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## A novel AIE fluorescent probe for the monitoring of aluminum ions in living cells and zebrafish†

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A novel fluorescent probe BTD with aggregation induced emission (AIE) characteristics for the monitoring of Al<sup>3+</sup> was developed. This fluorescent probe could be used to detect Al<sup>3+</sup> in aqueous solution under mild conditions, along with high sensitivity and high selectivity. The detection limit of the probe BTD for Al<sup>3+</sup> is as low as 3.25 nM, which is below the WHO recommendation concentration (7.41 μM) for drinking water. Furthermore, this probe was successfully applied to the sensing of Al<sup>3+</sup> in living cells and zebrafish.

### Introduction

Aluminum, the third most abundant element on the Earth's crust, is widely used in daily life, such as in utensils, food additives, building equipment, water purification, and pharmaceutical products.<sup>1–3</sup> However, as a non-essential toxic element in the biological system, the accumulation of excessive Al<sup>3+</sup> could induce various diseases, including Parkinson's disease, Alzheimer's disease, and amyotrophic lateral sclerosis.<sup>4–9</sup> Moreover, the water-soluble Al<sup>3+</sup> resulted by acid rain could cause serious damage to growing plants and the environment.<sup>10–12</sup> Therefore, the development of an effective method to trace Al<sup>3+</sup> is of great significance to human health and environment protection.

Though traditional analysis and detection techniques, such as chromatography, spectroscopy, and electrochemical analysis, are available to detect heavy transition metal ions, they are not convenient for the analysis of plentiful samples because of expensive equipment, high cost and time-consuming procedures.<sup>13–19</sup> By contrast, significant progress has been achieved in the development and application of fluorescent probes for the selective binding and identification of different metals, exhibiting unique properties including operational simplicity, low cost, high sensitivity and high selectivity.<sup>20,21</sup> Until now, some fluorescent probes for detecting Al<sup>3+</sup> have been reported based on internal charge transfer (ICT),<sup>22–24</sup> photo-induced electron transfer (PET),<sup>25–29</sup> chelation-enhanced fluorescence (CHEF),<sup>30–32</sup> and fluorescence resonance energy transfer (FRET) mechanisms.<sup>33</sup> However, most of these probes need

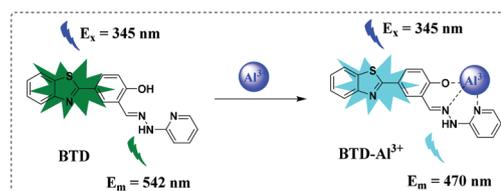
to be applied in the organic/water mixture for the detection of Al<sup>3+</sup>; the Al<sup>3+</sup> ion easily dissolves in water medium. The poor water-solubility of these reported probes hinders their further application in environmental and biological systems. In recent years, fluorescent probes displaying aggregation-induced emission (AIE) characteristics have attracted great attention, and a lot of practical applications have been realized.<sup>34–40</sup> Hence, it is valuable to develop new AIE probes with high selectivity and high sensitivity for the quantification and bioimaging of Al<sup>3+</sup>.

In this work, we rationally design and develop a novel fluorescent probe BTD with AIE characteristics, which exhibits fluorescence 'turn-on' for Al<sup>3+</sup> in almost pure water (Scheme 1). This probe exhibits high sensitivity and high selectivity for the monitoring of Al<sup>3+</sup> in water samples. Furthermore, the probe was successfully applied to detect Al<sup>3+</sup> in BEL-7402 cells and zebrafish.

### Experimental

#### General information

The chemicals and solvents were purchased from Aladdin (Shanghai, China) and used without further purification. TLC analysis was performed using precoated silica plates. UV-vis absorption spectra were obtained on a UV-2450 spectrophotometer (Shimadzu Co., Japan). All the experimental pure water was obtained from a Millopor-Q water ultrapurification



**Scheme 1** Proposed mechanism for sensing Al<sup>3+</sup>.

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system.  $^1\text{H}$  NMR and  $^{13}\text{C}$  NMR spectra were obtained with tetramethyl silane (TMS) as the internal standard on a BRUKER AVANCE-500 spectrometer and the chemical shifts ( $\delta$ ) were expressed in ppm and coupling constants ( $J$ ) were in Hertz. The IR spectrum was recorded on a NEXUS with KBr pellets and reported in  $\text{cm}^{-1}$ . Mass analyses were performed using a Waters Q-ToF Premier mass spectrometer with an ESI ion source (Waters QTOF Premier, U.S.A.). Cells were imaged using a fluorescence confocal microscope (Zeiss LSM 880, Germany). Zebrafish experiments were conducted on a fluorescence confocal microscope system (Leica SP8, Germany).

### General procedure for UV-visible spectroscopy and fluorescence measurements

The stock solution of probe BTD (1.0 mM) was prepared in DMSO. Stock solutions (10.0 mM) of various metal ions including  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Li}^+$ ,  $\text{Ag}^+$ ,  $\text{Ba}^{2+}$ ,  $\text{Ca}^{2+}$ ,  $\text{Co}^{2+}$ ,  $\text{Zn}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Mn}^{2+}$ ,  $\text{Pb}^{2+}$ ,  $\text{Cd}^{2+}$ ,  $\text{Cu}^{2+}$ ,  $\text{Sn}^{2+}$ ,  $\text{Fe}^{2+}$ ,  $\text{Fe}^{3+}$ ,  $\text{Cr}^{3+}$ ,  $\text{Bi}^{3+}$ ,  $\text{Ni}^{2+}$ ,  $\text{Zr}^{4+}$ ,  $\text{Ge}^{4+}$ , Cys, Hcy, GSH,  $\text{S}^{2-}$ ,  $\text{SO}_3^{2-}$ , Gly, Glu, Met, Asp, Thr, Lys, Try, and His were prepared in deionized water. These stock solutions were further diluted to the required concentration for measurement. Test solutions were prepared as follows: 20  $\mu\text{L}$  of BTD solution (1.0 mM) and appropriate amounts of analyte solution were added into a test tube, and the solution was diluted to 2 mL with pure water. All the absorption and fluorescence spectra were obtained at room temperature after shaking well.

