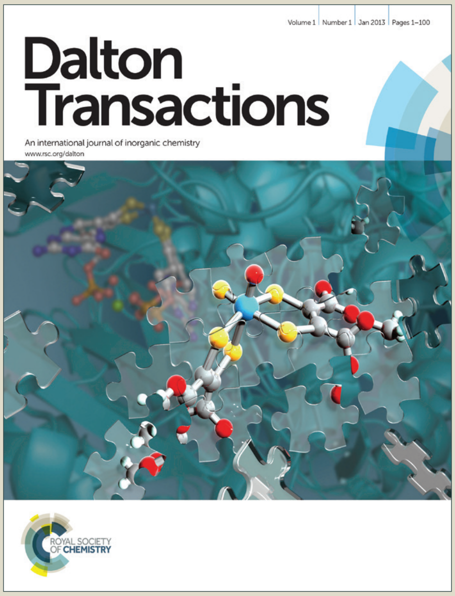
Dalton Transactions

Accepted Manuscript

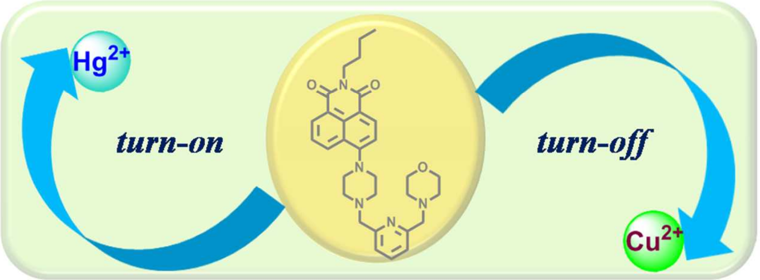
This article can be cited before page numbers have been issued, to do this please use: C. Huang, H. Li, Y. Luo and L. Xu, *Dalton Trans.*, 2014, DOI: 10.1039/C4DT00014E.



ROYAL SOCIETY OF CHEMISTRY

www.rsc.org/dalton

View Article Online
DOI: 10.1039/C4DT00014E



A bifunctional fluorescent probe **NPM** exhibits highly selective fluorescence *turn-on* for Hg^{2+} and *turn-off* for Cu^{2+} was synthesized.

Dalton Transactions

View Article Online
DOI: 10.1039/C4DT00014E

Cite this: DOI: 10.1039/c0xx00000x

www.rsc.org/xxxxxx

PAPER

A naphthalimide-based bifunctional fluorescent probe for the differential detection of Hg^{2+} and Cu^{2+} in aqueous solution

Chang-Bo Huang,[a] Hao-Ran Li,[b] Yuanyuan Luo[c] and Lin Xu*[a]

Received (in XXX, XXX) Xth XXXXXXXXX 20XX, Accepted Xth XXXXXXXXX 20XX
DOI: 10.1039/b000000x

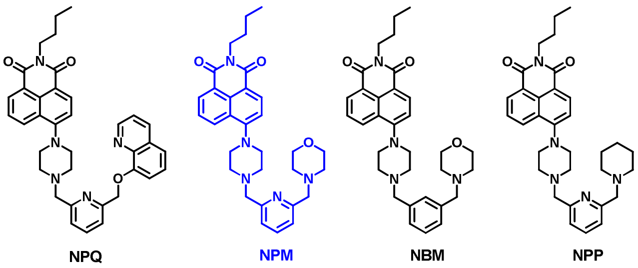
A novel fluorescent probe **NPM** based on naphthalimide was designed and synthesized. Interestingly, **NPM** exhibited highly selective fluorescence *turn-on* for Hg^{2+} and *turn-off* for Cu^{2+} in aqueous solution (10 mM HEPES, pH 7.5). Its fluorescence intensity was enhanced in a linear fashion with the concentration of Hg^{2+} and decreased in a nearly linear fashion with the concentration of Cu^{2+}, respectively. Thus **NPM** could be potentially used for the quantification of Hg^{2+} and Cu^{2+} in aqueous solution. A series of model compounds were rationally designed and synthesized in order to explore the sensing mechanisms and binding modes of **NPM** with Hg^{2+} and Cu^{2+}.

Introduction

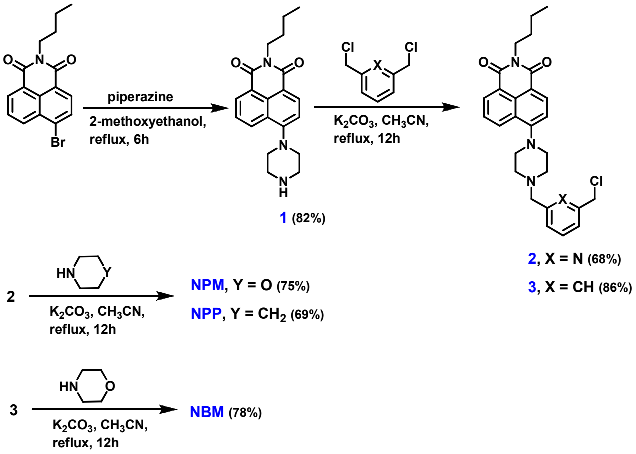
In the past few years, the development of fluorescent probes for detecting of heavy and transition metal (HTM) ions has attracted increasing attention owing to their simplicity, high sensitivity, and real-time detection.[1,2] Among various HTMs, Hg^{2+} and Cu^{2+} are of particular interest due to their diverse physiological roles in living systems and their environmental impact. Hg^{2+}, as one of the most highly toxic metals, could easily pass through biological membranes, such as skin, respiratory system, and gastrointestinal tissues. Excessive exposure and accumulation of mercury could lead to a number of severe health problems such as brain damage, kidney failure, and various cognitive and motion disorders.[3] Cu^{2+} is the third most abundant of the essential nutrient required for normal cell growth and development, which plays critical roles in many biological processes, such as blood formation and functioning of various enzymes. Moreover, as well as its deficiency, Cu^{2+} overload can result in a variety of diseases, such as parkinson's disease, epileptic seizures, renal and liver damage.[4] Therefore, the development of new fluorescent probes for the determination of Hg^{2+} or Cu^{2+} is highly desirable. Up to now, many fluorescent probes for Hg^{2+} or Cu^{2+} were reported in recent literature.[5,6] However, some of the reported fluorescent probes for Hg^{2+} or Cu^{2+} can be used only in organic medium or organic-containing solution, which limits their practical application.[7] Even then, some of the reported fluorescent probes sometimes suffer from the intricate synthetic procedures.[8] Therefore, there is a great need for the construction of new fluorescent probes that can detect Hg^{2+} or Cu^{2+} in aqueous solution by a simple synthetic approach.

