15. Cryptates XXIV[1]): Structure and Stability of Mononuclear and Binuclear Cation Inclusion Complexes of Cylindrical Macrotricyclic Ligands

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Summary

The cylindrical macrotricyclic ligands **1–3** yield inclusion complexes, [3]-cryptates, with various metal cations. NMR. studies indicate the successive formation of a mononuclear and a binuclear complex. The former is probably unsymmetrical undergoing fast intramolecular cation exchange; the latter is symmetrical, with a cation located on each macrocyclic subunit of the macrotricyclic system. A heteronuclear (Ag^+, Pb^{2+}) complex has been observed. The stability constants of the mononuclear and binuclear alkali and alkaline-earth cation complexes of ligands **1–3** have been determined by potentiometric methods. The stabilities are comparable to those of the complexes of the isolated macrocyclic subunit **5b**. The binuclear complexes are almost as stable as the mononuclear ones even in highly charged species like for instance the complex of ligand **2** with two barium cations. Cylindrical macrotricyclic ligands are topologically well suited for the designed positioning of two metal cations in a binuclear inclusion complex.

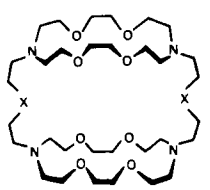
Introduction. – The design of receptors and carriers for spherical substrates, the alkali and alkaline-earth cations (*spherical recognition*) [2], has made use of ligand topologies which define circular (two dimensional) or spheroidal (three dimensional) cavities, *i.e.* respectively macrocyclic [3] or macrobicyclic [2] [4] molecules containing appropriate binding sites.

Such ligands form inclusion complexes, *cryptates* [2] [5], in which the cation is contained inside the molecular cavity, whose size, shape, binding sites determine the stability, the selectivity, and the exchange rates of the complexes. The macrobicyclic [2]-cryptates present particularly high stabilities and unusual selectivities [6].

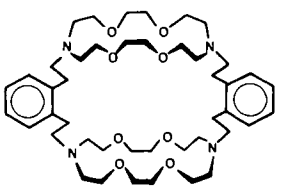
Macrotricyclic molecules may be either of *cylindrical* or *spherical* topology [1]. Ligands of both types have been synthesized recently [1] [7–10] and the formation of macrotricyclic cation inclusion complexes, [3]-*cryptates*, has been reported [1] [7] [9–12].

[1]) Previous paper see [1].
[2]) ERA 265 of the CNRS.

The cylindrical ligands are formed by two rings connected by two (or eventually more) bridges (see structures **1–4**). They define *two lateral cavities*, the macrocyclic units, and *one central cavity* inside the macrotricycle, whereas the macrocyclic, macrobicyclic and spheroidal macrotricyclic ligands contain a single central cavity [1]. The sizes and properties of the three cavities may be modified by changing the size of the rings, the length of the bridges and the nature of the binding sites. Such ligands could in principle form three types of complexes: *mononuclear* with one cation, *binuclear* with two cations, and *cascade complexes* [13] by subsequent inclusion of a substrate between the two metal cations located on each side in the two macrocycles. The cylindrical macrotricycles thus represent a class of molecules which might display a variety of new complexation properties. We have previously described the synthesis of the ligands **1–3** [1]. We now report a study of the structure and the determination of the stability constants of the [3]-cryptate complexes which they form with a number of metal cations. Because of the nature of the binding sites present in compounds **1–3** (O and N atoms) the results concern mainly alkali and alkaline-earth cations (AC's and AEC's). The properties of compound **4** [7] [12] and of a chiral macrotricyclic ligand [9] have been described earlier.



1 X=CH_2
2 X=O



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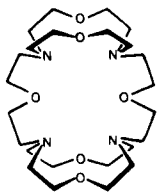

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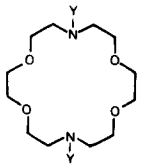
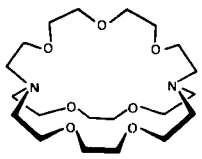


5a Y=H
5b Y=Me



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Formation and structure of metal cation complexes of the macrotricyclic ligands 1, 2, 3. – The formation of metal cation complexes by the ligands **1**, **2**, **3** in the presence of alkali and alkaline-earth salts, $AgNO_3$, $Pb(NO_3)_2$, may be observed by ^1H- and ^{13}C-NMR. spectroscopy. Most complexation studies have been performed with compound **2**. Dissolution of KSCN, NaI *etc.* in $CDCl_3$ by ligand **2** leads to marked spectral changes up to 2:1 stoichiometry. Similar behaviour is found with **2** in methanol/water (M/W) on addition of $AgNO_3$, $Ba(NO_3)_2$ or $Pb(NO_3)_2$. In these cases the successive formation of two species of 1:1 and 2:1 cation/ligand stoichiometries is observed. No further changes occur at higher levels of added salt. Fig. 1–3 illustrate the spectral changes observed in several cases. When less than 2 equivalents of salt

