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We designed and synthesised a novel copillar[5]arene PF5, which can be self-inclusion produce a strong blue fluorescence. Pillar[5]arene-based chemosensor PF5 could be a sequential fluorescence sensor for ferric ions ($\text{Fe}^{3+}$) following by fluoride ions with high sensitivity and selectivity in aqueous solution. When Fe$^{3+}$ was added to the solution of sensor PF5, the blue fluorescence emission will be quenched. While after the addition of F$^-$, the blue fluorescence emission of the PF5–Fe$^{3+}$ system will be back to the original level. The PF5 has specific selectivity to Fe$^{3+}$ and common cations (Hg$^{2+}$, Ag$^+$, Ca$^{2+}$, Cu$^{2+}$, Zn$^{2+}$, Cd$^{2+}$, Ni$^{2+}$, Pb$^{2+}$, Co$^{2+}$, Cr$^{3+}$, Mg$^{2+}$, Fe$^{2+}$, Al$^{3+}$) couldn’t interfere in the detection process. In addition, PF5–Fe$^{3+}$ has specific selectivity to F$^-$ and common anions (Cl$^-$, Br$^-$, I$^-$, AcO$^-$, NO$_2^-$, NO$_3^-$, HSO$_4^-$, ClO$_4^-$, SCN$^-$, CN$^-$) also have no obvious interfere in the detection process. The detection limit of the sensor PF5 for Fe$^{3+}$ is $9.0 \times 10^{-7}$ mol/L, and the detection limit of F$^-$ is 2.59$ \times 10^{-8}$ mol/L. Moreover, test strips based on the sensor were fabricated, which could be very good sequential test kits for ferric ions ($\text{Fe}^{3+}$) and fluoride ions. Moreover, the sensor PF5 could also sequential detect Fe$^{3+}$ in tap water and F$^-$ in toothpastes.

Introduction

Among different kinds biologically important metals and nonmetal, iron and fluorine are both the most plentiful necessary elements found in the human body and are critical to maintain significant physiological processes. Given the physiological implications of ferric and fluoride, their detection are very important. The detection of Fe(III) at minute quantity is very meaningful, because iron, with its chemical diversity, is critical for the appropriate functioning of most organisms in the whole spectrum of the biological system.\(^1\) In the human body, iron is one of the most necessary trace elements; poverty of ferric ion (Fe(III)) in the body causes anemia, liver damage, hemochromatosis, Parkinson’s disease, and cancer.\(^2\) Ferric ions also play critical roles in the metabolism and growth of living cells and catalytic many physiological processes.\(^3\) A sanitary security limit for the Fe$^{3+}$ ion was restricted to 2 mg L$^{-1}$ by the World Health Organization. Therefore, it is important to exploit simple, rapid, and efficient methods for the prosecutions of Fe$^{3+}$ at a trace level in the circumstance, biological and food specimen.\(^4\) Up to now, several fluorescent receptors for iron and fluoride ions have been reported, however, the realization of both Fe$^{3+}$ and F$^-$ for fluorescence measurements is still a challenge. Fluoride ions are one of the most attractive targets because of their significant meaning for environmental and health concerns. The fluoride ion has unique chemical properties and widespread the existence of in pharmacy and toothpaste and used to prevent tooth decay, enamel demineralization while wearing orthotic devices, and treatment for osteoporosis. However, a high intake of fluoride can result in serious side effect of fluoride, namely fluorosis, which may cause jeopardize the kidneys in both humans and animals and result urinary stones. The United States Environmental Protection Agency (EPA) gives an executable drinking water standard for fluoride of 4 mg L$^{-1}$ to prevent skeletal fluorosis to prevent fluorosis.\(^5\) Accordingly, the design of new chemosensor for the simple and easy detection of Fe$^{3+}$ and F$^-$ of operation is subject to more and more attention.