In recent years, the construction of multi-ion responsive fluorescent probes with multiple emission modes received immense interest.[9] Fluorescent probes with a differential response towards multiple analytes are cost-effective and highly desirable for real-time applications. Moreover, such kind of fluorescent probes are indispensable for designing molecular logic gates and molecular keypad lock devices.[10] However, to the best of our knowledge, just two examples of bifunctional fluorescent probes capable of the simultaneous detection of Hg^{2+} and Cu^{2+} have been reported.[11] For example, Yin and co-workers reported a bifunctional probe that can recognize Hg^{2+} and Cu^{2+} only in organic solvent (CH_3CN).[11a] Tian and Zhu reported another bifunctional probe **DCPP**.[11b] Although its sensing properties could be investigated in organic-containing solution (containing 60% CH_3CN as a co-solvent), **DCPP** displayed a relatively low sensitivity. The addition of five equivalents of Hg^{2+} to the solution of **DCPP** just induced 2.2-fold enhancement of the fluorescence intensity. Thus, it is still a challenge to develop bifunctional fluorescent probes for Hg^{2+} and Cu^{2+} in aqueous solution with high selectivity and sensitivity.

Recently, we have reported a highly sensitive and selective naphthalimide-based Ag^+ fluorescent probe **NPQ**, which contains a hydroxyquinoline moiety as part of the receptor.[12] Herein, by the replacement of hydroxyquinoline moiety in **NPQ** with morpholine moiety, a novel fluorescent probe **NPM** was synthesized. Interestingly, **NPM** exhibited selective fluorescence *turn-on* response toward Hg^{2+} and selective fluorescence *turn-off* to Cu^{2+} in aqueous solution. With the aim to obtaining the insight into the possible sensing mechanisms and binding modes of



Scheme 1 The structures of fluorescent probes of **NPQ**, **NPM** and model compounds **NBM** and **NPP**.



Scheme 2 Synthesis of **NPM**, **NPP** and **NBM**.

NPM with Hg^{2+} and Cu^{2+}, two model compounds (**NBM** and **NPP**) were designed and synthesized as shown in Scheme 1.

Results and discussion

Synthesis of NPM, NBM, and NPP

Compounds **NPM**, **NBM**, and **NPP** were readily synthesized from *N*-butyl-4-bromo-1, 8-napthalimide via three step reactions in good yield as shown in Scheme 2. The structures of all compounds were verified by ^{1}H NMR, ^{13}C NMR, and HRMS.

pH effect of NPM

The absorption and emissive properties of **NPM** on changing the pH were determined as shown in Fig. S1. A slight change in the absorption spectra of **NPM** was observed when the pH>7.0. However, when the pH<7.0, a slight blue shift of the absorption spectra (from 398 nm to 387 nm) was found. As shown in Fig. S1(c), there was nearly no change in fluorescence intensity of **NPM** in the pH range from 10.0 to 7.5, suggesting that **NPM** was stable. When pH<7.0, the emission intensity of **NPM** was gradual increased, this may be due to the protonation of N atoms in pyridine, piperazine, and morpholine moiety. Therefore, it demonstrated that **NPM** could work in the pH range from 7.0 to 10.0.

The selectivity of NPM

To evaluate the selectivity of **NPM** in aqueous solution (10 mM HEPES, pH 7.5), various metal ions such as Zn^{2+}, Mn^{2+}, Ba^{2+}, Hg^{2+}, Ni^{2+}, Cu^{2+}, Co^{2+}, Pb^{2+}, Mg^{2+}, Cd^{2+}, Fe^{2+}, Al^{3+}, Ag^{+}, and Li^{+} were employed. As expected, **NPM** showed a weak fluorescence in aqueous solution due to the photoinduced electron transfer (PET) process from the electron-rich receptor to the excited naphthalimide fluorophore. As shown in Fig. 1a, the addition of Hg^{2+} to the solution of **NPM** induced a significant enhancement of fluorescence (ca. 11-fold) with the emission maximum at 529 nm. By contrast, under the identical conditions, when Cu^{2+} was added into the solution of **NPM**, an almost complete fluorescent emission quenching was observed. However, the addition of the other metal ions produced a negligible change in the fluorescence spectra of **NPM**. Therefore, the results disclosed that **NPM** was a Hg^{2+}-specific *turn-on* yet Cu^{2+}-specific *turn-off* fluorescent probe.

