# Tetrahedron Letters 54 (2013) 909-912

Contents lists available at SciVerse ScienceDirect

**Tetrahedron Letters** 

journal homepage: www.elsevier.com/locate/tetlet



# A red fluorescent 'turn-on' chemosensor for Hg<sup>2+</sup> based on triphenylamine-triazines derivatives with aggregation-induced emission characteristics

# Hao Zhang<sup>a</sup>, Yi Qu<sup>a</sup>, Yuting Gao<sup>a</sup>, Jianli Hua<sup>a,\*</sup>, Jing Li<sup>a</sup>, Bo Li<sup>b</sup>

<sup>a</sup> Key Laboratory for Advanced Materials and Institute of Fine Chemicals, East China University of Science and Technology, 130 Meilong Road, Shanghai 200237, PR China <sup>b</sup> Key Laboratory of Polar Materials and Devices, Ministry of Education, East China Normal University, Shanghai 200241, PR China

### ARTICLE INFO

Article history: Received 16 October 2012 Revised 21 November 2012 Accepted 27 November 2012 Available online 5 December 2012

Keywords: Hg<sup>2+</sup> AIE Fluorescent sensor Triphenylamine-triazines

#### ABSTRACT

A new sensitive and selective red fluorescence 'turn on' chemosensor **1** for Hg<sup>2+</sup> was developed by taking advantage of AIE feature of triphenylamine–triazines motif and the specific binding of thymine with Hg<sup>2+</sup>. Moreover, chemosensor **1** exhibited large two-photon absorption cross-section (3328 GM). © 2012 Elsevier Ltd. All rights reserved.

Mercury cations are extremely toxic and cause significant damage to environment and human health.<sup>1</sup> Thus, the sensitive and selective detection of Hg<sup>2+</sup> is crucial. A variety of designing strategies based on fluorescence techniques have been developed.<sup>2</sup> However, most of the fluorescent sensors display one or more drawbacks in terms of actual applicability. These include crosssensitivities from other metal ions (e.g., Ag<sup>+</sup>, Pb<sup>2+</sup> ions), synthetic difficulties, and fluorescence quenching in aqueous media. Therefore, it is worthwhile to find a useful mercury recognition mechanism for designing fluorescent sensor.

It is interesting to note that some organic molecules are practically non-luminescent in the solution state but become strongly emissive when aggregated. This intriguing phenomenon named aggregation-induced emission (AIE) is found by Tang and coworkers.<sup>3</sup> Recently, AIE materials have also been utilized for the development of new sensing systems. By proper structural modifications to the AIE molecules, their aggregation states can be influenced by the analytes through electrostatic attraction, coordination binding, etc., In this way, Tang and Zhang's groups reported many tetraphenylethylene and silole derivatives as fluorescence 'turn on' chemosensors for metal ions,<sup>4</sup> carbohydrate,<sup>5</sup> protein,<sup>6</sup> peparin,<sup>7</sup> lactic,<sup>8</sup> and so on. Among them, most reported chemosensors usually emitted blue fluorescence which can be strongly attenuated by a biological specimen.<sup>9</sup> It is well known that the wavelength range in the red region corresponds to the transparency window of a biological specimen, enabling optimal penetration of light into various biological media.<sup>10</sup> Therefore, the red-emitting probes are necessary for biophotonic application.

Triarylamine has been widely used in opto- and electro-active materials for its good electron donating and transporting capability, as well as its special propeller starburst molecular structure. And 1,3,5-triazine-based compounds show good optical and electrical properties due to their high electron affinity and symmetrical structure.<sup>11</sup> Recently, our group has reported deep orange multibranched triphenylamine end-capped triazine derivatives that exhibited AIE properties and large two-photon absorption cross section.<sup>12</sup> In this work, we have developed new red fluorescence 'turn on' chemosensor **1** for  $Hg^{2+}$  by making use of the unique AIE feature of the triphenylamine-triazines motif and the selective binding abilities of thymine (Scheme 1). As will be discussed below, the sensing mechanism of 1 toward Hg<sup>2+</sup> is attributed to two facts: (1) triphenylamine-triazines derivative 1 shows weak fluorescence in solution, but it becomes strong red fluorescence after aggregation; (2) the intermolecular coordination of **1** with Hg<sup>2+</sup> will lead to aggregation and fluorescence enhancement.

