

**THE DETERMINATION OF COMPLEX STABILITIES WITH NEARLY  
INSOLUBLE LIGANDS. COMPLEXATION OF ALKALI IONS BY  
UNSUBSTITUTED CALIXARENES IN AQUEOUS SOLUTIONS**

**Hans-Jürgen Buschmann, Gerhard Wenz, Ernst Cleve and Eckard Schollmeyer**

*Deutsches Textilforschungszentrum Nord-West e.V., Frankenring 2, D-47798 Krefeld,  
Germany*

*Received 12.7.1999*

**Abstract**

The complex formation between the in water nearly insoluble calix[n]arenes (n=4,5,6,8), their p-tert-butyl derivatives and the alkali ions and  $\text{NH}_4^+$  has been studied in aqueous solutions at 25 °C under slight acidic conditions to prevent an ionization of the calixarenes. Due to the complexation the total concentration of the calixarenes in solution increases. This effect can easily be detected using spectrophotometric methods. The stability constants depend on the ring size of these calixarenes. Calix[6]arene forms the most stable complex. No complexation is observed between the p-tert-butylcalix[n]arenes and the monovalent cations. The spectrophotometric methods allow the quantitative determination of the stability constants. The main advantage of this method is that only very small amounts of the ligands are used.

**INTRODUCTION**

The first complexation reactions of the in water nearly insoluble calixarenes with cations were published by R.M. Izatt et al. [1,2]. These authors studied the transport of cations through liquid membranes by calixarenes. They used basic conditions in the aqueous phase. Thus, the calixarenes are deprotonated. To promote the complexation behaviour of calixarenes in water several types of derivatives possessing higher solubility in water have been synthesized [3-6]. The complexation behaviour of such derivatives depends upon the nature of the substituents.

Up to now the in water nearly insoluble unsubstituted calixarenes, see Figure 1, did not allow the determination of stability constants under neutral conditions. Thus, no stability constants of these calixarenes with cations have been published so far. On the other hand crystal structures demonstrates the formation of inclusion complexes between p-tert-butyl-calix[4]arene and  $\text{Cs}^+$  [7,8]. From the crystal structure it is evident that the cation is located within the calixarene cup.

To get further information about the complex formation between alkali ions and different calixarenes we used a new spectrophotometric method to determine the complex stabilities of the formed complexes [9-14].

## EXPERIMENTAL

### Reagents

The different calixarenes, see Figure 1, were synthesized according to published procedures [15-18]. The anhydrous salts  $\text{NH}_4\text{Cl}$ ,  $\text{LiCl}$ ,  $\text{NaCl}$ ,  $\text{KCl}$ ,  $\text{RbCl}$  and  $\text{CsCl}$  (all Merck) were of the highest purity available and used without further purification.

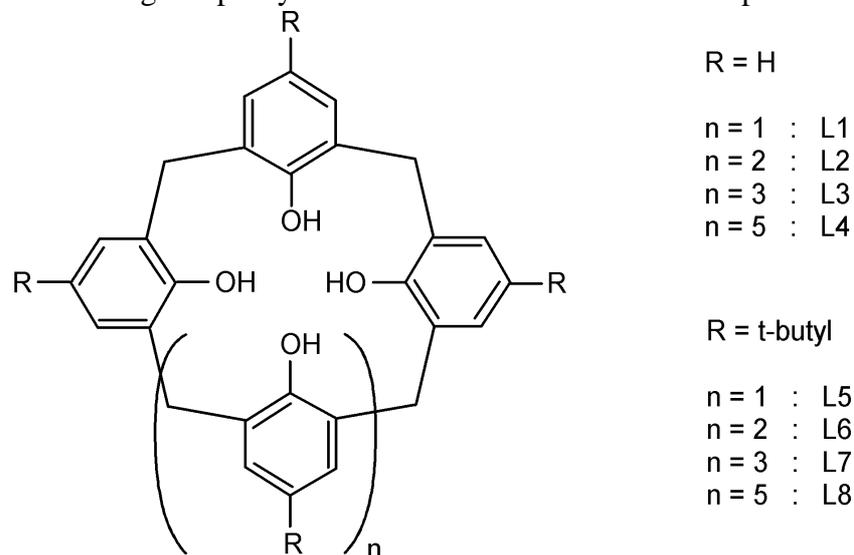


Figure 1. Structures of the calixarenes

### Methods

All solutions were prepared using doubly distilled water conditioned with hydrochloric acid (0.01 mol/l) at  $\text{pH} = 4.5$  to avoid the formation of calixarene anions. The solid ligands were added to solutions of the salts ( $2 \times 10^{-3}$ – $2 \times 10^{-2}$  mol  $\text{l}^{-1}$ ). The amount of the

ligand added was high enough to ensure the formation of saturated solutions. The solutions were thermostated at 25 °C for five weeks and shaken at intervals. After filtration of the saturated solutions (polycarbonate membrane filter, 0.4 μm) to separate the solid ligand the spectra were recorded using a Varian Cary 5E spectrophotometer.

