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Cesium Complex of an Unsymmetrical Calix[4]crown-dibenzocrown-6

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Abstract

An unsymmetrical calix[4]-*bis*-crown ether having both conventional crown-6 and dibenzocrown-6 rings in a fixed 1,3-alternate conformation was synthesized with good yield by the reaction of a monocyclic calix[4]crown-6 with dibenzodimesylate in the presence of cesium carbonate. The cesium ion selectivity among alkali metal ions increased compared to symmetrical calix[4]-*bis*-crown-6. The solid state structure of the ligand-cesium complex illustrates a 1:2 complex ratio. On the contrary, in solution, e.g., extraction equilibrium and ^{1}H NMR experiment gave a 1:1 complex ratio. From the result of the chemical shift change upon metal ion complex, the cesium ion seems to prefer the dibenzocrown loop to the conventional crown-6 ring.

Introduction

Calixarenes have been interesting in their great number of applications in selective separation of specific metal or molecular inclusions [1–4]. In particular, the four phenolic OH of the calix[4]arene lower rim can be further functionalized to feasibly give various ionic receptors [5]. Calixcrown ethers in which the proper-sized crown rings are incorporated into the calixarene framework have also attracted intense interest as a specific metal-selective extractant. Especially, calix[4]crown-6 in which the pentaethylene glycol unit connects with the 1,3-dialkyloxy calix[4]arene framework within the 1,3-alternate type was known to give high cesium ion selectivity over other alkali metal ions [6–14]. This cesium ion selectivity was ascribed not only to size agreement of the crown ether moiety based on electrostatic interaction between the electron donor atom and metal cation, but also to cation-π interaction between two rotated aromatic nuclei and the cesium cation. 1,3-Alternate calix-*bis*-crowns have particularly interesting molecular features including (i) two crown loops able to adopt 1 : 2 complexation and (ii) cation-π interaction between two rotated benzene rings and the metal ion [15]. Previously Thuéry [12] and Kim [8] have reported that introduction of phenyl groups on the oxyethylene glycol unit of the calixcrown frame enhanced the specific metal ion selectivity because the benzo unit of the crown loop provides characteristic sp^2 carbon followed by a flattened crown cavity. Vicens group also recently reported that unsymmetrical calix-*bis*-crown-6 containing both crown-6 and arylene-modified crown-6 formed a 1 : 1 complex [16]. Interestingly, the cesium ion was located in the arylene-modified crown-6 instead of in the conventional crown ether loop, which was proved by X-ray crystal structure analysis.

There are some contrary discussion for the Cs$^+$-π interaction in this 1,3-alternate calixdibenzocrown system. For instance, Lamare reported that the presence of benzo or dibenzo groups on the ethylene glycol unit of the calixcrown loop does not support an increase in Cs-π interactions compared to the simple calixcrown compound by MD calculation [17, 18]. Arnaud-Neu *et al.* also reported a detailed thermodynamic study in which for the Cs/Na selectivity the presence of benzo substituents has no significant influence on cesium complexation, but disfavors sodium complexation [19].

In parallel to the previous studies of the calix-*bis*-crowns, we have synthesized the unsymmetrical calix-*bis*-crown (the term 'unsymmetrical' of calix-*bis*-crown was firstly used by Asfari [20]) including both crown-6 and dibenzocrown-6 loops (**3**) to observe which cavity between crown-6 and dibenzocrown-6 prefers cesium ion with regard to distance of Cs–O and of Cs–C of the two rotated benzene rings. In addition, we investigated the metal ion complex ratio and ^{1}H NMR chemical shift behaviors upon cesium ion complexation.

Results and discussion

The synthesis of compound **3** is illustrated in Scheme 1. Previously, we reported that use of potassium carbonate as a base gave a higher yield than that of cesium carbonate in the

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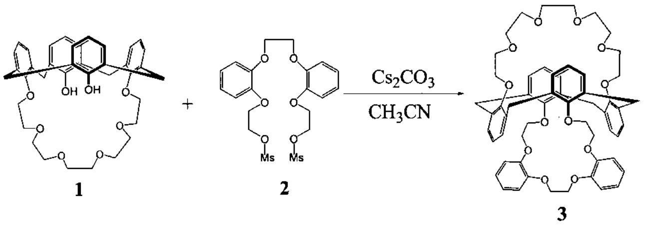

Scheme 1.

