

Cadmium-113 NMR and Theoretical Studies of Complexation of Cadmium Ion with 15-Crown-5 and Benzo-15-Crown-5 in Acetonitrile and Its Binary Mixtures with Water and Nitromethane

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Abstract

Cadmium-113 nuclear magnetic resonance was used as a sensitive probe to study the interaction of Cd²⁺ ion with 15-crown-5 and benzo-15-crown-5 in acetonitrile and its binary mixtures with water and nitromethane. The observed ¹¹³Cd-NMR chemical shift changes at a constant Cd²⁺ ion concentration and varying crown concentrations were found to be consistent with a fast exchange model. The formation constants of the resulting 1:1 complexes were evaluated from computer fitting of the chemical shift-mole ratio data to an equation which relates the observed chemical shifts to the formation constant. The geometries of the macrocyclic ligands and their cadmium complexes were optimized by an *ab initio* method, and the calculated binding energies of the resulting complexes were compared. Both the ¹¹³Cd-NMR and *ab initio* studies revealed that, in all cases, 15-crown-5 forms a more stable Cd²⁺ complex than benzo-15-crown-5. In the case of the both crown ethers, there is an inverse relationship between the stability of complexes and solvating ability of the solvent systems used.

Introduction

Growing attention is paid to crown-ether chemistry in a variety of scientific and technological areas [1–4], though over three decades has passed since Pedersen first synthesized these series of compounds [5]. The elucidation of crown ether chemistry has been followed by studies on syntheses of compounds bearing superior complexation abilities and/or novel selectivities; such effort is still continuing [6, 7]. The specificity and strength of the binding are depended, in part, on the crown ether cavity size, the type and number of donor atoms (e.g., oxygen, nitrogen, sulfur) and the nature of solvent [8–10]. In addition, many theoretical investigations have been undertaken to understand better the fundamental interaction between ions and crown ethers and their relationship to molecular recognition [11–13].

Cadmium is a highly toxic metal and is known as a significant environmental pollutant with a wide variety of adverse effects. Occupational exposure to cadmium has long been known to be harmful to the kidney, lung and liver [14, 15]. Many organic compounds, including crown ethers, play an important role in complexing

cadmium and are important determinants of the environmental fate and transport of Cd²⁺ [16, 17].

It is important to develop methods capable of the precise determination of complexation constants that could be the most powerful and simplest criterion to show the efficiency of a compound. Among a variety of physico-chemical methods employed for such studies [1, 3], the nuclear magnetic resonance technique (NMR) is particularly sensitive to small changes in the electronic environment of a magnetic nucleus brought about upon complexation with different ligands. From this NMR information, the complexation constant and the related thermodynamic properties can be quantitatively evaluated [10, 18, 19].

Cadmium-113, which is one of the common isotopes of cadmium, is readily observed by NMR and the free cadmium ion produces a single sharp peak in the NMR spectrum. ¹¹³Cd is an excellent metal ion probe due to its relatively high natural abundance of the spin $I = 1/2$ isotope (12.26%). Furthermore, the ¹¹³Cd chemical shift covers a wide range from 750 to –200 ppm, so that the nature of coordinating ligands and their coordination numbers can be strongly reflected in the chemical shift. ¹¹³Cd-NMR method is widely exploited for studies on metal binding sites of natural organic matters and biomolecules [20–23].

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In view of the important role of crown ethers in cadmium complexation and transport in environment, in this paper, we conducted a ^{113}Cd -NMR study of the binding of Cd^{2+} ion to 15-crown-5 (15C5) and benzo-15-crown-5 (B15C5) in acetonitrile (AN) and its binary mixtures with water and nitromethane (NM). To the best of our knowledge, there is no previous report on the use of ^{113}Cd -NMR in complexation studies of Cd^{2+} ion with macrocyclic ligands.

Experimental

Reagent grade cadmium nitrate (Fluka) and crown ethers 15C5 and B15C5 (both from Merck) were of the highest purity available and used without any further purification except for vacuum drying. Acetonitrile (AN, Fluka) and nitromethane (NM, Aldrich) were dried over 4 Å molecular sieves before use. Doubly distilled deionized water was used. Deuterated acetonitrile (>99% purity) as a lock signal for NMR experiment was purchased from Merck. The binary mixed solvents 60%AN-40% NM and 40%AN-60% NM, 20%AN-80% NM and 80%AN-20% H_2O were prepared by weight.

