

# A Simplified and Turn-on Fluorescence Chemosensor Based on Coumarin Derivative for Detection of Aluminium(III) Ion in Pure Aqueous Solution

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A novel chemosensor **L** based on coumarin Schiff-base was synthesized and investigated. Sensor **L** showed remarkable selectivity for  $\text{Al}^{3+}$  in Tris-HCl aqueous buffer solution (pH 7.2), and the selectivity was not affected by the presence of a large excess of other competitive ions. The sensor responded rapidly to  $\text{Al}^{3+}$  in aqueous solutions with a 2:1 stoichiometry. Meanwhile, it indicated significant improvement of quantum efficiency and ideal fluorescent lifetime.

**Keywords** Coumarin derivative, fluorescent chemosensor, L-serine, aluminium(III) ion

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## Introduction

Aluminum is the most abundant element in the earth and is widely used in our daily life, such as in food additives, medicines and the production of light alloy, *etc.*<sup>1</sup> In organisms, aluminium which is present as  $\text{Al}^{3+}$ , is highly important in order to maintain the health. However, an excess of  $\text{Al}^{3+}$  has severe toxicity, which not only influences plant growth<sup>2</sup> but also damages the central nervous system to cause human illnesses like dementia and impairment of memory, idiopathic Parkinson's disease, Alzheimer's disease and even breast cancer.<sup>3-7</sup> Therefore, it is necessary to develop a simple and convenient method to detect  $\text{Al}^{3+}$  for environmental and biological studies.

Sensing analysis technology has attracted significant focus because of the advantages including capability of visualization, easy operational procedure, rapid response time, cost effective equipment, convenience afforded due to the lack of need for expensive instruments and complex operation steps, high sensitivity and selectivity.<sup>8-21</sup> The technology has been applied for the determination of medicine,<sup>22-25</sup> biomolecules,<sup>26-29</sup> TNP,<sup>30</sup> metal ions,<sup>31-50</sup> anions,<sup>51</sup> and so on.<sup>52</sup>

Fluorescent sensors, as an important sensing analysis method, have also attracted considerable attention for visual detection of metal ions. In recent years, a series of fluorescent sensors for  $\text{Al}^{3+}$  have so far been reported. Among them (Table S1, Supporting Information), some were operated in organic solvent or in aqueous solution of organic solvent,<sup>53-56</sup> others showed less sensitivity to  $\text{Al}^{3+}$  with poor detection limits,<sup>57,58</sup> and still others were severely disturbed by  $\text{Hg}^{2+}$ ,  $\text{Cu}^{2+}$  or  $\text{Fe}^{3+}$  in the process of  $\text{Al}^{3+}$  detection.<sup>55,59-62</sup> Hence, the development of novel, pure water-soluble, sensitive and interference-free fluorescent chemosensors for  $\text{Al}^{3+}$  detection is still highly desired.

In this work, we designed a water-soluble fluorescence

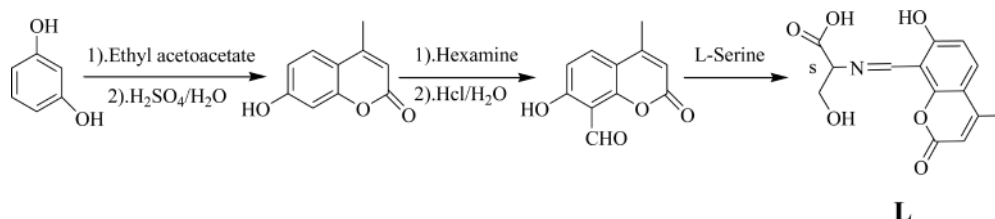
chemosensor for  $\text{Al}^{3+}$  based on a coumarin derivative. The sensor system was composed of a coumarin fluorophore and a receptor of L-serine. By virtue of their excellent properties, such as a high fluorescence quantum yield, large Stokes shift, low toxicity, ease of modification and visible wavelength emission, coumarin and its derivatives have an ideal skeleton structure for the construct ion of various fluorescent probes.<sup>63</sup> L-serine not only can combine with metal ions but also greatly enhances the water solubility of coumarin derivative. Therefore, compared with above-mentioned sensors, Sensor **L** has been proven to be a simple, convenient, rapid synthesis of a probe that shows excellent water solubility, high selectivity and sensitivity, the advantage of low cost, and visual fluorescent switching behavior towards aluminium ions. Sensor **L** is shown in Scheme 1.