Table 1. Association constants and free energies for the complexation of ligands with alkali metal picrates at 25 °C[a]

Compound	Metal ion	Log K_a (M^{-1})	$-\Delta G°$ (kcal/mol)
3	Na^+	6.45	8.79
	K^+	7.23	9.85
	Rb^+	8.67	11.82
	Cs^+	9.28	12.65
Calix[4]-*bis*-crown-6 [11]	Na^+	6.42	8.76
	K^+	7.52	10.26
	Rb^+	8.48	11.57
	Cs^+	9.08	12.39

[a]The average value of three independent determinations.

synthesis of calix[4]-*mono*-crown, regardless of the cavity size of the crown ether loop [11]. So, the use of only one equivalent of K_2CO_3 in the reaction of calix[4]arene with pentaethylene glycol ditosylate gave the desired precursor **1** in 70% yield. The use of more than one equivalent provided complicated TLC information including several conformational isomers. For **1**, referring to the nuclear magnetic resonance spectrum with use of tetramethyl silane (TMS) as a standard, AB quartet splitting patterns (J = 13 Hz, $\Delta\nu$ = 452 Hz, chemical shift difference value) were observed, indicating a characteristic cone conformation. Next cyclization of calix[4]monocrown-6 with dibenzodimesylate **2** [8, 10] in the presence of Cs_2CO_3 gave the desired product **3** in 70–80% yield. The 1,3-alternate conformation of **3** was assigned from the NMR spectrum which showed the singlet peak at 3.80 ppm in ^1H NMR corresponding to 8 hydrogens (Ar–CH_2–Ar) and one signal at 38 ppm in the ^{13}C NMR for four bridging methylene carbons (Ar–CH_2–Ar). No other isomers were identified by this NMR investigation.

The complexation behavior of this compound toward alkali metal ion was studied with two-phase picrate extraction, solid-state structure, and the metal ion induced chemical shift change in ^1H NMR spectra. The association constants (log K_a) and binding free energy (ΔG) from the results of two-phase extraction are listed in Table 1. It shows cesium ion selectivity over other alkali metal ions. Compared to the result for symmetrical calix[4]-*bis*-crown-6 not containing the dibenzo unit, the Cs^+/Na^+ selectivity of **3** was observed to be slightly increased. This enhanced selectivity of cesium ion is ascribed to the flattening of the polyether chains [10] by two benzo groups on the crown loop in which sp^3 carbons are replaced by sp^2 ones.

First of all, to obtain a better understanding of the complexation behavior of this unsymmetrical calix[4]-*bis*-crown-6 (**3**), we investigated the complex ratio by plotting log $D_M/[Pic^-]_a$ against log $[\mathbf{H}]_o$ from the results of stoichiometric coefficient (q) and extraction constant (K_{ex}) [21]. The plot gave a straight line with slope of unity (q) indicating that **3** forms a complex with cesium ion in a 1 : 1 ratio. For this 1 : 1 complexation, it has been reported that although calix-*bis*-crowns have two cavities that can simultaneously capture two metal ions, they have been shown to have even worse extractability than calix-*mono*-crowns, probably due not only to electrostatic repulsion between the two metal ions, but also to an induced conformation change that does not favor binding of the second metal [22]. The latter is in opposition to Asfari's report that such a conformation change of 1 : 1 and 1 : 2 complexes was not observed [23].

