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A novel chromatism switcher with double receptors selectively for Ag^+ in neutral aqueous solution: 4,5-diaminoalkeneamino-*N*-alkyl-l,8-naphthalimides

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Abstract—Two novel fluorosensors of 4,5-disubstituted-*N*-alkyl-l,8-naphthalimide derivatives (**H1**, **H2**, **H3**) with double ethylenediamino receptors, double propylenediamino receptors, or one methylpiperazine receptor were synthesized, respectively. Their fluorescence and absorption in the presence or absence of nine metal ions were studied. In the presence of Ag^+, **H1**'s absorption moved to long wavelength with color change from yellow-green to red, its quenching and red shift in fluorescence were also remarkable. Similarly, **H1**'s fluorescence was also strongly quenched in the presence of Cu^{2+}. In addition, **H1** and **H2** show high pH sensitively. There was 139-folds fluorescence enhancement for **H1**, 22-folds for **H2**, and 4-folds for **H3** when pH was changed from 8 to 3, respectively.

The development of fluorescent devices for the sensing and reporting of chemical species is currently of significant importance for both chemistry and biology.[1] More specifically, chemsensors for the detection and measurement of transition metal ions are actively being investigated, because transition metal ions are essential trace elements in biological systems and significant elements in environmental chemistry.[2–10] Essential requisites of such a sensor are high sensitivity and selectivity, since its main applications are addressed to the analysis of environmental or biological samples. In addition, its ability to operate in water is extremely important.[9]

We have focused on the use of 4,5-diamino-1,8-naphthalimide derivatives as fluorescence sensors to detect transition metal ions in water. It is known that the highly fluorescent and photo-stable 1,8-naphthalimide derivatives, for example, 4-amino-1,8-naphthalimides, function as fluorescent dyes for synthetic polymers and textile materials,[11] liquid-crystal additives,[12] electrooptically sensitive materials in laser technology,[13] DNA intercalators,[14] and fluorescent markers[15] in medicine and biology. More recently, 1,8-naphthalimide derivatives with ethylenediamine functionality or analogs as a guest binding site, have been developed as signaling molecules to respond to transition metal ions by fluorescence enhancement in organic solvent.[16,17] However few selective fluoroionophores derived from them were reported. In addition, transition metal ions are easier to chelate and detect in organic solvents, because of their relatively small solvation energies. It is rather difficult to recognize transition metal ions in aqueous solvents because of their strong hydration, which is relevant to biological and environmental applications.

4-Aminonaphthalimide fluorophore is an electronic push–pull system containing one electron-donating group and is usually connected to one ethylenediamino receptor in PET (Photo-induced Electron Transfer) based sensors, we hypothesized that its fluorescence intensity would increase with the introduction of two electron-donating ethylenediamino groups or analogs to the *para*-positions of electron-withdrawing carboximide moiety and if such two receptors in coordination with each other would improve sensitivity and selectivity for transition metal cations, as well as hydrophilic ability.

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Here we report the synthesis and signaling properties of **H1**, **H2**, and **H3**. **H1** is able to detect Ag^+ and Cu^{2+} ions in Tris–HCl aqueous at pH 7.5. In the presence of Ag^+, the absorption of **H1**'s aqueous solution was red shifted, observable by a change in color from yellow-green to red, its quenching and red shift in fluorescence were also remarkable, therefore **H1** is a two-channel molecular switcher for the optical detection of Ag^+.[18] And the fluorescence quenching of **H1** was very strong in the presence of Cu^{2+}. In addition, there is a 139-folds fluorescence enhancement for **H1**, 22-folds for **H2**, and 4-folds for **H3** when pH value was changed from 8 to 3, respectively.

