Tetrahedron Letters 57 (2016) 3407–3411

Contents lists available at ScienceDirect

Tetrahedron Letters

journal homepage: www.elsevier.com/locate/tetlet

A novel urea-derived fluorescent sensor for highly selective and sensitive detection of Fe^{3+}

Xingxing Wu, Shanshan Zhang, Qingfen Niu *, Tianduo Li *

Shandong Provincial Key Laboratory of Fine Chemicals, School of Chemistry and Pharmaceutical Engineering, Qilu University of Technology, Jinan 250353, People's Republic of China

ARTICLE INFO

Article history:
Received 2 May 2016
Revised 19 June 2016
Accepted 21 June 2016
Available online 21 June 2016

Keywords:
Fluorescent sensor
Urea derivative
Metal ion
Fe^{3+}
Quenching

ABSTRACT

A novel urea-derived fluorescent sensor MDSU for Fe^{3+} was designed and synthesized. Its sensing behavior to metal ions was investigated by absorption and fluorescence spectra. In DMSO/H_2O (1:1, v/v) solution, sensor MDSU showed a highly selective and sensitive recognition to Fe^{3+} over other competitive metal ions. This sensor formed a 1:1 complex with Fe^{3+} and displayed fluorescence quenching. Moreover, sensor MDSU can rapidly detect Fe^{3+} in real time with a lower detection limit of 1.816×10^{-7} M.

Introduction

Heavy and transition metal (HTM) ions induce a large number of environmental issues, and thereby great efforts have been focused on their detection.[1,2] Among HTM elements, iron is one of the most essential elements or fulfilling normal physiological function in human body, which plays key functional roles in miscellaneous fundamental biological processes at the cellular level ranging from electron transfer, cellular metabolism, energy generation, gene expression, neurotransmission, regulation of metalloenzymes, DNA synthesis as well as differentiation.[3–9] In particular, its deficiency or overload can cause various disorders and diseases such as anemia and hemochromatosis.[10–18] In order to protect the human health, it is very important to monitor the concentration levels of Fe^{3+} in the environment and even many scientific fields. Thus, the development of the sensitive and selective detection approaches in biological systems is of great importance for deeper investigating of physiological and pathophysiological functions of Fe^{3+} in living organisms.

Fluorescent sensors for metal ions have found widespread use in both environmental monitoring and biological studies,[19–28] owing to their significant advantages including non-destructive character, simplicity, high sensitivity and selectivity, desirable photo-physical properties, good water solubility, instantaneous response and so on.[20,29] In recent years, a number of fluorescent sensors for selective detection of Fe^{3+} have been developed,[30–43,5,44,45] but some of them exhibited evident drawbacks such as the synthetic difficulty, the interference from co-existing ions during the detection process and time-consuming,[41–43,5,44,45] which restricted their practical performance. Therefore, the design and development of more selective and sensitive, efficient and stable fluorescent sensors for detection of Fe^{3+} is urgent.

In this study, we report the design and synthesis of a new turn-off fluorescent sensor MDSU based on urea-derived architecture[46] that can selectively detect Fe^{3+} in DMSO/H_2O (1:1, v/v) solution. The sensing behavior of MDSU to various metal ions was studied by absorption and fluorescence spectra. The investigated results displayed that MDSU exhibited high selectivity, sensitivity, and rapid fluorescence quenching response to Fe^{3+} over other metal cations such as Na^+, K^+, Ag^+, Ca^{2+}, Hg^{2+}, Al^{3+}, Co^{2+}, Cu^{2+}, Ni^{2+}, Zn^{2+}, Pb^{2+}, Cd^{2+}, Fe^{2+}, and Cr^{3+}. Moreover, the recognition process of MDSU is reversible by adding a Fe^{3+} bonding agent EDTA. In addition, the sensor MDSU can fast detect Fe^{3+} in real time, permitting its incorporation into a portable Fe^{3+} detection kit in aqueous environment.