On the contrary, the crystal structure of the complex and its crystal data indicate a 1 : 2 ratio as shown in Figure 1 and Table 2, respectively. Attempts to obtain a 1 : 1 complexed single crystal using the same equivalent of the cesium picrate failed. From the crystal structure, we observed interesting points regarding the distances between cesium ions (Cs1 and Cs2) and oxygen atoms comprising the crown ether loops of calixarene. As listed in Table 3, the distances of Cs(2) ion and O(7 and 12) are 3.126 and 3.085 Å, respectively which are a little shorter than those of Cs(1) ion and O(1 and 6), indicating that Cs(2) locates closer to the phenoxy-oxygen atoms of the calixarene. In addition, shorter bond lengths of Cs(2)–O(8-11) than those of Cs(1)–O(2–5) in which oxygen atoms are of sp^2 character indicates that the crown loop containing dibenzo group is more suitable than crown-6 with respect to the metal-crown cavity complimentarily. Distances of Cs(2)–O(8-11) atoms are even slightly shorter than those of cesium complexed 1,3-dioctyloxycalix[4]arene dibenzocrown ether reported by Lamare [17, 18], which is probably due to a significant change of the dibenzocrown conformation by introduction of the upper crown loop. Dibenzocrown seems to bring the better situation to the cesium ion. In addition, considering cesium-π interaction between these two metal ions and the *para*-carbons of the two rotated benzene rings, the sum of the half-thickness of the benzene p-electron (1.70 Å) and the Cs^+ radius (1.69 Å) is 3.39 Å [24]. Thus, the distances between the cesium ions and the *para* carbons of the benzene rings in this study are close enough for cation-π interaction. Looking carefully and in detail, Cs(2) locates slightly closer to C(10) and C(28) than the Cs(1) to C(4) and C(34), respectively. In addition, the bond angle of C(10)-Cs(2)-C(28) (159.0 deg) was observed to be greater than that (149.6 deg) of C(4)–Cs(1)–C(34), implying that Cs(2) surrounded by the dibenzocrown ring can have greater cation-π interaction than Cs(1) with the conventional crown ether loop. Therefore, from the bond distances between cesium ion and the oxygen atoms as well as the extent of the cation-π interaction shown from X-ray crystal structure, we can conclude that the cesium ion seems to be more tightly encapsulated by dibenzocrown ether than by the crown ether-6. To the best of our knowledge, this is the first example of an X-ray

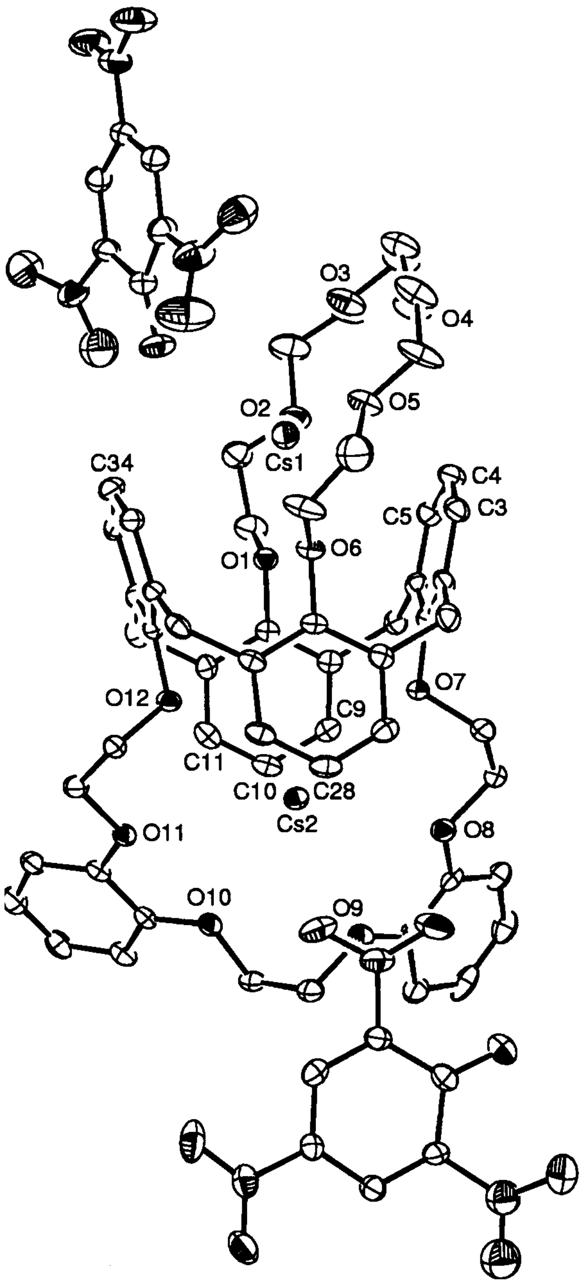

Figure 1.