All Nuclear magnetic resonance measurements were carried out on a Bruker DRX 500 AVANCE Spectrometer with field strength of 11.744 T. At this field, cadmium-113 resonates at 110.914 MHz. A 0.5 M cadmium nitrate in D_2O was used as an external reference and the reported Cd-113 chemical shifts refer to this solution. The paramagnetic (downfield) shift from the reference is designated as being positive. All chemical shift measurements were carried out at a probe temperature of 25.0 ± 0.1 °C. The concentration of all cadmium nitrate solutions used was 0.05 M.

Since a large number of scans are required to obtain usable ^{113}Cd -NMR spectra of dilute solutions of cadmium, it is seldom experimentally practical to use pulse delays that are sufficient to allow complete relaxation of the free Cd^{2+} ion. Accordingly, the relative abundance

of the free Cd^{2+} ion may be underestimated whenever both free and complexed forms of cadmium are present in solution. Typical acquisition parameters were 55555.55 Hz sweep width, 512–1024 scans, 2.5 s relaxation delay, 0.3 s acquisition time and 5 μs pulse width (30° pulse) without proton decoupling. A 2.0 Hz line broadening was applied.

Results and discussions

NMR studies

Cadmium-113 chemical shifts were monitored as a function of crown/ Cd^{2+} ion mole ratios in different solvent systems used and the resulting mole ratio plots for 15C5 and B15C5 complexes are shown in Figures 1 and 2, respectively. In all cases, only one population average signal was observed, irrespective of the crown/metal ion ratio. In general, if the mean lifetime for the exchange of the metal ion between the two sites (i.e., free ion in the bulk solution and the complex) is smaller than $\sqrt{2/\pi}\Delta\nu$ ($\Delta\nu$ is the difference between the characteristic resonance frequencies of the two sites in Hertz), only one population average resonance is observed.

From the chemical shift-mole ratio data shown in Figures 1 and 2, it is seen that the resonance frequency of cadmium-113 is shifted upfield upon addition of both crown ethers until a crown/ Cd^{2+} mole ratio of about 1 is reached. Further addition of the ligand does not change the cadmium resonance frequency considerably. Such a behavior indicates the formation of a relatively stable 1:1 complex in solution. This is not unexpected, since Cd^{2+} ion with an ionic size of 1.96 Å [24] has a suitable fitting condition inside the cavity of 15-crown-5 with a size of 1.7–2.2 Å [25].

In order to get further information about the stoichiometry and stability of Cd^{2+} -15C5 complex in AN solutions, the complexation reaction was studied by ^1H NMR spectroscopy. In this case, a 0.05 M solution of

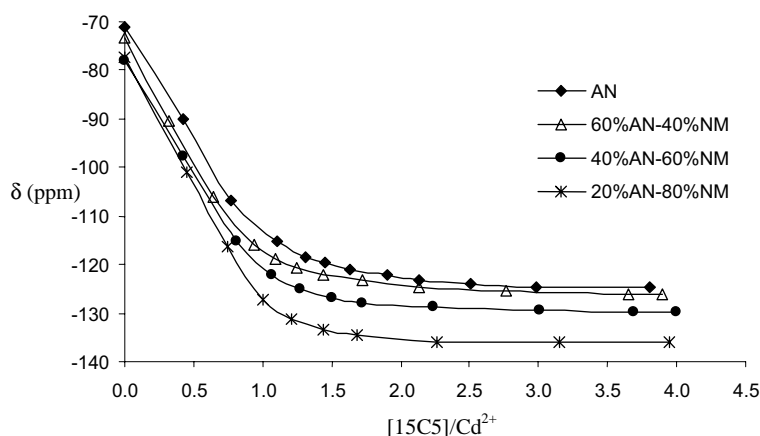


Figure 1. Variation of ^{113}Cd chemical shift as a function of $[\text{15C5}]/[\text{Cd}^{2+}]$ mole ratio in different binary AN–NM mixtures.