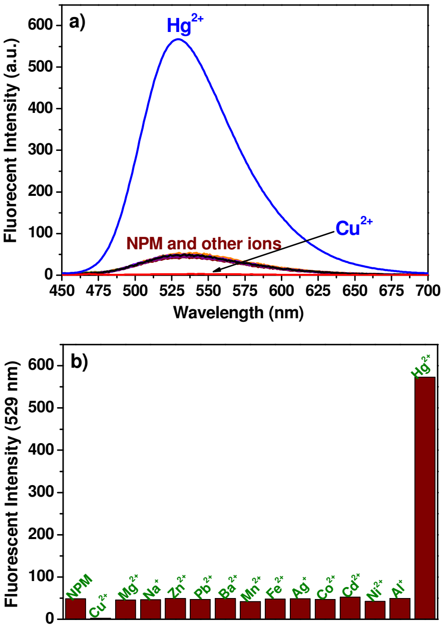


Fig. 1 (a) The fluorescence spectra and (b) fluorescent intensity at 529 nm of **NPM** (10 μM) in the presence of 20 μM of various metal ions such as Zn^{2+}, Mn^{2+}, Ba^{2+}, Hg^{2+}, Ni^{2+}, Cu^{2+}, Co^{2+}, Pb^{2+}, Mg^{2+}, Cd^{2+}, Fe^{2+}, Al^{3+}, Ag^{+}, and Li^{+} in aqueous solution (10 mM HEPES, pH 7.5). (λ_{ex} = 405 nm.)

Achieving high selectivity toward Hg^{2+} and Cu^{2+} over the other competitive species coexisting is a very important feature to evaluate the performance of the fluorescent probe **NPM**. Therefore, the competition experiments were also conducted for **NPM**. Fig. S3a indicated that when Hg^{2+} was added respectively into the solution of **NPM** in the presence of other ions such as Zn^{2+}, Mn^{2+}, Ba^{2+}, Ni^{2+}, Co^{2+}, Pb^{2+}, Mg^{2+}, Cd^{2+}, Fe^{2+}, Al^{3+}, Ag^{+}, and Li^{+}, the emission spectra displayed a similar pattern at nearly 529 nm to that with Hg^{2+} only. Similarly, as shown in Fig. S3b, when Cu^{2+} was added respectively to the solution of **NPM** in the presence of the other metal ions including Zn^{2+}, Mn^{2+}, Ba^{2+}, Ni^{2+}, Co^{2+}, Pb^{2+}, Mg^{2+}, Cd^{2+}, Fe^{2+}, Al^{3+}, Ag^{+}, and Li^{+}, the emission spectra of **NPM** were almost identical to that in the presence of Cu^{2+} alone. The results implied that **NPM** exhibited high selectivity for Hg^{2+} and Cu^{2+} even in the presence of other competitive metal ions.

Hg^{2+}-titration and spectral responses

The responses of **NPM** to Hg^{2+} were investigated in detail as shown in Fig. 2. Upon adding Hg^{2+}, the fluorescence intensity increased by about 11-fold, accompanied by a slightly hypsochromic shift from 533 nm to 529 nm in emission spectrum. The extinction coefficients and the fluorescence quantum yields of **NPM** and the complex of **NPM** with Hg^{2+} were determined to be 6173, 6231, 0.016, and 0.139, respectively. Significantly, the fluorescence enhancement at 529 nm was linear in regarding the concentration of Hg^{2+} at low μM levels (R^2 = 0.9745). Additionally, the limit of detection of **NPM** toward Hg^{2+} was calculated to be 6.11×10^{-8} M. The results indicated that **NPM** was sensitive to Hg^{2+} and could be potentially used to quantitatively detect Hg^{2+} concentration in aqueous solution.

Cu^{2+}-titration and spectral responses

The absorption and fluorescence titrations of **NPM** with Cu^{2+}

View Article Online
DOI: 10.1039/C4DT00014E

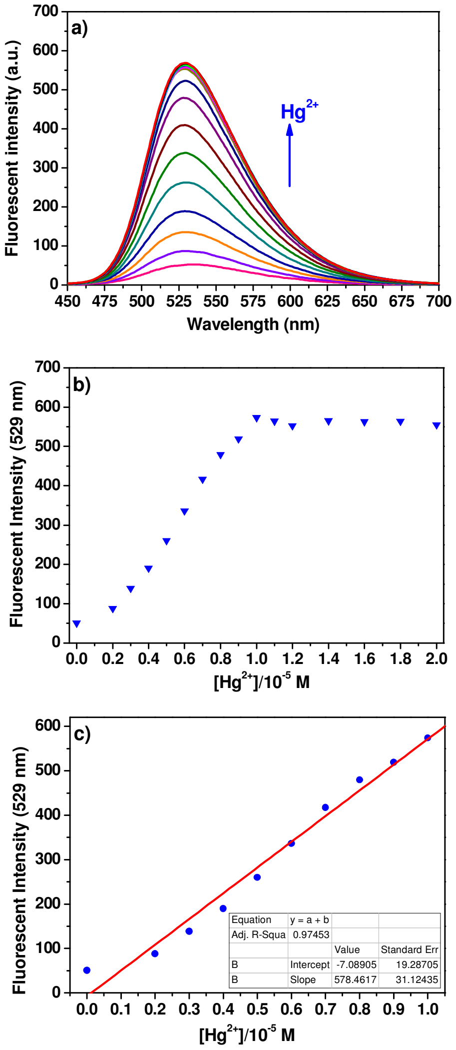


Fig. 2 (a) Fluorescence spectra of **NPM** (10 µM) upon the addition of Hg^{2+} (2–20 µM) in aqueous solution (10 mM HEPES, pH 7.5); (b) and (c) curve of fluorescence intensity at 529 nm of **NPM** (10 µM) versus increasing concentrations of Hg^{2+}. (λ_{ex} = 405 nm.)