The synthesis of **1** started from 2,4,6-tri(*p*-tolyl)-1,3,5-triazine as shown in Scheme S1. Bromination of 2,4,6-tri(*p*-tolyl)-1,3,5-triazine afforded 2,4,6-tris(4-(bromomethyl)phen-yl)-1,3,5-triazine, followed by reaction with trimethyl phosphate, yielding triazine derivative **2**. The important intermediate aldehyde **4** was synthesized by the Ullmann reaction between triphenylamine aldehyde **3** and *N*,*N*-diphenylamine. Then, compound **5** was obtained by the Wittig–Horner reaction of compound **2** and **4**. Compound **7** 



<sup>\*</sup> Corresponding author. Tel.: +86 21 64250940; fax: +86 21 64252758. *E-mail address*: jlhua@ecust.edu.cn (J. Hua).

<sup>0040-4039/\$ -</sup> see front matter @ 2012 Elsevier Ltd. All rights reserved. http://dx.doi.org/10.1016/j.tetlet.2012.11.131



Scheme 1. Molecular structure of compound 1.

was easily synthesized by two nucleophilic substitution reaction. Finally, the target compound **1** was obtained by the Horner–Wadsworth–Emmons reaction between compound **5** and **7**. Their structures were characterized by spectroscopic methods. The synthetic details and characterization data are provided in the Supplementary data.

Figure 1 showed the fluorescence spectrum of compound **1** with different amounts of Hg(CH<sub>3</sub>COO)<sub>2</sub> in DMSO/H<sub>2</sub>O (9:1, v/v). Compound 1 showed a very weak emission at this concentration (see Fig. S1), with a quantum yield ( $\phi_{\rm F}$ ) of 0.012 (relative to Rhodamine B as a standard). However, after addition of  $Hg(CH_3COO)_2$ , the emission band at 610 nm emerged and the fluorescence intensity started to increase gradually as displayed in the inset of Figure 1. Moreover, the fluorescence intensity of 1 at 610 nm increased almost linearly with the concentration of Hg<sup>2+</sup> in the range of 0- $50 \,\mu\text{M}$  as shown in the inset of Figure 1, at which it showed an approximately 20-fold increase relative to the original value ( $\varphi_{\rm F}$  = 0.24) after addition of **1** equiv of Hg<sup>2+</sup> ( $\lambda_{\rm ex}$  = 400 nm). As can be seen in the inset of Figure 1, the fluorescence difference for the solution of **1** before and after addition of Hg<sup>2+</sup> can be distinguished visually and the resulting mixture displayed an intense red emission. The detection limit of Hg<sup>2+</sup> was estimated to be ca.  $6.6 \times 10^{-8}$  M (K = 18.18). The dramatic enhancement in the fluores-



**Figure 1.** Fluorescence spectra of compound  $\mathbf{1} (5 \times 10^{-5} \text{ M})$  in DMSO/H<sub>2</sub>O (9:1, v/v) in the presence of increasing amounts of Hg(CH<sub>3</sub>COO)<sub>2</sub> (From 0 to 70 µM);  $\lambda_{ex} = 400 \text{ nm}$ . Inset: (1) the plot of the fluorescence intensity ( $I_{610}$ ) versus the concentration of Hg(CH<sub>3</sub>COO)<sub>2</sub>. (2) The photos of the solution of compound  $\mathbf{1}$  before and after addition of  $\mathbf{1}$  equiv of Hg(CH<sub>3</sub>COO)<sub>2</sub> under UV light illumination (365 nm).

