

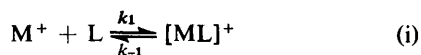
Ligands for the Alkali Metals. Part 6.¹ Some Bis(crown) Schiff Bases which form Pocket Complexes with Alkali-metal Cations of Appropriate Size

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Three homologous series of bis(crowns) have been produced by condensation of the appropriate formylbenzocrown with long-chain α,ω -diaminoalkanes. The ligands may be viewed as pocket or crevice sites for alkali-metal cations, lined with donor groups to provide ion-dipole interaction and terminated by a hydrophobic methylene chain. The interaction of these ligands with alkali-metal cations has been investigated by spectroscopic techniques and solvent extraction. Pocket complexes of these bis(crowns) with alkali-metal cations were apparently formed in 'best-fit' situations: thus bis(crown-5) compounds formed pocket complexes with cations larger than sodium, while bis(crown-6) ligands formed pocket complexes with cations larger than potassium. The bis(crown-4) ligands did not appear to complex strongly with any cation. The rates of trapping and release of alkali-metal cations from some of these ligands in methanol solution, investigated by temperature-jump techniques, indicate behaviour distinct from that of any of the crown and cryptand types described in the literature.

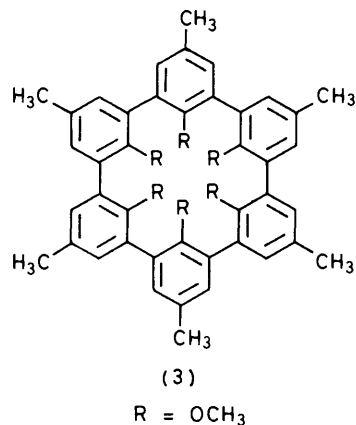
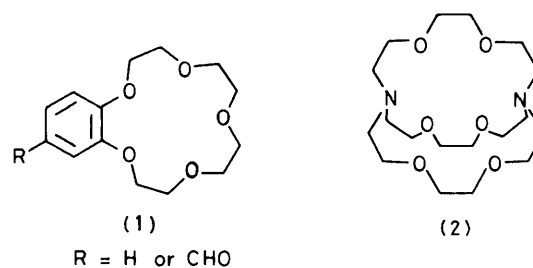
Selectivity for the alkali-metal cations is displayed most importantly in biochemical systems such as the sodium pump. There is ever-expanding interest in the chemistry of synthetic ionophores which can model such a biochemical function, and indeed which can exploit for chemical purposes the design features of natural ligands. Patterns for the design of improved ligands were laid down at an early stage, *e.g.* in the contributions of Bromels and Pedersen² to the patent literature, by Lehn,³ Simon *et al.*,⁴ and others.⁵ It was realised that crowns like (1) (and particularly derivatives containing other functional groups) are easily made, while cryptands require a more time-consuming synthesis.

It has become clear that in the process by which an ionophore complexes a cation (in a single solvent) the rate of cation release from the complex [equation (i)] is the most



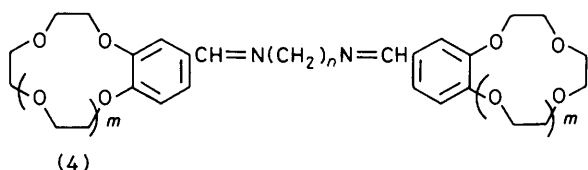
important factor differentiating between one cation and another.^{6,7} The rate of cation release is itself a function of how well the ligand screens the particular cation from interaction with solvent and other local species. Simple crowns like (1) have the disadvantage that the complexed cation in a circular cavity is only partially screened from the influence of the surrounding medium.⁸ The cryptands, *e.g.* (2), in which a cation may be *englobé* rather than encircled, provide better screening, and thermodynamically are much stronger complexing agents [equation (i)] for which the rate of cation release is much less. [Thus k_{-1} for the cryptand (2) is 7.5 s^{-1} at 25°C for K^+ ions in water compared to $3.7 \times 10^6 \text{ s}^{-1}$ for 18-crown-6 (1,4,7,10,13,16-hexaoxacyclo-octadecane).^{6,9}] Each of these ligands has considerable flexibility, so that each can adapt its shape to ligate cations in a range of sizes. In stark contrast are the spherands like (3), which has a quite rigid spherical cavity and acts as a cation sink.⁵ Cations are trapped with high specificity in, and released extremely slowly from, such a cavity.¹⁰

