

Highly sensitive and selective Pd²⁺ sensor of naphthalimide derivative based on complexation with alkynes and thio-heterocycle†

Liping Duan, Yufang Xu and Xuhong Qian*

Received (in Cambridge, UK) 2nd September 2008, Accepted 2nd October 2008

First published as an Advance Article on the web 29th October 2008

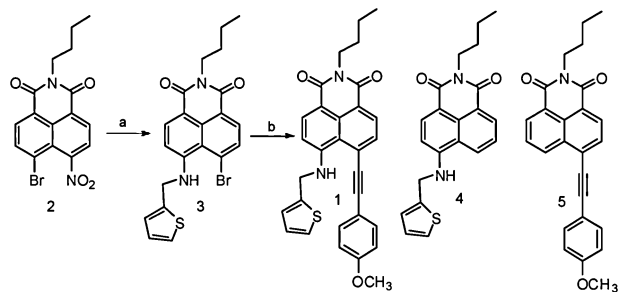
DOI: 10.1039/b815298e

A new fluorescent Pd²⁺ sensor **1**, *N*-butyl-4-(*p*-methoxyphenylethynyl)-5-thiophenemethylamino-1,8-naphthalimide, was designed and synthesized. It showed highly selective on-off fluorescence changes for Pd²⁺ among the representative transition and heavy metallic cations, and its fluorescence was efficiently quenched by 5 equivalents of Pd²⁺ in buffer solution. The sensor also displayed a selective chromogenic behavior toward Pd²⁺ from yellow to black-red, which could be easily observed by the naked eye.

Development of highly sensitive and selective fluorescent sensors for heavy and transition metal ions is of current interest because of their significant importance in chemistry, biology, and environmental science. Pd²⁺ plays an important role in the production of dental and medicinal devices, jewellery, automobile and catalytic¹ converters, so the investigation on the methodology for highly selective and sensitive detection of Pd²⁺ and its derivatives has attracted tremendous attentions. The majority of the known methods include atomic absorption spectrometry (AAS), plasma emission spectroscopy (ICP-AES), solid phase microextraction–high performance liquid chromatography (SPME–HPLC), X-ray fluorescence, *etc.*² These methods have the characteristics of fast measurement and good sensitivity, but they need expensive facilities, complicated sample-pretreatment procedures and well-controlled experimental conditions. Colorimetric technique is frequently applied to the determination of Pd²⁺. The mechanism of this detection method is the complexation of Pd²⁺ with either *N,N*-dimethyl-4-nitrosoaniline or 5, 10, 15, 20-tetrakis(4-sulfophenyl) porphine (TPPS₄). The former results in a yellowish orange complex, which can be analyzed by UV-vis spectroscopy with low detection limits.^{3a} As to the latter, other heavy metallic cations can also form complex with TPPS₄ and thus cause determination interferences.^{3b} There are also few interesting examples of fluorescent detection for Pd²⁺ and its derivatives based on chemical reaction in solution.⁴ We are interested in developing highly sensitive and selective fluorescent Pd²⁺ sensor based on the complexation in aqueous solution, which may provide a new strategy for design of Pd²⁺ sensor without complicated sample-pretreatment procedures, and eliminate obvious interferences from the other transition metallic cations during the fluorescence or UV measurement.

Recently we did systematic investigations on fluorescent sensors of naphthalimide derivatives for Cu²⁺ and Cd²⁺ based on the internal charge transfer (ICT) mechanism,⁵ on which some substituting groups with potential chelating abilities were introduced into the naphthalimide ring at 4, 5-position. As we know, the thiophene moiety is often employed in material fields such as conjugated polymer, optoelectronic device, conductivity-based sensory device, bio-diagnostics device, novel drug, and nonlinear optical material.⁶ Sulfur-containing chains were ever used for binding with heavy or transition metallic cations. Pd²⁺ is a “soft” metal that may be easy to form stable complexes with sulfur-containing amino acids, peptides and proteins.⁷ On the other hand, it is well-known that alkynes are able to coordinate with π -philic metal ions, such as Ag⁺, Ni²⁺, Co²⁺, Hg²⁺, and Pd²⁺ through the ($\pi \rightarrow d$) donations.⁸ Bearing these in mind, we designed and synthesized a simple and aqueous-soluble sensor **1**, with *N*-butyl-4-amino-1,8-naphthalimide as the fluorophore, thiophenemethylamine and phenylethyne as receptors for the detection of Pd²⁺ and its derivatives.