Table 2. Crystal data for the X-ray diffraction studies on **3** **(Cs^+Pic^-)$_2$**

Formula	$C_{62}H_{64}Cs_2N_6O_{26}$
f.w.	1575.01
Crystal system	triclinic
Space group	$P-1$
a (Å)	12.953(3)
b (Å)	13.061(2)
c (Å)	21.410(2)
α (°)	83.650(10)
β (°)	83.150(14)
γ (°)	86.522(17)
V (Å^3)	3570.2(10)
Z	2
F(000)	1592
Calculated density (g cm^{-3})	1.465
Radiation (Å) (Mo-Kα)	0.71069
No. of reflns for meads.	25
θ range (°)	11.53–12.64
μ (mm^{-1})	1.102
Temperature (K)	289
Crystal size (mm)	0.36 × 0.30 × 0.23
Color	yellow
Diffractometer	Enraf-Nonius CAD-4
Data collection method	$\omega/2\theta$ scans
Absorption correction	psi-scan
No. of unique reflns.	12689
No. of observed reflns. (Io $\geq$ 2 σ(Io))	7921
θ max (°)	25.0
hkl range	−14 15; −15 15; 0 25
Interval (min)	300
R_{int}	0.0312
No. of parameters	899
R & Rw	0.0688 & 0.1754
GOF	1.027
$(\Delta/\sigma)_{\max}$	0.000
$(\Delta\rho)_{\max}$ (e/Å^3)	1.524
$(\Delta\rho)_{\min}$ (e/Å^3)	−0.770
Extinction correction	none

crystal structure that two cesium ions are encapsulated in an unsymmetrical calix[4]-*bis*-crown ether in which crown-6 and dibenzocrown-6 are simultaneously incorporated into a calix[4]arene framework in the 1,3-alternate conformation. However, although this unsymmetrical calix-*bis*-crown shows higher complex ability for cesium ion than does the symmetrical one, it seems to be less efficient mainly due to synthetic difficulty.

To investigate the location of the cesium ion more precisely, ^{1}H NMR of the cesium complex were recorded. 1 : 1 Complexation was observed by calculation of the proton integration of the picrate anion. Unfortunately, we could not accurately distinguish the extent of the cation-π interaction due to complicated chemical shift changes and peak-broadening for hydrogen atoms on the *para*-carbons of

Table 3. Selected bond lengths [Å] and angles [deg] for **3** ·(Cs^+)$_2$

Cs(1)–O(1)	3.434(5)	Cs(2)–O(7)	3.126(5)
Cs(1)–O(2)	3.268(7)	Cs(2)–O(8)	3.205(5)
Cs(1)–O(3)	3.264(7)	Cs(2)–O(9)	3.159(6)
Cs(1)–O(4)	3.493(7)	Cs(2)–O(10)	3.360(5)
Cs(1)–O(5)	3.262(6)	Cs(2)–O(11)	3.379(5)
Cs(1)–O(6)	3.269(5)	Cs(2)–O(12)	3.085(5)
Cs(1)–C(3)	3.569(9)	Cs(2)–C(9)	3.547(8)
Cs(1)–C(4)	3.318(10)	Cs(2)–C(10)	3.348(8)
Cs(1)–C(5)	3.605(9)	Cs(2)–C(11)	3.499(8)
Cs(1)–C(34)	3.454(9)	Cs(2)–C(28)	3.414(8)
C(4)–Cs(1)–C(34)	149.6(2)	C(10)–Cs(2)–C(28)	159.0(2)

the two rotated benzene rings. Instead, we could observe the chemical shift changes of the oxyethylene glycol unit of the crown ether loop. No chemical shift change was observed in the case of the sodium and potassium ion complex. For the **3**·Rb^+ complex, a small change of chemical shift for the oxyethylene glycol unit of the dibenzo group was observed but difficult to assign due to peak broadening. For the **3**·Cs^+ complex, however, we could observe that triplet peaks corresponding to calixarene-$OCH_2\mathit{CH_2}O$- of the dibenzo-crown ring which appeared at 3.60 ppm moved to 4.13 ppm by 0.53 ppm lower field. This NMR chemical shift change upon cesium ion complexation may support the fact that the cesium ion is likely to be encapsulated in the dibenzocrown unit rather than in the conventional crown ether loop as in the solution state.

We now are preparing 1,3-dipropyloxycalixdibenzo-crown-6 previously synthesized by our group [10] and its cesium ion complex to compare with this unsymmetrical calix-*bis*-crown for the association constants and extent of Cs-π interaction followed by the detail conformational change of the dibenzocrown unit able to influence the Cs/Na selectivity.