In terms of practical use, selectivity in multiple phases involves other considerations such as lipophilicity. The high aqueous solubility of simple unsubstituted ligands like (1) and (2) can be a serious drawback. In three-phase systems (modelling primitive membranes) it is evident that very high complexing power (with concomitant slow cation release to the membrane exterior) can also be a drawback.^{11,12} Ranges of

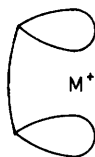


compounds intermediate in rates of trapping and release of cation, and of high lipophilicity, are of value in membrane applications.

Pedersen,¹³ the pioneer of crown ether chemistry, showed that simple crowns such as (1) would form 2:1 complexes with potassium and larger cations, suggesting the sandwich structure neatly confirmed by X-ray crystallographic studies of the potassium iodide complex.¹⁴ Linking of two crowns to provide sandwiching capacity in one molecule (for which the trivial name *clam* was suggested by Bromels and Pedersen²) was achieved by Bourgoin *et al.*¹⁵ Evidence for the first 'clam sandwich' was obtained in solution by these workers, employing a u.v. spectrophotometric distinction between loose and tight ion pairs involving a picrate counter ion. The clam idea has been greatly extended since it offers design potential: the crowns are easily synthesised and considerable scope



(4)

 $m = 1-3$ $n = 2-10 \text{ or } 12$ 

(5)

exists for linking the two crown faces together.^{16,17} The clam type should present possibilities intermediate between those for simple crowns and cryptands, with adequate screening of an enclosed cation, full use of the chelate and macrocyclic effects as in cryptands, yet affording an intuitively satisfying model for a pocket or crevice site for a cation of appropriate size.

Here we report on a series of bis(crown) Schiff-base ligands (4) in which some of these possibilities have been realised. They enable the study of the following features: (i) change of crown ring size ($m = 1-3$); (ii) change in length of the hinge ($n = 2-10$ or 12); (iii) absence of donor atoms in the hinge; (iv) constraints imposed by the rigidity of the two azomethine groups; (v) contrast with lipophilicity and other features of earlier clams.^{16,17} Solvent-extraction studies have shown compounds (4) to be effective ligands, providing heightened discrimination between cations large enough to form a pocket complex (2) and those not. A study of the rates of the ion-complexing reaction [equation (i)] of several of these ligands containing the benzo-15-crown-5 moiety ($m = 2$) shows k_{-1} , the dissociation rate constant, to be intermediate between the values for simple crowns and cryptands in methanol solution, but k_1 , the formation rate constant, to be much lower than for either crowns or cryptands. This, together with their improved lipophilicity and ease of synthesis, makes the bis(crowns) a convenient addition to the range of ligands for the alkali-metal cations.

Experimental

4'-Formylbenzo-15-crown-5.*—A crystalline product was obtained by condensing either 1,11-dichloro-5,6,9-trioxaundecane or tetraethylene glycol ditosylate † with 3,4-dihydroxybenzaldehyde in butanol with NaOH as base in a modification of a published method.¹ The best yield, however, was obtained using the ditosylate of tetraethylene glycol in acetonitrile with CsF as the base, as described by Reinhoudt *et al.*,¹⁸ which is suitable for base-sensitive substituents. Crystalline products for 4'-formylbenzo-18-crown-6 ‡ and 4'-formylbenzo-12-crown-4 ‡ were only obtained by the CsF method. The best method of isolation was chromatography by the Celite method¹⁹ using gradient-elution techniques (light

petroleum-diethyl ether mixtures). These three crowns had $\nu(\text{C=O})$ at $1\ 680-1\ 690\ \text{cm}^{-1}$ in their i.r. spectra, and sharp singlets in their ^1H n.m.r. spectra (CDCl_3 solution) at 9.8 p.p.m. downfield from SiMe_4 due to the CHO group, and they were characterised as shown below. The mass spectra of the crude reaction mixtures always showed weak ions corresponding to the dimer of the crown, but no pure sample of dimer was ever obtained, despite continued gradient elution.