The target compound *N*-butyl-4-(*p*-methoxyphenylethynyl)-5-thiophenemethylamino-1,8-naphthalimide was synthesized from the starting material *N*-butyl-4-bromo-5-nitro-1,8-naphthalimide,^{5a} through the corresponding 5-thiophenemethylamino intermediate **3** (Scheme 1).



Scheme 1 Synthesis of **1**. (a) 2-Thiophenemethylamine, DMF, room temperature, 65%; (b) 4-methoxyphenylethyne, Pd(PPh₃)₄, CuI, Et₃N, N₂, reflux, 85%.

The fluorescence of fluorophores is usually disturbed by proton in the detection of metal ions, so their low sensitivity to pH is desired. The effect of pH on the fluorescence of **1** was first determined in ethanol-water (60:40, v/v) solution. The emission spectrum of **1** had no obvious change in the pH range 12.0–2.0, *viz.* the change in pH value does not disturb the detection of Pd²⁺ (ESI, Fig. S1†). On the other hand, when pH was larger than 9.0, the fluorescence of the Pd²⁺–**1** complex disappeared and the complex decomposed, as Pd²⁺ is easy to bind with OH[−] anion and form Pd(OH)₂

State Key Laboratory of Bioreactor Engineering and Shanghai Key Laboratory of Chemical Biology, School of Pharmacy, East China University of Science and Technology, Shanghai, 200237, China.
E-mail: xhqian@ecust.edu.cn; Fax: +86-21-64252603

† Electronic supplementary information (ESI) available: Synthetic details, and spectroscopic data. See DOI: 10.1039/b815298e

precipitation in high pH solution, which would reduce its complexation with **1**. Therefore, all of the detections of metal cations were operated in the ethanol–water (60:40, v/v) solution at pH 7.2 maintained with HEPES buffer.

1 has two absorption peaks centered at 340 nm and 458 nm in ethanol–water (60:40, v/v) solution at pH 7.2. The addition of 5 equiv of Pd^{2+} to the solution of **1** within 1 min caused an enhancement in the absorbance at 340 nm with expanding the absorbance at 458 nm, meanwhile, new peak was found in absorbance at 270 nm which may indicate the formation of a stable complex (ESI, Fig. S2†). The sensor also showed a selective chromogenic behavior toward Pd^{2+} ion, that is, a color change from light-yellow to black-red, which was observed by naked eye. Fig. 1 displays the changes emission spectra of **1** with Pd^{2+} concentrations. It could be seen that with the increase of Pd^{2+} concentration, the fluorescence intensity of **1** at 565 nm decreased dramatically. The fluorescence quantum yield of **1** decreased from 0.24 to 0.03 (Determined by comparison with rhodamine B in ethanol ($\Phi = 0.49$)).⁹ Fig. 1(b) was the plot of fluorescence intensity vs. Pd^{2+} concentration, an approximate plateau was observed at 1:1 molar ratio. It suggested that **1** formed a 1:1 stoichiometrical complex with Pd^{2+} . The same result was obtained in DMSO. (ESI, Fig. S3†).

The quenching of fluorescence was apparently caused by the binding of Pd^{2+} with **1**. An obvious evidence for the formation of the complex came from the ESI-MS data. In the presence of Pd^{2+} , two peaks at 685.3 and 1093.2 m/z were observed, which attributed to the fragments $[\text{L}_1\text{PdCH}_2\text{Cl}_2]^+$ and $[\text{2L}_1 + \text{Pd}]^+$, respectively (ESI, Fig. S4†).

¹H-NMR experiments were carried out to confirm the coordination sites of **1** during the formation of the complex. When 1.0 equivalent of PdCl_2 (in DMSO) was added to the solution of **1**, the peak of the thiophenemethylamine C–H and N–H showed significant differences, which suggested two active coordination sites (N, S) were involved in the complexation with Pd^{2+} . The peak of proton in the benzylic-OCH₃ unit was shifted to down-field from 3.80 to 3.90, which attributed to the deshielding effect arising from the decrease of the electron density in the fluorophore caused by alkynes– Pd^{2+} complexation (ESI, Fig. S5†). In addition, the chemical shifts of the aromatic protons in the naphthalene moiety as well as CH₂ in benzyl peaks did not show any significant changes in the ¹H-NMR spectrum, therefore, we were able to exclude the interaction of