### Synthesis of 4-(benzo[d]thiazol-2-yl)phenol (1)

To a solution of 150 mL anhydrous DMF were added 2-amino-benzenethiol (18.78 g, 150 mmol) and 4-hydroxybenzaldehyde (18.32 g, 150 mmol); then, sodium pyrosulfite (24.52 g, 129 mmol) was added to the resulting solution. The mixture was refluxed for 4 h with stirring until no starting materials were indicated by TLC. The reaction mixture was cooled to room temperature, and then poured into 1 L of cold water, and a white solid was precipitated. Then the solid was filtered and dried under vacuum to yield the target compound **1** (28.8 g, 84.5%).  $^1\text{H}$  NMR (500 MHz, DMSO- $d_6$ )  $\delta$  10.22 (s, 1H), 8.07 (d,  $J = 8.0$  Hz, 1H), 7.98 (d,  $J = 8.2$  Hz, 1H), 7.93 (d,  $J = 8.6$  Hz, 2H), 7.49 (t,  $J = 7.6$  Hz, 1H), 7.39 (t,  $J = 7.6$  Hz, 1H), 6.94 (dd,  $J = 8.9$ , 2.5 Hz, 2H).  $^{13}\text{C}$  NMR (126 MHz, DMSO- $d_6$ )  $\delta$  167.9, 161.0, 154.2, 134.6, 129.5, 126.9, 125.4, 124.5, 122.8, 122.6, 116.6.

### Synthesis of 5-(benzo[d]thiazol-2-yl)-2-hydroxybenzaldehyde (2)

To a solution of 4-(benzo[d]thiazol-2-yl) phenol (5.00 g, 22 mmol) in trifluoroacetic acid (120 mL) was added hexamethylenetetramine (3.70 g, 26.4 mmol); then the mixture was refluxed for 5 h. After the reaction mixture was cooled to room temperature, hydrochloric acid (100 mL, 6 mol  $\text{L}^{-1}$ ) was added, and the organic layer was separated out. The aqueous layer was extracted with  $\text{CH}_2\text{Cl}_2$  (3  $\times$  10 mL). Then the combined organic layers were washed with brine, dried with anhydrous  $\text{Na}_2\text{SO}_4$  and concentrated under vacuum. The crude product was purified by column chromatography to yield a white solid (1.80 g, 32%).  $^1\text{H}$  NMR (500 MHz,  $\text{CDCl}_3$ )  $\delta$  11.27 (s, 1H), 10.03 (s, 1H), 8.35 (d,  $J = 2.3$  Hz, 1H), 8.22 (dd,  $J = 8.7$ , 2.3 Hz, 1H),

8.05 (d,  $J = 8.1$  Hz, 1H), 7.91 (dd,  $J = 8.0$ , 1.3 Hz, 1H), 7.53–7.48 (m, 1H), 7.42–7.38 (m, 1H), 7.12 (d,  $J = 8.8$  Hz, 1H).  $^{13}\text{C}$  NMR (126 MHz,  $\text{CDCl}_3$ )  $\delta$  196.4, 166.0, 163.5, 154.0, 135.7, 134.8, 132.8, 126.6, 126.1, 125.3, 123.1, 121.7, 120.7, 118.6.

### Synthesis of the probe BTD

To a solution of 10 mL ethanol were added 5-(benzo[d]thiazol-2-yl)-2-hydroxybenzaldehyde (300 mg, 1.18 mmol) and 2-hydrazinylpyridine (128 mg, 1.18 mmol). The resulting mixture was stirred overnight at room temperature. Then the residue was filtered and washed with cold ethanol three times. The solid was purified by column chromatography to yield the desired probe (291 mg, 71.5%).  $^1\text{H}$  NMR (500 MHz, DMSO- $d_6$ )  $\delta$  11.10 (d,  $J = 26.6$  Hz, 2H), 8.44–8.32 (m, 2H), 8.15 (dd,  $J = 5.0$ , 1.8 Hz, 1H), 8.11 (d,  $J = 7.9$  Hz, 1H), 8.03 (d,  $J = 8.0$  Hz, 1H), 7.92 (dd,  $J = 8.5$ , 2.4 Hz, 1H), 7.72–7.66 (m, 1H), 7.56–7.49 (m, 1H), 7.47–7.39 (m, 1H), 7.13 (d,  $J = 8.3$  Hz, 1H), 7.07 (d,  $J = 8.5$  Hz, 1H), 6.80 (dd,  $J = 7.2$ , 4.9 Hz, 1H).  $^{13}\text{C}$  NMR (126 MHz, DMSO- $d_6$ )  $\delta$  167.6, 158.9, 156.8, 154.2, 148.5, 138.6, 137.1, 134.7, 129.1, 127.0, 125.8, 125.5, 125.0, 122.9, 122.7, 122.1, 117.4, 115.7, 106.8.