Experimental

Instruments and chemicals

Melting points were taken by the use of a Mel-Temp of Fisher-Johns melting point apparatus without any correction. IR spectra were obtained with a Perkin-Elmer 1600 Series FT-IR as potassium bromide pellet and deposited on KBr window in the case of solid product and oil, respectively, are recorded in reciprocal centimeters. ^1H and ^{13}C NMR spectra were recorded with a 400 MHz Bruker ARX-400 and an 100 MHz spectrometer, respectively, the chemical shifts (δ) reported downfield from the internal standard, tetramethylsilane. The FAB^+ mass spectrum was obtained on a JEOL-JMS-HX 110A/110A High Resolution Tendem Mass Spectrometry in the Korea Basic Science Institute in Taejon, Korea.

Unless specified otherwise, reagent grade reactants and solvents were obtained from chemical suppliers and used as received. Dry solvents were prepared as follows: dichloromethane was freshly distilled from lithium aluminum hydride. Acetonitrile was pre-dried from molecular seives (3Å) and distilled over diphosphorus pentoxide. Compounds **1** [10], and **2** [8, 10] were prepared as described in the literature.

Synthesis

*Calix[4]-bis-crown-6 (**3**)*
Under nitrogen, a solution of 1,3-alternate calix[4]*mono*-crown-6 (**1**) (0.72 g, 1.17 mmol), dibenzomesylate (0.75 g, 1.17 mmol) and Cs_2CO_3 (1.9 g, 5.85 mmol) in 100 mL of acetonitrile was refluxed for 24 h. Acetonitrile was removed *in vacuo*. To the brownish solid, 100 mL of 5% HCl aqueous solution and 50 mL of CH_2Cl_2 were added and the organic layer was separated and washed with 50 mL of HCl aqueous solution. The organic layer was dried over anhydrous $MgSO_4$ and the solvent was removed *in vacuo* to give a brownish oil. Column chromatography was conducted with EtOAc-hexane (1 : 3) as eluent to give the desired product (0.87 g) as a white solid in 80% yield. M.p.: 98.6 °C. IR (KBr pellet, cm^{-1}): 3058, 2927, 2857, 1590, 1500, 1457, 1257, 1207, 1119, 938, 764. ^1H NMR ($CDCl_3$): δ 7.15–6.57 (m, 20 H), 4.4 (s, 4 H), 3.80 (q, 8 H, Ar-$\mathit{CH_2}$-Ar), 3.7 (s, 4 H), 3.62–3.54 (m, 16 H), 3.40 (t, 4 H), 3.29 (t, 4 H). 13C NMR ($CDCl_3$): 157.2, 156.76, 152.1, 149.6, 134.8, 134.5, 130.2, 129.9, 125.0, 123.7, 123.5, 123.2, 122.3, 115.6, 71.84, 71.8, 71.5, 70.7, 70.4, 70.3, 68.9, 67.6, 38.7. FAB MS m/z (M^+). Calcd. 924.7. Found: 925.1.

NMR of complex

Preparation of the NMR sample
A mixture of organic ligand **3** (20 mg) dissolved in $CDCl_3$ (10 mL) and excess metal picrate (over at least 5 equivalents) was stirred for 1 h. After filtration of the precipitated excess metal picrate, the filtrate was dried *in vacuo* to give a yellow solid complex **3**·M^+Pic^-.

X-ray crystal structure

Yellow crystals suitable for an X-ray analysis were obtained by slow evaporation from methanol solution of compound **3** and excess cesium picrate. The crystal of approximate dimension 0.36 × 0.30 × 0.23 mm was mounted and aligned on a CAD-4 diffractometer [25]. Intensities were collected with graphite-monochromatized Mo K_α radiation using the $\omega/2\theta$ scan technique at 289 K. Three standard reflections were measured every 3 h as orientation and intensity controls; intensity decay, 1.0%, was observed. The structure was solved by direct methods [26] and the least-squares refinement of the structure was performed by the program SHELXL97 [27]. All non-hydrogen atoms were refined anisotropically. H atoms were placed in calculated positions allowing to ride on their parent C atoms with Uiso(H) = 1.2 Ueq(C). The highest peak 1.52 $eÅ^{-3}$ and deepest hole -0.77 $eÅ^{-3}$ are at 2.82 Å from H(26)B and 0.95 Å from Cs(1), respectively. Selected bond lengths 2.83 and angles are listed in Table 3.

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