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"Turn-on" far-red fluorescence sensor for Y³⁺ based on Schiff-based tetraphenylethylene

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ABSTRACT

Far-red and "turn-on" fluorescence sensors were paid much attention due to their outstanding merits, but this kind of fluorescence probe for Y^{3+} was not presented up to date. In this work, a Schiff-base bridged *m*-aminobenzoic acid-decorating tetraphenylethylene was designed and synthesized in yield of 89%. It exhibited the far-red fluorescence at 550–670 nm in aqueous media based on AIE effect. It showed high selective sensing ability for Y^{3+} among all kinds of metal ions with the obvious "turn-on" fluorescence, which was observed for the first time for fluorescence sensor of Y^{3+} . The detection limit for Y^{3+} was as low as 2.23×10^{-7} M. The sensor mechanism of 1:1 stoichiometric ratio was clarified by fluorescence titration, FT-IR spectra, ¹H NMR and MS spectra. The selective sensing of Y^{3+} was further successfully applied on detecting Y^{3+} for tested paper, simulated water sample and bio-imaging of live cells, suggesting the good practical application potential of this fluorescence sensor on detecting Y^{3+} in complicated water media and living body environment.

1. Introduction

Yttrium is one of the rare earth elements bearing the many similarities with lanthanide elements [1,2]. In the past few decades, it has exhibited wide application in targeted radiotherapy, catalysis, fluorescent probes, hydroyttration reagents or the synthesis of nanomaterials, etc [3–7]. As more and more yttrium was used in reagents and biomedical products, it was inevitable that trace levels of yttrium was released into the environment as radioactive waste [8–10]. Thus, yttrium should be examined and recovered from a polluted environment. The traditional methods of detecting yttrium, such as inductively coupled plasma atomic emission spectrometry [11], inductively coupled plasma mass spectrometry (ICP-MS) [12], spectrophotometric determination [13] and electrochemical method [14–16], needed expensive instruments, complicated test procedures and long-time consumption. Therefore, it is hoped to develop more rapid, convenient and sensitive method for detecting the trace yttrium in waste water and life body.

On the other hand, fluorescent sensors have attracted much research attention due to their high sensitivity, low cost, and simple operation in recent years [17,18]. Generally, the ideal fluorescent probe should be: (a) "turn-on" type, which was favourable for reducing the background

interference and enhancing the sensitivity of detection in comparison with "turn-off" type [19]; (b) overcome the ACQ effect and emit strongly in aqueous media for the practical application prospect [20-28]; (c) the long-wavelength fluorescence with large Stokes shift due to the advantages of deep tissue infiltration, minimal self-absorption, low background noise and high signal-to-noise ratio of biological resources [29-31]; (d) high sensing selectivity and low detection limit [32]. However, normal fluorescence sensors easily aggregated in the aqueous media and caused the strong ACQ effect, which greatly limited the application in the actual environment and in vivo. In 2001, Tang's research group discovered aggregation-induced emission (AIE) which provided a new opinion for constructing novel fluorescent sensors in aqueous media. As to fluorescent sensors for Y^{3+} , only four examples were presented up to now and the obvious shortcomings existed in these cases. Chen *etc* reported a fluorescent probe for La^{3+} and Y^{3+} based on calix [6]arene at $\lambda_{em} = 405$ nm with low sensing selectively [33]. Fukuzumi and Okamoto described an yttrium ion-selective fluorescence sensor $\lambda_{em} = 610$ nm based on zinc porphyrin-quinone dyad in organic solution of PhCN only [1]. Liu group synthesized a selective fluorescence probe $\lambda_{em} = 490$ nm for Y³⁺ based on acylhydrazone Schiff base in organic solution of THF [2]. Souza and his co-workers introduced a

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Fig. 1. The emission spectra of SB-TPE in THF/H₂O solutions with different fractions of H₂O; Inserted: The ratio changes (I/I_o) of fluorescence intensities in THF/H₂O with different H₂O fractions; the fluorescence photograph of SB-TPE in pure THF and THF/H₂O with $f_w=95\%.~(1\times10^{-5}~M,~\lambda_{ex}=360~nm).$



Fig. 2. Fluorescence spectra of SB-TPE (1.0 \times 10⁻⁶ M) with different metal ions (3.0 \times 10⁻⁶ M) in THF/H₂O at f_w = 95%, λ_{ex} = 360 nm (inserted pictures: the photograph of SB-TPE solution with or without Y³⁺).

o-substituted diphenylphosphinic amide ligands with complexation abilities for Zn^{2+} , Cu^{2+} and Y^{3+} [34]. These literature surveys suggested, no high selective "turn-on" fluorescence probe for Y^{3+} with long-wavelength fluorescence in aqueous media was reported up to date. In this work, based on design and synthesis of a Schiff-base bridged *m*-aminobenzoic acid-decorating tetraphenylethylene, we wish to report the first "turn-on" fluorescence sensor for Y^{3+} with high selective sensing ability in aqueous media, which was further applied in detection of Y^{3+} and bio-imaging of live cells.