are added to the ligand solution, the three species, free ligand, 1:1 and 2:1 complexes, are present in amounts depending on the stabilities of the complexes. The spectra of the 1:1 species themselves are thus always partially obscured by the signals of the other species, but are nevertheless informative (see below). However the 2:1 species present well defined ^{13}C-NMR. spectra. Their formation has been confirmed by the isolation of crystalline complexes like: (**2**.2 NaI), (**2**.2 KSCN), (**2**.2 $Ba(SCN)_2$) [1]. Complexation may also be detected by using cation selective electrodes or by measuring changes in pH of the solution (see below).

Structure of the complexes: mononuclear and binuclear [3]-cryptates. The ^{13}C-NMR. spectra of the 2:1 cation/ligand complexes obtained with ligand **2** (Fig. 2 and 3) have

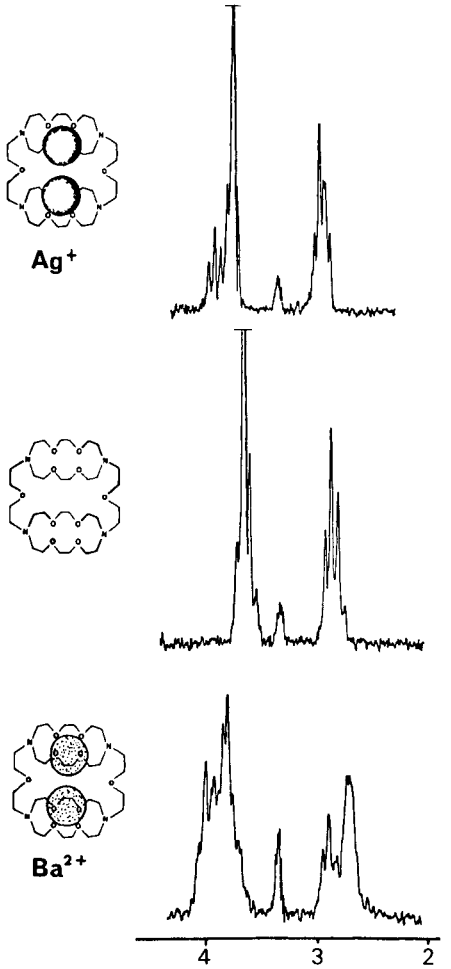

Fig. 1. *^{1}H-NMR. spectra of ligand* **2** *and of its binuclear 2 Ag^+ and 2 Ba^{2+} complexes* (100 MHz; in CD_3OD/H_2O 95:5; solvent peak at 3.35 ppm from TMS)

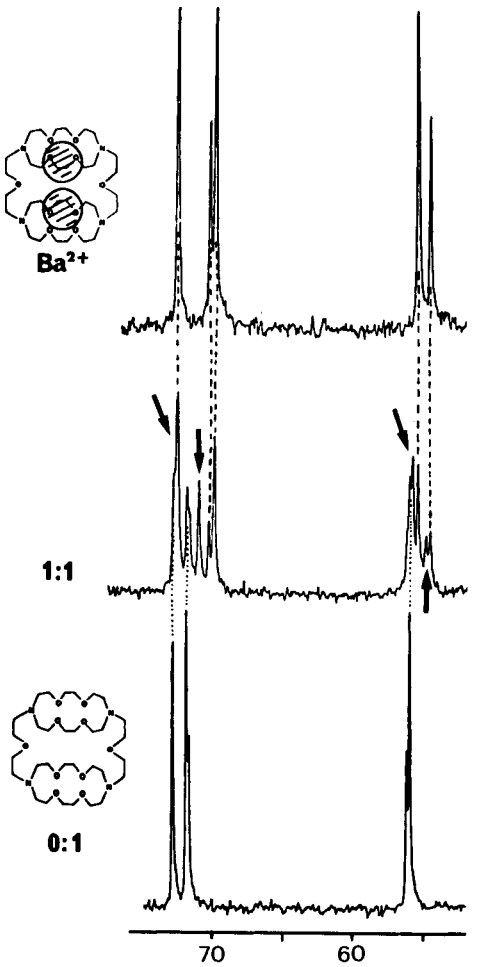

Fig. 2. *^{13}C-NMR. spectra of ligand* **2**, *alone (bottom), in the presence of 1 equivalent (middle) and excess (top) $Ba(NO_3)_2$* (25 MHz; in CD_3OD/H_2O 95:5; shifts in ppm from TMS). The arrows indicate the positions of the resonances of the 1:1 complex (see text)