Pillararenes, a new macrocyclic subject, have a stiffness architecture with an overall cylindrical or pillarlike shape.\(^6\) They have two openings of the tubular structures, and have exhibited distinguished recognition capabilities towards a variety of guests.\(^7\) Functional groups introduced on pillararenes often bring about unique properties that greatly stimulates the interest of chemists of various fields.\(^8\) Due to the hydrophobic nature of these macrocycles, host–guest complexation and self–assembly of pillararenes derivatives have been widely investigated in organic media. However, as many recognition events in nature occur in aqueous media, effort has also been directed towards the development of pillararene based receptors capable of recognizing guests in aqueous phase.\(^9\) Bearing this in mind, we imagine that by proper functionalization, pillararenes can serve as platforms for self–assembly and preorganizing chelating groups for ion sensor to which so far has not been widespread concen.\(^10\)
Pillar[5]arene–based recognition receptors that continuous recognition system in Fe$^{3+}$ and F$^-$ ion has not been reported.

In view of this, and as a part of our research interest in pillararenes chemistry and molecular recognition, we designed and synthesised a novel pillar[5]arene–based ions receptor PF5 linked 2–aminobenzothiazole at one sites which further self–organize into annularity supramolecular polymers at state of solution utilizing pillar[5]arene–based self–assembly interactions. Furthermore the chemosensor PF5 could be a sequential fluorescence sensor for ferric ions followed by fluoride ions with high sensitivity and selectivity in aqueous solution.

Results and discussion

The synthesis of sensor PF5 is shown in scheme 1 and the synthesis details in scheme S1. Sensor PF5 and intermediate have been characterized by $^1$H NMR, $^{13}$C NMR, and ESI mass spectrometry (Fig. S1–S6). The monomeric pattern DMP5 and G were also prepared as a control for comparison (Scheme S2). The target molecules and intermediates were characterized by $^1$H NMR spectrum (Fig. S7–S8).

To investigate whether the inclusion behavior was produced, the host–guest interaction between DMP5 and G was firstly studied. As shown in Fig. S9, the $^1$H NMR spectra of DMP5 with the addition of different equivalents of G showed that the chemical shifts of H$_{G2}$–G$_8$ on G gradually shifted upfield, and H$_{G1}$ slightly moving downfield, suggesting that the G deeply threaded into the cavity of the DMP5. Subsequently, variable concentration $^1$H NMR spectroscopy of PF5 in CDCl$_3$ was carried out (Fig. 1). It was found that the aggregates formed by self–inclusion were very stable in CDCl$_3$ solution (5 mL). As the concentration increased, the proton resonances did not exhibit obvious changes even at a high concentration of 50 mM, suggesting that PF5 did not form intermolecular complexes in CDCl$_3$, but as the concentration increased, the subtle signals of protons H$_1$ appear peak splitting, which indicated that the self–inclusion function of PF5 was very weak. This is similar to the previous report by Wang’s group.\footnote{12}

Furthermore, the correlation of the protons were further validated by a NOESY NMR spectrum of PF5, the aromatic protons H$_{b–c}$ have strong correlations with methyl protons (H$_h$) and methylene protons (H$_g$) on the pillar as well as alkyl chain protons (H$_i$), indicating that the monomers self–organization into strong fluorescence aggregates driven by the self–assembled between the pillar[5]arene units and benzothiazole units (Fig. S10). After adding iron, the cavity of pillar[5]arene units was occupied by Fe$^{3+}$, which with oxygen atoms of pillar[5]arene units undergoing complexation, making benzothiazole units free from the cavity of pillar[5]arene units. The self–inclusion of PF5 was collapsed, so that fluorescence quenching. Further added F$^-$, which combined the Fe$^{3+}$, the PF5 was self re–inclusion, bring about fluorescence recovery (Scheme 2). Therefore, it can be achieved assembly and application in sequential fluorescent sensing for Fe$^{3+}$ and F$^-$.\footnote{45}
To evaluate the binding ability of compound PF5 toward Fe\textsuperscript{3+} ions, we carried out UV–vis and fluorescence experiments in DMSO/H\textsubscript{2}O (8:2, v/v) by adding divisible of Fe\textsuperscript{3+} as its perchlorate salt. The absorption spectrum of compound PF5 (1.0 mM) exhibited a maximum absorption band at 360 nm. However, an obvious intensity increase took place upon treatment with 10 equiv. of Fe\textsuperscript{3+} (Fig. S11). Conversely, The fluorescence emission band of compound PF5 (1.0 mM) in the 380–540 nm range showed an obvious decrease when increase took place upon treatment with 10 equiv. of Fe\textsuperscript{3+} (Fig. S12). These phenomena confirmed the binding behaviour of Fe\textsuperscript{3+} by PF5. In order to investigate the Fe\textsuperscript{3+} recognition abilities of the sensor PF5 in DMSO/H\textsubscript{2}O (8:2, v/v) solution, a series of host–guest recognition experiments were carried out. The recognition profiles of the sensor PF5 toward various cations (including Fe\textsuperscript{3+}, Hg\textsuperscript{2+}, Ag\textsuperscript{+}, Ca\textsuperscript{2+}, Cu\textsuperscript{2+}, Zn\textsuperscript{2+}, Cd\textsuperscript{2+}, Ni\textsuperscript{2+}, Pb\textsuperscript{2+}, Co\textsuperscript{2+}, Cr\textsuperscript{3+}, Mg\textsuperscript{2+}, Fe\textsuperscript{2+} and Al\textsuperscript{3+}) were primarily investigated using fluorescence spectroscopy. In the fluorescence spectrum, the maximum emission of PF5 appeared at 432 nm in DMSO/H\textsubscript{2}O (8:2, v/v) while excited at \(\lambda_{ex}=360\) nm. When 10.0 equivalents of various anions was added to the solution of sensor PF5, the fluorescence emission band in the 380–540 nm range only Fe\textsuperscript{3+} showed one of the most obvious decrease. And when sensor PF5 was treated with selected cations, such as Hg\textsuperscript{2+}, Fe\textsuperscript{3+}, Ag\textsuperscript{+} (10 equiv.) in DMSO/H\textsubscript{2}O (8:2, v/v) showed little change, which can be considered as a good ON–OFF fluorescent switch.

