

A pyridinyl-functionalized tetraphenylethylene fluorogen for specific sensing of trivalent cations†

Cite this: *Chem. Commun.*, 2013, **49**, 1503

Received 15th November 2012,
Accepted 4th January 2013

DOI: 10.1039/c2cc38246f

www.rsc.org/chemcomm

Xiujuan Chen,^a Xiao Yuan Shen,^a Erjia Guan,^a Yi Liu,^a Anjun Qin,^a Jing Zhi Sun^{*a} and Ben Zhong Tang^{*ab}

A pyridinyl-functionalized tetraphenylethylene (Py-TPE) was synthesized and it demonstrated colorimetric and ratiometric fluorescent responses to trivalent metal cations (M³⁺, M = Cr, Fe, Al) over a variety of mono- and divalent metal cations.

Exploring fluorescent chemosensors for trivalent metal cations (M³⁺) is an important research subject. On the one hand, fluorescent techniques offer the feasibility of fast, facile and highly sensitive detection of target analytes. On the other hand, M³⁺ ions have their own biological significance and environmental importance. For example, Cr³⁺ is a necessary trace element in human nutrition. Overdose of Cr³⁺ negatively affects cellular structure and function and causes disturbance in glucose levels and lipid metabolism, while a deficiency of Cr³⁺ in humans can cause diabetes and cardiovascular disease.¹ Meanwhile, industrial runoff of Cr³⁺ may lead to detrimental pollution. As the third most abundant metal in the Earth's crust, Al³⁺ is also one of the common species of metal cations. It is common sense that increasing free Al³⁺ due to acidic rain and human activities in the environment and surface water is detrimental to growing plants.² And in recent years, it has been recognized that excessive intake of Al³⁺ leads to a wide range of diseases, such as Alzheimer's disease and osteoporosis.³ As to Fe³⁺, its vital roles in a variety of cell functions have been summarized in tutorial reviews.⁴

There have been research efforts to develop luminescence turn-on and/or ratiometric sensors based on available fluorogens such as rhodamine,⁵ fluorescein,⁶ BODIPY,⁷ and cyclometalated Ir(III) complex ([Ir(dfppy)₂phen]⁺).⁸ The sensing mechanism

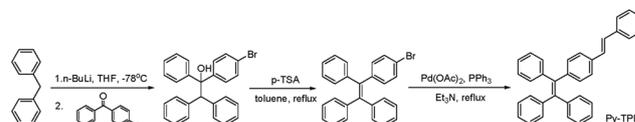
depends on the fluorogen's structure and the situation in which the fluorogen is used. For instance, Lu *et al.* reported a highly selective and sensitive fluorescent turn-on chemosensor for Al³⁺ based on a photoinduced electron transfer (PET) approach.⁹ Li and colleagues demonstrated that a dyad containing a rhodamine and a naphthalimide moiety could be used as a Cr³⁺-selective fluorescent probe for monitoring Cr³⁺ in living cells with a ratiometric fluorescent method.^{5c} The working mechanism is ascribed to fluorescent resonance energy transfer (FRET) from 1,8-naphthalimide to rhodamine. Dong and colleagues recently reported a fluorescent turn-on chemosensor for the selective detection of Al³⁺ based on an aggregation-induced emission (AIE) mechanism.¹⁰ AIE drives at a unique fluorescent behavior of some fluorogens that emit very weakly in dilute solution but become highly emissive when their molecules form aggregates or they are frozen in solid matrices.¹¹ The complexation of carboxylic groups on the pentaphenylpyrrole moiety and Al³⁺ results in molecular aggregation. More recently, Barba-Bon *et al.* described a highly efficient fluorescent probe for trivalent cations. The fluorescence (FL) turn-on was realized *via* the formation of 1 : 1 or 2 : 1 ligand–metal complexes.⁶