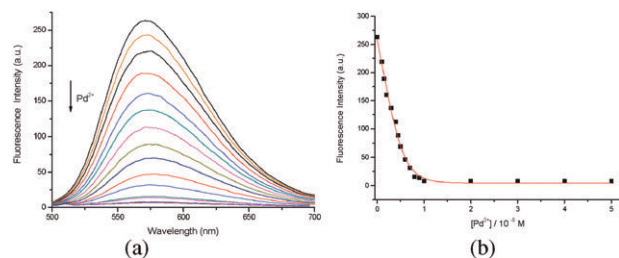
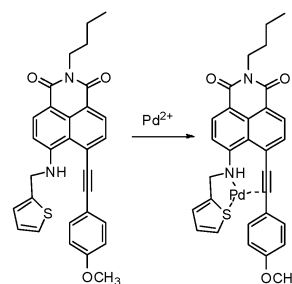


Fig. 1 Fluorescence spectra of compound **1**. (Conditions: **1** (1×10^{-5} M) in ethanol–water (60:40, v/v) solution at pH 7.2 maintained with HEPES buffer (50 mM) after the addition of 0, 0.1, 0.15, 0.2, 0.3, 0.4, 0.45, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 2, 3, 4 and 5 equivalents of Pd^{2+} ion, Excited slit width 5 nm, Emission slit width 5 nm, excitation at 365 nm.)

benzylic or naphthalene ring with Pd^{2+} , and the binding mode was suggested in Scheme 2.



Scheme 2 Proposed Pd^{2+} sensing process.

High selectivity is important for an excellent sensor. The addition of other metal ions such as Cu^+ , Pt^{2+} , Cu^{2+} , Co^{2+} , Zn^{2+} , Hg^{2+} , Ag^+ , and Pb^{2+} produced minor changes in both absorption and fluorescent spectra of **1**. The above results implied that its selectivity for Pd^{2+} was remarkable (Fig. 2). At the same time, to further confirm the role of coordination sites during the sensing of **1** to Pd^{2+} , we prepared a pair of model compounds (**4** and **5**, Scheme 1). It was found that the fluorescence was quenched slightly with the addition of heavy and transition metal ions, e.g. Hg^{2+} , Ag^+ , Pt^{2+} and Pd^{2+} , owing to heavy atom effect, and no selectivity was observed under the same condition (ESI, Fig. S9†). The high selectivity and sensitivity of **1** towards Pd^{2+} implies that it is essential to combine thiophenemethylamine and phenylethyne groups within **1**. Both the ligating moieties and steric interaction play important roles in the combination of Pd^{2+} .

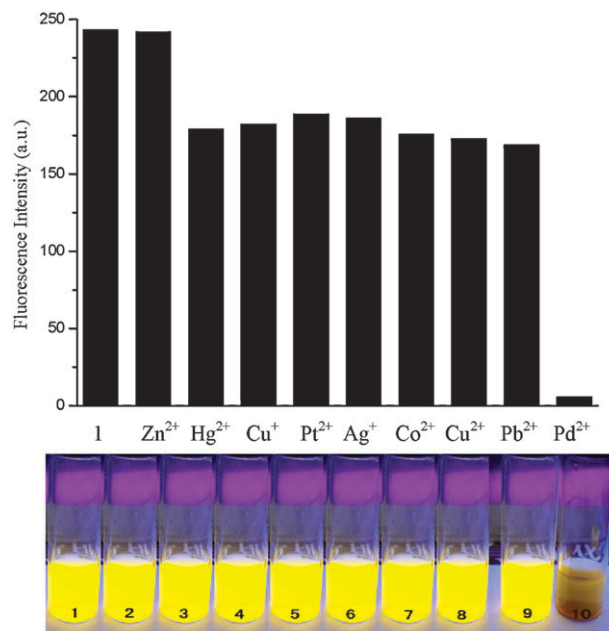


Fig. 2 Top: Fluorescence spectra of **1**. (Conditions: **1** (10 μM) in ethanol–water (60:40, v/v) solution at pH 7.2 maintained with HEPES buffer (50 mM) in the presence of different metal ions (5×10^{-5} M) at 25 °C.) Bottom: The fluorescence responses of **1** corresponding to the graph above.

