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A highly sensitive and selective fluorescent molecular sensor for Pb(II) based on a calix[4]arene bearing four dansyl groups

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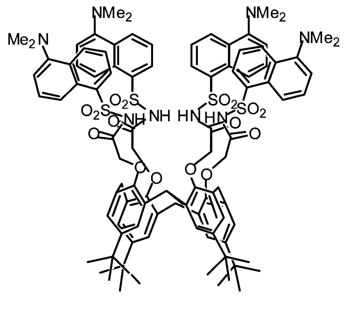
A new fluorescent molecular sensor based on a calix[4]arene bearing four dansyl groups exhibits very efficient binding in acetonitrile–water for lead and the changes of emission properties allows a detection limit of 4 μg L^{-1}.

Among heavy metal, lead is the most abundant and certainly the most toxic causing health problem such as digestive, neurologic, cardiac and mental troubles. Lead is particularly dangerous for children causing mental retardation. Thus, the level of this detrimental ion, which is present in tap water resulting of dissolution from household plumbing systems, is the object of several official norms. The World Health Organisation had established in 1996[1] the guideline for drinking-water quality, which included a lead maximal value of 10 μg L^{-1}. Currently the amount of lead is measured using atomic absorption or emission spectroscopies,[2] but the use of fluorescence will offer many advantages in terms of sensitivity, selectivity and low cost. In contrast to the variety of fluorescent molecular sensors developed for alkali and alkaline-earth cations,[3] there are only few examples of fluoroionophores developed for heavy metal ions[4] and in particular for lead.[5] Among the macrocyclic complexing agent for transition metal ions, calixarenes offer a number advantages in terms of selectivity and efficiency of binding.[6] In particular, Bartsch has shown that a calix[4]arene bearing *N*-(X)sulfonylcarboxamide exhibits good extraction selectivity for Hg^{2+} and Pb^{2+} over alkali and transition metal ions.[7] A calix[4]arene with two dansyl groups[8] as part of the *N*-sulfonylcarboxamide has been used for selective sensing by extraction of Hg^{2+} in acidic solutions in the millimolar concentration range. Moreover, it is well-known in coordination chemistry that the complexation of lead with a ligand containing at least three nitrogen donor atoms is favoured by the activation of the inert pair on the Pb^{2+} ion leading to a shortening of the Pb–N bond length and a much more covalent bonding.[9] In order to obtain a selective fluoroionophore for Pb^{2+}, we now report the synthesis and the fluorescence properties of a calixarene **1** containing four dansyl groups. The compound **2** has been studied as a reference compound.



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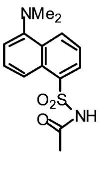

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The advantages of multichromophoric sensors have already been outlined in terms of sensitivity of detection and improved photochemical stability,[10] in particular for sensors based on dansyl dendrimers.[11]

The synthesis of the calixarene **1** was performed by condensation of dansylamide with calixarene tetracarboxylic acid[12] in the presence of KH.† The compound **2** was synthesized starting from acetic acid.‡ The photophysical and complexing studies have been performed in $CH_3CN–H_2O$ (60 : 40 v/v).

Before studying the binding effect of **1** upon complexation with cation, the protonation constants and the photophysical properties of the different acido-basic forms of **2** were determined by spectrophotometry and fluorescence titration.§ The pK_a corresponding to the protonation of the dimethylamino group was found to be 2.4. The acidity of the sulfonylcarboxamide group (pK_a is 6.3) shows that the carbonyl group leads to a decrease of 4 units of pK_a as compared to the ligand containing dansyl groups.[13] The absorption spectra of the LH_2^+, LH and L^- forms are almost the same as those of the corresponding forms of dansylamide. The deprotonation of the neutral form induces an enhancement of the fluorescence quantum yield of 4.5-fold (Φ_F = 0.11 (LH), 0.49 (L^-)).

In the case of **1**, the optimum pH, at which **1** is mainly in the neutral form in order to have the stronger photophysical effects upon lead binding, was found to be 5.2.