Herein, we demonstrate a different method for the fluorescent sensing of M³⁺ ions (M = Cr, Fe and Al) by using a pyridinyl-functionalized tetraphenylethylene (TPE) fluorogen. The chemical structure of the target compound (Py-TPE) and its synthetic route are displayed in Scheme 1, the experimental details are described in the ESI.† The resultant was characterized by ¹H-NMR, ¹³C-NMR, high-resolution mass spectrometry, elemental analysis and satisfactory results were obtained (ESI† and Fig. S1, S2 and S3). Our original intention of acquiring Py-TPE was to make use of the AIE properties of the TPE and the complexation ability of the pyridine moieties, because TPE is a representative AIE-active fluorogen and widely used as a converter to turn classical

^a MoE Key Laboratory of Macromolecule Synthesis and Functionalization, Department of Polymer Science and Engineering, Zhejiang University, Hangzhou 310027, China. E-mail: sunjz@zju.edu.cn; Fax: +86 (571)87953734; Tel: +86 571-87953734

^b Department of Chemistry, Institute for Advanced Study, State Key Laboratory of Molecular Neuroscience, and Division of Biomedical Engineering, The Hong Kong University of Science & Technology, Clear Water Bay, Kowloon, Hong Kong, China. E-mail: tangbenz@ust.hk; Fax: +86 852-23581594; Tel: +86 852-23587375

† Electronic supplementary information (ESI) available: Detailed synthesis and characterization of Py-TPE; UV and FL spectra for AIE and titration; frontier molecular orbital plots and energy diagrams of Py-TPE and protonated Py-TPE. See DOI: 10.1039/c2cc38246f



Scheme 1

chromophores into AIE-active ones.¹² In our expectation, complexation of metal cations and the pyridinyl moiety of Py-TPE would change the solubility and trigger molecular aggregation, thereby inducing emission from the TPE moiety. Consequently, metal cations could be detected in an FL turn-on strategy.

In dilute ethanol solution, Py-TPE emits very weakly. But it becomes highly emissive when a suspension is formed in ethanol–water (solvent–non-solvent) mixtures (Fig. S4, ESI†). This observation indicates that Py-TPE is an AIE-active compound. Moreover, the non-aggregation in ethanol–water solutions with low water fraction allows us to use Py-TPE as a fluorescent probe to detect metal cations that have acceptable solubility in aqueous media. We firstly tried the detection of Zn²⁺ in Py-TPE ethanol solution. As shown in Fig. 1, in comparison with the FL free from metal cations, there are no evident changes in the fluorescent features before and after the addition of Zn²⁺ into the solution. This result is out of our expectation. Because we have reckoned that Zn²⁺ has a strong affinity to the pyridinyl group and the derived complex has low solubility and readily precipitates in the solution, then the aggregates give rise to strong FL. To check whether the unexpected result is observed by chance or is a general phenomenon, we tried different metal cations in three categories. (i) Metal cations in the same period as Zn²⁺ in the periodic table of elements, including Cr³⁺, Mn²⁺, Fe²⁺/Fe³⁺, Co²⁺, Ni²⁺, and Cu²⁺. (ii) Some hazardous heavy metal ions such as Pb²⁺, Cd²⁺, Hg²⁺ and Ag⁺. (iii) A few metal cations in the IA, IIA and IIIA groups such as Na⁺, K⁺, Ca²⁺, Mg²⁺, and Al³⁺. The results are displayed in Fig. 1. Surveying these data, two characteristics can be found. The first is that all of the trivalent cations showed positive responses to the fluorescent probe, as quantitatively and visually revealed by Fig. 1A and B, respectively. And the second is that the emission colour changes from blue of Py-TPE to red when enough M³⁺ aqueous solution is added into the Py-TPE ethanol solution (Fig. 1C). In all of the tested M⁺ and M²⁺ ions, only Hg²⁺ shows a positive fluorescent response to Py-TPE. As revealed by the spectra and image in Fig. S5 (ESI†), orange fluorescence (peak at 597 nm)