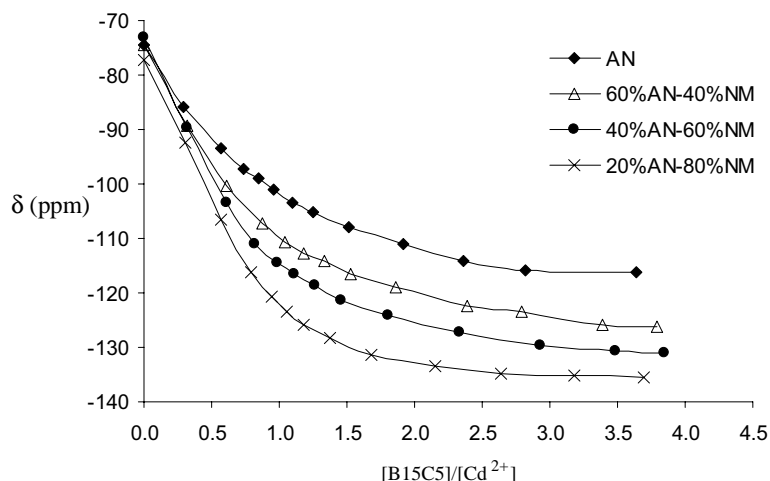


Figure 2. Variation of ^{113}Cd chemical shift as a function of $[\text{B15C5}]/[\text{Cd}^{2+}]$ mole ratio in different binary AN–NM mixtures.

15C5 in deuterated AN was titrated with Cd^{2+} ion and the chemical shift of the singlet ^1H NMR signal of the ligand was measured as a function of $\text{Cd}^{2+}/15\text{C5}$ mole ratio, and the resulting plot is shown in Figure 3. As is obvious, the gradual downfield shift of ^1H NMR begins to level off at a mole ratio of about 1, once again emphasizing the formation of a relatively stable complex in solution.

The formation constants of the resulting 1:1 complexes were calculated from the variation of ^{113}Cd chemical shift with the crown/ Cd^{2+} mole ratio. It has been shown that, in the cases where there is fast exchange between free and complexed metal ions, the observed chemical shift of the resulting single NMR signal is given by [26]:

$$\delta_{\text{obs}} = \left\{ \left[(K_f C_M - K_f C_L - 1) + (K_f^2 C_L^2 + K_f^2 C_M^2 - 2K_f^2 C_L C_M + 2K_f C_M + 1)^{1/2} \right] \times (\delta_M - \delta_{\text{ML}}) / 2K_f C_M \right\} + \delta_{\text{ML}}, \quad (1)$$

where K_f is the concentration formation constant for the 1:1 complex, C_L and C_M are the analytical concentration of the crown ether and Cd^{2+} ion, respectively, and δ_M and δ_{ML} are the respective chemical shifts of the free and complexed cadmium ion. A non-linear least-squares curve fitting program, KINFIT [27], was used to evaluate K_f and δ_{ML} values for the 1:1 complexes. A sample computer fit of the ^{113}Cd chemical shift-mole ratio data is shown in Figure 4.

All the resulting formation constants are listed in Table 1. As is immediately obvious, there is an excellent agreement between the K_f values for Cd^{2+} -15C5 in AN solution obtained by ^{113}Cd - and ^1H -NMR methods.

From the data given in Table 1 it is obvious that, in all solvent systems, the presence of a benzo group in B15C5 would cause a significant decrease in the stability of the resulting Cd^{2+} complex, compared with Cd^{2+} -15C5. This behavior could be due to some combination of the electron withdrawing effect of the benzo group, which weakens the electron-donor ability

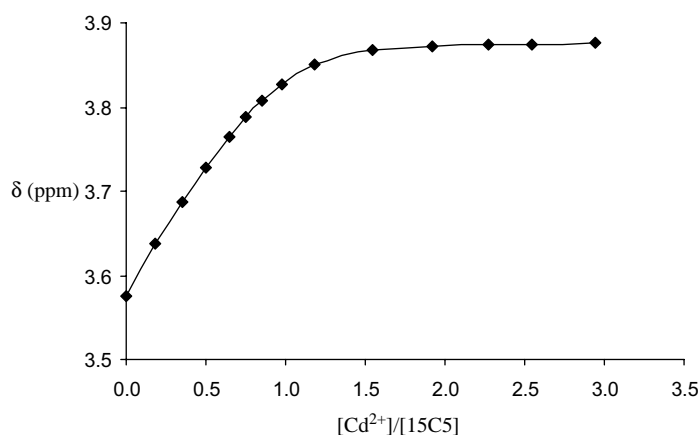


Figure 3. Variation of ^1H chemical shift as a function of $[\text{Cd}^{2+}]/[15\text{C5}]$ mole ratio in AN solution.

