A highly selective fluorescent sensor for Al^{3+} based on an aza-18-crown-6 derivative

Song Jingjing[a], **Hu Yang**[b], **Zhao Fang**[a] **and Hu Shengli**[a]*

[a]Hubei Collaborative Innovation Center for Rare Metal Chemistry, Department of Chemistry and Chemical Engineering, Hubei Normal University, Huangshi 435002, P.R. China

[b]Department of Chemistry and Chemical Engineering, The School of Art and Science of Hubei Normal University, Huangshi 435002, P.R. China

A new fluorescent sensor derived from 2,5-diphenyl-furan and aza-18-crown-6 has been synthesised. It can selectively bind Al^{3+} in aqeuous ethanol solution with fluorescence enhancement.

Keywords: sensor, fluorescence enhancement, aza-18-crown-6 derivative, Al^{3+}

Fluorescent chemosensors are widely used as powerful tools to detect neutral and ionic species owing to their high sensitivity, selectivity, versatility, and relatively simple handling.[1-3]Aluminium is the most abundant metal element in the earth's crust.[4,5] Its compounds are widely used in water treatment, in food additives, and in medicines.[6,7] Aluminium is not a biologically essential element, studies show that the unregulated amounts of aluminium in human body may lead to the malfunction of the central nervous system, Parkinson's disease, and Alzheimer's disease.[8,9] Therefore, it is of great necessity to develop powerful recognition and detection systems for monitoring aluminium cations in daily life. However, the detection of Al^{3+} has always been problematic due to the lack of spectroscopic characteristics and poor coordination ability compared to transition metals.[10] For this reason, the development of Al^{3+} probes is comparatively more difficult than those for other metal ions. So far, very few Al^{3+} selective fluorescent sensors have been reported.[11-16] Therefore, the development of new, efficient Al^{3+} fluorescent chemosensors is still a challenge.

We now report a novel and selective fluorescent chemosensor for Al^{3+}.We designed a PET[17] sensor **1**, in which an aza-18-crown-6 moiety is linked to a 2, 5-diphenyl-furan fluorophore and have shown that **1** possesses a highly selective response of fluorescence enhancement toward Al^{3+} in aqueous ethanol solution.

Results and discussion

The synthesis of chemosensor **1** is shown in Scheme 1. The IR, NMR and MS spectra and elemental analysis for the product are in good agreement with the proposed formulation of **1**.

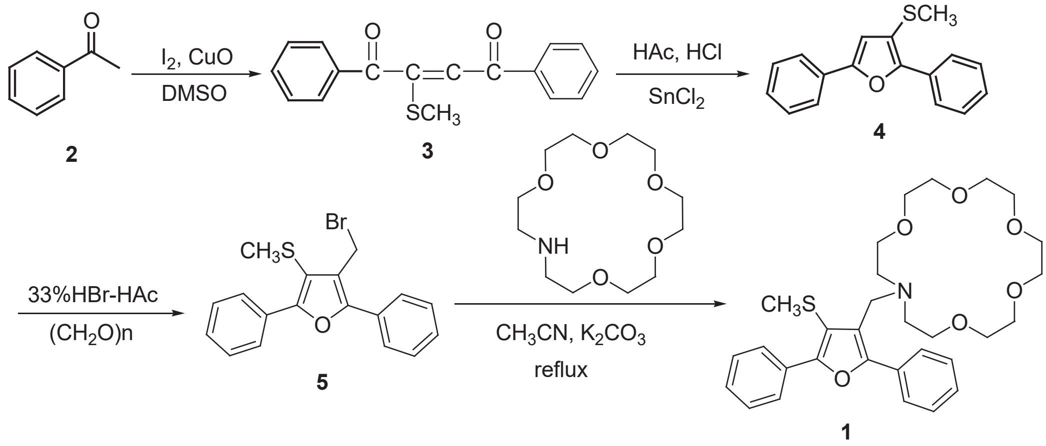
The binding properties of molecule **1** were investigated by UV-Vis absorption spectra and fluorescence measurement. Changes of the UV-Vis absorption spectra and fluorescence properties of a solution of **1** in EtOH/water, (1×10^{-5} M, 95:5, v/v solution), caused by various metal ions (K^+, Na^+, Mg^{2+}, Hg^{2+}, Cd^{2+}, Fe^{3+}, Al^{3+}, Zn^{2+}, Co^{2+}, Ni^{2+}, Cu^{2+}, Pb^{2+}, Cr^{3+}, and Mn^{2+}) (as their Cl^- or NO_3^- salts) are shown in Figs 1 and 2, respectively. The results show that Al^{3+} produced significant enhancement in the absorption spectra and fluorescent emission of **1**, the other tested metals only show relatively insignificant changes. So it can be concluded that **1** has higher selectivity for recognition of Al^{3+}.