## Experimental

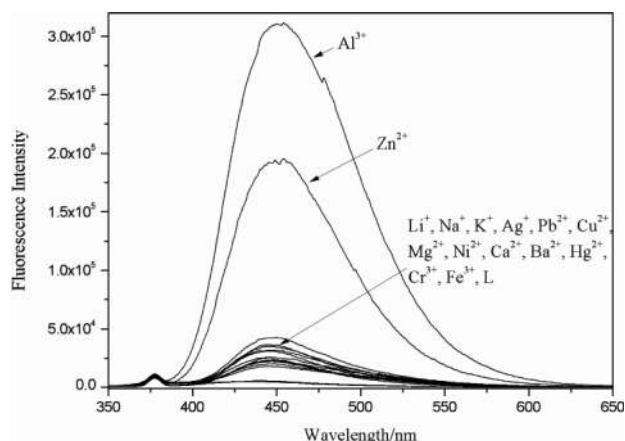
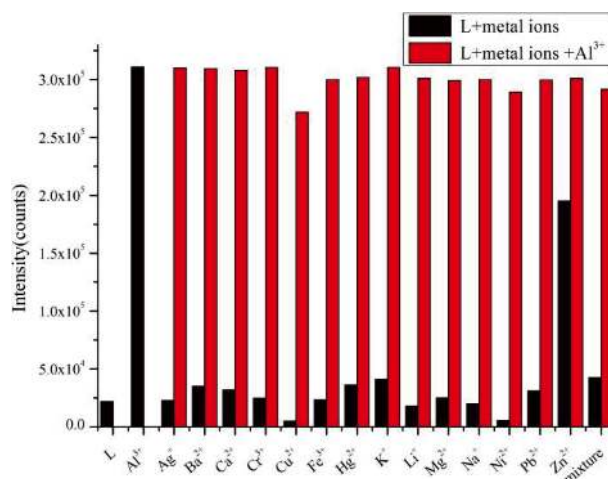
Melting point was determined using an SGW X-4 digital melting point apparatus (Shanghai Instrument Physical Optics Instrument Co., Ltd.). <sup>1</sup>H NMR spectrum was run on a Varian Mercury-Plus 300 NMR spectrometer using TMS as the internal standard (Varian, San Diego, CA). Elemental analysis was taken with a Vario EL CHNS elemental analyzer (Elementar, Germany). Mass spectrum was recorded with a VG ZAB-HS double focusing mass spectrometer (Thermo Onix Ltd., UK). Fluorescence spectra, fluorescence lifetime and quantum efficiency were measured with a Fluorolog 3-TSCPC (Horiba Jobin Yvon Inc., France). All chemicals were purchased from Aladdin Industrial Corp. (China) and used without further purification. The solvents were purified using standard methods.

Preparation of 8-formyl-7-hydroxy-4-methylcoumarin: A solution of 8-formyl-7-hydroxy-4-methylcoumarin was prepared by the known method.<sup>68</sup> First, 7-hydroxy-4-methylcoumarin (5.00 g, 0.0284 mol) and hexamine (10.0 g, 0.071 mol) in acetic acid (37 mL) were stirred for 5.5 h at 95°C. Then, hydrochloric acid (75 mL, HCl: H<sub>2</sub>O = 84:100, v/v) was added and further

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Scheme 1 Synthetic route of compound L.

Fig. 1 Fluorescence spectra of **L** (10.0 μM,  $\lambda_{ex}$  = 335 nm) with addition of various metal ions (100.0 μM) in aqueous solution (Tris-HCl, 10.0 mM, pH = 7.2).Fig. 2 Fluorescence responses of **L** (10.0 μM,  $\lambda_{ex}$  = 335 nm) to various metal ions (10.0 μM) (black column) (10.0 equiv.), and upon the subsequent addition of  $\text{Al}^{3+}$  (red column) in aqueous solution (Tris-HCl, 10.0 mM, pH = 7.2).

heated for 45 min. After cooling, the mixture was poured into ice-water (375 mL) and extracted with ethyl acetate (150 mL  $\times$  3). The organic layer was dried over sodium sulfate and the solvent removed. The residue was purified by column chromatography on silica gel using dichloromethane as eluent ( $R_f$  = 0.4) to provide the product as a light yellow solid. Yield 0.9 g (15.5%).  $^1\text{H}$  NMR ( $\text{CDCl}_3$ ,  $\delta$  ppm): 2.45 (s, 3H); 6.22 (s, 1H); 6.92 (d,  $J$  = 9.2 Hz, 1H); 7.74 (d,  $J$  = 8.8 Hz, 1H); 10.63 (s, 1H). MS  $m/z$ : 205[M+H] $^+$ .

