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# A new ratiometric Ag<sup>+</sup> fluorescent sensor based on aggregation-induced emission

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## ABSTRACT

The novel tetraphenylethylene(TPE)-based sensor **1** bearing bis(2-pyridin-2-ylmethyl)amine (BPA) units linked with triazole moieties could be obtained by click reaction efficiently. The results show that **1** can demonstrate a  $Ag^*$ -specific emission shift and highly sensitive fluorescent enhancement with a 1:2 binding ratio based on the aggregation-induced emission mechanism. Compound **1** is shown to behave as a ratiometric sensor.

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#### Introduction

The design and synthesis of highly sensitive and selective fluorescent chemosensors used for detection in the presence of heavy and transition metal (HTM) ions continues to grow at an unabated pace due to their important functions or produce toxic effects in environmental chemistry and biology.<sup>1</sup> Among the important precious metal ions, silver(I) (Ag<sup>+</sup>) has received considerable attention due to its toxic effects and bioaccumulation. For instance, silver ions inactivate sulfhydryl enzymes and combine with amine, imidazole, and carboxyl groups of various metabolites. Thus, the development of sensitive methods for the determination of trace amounts of silver ion in various media is of considerable importance for environmental protection and human health.<sup>2</sup>

The traditional analytical methods, such as atomic absorption spectroscopy, inductively coupled plasma mass spectroscopy and electrochemical analysis, have been reported for the trace-quantity determination of Ag<sup>+</sup>. But, most of those methods are expensive and time-consuming in practice. In comparison, fluorescence spectroscopy is widely used because of its high sensitivity and facile operation. More importantly, most fluorescent sensors are ready for in vivo and in vitro cellular imaging to make the fluorescence approach superior to other analytical methods. Therefore, much effort has been devoted to design various fluorescent sensors for the

detection of Ag<sup>+</sup>.<sup>3–5</sup> Nevertheless, most of the reported fluorescent chemosensor for Ag<sup>+</sup> are based on quenching mechanism.<sup>4</sup> Recently, the fluorescence 'turn on' chemosensors for Ag<sup>+</sup>, based on photoinduced electron transfer (PET) mechanism, internal charge transfer (ICT) mechanism, metal chelation enhancement and excimer/exciplex, are attracting increasing attention.<sup>2g,4-7</sup> In addition, various strategies have been adopted for the design of ratiometric fluorescent chemosensors because of such a ratiometric fluorescent sensor would offer an advantage over the intensitybased probes such as less sensitivity to the errors associated with the sensor concentration, photobleaching, instrument's sensitivity, and environmental effects. However, ratiometric fluorescent chemosensors for the detection of Ag<sup>+</sup> have remained rare up to now, due to the scarcity of suitable fluorophore prototypes displaying silver chelation-induced emission/excitation. <sup>4,6–11</sup> Thus, it is highly desirable to propose a novel sensor with ratiometric module for silver ions. To our best knowledge, ratiometric fluorescent sensor for Ag<sup>+</sup>, especially with fluorescent enhancement technique based on aggregation-induced emission (AIE) mechanism still remains rare.<sup>4a,12–14</sup> It is well known that the fluorogen in tetraphenylethylene (TPE) derivatives is nonemissive when dissolved but becomes highly emissive when aggregated due to its intramolecular rotations by the aggregate formation, thereby showing a novel effect of AIE.<sup>15</sup> Herein, inspired by the 'abnormal' AIE behavior of TPEs, we reported the synthesis via click reaction and the fluorescent properties of a new ratiometric fluorescence 'turn on' chemosensor 1 for Ag<sup>+</sup> by making use of AIE feature of tetraphenylethylene motif with bis(2-pyridin-2-ylmethyl)amine (BPA).



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## **Results and discussion**

The synthesis route of **1** is shown on Scheme 1. Initially, tetraphenylethylene derivate **2** was chosen as the starting material which was converted to dibromo **3** by reaction with NBS in the presence of catalytic amount of benzoyl peroxide (BPO) under reflux in CCl<sub>4</sub>. The target compound **1** was obtained from the further reaction of dibromo **3** with NaN<sub>3</sub> followed by the click reaction with BPA derivate **4**. Similarly, another tetraphenylethylene derivate **5** with BPA unit was also prepared similarly (Scheme 1). The chemical structures of these new compounds were established by spectroscopic and elemental analysis data.