cence intensity upon addition of Hg<sup>2+</sup> was attributed to the coordination of thymine moieties of **1** with Hg<sup>2+</sup> ions leading to the aggregation of **1** as schematically shown in Scheme 2. The corresponding absorption, <sup>1</sup>H NMR spectral studies, and scanning electron microscopy (SEM) analysis can prove the above assumption. (1) Figure S2 showed the absorption spectra of **1** ( $2.5 \times 10^{-5}$  M in DMSO/H<sub>2</sub>O, 9:1 v/v) in the presence of increasing amounts of  $Hg(CH_3COO)_2$  (from 0 to 30  $\mu$ M). The absorption band around 373 nm became weak and the absorption intensity in the range of 490–600 nm increased gradually in the presence of  $Hg^{2+}$ . This implied that the compound 1 molecule aggregated into nanoparticles in the presence of Hg<sup>2+</sup>, as it is well known that the Mie effect of nanoparticles causes such level-off tails in the absorption spectra.<sup>13</sup> (2) Variation of <sup>1</sup>H NMR spectra of **1** in the presence of Hg<sup>2+</sup> also indicated the aggregation of 1. As shown in Figure S3, the signals around 6.9–9.0 ppm due to aromatic protons of 1 were upfield shifted and became weak after the gradual addition of Hg<sup>2+</sup>. In addition, the signal around 11.55 ppm belonging to imide protons on thymine also became weak and that around 12.00 ppm belonging to the protons on CH<sub>3</sub>COOH (O-H) became strong in the presence of Hg<sup>2+</sup>. (3) SEM image analysis revealed that a nanoscopic aggregate was formed in the solution of 1 containing 1.0 equiv of  $Hg^{2+}$  (Figure S4 (a,b)). Evidently, the emission of **1** is induced by aggregation formation of the coordination of thymine moieties of 1 with Hg<sup>2+</sup> ions.

The selectivity of this assay for  $Hg^{2+}$  ions was investigated by measuring fluorescent responses in DMSO/H<sub>2</sub>O (9:1, v/v) solution upon excitation at 400 nm. Figure 2a indicated that 1 detected  $Hg^{2+}$  with high selectivity. No remarkable changes were detected after addition of other metal ions (Pb<sup>2+</sup>, Cu<sup>2+</sup>, Ba<sup>2+</sup>, Ni<sup>2+</sup>, Zn<sup>2+</sup>, Mg<sup>2+</sup>, Co<sup>2+</sup>, Na<sup>+</sup>, K<sup>+</sup>, and Ag<sup>+</sup>). And competition experiments were conducted to confirm a potential applicability of 1 for the selective detection of  $Hg^{2+}$  ion in the presence of 5 equiv of various metal ions (Fig. 2b, red bars). Different fluorescence changes were also obtained by photograph (Fig. 2a). The result shows that compound 1 has high selectivity toward  $Hg^{2+}$ , which is attributed to the coordination of thymine moieties of 1 with  $Hg^{2+}$  ions.

Compared to single-photon fluorescence imaging, two-photon fluorescence imaging has shown promising perspectives due to its lower phototoxicity, reduced substrate autofluorescence, and deeper tissue penetration.<sup>14</sup> Most of two-photon absorption (TPA) dyes' fluorescence is often quenched on aggregation,



Scheme 2. Schematic illustration of the coordination mode between 1 and Hg<sup>2+</sup>.



**Figure 2.** (a) The photo of the solution of **1** after addition of different metal ions; And the fluorescence intensity ( $I_{610nm}$ ) of compound **1** ( $5 \times 10^{-5}$  M) in DMSO/H<sub>2</sub>O (9:1, v/v) in the presence of 1.0 equiv of the Hg<sup>2+</sup>, K<sup>+</sup>, and Na<sup>+</sup> was 50 equiv, other metal ions are 5.0 equiv respectively; (b) The result of competition test Hg<sup>2+</sup> and selection ions; a 2.0 mL solution of compound **1** ( $5 \times 10^{-5}$  M) in DMSO/H<sub>2</sub>O (9:1, v/v) was used, K<sup>+</sup> and Na<sup>+</sup> were 50 equiv, other metal ions are 5.0 equiv, respectively. The excitation wavelength was 400 nm and emission intensity was measured at 610 nm.