![Fluorescence spectra responses of PF5 (1.0 mM) in DMSO/H\textsubscript{2}O (8:2, v/v) upon addition of 10.0 equiv. of Fe\textsuperscript{3+}, Hg\textsuperscript{2+}, Ag\textsuperscript{+}, Ca\textsuperscript{2+}, Cu\textsuperscript{2+}, Zn\textsuperscript{2+}, Cd\textsuperscript{2+}, Ni\textsuperscript{2+}, Pb\textsuperscript{2+}, Co\textsuperscript{2+}, Cr\textsuperscript{3+}, Mg\textsuperscript{2+}, Fe\textsuperscript{2+} and Al\textsuperscript{3+} ions (\(\lambda_{ex}=360\) nm). Inset: Photograph of PF5 (1.0 mM) upon adding 10.0 equiv. of various ions, which was observed under a UV–lamp (365 nm).](Image)

To further investigate the interaction between sensor PF5 and Fe\textsuperscript{3+}, fluorescence spectrum variation of sensor PF5 was monitored during titration with different concentrations of Fe\textsuperscript{3+} (Fig. 3). It turned out that, in DMSO/H\textsubscript{2}O (8:2, v/v) solution of PF5, with an increasing amount of Fe\textsuperscript{3+}, the fluorescence emission bands at 432 nm decreased by an extent of \(\sim 88.4\%\). The fluorescent titration curve of the PF5 toward the Fe\textsuperscript{3+} offers a good linear correlation at the concentration range 0–40.0 equivalents, from which the detection limit for Fe\textsuperscript{3+} is estimated to be 9.0 × 10\textsuperscript{−7} M (Fig. S13). And the stability constant \(K_a\) between PF5 and Fe\textsuperscript{3+} is 1.02×10\textsuperscript{6} M\textsuperscript{−1}.