the same number of peaks, with the same relative intensities as the free ligand. Thus these complexes must have real or averaged D_{2h} symmetry. The spectra at 1:1 salt/ligand ratios show that intermolecular cation exchange is slow on the NMR. time scale, so that the symmetry indicated by the spectra of the 2:1 species cannot be due to exchange averaging of peaks. On the other hand, it is known that the macrocyclic diamines **5a** and **5b** form complexes [5] [6] in which the metal cation is contained in the circular cavity of the macrocycle, as shown by the crystal structure of the [$K^+ \subset$ **5a**] SCN^- complex [14]. These data lead to the formulation of the 2:1 cation/ligand species as *binuclear [3]-cryptates, i.e.* inclusion complexes in which the two metal cations occupy equivalent locations in the macrotricyclic cryptand, each cation binding to one of the two rings on top or bottom of the molecule; when binding sites are present in the bridges as in **2**, the cations may also interact with them.

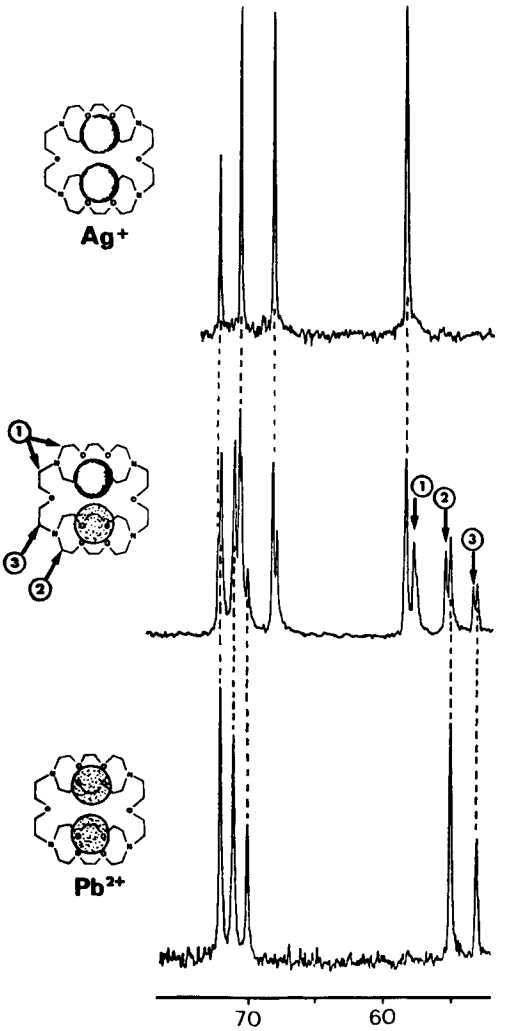

Fig. 3. ^{13}C-*NMR. spectra of the bimetallic homonuclear* $2Pb^{2+}$ (*bottom*) *and* $2Ag^+$ (*top*) *complexes of ligand* **2** (the middle spectrum is that of a sample containing an equivalent of each salt $AgNO_3$ and $Pb(NO_3)_2$; it contains the resonance of the heteronuclear Ag^+, Pb^{2+} complex; assignments are shown for the C–N signals (25 MHz; in CD_3OD/H_2O 95:5; shifts in ppm from TMS))

Furthermore, among its seven possible topologies [1], the ligand should take up the i_4 form, with all four nitrogen sites turned inside the molecular cavity, which provides optimal interaction with the metal cations. This is confirmed by the crystal structure of the complex **2**.2NaI which may be formulated as a binuclear cryptate [2 $Na^+ \subset$ **2**].2 I^- [15]. Each Na^+ cation interacts with the binding sites of one ring and with one of the oxygens in the bridges. This latter interaction causes the cation to sit somewhat 'on top' of the ring towards the inside of the central macrotricyclic cavity rather than 'in' the ring as found for the [$K^+ \subset$ **5a**] complex [14]; it also squeezes together the two bridges and contracts the central cavity. The Na^+, Na^+ distance is 6.40 Å. A similar situation is found in the crystal structure of the binuclear [3]-cryptate [2 $Ag^+ \subset$ **4**].$Ag(NO_3)_3^{2-}$, where the Ag^+ cations are closer together (3.88 Å) since they cannot penetrate into the small cavity of the twelve membered rings [16]. It may be expected that in the absence of binding sites in the bridges the cations will penetrate more inside the eighteen membered macrocycles which contain a cavity large enough to accomodate K^+ or Rb^+.