To determine the stoichiometry of compound **1** and Al^{3+} ion in the complex, Job's method[18] was employed by using the absorption changes at 304 nm as a function of molar fraction of Al^{3+}. A minimum emission was observed at a 0.33 ratio (Fig. 3), indicating that the Al^{3+} ion forms a 1:2 complex with the sensing compound **1**.

The sensitivity of the fluorescence emission response of **1** towards Al^{3+} was also examined under the same conditions with various Al^{3+} concentrations (Fig. 4). The fluorescence intensity (λ_{em} =378 nm) of **1** was increased continually upon addition of Al^{3+} with no significant in the position of the emission maxima. Upon gradual addition of up to 0.5 equiv of Al^{3+}, the solution showed an approximate 2-fold enhancement in the fluorescence intensity.

Based on the above fluorescence titration of **1** with Al^{3+}, the association constant K_{ass} was calculated to be 1.56×10^5 M^{-2} (error limits ≤10%) by a Benesi–Hildebrand plot[19] (Fig. 5). The limit of detection of **1** is found to be 4.11×10^{-7} M, which is calculated using $3\delta/S$,[20] where δ was the standard deviation of the blank signal, and S was the slope of the linear calibration plot.

To further gauge the selectivity for Al^{3+} ion compared to other metal ions, competition experiments of Al^{3+} ion mixed with other metal ions were carried out using fluorescence spectra



Scheme 1 The synthesis of sensor **1**.

---

* Correspondent. E-mail: hushengli168@126.com

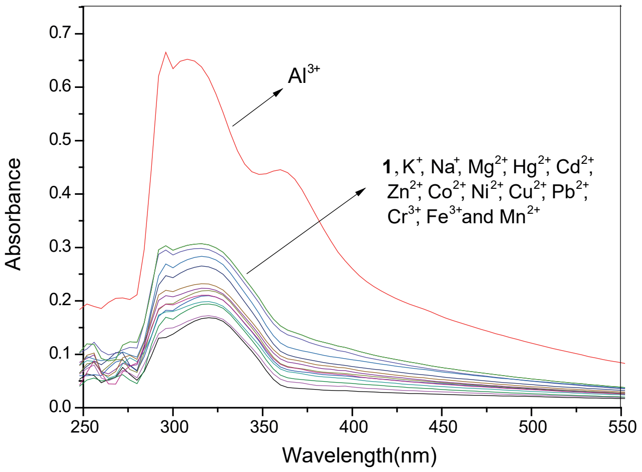


Fig. 1 Absorption spectra of **1** (1.0×10^{-5} M) in EtOH/water (95:5, v/v) containing HEPES buffer (10mM, pH= 7.0) solution in the presence of various metal ions (1×10^{-5}M).