### Cell imaging studies

The BEL-7402 cells were cultured in Dulbecco's modified Eagle's medium (DMEM, GIBCO) supplemented with 10% heat-inactivated fetal bovine serum (FBS, GIBCO), streptomycin (100  $\mu\text{g mL}^{-1}$ ) and penicillin (100  $\mu\text{g mL}^{-1}$ ). The cells were seeded into a 96 well culture plate and grown in DMEM medium under a humid atmosphere of 5%  $\text{CO}_2$  at 37  $^\circ\text{C}$  for 24 h. Subsequently, the cells were washed thrice with sterile phosphate buffered saline (PBS). For the detection of  $\text{Al}^{3+}$  in living cells, BEL-7402 cells were incubated with 2.0  $\mu\text{M}$  probe BTD in DMEM at 37  $^\circ\text{C}$  for 30 min and subsequently incubated with  $\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$  (0.1, 0.2 and 0.4 mM) for 30 min, respectively, and then washed with phosphate-buffered saline (PBS) three times. Cells were imaged using a fluorescence confocal microscope (Zeiss LSM 880, Germany). ( $\lambda_{\text{ex}} = 405$  nm,  $\lambda_{\text{em}} = 421$ –475 nm for the blue channel;  $\lambda_{\text{ex}} = 458$  nm,  $\lambda_{\text{em}} = 500$ –550 nm for the green channel). Scale bar: 50  $\mu\text{m}$ .

### Zebrafish confocal fluorescence imaging

For the detection of  $\text{Al}^{3+}$  *in vivo*, 3-day-old zebrafish was used for these experiments. All animal procedures were performed in accordance with the guidelines and approved by the Animal Ethics Committee (Hunan Normal University). Zebrafish was fed with E3 embryo media (15 mM NaCl, 0.5 mM KCl, 1 mM  $\text{MgSO}_4$ , 1 mM  $\text{CaCl}_2$ , 0.15 mM  $\text{KH}_2\text{PO}_4$ , 0.05 mM  $\text{Na}_2\text{HPO}_4$ , 0.7 mM  $\text{NaHCO}_3$ ,  $10^{-5}\%$  methylene blue; pH 7.5) at 28  $^\circ\text{C}$  for 30 min, then incubated with  $\text{Al}^{3+}$  (10, 20 and 50  $\mu\text{M}$ , 60 min) respectively, and finally incubated with the probe (5  $\mu\text{M}$ ) for 60 min. All the fishes were terminally anaesthetized using MS222, and images were obtained on a fluorescence confocal microscope system (Leica SP8, Germany). ( $\lambda_{\text{ex}} = 405$  nm,  $\lambda_{\text{em}} = 440$ –500 nm for the blue channel;  $\lambda_{\text{ex}} = 488$  nm,  $\lambda_{\text{em}} = 510$ –550 nm for the green channel). Scale bar: 0.5 mm.

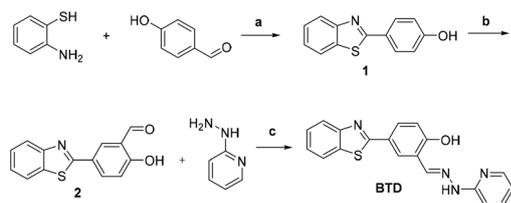
## Results and discussion

### Aggregation-induced emission (AIE) of the probe BTD

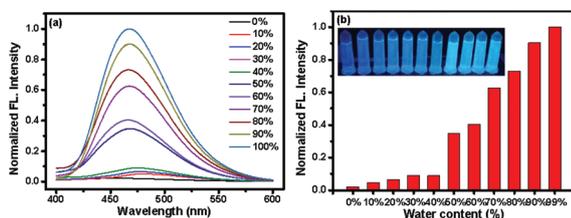
The probe BTD was easily synthesized, as shown in Scheme 2, *via* a three-step process. The probe and intermediates were characterized by  $^1\text{H}$  NMR and  $^{13}\text{C}$  NMR (Fig. S13–S18 $^\dagger$ ). Firstly, the AIE behavior of the probe in the presence of  $\text{Al}^{3+}$  was verified by obtaining the fluorescence spectra of the probe BTD with  $\text{Al}^{3+}$  in mixed solvents with varied acetone-to- $\text{H}_2\text{O}$  ratios. In pure acetone, almost no fluorescence was observed under excitation at 345 nm (Fig. 1). After the addition of water, the phenolic hydroxyl group, the N atoms on the pyridine and the C=N double bond have a unique affinity for  $\text{Al}^{3+}$  ions, resulting in the aggregation of the probe BTD, and the fluorescence intensities were gradually increased at 470 nm. The fluorescence intensity at 470 nm was enhanced with the increase in water content. And the content of 99% water leads to a *ca.* 49-fold increment in the fluorescence intensity. The changes in blue fluorescence could be obviously observed under UV light (Fig. 1, insert). These results suggested that the probe BTD was an AIE-active probe for the sensing of  $\text{Al}^{3+}$  ions.