2. Experimental

2.1. General

All chemical reagents were bought from commercial suppliers and used directly. TLC detection was carried out on pre-coated glass plates. Column chromatography was used for purification produces with silica gel (200–300 mesh). NMR spectra were examined in CDCl₃ on a Bruker-ARX 400 instrument at 25 °C. MS analyses were carried out on a Bruker mass spectrometer. The UV–Vis spectra were checked on a Varian UV–Vis spectrometer. The fluorescence spectra were investigated on a Hitachi F-4500 spectrometer in a conventional quartz cuvette (10 \times 10 \times 45 mm) at 25 °C. An Edinburgh Instrument FLS920 fluorescence



Scheme 1. The synthetic route for SB-TPE.

spectrometer with a 6-inch integrating sphere was applied to obtain the absolute fluorescence Φ_F value of the solution. The MCF-7 living cells were supplied by the school of Pharmacy, Fujian Medical University. All calculations were performed on the Gaussian 09 program at the B3LYP/ 6-31G (d) level using the density functional theory (DFT) method. Compounds **3** and **4** were prepared according to the published procedures [35,36].

2.2. Synthetic procedure for SB-TPE

Compound 4 (0.376 g, 1 mmol) and *m*-aminobenzoic acid (0.137 g, 1 mmol) were added to 20 mL of absolute ethanol. The mixture was stirred and refluxed for 12 h. TLC detection suggested the fulfillment of reaction. Then the solvent was removed under reduced pressure, and the residue was recrystallized from $CHCl_3/EtOH$ to obtain **SB-TPE** as a yellow powder (89% yield).

2.2.1. Bis-TPE

¹HNMR (400 MHz, CDCl₃) δ: 13.09 (s, 1H, OH), 12.83 (s, 1H, N=CH), 8.84 (s, 1H, OH), 7.86 (s, 1H, ArH), 7.53–7.62 (m, 2H, ArH), 7.33 (s, 1H, ArH), 6.97–7.20 (m, 16H, ArH), 6.73–6.75 (d, J = 8.0 Hz, ArH). ¹³C NMR (100 MHz, DMSO) δ: 167.37, 164.42, 159.46, 148.76, 143.71, 143.45, 140.80, 140.06, 136.58, 134.97, 134.75, 132.59, 131.22, 131.18, 131.12, 130.20, 128.42, 128.36, 128.30, 128.01, 127.13, 126.99, 126.35, 122.34, 119.31, 116.64. MALDI-TOF-MS (C₃₄H₂₅NO₃) Calcd. for m/z = 495.18, found: m/z = 495.108 (M⁺). Anal.calcd for C₃₄H₂₅NO₃: C 82.40, H 5.08, N 2.83; found C 82.37, H 5.11, N 2.77.

2.3. MTT assay

Methylthiazolyldiphenyl-tetrazolium (MTT) trials were applied to investigate the toxicity for MCF-7 cancer cells. The inoculated MCF-7 cancer cells were fostered at 37 °C for 24 h under 5% CO₂. The sample of **SB-TPE** (1.0×10^{-5} M) was then tracked in the cells after incubating for 24 h. The cultivated cells were washed by PBS buffer, and continue cultivating in 0.5 mg/mL MTT-PBS buffer for 3 h. Finally, 100 μ L of DMSO was used to dissolve the generated Formazan crystals, which was further detected by the absorption at 490 nm.

2.4. The experiment of living cell imaging

SB-TPE (3.0 mg) was dissolved in DMSO (1 mL), which was further treated with PBS buffer (pH = 7.4) to 1.0×10^{-5} M for imaging test. MCF-7 cancer cells after cultivation at the same circumstance of MTT trials were tinted by **SB-TPE** (1.0×10^{-5} M) with 24 h breeding. After



Fig. 3. (a) Fluorescence spectra of SB-TPE (1.0×10^{-6} M) with different concentrations of Y^{3+} in THF/H₂O at $f_w = 95\%$, $\lambda_{ex} = 360$ nm. (b) The fluorescence intensities of probe titration with equivalent concentration of Y^{3+} .

washing by PBS-buffer, the dyed cells were fostered in Y^{3+} solution (1.0 \times 10⁻⁵ M) at 37 °C for 1 h. The obtained cells were imaged by a confocal laser scanning microscope (CLSM, Zeiss LSM 710, Jena, Germany).