The ^{13}C-NMR. spectra of **2** in the presence of $Ba(NO_3)_2$ provide information about the complex of 1:1 stoichiometry (Fig. 2). Indeed at a $Ba(NO_3)_2$/**2** ratio of 1:1, the spectrum contains the resonances of the free ligand and of the 2:1 complex plus one well apparent peak in the *C*–O region and two peaks in the *C*–N region which could only come from the 1:1 complex. This first shows that *intermolecular exchange between the three species is slow*, an interesting feature which is receiving further attention. Unless one assumes that the ligand contracts for wrapping around the cation, the 1:1 species would be non-symmetrical with the cation located on one of the rings; however in such a species the double number of ^{13}C-NMR. resonances is expected, *i.e.* six at lower field in the *C*–O region and four in the *C*–N region, unless one admits multiple overlaps with the other signals present. On the other hand, if by analogy with the Ca^{2+} complex of ligand **4** [12], the non-symmetric 1:1 complex undergoes an intramolecular cation exchange process between the two rings (Fig. 4),

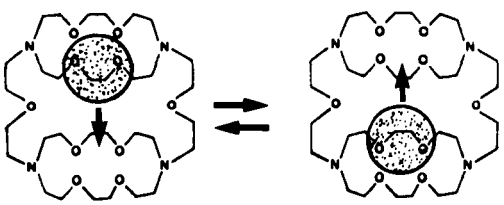

Fig. 4. *Intramolecular cation exchange process which may occur in the mononuclear complexes of ligands* **1–3**

only half of the resonances are expected at positions more or less half way between the signals of the free ligand and those of the 2:1 complex, if we assume that these are reasonable analogies for the free side and the complexed side of the 1:1 species. The relative intensities of the averaged signals would be 2:2:1 for C–O and 2:1 for *C*–N. Like at 25 MHz (Fig. 2), only one *C*–O and two *C*–N resonances (intensities 2:1) belonging to the 1:1 complex are observed in the ^{13}C-NMR. spectrum of the same sample determined at 63 MHz. As pictured in Fig. 2, this *C*–O signal is located between two *C*–O peaks of the free ligand and two *C*–O peaks of the 2:1 complex;

it may result from the overlap of two *C*–O resonances (intensities 2:1) of the 1:1 complex; the other *C*–O resonance lies probably below the signal at far left in Fig. 2.

Taken together, these data would indicate that the [$Ba^{2+} \subset$ **2**] complex is a non-symmetric cryptate undergoing fast intramolecular exchange and slow intermolecular exchange like [$Ca^{2+} \subset$ **4**] [12].

One can then describe the complexation properties of the cylindrical macrotricyclic cryptands **1**–**3** as the successive formation of non-symmetric mononuclear and symmetric binuclear [3]-cryptates as represented schematically in Fig. 5.

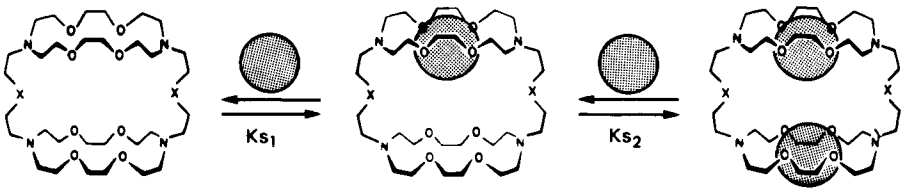

Fig. 5. *Schematic representation of the cation complexation processes of a cylindrical macrotricyclic ligand leading successively to an unsymmetrical mononuclear cryptate and to a symmetrical binuclear cryptate*

The 250-MHz-^{1}H-NMR. spectrum of ligand **2** confirms that the CH_2–N protons of the macrocyclic subunits are equivalent (see the corresponding 100-MHz spectrum in Fig. 1); this may either be accidental or arise from a *kinetic process* which exchanges the 'outside' and 'inside' faces (with respect to the central cavity) of the macrocyclic units. Such a process would involve both rotation of the ring between the bridges and inversion of the two corresponding bridgehead nitrogens; low temperature NMR. could give more information about these motions of the ligand. By contrast, in the 250-MHz spectrum of the [$2Ba^{2+} \subset$ **2**], the CH_2–N protons in the macrocycles now form an *AB* pair, whereas the CH_2–N protons in the bridges remain equivalent as in the free ligand. This clearly indicates that in the complex, binding of the cations hinders the motions which would lead to exchange of the internal and external faces of the rings and render the CH_2–N (ring) protons equivalent. Similar results have been obtained for the macrotricycle **4** and for its Rb^+ complex [17].

A heteronuclear bimetallic [3]-cryptate has also been observed as shown in Fig. 3. The ^{13}C-NMR. spectrum of a solution containing one equivalent of each component **2**, $AgNO_3$ and $Pb(NO_3)_2$, shows the resonances of the two homonuclear bimetallic cryptates [$2Ag^+ \subset$ **2**] and [$2Pb^{2+} \subset$ **2**] as well as a number of new resonances which can be attributed to the heteronuclear cryptate [$Ag^+Pb^{2+} \subset$ **2**]. Extensive signal overlap occurs in the *C*–O region, but the *C*–N region clearly shows three new peaks. The peak assignment is given in Fig. 3; the *C*–N resonances of the top and bottom rings are different in the mixed complex and shifted from the positions of the two homonuclear species. Intermolecular cation exchange between the three bimetallic complexes is slow. The fact that three distinct *C*–N resonances are observed for [$Ag^{2+}Pb^{2+} \subset$ **2**] also indicates that the intramolecular 'cation jig' by which these cations would exchange places inside the molecule, is slow on the NMR. time scale. The same should hold for the other stable binuclear complexes.