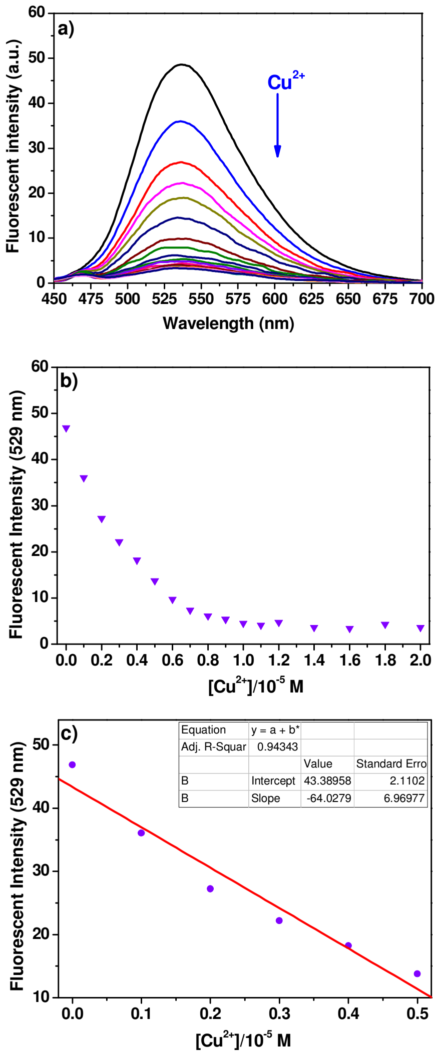


Fig. 3 Fluorescence spectra of **NPM** (10 µM) upon the addition of Cu^{2+} (1–20 µM) in aqueous solution (10 mM HEPES, pH 7.5); (b) and (c) curve of fluorescence intensity at 529 nm of **NPM** (10 µM) versus increasing concentrations of Cu^{2+}. (λ_{ex} = 405 nm.)

were performed as well as shown in Fig. 3 and Fig. S4. The stepwise Cu^{2+} addition to **NPM** led to a decrease in the fluorescence intensity at 529 nm, where the intensity became almost zero upon addition of 1 equiv. of Cu^{2+}. However, the addition of Cu^{2+} to **NPM** did not induce the wavelength change. The extinction coefficients and the fluorescence quantum yields of the complex of **NPM** with Cu^{2+} were determined to 5978 and 0.003, respectively. A nearly linear relationship was observed between the fluorescence intensity at 529 nm and the Cu^{2+} concentration at the range of 2.0–5.0 µM. This observation clearly supported that **NPM** enabled the quantitative detection of Cu^{2+} in aqueous media.

Job's plot analysis of Hg^{2+} and Cu^{2+}

In order to understand the coordination ratio of **NPM** with Hg^{2+} and Cu^{2+}, Job's plot analyses were carried out (Fig. 4). The results indicated that **NPM** formed 1 : 1 stoichiometrical complex both with Hg^{2+} and Cu^{2+}, which were further supported by the observation that the spectra change almost stopped upon adding 1 equiv. of Hg^{2+} or Cu^{2+} (Fig. 2b and 3b) to **NPM**. The association constants between **NPM** and Hg^{2+} and Cu^{2+} were determined to be 6.06 × 10^6 M^{-1} and 3.51 × 10^6 M^{-1} by using nonlinear least-square analysis, respectively.

PET quenching mechanism NPM

In order to get insight into the possible fluorescence sensing mechanism of **NPM**, the fluorescence spectra of free **NPM** and model compounds **NBM** and **NPP** were examined as shown in Fig. 5 and Fig. S6. A direct comparison between the fluorescence intensity of compound **NPM** with **NBM** at the same concentration clearly showed that nitrogen atom in the pyridine ring in **NPM** played a significant role in quenching the fluorescence of the naphthalimide moiety through a PET mechanism. The oxygen atom in morpholine moiety was not involved in quenching the fluorescence since the fluorescence intensity of compound **NPP** resembled that of **NPM**. It was possible that the piperazine nitrogen and morpholine nitrogen could also quench the fluoresence. However, the extent would be

View Article Online
DOI: 10.1039/C4DT00014E

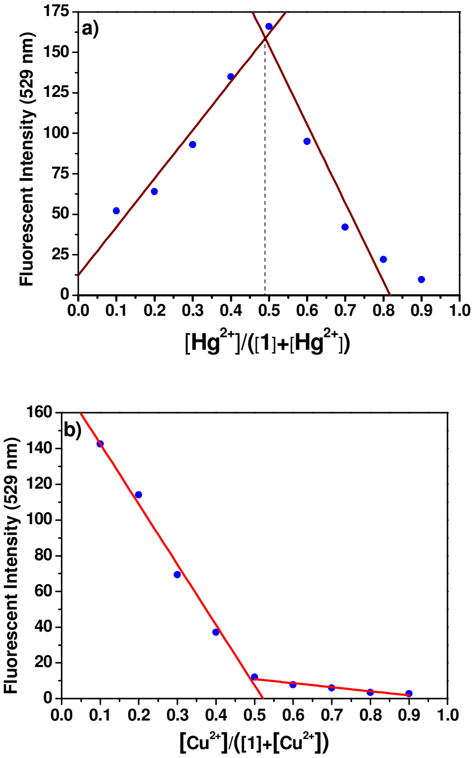


Fig. 4 (a) Job's plot of **NPM** and Hg^{2+} ([**NPM**] + $[Hg^{2+}]$ = 10 μM) and (b) Job's plot of **NPM** and Cu^{2+} ([**NPM**] + $[Cu^{2+}]$ = 10 μM) in aqueous solution (10 mM HEPES, pH 7.5). (λ_{ex} = 405 nm.)