**Figure 3.** (a) Open-aperture Z-scan traces of compound 1 (scattered circles are the experimental data, and the straight line is the theoretical fitted data); (b) Two-photon fluorescence emission spectra for compound 1 ( $5 \times 10^{-5}$  M) in DMSO/H<sub>2</sub>O (9:1, v/v) before and after addition of 1 equiv of Hg(CH<sub>3</sub>COO)<sub>2</sub>. The photos of the solution of compound 1 before and after addition of 1 equiv of Hg(CH<sub>3</sub>COO)<sub>2</sub> under the laser illumination (800 nm).

although they may show high fluorescence efficiency in solutions, which greatly limits their biophotonic applications. In this regard, chromophore with AIE offers a promising platform with large TPA cross section ( $\sigma$ ) data. The  $\sigma$  value of **1** was determined by the femtosecond open aperture Z-scan technique according to the previously described method.<sup>15</sup> The open-aperture Z-scan traces of compound **1** are shown in Figure 3a, and  $\sigma$  value of **1** is 3328 GM by fitting the experimental data with theoretical expression given in Ref.<sup>15</sup>. The high TPA properties of **1** are attributed to the extended  $\pi$ -system and enhanced intramolecular charge transfer from multibranched triphenylamine to triazine. Under the excitation of an 80 fs, 800 nm pule, compound **1** emitted intense red fluorescence in the DMSO/H<sub>2</sub>O (9:1, v/v) after addition of 1.0 equiv of Hg<sup>2+</sup>. As shown in Figure 3b, the two-photon fluorescence (TPF) was remarkably intensified by nanoaggregation.

In summary, a new red fluorescent sensor **1** for  $Hg^{2+}$  was developed by making use of the specific binding of thymine with  $Hg^{2+}$  as well as the AIE feature of triphenylamine-triazines motif. The aggregation was demonstrated by absorption, <sup>1</sup>H NMR spectral and TEM analyses of **1** in the presence of  $Hg^{2+}$ . This assay showed high selectivity and sensitivity for  $Hg^{2+}$  ions even in the presence of other metal ions in a mixture. Moreover, **1** exhibited large twophoton absorption cross-section (3328 GM), suggesting that the targeted two-photon imaging is highly desirable for biological applications.

# Acknowledgements

This work was supported by NSFC/China (2116110444 and 21172073), National Basic Research 973 Program (2013CB733 700), the Fundamental Research Funds for the Central Universities (WJ0913001and WJ1114050), and Ph. D. Programs Foundation of Ministry of Education of China (20090074110004).

# Supplementary data

Supplementary data(synthetic procedures and characterization data of compound **1**; the absorption and fluorescent titration study; <sup>1</sup>H NMR spectra and SEM images of compound **1** in the pres-

ence of  $Hg^{2*}$ ) associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.tetlet.2012.11.131.