Addition of Pb^{2+} to **1** causes a 52 nm blue shift of the fluorescence spectra and a 1.7-fold enhancement of the fluorescence quantum yield (Fig. 1). The absorption spectra are also shifted to higher energy (11 nm) upon lead binding. The effect can be compared to the results previously obtained on dansyl-containing ion sensors.[14] The blue shift is rationalized by the deprotonation of the sulfonamide group upon cation binding. Scheme 1(a) shows a possible structure of the 1 : 1 complex. Its fluorescence quantum yield is lower than that of the basic form of the free ligand. This can be explained by a

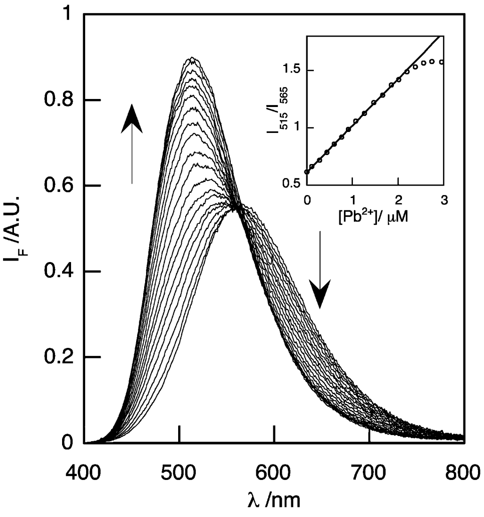

Fig. 1 Corrected fluorescence spectra of **1** (3.6 μM) in the presence of increasing concentration of Pb^{2+} in $CH_3CN–H_2O$ (60 : 40 v/v) in lutidine buffer, pH = 5.2. λ_{exc} = 350 nm. Inset: Ratiometric calibration curve I_{515}/I_{565} as a function of lead concentration.

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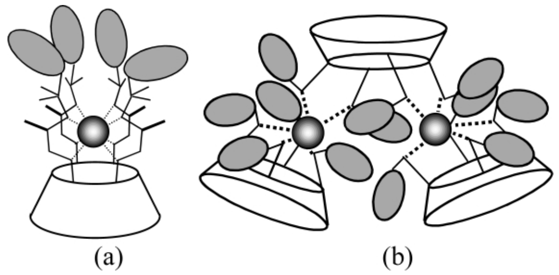

Scheme 1 Binding model of **1** with Pb^{2+}: (a) 1 : 1 ML and (b) 2 : 3 M_2L_3

reduction of the charge density of the anionic nitrogen atoms due to the interaction with the metal. The observed shift of the emission spectra allows a ratiometric measurement.[15] A linear response as a function of lead concentration was obtained from 0 to 2 μM. The detection limit calculated as three times the standard deviation of the background noise was found to be 0.02 μM (4 μg L^{-1}).

The stability of the complex was then examined. Careful analysis of the evolution of the emission spectra revealed that a 2 : 3 complex and a 1 : 1 complex with Pb^{2+} were successively formed with very high stability constants ($\log K_{2:3} = 33.5 \pm 1.5$ and $\log K_{1:1} = 10.0 \pm 0.5$). The photophysical properties of the 2 : 3 complex are similar to that of the 1 : 1 complex. This clearly means that all the dansyl groups are coordinated to Pb^{2+} in both cases. Thus, Scheme 1(b) represents a possible structure of the 2 : 3 complex which is consistent with a coordination number of six. Complexes resulting from oligomerisation of calixarenes have been previously reported in the literature.[16] In such a complex, activation of the Pb^{2+} inert pair leads to large stability constants.

The selectivity of **1** over other cations such as Hg^{2+}, Cd^{2+}, Ca^{2+}, Na^+, K^+, Cu^{2+} and Zn^{2+} was evaluated. The stability constants of the 1 : 1 complexes obtained with these cations are: $\log K_{Na^+} = 4.86$; $\log K_{K^+} = 3.69$; $\log K_{Hg^{2+}} = 6.5$; $\log K_{Ca^{2+}} = 7.23$; $\log K_{Cd^{2+}} = 7.3$; $\log K_{Cu^{2+}} = 4.8$. The selectivity towards Pb^{2+} with respect to the other cations (expressed as the ratio of the stability constants) was found to be higher than 1000. Moreover, the competition-based fluorescence effect profiles for these metal ions are shown in Fig. 2. The measurements were done with a very low concentration of ligand (0.02 μM). No significant interference was observed upon complexation with competing cations under these conditions.