3. Results and discussion

3.1. Synthesis and characterization

In order to obtain the fluorescence probe in aqueous media, tetraphenylethylene, which was a star molecule with strong AIE effect in poor solvent [37–41], was used to construct the target probe. On the other hand, it had been reported that the C=N group and C=O group contributed to binding Y^{3+} based on their synergetic complexation [1,2, 32,33]. Thus, SB-TPE was designed as target molecule, in which the carboxylic and Schiff-base group were favourable for not only binding Y^{3+} but also enhancing the push-pull electron effect of tetraphenyl-ethylene to achieve the long-wavelength fluorescence. The synthetic route of SB-TPE was shown in Scheme 1. Briefly, according to the published procedures [35,36], tetraphenylethylene derivatives 3 and 4 were prepared in yields of 32% and 46%, respectively. Target SB-TPE was obtained by Schiff-base condensation of compound 4 with *m*-aminobenzoic acid in yield of 89% after purification of recrystallization. The structure of SB-TPE was confirmed by ¹H and ¹³C NMR spectra, MALDI-TOF mass spectrometry, and elemental analysis (see SI). All characterization data were well in accordance with its structure. For example, three single peaks of COOH, N=CH, and OH appeared at



Fig. 4. Fluorescence changes of **SB-TPE** (1 × 10⁻⁶ M) with Y³⁺ in presence of the other metal ions (1 × 10⁻⁶ M, each) in THF/H₂O with $f_w = 95\%$, I and I₀ were the fluorescence intensity of **SB-TPE** with Y³⁺ or with Y³⁺ and other metal ion, respectively.



Fig. 5. The pH influence on the fluorescence intensities of SB-TPE (1 \times 10 $^{-6}$ M) with or without Y^{3+} (1 \times 10 $^{-6}$ M) in THF/H₂O with f_w = 95%, λ_{ex} = 360 nm.

13.09 ppm, 12.83 ppm and 8.84 ppm, respectively, which indicated the stable *trans*-structure of the Schiff-base group as shown in Scheme 1.

3.2. AIE properties

Firstly, the AIE property of SB-TPE was studied in THF/H₂O system. As shown in Fig. 1, SB-TPE has little fluorescence in pure THF solution. With the increase of H₂O content (f_w) in THF/H₂O mixture, the fluorescence maintained faintly when $f_w < 70\%$ but enhanced dramatically when $f_w > 70\%$. The fluorescence intensity at 590 nm reached the maximum value when $f_w = 95\%$, which increased by 81 times in comparison with that in pure THF solution. The fluorescence quantum yields of SB-TPE in pure THF solution and THF-H₂O with 95% were determined as 0.4% and 25.6%, respectively. These results certainly supported the strong AIE effect for SB-TPE. On the other hand, the fluorescence emission of SB-TPE appeared at 550-670 nm in the far-red region, which showed obvious red shift than that of normal TPE derivatives at 450-550 nm. This phenomenon could be attributed to the effect of the large conjugated effect associated with the Schiff-base bridge and the push-pull electron effect of electron-donating abilities of the hydroxyl group and the electron-withdrawing abilities of carboxyl

groups. **SB-TPE** emitted the red fluorescence with the Stokes shift of 215 nm. This far-red emission and large Stokes shift were also greatly favourable for biological fluorescent probe [30].

3.3. The sensor for metallic ions

The studying of sensing selectivity and sensitivity is of great significance. Therefore, the detecting abilities of **SB-TPE** for different metal ions in THF/H₂O at $f_w = 95\%$ were studied by fluorescence spectroscopy. Series of metal ions (nitrates of Y^{3+} , Li⁺, Na⁺, K⁺, Cs⁺, Mg²⁺, Ca²⁺, Sr²⁺, Ba²⁺, Al³⁺, Fe³⁺, Co²⁺, Ni²⁺, Cu²⁺, Zn²⁺, Cd²⁺, Ag⁺, Hg²⁺, Mn²⁺, Pb²⁺, Ce³⁺, La³⁺, Eu³⁺, Sc³⁺ and Pr³⁺) were added into the solution of **SB-TPE** to investigate the fluorescence change. As can be seen in Fig. 2, compared with the fluorescence of **SB-TPE** with no metal ion, the fluorescence intensities of **SB-TPE** after adding various cations fluctuated in small ranges except Y³⁺. The changes could not be distinguished by naked eyes. However, it could be observed that the fluorescence emission at 575 nm enhanced significantly by about 2.7 times after Y³⁺ was added in the solution of **SB-TPE**. The enhanced fluorescence could be seen obviously by naked eyes as shown in the inserted picture in Fig. 2. These results certainly supported that **SB-TPE** possessed the selective sensing abilities for Y³⁺ among all these tested cations by the "turn-on" fluorescence phenomenon.