#### **References and notes**

- 1. U.S. EPA, EPA-452/R-05-003, 2005.
- (a) Elizabeth, M. N.; Lippard, S. J. Chem. Rev. 2008, 108, 3443–3480; (b) Kim, H. N.; Nam, S. W.; Swamy, K. M. K.; Jin, Y.; Chen, X. Q.; Kim, Y.; Kim, S. J.; Park, S.; Yoon, J. Analyst 2011, 136, 1339–1343; (c) Liu, Y.; Li, M. Y.; Zhao, Q.; Wu, H. Z.; Huang, K. W.; Li, F. Y. Inorg. Chem. 2011, 50, 5969–5977; (d) Zheng, H.; Zhang, X. J.; Cai, X.; Bian, Q. N.; Yin, M.; Wu, G. H.; Lai, X. W.; Jiang, Y. B. Org. Lett. 2012, 14, 1986–1989.
- Luo, J.; Xie, Z.; Lam, J. W. Y.; Cheng, L.; Chen, H.; Qiu, C.; Kwok, H. S.; Zhan, X.; Liu, Y.; Zhu, D.; Tang, B. Z. Chem. Commun. 2001, 37, 1740–1741.
- (a) Liu, L.; Zhang, G. X.; Xiang, J. F.; Zhang, D. Q.; Zhu, D. B. Org. Lett. 2008, 10, 4581–4584; (b) Huang, G. X.; Zhang, G. X.; Zhang, D. Q. Chem. Commun. 2012, 48, 7504–7506; (c) Sun, F.; Zhang, G. X.; Zhang, D. Q.; Xue, L.; Jiang, H. Org. Lett. 2011, 13, 6378–6381; (d) Hong, Y.; Chen, S. J.; Leung, C. W. T.; Lam, J. W. Y.; Liu, J. Z.; Tseng, N. W.; Kwok, R. T. K.; Yu, Y.; Wang, Z. K.; Tang, B. Z. ACS Appl. Mater. Interfaces 2011, 3, 3411–3418.
- Liu, Y.; Deng, C.; Tang, L.; Qin, A. J.; Hu, R. R.; Sun, J. Z.; Tang, B. Z. J. Am. Chem. Soc. 2011, 133, 660–663.
- (a) Xue, W. X.; Zhang, G. X.; Zhang, D. Q.; Zhu, D. B. Org. Lett. 2010, 12, 2274–2277; (b) Hong, Y.; Meng, L.; Huang, X. H.; Tang, B. Z. J. Am. Chem. Soc. 2012, 134, 1680–1689; (c) Shi, H. B.; Liu, J. Z.; Geng, J. L.; Tang, B. Z.; Liu, B. J. Am. Chem. Soc. 2012, 134, 9569–9572.
- 7. Gu, X. G.; Zhang, G. X.; Zhang, D. Q. Analyst 2012, 137, 365-369.
- 8. Shen, X.; Zhang, G. X.; Zhang, D. Q. Org. Lett. 2012, 14, 1744-1747.
- Zhang, Y. H.; Wang, J. J.; Jia, P. F.; Yu, X. Q.; Liu, H.; Liu, X.; Zhao, N.; Huang, B. B. Org. Biomol. Chem. 2010, 8, 4582–4588.
- Allain, C.; Schmidt, F.; Lartia, R.; Bordeau, G.; Debuisschert, C. F.; Charra, F.; Tauc, P.; Fichou, M. T. ChemBioChem 2007, 8, 424–433.
- He, G. S.; Tan, L. S.; Zheng, Q.; Prasad, P. N. *Chem. Rev.* 2008, *108*, 1245–1330.
  (a) Jiang, Y. H.; Wang, Y. C.; Hua, J. L.; Tang, J.; Li, B.; Qian, S. X.; Tian, H. *Chem.*
- (a) Jiang, Y. H.; Wang, Y. C.; Hua, J. L.; Lang, J.; Li, B.; Qian, S. X.; Ian, H. Cnem. Commun. 2010, 46, 4689–4691; (b) Wang, B.; Wang, Y. C.; Hua, J. L.; Tian, H. Chem. Eur. J. 2011, 17, 2647–2655; (c) He, N. N.; Li, B.; Zhang, H.; Hua, J. L.; Jiang, S. Y. Synthetic Metal. 2012, 162, 217–224.
- Tang, B. Z.; Geng, Y.; Lam, J. W. Y.; Li, B.; Jing, X.; Wang, X.; Wang, F.; Pakhomov, A. B.; Zhang, X. Chem. Mater. **1999**, *11*, 1581–1589.
- 14. He, G.; Tan, L. S.; Zheng, Q.; Prasad, P. N. Chem. Rev. 2008, 108, 1245-1330.
- (a) Hua, J. L.; Li, B.; Meng, F. S.; Ding, F.; Qian, S. X.; Tian, H. Polymer **2004**, 45, 7143–7149; (b) Pawlicki, M.; Collins, H. A.; Denning, R. G.; Anderson, H. L. Angew. Chem Int. Ed. **2009**, 48, 3244–3266.