Transfer activity coefficients between water and methanol of complexes of some univalent and barium ions with dibenzocryptand 2.2.2, cryptand 2.2.2, and 18-crown-6

(ligands/complexation/hydrophobic solvation)

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ABSTRACT Stability constants, K_fLM^{n+} (in which L = ligand and M^{n+} = metal ion), of complexes of sodium, potassium, silver, thallium(I), and barium with dibenzocryptand 2.2.2 were determined at 25°C in water and methanol. Also determined were transfer activity coefficients between methanol and water of two ligands, dibenzocryptand 2.2.2 and 18-crown-6. From these data, transfer activity coefficients of complexes of these two ligands with the above cations have been calculated. For univalent ion complexes of these ligands and, in addition, for such complexes of dibenzo-18-crown-6 and cryptand 2.2.2, the logarithms of the transfer activity coefficients are of the order of 2.5 units more positive than those of the ligands. Even though methanol is a good hydrogen bond donor, as is water, it is concluded that in methanol only the first solvation layer is built around an ether oxygen of the uncomplexed ligand as compared with several hydration layers in water. Hydrogen bonding to these ether oxygens when these ligands are complexed is greatly decreased as a result of ionic M^{n+} -O bonding. Transfer activity coefficients of the barium complexes are found to be the same as those of the ligands. This is attributed to extensive solvation of LBa^{2+} .

Transfer activity coefficients, ${}^{MeOH}\gamma^W LM^+$ (L = ligand and M^+ = metal ion), between methanol (MeOH) and water (W) of complexes, LM^+ , of dibenzo-18-crown-6 (DB-18) with alkali, silver (I), and thallium(I) ions have been found (1) to be considerably more positive than those of the corresponding uncomplexed (solvated) ions and also that of the ligand. Using cryptand 2.2.2 (2.2.2) as a ligand, we arrived (2) qualitatively at the same conclusion that the values of ${}^{MeOH}\Delta^W \log K_f LM^+ + \log {}^{MeOH}\gamma^W M^+$ (equal to $\log {}^{MeOH}\gamma^W LM^+ - \log {}^{MeOH}\gamma^W L$) are very positive. Almost simultaneously with our paper (2), Abraham *et al.* (3) reported the value of $\log {}^{MeOH}\gamma^W 2.2.2 = -0.83$ at 25°C. Neither Abraham *et al.* nor we could confirm the conclusion of Villermaux and Delpuech (4) that $\log {}^{MeOH}\gamma^W LNa^+ = 0$ (L = cryptand 2.2.1) expressed in terms of free energy. Nor could we confirm the proposal by Lejaille *et al.* (5, 6) that ${}^{MeOH}\gamma^S LM^+ = {}^{MeOH}\gamma^S L$, S denoting water or various organic solvents and L being cryptands 2.1.1, 2.2.1, or 2.2.2.

The present study deals mainly with the determination of transfer activity coefficients between MeOH and W of complexes of dibenzocryptand 2.2.2 (DB-2.2.2), a ligand introduced by Lehn and colleagues (7). These authors reported that the ligand is slightly soluble in water but freely soluble in MeOH. They determined the stability constants, K_fLK^+ and K_fLBa^{2+} in MeOH/water, 95:5 (vol/vol). They noted that, by introduction of two benzo groups, the stability constant of the barium complex is decreased to a much greater extent than that of po-

tassium. Qualitatively, a similar effect is observed with the corresponding complexes of 18-cr-6 (8).

In the present paper we report values of the stability constants in water and MeOH of the complexes of DB-2.2.2 with Na^+ , K^+ , Tl^+ , Ag^+ , and Ba^{2+} . These have been determined mainly by the silver exchange method (2) and also potentiometrically with a cation selective electrode. In addition, we have determined the transfer activity coefficients of DB-2.2.2 and of 18-cr-6 using a method similar to that used by Abraham (3) for 2.2.2. From this data it becomes possible to evaluate ${}^{MeOH}\gamma^W LM^+$ and ${}^{MeOH}\gamma^W LBa^{2+}$ for the cryptands 2.2.2 and DB-2.2.2 and also for 18-cr-6.