### Spectroscopic response

Next, we examined the responses of the probe BTD (10  $\mu\text{M}$ ) in pure water (containing 1% DMSO) toward  $\text{Al}^{3+}$  at 37  $^\circ\text{C}$ . As shown in Fig. S1, $^\dagger$  upon the addition of 100  $\mu\text{M}$   $\text{Al}^{3+}$ , the initial absorption peak at 321 nm shifted to 327 nm. Meanwhile, the fluorescence spectrum of the probe BTD



**Scheme 2** Synthesis of the probe BTD. Reagents and conditions: (a) DMF,  $\text{Na}_2\text{S}_2\text{O}_5$  reflux; 84.5%; (b)  $\text{CF}_3\text{COOH}$ , HMTA, reflux; 32%; (c) EtOH, at room temperature; 71.5%.



**Fig. 1** (a) Normalized fluorescence spectra of the probe BTD (10  $\mu\text{M}$ ) in the presence of  $\text{Al}^{3+}$  (100  $\mu\text{M}$ ) in different water contents from 0% to 100%. (b) The corresponding normalized fluorescence intensity changes at 470 nm.  $\lambda_{\text{ex}} = 345$  nm, slit: 2.5/2.5. The inset photos indicated the color changes of the probe BTD (10  $\mu\text{M}$ ) in the presence of  $\text{Al}^{3+}$  (100  $\mu\text{M}$ ) in different water contents (0–100%) under a UV lamp at 365 nm, respectively.

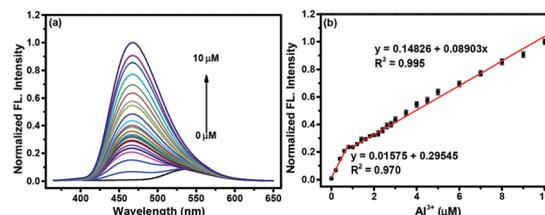
exhibited a weak fluorescence at 542 nm. After the probe was treated with 100  $\mu\text{M}$   $\text{Al}^{3+}$ , a significant fluorescence increment was observed at 470 nm by more than 338 times when excited at 345 nm, accompanied by a clear color change from green to blue (inset images of Fig. S1 $^\dagger$ ). Using quinoline sulfate in 0.1 M  $\text{H}_2\text{SO}_4$  aqueous solution as the standard, the fluorescence quantum yield was calculated to be 0.157. These results demonstrated that the probe BTD was a visual and fluorescence turn-on probe for the detection of  $\text{Al}^{3+}$  in pure water.

### Time-dependence and pH effect

The response time of the probe BTD with  $\text{Al}^{3+}$  in pure water (containing 1% DMSO) was also investigated. Upon addition of  $\text{Al}^{3+}$ , the fluorescence at 470 nm increased rapidly and reached equilibrium after 25 minutes (Fig. S2 $^\dagger$ ). Therefore, subsequent experiments for the monitoring of different analytes with the probe BTD were conducted for 25 min. Subsequently, the pH effect of the probe BTD for the monitoring of  $\text{Al}^{3+}$  was observed. As shown in Fig. S3, $^\dagger$  the fluorescence of the probe BTD remained the same in the pH range of 2–10, indicating that the probe BTD was stable in a wide pH range. However, in the presence of  $\text{Al}^{3+}$ , it showed significant fluorescence enhancements at pH 2–10. Thus, the probe BTD can be used for the detection of  $\text{Al}^{3+}$  over a wide pH range, including a physiologically relevant pH value, which is favorable for its biological applications in living cells and *in vitro*.

### Titration experiments

To evaluate the sensing ability of the probe BTD for  $\text{Al}^{3+}$ , fluorescence titration experiments were conducted. As shown in Fig. 2, the fluorescence at 470 nm enhanced gradually after the addition of  $\text{Al}^{3+}$  (0–10  $\mu\text{M}$ ). A good linear relationship was obtained in the  $\text{Al}^{3+}$  concentration range of 0–10  $\mu\text{M}$ . And the detection limit of the probe BTD for  $\text{Al}^{3+}$  was calculated to be as low as 3.25 nM based on the signal-to-noise ratio ( $S/N = 3$ ), which is as low as 7.41  $\mu\text{M}$   $\text{Al}^{3+}$  for bottled drinking water according to the World Health Organization (WHO) guidelines. Compared to some reported probes for  $\text{Al}^{3+}$  (Table S1 $^\dagger$ ), this probe exhibited high sensitivity. These results indicated that the probe BTD is sensitive for the detection of  $\text{Al}^{3+}$  in environmental and biological systems.



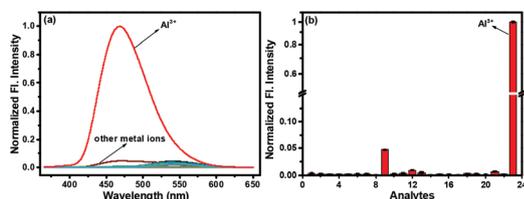
**Fig. 2** (a) Normalized fluorescence intensity spectra of the probe BTD (10  $\mu\text{M}$ ) in the presence of 0–10  $\mu\text{M}$   $\text{Al}^{3+}$  in pure water (containing 1% DMSO). (b) The linear changes in the normalized fluorescence intensity at 470 nm of the probe BTD and as a function of  $\text{Al}^{3+}$  concentration.  $\lambda_{\text{ex}} = 345$  nm, slit (nm): 2.5/2.5.