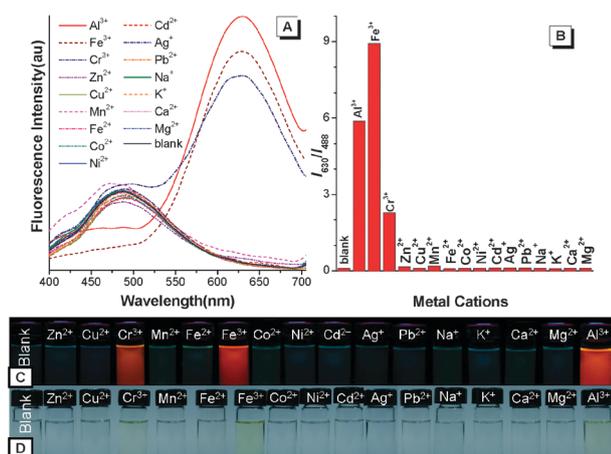


Fig. 1 (A) Fluorescence (FL) spectra of Py-TPE in ethanol and in ethanol–water mixture solutions in the presence of 10 equivalents of different metal cations. (B) Diagram of I_{630}/I_{488} corresponding to Py-TPE in ethanol and each metal cation in ethanol–water mixture solution. I_{630} and I_{488} are the maximal intensities of the blue and red emission bands, respectively. The data are extracted from (A). (C), (D) Photographs of the above solutions taken under UV light ($\lambda_{\text{ex}} = 365$ nm) and daylight, respectively. Concentration of Py-TPE ([Py-TPE]): 10 μM .

can be observed. Though Hg²⁺ can also induce a change in emission feature, it is easy to recognize Hg²⁺ from M³⁺ ions by the difference in emission colour (orange for Hg²⁺ and red for M³⁺ ions).

The first characteristic suggests that fluorescent response relates to the ionic valence rather than to the kind of cation. Some M²⁺ ions that have higher capacity for coordinating with the pyridine moiety (*i.e.* Zn²⁺, Co²⁺, and Cu²⁺) are regardless to the existence of Py-TPE and show no FL change. While the M³⁺ ions demonstrate evident fluorescent responses though it is well-known that pyridine is not a proper ligand to Cr³⁺, Fe³⁺ or Al³⁺. The second characteristic implies that the red emission may come from new fluorescent species other than Py-TPE aggregates, otherwise blue emission should be observed (see Fig. S4, ESI†). The fact that Py-TPE has not formed aggregates is also confirmed by the photographs of the mixtures taken in daylight, which show no precipitates in the solutions.

To gain a better understanding of the impact of M³⁺ on the fluorescent behaviour of Py-TPE, Cr³⁺ was used as a representative (named as Cr³⁺@Py-TPE system) and the FL changes of Py-TPE with different concentrations of Cr³⁺ ([Cr³⁺]) were monitored (Fig. 2). Without Cr³⁺, Py-TPE itself emits weak blue FL in ethanol solution with a maximum at 488 nm. When Cr³⁺ is introduced into the solution, the blue emission band is decreased. Meanwhile, a new red emission band with a peak at 630 nm grows as [Cr³⁺] increases. This red band begins to be visually observed at a [Cr³⁺] of 6 μM and becomes dominant when [Cr³⁺] is higher than 20 μM . These results indicate that Py-TPE has a higher Cr³⁺ cation sensitivity (as low as 6 μM) over the reported Cr³⁺ fluorescent probes based on chelating, PET and FRET mechanisms.^{5–9} The plot of I_{630}/I_{488} vs. [Cr³⁺] and the FL images of the mixtures shown in Fig. 2B and the inset provide visual and clear information of the colorimetric fluorescent detection of Cr³⁺ using Py-TPE as a fluorescent probe. Similar results were monitored in the cases of Fe³⁺ and Al³⁺ (Fig. S6 and S7, ESI†).