Determination of the stability constants. – *Methods.* The concentration stability constants [6] corresponding to the equilibria of formation of the 1:1 and 2:1 complexes shown in Fig. 5 are defined by the equations (1) and (2):

$$K_{s1} = \frac{[[M^{n+} \subset L]]}{[L][M^{n+}]} \quad (1)$$

$$K_{s2} = \frac{[[2\,M^{n+} \subset L]]}{[M^{n+} \subset L][M^{n+}]} \quad (2)$$

where [L], $[M^{n+}]$, $[[M^{n+} \subset L]]$, $[[2\,M^{n+} \subset L]]$ are respectively the concentrations of the ligand, the cation, the 1:1 cryptate and the 2:1 cryptate at equilibrium.

Two methods have been used for determining K_{s1} and K_{s2}: a) determination of free cation concentration using cation selective electrodes; b) analysis of the pH-metric titration curves in absence and in presence of cations, since ligands **1–3** are basic tetramines and complex formation changes the pH of the solution. Case a): K_{s1} and K_{s2} are calculated by analysis of the experimental curve obtained by measuring $[M^{n+}]$ with a cation selective electrode during titration of the ligand by the salt (see experimental part). Case b): in addition to the two complexation equilibria (Fig. 5, equations (1), (2)), there are alltogether twelve protonation equilibria, corresponding to the formation of the four protonated species of the ligand LH_m^{m+} (equation (3)), of the 1:1 complex $[M^{n+} \subset LH_m^{m+}]$ (equation (4)), and of the 2:1 complex $[2\,M^{n+} \subset LH_m^{m+}]$ (equation (5)) (with $m = 1$ to 4):

$$K_m = [LH_{m-1}^{(m-1)+}][H^+]/[LH_m^{m+}] \quad (3)$$

$$K_m^M = [[M^{n+} \subset LH_{m-1}^{(m-1)+}]][H^+]/[[M^{n+} \subset LH_m^{m+}]] \quad (4)$$

$$K_m^{2M} = [[2\,M^{n+} \subset LH_{m-1}^{(m-1)+}]][H^+]/[[2\,M^{n+} \subset LH_m^{m+}]] \quad (5)$$

Such a situation is of course not very practical, but simplifications may be made. As in the case of the diaza-macrobicycles [6] protonation of a nitrogen site participating in complexation of the metal cation is expected to destabilize the complex sufficiently for neglecting the corresponding equilibrium. This eliminates the four equilibria (5) and two of the equilibria (4). Two protonation equilibria remain for the 1:1 complex: the protonation of the two nitrogen sites on the uncomplexed side of the macrotricycle (see Fig. 5).

For each cation three titrations have been performed: for the free ligand, and for the ligand in the presence of two different concentrations of salt. The pK values of the ligands and the stability constants K_{s1} and K_{s2}, have been obtained by analysing the titration curves with a computer program (see experimental part). In most cases six equilibria were considered: the two complexations (1) and (2) and the four protonations (3); in a few instances two of the four protonations (4) of the 1:1 complex were added; the stability constants K_{s1} and K_{s2} obtained from both treatments were the same within the precision of the method.

Results. Table 1 contains the stability constants obtained for the complexes. Additional data for complexes of ligands **4**, **5b** and **6** [6] [7] [12] [17] are included

Table. *Stability Constants of the Mononuclear (log K_{s1}) and Binuclear (log K_{s2}) [3]-Cryptates of Alkaline and Alkaline-Earth Metal Cations* (K_s in 1 mol^{-1} at 25°)[a]

Ligand	Solvent		log K_{s1} (1), log K_{s2} (2) with cation						
			Na^+	K^+	Rb^+	Cs^+	Ca^{2+}	Sr^{2+}	Ba^{2+}
1	M/W	(1)	3.2	4.0	3.5	3.5	–	–	–
		(2)	1.5	3.2	3.0	2.5	–	–	–
2[b]	M/W	(1)	3.6	4.8	3.7	4.4	4.0	5.5	6.7
		(2)	3.2	3.9	3.3	3.0	–	5.5	6.3
	W	(1)	< 1.5	~ 1.5	~ 1.5	–	–	3.5	4.4
3	M/W	(1)	3.0	3.6	3.0	–	3.6	4.9	5.9
		(2)	2.9	2.7	2.8	–	–	5 ± 1	6 ± 1
4 [7] [12] [17]	W[c]	(1)	1.7	1.1	1.0	1.45	6.53	6.97	8.0
	M[c]	(1)	4.5	5.85	6.2	< 6.0	–	–	–
5b[d]	M/W	(1)	3.3	4.4	4.3	4.1	4.4	6.1	6.7
6 [6]	W	(1)	1.65	2.2	2.05	2.0	~ 2.0	3.4	6.0
	M/W	(1)	4.57	7.0	7.3	7.0	4.74	7.06	10.40