First, we attempted to determine the selective fluoroionophoric properties of **1** toward representative alkali (Li<sup>+</sup>, Na<sup>+</sup>, K<sup>+</sup>), alkaline earth (Mg<sup>2+</sup>, Ca<sup>2+</sup>), and transition-metal ions (Ni<sup>2+</sup>, Cu<sup>2+</sup>, Zn<sup>2+</sup>, Hg<sup>2+</sup>, Pb<sup>2+</sup>, Ag<sup>+</sup>, Cd<sup>2+</sup>). After systematically looking for selective signaling toward a specific target metal ion, we found that aqueous THF solutions are relatively well optimized sensing media. Therefore, all the fluorescence measurements were carried out in THF:H<sub>2</sub>O (1:2,v/v) solvent ([1] =  $1.0 \times 10^{-5}$  mol/L, [M] =  $4.0 \times 10$  $^{-5}$  mol/L), where the most pronounced selectivity toward Ag<sup>+</sup> ion was realized (Fig. 1). Figure 2 shows the fluorescence spectrum of compound **1** and those in the presence of different amounts of  $Ag^+$  in THF/H<sub>2</sub>O. Free compound **1** shows rather weak emission at 435 nm. However, after addition of Ag<sup>+</sup>, the emission band at 485 nm emerged and its intensity increased gradually when the ratio of  $[Ag^+]_{total}/[1]$  is below or equal to 2:1. Moreover, the fluorescence intensity of 1 at 485 nm increases linearly with the concentration of Ag<sup>+</sup> as shown in the inset of Figure 2, where a nearly linear plot of  $I_{485nm}$  versus the concentration of Ag<sup>+</sup> in the range of 0.2–2.0 µM was displayed (with an enhancement factor



Scheme 1. Synthesis of 1.



**Figure 1.** Variation of the fluorescence intensity at 485 nm ( $\lambda_{ex}$  = 320 nm) of compound 1 (1.0 × 10<sup>-5</sup> M) in THF/H<sub>2</sub>O (1:2, v/v) in the presence of 4.0 equiv of the respective metal ions.



**Figure 2.** Fluorescence titration spectra of compound **1**  $(1.0 \times 10^{-5} \text{ M})$  in the presence of different concentrations of Ag<sup>+</sup> in THF/H<sub>2</sub>O (1:2, v/v), [Ag<sup>+</sup>]/[**1**] = 0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4, 2.5. Inset the plot of the fluorescence intensity at 485 nm ( $\lambda_{ex}$  = 320 nm) vs the concentration of Ag<sup>+</sup>.

of about fourfold, linear dependency coefficient  $\gamma$  = 0.997). The detection limit of this  $Ag^+$  assay can reach 0.2  $\mu$ M. When the ratio reached 2:1, higher [Ag<sup>+</sup>]<sub>total</sub> did not lead to any further emission enhancement. The enhancement of emission intensity in Ag<sup>+</sup>-binding titration saturated at the addition of two equivalent of Ag<sup>+</sup> suggested that **1** forms a 1:2 complex with  $Ag^+$  in THF:H<sub>2</sub>O (1:2, v/v). Furthermore, the Job plot measurement was carried out by varying the concentration of **1** and the Ag<sup>+</sup> ion (see Supplementary data Fig. S1). The maximum point appears at the mole fraction of 0.67, close to the typical ligand mole fraction (0.66), indicated the 2:1 stoichiometry between Ag<sup>+</sup> and **1**. The remarkable bathochromic shift made compound 1 a potential ratiometric sensor for Ag<sup>+</sup>. Similar fluorescence enhancement was observed for 1 after the addition of Ag<sup>+</sup> salts with different counteranions (NO<sub>2</sub><sup>-</sup>, F<sup>-</sup>, BF<sub>4</sub><sup>-</sup>) and OAc<sup>-</sup>) (Supplementary data Fig. S2). In contrast, the titration result indicates that compound 5 reveals no fluorescent detective behavior toward Ag<sup>+</sup> and other metal ions (see Supplementary data Fig. S3).