EXPERIMENTAL

Dichloromethane and MeOH were Matheson, Coleman, & Bell "Omnisolv" products. MeOH was distilled over magnesium. Both *n*-hexadecane (Aldrich White Label) and 25% (wt/vol) aqueous solution of tetramethylammonium hydroxide, Eastman Kodak product, were used without further purification. Potassium picrate (9); sodium (10), potassium (10), and thallium(I) (9) nitrates; and sodium, potassium, and thallium(I) perchlorates (9) have been used previously. Barium perchlorate was a G. F. Smith Co. product, recrystallized from ethanol and assayed gravimetrically as barium sulfate, 99.5%. Barium nitrate was Baker Analyzed Reagent Grade, recrystallized from water. The barium salts were dried *in vacuo* at 70°C. Both 2.2.2 and DB-2.2.2 (Kryptofix 2.2.2 and Kryptofix 2.2.2 DB) were obtained from Merck, Darmstadt, Federal Republic of Germany and were used as received.

In partitioning experiments of DB-2.2.2 and 18-cr-6 between hexadecane and water or MeOH, the two phases were shaken in a separatory funnel for 20 min and allowed to stand for 1-2 hr. The appropriate phase was centrifuged at least twice for 10 min at $600 \times g$. The concentration of DB-2.2.2 in the hexadecane phase was found spectrophotometrically at 277 nm ($\epsilon = 5.93 \times 10^3 M^{-1} cm^{-1}$). In the aqueous phase, it was determined spectrophotometrically at 277 nm after extraction into dichloromethane ($\epsilon = 5.91 \times 10^3 M^{-1} cm^{-1}$). In the partitioning of 18-cr-6 between hexadecane and water or MeOH, an aliquot of the centrifuged hydrocarbon layer was extracted three times with an equal volume of water. The crown, which had been transferred quantitatively into the aqueous phase, was determined spectrophotometrically as complexed potassium picrate by making the solution 1 mM in potassium picrate and repeatedly extracting the complexed picrate into dichloromethane. The absorbance was then measured at 370 nm. By taking known

amounts of 18-cr-6 in water and using the above procedure, a linear calibration plot was obtained with $\varepsilon = 1.4_8 \times 10^4 \text{ M}^{-1} \text{ cm}^{-1}$. The concentration of 18-cr-6 potassium picrate in dichloromethane varied from 0.01 to 0.07 mM.

Potentiometric measurements of the negative log of the Ag^+ activity ($p_a \text{Ag}$) at 25°C in mixtures of DB-2.2.2 Ag^+ with alkali or barium ions in MeOH were carried out as described (2). A similar cell assembly was used in aqueous solution, except that the reference electrode was 10 mM AgNO_3/Ag equipped with a 10 mM tetraethylammonium nitrate double-junction salt bridge. All measurements were carried out at 25°C .

RESULTS

The solubility of DB-2.2.2 in 1 and 0.1 mM aqueous tetramethylammonium hydroxide and in pure water was 0.74₆, 0.65₆, and 0.62₂ mM, respectively. From the difference in solubility in pure water and that in which protonation was completely suppressed, the monoprotonation constant $K_f \text{LH}^+ = [\text{LH}^+]/[\text{H}^+][\text{L}]$ was found to be $10^{9.5}$ at 25°C as compared to $10^{9.71}$ for 2.2.2 reported by Anderegg (11). The solubility in MeOH was estimated to be $\gg 75 \text{ mM}$ from $\log^{\text{MeOH}} \gamma^{\text{W}} \text{DB-2.2.2} = 2.1$ (see below) and the solubility in water.