It is noticeable that there is an isosbestic point at 535 nm in Fig. 2A and similar points are also observed for the systems of Fe³⁺@Py-TPE and Al³⁺@Py-TPE (Fig. S6 and S7, ESI†). The existence of an isosbestic point further verifies that the red emission originates from distinct species from Py-TPE. The red-emission species cannot be complexes of M³⁺(Py-TPE)_x. On the one hand, Cr³⁺(Py-TPE)_x, Fe³⁺(Py-TPE)_x and Al³⁺(Py-TPE)_x should give different FL features due to the different electronic structures of the central cations. On the other hand, M³⁺(Py-TPE)_x would precipitate, because the coordination of the pyridine moiety with M³⁺ bestows the complex with a

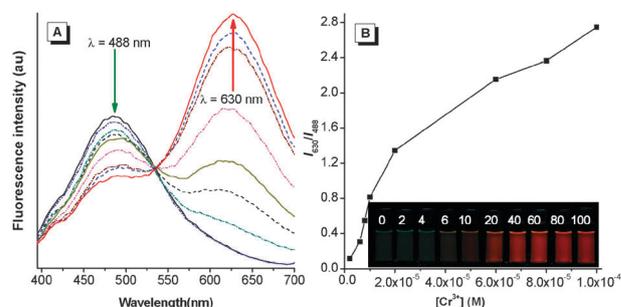


Fig. 2 (A) FL spectra of Py-TPE in ethanol and in ethanol–water mixture solutions with different concentrations of Cr³⁺ ([Cr³⁺]). (B) Plot of I_{630}/I_{488} versus [Cr³⁺]. The data are extracted from (A). The inset of (B) shows fluorescent images taken under UV light ($\lambda_{\text{ex}} = 365$ nm) for the solutions containing different [Cr³⁺], [Py-TPE] = 10 μM .

hydrophobic aromatic shell that makes the molecule hardly soluble in water–ethanol mixtures. However, the experimental results show that Cr^{3+} @Py-TPE, Fe^{3+} @Py-TPE and Al^{3+} @Py-TPE exhibit identical fluorescent behaviour and no precipitates have been observed for the three systems (Fig. 2B, Fig. S6 and S7, ESI[†]). Furthermore, the absorption spectra of Cr^{3+} @Py-TPE, Fe^{3+} @Py-TPE and Al^{3+} @Py-TPE systems all show evidently red-shifted absorption bands as compared to Py-TPE (Fig. S8 to S11, ESI[†]). These results indicate that the addition of M^{3+} to Py-TPE ethanol solution must have triggered the formation of new species in the mixture.

We next turned our attention to the pyridinyl moiety on Py-TPE which is a typical proton acceptor. Since water–ethanol mixture was used as the detection medium, it is possible to capture protons. Moreover, checking the database of K_{sp} (the constant of solubility product) of $\text{M}(\text{OH})_n$ ($n = 1, 2, \text{ and } 3$ for $\text{M}^+, \text{M}^{2+}, \text{ and } \text{M}^{3+}$ respectively), we found that $\text{Fe}(\text{OH})_3$, $\text{Al}(\text{OH})_3$ and $\text{Cr}(\text{OH})_3$ are the smallest three in all of our tested metal cations.¹³ Meanwhile, the order of K_{sp} for $\text{Fe}(\text{OH})_3$, $\text{Al}(\text{OH})_3$ and $\text{Cr}(\text{OH})_3$ is completely consistent with the order of I_{630}/I_{488} shown in Fig. 1B. It implies that M^{3+} is intensively hydrolyzed in water according to the master equation $\text{M}^{3+} + x\text{H}_2\text{O} \leftrightarrow \text{M}(\text{OH})_x^{3-x} + x\text{H}^+$. Thus the addition of M^{3+} aqueous solution into Py-TPE ethanol solution is equivalent to the addition of acid.