The syntheses of targets were shown in Scheme 1. Following the literatures,[19–21] **1** was prepared from acenaphthalene via chlorination and oxygenation. Compound **1** was condensed with dodecyl amine in ethanol at reflux for 10 h, and was cooled to room temperature to afford a yellow solid **2** after filtration, and purified by silica gel column chromatography using dichloromethane as eluent. **H1** and **H2** were prepared as follows with 77% and 52% yield, respectively. Compound **2** reacted with the corresponding amine in acetonitrile with reflux for 7 h under a nitrogen atmosphere, the reaction mixture was poured into water, extracted with ethyl acetate, dried over K_2CO_3, and evaporated, then the residue was dissolved in methanol and further purified by column chromatography using methanol–triethylamine (10:1, v/v) as eluent. While **H3** (yield 70%) was obtained when **2** reacted with methylpiperazineat the same conditions, **H4** was not obtained, as the methylpiperazine is a secondary amine, its steric hindrance is larger by comparison with that of dimethylaminoethylene (or propylene)amine. The structures of all products were identified by using ^1H NMR, ^{13}C NMR, and MS.[22]

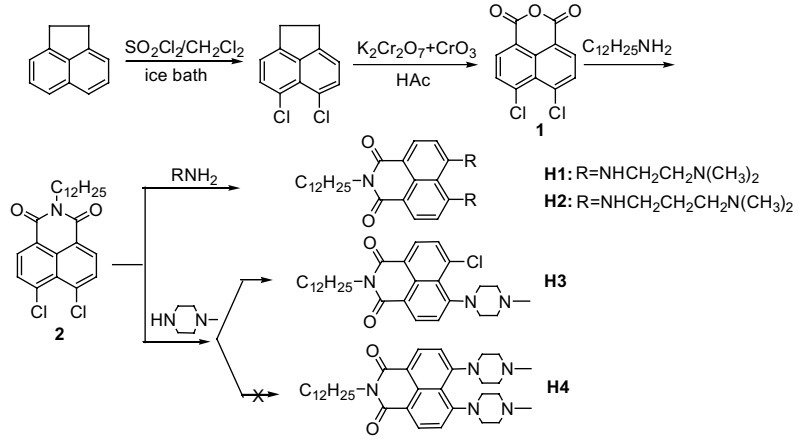
Addition of transition metal ions to the buffer solution of **H1** resulted in changes of color, which were sharply different (Fig. 1). When Ag^+ was added to the **H1** buffer solution, its color changed from yellow-green to red, yet the color of the **H1** solution did not change when other transition metal ions (Co^{2+}, Pb^{2+}, Zn^{2+}, Mg^{2+}, Hg^{2+}, Cd^{2+}, Ca^{2+}) were added.

Figure 1. The color response of **H1** to different transition metal ions.

By comparison with the other transition metal ions, Cu^{2+}-induced fluorescence quenching of the **H1** was the strongest, while its emission and absorption wavelength changed slightly. In the presence of Ag^+, the **H1**'s fluorescence was quenched with a red shift about 17 nm (**H1** in Fig. 2a), a red shift about 76 nm in its absorption was found by comparing with its absolute buffer solution (**H1** in Fig. 2c). It implies that there is a strong interaction between **H1** with Ag^+ or Cu^{2+} in Tris–HCl aqueous solution.

The electron densities of these naphthalimide fluorophores are very high due to the electron donors at 4- and 5-position, which strengthens the quenching between transition metal ions and electron-rich fluorophore. This is very different from the naphthalimide fluoroionophores with one electron-donating group, which showed the fluorescence enhancement through the inhibition of PET in the presence of transition metal ions and the weakness of the quenching between cation and the electron-deficient fluorophore.[17,23,24]

The influence of the concentrations of Cu^{2+} or Ag^+ on **H1**'s fluorescence intensity was shown in Figure 3a, respectively. The fluorescence intensity was quenched more than 90% during the concentration of Cu^{2+} at μmol/L level (Fig. 3a), and decreased linearly upon the concentrations ($0–1.2\times10^{-6}$ mol/L, $\Delta I = -13.47x - 1.03$, $R^2 = 0.9836$). When the concentration of Cu^{2+} was increased to 5.4×10^{-6} mol/L, which was half of that of **H1**, the fluorescence was quenched to constant minimum. Similarly, the fluorescence decreased linearly upon the concentrations of Ag^+ ($0–1.0\times10^{-5}$ mol/L, $\Delta I = -1.63x - 1.29$, $R^2 = 0.9824$) up to a ratio **H1**–Ag^+ of 1:1 and then leveled off. These phenomena were



Scheme 1. Synthetic procedures for **H1**, **H2**, and **H3**.