Preparation of 8-((s-2-carboxyl-1-hydroxy-2-ylimino)methyl)-7-hydroxy-4-methyl-2H-chromen-2-one (**L**): First, 8-formyl-7-hydroxy-4-methylcoumarin (0.19 g, 0.1 mmol) and **L**-serine (0.11 g, 0.1 mmol) were dissolved in anhydrous ethanol (20 mL). The reaction mixture was refluxed for 8 h under nitrogen and then the mixture was cooled to room temperature. The precipitate was filtered off, washed with cold ethanol two times and dried in vacuum to give the desired product as a yellow solid. Yield 0.23 g (78.8%). m.p. 215.5 – 217.2°C.  $^1\text{H}$  NMR ( $d_6$ -DMSO,  $\delta$  ppm): 2.36 (s, 3H); 2.51 (s, 1H); 3.81 (m, 2H); 3.8 (m, 1H); 4.60 (s, 1H); 6.04 (s, 1H); 6.59 (d,  $J$  = 9.2 Hz, 1H); 7.63 (d,  $J$  = 9.2 Hz, 1H); 8.92 (s, 1H); 14.67 (s, 1H).  $^{13}\text{C}$  NMR ( $d_6$ -DMSO,  $\delta$  ppm): 18.96, 62.75, 67.15, 104.37, 107.06, 108.09, 119.14, 131.55, 155.06, 156.18, 160.04, 161.19, 170.61, 175.34. MS  $m/z$ : 292.2[M-H] $^+$ . Found, %: C, 58.02; H, 4.57; N, 4.79. Calculated for  $\text{C}_{14}\text{H}_{13}\text{NO}_6$ : C, 57.73; H, 4.50; N, 4.81.

## Results and Discussion

In order to investigate the effect of various metal ions on the

fluorescence spectra of **L**, the ions  $\text{Li}^+$ ,  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Mg}^{2+}$ ,  $\text{Ca}^{2+}$ ,  $\text{Ba}^{2+}$ ,  $\text{Cr}^{3+}$ ,  $\text{Fe}^{3+}$ ,  $\text{Al}^{3+}$ ,  $\text{Ni}^{2+}$ ,  $\text{Cu}^{2+}$ ,  $\text{Zn}^{2+}$ ,  $\text{Ag}^+$ ,  $\text{Pb}^{2+}$  and  $\text{Hg}^{2+}$  (as their nitrate salts) were used to evaluate the metal ion binding properties of **L** in aqueous solution (Tris-HCl, 10.0 mM, pH = 7.2). Figure 1 shows the changes in the fluorescence spectra of **L** upon addition of various metal ions. As shown in Fig. 1, compound **L** had a large effect only with  $\text{Al}^{3+}$  and  $\text{Zn}^{2+}$  among the metal ions examined. In the presence of  $\text{Al}^{3+}$  and  $\text{Zn}^{2+}$ , **L** showed fluorescence enhancement so strong and a dramatic color change from colorless to light blue which could easily be identified by the naked eye under UV lamp during the detection process. Other metal ions gave no distinct response to **L** in the fluorescence spectra. This obvious feature reveals that compound **L** has high selectivity for  $\text{Al}^{3+}$  and  $\text{Zn}^{2+}$ .

To further investigate the interference of other metal ions on the detection of  $\text{Al}^{3+}$ , competition experiments were performed in which various metal ions (10.0 μM) were added to a solution of **L** in the presence of  $\text{Al}^{3+}$ . The total concentration of mixture ions was 100 times that of **L**; ions  $\text{Li}^+$ ,  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Mg}^{2+}$ ,  $\text{Ca}^{2+}$ ,  $\text{Ba}^{2+}$ ,  $\text{Cr}^{3+}$ ,  $\text{Fe}^{3+}$ ,  $\text{Al}^{3+}$ ,  $\text{Ni}^{2+}$ ,  $\text{Cu}^{2+}$ ,  $\text{Zn}^{2+}$ ,  $\text{Ag}^+$ ,  $\text{Pb}^{2+}$  and  $\text{Hg}^{2+}$  (as their nitrate salts). As shown in Fig. 2, the addition of other metal ions, even a mixture of interference ions, resulted in hardly any change of the fluorescence intensity of **L** in the presence of  $\text{Al}^{3+}$ . Nevertheless, the fluorescence intensity of **L** in the presence of  $\text{Zn}^{2+}$  was quenched dramatically with the addition of the mixture of competitive anions. The result suggested that **L** could be an effective sensor for the detection of  $\text{Al}^{3+}$  rather than  $\text{Zn}^{2+}$  in aqueous solution.