In summary, an aqueous soluble fluorescent Pd²⁺ sensor **1** was designed and synthesized, and it displayed high selective and sensitive fluorometric and colorimetric responses towards Pd²⁺ in aqueous solution within 1 min, which might be the better Pd²⁺ sensor based on complexation. It was selective, simple and easy for application.

This work was supported by the National Basic Research Program of China (2003CB114400) and Program of Shanghai Subject Chief Scientist and the National Natural Science Foundation of China (20536010). We also thank Dr J. Qian for valuable discussions.

References

- (a) T. Iwasawa, M. Tokunaga, Y. Obora and Y. Tsuji, *J. Am. Chem. Soc.*, 2004, **126**, 6554; (b) M. Lafrance and K. Fagnou, *J. Am. Chem. Soc.*, 2006, **128**, 16496; (c) J. Le Bars, U. Specht, J. S. Bradley and D. G. Blackmond, *Langmuir*, 1999, **15**, 7621.
- (a) K. Van Meel, A. Smekens, M. Behets, P. Kazandjian and R. Van Grieken, *Anal. Chem.*, 2007, **79**, 6383; (b) C. Locatelli, D. Melucci and G. Torsi, *Anal. Bioanal. Chem.*, 2005, **382**, 1567; (c) B. Dimitrova, K. Benkhedda, E. Ivanova and F. Adams, *J. Anal. At. Spectrom.*, 2004, **19**, 1394.
- (a) P. Sarkar, P. K. Paria and S. K. Majumdar, *J. Indian Chem. Soc.*, 1988, **65**, 117; (b) D. Kalný, A. M. Albrecht-Gary and J. Havel, *Anal. Chim. Acta*, 2001, **439**, 101.
- (a) F. Song, A. L. Garner and K. Koide, *J. Am. Chem. Soc.*, 2007, **129**, 12354; (b) R. J. T. Houk, K. J. Wallace, H. S. Hewage and E. V. Anslyn, *Tetrahedron*, 2008, **64**(36), 8271; (c) T. Schwarze, H. Müller, C. Dosche, T. Klamroth, W. Mickler, A. Kelling, H.-G. Löhmansröben, P. Saalfrank and H.-J. Holdt, *Angew. Chem., Int. Ed.*, 2007, **46**, 1671.
- (a) Z. Xu, X. Qian and J. Cui, *Org. Lett.*, 2005, **7**, 3029; (b) Z. Xu, Y. Xiao, X. Qian, J. Cui and D. Cui, *Org. Lett.*, 2005, **7**, 889; (c) C. Lu, Z. Xu, J. Cui, R. Zhang and X. Qian, *J. Org. Chem.*, 2007, **72**, 3554.
- (a) M. Berggren, O. Inganas, J. Rasmusson, G. Gustafsson, M. R. Andersson, O. Wennerstrom and T. Hjertberg, *Nature*, 1994, **372**, 444; (b) R. R. Wexler, W. J. Greenlee, J. D. Irvin, M. R. Goldberg, K. Prendergast, R. D. Smith and P. B. M. W. M. Timmermans, *J. Med. Chem.*, 1996, **39**, 625.
- (a) S. Fu, Z. Liu, S. Liu, J. Liu and A. Yi, *Anal. Chim. Acta*, 2007, **599**, 271; (b) V. Madhu and S. K. Das, *Eur. J. Inorg. Chem.*, 2006, 1505.
- (a) M. G. Organ, E. A. Arvanitis and S. J. Hynes, *J. Org. Chem.*, 2003, **68**, 3918; (b) L. Canovese, F. Visentin, G. Chessa, P. Uguagliati, C. Santo, G. Bandoli and L. Maini, *Organometallics*, 2003, **22**, 3230; (c) A. J. Canty, M. C. Denney, G. van Koten, B. W. Skelton and A. H. White, *Organometallics*, 2004, **23**, 5432; (d) C. Jia, W. Lu, J. Oyamada, T. Kitamura, K. Matsuda, M. Irie and Y. Fujiwara, *J. Am. Chem. Soc.*, 2000, **122**, 7252; (e) C. Jia, D. Piao, J. Oyamada, W. Lu, T. Kitamura and Y. Fujiwara, *Science*, 2000, **287**, 1992.
- K. G. Casey and E. L. Quitevis, *J. Phys. Chem.*, 1988, **92**, 6590–6594.