[a] Experimental conditions: for the alkali cation complexes: measurements performed in methanol/water (M/W) 95:5 using ion selective electrodes; for the alkaline-earth cations: measurements in aqueous solution (W) or in methanol (M/W) 9:1 using pH-metric titration; see also experimental part.

[b] log $K_{s1} \sim 12$ for Ag^+ and Pb^{2+}.

[c] log K_{s1} values for the 1:1 complexes. M: pure methanol solutions. In M/W 95:5 (log K_{s1}; log K_{s2}) are respectively (4.3; 1.5) for Na^+. For Ag^+ (log K_{s1}; log K_{s2}): (> 6.8; > 6.3) in W and (> 9.5; > 6.5) in methanol [7] [17].

[d] Values taken in part from [19]. Solvent M/W 95:5 in all cases.

for comparison purposes. The pK values for ligand protonation are the following: for ligand **2** pK_1, pK_2, pK_3, pK_4 = 8.76; 8.14; 6.74; 5.58 respectively in aqueous solution; 10.25; 8.91; 6.70; 5.62 respectively in M/W 9:1; for ligand **3**: 9.84; 8.82; 6.60; 6.13 respectively in M/W 9:1 (25°; 0.1 M NMe_4Br). These pK's have nothing special; the spread in pK values is smaller compared to triethylenetetramine for instance (9.92; 9.20; 6.67; 3.32 in aqueous solution) since the basic sites are farther apart. The measurements have been performed in M/W 95:5 solution with the alkali cations and ion selective electrodes, and in either aqueous solution or M/W 9:1 for the pH-metric determinations. The latter solvent was chosen because the H^+ activity in M/W mixtures appears to present an anomaly at the 95:5 ratio [18]; the latter would however not affect the validity of the stability constants determined. The formation of both 1:1 and 2:1 complexes may in some cases be directly observed by inflexion points in the titration curves.

Since ligands **1–3** may exist in seven conformations differing by the orientation of the bridgehead nitrogens towards the inside or the outside of the molecular cavity [1], the complex stabilities measured here are relative to an equilibrium mixture of the ligand forms. The data in the Table confirm that cryptands **1–3** form complexes of both 1:1 and 2:1 cation/ligand stoichiometry, *i.e. mononuclear* and *binuclear* *[3]-cryptates* of alkali and alkaline-earth cations, in agreement with the NMR. studies

discussed above. These complexes thus bear up to four positive charges. The similarity between the stabilities of the 1:1 complexes formed by these macrotricycles **1–3** and by the macrocyclic ligand **5b** is further indication that in the 1:1 complexes of **1–3** the cation is located non-symmetrically, on one of the macrocycles of the macrotricyclic system.

Stability and selectivity of the mononuclear [3]-cryptates. – The stability constants of the 1:1 complexes of cryptands **1–3** with the same cation increase in the sequence **3** < **1** < **2**; they differ at most by a factor of about 10. Using **1** as reference point, the higher stability of the complexes of **2** may be ascribed to interaction of the cation with one or both of the oxygen sites in the bridges, as is found in the crystal structure of $[2Na^+ \subset \mathbf{2}].2I^-$ [15]; the lower stability of the complexes of **3** could arise from the presence of larger organic groups shielding more the cations from the polar solvent and/or from increased rigidity of the molecule. The stabilities of the complexes of **1–3** are comparable to those of the model macrocyclic subunit **5b**, as already noted, but are lower than those of the smaller macrocycle **4** and much lower than those of the macrobicycle **6**. This may arise from a more rigid positioning of the binding sites in **4** with stronger participation of the bridges due to the small size of the ring which displaces the cations towards the interior of the macrotricycle (see the crystal structure of $[2Ag^+ \subset \mathbf{4}].Ag(NO_3)_3^{2-}$ [16]). The comparatively high stabilities of the macrobicyclic cryptates of **6** may come from the tighter envelopment of the cations by the binding sites, despite the fact that the cavity of **6** is already too large for K^+ and Rb^+ [6].