As shown in Fig. 3, the free ligand **L** (10.0 μM) alone

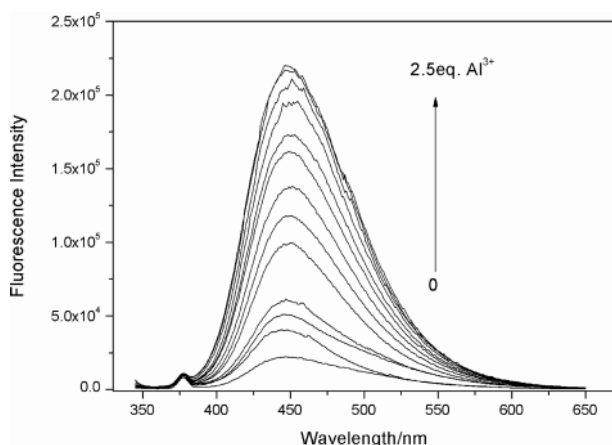


Fig. 3 Fluorescence spectra of **L** (10.0 μM,  $\lambda_{\text{ex}} = 335$  nm) upon the titration of  $\text{Al}^{3+}$  (0–2.5 equivalent) in aqueous solution (Tris-HCl, 10.0 mM, pH = 7.2).

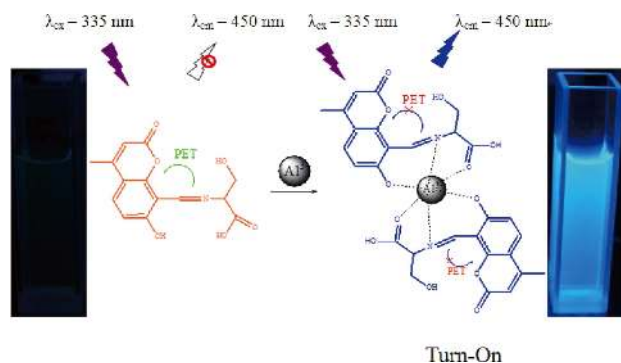


Fig. 4 The plausible binding mode of **L** with  $\text{Al}^{3+}$ , and fluorescence mechanism of PET processes.

displayed weak fluorescence intensity at 450 nm when it was excited at 335 nm in aqueous solution (Tris-HCl, 10.0 mM, pH = 7.2). Upon addition of  $\text{Al}^{3+}$  into the aqueous solution of **L** (10.0 μM), the fluorescence intensity clearly increased. When the concentration of  $\text{Al}^{3+}$  reached 2.0 equiv., the fluorescence intensity reached the maximum value (about 21-fold enhancement). This phenomenon is understood as a mechanism of PET (photo-induced electron-transfer).<sup>64,65</sup> The lone pair electrons from the Schiff-base nitrogen atom and oxygen atom of L-serine contributed to the PET processes, which quenched the fluorescence emission of **L**. Then the quenched fluorescence could relapse dramatically upon chelating metal ion by inhibiting the PET processes and producing a highly efficient chelation-enhanced fluorescence effect (Fig. 4). As a result, the fluorescence intensity of **L** ( $\Phi_{\text{f}} = 0.87\%$ ) increased remarkably at 450 nm ( $\Phi_{\text{f}} = 21.98\%$ ) upon the addition of  $\text{Al}^{3+}$  ions. Thus we can conclude that **L** may serve as a “turn-on” sensor for  $\text{Al}^{3+}$ .

In order to further investigate the sensitivity of **L** to  $\text{Al}^{3+}$ , the detection limits of **L** for  $\text{Al}^{3+}$  were tested upon excitation at 335 nm in aqueous solution.<sup>66</sup> As shown in Fig. 5, the plots of  $F/F_0$  vs.  $\text{Al}^{3+}$  concentration (0–12.0 μM) show a good linear Stern-Volmer relationship:  $F/F_0 = 5.73[\text{Al}^{3+}] + 1.84$  ( $R_2 = 0.9903$ ), and the relative standard deviation for five repeated measurements of 0 μM of  $\text{Al}^{3+}$  was 1.27%. The detection limit (DL) for  $\text{Al}^{3+}$  was  $6.65 \times 10^{-8}$  mol/L (signal to noise ratio of