3.4. Titration of sensing Y^{3+}

The detailed sensing behavior of **SB-TPE** for Y^{3+} was studied by fluorescence titration in THF/H₂O at $f_w = 95\%$ with $\lambda_{ex} = 360$ nm. As shown in Fig. 3(a), the fluorescence intensities increased gradually with the increase of equivalent concentration of Y^{3+} . The rapid increase occurred when the equivalent concentration of Y^{3+} was smaller than 1.0, and the slow increase appeared as the equivalent concentration bigger than 1.0. These results suggested the inflection point for titration was 1.0 of equivalent concentration, indicating the 1:1 of stoichiometric ratio for SB-TPE with Y³⁺. Furthermore, the corresponding plot of fluorescence intensities versus equivalent concentrations of Y³⁺ was exhibited in Fig. 3 (b). One can see that the fluorescence intensities of SB-TPE displayed a good linear relationship with the equivalent concentration of Y^{3+} in the range of 0.0–1.0. According to the formula of detection limit $DL = K \times Sb1/S$ (where K = 2 or 3, here the value was set as 2, Sb1 was the standard deviation of the blank solution, S was the value of the slope of the regression line), the detection limit of Y^{3+} was calculated as 2.23×10^{-7} M. By compared with the reported detection limit and selectivity in literatures (Table S1) [1,2,33,42,43], this detection limit was low and the selectivity was good, indicating the excellent application prospect of sensing trace Y^{3+} .

3.5. Interference experiments and pH influences

In order to further explore sensing selectivity of **SB-TPE** for Y^{3+} , the interference experiments for sensing Y^{3+} were investigated in presence of other metal ions. The results were shown in Fig. 4. It can been seen that these values of I/Io were near 1.0, suggesting that the fluorescence intensities of SB-TPE for Y^{3+} changed a little in presence of other interference metal ions. These results meant the excellent sensing selectivity of **SB-TPE** for Y³⁺. The pH influences on fluorescence sensing were also explored as shown in Fig. 5. It was found that the fluorescence remained stable between pH = 4-8. When the pH > 8, the fluorescence intensity decreased rapidly, which could be ascribed to that, in the solution of high pH values, the carboxyl and phenolic hydroxyl of SB-TPE were easily deprotonated, resulting in the good water solubility and low fluorescence finally. SB-TPE was treated at different pH and then neutralized to pH = 7, which was further examined by the UV absorption spectra. The results suggested that the absorption peaks showed no obvious change (Fig. S9), indicating the good stability of SB-TPE at different pH. The stable fluorescence in pH = 4-8 were favourable for



Fig. 6. The contrast ¹H NMR spectra of SB-TPE and SB-TPE with Y³⁺; Inserted: The proposed sensing mechanism of SB-TPE with Y³⁺.



Fig. 7. (A) The LUMO and HOMO of Bis-TPE; (B) The LUMO and HOMO of **Bis-TPE** with Y^{3+} .

normal environment and in vivo detection.

3.6. Stoichiometry and mechanism for sensing Y^{3+}

The stoichiometric ratio of **SB-TPE** with Y^{3+} was studied by the Job's plots as displayed in Fig. S4. It can be seen that the inflection point

appeared at the $f_{SB-TPE} = 0.5$, suggesting the 1:1 stoichiometric ratio for **SB-TPE** with Y³⁺. The complexation MS spectrum of **SB-TPE** with excess Y^{3+} (5 eq.) displayed only the binding peak at 582.915 (Fig. S11), which was in accordance with the molecular weight of $(M + Y^{3+}-2H)^+$, indicating the 1: 1 stoichiometry ratio again.

The FT-IR and ¹H NMR spectrum were also used to investigate the sensing mechanism of SB-TPE with Y³⁺. As shown in Fig. S5, by comparing with the FT-IR spectrum of SB-TPE, the FT-IR spectrum of **SB-TPE** with Y^{3+} exhibited obvious shifts for the peaks of C=O and OH functional groups, implying that the carboxyl and phenolic hydroxyl group took part in the sensing Y^{3+} . The comparison of ¹H NMR spectra of **SB-TPE** and **SB-TPE** + Y^{3+} (1:1) showed that the proton signals of COOH and OH groups disappeared or weakened dramatically and the signal of HC=N exhibited some shift, indicating the COOH, OH and C=N groups were involved in sensing Y^{3+} (Fig. 6). The other ions such as Sc^{3+} exhibited little change after complexation (Fig. S8). Thus, based on the above results, the possible sensing mechanism was proposed as Fig. 6.