An example for the increase of the absorbance due to complex formation is given in Fig. 2 for the complexation of Cs<sup>+</sup> by calix[6]arene.

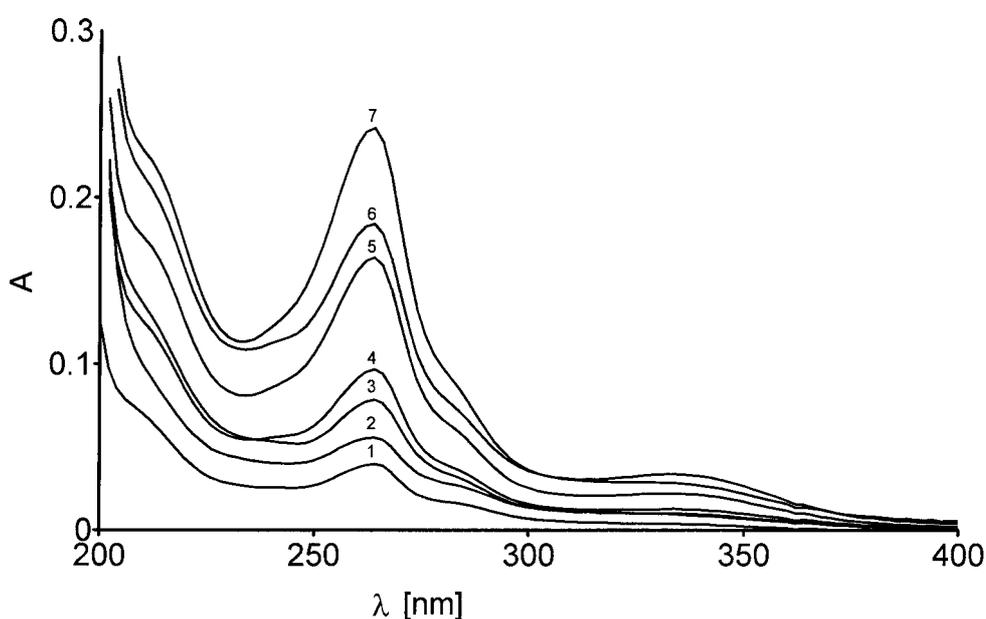


Figure 2. UV spectra of the saturated solutions of the ligand calix[6]arene in the presence of different concentrations of CsCl ((1)  $2 \times 10^{-3}$ , (2)  $4 \times 10^{-3}$ , (3)  $8 \times 10^{-3}$ , (4)  $1 \times 10^{-2}$ , (5)  $1.2 \times 10^{-2}$ , (6)  $1.6 \times 10^{-2}$ , (7)  $2 \times 10^{-2}$  mol/l) in aqueous solutions at 25 °C

#### *Treatment of the experimental data*

The formation of a 1:1 complex between a ligand L and a cation  $M^{n+}$  can be described by:



The corresponding stability constant is defined as:

$$K = \frac{[LM^{n+}]}{[L][M^{n+}]} \quad (2)$$

If only the ligand and the complex formed absorb at a given wavelength the experimentally measured absorptivity  $A'$  for an optical path length  $d$  is given by equation (3),

$$A = \frac{A'}{d} = \varepsilon_1[L] + \varepsilon_2[LM^{n+}] \quad (3)$$

with the molar absorptivities of the ligand  $\varepsilon_1$  and complex  $\varepsilon_2$ , respectively. The salt solution is saturated with the ligand so the first term in equation (3) is constant. As a result one gets:

$$A_0 = \varepsilon_1[L]_{\text{sat}} \quad (4)$$

$[L]_{\text{sat}}$  denotes the solubility of the ligand in the pure solvent. Using equation (2) and equations (5) and (6) describing the material balances,

$$c_M = [M^{n+}] + [LM^{n+}] \quad (5)$$

$$c_L = [L]_{\text{sat}} + [LM^{n+}] \quad (6)$$

with  $c_M$  and  $c_L$  as the total concentration of the ion and the ligand in solution, equation (3) can be transformed into equation (7).

$$\frac{A}{A_0} - 1 = \frac{(\varepsilon_2 / \varepsilon_1)K}{1 + K[L]_{\text{sat}}} c_{\text{salt}} \quad (7)$$

Plotting  $(A/A_0)-1$  as a function of the total salt concentration  $c_{\text{salt}}$  one gets a straight line with the slope  $b$ . This is shown in Fig. 3 for the complexation of  $\text{Cs}^+$  by different calixarenes.