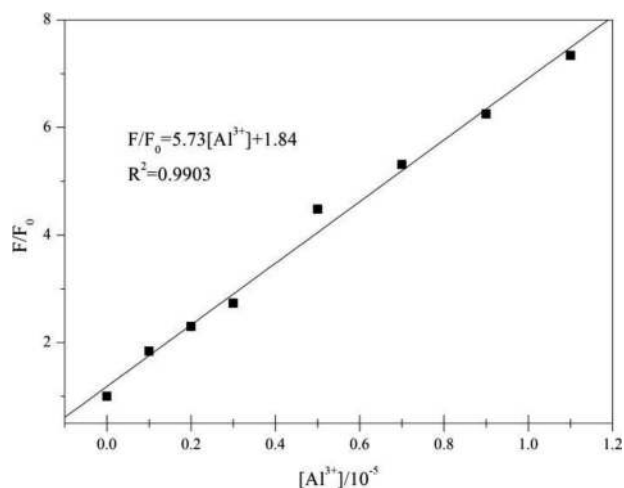


Fig. 5 The Stern-Volmer relationship plot of  $F/F_0$  vs.  $[\text{Al}^{3+}]$  in aqueous solution (Tris-HCl, 10.0 mM, pH = 7.2), DL =  $6.65 \times 10^{-8}$  mol/L;  $[\text{L}] = 10.0$  μM;  $\lambda_{\text{ex}} = 335$  nm.

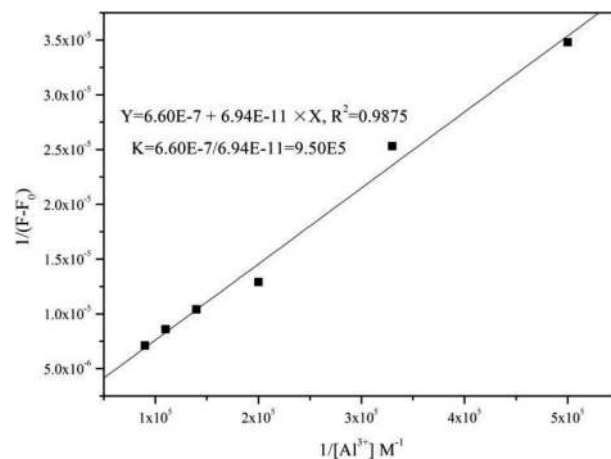


Fig. 6 Benesi-Hildebrand plot ( $\lambda_{\text{ex}} = 335$  nm) of **L** and  $\text{Al}^{3+}$  in aqueous solution (Tris-HCl, 10.0 mM, pH = 7.2).

3:1) when the concentration of **L** was 10.0 μM, which illustrated that the detection of **L** toward  $\text{Al}^{3+}$  was highly sensitive.

As shown in Fig. 6, the association constant  $K$  of the complex **L**- $\text{Al}^{3+}$  was then calculated to be  $9.50 \times 10^5 \text{ M}^{-1}$  with a linear relationship by the Benesi-Hildebrand method, Eq. (1).<sup>67</sup>

$$\frac{1}{F - F_{\text{min}}} = \frac{1}{K(F_{\text{max}} - F_{\text{min}})[\text{Al}^{3+}]} + \frac{1}{F_{\text{max}} - F_{\text{min}}} \quad (1)$$

To test the stoichiometry of the complexing behavior of **L** with  $\text{Al}^{3+}$  in depth, the molar ratio method for the absorbance was applied. By keeping the total concentration of  $\text{Al}^{3+}$  and **L** at 20.0 μM, and changing the molar ratio of **L** and  $\text{Al}^{3+}$  from 0 to 0.9, the fluorescence intensity of **L** in the absence ( $F_0$ ) and presence ( $F$ ) of  $\text{Al}^{3+}$  ion were determined, respectively. A plot of  $(F - F_0)$  versus  $[\text{L}]/([\text{L}] + [\text{Al}^{3+}])$  shows that the value goes through a maximum at a molar fraction of about 0.7, indicating a 2:1 stoichiometry complex formation exactly (Fig. 7).