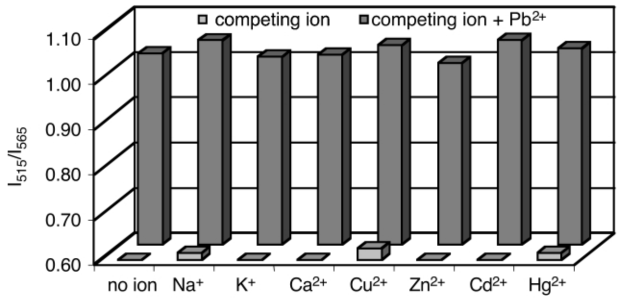

Fig. 2 Response I_{515}/I_{565} of **1** (0.02 μM in CH_3CN–H_2O (60 : 40 v/v) in lutidine buffer, pH = 4.2, in the presence of selected metal ions 0.02 μM. λ_{exc} = 350 nm.

In conclusion, **1** can detect Pb^{2+} very efficiently and selectively in a mixture of CH_3CN and H_2O. The estimated detection limit is unprecedented (4 μg L^{-1}) and compatible with the level defined by Health Institution.

Notes and references

† *Synthesis* of **1**: *p-tert*-butylcalix[4]arene-tetraacetic acid (1 mmol) and oxalyl chloride (20 mmol) in dry benzene were refluxed for 5 h under argon atmosphere. The mixture was evaporated *in vacuo*, then dissolved in a solution of potassium hydride (20 mmol) and dansylamide (6 mmol) in dry THF, and stirred for 12 h at room temperature under argon. After destroying the excess KH and evaporation of the solvent, the crude product was purified by column chromatography (SiO_2, CH_2Cl_2–CH_3OH 98 : 2) to give a yellow solid which was dissolved in CH_2Cl_2. The solution was washed with 1 M HCl and then with water, dried over $MgSO_4$, and evaporated *in vacuo* to provide a 69% yield of bright yellow solid. Mp 190–191°C; δ_H (300 MHz, $CDCl_3$): 1.00 (s, 36H), 2.79 (s, 24H), 2.89 (d, *J* 12.9, 4H), 4.09 (d, *J* 12.9, 4H), 4.30 (s, 8H), 6.61 (s, 8H), 7.01 (d, *J* 7.7, 4H), 7.49 (m, 8H), 8.41 (d, *J* 8.8, 4H), 8.53 (m, 8H); Anal. Calc. for $C_{100}H_{112}N_8O_{16}S_4 \cdot H_2O$: C, 65.69; H, 6.28; N, 6.13; S, 7.02. Found: C, 65.55; H, 6.31; N, 5.93; S, 7.12%.

‡ *Synthesis* of **2**: model compound **2** was prepared analogously to **1** from acetic acid as a yellow solid in 45% yield. Mp 211°C; δ_H (300 MHz, $CDCl_3$): 2.03 (s, 3H), 2.90 (s, 6H), 7.20 (d, *J* 7.7, 1H), 7.59 (dd, J_1 7.7, J_2 8.5, 2H), 8.20 (d, *J* 8.5, 1H), 8.45 (s, 1H), 8.47 (d, *J* 7.7, 1H), 8.63 (d, *J* 8.5, 1H); Anal. Calc. for $C_{14}H_{16}N_2O_3S \cdot 0.5H_2O$: C, 55.80; H, 5.69; N, 9.30; S, 10.64. Found: C, 55.99; H, 5.36; N, 9.12; S, 10.80%.

§ The protonation and complexation constants were determined by global analysis of the evolution of all the absorption or fluorescence spectra by using the Specfit Global Analysis System V3.0 for 32-bit Windows system.

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