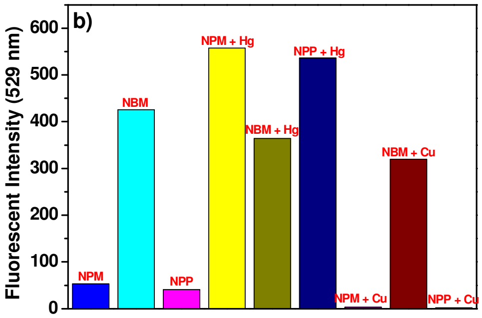
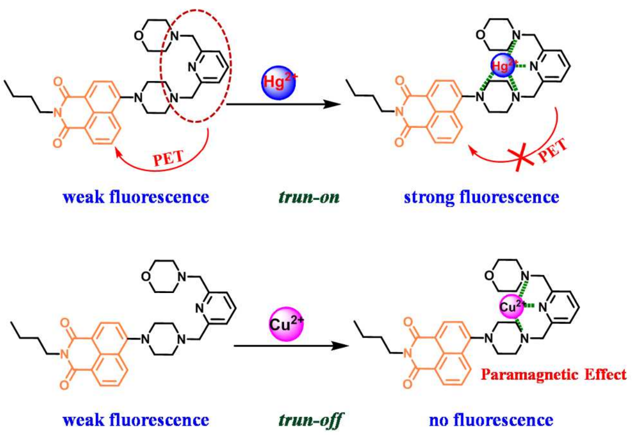


Fig. 5 Fluorescent intensity at 529 nm of **NPM**, **NBM**, and **NPP** (all compounds were 10 μM) in the absence and presence of Hg^{2+} (20 μM) and Cu^{2+} (20 μM) in aqueous solution (10 mM HEPES, pH 7.5). (λ_{ex} = 405 nm.)

expected to be minimal due to its high pKa value.[12] In addition to the fluorescence quenching via PET mechanism, we believe that the higher degree of molecular flexibility of **NPM** also has fundamental implications.

The fluorescence enhancement of the **NPM** response to Hg^{2+} might be attributed to photoinduced electron transfer (PET) and chelation-enhanced fluorescence (CHEF) mechanisms as follows. Before coordination with Hg^{2+}, **NPM** gave a weak fluorescence because of the lone electron pairs of the N atoms in pyridine, piperazine, and morpholine moiety being located close to the naphthalimide fluorophore, which resulted in an intramolecular photoinduced electron transfer (PET). However, when **NPM** was coordinated with Hg^{2+}, the PET process was blocked synchronously and the complex was more rigid, thus a significant enhancement of fluorescence was observed.



Scheme 3 Proposed binding modes of **NPM** with Hg^{2+} and Cu^{2+}.

In contrast, the fluorescence quenching of **NPM** upon titration with Cu^{2+} was due to the well-known paramagnetic effect of Cu^{2+}, which quenched excited state of fluorophore by energy and/or electron transfer.[6e]

Binding models of NPM with Hg^{2+} and Cu^{2+}

To understand the binding modes of **NPM** with Hg^{2+} and Cu^{2+}, the fluorescence responses of **NPM**, **NBM**, and **NPP** to Hg^{2+} and Cu^{2+} were conducted as shown in Fig. 5 and Fig. S6. Model compound **NPP** lacking the oxygen atom showed the similar fluorescence response toward Hg^{2+} and Cu^{2+}, which indicated that the morpholine oxygen atom in **NPM** played a negligible role in the binding with Hg^{2+} and Cu^{2+}. Moreover, the results revealed that **NPP** was also a Hg^{2+}-specific *turn-on* yet Cu^{2+}-specific *turn-off* fluorescent probe. The lower binding ability of **NBM** with Hg^{2+} and Cu^{2+} compared to **NPM** verified that the pyridine nitrogen played a major role in both Hg^{2+} and Cu^{2+} binding. Furthermore, it is commonly observed that a hypsochromic shift in absorption or emission maximum usually occurs when the nitrogen, which is also the donor of a push–pull system, chelates to metal ions.[13] Therefore, we believe that the pyrazine nitrogen that links to the naphthalimide ring was involved in Hg^{2+} chelation.

Based on the absorption and fluorescence titration spectra, the Job's plots, and the coordination chemistry of Hg^{2+} and Cu^{2+}, we proposed the plausible fluorescence sensing mechanisms and binding modes of the probe **NPM** with Hg^{2+} and Cu^{2+} as shown in Scheme 3.

Conclusions

In conclusion, a novel naphthalimide-based fluorescent probe **NPM** was developed successfully. **NPM** displayed high selectivity and sensitivity for Hg^{2+} and Cu^{2+} with fluorescence *turn-on* and *turn-off* in aqueous solution, respectively. Moreover, it was found that its fluorescence intensity was enhanced in a linear fashion with the concentration of Hg^{2+} and decreased in a nearly linear fashion with the concentration of Cu^{2+}, respectively, which indicated that the probe **NPM** could be potentially used as a bifunctional probe for the quantification of Hg^{2+} and Cu^{2+}. The sensing mechanisms and binding modes of **NPM** with Hg^{2+} and

View Article Online
DOI: 10.1039/C4DT00014E

Cu^{2+} were confirmed by Job's plot analyses and the comparison with a series of model compounds. Considering its obvious advantages such as convenience in preparation, excellent sensing ability towards Hg^{2+} and Cu^{2+}, and mild detection environment, **NPM** was expected to have a variety of applications such as environmental monitoring and surveillance.