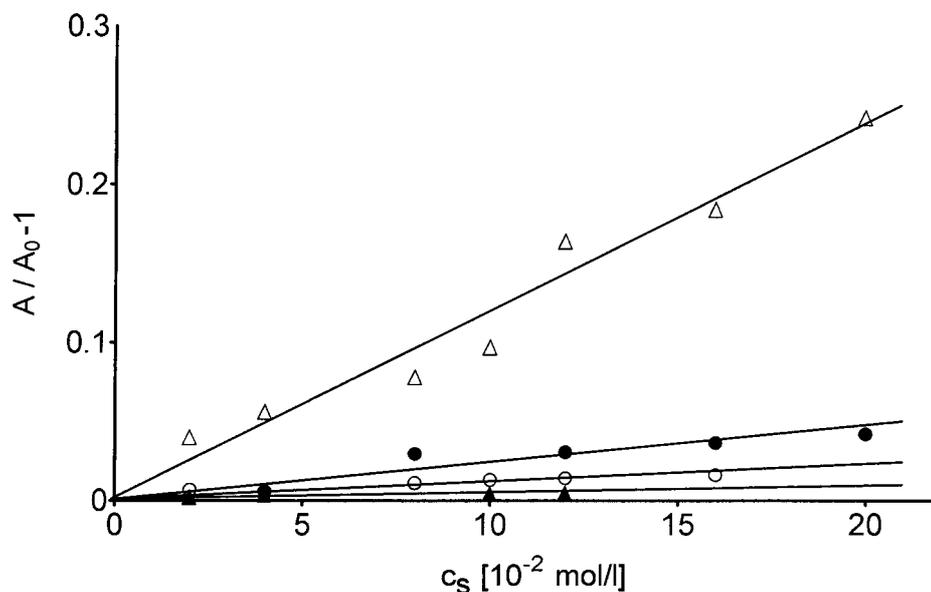


Figure 3. Plot of  $(A/A_0)-1$  at 272 nm of saturated solutions of the ligands calix[4]arene ( $\Delta$ ), calix[5]arene ( $\circ$ ), calix[6]arene ( $\triangle$ ) and calix[8]arene ( $\bullet$ ) as a function of the total salt concentration  $c_s$  of CsCl in aqueous solutions at 25 °C

From this slope the stability constant of the complex formed in solution can be calculated according to equation (8), if the molar absorptivities and the solubility of the ligand are known.

$$K = \frac{b}{(\epsilon_2 / \epsilon_1) - b[L]_{\text{sat}}} \quad (8)$$

If both the molar absorptivities are nearly equal and the solubility of the ligand is low the stability constant  $K$  is given by the slope  $b$ . The correctness of these assumptions has already been proved in case of benzocrown ethers and cryptands[9-14].

## RESULTS AND DISCUSSION

With the exception of  $\text{Cs}^+$  no increase in absorbance of the solutions saturated with calixarenes in the presence of alkali ions and the  $\text{NH}_4^+$  ion is observed. It is possible that only very weak or no complexes with these cations are formed. The results for the complexation of  $\text{Cs}^+$  by different calixarenes are summarized in Table 1. The stability

constants were calculated using equation (8) without the knowledge of the solubility of the ligands and the molar absorptivities.

Table 1

Stability constants  $\log K$  ( $K$  in  $\text{dm}^3/\text{mol}$ ) for the complexation of  $\text{Cs}^+$  by different calixarenes in aqueous solutions at 25 °C

ligand	L1	L2	L3	L4	L5	L6	L7	L8
$\log K$	$1.80 \pm 0.32$	$2.10 \pm 0.24$	$3.37 \pm 0.20$	$2.03 \pm 0.15$	- <sup>a</sup>	- <sup>a</sup>	- <sup>a</sup>	- <sup>a</sup>

<sup>a</sup> no increase in absorbance

Only the unsubstituted calixarenes form complexes with  $\text{Cs}^+$ . The most stable complex is formed with calix[6]arene (L3). The size of the calixarenes has a great influence upon the stability of the complexes formed. Obviously the soft  $\text{Cs}^+$  ion is able to interact with the  $\pi$ -electrons of the benzene moieties of the calixarenes. Such cation- $\pi$  interactions of calixarenes have been studied using  $^1\text{H}$  NMR spectroscopy [19].

