DE GRUYTER Heterocycl. Commun. 2015; aop

Bing Zhao, Yue Fang, Ming-jie Ma, Qi-Gang Deng*, Yu Xu and Li-yan Wang

A new on-fluorescent sensor for Ag^+ based on benzimidazole bearing bis(ethoxycarbonylmethyl) amino groups

DOI 10.1515/hc-2015-0002
Received January 19, 2015; accepted March 20, 2015

Abstract: A new fluorescent sensor based on a benzimidazole unit bearing bis(ethoxycarbonylmethyl) amino groups was designed and synthesized. The ligand exhibits strong sensitivity and selectivity for Ag^+ by enhanced fluorescent intensity in the presence of a wide range of other tested metal ions in methanol. The colorimetric and fluorescent response to Ag^+ can be conveniently detected even by the naked eye, which offers a facile method for visual detection of Ag^+.

Keywords: Ag^+ ion; benzimidazole; fluorescent sensor; naked eye.

Introduction

Some metal ions, such as Ca^{2+}, Fe^{3+}, Zn^{2+}, K^+, Mg^{2+}, Ag^+, and Na^+, are playing a key biological role in human body [1], whereas other heavy metal ions, including Al^{3+}, Cd^{2+}, Cr^{3+}, Hg^{2+}, and Pb^{2+}, can be harmful to organisms [2]. Accordingly, the development of fluorescent probes for the detection of various metal ions is becoming an important research area [3–6]. Over the last decades, the rational design and synthesis of efficient sensors to selectively recognize targets has been a hot topic in molecular recognition studies. Generally, a typical sensor is devised by a covalent linkage of three parts, namely, a receptor unit, a spacer unit, and a signaling unit, although there are some examples of spacer-free probes also. Usually, highly selective probes for transition or heavy elements that give a positive response rather than fluorescent quenching upon the ion binding are preferred to promote the sensitivity factor [7–10]. The design of such turn-on silver ion (Ag^+) sensors is an intriguing challenge because many transition elements often cause fluorescent quenching [11].

Most of the reported signaling units are mainly based on rhodamine [12] and coumarin fragments [13]. The imidazole unit [14, 15] is a newer fluorescent group that is becoming important in the field of chemosensors given its fluorescence off-on behavior that results from its particular structural properties [16]. Park and coworkers [17] have shown that a proper substitution of a tetraphenylimidazole scaffold can lead to white light-emitting compounds by the combination of excited-state intramolecular proton transfer and restricted energy transfer. In addition, a polymer containing thienoimidazole systems can be used for both colorimetric and ratiometric detections of Hg^{2+} as well as fluorometric detection of Zn^{2+} via fluorescence turn-on response with augmented lifetime via the chelation of metal ions to both *S* and *N* heteroatoms [18]. Unfortunately, in the existing reports, the fluorescence enhancement in most cases is small and usually suffers from a high background interference. To our knowledge, few reports have been devoted to fluorescence enhancement of probes for Ag^+.

Results and discussion

In continuation of our work on imidazole derivatives [19], a new silver ion probe **L** was synthesized and studied. The synthetic route to the ligand compound-bearing bis(ethoxycarbonylmethyl)amino and benzimidazole functionalities is outlined in Scheme 1.

The fluorescence properties of ligand **L** were investigated by UV-vis absorption and fluorescence emission spectra in methanol. The UV absorption spectrum of **L** in the presence of various cations is presented in Figure 1. The metal-free ligand shows no absorption higher than 350 nm. The addition of 10 equivalents of metal ion, including K^+, Na^+, Ca^{2+}, Mg^{2+}, Ba^{2+}+, Zn^{2+}, Fe^{3+}, Pb^{2+}, Cu^{2+},

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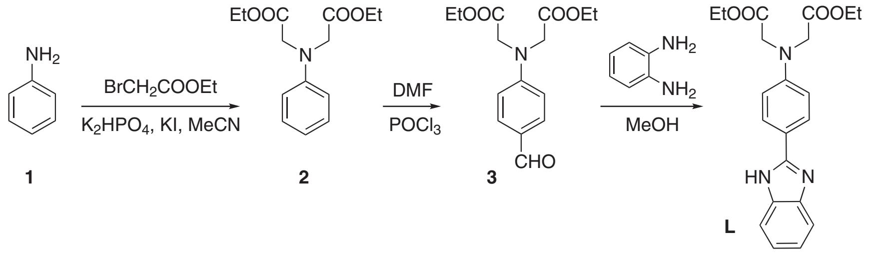
***Corresponding author: Qi-Gang Deng,** Chemistry and Chemical Engineering Institute, Qiqihar University, Qiqihar 161006, China, e-mail: dqigang@163.com
Bing Zhao, Yue Fang, Ming-jie Ma, Yu Xu and Li-yan Wang: Chemistry and Chemical Engineering Institute, Qiqihar University, Qiqihar 161006, China