Experimental

Materials and measurements

Unless otherwise mentioned, all the reagents were of analytic grade. ^{1}H-NMR and ^{13}C-NMR spectra were measured on a Bruker AM-400 spectrometer with chemical shifts reported as ppm (in $CDCl_3$). Mass spectrometry data were obtained with a HP 5989A spectrometer. Absorption spectra were determined on a Varian Cary 100 Spectrophotometer. Fluorescence spectra were determined on a Varian Cary Eclipse. Emission slit widths of the experiment of Job's plot of **NPM** and Cu^{2+} were 5 and 10, the influence of pH on and fluorescence of NPM were 2.5, 5 nm, the other slit widths were 5, 5.

The metal salts used were $Fe(ClO_4)_2$, $Zn(ClO_4)_2 \cdot 6H_2O$, $Co(ClO_4)_2 \cdot 6H_2O$, $Ni(ClO_4)_2 \cdot 6H_2O$, $Ba(ClO_4)_2 \cdot 3H_2O$, $Pb(ClO_4)_2 \cdot 3H_2O$, $Cd(ClO_4)_3 \cdot 6H_2O$, $Cu(ClO_4)_2 \cdot 6H_2O$, $Mn(ClO_4)_2 \cdot 6H_2O$, $LiClO_4 \cdot 3H_2O$, $NaClO_4 \cdot H_2O$, $AgClO_4 \cdot H_2O$, $Hg(ClO_4)_2 \cdot 3H_2O$, $Mg(ClO_4)_2 \cdot 6H_2O$.

Synthesis

Compound NPM. Anhydrous potassium carbonate (138 mg, 1.0 mmol), compounds **2** (238 mg, 0.5 mmol) and morpholine (435 mg, 5.0 mmol) were dissolved in acetonitrile (10 mL), and the reaction mixture was refluxed for 12 h under argon atmosphere. The mixture was filtered, and the solvent was removed in a vacuum to give a yellow solid. The crude product was then chromatographed on silica gel using dichloromethane–methanol 30 : 1 (v/v) as eluant to afford 198 mg (75%) **NPM** as a yellow solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.56 (d, J = 7.2 Hz, 1H), 8.50 (d, J = 8.0 Hz, 1H), 8.38 (d, J = 8.4 Hz, 1H), 7.73–7.65 (m, 2H), 7.47 (s, 2H), 7.21 (d, J = 8.0 Hz, 1H), 4.15 (t, J = 7.6 Hz, 2H), 3.88 (s, 2H), 3.80 (s, 6H), 3.35 (s, 4H), 2.91 (s, 4H), 2.65 (s, 4H), 1.74–1.63 (m, 2H), 1.49–1.37 (m, 2H), 0.96 (t, J = 7.2 Hz, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz) δ: 164.49, 164.03, 155.66, 137.29, 132.51, 131.10, 130.13, 129.83, 126.13, 129.83, 126.13, 125.72, 123.32, 116.94, 115.04, 66.43, 64.16, 53.45, 53.28, 52.71, 40.11, 30.26, 20.42, 13.90. ESI-MS for $C_{31}H_{38}N_5O_3$ [(M + H)$^+$]: 528.47. HR-ESI-MS calcd for $C_{31}H_{38}N_5O_3$ [(M + H)$^+$]: 528.2969, found: 528.2994.

The other model compounds were synthesized as shown in Schemes S1–S2.†

Acknowledgements

The work was financially supported by the National Natural Science Foundation of China (No. 21302058), the Research Fund for the Doctoral Program of Higher Education of China (No. 20130076120006), and the Fundamental Research Funds for the Central Universities. We also appreciate valuable discussion with Prof. Hai-Bo Yang (East China Normal University).

Notes and references

[a] *Department of Chemistry, East China Normal University, 3663 N. Zhongshan Road, Shanghai 200062, P. R. China.
E-mail: lxu@chem.ecnu.edu.cn*
[b] *Futian Second People's Hospital, Shenzhen 518049, P. R. China.*
[c] *School of Pharmacy, East China University of Science and Technology, Shanghai 200237, P. R. China.*

† Electronic Supplementary Information (ESI) available: [details of any supplementary information available should be included here]. See DOI: 10.1039/b000000x/

1 (*a*) H. Li, J. Fan and X. Peng, *Chem. Soc. Rev.*, 2013, **42**, 7943; (*b*) L. Yuan, W. Lin, K. Zheng, L. He and W. Huang, *Chem. Soc. Rev.*, 2013, **42**, 622; (*c*) S. D Bull, M. G. Davidson, J. M. H. van den Elsen, J. S. Fossey, A. T. A. Jenkins, Y.-B. Jiang, Y. Kubo, F. Marken, K. Sakurai, J. Zhao and T. D. James, *Acc. Chem. Res.*, 2013, **46**, 312; (*d*) L. M. Hyman and K. J. Franz, *Coord. Chem. Rev.*, 2012, **256**, 2333; (*e*) S. K Sahoo, D. Sharma, R. K. Bera, G. Crisponic and J. F Callan, *Chem. Soc. Rev.*, 2012, **41**, 7195; (*f*) M. Vendrell, D. Zhai, J. C. Er and Y.-T. Chang, *Chem. Rev.*, 2012, **112**, 4391; (*g*) H. N. Kim, W. X. Ren, J. S. Kim and J. Yoon, *Chem. Soc. Rev.*, 2012, **41**, 3210; (*h*) A. Bencini and V. Lippolis, *Coord. Chem. Rev.*, 2012, **256**, 149; (*i*) H. M. Kim and B. R. Cho, *Chem.-Asian. J.*, 2011, **6**, 58; (*j*) X. Qian, Y. Xiao, Y. Xu, X. Guo, J. Qian and W. Zhu, *Chem. Commun.*, 2010, **46**, 6418; (*k*) M. Beija, C. A. M. Afonso and J. M. G. Martinho, *Chem. Soc. Rev.*, 2009, **38**, 2410; (*l*) E. M. Nolan and S. J. Lippard, *Chem. Rev.*, 2008, 108, 3443; (*m*) S. W. Thomas III, G. D. Joly and T. M. Swager, *Chem. Rev.*, 2007, **107**, 1339; (*n*) D. T. Quang and J. S. Kim, *Chem. Rev.*, 2010, **110**, 6280; (*o*) A. P. de Silva, H. Q. N. Gunaratne, T. Gunnlaugsson, A. J. M. Huxley, C. P. McCoy, J. T. Rademacher and T. E. Rice, *Chem. Rev.*, 1997, **97**, 1515.