Adaptability and also responsiveness were determined using the lifetimes of **L** and  $\text{Al}^{3+}$  by time-resolved fluorescence spectrofluorometer. The fluorescence lifetime was measured at

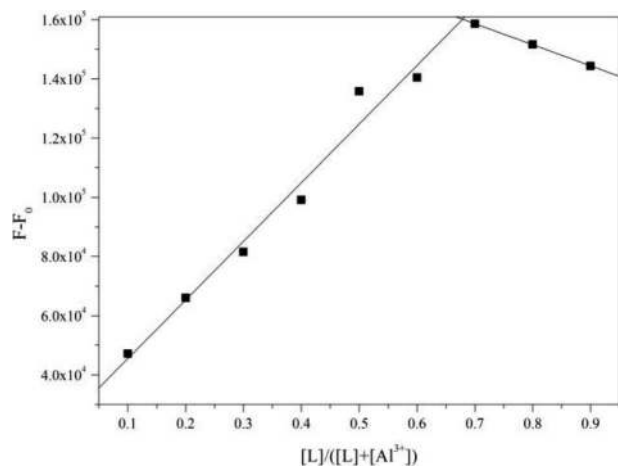


Fig. 7 Job's plot of the complexation between **L** and Al<sup>3+</sup>, total concentration of **L** and Al<sup>3+</sup> is 20.0 μM.

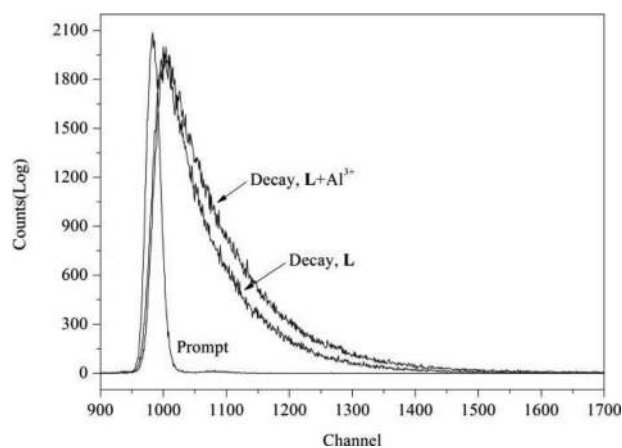


Fig. 8 Fluorescence decay curves of **L** and **L**+Al<sup>3+</sup> in aqueous solution (Tris-HCl, 10.0 mM, pH = 7.2) obtained at λ<sub>ex</sub> = 335 nm.

the excitation 280 nm of NanoLED source. The decays of **L** were found to be monoexponential. The lifetime decays in the absence of Al<sup>3+</sup> and in the presence of Al<sup>3+</sup> are shown in Fig. 8. The average lifetimes of **L** and **L**+Al<sup>3+</sup> were 4.77 ns (XSQ = 1.03) and 4.58 ns (XSQ = 1.13), respectively. The unapparent change of lifetime demonstrates that **L** possesses good responsiveness and adaptability to Al<sup>3+</sup>.

## Conclusions

In conclusion, a water-soluble fluorescent chemosensor **L** for aluminium ion based on coumarin schiff-base conjugate has been designed and synthesized. It showed high sensitivity and selectivity for Al<sup>3+</sup> recognition in comparison to other metal ions in aqueous solution. The sensor **L** exhibited 2:1 coordinates with Al<sup>3+</sup> and high quantum efficiency in aqueous solution. We believe that the fluorescence sensor **L** may be utilized for the detection and analysis of various aluminum-related issues in environmental, biological and medical areas.

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## Supporting Information

Comparison of some chemosensors for Al<sup>3+</sup> ions, and additional figures. These materials are available at <http://www.jsac.or.jp/analsci/>.