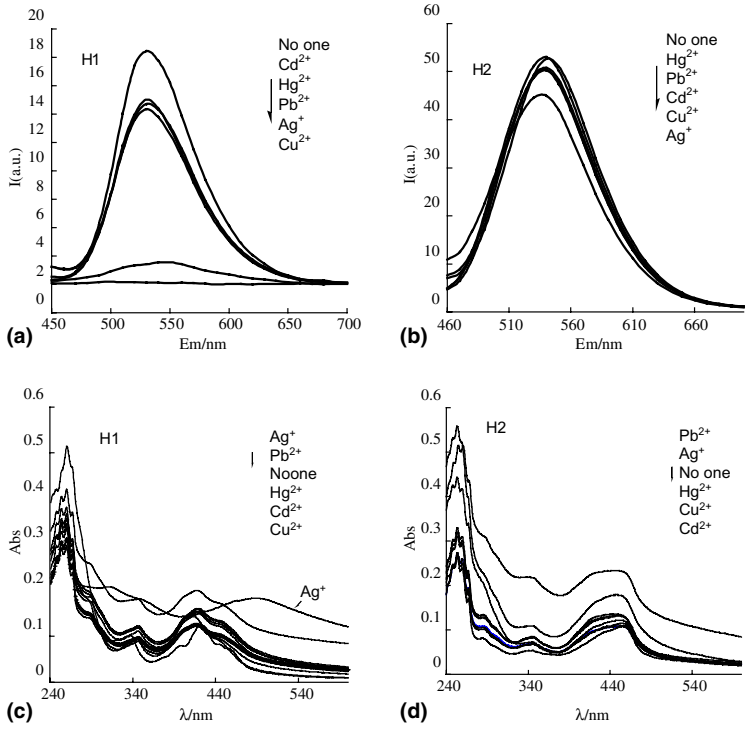


Figure 2. Fluorescence and absorption of **H1** (a, c) and **H2** (b, d) (1×10^{-5} mol/L) in Tris–HCl aqueous solution (0.01 mol/L, methanol–water = 1:19, v/v, pH = 7.5) in the presence of different metal ions (5×10^{-5} mol/L).

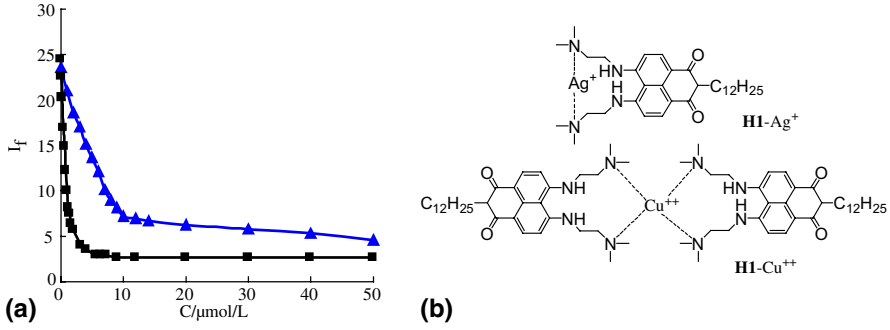


Figure 3. (a) The fluorescence intensity of **H1** (1×10^{-5} mol/L) responds to the different concentrations of Cu^{2+} (■) and Ag^{+} (▲) in Tris–HCl aqueous (pH = 7.5, methanol–water = 1:19, v/v). (b) Structure of the complex **H1**–Ag^{+} and the complex **H1**–Cu^{2+}.

diagnostic for the formation of a complex with 2:1 stoichiometry between **H1** and Cu^{2+}, and a complex with 1:1 between **H1** and Ag^{+} (Fig. 3b).

Ag^{+} and Cu^{2+} resulted in different response in the absorption or fluorescence of **H1**. Comparatively speaking, 4d orbital is far from the nucleus of Ag^{+} with large radius, the attraction of its nucleus to 4d electrons is relatively weaker than compared with the case for Cu^{2+} with small radius and 3d electrons. As a result, the intramolecular d–π interaction of the complex Ag^{+}–**H1** was very strong, which resulted in a red shift in the absorption and emission as well as the color change of **H1**'s solution. In fact, some researchers have confirmed that there was an intramolecular d–π interaction in some coordinated systems.[25,26] The fact that Cu^{2+} was bound with two **H1** (Fig. 3a) implies that four dimethylamino groups of two **H1** might coordinate with one Cu^{2+}. Because of far distances and weak interaction between Cu^{2+} and **H1**'s fluoropfores, absorption and fluorescence wavelength of **H1** were almost unchanged in the presence of Cu^{2+}.