The *selectivities* of the 1:1 complexes are not very pronounced and ressemble those of the complexes formed by ligands **4**, **5b** and **6**. Ligands **1–3** favor K^+ over the other alkali, but whereas the complexation ability of **1** decreases slightly from K^+ to Cs^+, **2** forms a Cs^+ complex which is more stable than its Rb^+ complex. The former behaviour ressembles that of the macrocycle **5b**, the subunit of ligand **1**. The latter behaviour is analogous to that of the macrotricycle **4**; this selectivity pattern may arise from the interaction of the large Cs^+ cation with the two oxygen sites contained in the bridges of ligands **2** and **4**.

Stability and selectivity of the binuclear [3]-cryptates. – Despite the comparatively less accurate results, two main features emerge from the data on the binuclear complexes (Table). a) log K_{s2} is lower than log K_{s1}, but only by a relatively small factor; b) the 2:1 complexation selectivities are similar to the 1:1 selectivities. At a distance of about 6–7 Å the electrostatic repulsion of two charges is about 1.5 kcal/mol (with a dielectric constant of 35.5 for M/W mixture), amounting to $\Delta pK_s = \log K_{s1} - \log K_{s2} \sim 1.1$. This is in the range of the ΔpK_s values found here (Table) but still too large. Thus, it appears that complexation of the second cation is almost as easy as complexation of the first. In other words, the macrotricycle contains *two almost independent macrocyclic units*. It is quite striking that inclusion of a second large cation like Cs^+ or of a second doubly charged cation like Ba^{2+} is so easy. For Cs^+ which cannot penetrate entirely into the lateral macrocycles, external complexation could occur too. On the other hand for the smaller ligand **4** the 2:1 complexes are several powers of ten less stable than the 1:1 complexes. A cation-cation distance of

3.8 Å as in [$2Ag^+ \subset$ **4**] [16] leads to 2.5 kcal/mol electrostatic repulsion, *i.e* $\Delta pK_s \sim$ 1.8; additional destabilization may arise from greater conformational strain and perhaps lower local dielectric constant than in the 2:1 complexes of the larger macrotricycles **1–3**. The *solvent effect* on complex stability should be similar to that found for the macrobicyclic complexes [6]. From M/W 95:5 to aqueous solution, one may expect a decrease in stability by a factor of about 10^2–10^3, as is indeed found for the complexes of ligand **2** (see Table).

Conclusion. – It has been shown that the cylindrical macrotricyclic ligands **1–3** form mononuclear and binuclear complexes of appreciable stability with alkali and alkaline-earth cations. The stabilities and selectivities of complexation are such that one may consider **1–3** as containing two almost independent macrocyclic subunits. This result is of importance in further development of the chemistry of macrotricyclic cryptates, especially towards the complexation of transition metal cations. Indeed it indicates that in such systems the macrocyclic sites may be used to select a given cation, with stabilities and selectivities comparable to those of the isolated macrocycle. Furthermore the structure of the macrotricycle determines the relative positions of the macrocyclic subunits and thus also the positions of the complexed cations, a feature of much interest in the study of cation-cation interactions, electron transfers, substrate inclusion between the cations and catalysis.

Experimental Part

Materials and apparatus. The synthesis of the ligands **1–3** has been described previously [1]. The inorganic salts were reagent grade. The NMR. spectra were measured on a *Varian* XL-100-15 spectrometer equipped with the *Fourier*-Transform accessory; the 63-MHz-^{13}C-NMR. spectrum was obtained on a *Cameca* 250 superconducting spectrometer. For the determination of the stability constants, the equipment used as well as the experimental procedure were the same as in previous work [6] except when specified.

Measurements with cation selective electrodes. The standard conditions were: 0.02 M ligand + 0.1 M NEt_4Br in M/W 95:5 (in volume) + 6 µl NEt_4OH (25% in water) per ml of solution. This solution was titrated with 0.1 M alkali salt in the same solvent and measuring the free cation concentration $[M^{n+}]$ with the suitable cation selective electrode [6]. A calibration curve of the electrode was obtained by performing the same titration in the absence of ligand. A computer program was written for calculating the stability constants K_{s1} and K_{s2} of the 1:1 and 2:1 complexes by least squares fitting of equation (6) below to the experimental titration curve $-\log [M^{n+}] = f(n)$.