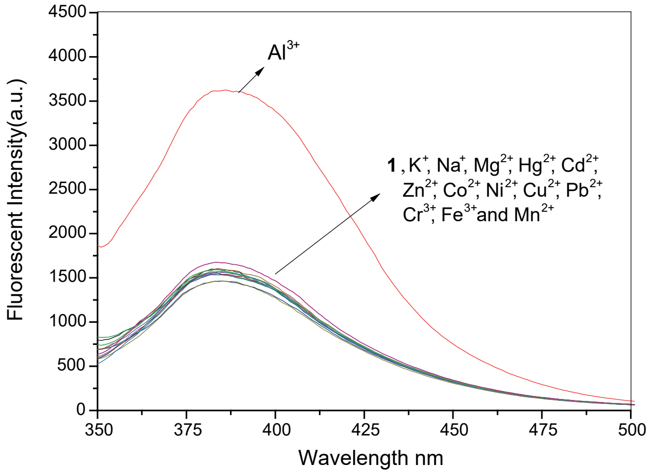


Fig. 2 Fluorescence emission changes of **1** (1×10^{-5} M) in EtOH/water (95:5, v/v) containing HEPES buffer (10mM, pH= 7.0) solution in the presence of 1×10^{-5} M of various metal ions (excitation at 333 nm).

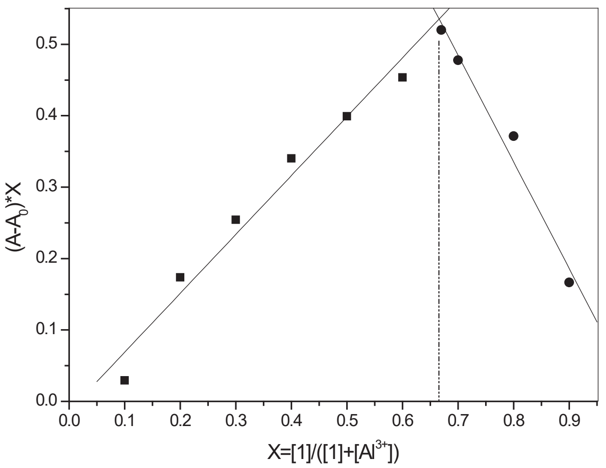


Fig. 3 Job's plot of a 2:1 complex of **1** (1×10^{-5} M) with Al^{3+}. Total [**1**] + [Al^{3+}] = 1×10^{-5} M.

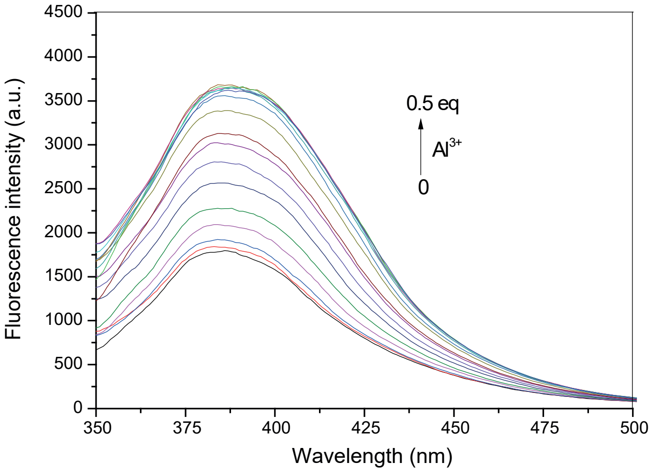


Fig. 4 Fluorescence emission spectra (excitation at 333 nm) of **1** (1×10^{-5}M) EtOH/water (95:5, v/v) containing HEPES buffer(10mM, pH=7.0) solution in the presence of Al^{3+}.

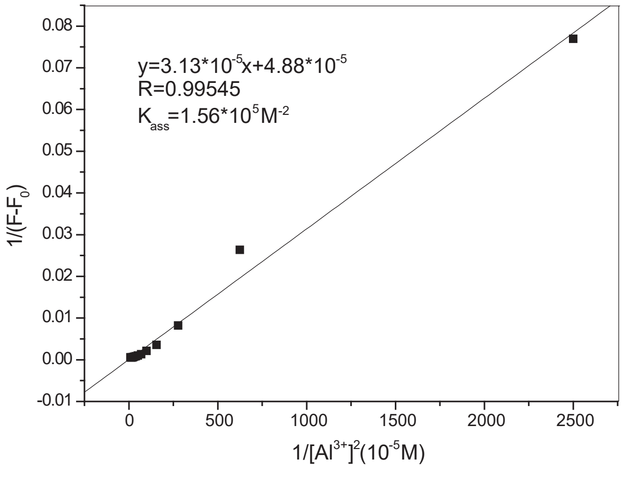


Fig. 5 Association constant (Kass) determined with fluorescence data using the Benesi–Hildebrand equation.