### Selectivity and anti-interference

Subsequently, the selectivity of the probe BTD toward  $\text{Al}^{3+}$  was evaluated. Water-soluble metal species were tested, including  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Li}^+$ ,  $\text{Ag}^+$ ,  $\text{Ba}^{2+}$ ,  $\text{Ca}^{2+}$ ,  $\text{Co}^{2+}$ ,  $\text{Zn}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Mn}^{2+}$ ,  $\text{Pb}^{2+}$ ,  $\text{Cd}^{2+}$ ,  $\text{Cu}^{2+}$ ,  $\text{Sn}^{2+}$ ,  $\text{Fe}^{2+}$ ,  $\text{Fe}^{3+}$ ,  $\text{Cr}^{3+}$ ,  $\text{Bi}^{3+}$ ,  $\text{Ni}^{2+}$ ,  $\text{Zr}^{4+}$  and  $\text{Ge}^{4+}$ . As shown in Fig. 3, among these analytes, only  $\text{Al}^{3+}$  could induce a significant fluorescence enhancement, while no fluorescence was observed for the other competing analytes. Competition experiments were carried out in the presence of various metal ions and  $\text{Al}^{3+}$  under the same conditions (Fig. S4†). The fluorescence changes of the probe solution caused by the coexistence of other ions with  $\text{Al}^{3+}$  and the presence of  $\text{Al}^{3+}$  alone are similar, except for  $\text{Co}^{2+}$ ,  $\text{Cu}^{2+}$ ,  $\text{Sn}^{2+}$ ,  $\text{Fe}^{2+}$ ,  $\text{Fe}^{3+}$  and  $\text{Ni}^{2+}$ , which could slightly reduce the fluorescence intensity at 470 nm. These results demonstrated that the probe BTD had good selectivity and anti-interference ability for the detection of  $\text{Al}^{3+}$  and has the potential for monitoring  $\text{Al}^{3+}$  in complex systems.

### Reversibility

Reversibility and regeneration are also essential factors for the development of devices for sensing analytes in practical applications.<sup>41–53</sup> We first evaluated the fluorescence response of the *in situ* product BTD- $\text{Al}^{3+}$  toward other analytes, such as Cys, Hcy, GSH,  $\text{S}^{2-}$ ,  $\text{SO}_3^{2-}$ , Gly, Glu, Met, Asp, Thr, Lys, Try, and His. As shown in Fig. S5,† fluorescence at 470 nm was significantly quenched only after Lys was added to the solution of the product BTD- $\text{Al}^{3+}$ . However, negligible fluorescence changes were observed for other analytes under the same conditions. Subsequently, the fluorescence intensity of the solution of the product BTD- $\text{Al}^{3+}$  was rapidly quenched for 2 min upon addition of 500  $\mu\text{M}$  Lys (Fig. S6†). As shown in Fig. S7,† the alternate addition of a constant amount of  $\text{Al}^{3+}$  (50  $\mu\text{M}$ ) and Lys (500  $\mu\text{M}$ ) to the aqueous solution of probe BTD would result in switchable changes in the fluorescence intensity at 470 nm. And this reversible fluorescence interconversion could be repeated more than 4 times by the modulation of the  $\text{Al}^{3+}$ /Lys addition. These results indicated that the probe BTD could be applied to the reversible detection of  $\text{Al}^{3+}$  in environment and biological systems. In addition, the probe- $\text{Al}^{3+}$  complex could be used to detect lysine (Fig. S8†).



**Fig. 3** (a) Normalized fluorescence spectra responses of the probe BTD (10  $\mu\text{M}$ ) to various metal ions in pure water (containing 1% DMSO). (b) The corresponding normalized fluorescence intensity changes at 470 nm. Various metal ions (100  $\mu\text{M}$ ) including: 1. None; 2.  $\text{Na}^+$ ; 3.  $\text{K}^+$ ; 4.  $\text{Li}^+$ ; 5.  $\text{Ag}^+$ ; 6.  $\text{Ba}^{2+}$ ; 7.  $\text{Ca}^{2+}$ ; 8.  $\text{Co}^{2+}$ ; 9.  $\text{Zn}^{2+}$ ; 10.  $\text{Mg}^{2+}$ ; 11.  $\text{Mn}^{2+}$ ; 12.  $\text{Pb}^{2+}$ ; 13.  $\text{Cd}^{2+}$ ; 14.  $\text{Cu}^{2+}$ ; 15.  $\text{Sn}^{2+}$ ; 16.  $\text{Fe}^{2+}$ ; 17.  $\text{Fe}^{3+}$ ; 18.  $\text{Cr}^{3+}$ ; 19.  $\text{Bi}^{3+}$ ; 20.  $\text{Ni}^{2+}$ ; 21.  $\text{Zr}^{4+}$ ; 22.  $\text{Ge}^{4+}$ ; 23.  $\text{Al}^{3+}$ .  $\lambda_{\text{ex}} = 345 \text{ nm}$ , slit (nm): 2.5/2.5.

### Sensing mechanism

The sensing mechanism of the probe BTD toward  $\text{Al}^{3+}$  was carefully investigated. The Job's plot titration experiments of the probe BTD with  $\text{Al}^{3+}$  were first carried out to determine the binding ratio between the probe BTD and  $\text{Al}^{3+}$ . As shown in Fig. S9,† the maximum fluorescence intensity was obtained when the molar ratio of the probe BTD with  $\text{Al}^{3+}$  was 0.5, indicating a 1:1 metal-ligand chelation ratio between the probe BTD and  $\text{Al}^{3+}$ . Mass spectrometry analysis was further conducted, as shown in Fig. S10.† The peak at  $m/z$  565.15 was attributed to  $[\text{BTD} - \text{Al}^{3+} + 2\text{SO}_4^{2-} + \text{H}^+]^-$  [calcd,  $m/z$ : 564.97]. Moreover, the FT-IR spectra of free probe BTD and the complex of probe BTD and  $\text{Al}^{3+}$  were obtained, respectively (Fig. S11†). These results further confirmed the binding mode of the probe BTD with  $\text{Al}^{3+}$ . According to the analyses of Job's plot, ESI-MS and FT-IR spectra, the proposed mechanism for the sensing of  $\text{Al}^{3+}$  using the probe BTD was reasonable (Scheme 1).

