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Highly selective fluorescent sensing of Pb^{2+} by a new calix[4]arene derivative

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Abstract—A new chemosensor was synthesized by the alkylation of *p-tert*-butyl-calix[4]arene with three *N*,*N*-diethylacetamide groups and one methyl 3-ethoxy-naphthalene-2-carboxylate, which exhibited highly selective fluorescent response to Pb^{2+} over alkali, alkali earth metal ions and some transition metal ions in $CH_3CN–H_2O$.

Lead (II) ion is one of the most toxic metal ions both to the environment and human body. A wide variety of symptoms, including memory loss, irritability, anemia, muscle paralysis, and mental retardation, have been attributed to lead poisoning.[1] Due to the toxicity of Pb^{2+}, selective signaling of Pb^{2+} is a very important topic for the detection and treatment of the toxic metal ion in various chemical and biological systems.[2,3] Although analytic methods based on atomic absorption and emission spectra for detecting Pb^{2+} have been well-developed, inexpensive, and real-time chemosensors for Pb^{2+} are still pursued eagerly.

Among the chemosensory systems, the fluorescent method will offer many advantages, such as sensitivity, selectivity, switchability, and low cost. Calixarenes are ideal frameworks or building blocks for the development of fluorescent receptors for molecular recognition via the incorporation of an appropriate sensory group. Many fluorescent chemosensors based on calixarenes have been synthesized and show highly selective recognition to alkali and alkaline-earth cations.[4] However, there are only few examples in the literature of calixarenes being used as chemosensors for the heavy metal ions,[5] especially for Pb^{2+}.[6] Herein, we have designed and synthesized a new fluorescent compound with three *N*,*N*-diethylacetamide groups as primary ionophore and a naphthyl ring as fluorophore and secondary ionophore, which shows selective spectra response to Pb^{2+}.

The synthesis of fluorescent chemosensor **3** was convenient through the selective alkylation of *p-tert*-butyl-calix[4]arene **1** with methyl 3-(2-bromoethoxy)-naphthalene-2-carboxylate and *N*,*N*-diethyl-2-chloroacetamide in succession (Scheme 1). We firstly synthesized the mono-alkylated calixarene **2** in 50% yield by the reaction of **1** and 2-methoxycarbonyl-3-(2′-bromoethoxy)naphthalene in the presence of $Ba(OH)_2·8H_2O$ and BaO according to the literature.[7] After further trialkylation of **2** with *N*,*N*-diethyl-2-chloroacetamide in the presence of NaH, the fluorescent ligand **3** could be obtained in 67% yield. Its structure was identified by FT-IR, ^1H NMR, ^{13}C NMR, MALDI-TOF MS, and elemental analyses,[8] indicating that the calix[4]arene backbone of the compound adopted the cone conformation.

The absorption spectra of **3** ($1\times10^{-5}\,mol\,L^{-1}$) in $CH_3CN/H_2O = 3/1$ (pH = 5.2, adjusted with $HClO_4$) were illustrated in Figure 1. Maximum bands were observed at 274 and 340 nm. Upon the addition of 0.5–3.5 equiv of Pb^{2+}, three isobestic points at 260, 278, and 310 nm occurred, which indicated the formation of complex.

In the fluorescent spectra of **3**, the maximum excitation and emission wavelengths were observed at 338 and 410 nm, respectively. The fluorescence intensity of **3** in the presence of increasing amounts of Pb^{2+} was shown

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Keywords: Calix[4]arene; Fluorescent chemosensor; Recognition; Lead (II).

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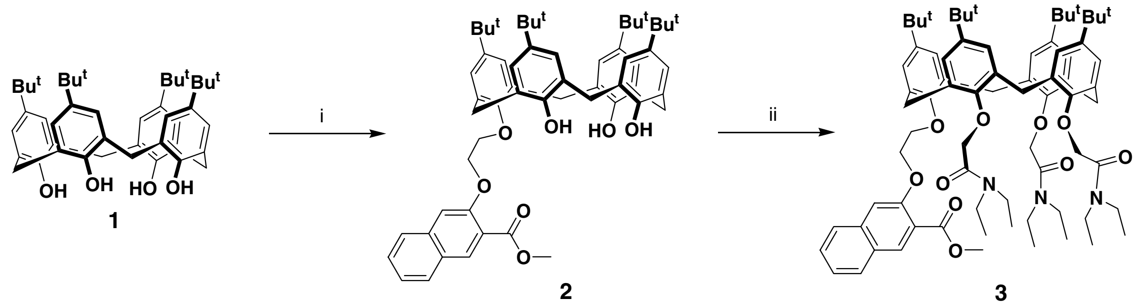

Scheme 1. Reagents and conditions: (i) 2-methoxycarbonyl-3-(2′-bromoethoxy)naphthalene, $Ba(OH)_2{\cdot}8H_2O$, BaO, DMF, rt, 12 h, 50%; (ii) *N*,*N*-diethyl-2-chloroacetamide, NaH, DMF/THF, rt, 12 h, 67%.