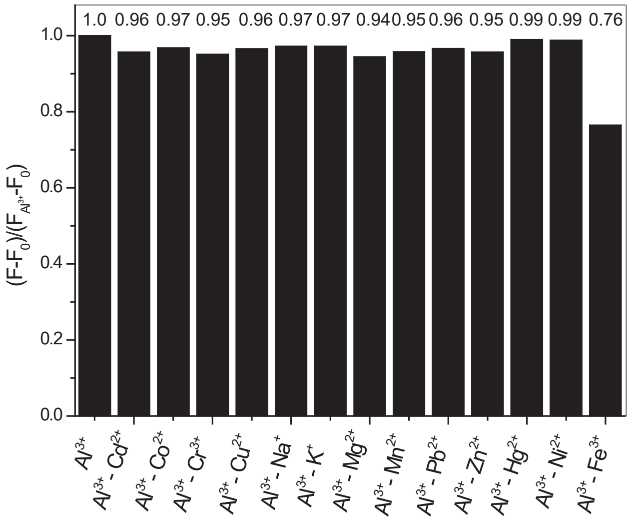
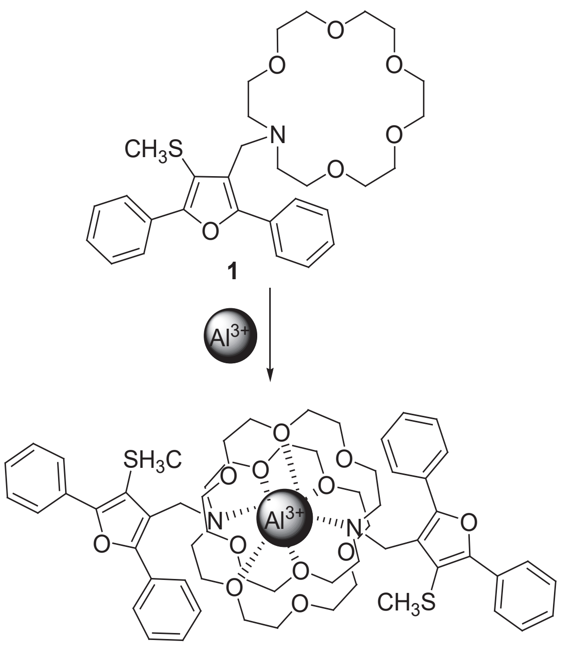


Fig. 6 Competitive experiments in the 1+Al^{3+}system with interfering metal ions. [**1**] = 1×10^{-5} M, [Al^{3+}] = 1×10^{-5} M, and [M_{n+}] = 1×10^{-5} M. λ_{ex} = 333 nm.



Scheme 2 Proposed 2:1 binding model of **1** with Al^{3+}.

and the results are shown in Fig. 6. The fluorescence intensity of **1** (1×10^{-5} M) in the presence of 1 equiv of the Al^{3+} ion was almost unaffected by the addition of 1 equiv. of competing metal ions (Cd^{2+}, Co^{2+}, Cr^{3+}, Cu^{2+}, Na^{+}, K^{+}, Mg^{2+}, Mn^{2+}, Pb^{2+}, Zn^{2+}, Hg^{2+}, Ni^{2+}, and Fe^{3+}). These results suggest that molecule **1** could be used as a selective fluorescent chemosensor for Al^{3+}.