Such fluorescence enhancement observed for 1 in the presence of Ag<sup>+</sup> is attributed to the coordination of BPA moieties of 1 with Ag<sup>+</sup> ions leading to the formation of coordination complexes which may further aggregate due to the low solubility; as a result, the fluorescence due to the tetraphenylethylene unit of 1 increases.<sup>14,15</sup> The UV-vis spectrum of the titration of Ag<sup>+</sup> into compound 1 supports this assumption. Compound 1 exhibits the variation of the absorption spectrum of **1** after the addition of  $Ag^+$  (see Supplementary data Fig. S4). The absorption around 320 nm decreased gradually in the presence of Ag<sup>+</sup>, leading to the isobestic point at 300 nm which implies the aggregation of the complex between 1 and Ag<sup>+</sup>. Additionally, TEM analysis with the solution of 1 containing 1.0 equiv of Ag<sup>+</sup> indicates the formation of aggregates with fiber-like structure (Supplementary data Fig. S5). Moreover, the variation of <sup>1</sup>H NMR spectra of **1** in the presence of Ag<sup>+</sup> also indicates the aggregation of **1**. <sup>1</sup>H NMR titration experiments were carried out in THF- $d_8/D_2O$  (1:2, v/v). The partial spectral changes are shown in Figure 3. Upon addition of Ag<sup>+</sup> ion (from 0.4 to 2.0 equiv) to the solution of compound 1, as expected, the chemical shifts of pyridyl proton H<sub>a</sub> and proton H<sub>b</sub> on the triazole ring and the acyclic protons H<sub>c</sub> show downshift. In contrast to these, the acvclic proton H<sub>d</sub> undergoes significant upshift. Furthermore, the characterization by <sup>1</sup>H NMR spectroscopy indicated the desired coordination of **1** with  $Ag^+$  ion by broadened signals of  $H_a$ ,  $H_b$ ,  $H_c$ , and  $H_d$  protons. Very notably, when the Ag<sup>+</sup> ion concentration was not more than 1 equiv (e.g., from 0 to 0.8 equiv) the chemical shifts of H<sub>b</sub> and H<sub>d</sub> exhibit upshift from 7.90 to 7.95 ppm and from 7.75 to 7.84 ppm, respectively. But when the ion concentration is increasing from 0.8 to 2.0 equiv, the chemical shift of H<sub>b</sub> undergoes downshift process. Meanwhile the singlet peak of H<sub>d</sub> was split to doublet peaks. This result implies that the intramolecular coordination types between 1 and  $Ag^+$  at different ion concentrations. When the  $Ag^+$  ion was of lower concentration ( $\leq 1$  equiv of **1**), two molecules of **1** coordinate with one Ag<sup>+</sup> ion at head to tail type. As the Ag<sup>+</sup> ion concentration increases, one molecule **1** coordinate with two Ag<sup>+</sup> ions with its two chelating BPA groups (Scheme 2).<sup>5b,16</sup> These two different binding modes can explain the change of the wavelength of maximum emission. As shown in Figure 2,



**Figure 3.** Partial <sup>1</sup>H NMR spectra (500 MHz) of compound **1** ( $1 \times 10^{-3}$  M) in THF*d*<sub>8</sub>/D<sub>2</sub>O (1:2, v/v) in the presence of increasing amounts of Ag<sup>\*</sup>: 0; 0.4; 0.8; 1.6; 2.0 equiv [from (1) to (5)].



Scheme 2. Proposed binding modes of 1 with Ag<sup>+</sup>.

upon addition of  $Ag^+$  from 0.2 to 0.8 equiv, the wavelength of maximum emission changed from 435 nm to 485 nm, while upon addition of  $Ag^+$  from 1.0 to 2.5 equiv, a little bathochromic shift was observed.

An important feature of many prospective metal ion sensors is its ability to function in competition with other relevant metal ions. The competition experiments between Ag<sup>+</sup> and the selected metal ions were shown in Figure S6 (Supplementary data). When 4.0 equiv of  $Ag^+$  was added into the solution of **1** (10  $\mu$ M) in the presence of 4.0 equiv of other metal ions, the emission spectra displayed a pattern similar to that with Ag<sup>+</sup> only with most of the metal ions studied ( $\lambda_{em} = 485 \text{ nm}$ ,  $\lambda_{ex} = 320 \text{ nm}$ ) except Hg<sup>+</sup>/Zn<sup>2+</sup> which also gave the clear fluorescence enhancement (threefold/ onefold, respectively) and Cu<sup>2+</sup> which quenched the fluorescence due to the metal-to-ligand charge transfer upon excitation or the high affinity for the competition metal ion with BPA and triazole unit.<sup>16c,17</sup> Thus sensor **1** can be used as a selective fluorescent sensor for Ag<sup>+</sup> in the presence of most competing metal ions. In addition, we evaluated the effect of pH change on the fluorescence intensity of 1 in the absence and presence of Ag<sup>+</sup> ion. The fluorescence intensity measurements were made in the absence and presence of a 4.0 equiv of Ag<sup>+</sup> in  $1.0 \times 10^{-5}$  M solution of 1 at different pH values. The pH of solution was adjusted by either HClO<sub>4</sub> or NaOH. As shown in Figure S7 (Supplementary data), sensor 1 displayed good fluorescence sensing ability to Ag<sup>+</sup> and in the absence of Ag<sup>+</sup> over a wide range of pH, and the intensity was almost stable around pH = 4.0–12.0, which makes it suitable for application in physiological conditions. These results indicate that 1 can be employed as a selective fluorescent probe to recognize and distinguish Ag<sup>+</sup> in the presence of various interfering and biologically relevant metal ions.

### Conclusion

In conclusion, a novel tetraphenylethylene (TPE)-based sensor **1** incorporating bis(2-picoly)amine (BPA) motifs and triazole units was prepared via click reaction successfully. Compound **1** demonstrates a Ag<sup>+</sup>-specific ratiometric and highly sensitive turn-on sensing behavior based on the aggregation mechanism. The spectroscopic properties of compound **1** indicate that it is a potential powerful sensor which is likely to image free silver ions in extremely low range in biological system.

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## Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tetlet.2011.11.107.

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