2 (*a*) H. Y. Au-Yeung, J. Chan, T. Chantarojsiri and C. J. Chang, *J. Am. Chem. Soc.*, 2013, **135**, 15165; (*b*) T. Egawa, K. Hirabayashi, Y. Koide, C. Kobayashi, N. Takahashi, T. Mineno, T. Terai, T. Ueno, T. Komatsu, Y. Ikegaya, N. Matsuki, T. Nagano and K. Hanaoka, *Angew. Chem. Int. Ed.*, 2013, **52**, 3874; (*c*) L. Xu, M.-L. He, H.-B. Yang and X. Qian, *Dalton Trans.*, 2013, **42**, 8218; (*d*) P. Li, L. Fang, H. Zhou, W. Zhang, X. Wang, N. Li, Ho. Zhong and B. Tang, *Chem. Eur. J.*, 2011, **17**, 10520; (*e*) D.-H. Li, J.-S. Shen, N. Chen, Y.-B. Ruan and Y.-B. Jiang, *Chem. Commun.*, 2011, **47**, 5900; (*f*) M. Taki, S. Iyoshi, A. Ojida, I. Hamachi and Y. Yamamoto, *J. Am. Chem. Soc.*, 2010, **132**, 5938; (*g*) S. V. Wegner , H. Arslan , M. Sunbul , J. Yin and C. He, *J. Am. Chem. Soc.*, 2010, **132**, 2567; (*h*) Z. Xu, K.-H. Baek, H. N. Kim, J. Cui, X. Qian, D. R. Spring, I. Shin and J. Yoon, *J. Am. Chem. Soc.*, 2010, **132**, 601; (*i*) M. Ishida, Y. Naruta and F. Tani, *Angew. Chem. Int. Ed.*, 2010, **49**, 91; (*j*) F. Qian, C. Zhang, Y. Zhang, W. He, X. Gao, P. Hu and Z. Guo, *J. Am. Chem. Soc.*, 2009, **131**, 1460; (*k*) L. Marbella, B. Serli-Mitasev, P. Basu, *Angew. Chem. Int. Ed.*, 2009, **48**, 3996; (*l*) G. M. Cockrell, G. Zhang, D. G. VanDerveer, R. P. Thummel and R. D. Hancock, *J. Am. Chem. Soc.*, 2008, **130**, 1420; (*m*) X. Zhang, Y. Xiao and X. Qian, *Angew. Chem. Int. Ed.*, 2008, **47**, 8025; (*n*) H. M. Kim, M.S. Seo, M.J. An, J. H. Hong, Y.S. Tian, J.H. Choi, O. Kwon, K. J. Lee and B.R. Cho, *Angew. Chem. Int. Ed.*, 2008, **47**, 5167; (*o*) F. Song , A. L. Garner and K. Koide, *J. Am. Chem. Soc.*, 2007, **129**, 12354; (*p*) X. Peng, J. Du, J. Fan, J. Wang, Y. Wu, J. Zhao, S. Sun and T. Xu, *J. Am. Chem. Soc.*, 2007, **129**, 1500.

3 (*a*) O. Brümmer, J. J. La Clair and K. D. Janda, *Bioorg. Med. Chem.*, 2001, **9**, 1067; (*b*) P. B. Tchounwou, W. K. Ayensu, N. Ninshvili and D. Sutton, *Environ. Toxicol.*, 2003, **18**, 149; (*c*)W. F. Fitzgerald, C. H. Lamborg and C. R. Hammerschmidt, *Chem. Rev.*, 2007, **107**, 641; (*d*) J. H. Lee, J. H. Youm and K. S. Kwon, *J. Prev. Med. Public Health*, 2006, **39**, 199.

4 (*a*) C. Vulpe, B. Levinson, S. Whiteny, S. Packman and J. Gitschier, *Nat. Genet.*, 1993, **3**, 7; (*b*) P. G. Georgopoulos, A. Roy, M. J. Yonone-Lioy, R. E. Opiekun and P. J. Lioy, *J. Toxicol. Environ. Health, Part B*, 2001, 4, 341.