In fact, a solid methanolate DB-2.2.2-0.94 MeOH was obtained upon exposure of the cryptand to MeOH vapor for a week. In order to evaluate $\log^{\text{MeOH}} \gamma^{\text{W}} \text{L}$, an indirect method, described for 2.2.2 by Abraham (3), was used in which DB-2.2.2 or 18-cr-6 was partitioned between MeOH and *n*-hexadecane and between water and *n*-hexadecane, respectively. With 18-cr-6 the partition coefficients were found to be independent of concentration. This has not been found true with DB-2.2.2. The following values of the apparent partition coefficient, $P_{\text{app}} = \Sigma [\text{L}]_{\text{hexadecane}}/[\text{L}]_{\text{MeOH}}$ were obtained when 10 ml of 0.64, 1.28, 1.60, 3.20, and 3.51 mM DB-2.2.2 in MeOH were shaken with 20 ml of hexadecane: 0.050, 0.057, 0.055, 0.089, and 0.087. It appears that DB-2.2.2 is dimerized in the hydrocarbon phase with a dimerization constant of 2.1×10^2 . In deriving the partition coefficient between hexadecane and water, hydrolysis in the aqueous phase was taken into account. As an example, 40 ml of 0.332 mM DB-2.2.2 in water was extracted with 15 ml of hexadecane. In the aqueous phase after extraction, $\Sigma [\text{L}]_{\text{W}} = [\text{L}]_{\text{W}} + [\text{LH}^+]_{\text{W}} = 0.170 \text{ mM}$, and $[\text{L}]_{\text{W}} = 0.110 \text{ mM}$. By difference, $\Sigma [\text{L}]_{\text{hexadecane}} = 0.435 \text{ mM}$, and the ratio $\Sigma [\text{L}]_{\text{hexadecane}}/[\text{L}]_{\text{W}} = 3.96$. Assuming the dimerization constants in hexadecane saturated with water and in hexadecane saturated with MeOH to be the same, we found $P = 3.42$. In Table 1 are listed the partition coefficients of DB-2.2.2 and 18-cr-6 between hexadecane and water or MeOH.

All salts used under our experimental conditions can be considered completely dissociated with the exception of barium perchlorate in MeOH. Conductance data in MeOH of 0.1–5.5 mM barium perchlorate alone and in the presence of 10 mM 2.2.2 were treated by the method of Dawson and Golben (12). Values of $\lambda_0 \text{Ba}^{2+}$ and $K_d \text{BaClO}_4^+$ were found equal to 56.0 and

$2.3_5 \times 10^{-3}$, respectively, by taking $\lambda_0 \text{ClO}_4^- = 70.8$ (13). Corresponding values for 2.2.2 Ba^{2+} were found to be 44.2 and 5.5×10^{-3} , respectively. In water, $K_f \text{DB-2.2.2 Ag}^+$ was found from potentiometric measurements with the silver electrode in 0.7 mM DB-2.2.2/0.15–0.45 mM AgNO_3 and in the absence and presence of 0.1 mM tetramethylammonium hydroxide. Complexation of DB-2.2.2 with Ag^+ is sufficiently extensive that hydrolysis is negligible even in absence of base. No turbidity due to silver hydroxide was observed.

Silver exchange experiments involving the reaction $\text{LAg}^+ + \text{M}^{n+} \rightleftharpoons \text{LM}^{n+} + \text{Ag}^+$ (L being DB-2.2.2) were carried out in water in 2–15 mM MNO_3 or $\text{Ba}(\text{NO}_3)_2/0.3 \text{ mM AgNO}_3/0.5 \text{ mM DB-2.2.2/1 mM Me}_4\text{NOH}$. In MeOH the solutions were 1–7 mM in MClO_4 , 0.2 mM in AgNO_3 , and 1 mM in DB-2.2.2. Equilibrium with DB-2.2.2 Ag^+ in MeOH was attained after 20–30 min, except with barium, in which case 6 days were required. The reaction of 2.2.2 Ag^+ with barium also was slow, equilibrium being attained after 2 days. The latter exchange was close to quantitative. In aqueous media, all equilibria were attained within 10 min. Literature references for calculation of $K_f \text{LM}^+$ of univalent ion cryptates from silver exchange data have been listed (2).

In methanolic systems containing $\text{Ba}(\text{ClO}_4)_2$, AgNO_3 , and ligand,

By substituting Eq. 3 and the expression for $K_d \text{BaClO}_4^+$ into Eq. 1 and neglecting $[\text{LBaClO}_4^+]$, Eq. 4 results.