Following this concept, we investigated the influence of protons on the FL behavior of Py-TPE. As shown in Fig. 3, on adding trifluoroacetic acid (TFA) into Py-TPE ethanol solution, the FL features gradually change. The red emission peak at 630 nm manifests in the spectra at a TFA concentration ($[\text{TFA}]$) of 4 μM . This red band becomes predominant when $[\text{TFA}]$ is equal to and/or higher than 8 μM . The blue emission of Py-TPE (peak at 488 nm) vanishes when $[\text{TFA}]$ is equal to or higher than 40 μM . The proton-induced changes in FL intensity and colour are demonstrated by the plot of I_{630}/I_{488} vs. $[\text{TFA}]$ and the images in the inset of Fig. 3B. In addition, there exists an isosbestic point at 535 nm in Fig. 3A, which indicates that the blue and red emission bands are ascribed to Py-TPE and protonated Py-TPE species, respectively (inset of Fig. 3B, Fig. S12, ESI[†]). Theoretical calculations suggest that the protonated Py-TPE, as compared to Py-TPE, has an extended conjugation and a narrowed energy gap (Fig. S13, ESI[†]). Thus the protonated species can emit red FL. The remarkable homology

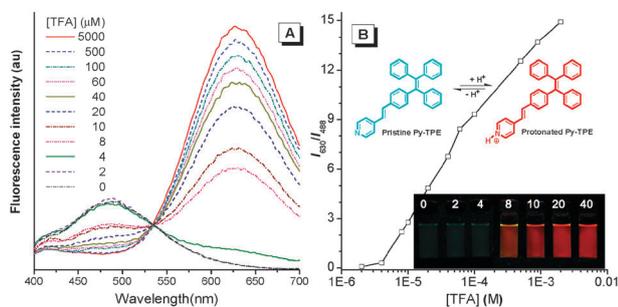


Fig. 3 (A) FL spectra of Py-TPE in ethanol solutions with different concentrations of trifluoroacetic acid or TFA ($[\text{TFA}]$). (B) Plot of I_{630}/I_{488} versus $[\text{TFA}]$. The inset of (B) displays FL images taken under UV light ($\lambda_{\text{ex}} = 365 \text{ nm}$) for the solutions containing different amounts of TFA. $[\text{Py-TPE}] = 10 \mu\text{M}$. The inset chemical equation shows the formation of protonated Py-TPE upon acceptance of a proton by the pyridinyl moiety.

of the fluorescent behaviour observed for H^+ @Py-TPE and M^{3+} @Py-TPE ($\text{M} = \text{Cr}, \text{Fe}, \text{Al}$) indicates that the colorimetric and ratiometric responses of Py-TPE to M^{3+} come intrinsically from a proton-binding-induced fluorescence change.

In summary, pyridinyl-functionalized TPE (Py-TPE) has been synthesized and displays weak blue FL in solution. When various mono-, di- and trivalent metal cations were added into the Py-TPE ethanol solution, only Fe^{3+} , Cr^{3+} and Al^{3+} can alter the emission feature from weak blue to strong red. By analyzing the similarity between the fluorescent responses of Py-TPE to Fe^{3+} , Cr^{3+} and Al^{3+} and comparing the K_{sp} values of $\text{M}(\text{OH})_n$ for all the measured metal cations, we deduced that the red emission band originates from protonated Py-TPE. This deduction has been validated by both a comparative study of the fluorescent responses of Py-TPE to TFA in different concentrations and theoretical predictions. It is concluded that the differentiated FL response of Py-TPE to M^{3+} over other tested M^{2+} and M^+ ions depends on the higher hydrolyzing ability of the M^{3+} , which releases more protons in the water–ethanol mixture. This fluorescent detection of trivalent cations is achieved by a mechanism distinct from literature reported ones. The colorimetric (blue to red) and ratiometric (I_{630} vs. I_{488}) characteristics of this kind of fluorescent probe have their own advantages. In addition, the emission maxima at 630 and 488 nm perfectly match with red and blue laser sources. This colorimetric and ratiometric FL probe may find promising applications as an active element of chemo- and biosensors.