Table 1 Recovery results of Y^{3+} in actual water samples.

Sample	Found	Added (µM)	Total found (μM)	Recovery (%)	Std Dev (%)
Tap water	0	1	0.91	91.0	1.6
	0	2	1.98	99.0	2.0
	0	3	2.92	97.3	3.5
River water	0	1	0.99	99.0	2.2
	0	2	1.91	95.5	3.1
	0	3	2.89	96.3	1.7
Lake water	0	1	0.93	93.0	2.1
	0	2	1.88	94.0	2.9
	0	3	2.91	97.0	3.6



Fig. 8. Fluorescence photographs of SB-TPE with corresponding ion under UV light (365 nm). $1 = Y^{3+}$, $2 = Li^+$, $3 = Na^+$, $4 = K^+$, $5 = Cs^+$, $6 = Mg^{2+}$, $7 = Ca^{2+}$, $8 = Cs^{2+}$, $1 = K^{2+}$, $1 = K^{2+}$, $1 = K^{2+}$, $1 = K^{2+}$, $2 = Li^+$, $3 = Na^+$, $4 = K^+$, $5 = Cs^+$, $6 = Mg^{2+}$, $7 = Ca^{2+}$, $8 = Cs^{2+}$, $1 = K^{2+}$, 1 = K $Sr^{2+}, 9 = Ba^{2+}, 10 = Al^{3+}, 11 = Fe^{3+}, 12 = Co^{2+}, 13 = Ni^{2+}, 14 = Cu^{2+}, 15 = Zn^{2+}, 16 = Cd^{2+}, 17 = Ag^+, 18 = Hg^{2+}, 19 = Mn^{2+}, 20 = Pb^{2+}, 21 = Ce^{3+}, 22 = La^{3+}, 22 = La^{3+}, 22 = La^{3+}, 23 = La^{3+}, 24 = La^{$ $23 = Eu^{3+}$, $24 = Sc^{3+}$ and $25 = Pr^{3+}$.



Fig. 9. Confocal fluorescence images of MCF-7 cells treated by SB-TPE $(1.0 \times 10^{-5} \text{ M})$ with or without Y^{3+} . (A)–(C) MCF-7 cells; (D)–(F) MCF-7 cells with SB-TPE; (G)–(I) MCF-7 cells with SB-TPE and Y^{3+} ; Left images meant bright field images, middle images meant fluorescence images, and right images meant the merged images of fluorescence and bright field ($\lambda_{ex} = 405 \text{ nm}$). The same scale bar for all images (as enlarged for image H).

The HOMO and LUMO orbits before and after sensing Y^{3+} were calculated by Gaussian 09. As shown in Fig. 7, the energy gap after sensing Y^{3+} was smaller than that before sensing, which was consistent with the fluorescence enhancement after sensing Y^{3+} .

3.7. Application in test paper

Test paper was usually used to evaluate in practical application. Therefore, the test paper with **SB-TPE** was prepared by soaking a neutral filter paper in a solution of 0.1 mM **SB-TPE** in THF solution for 5 min. After evaporating to dryness at room temperature, the test paper was cut into circular sections for later use. Then, five drops of a solution containing 0.1 mM metal ions (Y^{3+} , Li⁺, Na⁺, K⁺, Cs⁺, Mg²⁺, Ca²⁺, Sr²⁺, Ba²⁺, Al³⁺, Fe³⁺, Co²⁺, Ni²⁺, Cu²⁺, Zn²⁺, Cd²⁺, Ag⁺, Hg²⁺, Mn²⁺, Pb²⁺, Ce³⁺, La³⁺, Eu³⁺, Sc³⁺ and Pr³⁺) were added to tested paper, respectively. As shown in Fig. 8, only tested paper containing Y^{3+} exhibited the noticeable color change from pale red to bright red, indicating the good practical application for sensing Y^{3+} .

3.8. Application for sensing Y^{3+} in water sample

In order to evaluate the application of **SB-TPE** for sensing Y^{3+} in the

actual environment, the samples of tap water, river water, and lake water with different amounts of Y^{3+} were prepared and then examined by fluorescence spectra. The Y^{3+} contents were calculated by standard working curve and compared with the original concentrations as summarized in Table 1. It can be seen that the Y^{3+} concentration detected by **SB-TPE** in different water samples was close to the original concentrations with the small errors (<4%). These results indicated the excellent application prospect for detecting Y^{3+} in actual water environments.