The value of $[\text{BaClO}_4^+]$ from Eq. 4 was introduced into Eq. 1 to evaluate the Ba^{2+} concentration. A constant value of $K_f \text{LBa}^{2+}$ was found in solutions containing 2.18–9.77 mM $\text{Ba}(\text{ClO}_4)_2$, 0.22 mM AgNO_3 , and 0.83–0.93 mM DB-2.2.2. Corresponding values of ligand concentration decreased from 1.8 mM to 0.16 mM. The ratio $[\text{LBaClO}_4^+]/[\text{BaClO}_4^+] = K_f \text{LBaClO}_4^+ [\text{L}]$ decreased accordingly, with increasing concentration of barium. The presence of a significant amount of LBaClO_4^+ , as compared to the concentration of BaClO_4^+ , would be incorporated into the calculated value of $K_f \text{LBa}^{2+}$.

As a check on the silver exchange method, a potassium ion selective electrode was used in aqueous potassium solutions

Table 1. Partition coefficients of cryptands and 18-cr-6 between hexadecane and MeOH or water

L	$P_{\text{hex/MeOH}}$	$P_{\text{hex/water}}$	$\log^{\text{MeOH}} \gamma^{\text{W}} \text{L}$
2.2.2	0.087 ₀ *	0.0129*	−0.83
DB-2.2.2	0.040	5.4 ± 1.8	$2.1_3 \pm 0.15$
18-cr-6	0.018 ₀	3.9×10^{-4}	−1.6 ₆
DB-18	—	—	1.8 ₅ †

hex, hexadecane.

* From Abraham, ref. 3, who used tetradecane as the hydrocarbon.

† Ref. 1.

Table 2. Complexation constants ($\log K_f \text{LM}^{n+}$) of DB-2.2.2 with various ions in water and MeOH*

Ion	Water	MeOH
Na^+	3.4 ₄ [3.9]	7.3 ₇ [7.8]
K^+	4.3 ₆ , 4.6 ₂ †[5.4]	8.6 ₀ [10.6]
Tl^+	4.6 ₁ [6.3]	7.9 [10.0 ₅]
Ag^+	8.90 [9.6]	11.7 ₈ [11.9 ₅]
Ba^{2+}	5.6 ₅ [9.5]	8.8 ₇ [12.9]‡

* Values for 2.2.2 are in brackets. Each value is the average from several authors.

† From cation-selective electrode measurements, all others from silver exchange studies.

‡ Our estimate.

containing 0.54 mM DB-2.2.2, 0.06–0.23 mM KNO₃, and 1 mM Me₂NOH (Table 2). Complexation constants of DB-2.2.2 with Na⁺, K⁺, Tl⁺, Ag⁺, and Ba²⁺ in water and MeOH are entered in Table 2. Values from various sources for each of the above univalent ions with 2.2.2 have been tabulated (8). As reported by Lehn and Sauvage (14), the constant of barium with 2.2.2 is 10^{9.5} in water and approximately 10¹² in MeOH/water, 95:5 (vol/vol). Using the silver exchange method, we estimate in MeOH a value of 10^{12.9 ± 0.2}.

DISCUSSION

It is well known that two benzo groups, when attached to a macrocyclic ligand, exert an electron withdrawing effect on the ether oxygens. As a result, the stability constant, K_fLM^{n+} , of a complexed metal ion is smaller when the ligand is dibenzo-substituted than when it is unsubstituted. This effect increases with increasing charge of the cation (7). For example, in MeOH, $\log K_f2.2.2M^{n+} - \log K_fDB-2.2.2M^{n+}$ is of the order of 4.0 for LBa²⁺ and equal to 2.0 for LK⁺ (see Table 2). For ions of the same charge, the dibenzo effect is larger when they fit the cavity of the macrocycle than when they are smaller (e.g., for LNa⁺ and LAg⁺, the above difference is 0.4 and 0.2, respectively, as compared to 2.0 for LK⁺). Similar differences have been found with the two crown ethers.