Based on above spectroscopy studies and Job's plot, a sandwich-type complex model seems to be reasonable for the binding site of **1** with Al^{3+} (Scheme 2). Free **1** shows a relatively weak fluorescence emission at 378 nm because of photo-induced electron transfer (PET) from lone pair electrons on nitrogen atoms in aza-18-crown-6 moieties quenching emission of 2,5-diphenylfuran. When Al^{3+} was added into a solution of **1**, interruption of the PET process occurred and a strong emission was observed with a peak centred at 378 nm.

In conclusion, a new fluorescent molecule **1** derived from 2,5-diphenylfuran and aza-18-crown-6 has been designed and synthesised. Its binding properties, investigated by fluorescence spectroscopy, show that it can selectively bind Al^{3+} in aqueous ethanol solution.

Experimental

All reagents, obtained from commercial sources, were of AR grade. Melting points were determined with an XT4A micromelting point apparatus and were uncorrected. ^{1}H NMR spectra were recorded on a Bruker 300 spectrometer with TMS as internal reference and $CDCl_3$ as solvent. IR were recorded on a PerkinElmer PE–983 IR spectrometer as KBr pellets with absorption in cm^{-1}. MS were obtained with a Finnigan Trace MS instrument using the EI method. Elemental analyses were performed with a Vario EL-III instrument. Absorption spectra were determined on UV-2501 PC spectrophotometer and fluorescence spectra on a Hitachi F-4500 instrument.

Synthesis

3-(Methylthio)-2,5-diphenylfuran (**4**)[21] and 3-(methylthio)-4-bromomethyl-2,5-diphenyl-furan(**5**)[22] were prepared according to the reported procedures.

*2-((4-((Benzo[*d*]thiazol-2-ylthio)methyl)-2,5-diphenylfuran-3-yl)methylthio)benzo[*d*]-thiazole*(**1**): Compound **5** (0.358 g, 1.0 mmol) and aza-18-crown-6 (0.263 g, 1.0 mmol) were dissolved in CH_3CN (20 mL) and K_2CO_3 (0.55 g, 4.0 mol) was added. The resultant mixture was refluxed for 3 h, cooled to room temperature, diluted with 2N HCl (50 mL) and extracted with EtOAc (3 × 20 mL). The extracts were washed with brine (2×20 mL) and dried over anhydrous $MgSO_4$. After filtration and rotary evaporation the residue was purified by flash chromatography with petroleum as elute to give compound **1** (0.42g, 78%) as an oily solid. IR (KBr, cm^{-1}): 3439, 2909,1639, 1448, 1354, 1255, 1107, 950, 737. ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.25–8.23(m, 2H), 8.01–7.99(m, 2H),7.46–7.28 (m, 6H), 3.80(s, 2H);3.65–3.60 (m, 19H), 2.89–2.84(m, 5H), 2.27(s, 3H);^{13}C NMR (75 MHz, $CDCl_3$): δ 151.9, 150.0, 130.6, 130.3, 128.3, 128.2,127.6, 127.4, 126.4, 125.5, 122.8, 117.2, 70.5, 70.4, 70.3, 70.0, 69.5, 53.2, 48.6, 19.1. ESI-MS: *m/z* 542[M+1]$^+$. Anal. calcd for $C_{30}H_{39}NO_6S$ (541.25): C, 66.52; H, 7.26; N, 2.59; found: C, 66.45; H, 7.23; N, 2.54%.

Binding studies

A stock solution of compound **1** was prepared by dissolution in EtOH/water (95:5, v/v) containing HEPES buffer (10mM, pH=7.0; 1.0×10^{-5}M). Solutions of metal ions were prepared from $Pb(NO_3)_2$, $Al(NO_3)_3$ and the chlorides of K^+, Na^+, Mg^{2+}, Hg^{2+}, Cd^{2+}, Fe^{3+}, Cu^{2+}, Zn^{2+}, Co^{2+}, Ni^{2+}, Cr^{3+}, and Mn^{2+}, respectively, and were dissolved in EtOH (3.0×10^{-3} M). Fluorescence titration was performed by placing a solution of compound **1** (3 mL) in a quartz cell of 1 cm optical path length, and adding different stock solutions of cations into the quartz cell portionwise using a microsyringe each time.