3.9. Application in living cell imaging

The living cell imaging of fluorescent probe had been used as a good method to evaluate the real application of sensing examination, exhibiting the broad application prospects. A confocal laser scanning microscope (CLSM) was employed to study the application of **SB-TPE** to detect Y^{3+} in living cells. The metabolic activity of MCF-7 cells was obtained by MTT analysis. The average IC₅₀ values of MCF-7 cells in 24 h and 48 h were 95.1 and 46.6 μ M, respectively (Fig. S6). These results indicated the lower biological toxicity of **SB-TPE**. Further, **SB-TPE** was added to MCF-7 cells in a cultural medium, and then incubated at 37 °C for 1 h in an incubator to fix MCF-7 cells. Fluorescence imaging was examined at $\lambda_{ex} = 405$ nm. The weak red fluorescence image was observed as shown

in Fig. 9. With the addition of Y^{3+} in the cultural medium, the red fluorescence enhanced obviously. These results suggested that **SB-TPE** had good living cell imaging performance and sensing ability for Y^{3+} in the living cell environment, providing a good application prospect for **SB-TPE** to detect Y^{3+} in living system, which was observed for the first time in organic fluorescence sensors.

4. Conclusion

In summary, this work reported the first example of "turn-on" far-red fluorescence sensor for Y^{3+} . By condensation of *o*-formal hydroxyltetraphenylethylene with *m*-aminobenzoic acid, target SB-TPE was obtained in yield of 89%. SB-TPE showed the far-red fluorescence at 550-670 nm in aqueous media due to AIE effect. The sensing experiments for series of metallic ions indicated that SB-TPE possessed the selective sensing ability for Y³⁺ in aqueous media with strong enhanced fluorescence. The detection limit for Y^{3+} attained 2.23 $\times 10^{-7}$ M. The sensor mechanism of 1:1 stoichiometric ratio was confirmed by the method of fluorescence titration, FT-IR spectra, ¹H NMR and MS spectra. The test paper and simulated water sample was used to examine the practical application, suggesting the good application prospect of SB-**TPE** in real samples. The experiment of living cell imaging implied the good bioimaging performance for detecting Y^{3+} in living body environment. This work gave a good example of "turn-on" far-red fluorescence sensor for detecting Y^{3+} in complicated water media and living body environment.

CRediT authorship contribution statement

Shengjie Jiang: Investigation. Shibing Chen: Investigation, Formal analysis. Hongyu Guo: Formal analysis. Fafu Yang: Writing - original draft.

Declaration of competing interest

The authors declared that there is no Conflict of Interest for this paper entitled "Turn-on near-infrared fluorescence sensor for Y^{3+} based on Schiff-based tetraphenylethylene (Authors: Shengjie Jiang, Shibing Chen, Hongyu Guo, and Fafu Yang)", which was submitted to *Dyes and Pigments*.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.dyepig.2020.108717.

References

- Okamoto K, Fukuzumi S. An yttrium ion-selective fluorescence sensor based on metal ion-controlled photoinduced electron transfer in zinc porphyrin-quinone dyad. J Am Chem Soc 2004;43:13922–3.
- [2] Zhang D, Zang ZP, Zhou XY, Zhou Y, Tang XL, Wei RP, Liu WS. A selective fluorescence probe for yttrium(III) based on acylhydrazone Schiff base. Inorg Chem Commun 2009;11:1154–6.
- [3] Anderson CJ, Welch MJ, Welch MJ. Radiometal labeled agents (non-technetium) for diagnostic imaging. Chem Rev 1999;99:2219–34.
- [4] Liu DS, Zhou DH, Yang H, Li JF, Cui CM. Yttrium dialkyl supported by a silaamidinate ligand: synthesis, structure and catalysis on cyclotrimerization of isocyanates. Chem commun 2019;55:12324–7.
- [5] Levine DS, Tilley TD, Andersen RA. Efficient and selective catalysis for hydrogenation and hydrosilation of alkenes and alkynes with PNP complexes of scandium and yttrium. Chem Commun 2017;53:11881–4.