We next consider the free energies of transfer of the uncomplexed ligands and their metal ion complexes going from MeOH to water. From the negative values of $\log {}^{MeOH}\gamma^W L$ (Table 1) it appears that both 18-cr-6 and 2.2.2 are strongly hydrated, despite the hydrophobic character of the $-(CH_2)_2-$ groups. Even though MeOH, is a good hydrogen bond donor, as is water, it is concluded that only the first solvation layer of MeOH is built around an ether oxygen, whereas several layers of water can be. This is reflected in the very negative values of $T(\Delta S_{tr})_{MeOH \rightarrow W}$ of -12.8 and -11.3 kcal deg. mol⁻¹ for 2.2.2 and 18-cr-6, respectively (3), ΔS_{tr} and T denoting entropy of transfer and temperature (298 K), respectively.

From the data in Tables 1 and 2 values of $\log {}^{MeOH}\gamma^W LM^{n+}$ have been calculated (Table 3). For comparison, values of $\log {}^{MeOH}\gamma^W M^{n+}$ (9) and $\log {}^{MeOH}\gamma^W Ba^{2+}$ [Parker *et al.* (15)] have been included in Table 3. Upon complexation of ligand with Mⁿ⁺, the "donating strength" of the ether oxygen is greatly reduced by ionic M⁺–O bonding and much more so by Ba²⁺–O bonding. This effects a weakening of the methanolation and, particularly, the hydration layer(s) around the ether oxygens.

Table 3. Values of $\log {}^{MeOH}\gamma^W LM^{n+}$ (and $\log {}^{MeOH}\gamma^W M^{n+}$)

LM ⁿ⁺	2.2.2	DB-2.2.2	18-cr-6	DB-18	$\log {}^{MeOH}\gamma^W M^{n+}$
LNa ⁺	1.7	4.5	0.4 ₄	3.7 ₅	–1.5
LK ⁺	2.6	4.4	0.6 ₄	3.5 ₆	–1.8
LAg ⁺	0.5	3.7	0.1	3.3 ₄	–1.3
LTl ⁺	2.3	4.7	0.8	3.6	–0.7
LBa ²⁺	–0.8	2.1	–1.7 ₆	0.9 ₆	–3.2

As a result, values of $\log {}^{MeOH}\gamma^W LM^{n+}$ are more positive than that of the uncomplexed ligand. In spite of the stronger Ba²⁺–O bonding, the effective charge of the cation in LBa²⁺ is considerably greater than that of K⁺ in LK⁺. Consequently, solvation of LBa²⁺ is also considerably greater than that of LK⁺. For three ligands in Table 3, $\log {}^{MeOH}\gamma^W LK^+ - \log {}^{MeOH}\gamma^W LBa^{2+} = 2.3$. The deviating value of 3.4 for cryptand 2.2.2 complexes might be attributed to the uncertainty of $K_f2.2.2Ba^{2+}$ in MeOH. The relatively large effective charge of Ba²⁺ in LBa²⁺ is reflected in the very much slower equilibration in MeOH between LBa²⁺ and Ag⁺ than that between LK⁺ and Ag⁺. It is of interest to note that for a univalent central metal atom, values of $\log {}^{MeOH}\gamma^W LM^{n+}$ are 2.5–3.5 units more positive when L is a dibenzo-substituted cryptand or crown ether than when it is unsubstituted. Almost the same difference is found for the uncomplexed ligands, which is attributed primarily to the hydrophobic entropy effect. From a comparison of values of $\log {}^{MeOH}\gamma^W L$ in Table 1 with those of $\log {}^{MeOH}\gamma^W LM^{n+}$ in Table 3, it is evident that for cryptates 2.2.2 the proposal (5, 6) that $\gamma_{LM^{n+}} = \gamma_L$ does not hold when water is a reference solvent. It is fortuitous that $\log {}^{MeOH}\gamma^W LBa^{2+} = \log {}^{MeOH}\gamma^W L$, which is accounted for by solvation of the barium complex.

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