Cu^{2+}).

instead of CH_3CN-H_2O buffered solution was explored. Without water, the aforementioned Cu^{2+} induced color change and fluorescence turn on processes could not occur. These results suggest that the Cu^{2+} recognition event is associated with probe hydrolysis. The reaction product of a high concentration detection solution (0.1 mM of **1**+5 equiv. of Cu^{2+}) was proved to be rhodamine B by thin layer chromatography (TLC) and high resolution ESI-MS analysis. The most prominent peak detected at *m/z* 443.2357 ($[M+H]^+$, calculated for 443.2329) presented a solid evidence for the formation of rhodamine B as a final product (Fig. 9). Similar to some reported rhodamine B based chemodosimeters,[17] a Cu^{2+} promoted hydrolysis of **1** to release rhodamine B is responsible for its fluorescent and colorimetric dual mode recognition to Cu^{2+}, and the proposed mechanism for Cu^{2+} induced hydrolysis of **1** was illustrated in Scheme 1.

Conclusions

A known Hg^{2+} selective rhodamine B based probe **1** was applied as a Cu^{2+} probe by changing the solvent system. Probe **1** behaves high selectivity and sensitivity to Cu^{2+} in CH_3CN-H_2O (7:3, v/v, HEPES 10 mM, pH 7.0) solution. Although the exact effect of solvent system on metal ion selectivity was not clear at present, the solvent polarity was assumed to play a key role in the selectivity of **1** to Cu^{2+}. Further studies on solvent effect are underway.

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References

1. (a) Que, E. L.; Domaille, D. W.; Chang, C. J. *Chem. Rev.* **2008**, *108*, 1517. (b) Robinson, N. J.; Winge, D. R. *Annu. Rev. Biochem.* **2010**, *79*, 537.
2. Deraeve, C.; Boldron, C.; Maraval, A.; Mazarguil, H.; Gornitzka, H.; Vendier, L.; Pitié, M.; Meunier, B. *Chem.-Eur. J.* **2008**, *14*, 682.
3. Lee, J. C.; Gray, H. B.; Winkler, J. R. *J. Am. Chem. Soc.* **2008**, *130*, 6898.
4. (a) Xu, Z.; Xiao, Y.; Qian, X.; Cui, J.; Cui, D. *Org. Lett.* **2005**, *7*, 889. (b) Xu, Z.; Qian, X.; Cui, J. *Org. Lett.* **2005**, *7*, 3029. (c) Jung, H. S.; Kwon, P. S.; Lee, J. W.; Kim, J. I.; Hong, C. S.; Kim, J. W.; Yan, S.; Lee, J. Y.; Lee, J. H.; Joo, T.; Kim, J. S. *J. Am. Chem. Soc.* **2009**, *131*, 2008. (d) Xu, Z.; Yoon, J.; Spring, D. R. *Chem. Commun.* **2010**, *46*, 2563. (e) Xu, Z.; Zhang, L.; Guo, R.; Xiang, T.; Wu, C.; Zheng, Z.; Yang, F. *Sens. Actuators B* **2011**, *156*, 546. (f) Xu, Q.; Lee, K. M.; Wang, F.; Yoon, J. *J. Mater. Chem.* **2011**, *21*, 15214. (g) Tang, L., Guo, J.; Cao, Y.; Zhao, N. *J. Fluores*. **2012**, *22*, 1603. (h) Tang, L.; Cai, M. *Sens. Actuators B* **2012**, *173*, 862. (i) Jung, J. Y.; Kang, M.; Chun, J.; Lee, J.; Kim, J.; Kim, J.; Kim, Y.; Kim, S.-J.; Lee, C.; Yoon, J. *Chem. Commun.* **2013**, *49*, 176.
5. Kim, H. N.; Lee, M. H.; Kim, H. J.; Kim, J. S.; Yoon, J. *Chem. Soc. Rev.* **2008**, *37*, 1465.
6. Chen, X.; Pradhan, T.; Wang, F.; Kim, J. S.; Yoon, J. *Chem. Rev.* **2012**, *112*, 1910.
7. Mao, J.; Wang, L.; Dou, W.; Tang, X.; Yan, Y.; Liu, W. *Org. Lett.* **2007**, *9*, 4567.
8. Tong, H.; Wang, L.; Jing, X.; Wang, F. *Macromol. Rapid Commun.* **2002**, *23*, 877.
9. Ashokkumar, P.; Ramakrishnan, V. T.; Ramamurthy, P. *J. Phys. Chem. B* **2011**, *115*, 84.
10. (a) Hao, E.; Meng, T.; Zhang, M.; Pang, W.; Zhou, Y.; Jiao, L. *J. Phys. Chem. A* **2011**, *115*, 8234. (b) Xu, L.; Xu, Y.; Zhu, W.; Sun, X.; Xu, Z.; Qian, X. *RSC Adv.* **2012**, *2*, 6323.
11. Sen, S.; Sarkar, S.; Chattopadhyay, B.; Moirangthem, A.; Basu, A.; Dhara, K.; Chattopadhyay, P. *Analyst* **2012**, *137*, 3335.
12. Pandey, R.; Yadav, M.; Shahid, M.; Misra, A.; Pandey, D. S. *Tetrahedron Lett.* **2012**, *53*, 3550.
13. (a) Schmittel, M.; Lin, H.-W. *Angew. Chem. Int. Ed.* **2007**, *46*, 893. (b) Singh, N.; Mulrooney, R. C.; Kaur, N.; Callan, J. F. *Chem. Commun.* **2008**, 4900. (c) Singh, N.; Kaur, N.; Ni Choitir, C.; Callan, J. F. *Tetrahedron Lett.* **2009**, *50*, 4201. (d) Jung, H. J.; Singh, N.; Lee, D. Y.; Jang, D. O. *Tetrahedron Lett.* **2010**, *51*, 3962. (e) Komatsu, H.; Citterio, D.; Fujiwara, Y.; Minamihashi, K.; Araki, Y.; Hagiwara, M.; Suzuki, K. *Org. Lett.* **2005**, *7*, 2857. (f) Tang, L.; Li, F.; Liu, M.; Nandhakumar, R. *Spectrochimi. Acta Part A* **2011**, *78*, 1168.
14. (a) Yang, Y.-K.; Yook, K.-J.; Tae, J. *J. Am. Chem. Soc.* **2005**, *127*, 16760. (b) Yang, R.; Liu, W.-X.; Shen, H.; Huang, H.-H.; Jiang, Y.-B. *J. Phys. Chem. B* **2008**, *112*, 5105.
15. (a) Yang, X.-F.; Li, Y.; Bai, Q. *Anal. Chimi. Acta* **2007**, *584*, 95. (b) Page, L. E.; Zhang, X.; Jawaid, A. M.; Snee, P. T. *Chem. Commun.* **2011**, *47*, 7773.
16. Lin, W.; Yuan, L.; Cao, Z.; Feng, Y.; Long, L. *Chem.-Eur. J.* **2009**, *15*, 5096.
17. (a) Hu, Z.-Q.; Wang, X.-M.; Feng, Y.-C.; Ding, L.; Lu, H.-Y. *Dyes Pigm.* **2011**, *88*, 257. (b) Chen, X.; Jia, J.; Ma, H.; Wang, S.; Wang, X. *Anal. Chim. Acta* **2009**, *632*, 9.