5 (*a*) H. Zheng, X.-J. Zhang, X. Cai, Q.-N. Bian, M. Yan, G.-H. Wu, X.-W. Lai and Y.-B. Jiang, *Org. Lett.*, 2012, **14**, 1986; (*b*) A. Mitra, A. K. Mittal and C. P. Rao, *Chem. Commun.*, 2011, **47**, 2565; (*c*) M. Dong, Y.-W. Wang and Y. Peng, *Org. Lett.*, 2010, **12**, 5310; (*d*) X. Guo, X. Qian and L. Jia, *J. Am. Chem. Soc.*, 2004, **126**, 2272; (*e*) Y.-K. Yang, K.-J. Yook and J. Tae, *J. Am. Chem. Soc.*, 2005, **127**, 16760;

View Article Online
DOI: 10.1039/C4DT00014E

(*f*) A. Caballero, R. Martínez, V. Lloveras, I. Ratera, J. Vidal-Gancedo, K. Wurst, A. Tárrage, P. Molina and J. Veciana, *J. Am. Chem. Soc.*, 2005, **127**, 15666; (*g*) C. Chen, R. Wang, L. Guo, N. Fu, H. Dong and Y. Yuan, *Org. Lett.*, 2011, **13**, 1162; (*h*) J. Du, J. Fan, X. Peng, P. Sun, J. Wang, H. Li and S. Sun, *Org. Lett.*, 2010, **12**, 476; (*i*) L. Xu, Y. Xu, W. Zhu, Z. Xu, M. Chen and X. Qian, *New J. Chem.*, 2012, **36**, 1435; (*j*) W. Xuan, C. Chen, Y. Cao, W. He, W. Jiang and W. Wang, *Chem. Commun.*, 2012, **48**, 7292.

6 (*a*) Z. Liu, C. Zhang, X. Wang, W. He and Z. Guo, *Org. Lett.*, 2012, **14**, 4378; (*b*) D. Wang, Y. Shiraishi and T. Hirai, *Chem. Commun.*, 2011, **47**, 2673; (*c*) S. Goswami, D. Sen and N. K. Das, *Org. Lett.*, 2010, **12**, 856; (*d*) H. S. Jung, P. S. Kwon, J. W. Lee, J. Kim, C. S. Hong, J. W. Kim, S. Yan, J. Y. Lee, J. H. Lee, T. Joo and J. S. Kim, *J. Am. Chem. Soc.*, 2009, **131**, 2008; (*e*) L. Xu, Y. Xu, W. Zhu, B. Zeng, C. Yang, B. Wu and X. Qian, *Org. Biomol. Chem.*, 2011, **9**, 8284; (*f*) G.-K. Li, Z.-X. Xu, C.-F. Chen and Z.-T. Huang, *Chem. Commun.*, 2008, 1774; (*g*) W. Lin, L. Long, B. Chen, W. Tan and W. Gao, *Chem. Commun.*, 2010, **46**, 1311; (*h*) G.-Y. Lan, C.-C. Huang and H.-T. Chang, *Chem. Commun.*, 2010, **46**, 1257; (*i*) Z. Xu, X. Qian and J. Cui, *Org. Lett.*, 2005, **7**, 3029.

7 (*a*) Y. Che, X. Yang and L. Zang, *Chem. Commun.*, 2008, 1413; (*b*) M. Kumar, R. Kumar and V. Bhalla, *Chem. Commun.*, 2009, 7384; (*c*) K. K. Sadhu, S. Sen and P. K. Bharadwaj, *Dalton Trans.*, 2011, **40**, 726; (*d*) Y.-B. Ruan, S. Maisonneuve and J. Xie, *Dyes Pigm.*, 2011, **90**, 239; (*e*) X. Zhang, Y. Shiraishi and T. Hirai, *Org. Lett.*, 2007, **9**, 5039; (*f*) J. Xie, M. Ménand, S. Maisonneuve and R. Métivier, *J. Org. Chem.*, 2007, **72**, 5980.

8 (*a*) Y. Yang, T. Cheng, W. Zhu, Y. Xu and X. Qian, *Org. Lett.*, 2011, **13**, 264; (*b*) J. Wang, X. Qian and J. Cui, *J. Org. Chem.*, 2006, **71**, 4308.

9 (*a*) S. Ozlem and E. U. Akkaya, *J. Am. Chem. Soc.*, 2009, **131**, 48; (*b*) Z. Q. Hu, C. Lin, X. M. Wang, L. Ding, C. L. Cui, S. F. Liu and H. Y. Lu, *Chem. Commun.*, 2010, **46**, 3765; (*c*) M. Dong, Y. W. Wang and Y. Peng, *Org. Lett.*, 2010, **12**, 5310; (*d*) R. Guliyev, S. Ozturk, Z. Kostereli, E. U. Akkaya, *Angew. Chem. Int. Ed.*, 2011, **50**, 9826; (*e*) T. Cheng, T. Wang, W. Zhu, Y. Yang, B. Zeng, Y. Xu and X. Qian, *Chem. Commun.*, 2011, **47**, 3915.

10 (*a*) A. P. de Silva and S. Uchiyama, *Nature Nanotechnol.*, 2007, **2**, 399; (*b*) O. A. Bozdemir, R. Guliyev, O. Buyukcakir, S. Selcuk, S. Kolemen, G. Gulseren, T. Nalbantoglu, H. Boyaci and E. U. Akkaya, *J. Am. Chem. Soc.*, 2010, **132**, 8029.

11 (*a*) J. Huang, X. Ma, B. Liu, L. Cai, Q. Li, Y. Zhang, K. Jiang and S. Yin, *J. Lumin.*, 2013, **141**, 130; (*b*) Z. Guo, W. Zhu, L. Shen and H. Tian, *Angew. Chem. Int. Ed.*, 2007, **46**, 5549.

12 L. Xu, Y. Xu, W. Zhu, C. Yang, L. Han and X. Qian, *Dalton Trans.*, 2012, **41**, 7212.

13 (*a*) Z. Xu, Y. Xiao, X. Qian, J. Cui and D. Cui, *Org. Lett.*, 2005, **7**, 889; (*b*) C. Zhang, Z. Liu, Y. Li, W. He, X. Gao and Z. Guo, *Chem. Commun.*, 2013, **49**, 11430.