- [6] Motolko KSA, Emslie DJH, Jenkins HA. Yttrium and aluminum alkyl complexes of a rigid bis-anilido NON-donor ligand: synthesis and hydroamination catalysis. Organomet 2017;36:1601–8.
- [7] Miao W, Li SH, Zhang HX, Cui D, Wang YR, Huang BT. Mixed ligands supported yttrium alkyl complexes: synthesis, characterization and catalysis toward lactide polymerization. J Org Chem 2007;692:4828–34.
- [8] Yeong CH, Cheng MH, Ng KH. Therapeutic radionuclides in nuclear medicine: current and future prospects. J Zhejiang Univ - Sci B 2014;15:845–63.
- [9] Dietz ML, Horwitz EP. Improved chemistry for the production of yttrium-90 for medical applications. Appl Radiat Isot 1992;43:1093–101.
- [10] Horovitz CT. Biochemistry of scandium and yttrium. New York: Kluwer Academic/ Plenum Publishers; 1999. Part 1.
- [11] Koshel ES, Baranovskaya VB, Gubanova TY. Direct arc atomic emission analysis of yttrium, gadolinium, and neodymium oxides. Inorg Mater Appl Res 2016;52: 1449–54.
- [12] Zhu Z, Zheng A. Fast determination of yttrium and rare earth elements in seawater by inductively coupled plasma-mass spectrometry after online flow injection pretreatment. Molecules 2018;23:1420–3049.
- [13] Thanasarakhan W, Kruanetr S, Deming RL, Liawruangrath B, Wangkarn S, Liawruangrath S. Sequential injection spectrophotometric determination of tetracycline antibiotics in pharmaceutical preparations and their residues in honey and milk samples using yttrium (III) and cationic surfactant. Talanta 2011;84: 1401–9.
- [14] Hussain MM, Rahman MM, Arshad MN, Asiri AM. Trivalent Y³⁺ ionic sensor development based on (E)- Methyl-N'-nitrobenzylidenebenzenesulfonohydrazide (MNBBSH) derivatives modified with nafion matrix. Sci Rep 2017;7. https://doi. org/10.1038/s41598-017-05703-4.
- [15] Zavar MHA, Heydari S, Rounaghi GH, Sadeghian H. Nano-level monitoring of yttrium by a novel PVC-membrane sensor based on 2,9-dihydroxy-1,10-diphenoxy-4,7-dithiadecane. Croat Chem Acta 2012;85:131–7.
- [16] Hussein MA, Alam MM, Albeladi HK, El-Shishtawy RM, Asiri AM, Rahman MM. Nanocomposite containing cross-linked poly(Methyl-methacrylate)/multiwall carbon nanotube as a selective Y³⁺ sensor probe. Polym Compos 2019;40:1673–84.
- [17] Feuster EK, Glass TE. Detection of amines and unprotected amino acids in aqueous conditions by formation of highly fluorescent iminium ions. J Am Chem Soc 2003; 125:16174–5.
- [18] Longstreet AR, Jo M, Chandler RR, Hanson K, Zhan N, Hrudka JJ, Mattoussi H, Shatruk M, Mcquade DT. Ylidenemalononitrile enamines as fluorescent "turn-on" indicators for primary amines. J Am Chem Soc 2014;136:15493–6.
- [19] Tseng MH, Hu CC, Chiu TC. A fluorescence turn-on probe for sensing thiodicarb using rhodamine B functionalized gold nanoparticles. Dyes Pigments 2019;171: 107674.
- [20] Qiu JB, Chen YX, Jiang SJ, Guo HY, Yang FF. A fluorescent sensor based on aggregation-induced emission: highly sensitive detection of hydrazine and its application in living cell imaging. Analyst 2018;143:4298–305.
- [21] Jiang SJ, Chen SB, Wang ZC, Guo HY, Yang FF. First fluorescence sensor for simultaneously detecting three kinds of IIB elements (Zn²⁺, Cd²⁺ and Hg²) based on aggregation-induced emission. Sensor Actuator B 2020;308:127734.
- [22] Qiu JB, Jiang SJ, Guo HY, Yang FF. An AIE and FRET-based BODIPY sensor with large Stoke shift: novel pH probe exhibiting application in CO₃² detection and living cell imaging. Dyes Pigments 2018;157:351–8.
- [23] Li XQ, Gu JP, Zhou Z, Liu WQ, Gao JW, Wang QM. Precise control for the aggregation and deaggregation with the aid of a tetraphenylethylene derivative: luminescence modulation and sensing performance. Dyes Pigments 2020;172: 107844–50.
- [24] Zhou Z, Zhang CC, Zheng YH, Wang QM. Aggregation induced emission mediated controlled release by using a built-in functionalized nanocluster with theranostic features. I Med Chem 2016;59:410–8.
- [25] Liu JZ, Lam JWY, Tang BZ. Acetylenic polymers: syntheses, structures, and functions. Chem Rev 2009;109:5799–867.
- [26] Wan Q, Huang Q, Liu MY, Xu DZ, Huang HY, Zhang XY, Wei Y. Aggregationinduced emission active luminescent polymeric nanoparticles: non-covalent fabrication methodologies and biomedical applications. Appl Mater Today 2017;9: 145–60.
- [27] Mao LC, Liu YZ, Yang SJ, Li YX, Zhang XY, Wei Y. Recent advances and progress of fluorescent biochemosensors based on aggregation-induced emission molecules. Dyes Pigments 2020;162:611–23.
- [28] Jiang RM, Liu MY, Chen TT, Huang HY, Huang Q, Tian JW, Wen YQ, Gao QQ, Zhang XY, Wei Y. Facile construction and biological imaging of cross-linked fluorescent organic nanoparticles with aggregation-induced emission feature through a catalyst-free azide-alkyne click reaction. Dyes Pigments 2018;148: 52–60.
- [29] Jiang SJ, Hu XJ, Qiu JB, Guo HY, Yang FF. A fluorescent sensor for folic acid based on crown ether-bridged bis-tetraphenylethylene. Analyst 2019;144:2662–9.
- [30] Ni Y, Wu J. Far-red and near infrared BODIPY dyes: synthesis and applications for fluorescent pH probes and bio-imaging. Org Biomol Chem 2014;12:3774–91.
- [31] Han CY, Jiang SJ, Qiu JB, Guo HY, Yang FF. A diphenylacrylonitrile conjugated porphyrin with near-infrared emission by AIE-FRET. New J Chem 2019;43: 3317–22.
- [32] Mei J, Huang Y, Tian H. Progress and trends in AIE-based bioprobes: a brief overview. ACS Appl Mater Interfaces 2018;10:12217–61.
- [33] Liu JM, Chen CF, Zheng QY, Huang ZT. A selective fluorescent probe for La³⁺ and Y³⁺ based on calix[6]arene. Tetrahedron Lett 2004;45:6071–4.
- [34] Medeiros ACRF, Gouvêa MM, Felipe TV, Marques FFC, Bernardino AMR, Ortiz FL, Souza MC. New o-substituted diphenylphosphinic amide ligands: synthesis,