Electronic Supplementary information

^{1}H NMR (300 MHz, $CDCl_3$) of and the ^{13}C NMR ($CDCl_3$) of **1** is available through stl.publisher.ingentaconnect.com/content/stl/jcr/supp-data

We thank the Science Technology Foundation for Creative Research Group of HBDE(2013) and Training Programs of Innovation and Entrepreneurship for Undergraduates of China (201313256002) for financial support.

Received 1 August 2015;accepted 15 September 2015
Paper 1503519 doi: 10.3184/174751915X14425101743684

References

1 A. P. de Silva, H. Q. N. Gunaratne, T. Gunnlaugsson, A. J. M. Huxley, C. P. McCoy, J. T. Rademacher and T. E. Rice, *Chem. Rev.*, 1997, **97**, 1515.
2 L. Tang, Y. Li and J. Qian, *J. Chem. Res.*, 2010, 216.
3 H. Wang, Y. Feng and S. Meng, *J. Chem. Res.*, 2012, 587.
4 Z. Krejpcio and R. W. P. Wojciak, *Pol. J. Environ. Stud.*, 2002, **11**, 251.
5 J. Barcelo and C. Poschenrieder, *Environ. Exp. Bot.*, 2002, **48**, 75.
6 M. G. Sont, S. M. White, W. G. Flamm and G. A. Burdock, *Regul. Toxicol. Pharmacol.*, 2001, **33**, 66.
7 N. W. Bavlor, W. Egan and P. Richman, *Vaccine*, 2002, **20**, S18.
8 D. P. Perl, D. C. Gajdusek, R. M. Garruto, R. T. Yanagihara and C. J. Gibbs, *Science*, 1982, **217**, 1053.
9 D. P. Perl and A. R. Brody, *Science*, 1980, **208**, 297.
10 K. Soroka, R. S. Vithanage, D. A. Phillips, B. Walker and P. K. Dasgupta, *Anal. Chem.*, 1987, **59**, 629.
11 Y. Lu, S. S. Huang, Y. Y. Liu, S. He, L. C. Zhao and X. S. Zeng, *Org. Lett.*, 2011, **13**, 5274.
12 Y. K. Jang, U. C. Nam, H. L. Kwon, I. H. Hwang and C. Kim, *Dyes Pigments*, 2013, **99**, 6.
13 A. Sahana, A. Banerjee, S. Lohar, B. Sarkar and S. K. Mukhopadhyay, *Inorg. Chem.*, 2013, **52**, 3627.
14 S.H. Kim, H.S. Choi, J. Kim, S.J. Lee, D.T. Quang and J.S. Kim, *Org. Lett.*, 2010, **12**, 560.
15 M.L. Ramos, L.L.G. Justino, A.I.N. Salvador, A.R.E. de Sousa, P.E. Abreu, S.M. Fonseca and H. D. Burrows, *Dalton Trans.*, 2012, **41**, 12478.
16 J.Y. Jung, S.J. Han, J. Chun, C. Lee and J. Yoon, *Dyes Pigments*, 2012, **94**, 423.
17 B. Ramachandram, G. Saroja, N. B. Sankaran and A. Samanta, *J. Phys. Chem. B*, 2000, **104**, 11824.
18 P. Job, *Ann. Chim.*,1928, **9**, 113.
19 H. A. Benesi and J. H. Hildebrand, *J. Am. Chem. Soc.*, 1949, **71**, 2703.
20 B. P. Joshi, J. Park, W. I. Lee and K.H. Lee, *Talanta*, 2009, **78**, 903.
21 S.-L. Hu, C.-H. Xu, S.-S. Zhang, W.-B. Sun and Q. Gao, *J. Chem. Res.*, 2013, **36**, 210.
22 S. Hu, G. Wu, C. Xu, J. Dong and Q. Gao, *J. Photochem. Photobiol. A*, 2013, **270**, 37.