![Time–dependent of PF5 (1.0 × 10\textsuperscript{−5} M) upon addition of Fe\textsuperscript{3+} (10.0 × 10\textsuperscript{−5} M) in DMSO/H\textsubscript{2}O (8:2, v/v) with a plot of fluorescence intensity that is estimated as the peak height at 432 nm.](Image)
ions (Hg$^{2+}$, Ag$^+$, Ca$^{2+}$, Cu$^{2+}$, Zn$^{2+}$, Cd$^{2+}$, Ni$^{2+}$, Pb$^{2+}$, Co$^{2+}$, Cr$^{3+}$, Mg$^{2+}$, Fe$^{3+}$ and Al$^{3+}$) in DMSO/H$_2$O (8:2, v/v). The results of these studies have revealed that these competing ions exerted no or little influence on the fluorescence emission spectra of sensor PF5 with Fe$^{3+}$, which further indicated that PF5 has specific selectivity to Fe$^{3+}$ (Fig. 5). To further verify the resistance to interference of PF5 with Fe$^{3+}$, we have to perform metal ion competitive experiments by applying higher concentrations of competitive metal ions compare to the analyze, competitive experiments were carried out in the presence of 20 equiv. of Fe$^{3+}$ and 20 equiv. of various other ions (Hg$^{2+}$, Ag$^+$, Ca$^{2+}$, Cu$^{2+}$, Zn$^{2+}$, Cd$^{2+}$, Ni$^{2+}$, Pb$^{2+}$, Co$^{2+}$, Cr$^{3+}$, Mg$^{2+}$, Fe$^{3+}$ and Al$^{3+}$) in DMSO/H$_2$O (8:2, v/v). The results also showed that that these competing ions exhibited no or little influence on the fluorescence emission spectra of sensor PF5 with Fe$^{3+}$ (Fig. S15). Additionally, the fluorescence of Job’s plot indicates that PF5 and Fe$^{3+}$ were formed a 1 : 1 complex (Fig. S16).

Since the in situ generated PF5–Fe$^{3+}$ complex exhibited almost complete fluorescence quenching and F$^-$ is well-known to bind strongly to Fe$^{3+}$ ions, we wonder if we can exploit this ensemble system as a turn–on fluorescent sensor for F$^-$ anions which is known to play important roles in a wide range of chemical and biological processes. Thus, the PF5–Fe$^{3+}$ complex prepared by mixing an equal amount of PF5 and Fe(CIO$_4$)$_3$ (10.0 mM) in the same mixed aqueous solution, was treated separately with 1.5 equiv. of different anions (F$^-$, Cl$^-$, Br$^-$, I$^-$, AcO$^-$, NO$_3^-$, HSO$_4^-$, ClO$_4^-$, CN$^-$ and SCN$^-$). When a fluoride ion is added to the PF5–Fe$^{3+}$ system, the fluorescence intensity is completely regenerated (Fig. 6), as also indicated visually by the fluorescent color change (Fig. 6, inset). However, a series of host–guest recognition experiments were carried out, we found that other anions (Cl$^-$, Br$^-$, I$^-$, AcO$^-$, NO$_3^-$, HSO$_4^-$, ClO$_4^-$, CN$^-$ and SCN$^-$) show very little response (Fig. S17). The observed fluorescence and color regeneration can be ascribed to the snatching of Fe$^{3+}$ from its chelated complexes by F$^-$, resulting in the formation of more stable species [FeF$_4$]$_{3-}$ and the release of free ligand PF5. PF5 was re-assembled into annulus fluorescent polymer.

![Fluorescence Intensity](image1)

**Fig. 5** Fluorescence intensities of PF5 (1.0 mM) in the presence of 10.0 equiv. of various ions containing 10.0 equiv. of Fe$^{3+}$ in DMSO/H$_2$O (8:2, v/v) ($\lambda_{ex} = 360$ nm).

![Fluorescence Intensity vs pH](image2)

**Fig. 6** Fluorescence emission spectra of PF5–Fe$^{3+}$ (10 mM) in the presence of 1.5 equiv. F$^-$ in a mixed aqueous medium (DMSO/H$_2$O, 8:2, v/v); ($\lambda_{ex} = 360$ nm). Inset: Photograph of PF5–Fe$^{3+}$ (10 mM) upon adding 1.5 equiv. F$^-$, which was observed under a UV–lamp (365 nm).

The selectivity of PF5–Fe$^{3+}$ ensemble as a fluorescent sensor for F$^-$, It was also examined over a wide range of pH values as shown in Fig. 7. The detection of F$^-$ can work well in the pH range of 1.0–12.0 in DMSO/H$_2$O (8:2, v/v).

![Fluorescence Intensity vs pH](image3)

**Fig. 7** Influence of pH on the fluorescence of PF5–Fe$^{3+}$ complex (10 mM) with fluoride ion (1.5 equiv.) in DMSO/H$_2$O (v/v = 8:2). Inset: pH fluorescence of a full scan.