Scheme 1

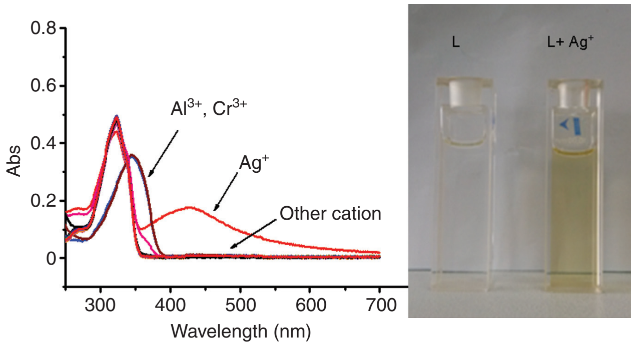


Figure 1 Absorption spectra of **L** (10 µm) in the presence of 10 equivalents of different metal ions in methanol.

Co^{2+}, Ni^{2+}, Cd^{2+}, and Hg^{2+}, results in a little change in absorption (Figure 1), as analyzed by the UV absorption spectrum and the visible absorption observed by the naked eye. Upon the addition of 10 equivalents of Cr^{3+} or Al^{3+}, the UV absorption peak exhibits a slightly red shift from 323 to 345 nm. By contrast, in the presence of Ag^+ ion under otherwise similar conditions, the solution of **L** undergoes a significant color change from colorless to dark yellow (inset in Figure 1) with an emergence of a new absorption peak at approximately 424 nm. These results show the selectivity of the interaction of compound **L** with silver ion in the presence of other ions.

During the spectrophotometric titration of the solution of **L** in methanol by solution of $AgNO_3$ in the same solvent, the optical density of the ligand absorption band (λ_{max}=323 nm) decreases, and the characteristic absorption band of the complex Ag-**L** with λ_{max}=424 nm appears and grows gradually with the increasing concentration of Ag^+ (not shown). This process parallels the color change observed by the naked eye.

The insert shows color change to the naked eye upon the addition of Ag+ to the solution of **L** under otherwise similar conditions.

To further investigate the interaction of Ag^+ and **L**, the fluorescence spectra were analyzed (Figure 2). Compound **L** shows a very weak fluorescence at 424 nm in the absence of metal ions with the fluorescence intensity of approximately 26 a.u. After the addition of metal ion, including Ba^{2+}, Ca^{2+}, Cd^{2+}, Co^{2+}, Cu^{2+}, Fe^{3+}, Hg^{2+}, K^+, Mg^{2+}, Na^{2+}, Ni^{2+}, Pb^{2+}, or Zn^{2+}, changes in the fluorescence emission are minimal. Even in the presence of Al^{3+} or Cr^{3+} when a slight red shift in UV absorption is observed, the fluorescence spectra are still very similar to that of the free ligand **L**. By contrast, the addition of Ag^+ (10 equivalents) causes a remarkable enhancement of fluorescence intensity at

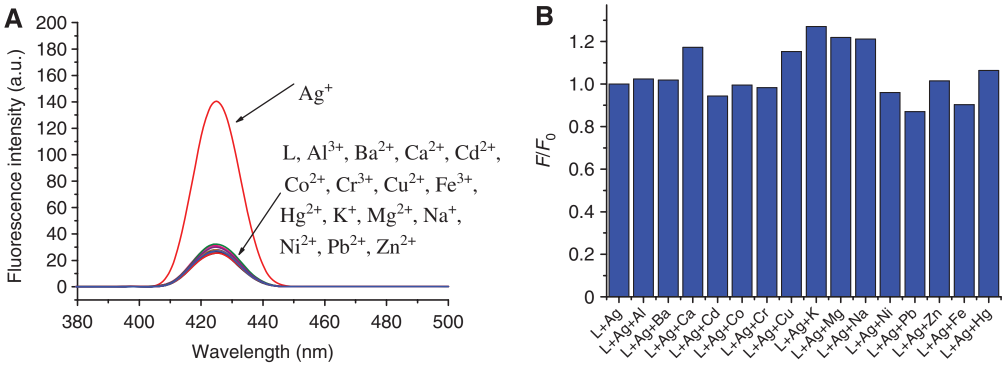


Figure 2 Selective fluorescent spectrum of the interaction of Ag ion and **L**. (A) Fluorescence spectra of **L** (10.0 µm) in the absence and presence of various cations (100.0 µm) in methanol solution (λ_{ex}=323 nm). (B) Fluorescence intensity ratios F/F_0 of **L** (5.0×10^{-7} M, constant) at 424 nm (λ_{ex}=323 nm) in methanol in the presence of Ag+ only (F_0) and in the presence of Ag+ and 10 equivalents of additional metal ion (F).