Experimental

Apparatus and reagents

All analytical grad chemicals were purchased from commercial sources and used without further purification. ^1H NMR and ^{13}C

---

* Corresponding authors. Tel.: +86 (531)89631760; fax: +86 (531)89631208.
E-mail addresses: qf_niu1216@qlu.edu.cn (Q. Niu), litianduo@163.com (T. Li).

http://dx.doi.org/10.1016/j.tetlet.2016.06.089
0040-4039/

NMR spectra were recorded on a Bruker Avance II 400 using TMS as an internal standard operating at 300 MHz for ^{1}H NMR and 100 MHz for ^{13}C NMR in DMSO-d_6, respectively. Infrared measurements with the KBr pellet technique were performed within the 4000–400 cm^{-1} region on a Bruker ALPHA FT-IR spectrometer. All UV–Vis absorption spectra were recorded with a Shimadzu UV-2600 spectrophotometer at room temperature. All fluorescence measurements were carried out on a Hitachi F-4600 fluorescence spectrophotometer with a scan rate at 1200 nm/min at room temperature.

Analysis

All tests described in this letter were carried out at room temperature. All the metal salts of $NaNO_3$, $Ca(NO_3)_2{\cdot}4H_2O$, $Al(NO_3)_3{\cdot}9H_2O$, $Pb(NO_3)_2$, $Cu(NO_3)_2{\cdot}3H_2O$, $AgNO_3$, $Zn(NO_3)_2{\cdot}6H_2O$, $Cd(NO_3)_2{\cdot}4H_2O$, $Fe(NO_3)_3{\cdot}9H_2O$, $Co(NO_3)_2{\cdot}6H_2O$, $Ni(NO_3)_2{\cdot}6H_2O$, KNO_3, $Hg(NO_3)_2{\cdot}H_2O$, $FeCl_2{\cdot}4H_2O$, and $CrCl_3{\cdot}6H_2O$ were dissolved in water to prepare the stock solution with the concentration of 1.0×10^{-3} M. MDSU was dissolved in DMSO to give the stock solution (5.0×10^{-3} M) and diluted with a mixed solution of DMSO/H_2O to prepare the analytical solution (5.0×10^{-5} M) (DMSO/H_2O, 1/1, v/v). The stock solution of the metal cations and MDSU was used directly in the spectroscopic measurement. For the sensitivity measurement, different concentrations of Fe^{3+} ions were added to the assay solution, and the fluorescence spectra were recorded. The selectivity was checked by addition of Na^{+}, K^{+}, Ag^{+}, Ca^{2+}, Hg^{2+}, Al^{3+}, Co^{2+}, Ni^{2+}, Cd^{2+}, Zn^{2+}, Pb^{2+}, Cu^{2+}, Fe^{2+}, and Cr^{3+} in to the stock solution. For fluorescence measurements, both the excitation and emission slit widths were 5 nm. The excitation wavelength was set at 300 nm.

Synthesis of the fluorescent sensor MDSU

The sensor MDSU was synthesized according to the route as shown in Scheme 1. A mixture of bis(4-isocyanatophenyl)methane (0.25 g, 1.0 mmol) and 2-aminothiophenol (0.25 g, 2.0 mmol) was refluxed in acetone with constant stirring for 1.5 h. The solution was cooled to room temperature and the crude product precipitated. Then the crude product was recrystallized from DMF to afforded the desired sensor MDSU (0.41 g, 82%) as a white solid. Mp = 204–206 °C; ^{1}H NMR (400 MHz, DMSO-d_6) (Fig. S1) δ = 10.53 (s, 2H, C(=O)NH), 9.44 (s, 2H, C(=O)NH), 8.21 (s, 1H, Ar–H), 8.15 (d, J = 4.0 Hz, 1H, Ar–H), 7.47 (d, J = 8.0 Hz, 1H, Ar–H), 7.39 (d, J = 4.0 Hz, 3H, Ar–H), 7.32 (s, 3H, Ar–H), 7.09 (d, J = 4.0 Hz, 6H, Ar–H), 7.02 (d, J = 8.0 Hz, 1H, Ar–H), 3.78 (s, 2H, CH_2); ^{13}C NMR (100 MHz, DMSO-d_6) (Fig. S2) δ = 152.5, 152.3, 142.2, 137.6, 137.4, 136.7, 135.2, 133.7, 130.7, 130.1, 128.9, 123.1, 122.4, 121.7, 120.9, 119.2, 118.5, 116.7, 114.7, 40.3; IR (KBr, cm^{-1}) (Fig. S3) ν = 3309, 1646, 1608, 1565.