### Detection of $\text{Al}^{3+}$ in real water samples

To verify whether the probe BTD could detect  $\text{Al}^{3+}$  ions in real water samples or not, this probe was applied to quantify  $\text{Al}^{3+}$  ions in Xiangjiang water and tap water. As shown in Table 1, after the addition of 3  $\mu\text{M}$  and 6  $\mu\text{M}$   $\text{Al}^{3+}$  ions to different water samples respectively, good results were obtained and the recovery of  $\text{Al}^{3+}$  ranged from 97.3% to 102.2%. Thus, the probe BTD was suitable to detect  $\text{Al}^{3+}$  ions in the water samples.

### Imaging $\text{Al}^{3+}$ in living cells

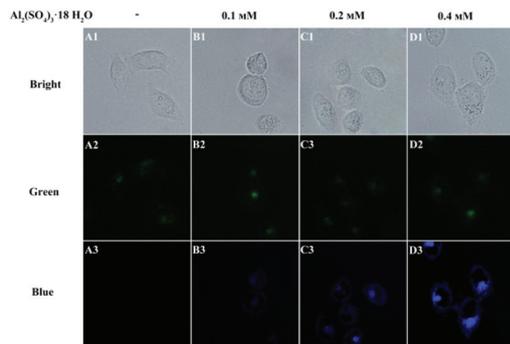
Encouraged by the aforementioned results, the probe BTD was further applied to the imaging of  $\text{Al}^{3+}$  in living cells using a laser scanning confocal microscope. According to the results from MTT assays in BEL-7402 cells, the probe BTD has low cytotoxicity towards living cells (Fig. S12†). As shown in Fig. 4, when BEL-7402 cells were incubated with the probe BTD (2.0  $\mu\text{M}$ ) for 30 min, a faint green fluorescence was observed (Fig. 4, A1–A3), while, after the addition of  $\text{Al}^{3+}$  (0.1–0.4 mM), blue fluorescence was observed (Fig. 4, B1–D3). These results indicated that the probe BTD was successfully applied to the imaging of  $\text{Al}^{3+}$  in living cells.

### Imaging of $\text{Al}^{3+}$ in zebrafish

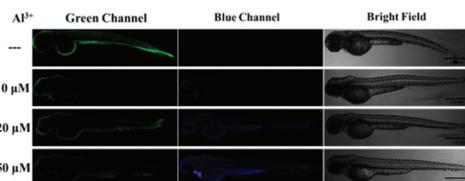
Finally, the probe BTD was applied to image  $\text{Al}^{3+}$  in zebrafish. As shown in Fig. 5, when the zebrafish were treated with the probe BTD (5  $\mu\text{M}$ ) for 60 min, a green fluorescence was observed. When the zebrafish was preincubated with  $\text{Al}^{3+}$  (10, 20, and 50  $\mu\text{M}$ , respectively) and then incubated with the

**Table 1** Quantification of  $\text{Al}^{3+}$  with the probe BTD in real water samples. RSD (%),  $n = 3$

Samples	$\text{Al}^{3+}$ ( $\mu\text{M}$ )	Spiked ( $\mu\text{M}$ )	Detected ( $\mu\text{M}$ )	Recovery (%)	RSD (%)
Xiang jiang River	0.00	3.00	2.92	97.3	0.67
		6.00	5.94	99.0	0.52
Tap water	0.00	3.00	2.94	98.0	0.85
		6.00	6.13	102.2	1.23



**Fig. 4** Confocal fluorescence images of exogenous  $\text{Al}^{3+}$  in BEL-7402 cells. (A1–D3) The cells were incubated with the probe BTD ( $2.0 \mu\text{M}$ ) for 30 min and then incubated with 0.1 mM, 0.2 mM and 0.4 mM  $\text{Al}^{3+}$  for 30 min, respectively. ( $\lambda_{\text{ex}} = 405 \text{ nm}$ ,  $\lambda_{\text{em}} = 421\text{--}475 \text{ nm}$  for the blue channel;  $\lambda_{\text{ex}} = 458 \text{ nm}$ ,  $\lambda_{\text{em}} = 500\text{--}550 \text{ nm}$  for the green channel.) Scale bar:  $50 \mu\text{m}$ .



**Fig. 5** Confocal fluorescence imaging of exogenous  $\text{Al}^{3+}$  in zebrafish. Top row: zebrafish were incubated with the probe BTD ( $5 \mu\text{M}$ ) for 60 min. Others: zebrafish were preincubated with 10, 20 and  $50 \mu\text{M}$   $\text{Al}^{3+}$  for 60 min and then incubated with the probe BTD ( $5 \mu\text{M}$ ) for 60 min, respectively. ( $\lambda_{\text{ex}} = 405 \text{ nm}$ ,  $\lambda_{\text{em}} = 440\text{--}500 \text{ nm}$  for the blue channel;  $\lambda_{\text{ex}} = 488 \text{ nm}$ ,  $\lambda_{\text{em}} = 510\text{--}550 \text{ nm}$  for the green channel). Scale bar:  $0.5 \text{ mm}$ .

probe BTD, a green fluorescence disappeared, and the blue fluorescence was increased. These results demonstrated that the probe BTD is an effective candidate for the monitoring of  $\text{Al}^{3+}$  fluctuation in zebrafish.