To further investigate the interaction between sensor PF5–Fe$^{3+}$ and F$^-$, fluorescence spectrum variation of sensor PF5–Fe$^{3+}$ was monitored during titration with different concentrations of F$^-$ (Fig. 8). The fluorescent titration curve of the PF5–Fe$^{3+}$ complex toward the fluoride ion offers a good linear correlation at the concentration range 0–1.5 equivalents, from which the detection limit for fluoride is estimated to be 2.59 × 10$^{-8}$ M (Fig. S18). This value is much lower than the limit concentration level (4.00 mg L$^{-1}$) in drinking water set by USEPA.$^{13}$
Fig. 8 Fluorescence titration of the PF5–Fe3+ complex (10 mM) with fluoride ion in a mixed aqueous medium (DMSO/H2O (8:2, v/v); λex = 360 nm). Inset: Photograph of PF5–Fe3+ (10 mM) upon adding 1.5 equiv. of F−, which was observed under a UV–lamp (365 nm).

Control experiments of PF5–Fe3+ even in the presence of 1.5 equiv. of each of the anions indicated the absence of interaction between PF5–Fe3+ and anions in same solvent system. Competition experiments were conducted by adding fluoride (1.5 equiv.) to the solution of PF5–Fe3+ in the presence of 2.0 equiv. of other anions (Fig. 9). The fluorescence emission spectra display nearly an identical pattern to that with F− alone, suggesting that all of the tested anions do not interfere in the sensing of F−. In addition, the fluorescent intensity could be turned off and on repeatedly with the alternate addition of Fe3+ and F− ions at least in six cycles (Fig. S19). All the above results indicate that the PF5–Fe3+ ensemble could serve as an outstanding sensitive and selective fluorescent OFF–ON sensor for F−.

Fig. 9 Fluorescence intensity changes of PF5–Fe3+ ensemble (10 mM) in the presence of other anions (1.5 equiv.) followed by addition of F− (1.5 equiv.) in a mixed aqueous medium (DMSO/H2O (8:2, v/v); λex = 360 nm).

To further investigate the practical application of chemosensor PF5, test strips were fabricated by immersing filter papers into DMSO/H2O (v/v = 8:2) solution of PF5 (2×10−3 M) and then drying them in air. The test strips containing PF5 were utilized to sequential sense Fe3+ and F−. As shown in Fig. 10, when first added Fe3+ on the test strips, an obvious color change and subsequently joined F− the color of test strips once again changes which served as convenient and efficient sequential Fe3+ and F− test kits.

Fig. 10 Photographs of PF5 on test strips only PF5 and alternately added Fe3+ and F−.

We also investigated the practical utilities of the probe in daily life sample, we have chosen to detect Fe3+ in tap water and F− in toothpastes to implement the following experiment. Fluorescence emission spectra of PF5 (1.0 mM in 5 mL DMSO) is just like 1 line shown in Fig. 11. Followed: (a) upon titration of concentrated tap water (1.0 mL) to get 2 line; (b) soluble components of Colgate toothpaste sample (10 equiv.) added to solution of (2) to obtain 3 line; (c) soluble components of Colgate toothpaste sample (10 equiv.) added to solution of (3) to obtain 4 line; (d) soluble components of Colgate toothpaste sample (10 equiv.) added to solution of (4) to obtain 5 line. Significant color change can be directly seen the sensor PF5 is also could sequential detect Fe3+ in tap water and F− in real samples like toothpastes (Fig. 11), confirming that PF5 is a promising Fe3+ and F− probe for practical applications. Therefore, this novel functionalized pillar[5]arene PF5 can be used as an original fluorescent sensor for sequential detecting Fe3+ and F− ions, which showed excellent stability, reversibility, as well as repeatability. (Fig. S20).

Fig. 11 Fluorescence emission spectra of PF5 (1.0 mM in DMSO) sequential detect Fe3+ in tap water and F− in real samples like toothpastes. Insets: photographs illustrating of optical changes upon addition of analyte. Excitation wavelength is 360 nm.
Conclusions

In summary, a novel functionalized pillar[5]arene was synthesized, which can be self-inclusion produce a strong blue fluorescence. Followed by PF5 could act as a chemosensor for ferric (□) and fluoride ions through a competitive complexation reaction. For the first time, the recognition ability of specifically (1308RJZA221) and the Program for Changjiang Scholars and Innovative Research Team in University of Ministry of Education of China (IRT1177).

Notes and references

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