The fluorescence and absorption of **H2** did not change in the presence of transition metal ions (**H2** in Fig. 2b and d), which were different from the case of **H1**. The molecular modeling calculation (Pcmodel 6.0) suggested that, the two ethylenediamino groups of **H1** formed a cavity-like receptor with appropriate size for Ag^{+}, which resulted in strong interaction and short distance between Ag^{+} and **H1**'s fluorophore (6.144 and 6.565 Å from Ag^{+} to 4- or 5-position of naphthalene ring, respectively). However, the two propylenediamino groups of **H2** formed a cavity-like receptor with larger size and resulted in relatively weak interaction (by comparison of Fig. 4a and b) and far distance between Ag^{+} and **H2**

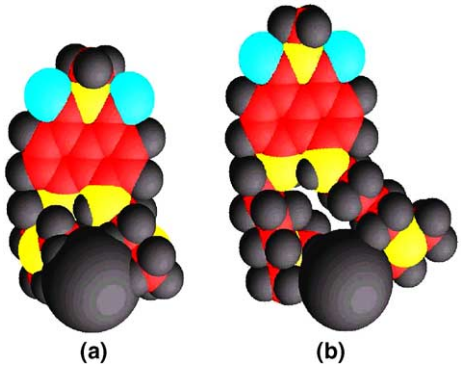


Figure 4. The calculated results (in CPK model) for the interaction between Ag^+ and **H1** (a), Ag^+ and **H2** (b) based on MMX-E of PCmodel 6.0 software.

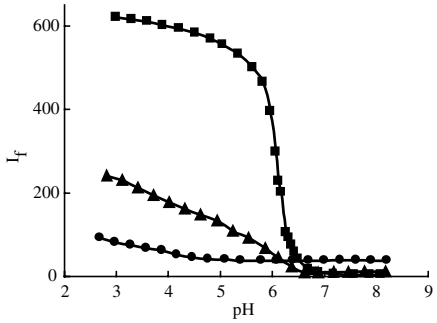


Figure 5. The influence of pH on fluorescence of **H1** (■), **H2** (▲), and **H3** (●) (1×10^{-5} mol/L) in a solution of ethanol and water (1:4, v/v).

(14.424 and 14.504 Å, respectively). Similarly, the chain length of propylenediamino group is longer than that of ethylenediamino group, which resulted in far distance and weak interaction between Cu^{2+} and **H2**'s fluorophore. In addition, almost no fluorescence or absorption signal response was observed for **H3** in the presence of transition metal cations.

The pH sensitivities of **H1**, **H2**, and **H3** as PET fluorescent sensor were also studied for the sake of exploring its potential application to detect protons in a microenvironment. As shown in Figure 5, **H1**, **H2**, and **H3** responded sharply to pH: there was 139-fold fluorescence enhancement for **H1**, 22-fold for **H2**, and 4-fold for **H3** when pH from 8 to 3, respectively.

Obviously, **H1** is a novel chemosensor of naphthalimide with double ethylenediamino receptors for Ag^+ with high sensitivity and selectivity, it could be used in aqueous condition, which is very different from the known fluorescent quenching sensors for Ag^+.[27–31] In fact, so far, very few papers have been published concerning the selective signaling response between Ag^+ and fluorescence probes of anthracene with receptor, for example, polythiazaalkane, polythiaalkane, pyrazolylmethyl, thioazacrown, and so on.[27–31] For silver cation, **H1** probably was the first two-channel molecular switcher for the optical detection of Ag^+. Further applications of **H1** in chemical biology and structure–properties relationships are currently under investigation.