## Conclusions

In summary, a novel fluorescent probe BTD for the monitoring of  $\text{Al}^{3+}$  has been developed based on the AIE mechanism. The probe BTD is easily prepared through a simple three-step process, which could detect  $\text{Al}^{3+}$  in water samples under mild conditions. And this probe exhibited a fast response, high selectivity, and good sensitivity toward  $\text{Al}^{3+}$ . Furthermore, the probe BTD was successfully applied to the sensing of  $\text{Al}^{3+}$  in living cells and zebrafish, which would be helpful for the understanding of the pathological functions of  $\text{Al}^{3+}$  in biological systems.

## Author contributions

Yabing Gan: methodology, investigation, formal analysis, and writing – original draft. Guoxing Yin: investigation and vali-

ation. Zhaomin Xu: investigation and validation. Jianhua Wang: conceptualization, methodology, and writing – review & editing. Peng Yin: supervision, conceptualization, funding acquisition, project administration, and writing – review & editing.

## Conflicts of interest

There are no conflicts to declare.

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## Notes and references

- 1 E. Delhaize and P. R. Ryan, *Plant Physiol.*, 1995, **107**, 315–321.
- 2 B. Valeur and I. Leray, *Coord. Chem. Rev.*, 2000, **205**, 3–40.
- 3 H. Okubo, *Proc. Natl. Acad. Sci. U. S. A.*, 1988, **85**, 3888–3892.
- 4 S. W. King, J. Savory, M. R. Wills and H. J. Gitelman, *Crit. Rev. Clin. Lab. Sci.*, 1981, **14**, 1–20.
- 5 I. S. Parkinson, M. K. Ward and D. N. Kerr, *J. Clin. Pathol.*, 1981, **34**, 1285.
- 6 T. P. Flaten, *Brain Res. Bull.*, 2001, **55**, 187–196.
- 7 V. K. Gupta, A. K. Jain and G. Maheshwari, *Talanta*, 2007, **72**, 1469–1473.
- 8 G. D. Fasman, *Coord. Chem. Rev.*, 1996, **149**, 125–165.
- 9 L. K. Kumawat, N. Mergu, M. Asif and V. K. Gupta, *Sens. Actuators, B*, 2016, **231**, 847–859.
- 10 Neeraj, A. Kumar, S. K. Asthana, Shweta and K. K. Upadhyay, *J. Photochem. Photobiol., A*, 2016, **329**, 69–76.
- 11 W. A. Banks and A. J. Kastin, *Neurosci. Biobehav. Rev.*, 1989, **13**, 47–53.
- 12 V. Rondeau, H. Jacquemin-Gadda, D. Commenges, C. Helmer and J.-F. Dartigues, *Am. J. Epidemiol.*, 2009, **169**, 489–496.
- 13 M. Frankowski, A. Ziola-Frankowska and J. Siepak, *Talanta*, 2010, **80**, 2120–2126.
- 14 R. N. Goyal, V. K. Gupta and S. Chatterjee, *Biosens. Bioelectron.*, 2009, **24**, 3562–3568.
- 15 C.-H. Guo, G.-S. W. Hsu, C.-J. Chuang and P.-C. Chen, *Environ. Toxicol. Pharmacol.*, 2009, **27**, 176–181.
- 16 H. Wang, Z. Yu, Z. Wang, H. Hao, Y. Chen and P. Wan, *Electroanalysis*, 2011, **23**, 1095–1099.
- 17 B. J. Sanghavi and A. K. Srivastava, *Analyst*, 2013, **138**, 1395–1404.
- 18 B. J. Sanghavi, S. Sitaula, M. H. Griep, S. P. Karna, M. F. Ali and N. S. Swami, *Anal. Chem.*, 2013, **85**, 8158–8165.
- 19 N. S. Gadhari, B. J. Sanghavi and A. K. Srivastava, *Anal. Chim. Acta*, 2011, **703**, 31–40.
- 20 B. M. Luby, D. M. Charron, C. M. MacLaughlin and G. Zheng, *Adv. Drug Delivery Rev.*, 2017, **113**, 97–121.

