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A highly selective chemosensor for copper ion based on ICT fluorescence

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Abstract

Simple structural compounds **1** to **3** were synthesized. The presence of Cu^{2+} resulted in the fluorescence and absorption spectra change of **1** and **2**, which indicated that **1** and **2** showed a highly selective response to Cu^{2+} over other metal ions. However, **3** showed no selectivity for metal ions, which means that the compound could bind with several metal ions, such as, Ni^{2+}, Zn^{2+}, Cd^{2+}, Hg^{2+}, Pb^{2+}, Fe^{3+}, Mg^{2+}, Ca^{2+}, and Co^{2+}, except Cu^{2+} and Ag^{+}. The different spectral responses were attributed to the difference in binding sites for **1** and **3**.

Keywords: 4-Dimethylaminobenzoylamino derivatives; ICT fluorophore; Cu^{2+}; Dual spectral response

Copper ion plays an important role in the fundamental physiological processes of organisms ranging from bacteria to mammals [1]. The selective sensing of Cu^{2+} is a very important topic for the detection and treatment of various chemical systems, including living systems [2]. However, Cu^{2+} can be toxic if its level exceeds cellular requirements. Thus, designing sensors for Cu^{2+} has recently drawn worldwide attention. Among fluorescent sensors, the binding of Cu^{2+} with an ionophore resulted in fluorescence enhancement [3] or fluorescence quenching [4] via photo-induced electron transfer. Ratiometric assay has also been utilized recently to increase selectivity and sensitivity. Ratiometric fluorescent probes allow signal rationing, and thus increase the dynamic range and provide built-in correction for environmental effects [5]. Therefore, a few Cu^{2+} ratiometric sensors have been reported [6]. Sensors containing intramolecular charge transfer (ICT) fluorophore [6d,6f] or excimer-forming pyrene moieties [3g,7] usually emit dual fluorescence. *p*-Dimethylaminobenzoylamino is an ICT fluorophore and the N atom of amino could coordinate with metal ions [6f,8], whereas amino acetic acid moiety serves as a good ligand for metal ions [3f]. The combination of these two moieties could thus form a promising fluorescent probe for metal ions. In this paper, simple structural compounds **1–3** that could emit dual fluorescence were synthesized. Compared with **3**, **1** and **2** selectively recognize Cu^{2+} over other metal ions because of the difference in binding sites between **1** or **2** and **3**.

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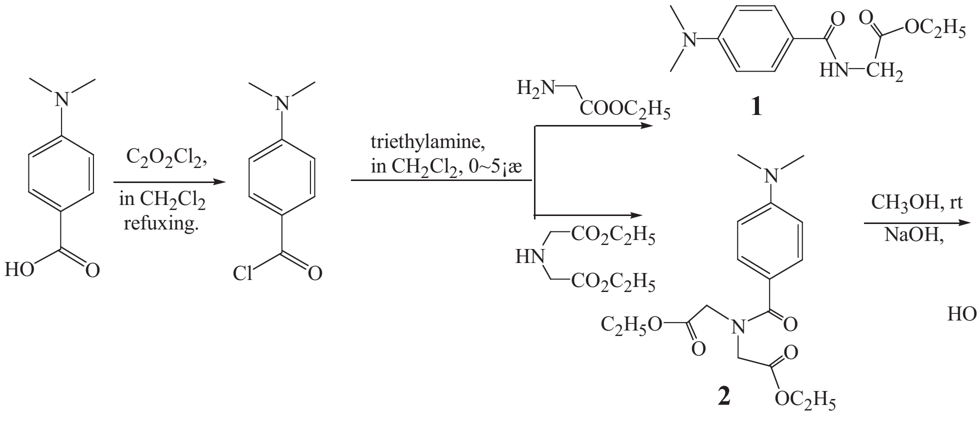

Scheme 1. Structure of fluorescent compounds **1–3**.

1. Experimental

All fluorescence measurements were conducted on an F-4600 spectrofluorimeter (Hitachi, Japan) equipped with a xenon lamp source and a 1.0 cm quartz cell. Absorption spectra were recorded on a Shimadzu-2501 UV–vis spectrophotometer (Japan) with a 1.0 cm quartz cell. ^{1}H NMR spectra were obtained on a Bruker Avance 600 MHz NMR spectrometer with TMS as the internal standard. ESI mass spectra were recorded using a Waters ZQ4000/2695 LC–MS spectrometer. Infrared spectra were obtained as KBr pellets on a Nicolet 5700 FTIR spectrometer.