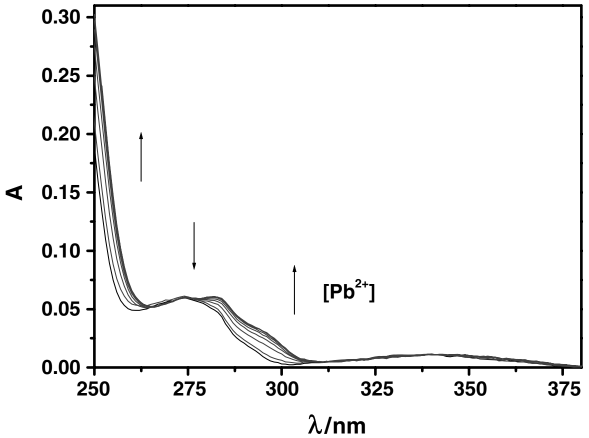

Figure 1. Absorption spectra of **3** (1×10^{-5} mol L^{-1} in MeCN/H_2O = 3/1, pH = 5.2) upon the addition of Pb^{2+}. The concentration of Pb^{2+} were 0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5×10^{-5} mol L^{-1}, respectively.

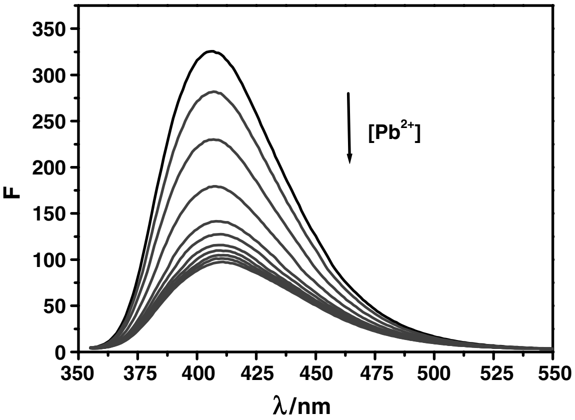

Figure 2. Emission spectra of **3** (1×10^{-5} mol L^{-1} in MeCN/H_2O = 3/1, pH = 5.2) upon the addition of Pb^{2+} (λ_{ex} = 338 nm). The concentration of Pb^{2+} were 0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0×10^{-5} mol L^{-1}, respectively.

in Figure 2. The intensity decreased continually upon the addition of Pb^{2+}, and when the total amount of Pb^{2+} ion exceeded 2 equiv of the host **3**, a plateau was achieved. Evidently, the binding between the *N*,*N*-diethylacetamide groups and Pb^{2+} caused this pronounced quenching, and electron energy transfer (ET) between Pb^{2+} and the naphthyl ring would be the major factor quenching the fluorescence. According to Job's plot, host **3** and Pb^{2+} formed a 1:1 complex and the association constant between the host and metal ion was 6.5×10^4 M^{-1}, deduced by Stern–Volmer equation.

Some other transition metal ions, for example, Co^{2+}, Ni^{2+}, Cu^{2+}, Zn^{2+}, Mn^{2+}, Hg^{2+}, Ag^{+}, and the alkali, alkali earth metal ions had little effect on the fluorescence of chemosensor **3** under the same condition, which indicated **3** as a highly selective fluorescent chemosensor for Pb^{2+} ion (Fig. 3).

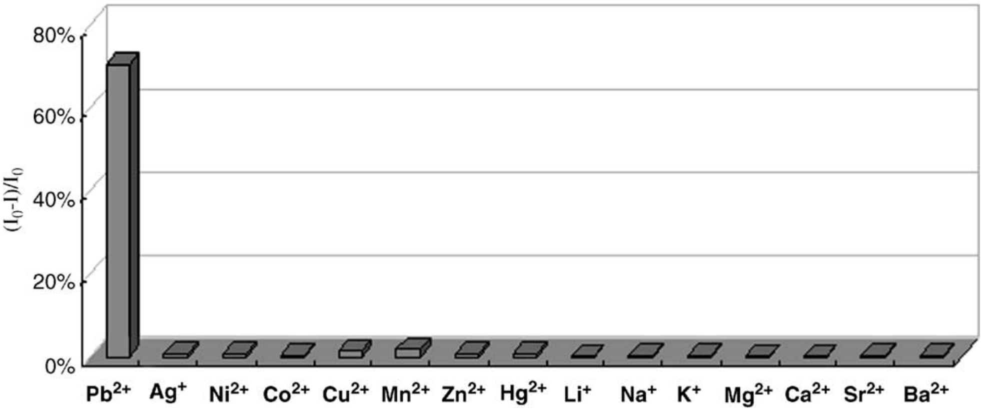

Figure 3. The percentage of emission of **3** quenched by adding metal ions (5×10^{-5} mol L^{-1}) to the solution of compound **3** (1×10^{-5} mol L^{-1}) in MeCN–H_2O (3:1, v/v; pH = 5.2). Metal ions were used in the form of their ClO_4^- or Cl^- salts.