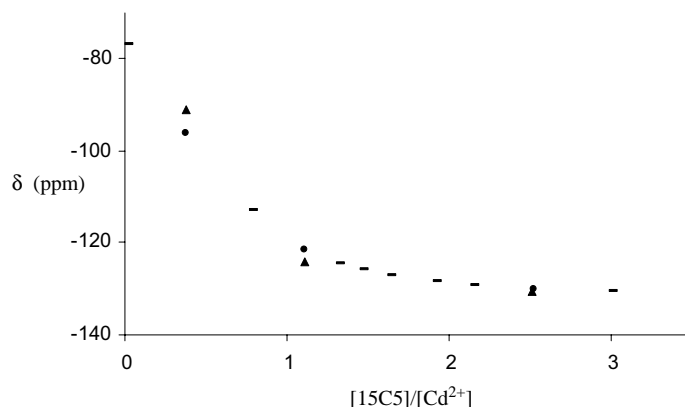


Figure 4. Computer fit of the mole ratio data for Cd^{2+} -15C5 complex in AN solution; (●) experimental point; (▲) calculated point; (—) experimental and calculated points are the same within the resolution of the plot.

Table 1. Formation constants of Cd^{2+} complexes with 15C5 and B15C5 in different solvent systems at 25 °C

15C5		B15C5	
Solvent	$\log K_f$	Solvent	$\log K_f$
AN	2.35 ± 0.04	AN	1.81 ± 0.03
AN ^a	2.33 ± 0.03	—	—
80%AN-20% H ₂ O	1.40 ± 0.02	80%AN-20% H ₂ O	1.02 ± 0.04
60%AN-40% NM	2.42 ± 0.04	60%AN-40% NM	2.02 ± 0.04
40%AN-60% NM	2.64 ± 0.03	40%AN-60% NM	2.25 ± 0.06
20%AN-80% NM	2.77 ± 0.02	20%AN-80% NM	2.25 ± 0.05

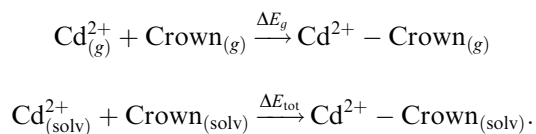
^a¹H NMR result.

of the ring oxygens, and the reduced flexibility of the macrocycle, which prevents the molecule wrapping itself around the cation. The net result is a much weaker cation–crown interaction.

The fundamental importance of solvent properties on the stabilities of the Cd^{2+} -crown ether complexes is quite evident from the data given in Table 1. As seen, the complex stability in the solvent systems used decreases in the order 20%AN-80% NM > 40%AN-60% NM > 60%AN-40% NM > AN > 80%AN-20%H₂O. It is well known that the solvating ability of the solvent, as expressed by the Gutmann donor number [28], plays a key role in different complexation reactions [18, 29–33]. Acetonitrile and nitromethane are solvents of similar dielectric constant (i.e., $\epsilon_{\text{AN}} = 37.5$ and $\epsilon_{\text{NM}} = 35.6$) but of quite different donor numbers (i.e., $\text{DN}_{\text{AN}} = 14.1$ and $\text{DN}_{\text{NM}} = 2.7$) [28]. Consequently, in the process of complexation of Cd^{2+} with crown ethers 15C5 and B15C5, AN more strongly competes with ligand for the metal ion than does NM. Thus, it is not surprising that addition of NM to AN will increase the stability of Cd^{2+} -crown ether complexes considerably. On the other hand, as expected, the addition of water (even in a 20% level), as a solvent of both high dielectric constant and high donor number (i.e., $\epsilon_{\text{H}_2\text{O}} = 78.4$ and $\text{DN}_{\text{H}_2\text{O}} = 33$) [34], can cause a strong competition of the solvent molecules with the crown ethers for Cd^{2+} ion and, consequently, resulted in the least stable complexes in the series.