## References

1. Y. Zhao, Z. Lin, H. Liao, C. Duan, and Q. Meng, *Inorg. Chem. Commun.*, **2006**, 9, 966.
2. E. Álvarez, M. L. Fernández-Marcos, C. Monterroso, and M. J. Fernández-Sanjurjo, *For. Ecol. Manage.*, **2005**, 211, 227.
3. A. C. Alfrey, *Adv. Clin. Chem.*, **1983**, 23, 69.
4. D. P. Perl and A. R. Brody, *Science*, **1980**, 208, 297.
5. D. P. Perl, D. C. Gajdusek, R. M. Garruto, R. T. Yanagihara, and C. J. Gibbs, *Science*, **1982**, 217, 1053.
6. P. D. Darbre, *J. Inorg. Biochem.*, **2005**, 99, 1912.
7. T. P. Flaten, *Brain Res. Bull.*, **2001**, 55, 187.
8. Z. C. Liao, Z. Y. Yang, Y. Li, B. D. Wang, and Q. X. Zhou, *Dyes Pigm.*, **2013**, 97, 124.
9. X. Sun, Y. W. Wang, and Y. Peng, *Org. Lett.*, **2012**, 14, 3420.
10. J. Lee, H. Kim, S. Kim, J. Y. Noh, E. J. Song, C. Kim, and J. Kim, *Dyes Pigm.*, **2013**, 96, 590.
11. G. Sivaraman, T. Anand, and D. Chellappa, *Anal. Methods*, **2014**, 6, 2343.
12. T. Anand, G. Sivaraman, and D. Chellappa, *J. Photochem. Photobiol., A*, **2014**, 281, 47.
13. T. Anand, G. Sivaraman, A. Mahesh, and D. Chellappa, *Anal. Chim. Acta*, **2015**, 853, 596.
14. G. Sivaraman, T. Anand, and D. Chellappa, *RSC Adv.*, **2013**, 3, 17029.
15. G. Sivaraman, V. Sathiyaraja, and D. Chellappa, *J. Lumin.*, **2014**, 145, 480.
16. C. Arivazhagan, R. Borthakur, and S. Ghosh, *Organometallics*, **2015**, 34, 1147.
17. G. Sivaraman, T. Anand, and D. Chellappa, *Analyst*, **2012**, 137, 5881.
18. G. Sivaraman, T. Anand, and D. Chellappa, *Anal. Methods*, **2014**, 6, 2343.
19. R. N. Goyal, V. K. Gupta, and S. Chatterjee, *Electrochim. Acta*, **2008**, 53, 5354.
20. G. Sivaraman and D. Chellappa, *J. Mater. Chem. B*, **2013**, 1, 5768.
21. G. Sivaraman, T. Anand, and D. Chellappa, *ChemPlusChem*, **2014**, 79, 1761.
22. R. Jain, V. K. Gupta, N. Jadon, and K. Radhapyari, *Anal. Biochem.*, **2010**, 407, 79.
23. R. N. Goyal, V. K. Gupta, and N. Bachheti, *Anal. Chim. Acta*, **2007**, 597, 82.
24. V. K. Gupta, R. Jain, K. Radhapyari, N. Jadon, and S. Agarwal, *Anal. Biochem.*, **2011**, 408, 179.
25. V. K. Gupta, A. Nayak, S. Agarwal, and B. Singhal, *Comb. Chem. High Throughput Screening*, **2011**, 14, 284.
26. K. Z. Kamali, A. Pandikumar, G. Sivaraman, H. N. Lim, S.