Results and discussion

Absorption spectroscopic studies on metal ions

The optical behavior of MDSU was initially studied using UV–Vis absorption in DMSO/H_2O (1:1, v/v) solution. As shown in Figure 1, UV–Vis absorption spectra of sensor MDSU (50 μM) exhibited one weak absorption band at 247 nm. Upon the addition of Fe^{3+} (100 μM), the absorption spectra of sensor MDSU showed obvious changes, the absorption intensity of peak at 247 nm dramatically increased, accompanied with a new absorption band clearly observed around 325 nm. These changes are due to the sensor MDSU to metal charge transfer and it appears that the core functionality required for MDSU to efficiently bind Fe^{3+} upon excitation are —C=O and a —SH groups. However, no significant changes of the absorption were observed upon the addition of various metal ions such as Na^{+}, K^{+}, Ca^{2+}, Co^{2+}, Ni^{2+}, Cu^{2+}, Zn^{2+}, Pb^{2+}, Ag^{+}, Cd^{2+}, Hg^{2+}, Al^{3+}, Cr^{3+}, and Fe^{2+} ions (100 μM, respectively). This indicated that the sensor MDSU can selectively detect Fe^{3+} ions in DMSO/H_2O (1:1, v/v) solution over other metal ions.

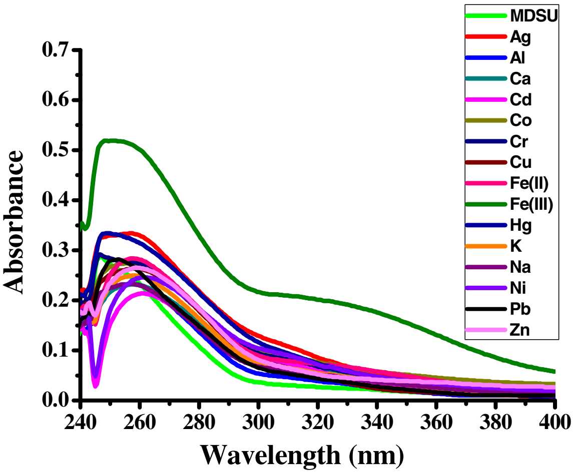


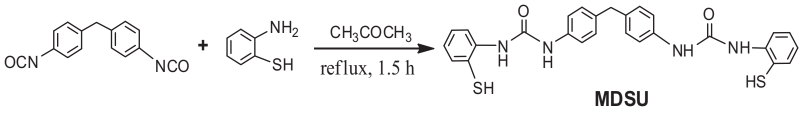
Figure 1. UV–Vis absorption spectra of MDSU (50 μM) in the presence of 2.0 equiv of different metal cations.

Selectivity studies and effects of metal ions

The effect of Fe^{3+} on the fluorescence properties of MDSU was investigated in DMSO/H_2O (1:1, v/v) solution. As shown in Figure 2, the free MDSU (50 μM) showed a degree of fluorescence intensity with emission maxima around 361 nm, surprisingly, a complete fluorescence quenching was observed in the presence of Fe^{3+} ions (2.0 equiv), indicating the formation of a new complex between MDSU and Fe^{3+}. The fluorescence quantum yield of sensor MDSU displayed a fluorescence quenching (from $\Phi_{\text{free}} = 0.18$ to $\Phi_{\text{Fe}}^{3+} = 0.0074$) upon binding to Fe^{3+} with respect to quinine sulfate in 0.1 N H_2SO_4 solution ($\Phi_s = 0.54$).[47] Nevertheless, other metal ions including Na^{+}, K^{+}, Ca^{2+}, Co^{2+}, Ni^{2+}, Cu^{2+}, Zn^{2+}, Pb^{2+}, Ag^{+}, Cd^{2+}, Hg^{2+}, Al^{3+}, Cr^{3+}, and Fe^{2+} ions (2.0 equiv) induced small significant change in the emission spectra relative to the free MDSU. These distinct observations further confirmed that MDSU displayed high selectivity toward Fe^{3+} in DMSO/H_2O (1:1, v/v) solution.

The complexation of MDSU with Fe^{3+}

In order to further illustrate the stoichiometry of MDSU and Fe^{3+}, the fluorescence titration experiment of MDSU with Fe^{3+} was therefore carried out in DMSO/H_2O (1/1, v/v) solution. As



Scheme 1. The synthetic route for the sensor MDSU.