The concentration of free cation $[M^{n+}]$ as a function of only K_{s1}, K_{s2} and the initial concentrations of ligand $[L_o]$ and cation $[M_o^{n+}]$ is given by equation (6) [20].

$$-\log [M^{n+}] = \frac{\log K_{s1} + \log K_{s2}}{2} + \log \frac{2(2-n)}{[R^2(1-n)^2 + 4n(2-n)]^{1/2} - R(1-n)} \qquad (6)$$

$$\text{with } n = ([M_o^{n+}] - [M^{n+}])/[L_o]$$

$$\log R = (\log K_{s1} - \log K_{s2})/2$$

pH-metric measurements. The apparatus used was an automatic titration set up (*Tacussel*, units TT100, TT200, TT300). The reference calomel electrode was fitted with a bridge containing a non complexable cation, 0.1 M NMe_4Br in M/W 9:1 (in volume). The measuring electrode was a *Tacussel* electrode for aqueous solutions or a special electrode (*Tacussel* MeOH B10) for measurements in M/W 9:1. In M/W the electrodes were calibrated using an oxalate buffer at pH 3.59 and a succinate buffer at pH 6.56, both buffers in M/W 9:1. In this solvent the dissociation constant of water was

determined $pK_w = 15.56 \pm 0.03$. All experiments were back titrations by NMe_4OH 0.1 M (in W or M/W) of solutions containing a sufficient amount of acid for complete protonation of the ligand. The standard ligand solution was (0.045 M HNO_3 + 0.01 M ligand + 0.055 M NMe_4Br in W or M/W). The pK_m values of the ligands were determined on a mixture of ligand solution (1.5 ml) and 0.1 M NMe_4Br solution (1.5 ml) in M or M/W. For determination of the stability constants titrations were performed at 1:1 and 2:1 salt/ligand ratios; the solutions were: (1.5 ml ligand solution + 0.15 ml 0.1 M salt/1.35 ml 0.1 M NMe_4Br) and (1.5 ml ligand solution + 0.3 ml 0.1 M salt + 1.2 ml 0.1 M NMe_4Br). The data from the two titration curves were analysed with the computer program SCO 75 [21] or Variat [22][3]).

The *error limits* are about $\pm$ 0.2 for log K_{s1} and $\pm$ 0.4 for log K_{s2} values.

REFERENCES

[1] *J. M. Lehn, J. Simon & J. Wagner*, Nouv. J. de Chimie, in press.
[2] *J. M. Lehn*, Structure and Bonding *16*, 1 (1973).
[3] *C. J. Pedersen & H. K. Frensdorff*, Angew. Chem. *84*, 16 (1972); Angew. Chem. Internat. Ed. *11*, 16 (1972); *C. J. Pedersen*, J. Amer. chem. Soc. 89, 7017 (1967).
[4] *B. Dietrich, J. M. Lehn, J. P. Sauvage & J. Blanzat*, Tetrahedron *29*, 1629 (1973).
[5] *B. Dietrich, J. M. Lehn & J. P. Sauvage*, Tetrahedron *29*, 1647 (1973).
[6] *J. M. Lehn & J. P. Sauvage*, J. Amer. chem. Soc. *97*, 6700 (1975).
[7] *J. Cheney, J. M. Lehn, J. P. Sauvage & M. E. Stubbs*, J. chem. Soc. Chem. Commun. *1972*, 1100.
[8] *J. M. Lehn, J. Simon & J. Wagner*, Angew. Chem. *85*, 621 (1973); Angew. Chem. Internat. Ed. *12*, 578 (1973).
[9] *B. Dietrich, J. M. Lehn & J. Simon*, Angew. Chem. *86*, 443 (1974); Angew. Chem. Internat. Ed. *13*, 496 (1974).
[10] *E. Graf & J. M. Lehn*, J. Amer. chem. Soc. *97*, 5022 (1975).
[11] *J. M. Lehn, J. Simon & J. Wagner*, Angew. Chem. *85*, 622 (1973); Angew. Chem. Internat. Ed. *12*, 579 (1973).
[12] *J. M. Lehn & M. E. Stubbs*, J. Amer. chem. Soc. *96*, 4011 (1974).
[13] *J. M. Lehn*, Pure appl. Chemistry in press.
[14] *D. Moras, B. Metz, M. Herceg & R. Weiss*, Bull. Soc. chim. France *1972*, 551.
[15] *M. Mellinger, J. Fischer & R. Weiss*, Angew. Chem. *85*, 828 (1973); Angew. Chem. Internat. Ed. *12*, 771 (1973).
[16] *R. Wiest & R. Weiss*, J. chem. Soc. Chem. Commun. *1973*, 678.
[17] *M. E. Stubbs & J. M. Lehn*, unpublished results.
[18] *D. B. Rorabacher, W. J. MacKellar, F. R. Shu & S. M. Bonavita*, Analyt. Chemistry *43*, 561 (1971).
[19] *B. Dietrich, J. M. Lehn & J. P. Sauvage*, J. chem. Soc. Chem. Commun. *1971*, 15.
[20] *P. Souchay & J. Lefèbvre*, «Equilibres et réactivités des complexes en solution», Masson et Cie, Paris 1969.
[21] *I. G. Sayce*, Talanta *15*, 1397 (1968); *18*, 653 (1971).
[22] *T. Kaden & A. Zuberbühler*, Talanta *18*, 61 (1970).

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