- P. Wren, T. Sun, and N. M. Huang, *RSC Adv.*, **2015**, *5*, 17809.
27. T. Anand, G. Sivaraman, and D. Chellappa, *J. Photochem. Photobiol., A*, **2014**, *281*, 47.
28. R. N. Goyal, V. K. Gupta, and S. Chatterjee, *Talanta*, **2008**, *76*, 662.
29. R. N. Goyal, V. K. Gupta, N. Bachheti, and R. A. Sharma, *Electroanalysis*, **2008**, *20*, 757.
30. G. Sivaraman, B. Vidya, and D. Chellappa, *RSC Adv.*, **2014**, *4*, 30828.
31. V. K. Gupta, S. Chandra, and R. Mangla, *Electrochim. Acta*, **2002**, *47*, 1579.
32. V. K. Gupta, A. K. Singh, S. Mehtab, and B. Gupta, *Anal. Chim. Acta*, **2006**, *566*, 5.
33. V. K. Gupta, L. P. Singh, R. Singh, N. Upadhyay, S. P. Kaur, and B. Sethif, *J. Mol. Liq.*, **2012**, *174*, 11.
34. V. K. Gupta, A. K. Jain, G. Maheshwari, H. Lang, and Z. Ishtaiwi, *Sens. Actuators, B*, **2006**, *117*, 99.
35. R. Prasad, V. K. Gupta, and A. Kumar, *Anal. Chim. Acta*, **2004**, *508*, 61.
36. V. K. Gupta, A. K. Singh, M. A. Khayat, and B. Gupta, *Anal. Chim. Acta*, **2007**, *590*, 81.
37. V. K. Gupta, B. Sethi, R. A. Sharma, S. Agarwal, and A. Bharti, *J. Mol. Liq.*, **2013**, *177*, 114.
38. V. K. Gupta, A. K. Jain, and P. Kumar, *Sens. Actuators, B*, **2006**, *120*, 259.
39. V. K. Gupta, S. Jain, and S. Chandra, *Anal. Chim. Acta*, **2003**, *486*, 199.
40. T. Anand, G. Sivaraman, P. Anandh, D. Chellappa, and S. Govindarajan, *Tetrahedron Lett.*, **2014**, *55*, 671.
41. V. K. Gupta, A. K. Jain, P. Kumar, S. Agarwal, and G. Maheshwari, *Sens. Actuators, B*, **2006**, *113*, 182.
42. V. K. Gupta, M. R. Ganjali, P. Norouzi, H. Khani, A. Nayak, and S. Agarwal, *Crit. Rev. Anal. Chem.*, **2011**, *41*, 282.
43. S. K. Srivastava, V. K. Gupta, and S. Jain, *Anal. Chem.*, **1996**, *68*, 1272.
44. A. K. Jain, V. K. Gupta, L. P. Singh, and J. R. Raisonni, *Electrochim. Acta*, **2006**, *51*, 2547.
45. V. K. Gupta, R. Mangla, U. Khurana, and P. Kumar, *Electroanalysis*, **1999**, *11*, 573.
46. V. K. Gupta, S. Jain, and U. Khurana, *Electroanalysis*, **1997**, *9*, 478.
47. A. K. Jain, V. K. Gupta, L. P. Singh, and U. Khurana, *Analyst*, **1997**, *122*, 583.
48. V. K. Gupta, R. Prasad, P. Kumar, and R. Mangla, *Anal. Chim. Acta*, **2000**, *420*, 19.
49. V. K. Gupta, S. Chandra, and H. Lang, *Talanta*, **2005**, *66*, 575.
50. T. Anand, G. Sivaraman, P. Anandh, D. Chellappa, and S. Govindarajan, *Tetrahedron Lett.*, **2014**, *55*, 671.
51. T. Anand, G. Sivaraman, M. Iniya, A. Siva, and D. Chellappa, *Anal. Chim. Acta*, **2015**, *876*, 1.
52. V. K. Gupta, R. Prasad, and A. Kumar, *Talanta*, **2003**, *60*, 149.
53. C.-J. Liu, Z.-Y. Yang, L. Fan, X.-L. Jin, J.-M. An, X.-Y. Cheng, and B.-D. Wang, *J. Lumin.*, **2015**, *158*, 172.
54. P.-J. Hung, J.-L. Chir, W. Ting, and A.-T. Wu, *J. Lumin.*, **2015**, *158*, 371.
55. O. Alici and S. Erdemir, *Sens. Actuators, B*, **2015**, *208*, 159.
56. X.-F. Bao, Q.-S. Cao, Y.-Z. Xu, Y.-X. Gao, Y. Xu, X.-M. Nie, B.-J. Zhou, T. Pang, and J. Zhu, *Bioorg. Med. Chem.*, **2015**, *23*, 694.
57. K. Velmurugan, S. Mathankumar, S. Santoshkumar, S. Amudha, and R. Nandhakumar, *Spectrochim. Acta, Part A*, **2015**, *139*, 119.
58. Y.-W. Wang, M.-X. Yu, Y.-H. Yu, Z.-P. Bai, Z. Shen, F.-Y. Li, and X.-Z. You, *Tetrahedron Lett.*, **2009**, *50*, 6169.
59. V. K. Gupta, S. K. Shoor, L. K. Kumawat, and A. K. Jain, *Sens. Actuators, B*, **2015**, *209*, 15.
60. W.-H. Ding, D. Wang, X.-J. Zheng, W.-J. Ding, J.-Q. Zheng, W.-H. Mu, W. Cao, and L.-P. Jin, *Sens. Actuators, B*, **2015**, *209*, 359.
61. X.-H. Jiang, B.-D. Wang, Z.-Y. Yang, Y.-C. Liu, T.-R. Li, and Z.-C. Liu, *Inorg. Chem. Commun.*, **2011**, *14*, 1224.
62. Y. K. Jang, U. C. Nam, H. L. Kwon, I. H. Hwang, and C. Kim, *Dyes Pigm.*, **2013**, *99*, 6.
63. Y.-X. Song, Z. Chen, and H.-Q. Li, *Curr. Org. Chem.*, **2012**, *16*, 2690.
64. J. S. Kim, K. H. Noh, S. H. Lee, S. K. Kim, and J. Yoon, *J. Org. Chem.*, **2003**, *68*, 597.
65. J.-M. An, Z.-Y. Yang, M.-H. Yan, and T.-R. Li, *J. Lumin.*, **2013**, *139*, 79.
66. Y. Wang, L.-L. Shi, H.-H. Sun, Z.-B. Shang, J.-B. Chao, and W.-J. Jin, *J. Lumin.*, **2013**, *139*, 16.
67. H. A. Benesi and J. H. Hildebrand, *J. Am. Chem. Soc.*, **1949**, *71*, 2703.
68. X.-G. Zhou and M.-S. Peng, *Asian J. Chem.*, **2013**, *25*, 4509.