The structures of compounds **1–3** and the synthesis methods are depicted in Scheme 1. These structures were characterized by ^{1}H NMR, ESI mass, and IR data, which were consistent with the proposed formulation. **1**: ^{1}H NMR (600 Hz, $CDCl_3$): δ 1.29–1.33 (t, 3H, CH_3), 3.03 (s, 6H, CH_3), 4.22–4.28 (m, 4H, CH_2), 6.68 (d, 2H, J = 8.87 Hz, ArH), 7.72 (d, 2H, J = 8.89 Hz, ArH); ESI mass: m/z calcd. for $C_{13}H_{16}N_2O_3$ [M+H$^+$] 249.12, found [M+H$^+$] 249.37. **2**: ^{1}H NMR (600 Hz, $CDCl_3$): δ 1.23–1.31 (t, 6H, CH_3), 2.99 (s, 6H, CH_3), 4.20–4.25, (m, 8H, CH_2), 6.65 (d, 2H, J = 8.78 Hz, ArH), 7.38 (d, 2H, J = 8.78 Hz, ArH); ESI mass: m/z calcd. for $C_{17}H_{24}N_2O_5$ [M+H$^+$] 337.17, [M+Na$^+$] 359.16; found [M+H$^+$] 337.22, [M+Na$^+$] 359.22. **3**: ^{1}H NMR (600 Hz, D_2O): δ 3.11 (s, 6H, CH_3), 3.93 (s, 2H, CH_2), 4.13 (s, 2H, CH_2), 7.32 (d, 2H, J = 8.51 Hz, ArH), 7.52 (d, 2H, J = 8.50 Hz, ArH); ESI mass: m/z calcd. for $C_{13}H_{16}N_2O_5$ [M+H$^+$] 281.11; found [M+H$^+$] 281.03.

2. Results and discussion

Compounds **1–3** emitted dual fluorescence in acetonitrile. The spectral parameters are presented in Table 1. The shorter wavelength emission originated from the local excited state (LE), and the longer wavelength emission came from the charge transfer state (CT). The intensity ratio of CT emission to LE emission for **1** or **2** was larger than that for **3,** which implied that the ester group was favored for the charge transfer state in *p*-dimethylaminobenzoylamino derivatives. Meanwhile, both emission wavelengths red shifted when the ether group was replaced by carboxyl. However, the total quantum yield was higher for **3** than for **1** or **2**.

The fluorescence and absorption titrations of **1** against Cu^{2+} were performed and presented in Fig. 1. As seen in Fig. 1a, **1** emitted dual fluorescence in acetonitrile, which peaked at 365 and 480 nm. Upon addition of Cu^{2+}, both intensities decreased while the peak position was kept constant. Similar quenching was observed when the excitation

Table 1
Spectral parameters of receptor **1–3** in acetonitrile.

Receptor	λ_{max} (nm)	ε (mol^{-1} L cm^{-1})	λ_{ex} (nm)	λ_{LE} (nm)	λ_{CT} (nm)	I_{CT}/I_{LE}	Φ_F[a]
1	298	2.41×10^4	299	365	480	2.34	0.035
2	288	1.74×10^4	287	372	491	1.41	0.042
3	281	1.10×10^4	283	360	467	0.40	0.053

[a] The total quantum yield including LE and CT emission.

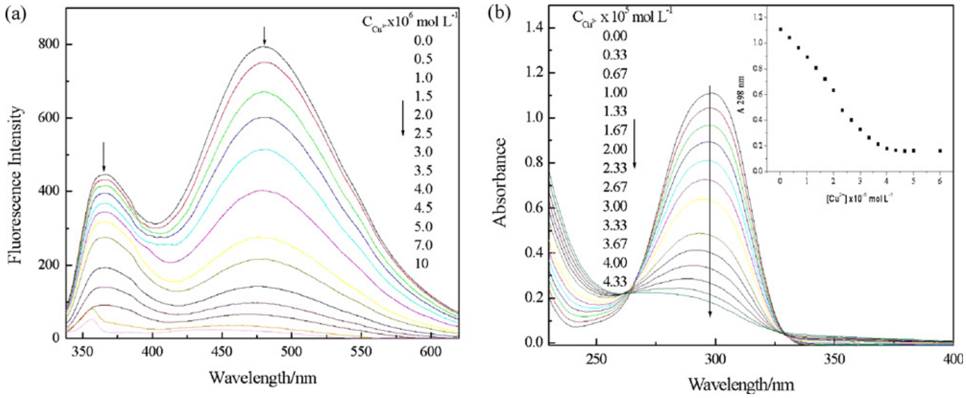

Fig. 1. (a) Fluorescence spectral change of **1** (3.5×10^{-6} mol L^{-1}) in the presence and absence of Cu^{2+} in acetonitrile. The excitation wavelength was set at 310 nm. (b) Absorption spectral change of **1** (4.0×10^{-5} mol L^{-1}) with the addition of Cu^{2+} in acetonitrile.

was set at 264 nm, an isosbestic point. The intensity ratio between 480 nm and 365 nm showed good linear relationship with the concentration of Cu^{2+} ranging from 0 to 2.5×10^{-6} mol L^{-1} with a linear correlation coefficient (R) of 0.9914. The absorption spectrum of **1** changed with the addition of Cu^{2+} as presented in Fig. 1b. The peak at 298 nm derived from **1** slightly blue shifted along with the decreased absorbance when increasing amounts of Cu^{2+} were added. Clear isosbestic points at 264 and 329 nm were observed to demonstrate the existence of a well-defined stoichiometric complex. Absorbance at 298 nm leveled off (as seen in the inset plot of Fig. 1b) after introduction of 1 equivalent of Cu^{2+}. This finding indicates the formation of a 1:1 complex. The binding constant (K_b) of copper complex was calculated as 5.1×10^7 mol^{-1} L by non-linear fitting [8b]. The paramagnetic effect is the principal cause of the fluorescence quenching by the d^9 Cu(II) ion [9]. Thus, **1**-Cu complex formation was assumed to result in fluorescence quenching. Evidence of **1**-Cu formation via ESI-mass was also provided. However, such evidence failed because of complex decomposition at a high temperature.