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characterization and complexation with $\rm Zn^{2+},\, Cu^{2+}$ and $\rm Y^{3+}.$ New J Chem 2019; 43:13881–90.

- [35] Yuan WZ, Yu ZQ, Lu P, Deng C, Lam JWY, Wang Z, Chen EQ, Ma Y, Tang BZ. High efficiency luminescent liquid crystal: aggregation-induced emission strategy and biaxially oriented mesomorphic structure. J Mater Chem 2012;22:3323–6.
- [36] Jiang SJ, Qiu JB, Chen SB, Guo HY, Yang F. Double-detecting fluorescent sensor for ATP based on Cu²⁺ and Zn²⁺ response of hydrazono-bis-tetraphenylethylene. Spectrochim Acta, Part A 2020;227:117568.
- [37] Jiang J, Qiu J, Lin L, Guo H, Yang F. Columnar self-assembly of tetraphenylethylene with multiple cholesterol units: synthesis, mesophase and circularly polarized luminescence based on chiral transfer. Dyes Pigments 2019; 163:363–70.
- [38] Jiang S, Qiu J, Chen Y, Guo H, Yang F. Luminescent columnar liquid crystals based on AIE tetraphenylethylene with hydrazone groups bearing multiple alkyl chains. Dyes Pigments 2018;159:533–41.

- [39] Song FY, Zhao Z, Liu ZY, Lam JWY, Tang BZ. Circularly polarized luminescence from AIEgens. J Mater Chem C 2020;8:3284–301.
- [40] Feng HT, Lam JWY, Tang BZ. Self-assembly of AIEgen. Coord Chem Rev 2020;406: 213142.
- [41] Li J, Wang JX, Li HX, Song N, Wang D, Tang BZ. Supramolecular materials based on AIE luminogens (AIEgens): construction and applications. Chem Soc Rev 2020; 49:1144–72.
- [42] Shen M, Li CM, Na D, Hao ZQ, Li XY, Guo LB, Lu YF, Zeng XY. Determination of yttrium in titanium alloys using laser-induced breakdown spectroscopy assisted with laser-induced fluorescence. J Anal Atom Spectrom 2018;33:658–62.
- [43] Wood DF, Adams MR. Spectrophotometric determination of yttrium in chromium and chromium-base alloys with arsenazo III. Analyst 1970;95:556–61.