- 21 J. A. Kaczmarek, J. A. Mitchell, M. A. Spence, V. Vongsouthi and C. J. Jackson, *Curr. Opin. Struct. Biol.*, 2019, **57**, 31–38.
- 22 Y.-J. Liu, F.-F. Tian, X.-Y. Fan, F.-L. Jiang and Y. Liu, *Sens. Actuators, B*, 2017, **240**, 916–925.
- 23 P. Torawane, K. Tayade, S. Bothra, S. K. Sahoo, N. Singh, A. Borse and A. Kuwar, *Sens. Actuators, B*, 2016, **222**, 562–566.
- 24 Z. Li, C. Liu, J. Wang, S. Wang, L. Xiao and X. Jing, *Spectrochim. Acta, Part A*, 2019, **212**, 349–355.
- 25 G. T. Selvan, M. Kumaresan, R. Sivaraj, I. V. M. V. Enoch and P. M. Selvakumar, *Sens. Actuators, B*, 2016, **229**, 181–189.
- 26 M. Mukherjee, B. Sen, S. Pal, A. Maji, D. Budhadev and P. Chattopadhyay, *Spectrochim. Acta, Part A*, 2016, **157**, 11–16.
- 27 M. A. Kozlov, D. Y. Uvarov, S. A. Gorbato, N. G. Kolotirina, A. D. Averin, V. V. Kachala, K. A. Lyssenko, I. V. Zavarzin and Y. A. Volkova, *Eur. J. Org. Chem.*, 2019, 4196–4206.
- 28 J.-H. Wang, D.-R. Gao, X.-Y. Wang, Y.-M. Lu, W.-X. Shen and Y.-Y. Lv, *Sens. Actuators, B*, 2019, **294**, 14–23.
- 29 G. Zhu, Y. Huang, C. Wang, L. Lu, T. Sun, M. Wang, Y. Tang, D. Shan, S. Wen and J. Zhu, *Spectrochim. Acta, Part A*, 2019, **210**, 105–110.
- 30 S. Mukherjee, P. Mal and H. Stoeckli-Evans, *J. Lumin.*, 2016, **172**, 124–130.
- 31 L. Bai, F. Tao, L. Li, A. Deng, C. Yan, G. Li and L. Wang, *Spectrochim. Acta, Part A*, 2019, **214**, 436–444.
- 32 Y. Li, Q. Niu, T. Wei and T. Li, *Anal. Chim. Acta*, 2019, **1049**, 196–212.
- 33 M. Arduini, F. Felluga, F. Mancin, P. Rossi, P. Tecilla, U. Tonellato and N. Valentinuzzi, *Cheminform*, 2003, **34**, 1606–1607.
- 34 Y. Hong, J. W. Y. Lam and B. Z. Tang, *Chem. Soc. Rev.*, 2011, **40**, 5361–5388.
- 35 Y. Liu, Y. Tang, N. N. Barashkov, I. S. Irgibaeva, J. W. Y. Lam, R. Hu, D. Birimzhanova, Y. Yu and B. Z. Tang, *J. Am. Chem. Soc.*, 2010, **132**, 13951–13953.
- 36 X. Chen, X. Y. Shen, E. Guan, Y. Liu, A. Qin, J. Z. Sun and B. Z. Tang, *Chem. Commun.*, 2013, **49**, 1503–1505.
- 37 J. Wu, F. Du, P. Zhang, I. A. Khan, J. Chen and Y. Liang, *J. Inorg. Biochem.*, 2005, **99**, 1145–1154.
- 38 Z. Qiao, Y. Wu, B. Tang, R. Perestrelo and R. Bhalla, *Tetrahedron Lett.*, 2019, **60**, 150918.
- 39 J. Luo, Z. Xie, J. W. Lam, L. Cheng, H. Chen, C. Qiu, H. S. Kwok, X. Zhan, Y. Liu and D. Zhu, *Chem. Commun.*, 2001, **18**, 1740–1741.
- 40 Y. Hong, J. W. Y. Lam and B. Z. Tang, *Chem. Commun.*, 2009, **40**, 4332–4353.
- 41 Y.-J. Tang, S. He, X.-F. Guo and H. Wang, *Analyst*, 2021, **146**, 7740–7747.
- 42 Y. Ma, W. Gao, L. Zhu, Y. Zhao and W. Lin, *Analyst*, 2020, **145**, 1865–1870.
- 43 Y. Zhang, Y. Zuo, T. Yang, Z. Gou, X. Wang and W. Lin, *Analyst*, 2019, **144**, 5075–5080.
- 44 J. Xiong, Z. Li, J. Tan, S. Ji, J. Sun, X. Li and Y. Huo, *Analyst*, 2018, **143**, 4870–4886.
- 45 M. Ren, L. Wang, X. Lv, Y. Sun, H. Chen, K. Zhang, Q. Wu, Y. Bai and W. Guo, *Analyst*, 2019, **144**, 7457–7462.
- 46 Q. Wu, L. Feng, J. B. Chao, Y. Wang and S. Shuang, *Analyst*, 2021, **146**, 4348–4356.
- 47 Z. Liu, X. Zhou, Y. Miao, Y. Hu, N. Kwon, X. Wu and J. Yoon, *Angew. Chem., Int. Ed.*, 2017, **56**, 5812–5816.
- 48 H. Ren, F. Huo and C. Yin, *New J. Chem.*, 2021, **45**, 9096–9101.
- 49 W. Zhang, T. Liu, F. Huo, P. Ning, X. Meng and C. Yin, *Anal. Chem.*, 2017, **89**, 8079–8083.
- 50 T.-B. Ren, S.-Y. Wen, L. Wang, P. Lu, B. Xiong, L. Yuan and X.-B. Zhang, *Anal. Chem.*, 2020, **92**, 4681–4688.
- 51 Y. Ma, W. Gao, L. Zhu, Y. Zhao and W. Lin, *Chem. Commun.*, 2019, **55**, 11263–11266.
- 52 X. Liu, X. Gong, J. Yuan, X. Fan, X. Zhang, T. Ren, S. Yang, R. Yang, L. Yuan and X.-B. Zhang, *Anal. Chem.*, 2021, **93**, 5420–5429.
- 53 Y. Ma, Y. Tang, Y. Zhao and W. Lin, *Anal. Chem.*, 2019, **91**, 10723–10730.