424 nm by a factor of approximately 5.5 (Figure 2A). To validate the selectivity of **L** toward Ag^+, competition experiments in the presence of Ag^+ only (fluorescence intensity F_0) and in the presence of Ag^+ and other ions (fluorescence intensity F) were conducted. As shown in Figure 2B, the maximum fluorescence intensity ratio F/F_0 is approximately 1.28 for K^+ and the minimum value of 0.86 is observed in the presence of Pb^{2+}. These results demonstrate that the enhancement in fluorescence intensity resulting from the addition of Ag^+ is not influenced significantly by the addition of the background metal ions. Additional experiments showed that the fluorescence quantum yield of the ligand **L** at 424 nm is increased from 0.21 to 0.72 in the presence of Ag^+ in methanol solution.

The fluorescence titration experiments of **L** with Ag^+ in a methanol solution were also investigated in the range of molar ratios $[Ag^+]/[\mathbf{L}]=0–60$. The fluorescence intensity increases with the increasing concentration of Ag+ and reaches a plateau with a ratio of $[Ag^+]/[\mathbf{L}] >20$ (not shown).

To determine the stoichiometry of the Ag-**L** complex, Job's method was applied using fluorescence titration experiments (Figure 3). As can be seen, the fluorescence intensity reaches a maximum for the ratio of $[Ag^+]/\{[Ag^+]+[\mathbf{L}]\}$ of 0.5, which indicates a 1:1 stoichiometry of Ag^+ to **L** in the complex.

Conclusions

A new fluorescence probe L for Ag+ was synthesized and analyzed. The enhancement in fluorescence intensity of **L** upon interaction with Ag^+ may be explained on the basis of the thermodynamically favorable photoinduced electron transfer (PET) mechanism between **L** and Ag^+. The binding of Ag^+ to **L** through the lone pairs of N and O atoms hinders the PET process leading to fluorescence intensity enhancement.

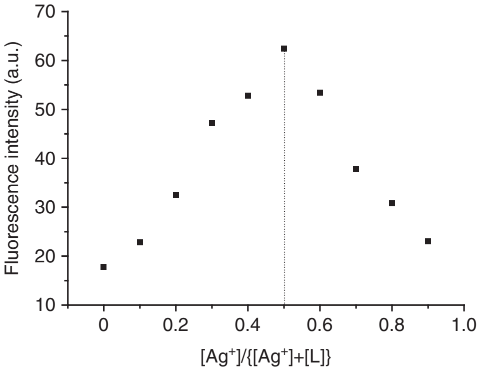


Figure 3 A 1:1 stoichiometry of the host-guest relationship realized from the Job's plot between the probe **L** and the Ag^+.

Experimental

^1H NMR (600 MHz) and ^{13}C NMR (150 MHz) spectra were measured on the Bruker instrument. UV-vis absorption spectra were recorded on a TU-1901 ultraviolet and visible spectrophotometer (1 cm quartz cell) at 25°C. Fluorescence measurements were conducted on a Perkin Elmer LS55 fluorescence spectrometer using a 1-cm quartz cell at 25°C, with excitation and emission slit widths of 10 and 4 nm, respectively, and excitation wavelength at 323 nm. Starting materials **2** and **3** were synthesized according to the reported procedures [20].

Synthesis of ethyl *N*-{[4-(1*H*-benzimidazol-2-yl)] phenyl]}-*N*-[(ethoxycarbonyl)methyl]-aminoacetate (L)

A mixture of *o*-phenylenediamine (5.30 g, 5 mmol) and compound **3** (1.46 g, 5 mmol) in methanol was heated under reflux at 65°C for approximately 6 h until the reaction was completed, as judged by TLC analysis, and then concentrated under reduced pressure. The crude product **L** was subjected to silica gel column chromatography eluting with mixtures of hexanes and ethyl acetate in the ratios from 10:1 to 7:3. The free base **L** was obtained in 77% yield as a gray solid; mp 170.4–171.4°C; IR (KBr, cm^{-1}): 3241, 3109, 2947, 2865, 1678, 1603, 1559, 1511, 1432, 1285, 1103; ^1H NMR (600 MHz, DMSO-d_6): δ 12.55 (s, 1H), 7.96 (d, 2H, J = 8.4 Hz), 7.57 (d, 1H, J = 7.2 Hz), 7.45 (d, 1H, J = 7.2 Hz), 7.13 (m, 2H), 6.71 (d, 2H, J = 8.4 Hz), 4.29 (s, 4H), 4.15 (q, 4H, J = 13.8 Hz), 1.22 (t, 6H, J = 7.2 Hz); ^{13}C NMR (150 MHz, DMSO-d_6): δ 170.7, 152.3, 149.5, 128.0, 119.4, 112.4, 61.0, 53.0, 14.6. Anal. Calcd for $C_{21}H_{23}N_3O_4$: C, 66.13; H, 6.08; N, 11.02. Found: C, 66.29; H, 6.17; N, 10.99.

Acknowledgments: This work was supported by the Program for Education Department of Heilongjiang Province (no. 12541862) and Qiqihar University Graduate Innovation Fund Grants (No. YJSCX2014-028X).

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