The presence of the tert-butyl group at the para position of the ligands (L5-L8) drastically influences the complex formation in solution. Thus, even with  $\text{Cs}^+$  no complex formation could be detected.  $^1\text{H}$  NMR investigations confirmed the cation- $\pi$  interactions and the influence of tert-butyl groups on calixarene complexes [20].

The presented results demonstrate the possibility to measure stability constants with nearly insoluble ligands.

## ACKNOWLEDGEMENTS

The ligands calix[5]arene and p-tert-butylcalix[5]arene were kindly donated by Dr. V. Böhmer, University of Mainz, Germany.

## REFERENCES

- [1] R.M. Izatt, J.D. Lamb, R.T. Hawkins, P.R. Brown, S.R. Izatt and J.J. Christensen, *J. Am. Chem. Soc.* **1983**, *105*, 1782-1785.
- [2] S.R. Izatt, R.T. Hawkins, J.J. Christensen and R.M. Izatt, *J. Am. Chem. Soc.* **1985**, *107*, 63-66.

- [3] C.D. Gutsche, *Calixarenes*, The Royal Society of Chemistry, Cambridge, **1989**.
- [4] J. Vicens, V. Böhmer and J.E.D. Davies (Eds.), *Calixarenes*, Kluwer Academic Publishers, Dordrecht, **1991**.
- [5] J.-D. van Loon, W. Verboom and D.N. Reinhoudt, *Org. Prep. Proced. Int.* **1992**, 24, 437-462.
- [6] C.D. Gutsche, *Calixarenes Revisited*, The Royal Society of Chemistry, Cambridge, **1998**.
- [7] J.M. Harrowfield, M.I. Ogden, R.R. Richmond and A.H. White, *J. Chem. Soc., Chem. Commun.* **1991**, 1159-1161.
- [8] R. Assmus, V. Böhmer, J.M. Harrowfield, M.I. Ogden, W.R. Richmond, B.W. Skelton and A.H. White, *J. Chem. Soc., Dalton Trans.* **1993**, 2427-2433.
- [9] H.-J. Buschmann, E. Cleve, U. Denter and E. Schollmeyer, *J. Phys. Org. Chem.* **1994**, 7, 479-484.
- [10] H.-J. Buschmann, E. Cleve, U. Denter and E. Schollmeyer, *J. Phys. Org. Chem.* **1997**, 10, 781-785.
- [11] H.-J. Buschmann, E. Cleve, L. Mutihac and E. Schollmeyer, *Anal. Quim. Int. Ed.* **1998**, 94, 5-8.
- [12] H.-J. Buschmann, E. Cleve, L. Mutihac and E. Schollmeyer, *Rev. Roum. Chim.* **1998**, 43, 941-944.
- [13] H.-J. Buschmann, E. Cleve and E. Schollmeyer, *Inorg. Chem. Commun.* **1998**, 1, 292-294.
- [14] H.-J. Buschmann, E. Cleve, L. Mutihac and E. Schollmeyer, *J. Solution Chem.* **1998**, 27, 755-759.
- [15] C.D. Gutsche and M. Igbal, *Org. Synth.* **1990**, 68, 234-237.
- [16] C.D. Gutsche, B. Dhawan, M. Leonis and D. Stewart, *Org. Synth.* **1990**, 68, 238-242.
- [17] C.D. Munch and C.D. Gutsche, *Org. Synth.* **1990**, 68, 243-246.
- [18] C.D. Gutsche, J.A. Levine and P.K. Sujeeth, *J. Org. Chem.* **1985**, 50, 5802-5806.
- [19] P. Lhotak, R. Nakamura and S. Shinkai., *Supramol. Chem.* **1997**, 8, 333-344.
- [20] K. Araki, H. Shimizu and S. Shinkai, *Chem. Lett.* **1993**, 205-208.

### Povzetek

Raziskali smo tvorbo kompleksa med v vodi skoraj netopnimi kaliks[n]areni ( $n=4,5,6,8$ ), njihovimi *p-terc*-butilnimi derivati in alkalijskimi ter amonijevim ionom. V vodnih raz topinah se koncentracija kaliksarenov z aradi tvorbe kompleksa poveča, kar smo dokazali s spektrofotometričnimi metodami. Stabilnost kompleksov je odvisna od velikosti kaliksarenskega obroča. Najstabilnejše komplekse tvori kaliks [6]aren. Med *p-terc*-butilikaliks[n]areni in monovalentnimi kationi nismo opazili tvorbe kompleksov. S spektrofotometričnimi metodami smo določili konstante stabilnosti kompleksov.