Under identical condition the effects of other metal ions such as Ni^{2+}, Zn^{2+}, Ag^{+}, Cd^{2+}, Hg^{2+}, Pb^{2+}, Fe^{3+}, Mg^{2+}, Ca^{2+} and Co^{2+} on the spectrum of **1** were also investigated. Compared with **1**, only the presence of Pb^{2+} and Hg^{2+} made the emission of **1** slight quench when the same amount of metal ion was added. The addition of other metal ions resulted in little spectral change as seen in Fig. 2a. The results imply that **1** possessed a high selectivity toward Cu^{2+} over other metal ions.

The spectral responses of control compounds **2** and **3** to metal ions were also studied to elucidate high selectivity. Compound **2** had similar absorption and fluorescence spectral changes in the presence of metal ions. The binding constant of **2**-Cu was estimated as 8.5×10^6 mol^{-1} L, which was smaller than that of **1**-Cu. However, the moiety of $CON(CH_2COOC_2H_5)_2$ in compound **2** could provide more coordinating atoms compared with **1**. Apparently, the moiety of $CON(CH_2COOC_2H_5)_2$ was not the binding site for Cu^{2+}. Cu^{2+} was assumed to bind with the nitrogen atom of *p*-dimethylamino moiety, which was similar to a report in the literature [8b]. As the ester group is an electron-attracting

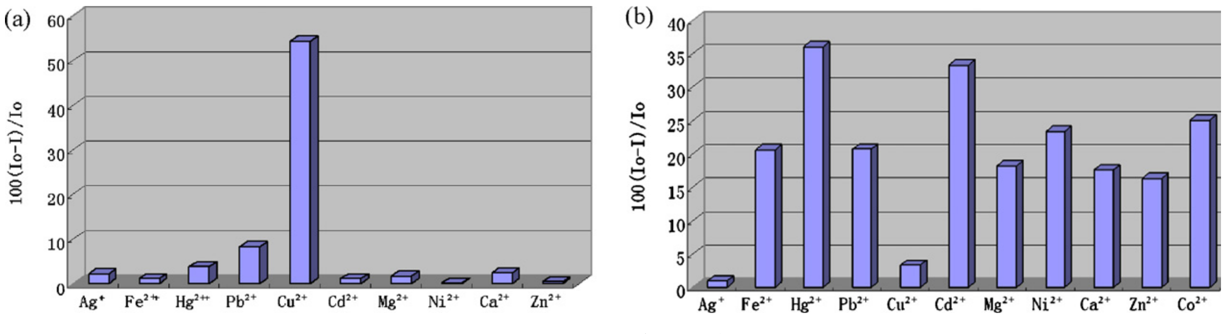

Fig. 2. (a) Fluorescence intensity change ($(I_0 - I/I_0) \times 100$) of **1** (1.0×10^{-5} mol L^{-1}) in the presence of various metal ions. Various ions have the same concentration like **1**. (b) Fluorescence intensity changes ($(I_0 - I/I_0) \times 100$) of **3** (5.0×10^{-6} mol L^{-1}) in the presence of various metal ions. Various ions have the same concentration like **3**.

group, there is one ester group in **1** and two ester groups in **2.** Thus, the electron cloud density of N in the *p*-dimethylamino moiety in **1** is larger than that in **2**. The affinity of **1** toward Cu^{2+} is stronger than that of **2.** Further, the fluorescence quenching of **1** with the addition of Cu^{2+} was assumed to undergo isc by excitation from S_1 to T_1 state of the fluorophore, that is deactivated by bimolecular non-radiative processes.

The fluorescence intensity change of **3** with the addition of metal ions is also studied and presented in Fig. 2b. For most metal ions such as Hg^{2+}, Fe^{3+}, Pb^{2+}, Cd^{2+}, Ca^{2+}, Mg^{2+}, Co^{2+}, except Cu^{2+} and Ag^+, the presence of the above ions initiates a decrease in the LE and CT fluorescence intensity of **3**. The carboxyl groups in **3** possessed strong affinities toward metal ions compared with nitrogen atom. Thus, **3** could bind with many metal ions. Obviously, the sensitivities of **3** to Hg^{2+}, Cd^{2+}, and Co^{2+} were higher than that of Cu^{2+}.

3. Conclusions

A simple compound, 4-dimethylaminobenzoylaminoacetic acid ethyl ester, was obtained. The total fluorescence intensity, intensity ratio, and absorbance changes could act as indexes for the determination of Cu^{2+}. The binding site was assumed to play a key role in the selectivity of **1** to Cu^{2+}.

Acknowledgments

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