Theoretical study

Initial uncomplexed and complexed ligands geometries were generated with molecular mechanic force field optimization. Each molecule was optimized at the *ab initio* restricted Hartree–Fock (RHF) level of theory using the Lanl2mb basis set for all atoms. Full optimization of all bond lengths, angles and torsion angles was carried out using the Gaussian 98 program [35] on a Pentium 4 workstation. Vibrational normal mode analyses were performed at the RHF level of theory to ensure that each optimized structure was a true minimum on the potential energy surface, and the zero-point vibrational energies were evaluated at the RHF level of theory. Gas phase binding energy (ΔE_g) was reported for the energy of the Cd^{2+} -crown's optimized structure relative to the sum of the energies of the optimized ligand and the free Cd^{2+} ion separately. The solvent effect was obtained using the polarized continuum (overlapping spheres) model (PCM) of Tomasi and Persico [36] and the total binding energy include solvent energy (ΔE_{tot}) for the following equations in AN was calculated at the RHF level of theory.



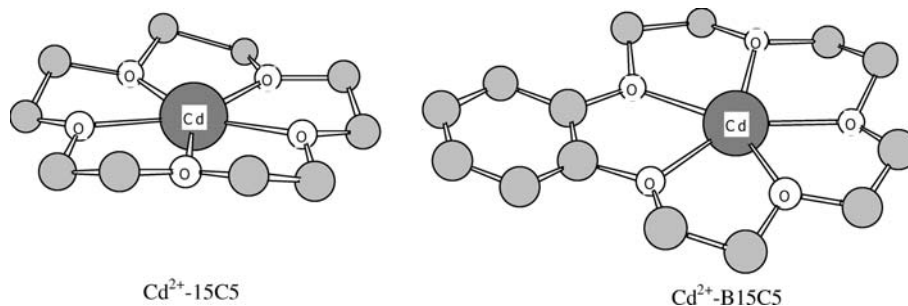


Figure 5. Optimized structures of cadmium complexes with 15C5 and B15C5 using the *ab initio* method.

Table 2. Selected geometric parameters, gas phase energy and total energy include solvent energy of Cd^{2+} complexes with 15C5 and B15C5

Complex	Average Cd···O distance	Average charge on ether oxygens	ΔE_g (kCal/mol)	ΔE_{tot} (kCal/mol)
$\text{Cd}^{2+}/15\text{C5}$	2.184	-0.257	-387.42	-243.82
$\text{Cd}^{2+}/\text{B15C5}$	2.186	-0.254	-385.81	-237.04

The optimized structure of 1:1 complexes of Cd^{2+} ion with 15C5 and B15C5 are shown in Figure 5. From these optimal geometries, the binding energy (ΔE_g), which is a direct measure of the stability of complex formation, was calculated. Selected geometric parameters of the optimized structure of Cd^{2+} complexes of ligands are summarized in Table 2. The increased average Cd···O distance of Cd^{2+} -B15C5 (2.186 Å) compared with Cd^{2+} -15C5 (2.184 Å) as well as the decreased average charge on ether oxygen in Cd^{2+} -B15C5 (-0.254) compared with Cd^{2+} -15C5 (-0.257) emphasized that the addition of a benzo group on the 15C5 ring would result in the decreased stability of the resulting complex. It should be noted that the average charge on ether oxygens in the free ligands 15C5 and B15C5 were calculated as -0.241 and -0.234, respectively. This behavior can be related to the electron withdrawing effect of the benzo group and reduced flexibility of the B15C5 ring. As expected, the presence of solvent molecules would cause to reduce the calculated total binding energy of these complexes; while, the extent of reduction in binding energy in Cd^{2+} -B15C5 is larger than that in Cd^{2+} -15C5. This behavior could be related to some π - π interaction between AN (as solvent) and the benzo group of B15C5 molecule that enhances the electron withdrawing effect of the benzo group and, consequently, more reduces the stability of the Cd^{2+} -B15C5 complex.

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