This work was supported by the National Science Foundation of China (51273175); the key project of the Ministry of Science and Technology of China (2013CB834704), the Research Grants Council of Hong Kong (603509, HKUST2/CRF/10, and 604711), and the University Grants Committee of Hong Kong (AoE/P-03/08).

Notes and references

- 1 J. B. Vincent, *Nutr. Rev.*, 2000, **58**, 67.
- 2 A. M. Zayed and N. Terrey, *Plant Soil*, 2003, **249**, 139.
- 3 E. Delhaize and P. R. Ryan, *Plant Physiol.*, 1995, **107**, 315.
- 4 (a) S. K. Sahoo, D. Sharma, R. K. Bera, G. Crisponi and J. F. Callan, *Chem. Soc. Rev.*, 2012, **41**, 7195; (b) N. F. Olivieri, *N. Engl. J. Med.*, 1999, **341**, 99.
- 5 (a) Y. Lei, Y. Su and J. Huo, *J. Lum.*, 2011, **131**, 2521; (b) W. Liu, S. Pu, D. Jiang, S. Cui, G. Liu and C. Fan, *Microchim. Acta*, 2011, **174**, 329; (c) Z. Zhou, M. Yu, H. Yang, K. Huang, F. Li, T. Yi and C. Huang, *Chem. Commun.*, 2008, 3387.
- 6 A. Barba-Bon, A. M. Costero, S. Gil, M. Parra, J. Soto, R. Martínez-Mañez and F. Sancenon, *Chem. Commun.*, 2012, **48**, 3000.
- 7 X. Qu, Q. Liu, X. Ji, H. Chen, Z. Zhou and Z. Shen, *Chem. Commun.*, 2012, **48**, 4600.
- 8 Y. Han, Y. You, Y. Lee and W. Nam, *Adv. Mater.*, 2012, **24**, 2748.
- 9 Y. Lu, S. Huang, Y. Liu, L. Zhao and X. Zeng, *Org. Lett.*, 2011, **13**, 5274.
- 10 T. Y. Han, X. Feng, B. Tong, J. B. Shi, L. Chen, J. G. Zhi and Y. P. Dong, *Chem. Commun.*, 2012, **48**, 416.
- 11 (a) Y. Hong, J. W. Y. Lam and B. Z. Tang, *Chem. Soc. Rev.*, 2011, **40**, 5361; (b) S. Zhang, A. Qin, J. Z. Sun and B. Z. Tang, *Prog. Chem.*, 2011, **23**, 623; (c) Y. Hong, J. W. Y. Lam and B. Z. Tang, *Chem. Commun.*, 2009, 4332.
- 12 (a) Q. Zhao, X. A. Zhang, Q. Wei, J. Wang, X. Y. Shen, A. Qin, J. Z. Sun and B. Z. Tang, *Chem. Commun.*, 2012, **48**, 11671; (b) Q. Zhao, K. Li, S. Chen, A. Qin, D. Ding, S. Zhang, Y. Liu, B. Liu, J. Z. Sun and B. Z. Tang, *J. Mater. Chem.*, 2012, **22**, 15128; (c) Q. Zhao, S. Zhang, Y. Liu, J. Mei, S. Chen, P. Lu, A. Qin, Y. Ma, J. Z. Sun and B. Z. Tang, *J. Mater. Chem.*, 2012, **22**, 7387.
- 13 At 25 °C, for $\text{Al}(\text{OH})_3$, $\text{Cr}(\text{OH})_3$, and $\text{Fe}(\text{OH})_3$, $K_{\text{sp}} = 4.6 \times 10^{-33}$, 1.0×10^{-33} , and 3.0×10^{-39} , respectively.