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22. **2**: mp 99.0–101.0 °C, ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.49 (d, $J = 8.0$ Hz, 2H), 7.85 (d, $J = 8.0$ Hz, 2H), 4.13 (α-CH_2, t, $J = 7.4$ Hz, 2H), 1.70–1.71 (m, β-CH_2, 2H), 1.38–1.24 (m, $-CH_2-$, 18H), 0.87 (t, $-CH_3$, $J = 6.6$ Hz, 3H). ^{13}C NMR (400 MHz, $CDCl_3$) δ 163.1, 138.2, 131.7, 126.2,

122.4, 40.9, 32.2, 29.8, 29.7, 29.6, 28.2, 27.3, 22.9, 14.4. **H1**: mp 131.8–133.2 °C, ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.40 (d, $J = 8.4$ Hz, 2H), 6.69 (d, $J = 8.4$ Hz, 2H), 4.12 (α-CH_2, t, $J = 7.6$ Hz, 2H), 3.29 (NH–CH_2, d, $J = 4.4$ Hz, 4H), 2.70 (C–CH_2–N, s, 4H), 2.29 (N–CH_3, s, 12H), 1.70 (β-CH_2, 2H), 1.40–1.24 (–CH_2–, m, 18H), 0.87 (–CH_3, t, $J = 6.8$ Hz, 3H). ^{13}C NMR (400 MHz, $CDCl_3$) δ 164.6, 62.7, 152.7, 143.1, 133.7, 128.4, 111.9, 111.3, 108.6, 106.5, 103.0, 57.5, 45.3, 43.4, 41.9, 41.6, 40.2, 36.3, 32.2, 31.9, 29.9, 29.7, 29.6, 29.3, 28.5, 27.9, 27.5, 25.5, 22.9, 17.6, 14.4. API-ES-MS: $[M+H]^+$ (m/z 538), $[M+Na]^+$ (m/z 560). **H2**: mp 71.8–73.1 °C, ^{1}H NMR (400 MHz, $CDCl_3$) δ ($\times 10^{-6}$): 8.39 (d, $J = 8.4$ Hz, 2H), 6.73 (d, $J = 8.8$ Hz, 2H), 4.11 (α-CH_2, t, $J = 7.6$ Hz, 2H), 3.36 (NH–CH_2, t, $J = 6.4$ Hz, 4H), 2.45 (C–CH_2–N, t, $J = 6.4$ Hz, 4H), 2.25 (N–CH_3, s, 12H), 1.90–1.91 (C–CH_2–C, m, 4H), 1.69–1.70 (β-CH_2, m, 2H), 1.32–1.23 (–CH_2–, m, 18H), 0.86 (–CH_3, t, $J = 6.8$ Hz, 3H). ^{13}C NMR (400 MHz, $CDCl_3$) δ 164.7, 152.7, 133.6, 132.4, 111.8, 111.4, 106.6, 58.5, 45.8, 44.2, 40.2, 32.1, 29.9, 29.7, 29.6, 28.5, 27.5, 26.2, 22.9, 14.3. API-ES-MS: $[M+H]^+$ (566), $[M+Na]^+$ (m/z 588). **H3**: mp 86.2–86.7 °C, ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.53 (d, $J = 8.4$ Hz, 1H), 8.43 (d, $J = 8.0$ Hz, 1H), 7.68 (d, $J = 8.0$ Hz, 1H), 7.33 (d, $J = 8.4$ Hz, 1H), 4.12 (α-CH_2, t, $J = 7.6$ Hz, 2H), 3.43 (–CH_2, d, $J = 12.8$ Hz, 2H), 3.15 (C–CH_2, t, $J = 10.8$ Hz, 2H), 2.95 (C–CH_2, d, $J = 10.8$ Hz, 2H), 2.75 (C–CH_2, t, $J = 10.0$ Hz, 2H), 2.48 (N–CH_3, s, 3H), 1.69 (β-CH_2, m, 2H), 1.37–1.24 (C–CH_2–, m, 18H), 0.86 (–CH_3, t, $J = 6.8$ Hz, 3H). ^{13}C NMR (400 MHz, $CDCl_3$) δ 163.9, 163.6, 155.2, 137.4, 133.2, 132.4, 130.9, 129.6, 122.9, 122.3, 117.1, 116.6, 54.5, 52.9, 45.9, 40.7, 32.2, 29.9, 29.9, 29.6, 29.6, 28.6, 27.4, 22.9, 14.4. API-ES-MS: $[M+H]^+$ (m/z 499).

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