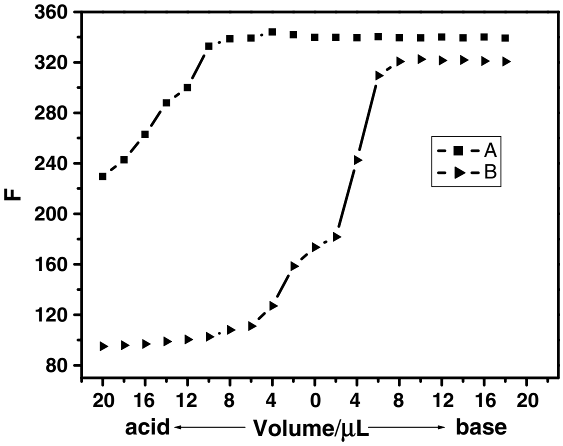

Figure 4. Fluorescence intensity of **3** (2 mL, 1×10^{-5} mol L^{-1}) upon the addition of acid or base (A) free **3**, (B) in the presence of 4 equiv Pb^{2+} in $MeCN–H_2O = 3:1$, v/v; acid: aqueous $HClO_4$, 0.01 mol L^{-1}; base: $(CH_3)_4NOH$, 0.01 mol L^{-1}.

The fluorescent respond to Pb^{2+} of chemosensor **3** could be disturbed seriously by some alkali and alkali earth metal ions, especially by Na^+. The reason might be due to the competition of complexation between calixarene with Pb^{2+} and Na^+. This chemosensor **3**, which consists of the four calixarene phenolic oxygens, one naphtholic oxygen, and three *N*,*N*-diethylacetamide carbonyl oxygens, should be a good ionophore for the hard metal ions, for example, alkali and alkali earth metal ions,[9] and the association constant between sodium ion and a typical receptor[10] similar to **3** is above 10^5, larger than that of **3** with Pb^{2+}. However, there is no ET effect between the fluorophore and the Na^+. Therefore, no fluorescent response occurs when the receptor only binds the Na^+. In the mixture system of **3**, Pb^{2+} and Na^+, sodium ion was favored to be bonded by **3**, and Pb^{2+} was out of the host–guest system.[4f,11] So host molecule **3** lost its fluorescent respond to Pb^{2+}.

The pH value of the solution could also affect the recognition experiment. As shown in Figure 4, OH^- would compete with host molecule **3** in complex of Pb^{2+}, and along with increasing the pH, Pb^{2+} can be gradually displaced from the recognition sites and be bound by OH^- in the solution under basic conditions. The phenomena were in agreement with the previous reports.[7,12]

In conclusion, we have synthesized a new fluorescent ionophore based on *p*-*tert*-butyl-calix[4]arene, using three *N*,*N*-diethylacetamides as the recognition site and methoxy-carbonylnaphthalene as the fluorescent group. It showed high selectivity to Pb^{2+}, and the association constant was up to 6.5×10^4 M^{-1}.

Acknowledgments

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8. Compound **3**: yield: 67%. Mp: 243–245 °C; ^{1}H NMR: δ 8.22 (s, 1H, naph-*H*), 7.82 (d, $J = 8.1$ Hz, 2H, naph-*H*), 7.57–7.55 (m, 2H, naph-*H*), 7.42 (t, $J = 7.7$ Hz, 1H, naph-*H*), 7.16 (s, 2H, Ar*H*), 7.08 (s, 2H, Ar*H*), 7.03 (d, $J = 10.1$ Hz, 2H, Ar*H*), 6.75 (d, $J = 11.7$ Hz, 2H, Ar*H*), 4.93–4.76 (m, 4H, $ArOCH_2CONR_2$, $ArOCH_2CH_2OAr$), 4.59–4.50 (m, 6H, $ArOCH_2CONR_2$, $ArOCH_2CH_2OAr$), 4.35–4.30 (m, 4H, $ArCH_2Ar$), 3.88 (s, 3H, $ArCOOCH_3$), 3.54–3.04 (m, 16H, $ArCH_2Ar$, NCH_2CH_3), 1.17 (s, 18H, $C(CH_3)_3$), 1.12 (s, 18H, $C(CH_3)_3$), 1.21–0.96 (m, 18H, NCH_2CH_3); ^{13}C NMR: δ 167.5, 166.9, 166.8, 154.5, 150.8, 150.4, 149.9, 148.2, 148.0, 147.2, 136.0, 134.7, 134.4, 134.3, 132.2, 128.6, 128.4, 127.6, 126.6, 126.0, 125.8, 125.7, 124.7, 122.2, 108.3, 75.0, 74.0, 73.8, 67.2, 52.3, 41.0, 40.9, 40.6, 40.3, 34.2, 34.1, 31.4, 31.3, 30.3, 30.0, 14.4, 14.0, 13.2, 13.1; IR (KBr): v 2960, 1719, 1644, 1479, 1455 cm^{-1}; MALDI-TOF MS: *m*/*z* 1238 ($[M+Na]^+$), 1252 ($[M+K]^+$). Anal. Calcd for $C_{76}H_{101}O_{10}N_3$: C, 75.03; H, 8.37; N 3.45. Found: C, 75.18; H, 8.42; N, 3.18.
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