4'-Formylbenzo-12-crown-4 had m.p. $81\ ^\circ\text{C}$ (Found: C, 61.6; H, 6.6%; M^+ 252. $\text{C}_{13}\text{H}_{16}\text{O}_5$ requires C, 61.9; H, 6.4%; M 252). The known compound 4'-formylbenzo-15-crown-5 had m.p. $78-79\ ^\circ\text{C}$ (lit.,²⁰ $78-79\ ^\circ\text{C}$) (Found: C, 60.5; H, 6.9%; M^+ 296. Calc. for $\text{C}_{15}\text{H}_{20}\text{O}_6$: C, 60.8; H, 6.8%; M 296), while 4'-formylbenzo-18-crown-6 had m.p. $60-61\ ^\circ\text{C}$ (lit.,²⁰ $60-62\ ^\circ\text{C}$) (Found: C, 59.8; H, 7.4; M^+ 340. Calc. for $\text{C}_{17}\text{H}_{24}\text{O}_7$: C, 60.0; H, 7.1%; M 340).

Bis(crown) Schiff Bases.—4'-Formylbenzo-15-crown-5 (1 g, 3.4 mmol) recrystallised from diethyl ether was dissolved in nitrogen-purged dry methanol (0.1 dm^3), and 1,6-diaminohexane (0.2 g, 1.7 mmol) dissolved in dry methanol (0.05 dm^3) was added dropwise to the solution which was then refluxed gently for 30 min, then reduced in volume to 0.005 dm^3 . After cooling, the solution deposited white crystals of 15,15'-hexamethylenedinitrilodimethylidynebis(2,3,5,6,8,9,11,12-octahydro-1,4,7,10,13-benzopentaoxacyclopentadecin) (4; $m = 2$, $n = 6$), which were separated by filtration. The compound could be recrystallised from dry methanol without decomposition. All the Schiff bases (4) were produced by this general method, and characterised by elementary analysis and accurate mass of the molecular ion (measured on an AEI MS9 instrument). Data for the entire series are given in Tables 1-3. Satisfactory ^1H n.m.r. and i.r. spectra were obtained for each compound of the series.

Solvent Extraction.—This was performed with 10- cm^3 aliquots of $1.4 \times 10^{-4}\ \text{mol dm}^{-3}$ picric acid in 0.1 mol dm^{-3} metal hydroxide ($M = \text{Na}, \text{K}, \text{Rb}, \text{or Cs}$) as the aqueous layer and $7 \times 10^{-5}\ \text{mol dm}^{-3}$ bis(crown) in methylene chloride as the organic layer. Since the clam has the potential to complex two cations (one per crown face), twice as much picrate was used as customary for this method.¹ When this work was begun there was no published quantitative examination of solvent extraction in which the picrate counter ion had been extracted in loose ion pairs, and absorption coefficients for picrate in methylene chloride were not known. Work of Bourgoïn *et al.*¹⁵ had shown that the picrate absorption maximum at *ca.* 360 nm shifts in a recognisable way for tight ion pairs in non-hydroxylic solvents, depending on the size of the cation to which it is paired. It is at lowest energy for $\text{Cs} < \text{Rb} < \text{K} < \text{Na}$ cations. For loose ion pairs with a very large effective cation size (and in which the cation is heavily screened from the picrate ion) the band is at *ca.* 379 nm (for K^+) and overlaps a shoulder at 420 nm, which does not move, so that there is an increase in intensity as well as a wavelength shift for the band at 360 nm. This distinctive indication of the presence of loose ion pairs with screened cations was found in our CH_2Cl_2 extracts as indicated below and absorption coefficients ϵ were estimated for the systems from the amount of picrate remaining in the aqueous layer (giving, by difference, the amount taken up in the organic layer) and the absorbance of the organic layer. All the sodium extracted by bis(crown-5) ligands was in tight ion pairs (in which the cation was exposed to picrate anion) with ϵ_{max} averaging $15\ 700 \pm 700\ \text{dm}^3\ \text{mol}^{-1}\ \text{cm}^{-1}$ at 365 nm. The potassium ions extracted were in loose ion pairs (except for extracts of the ligand with $n = 2$), ϵ_{max} averaging $23\ 000 \pm 600\ \text{dm}^3\ \text{mol}^{-1}\ \text{cm}^{-1}$ at *ca.* 379 nm. The rubidium ions likewise were extracted as

* 15-Formyl-2,3,5,6,8,9,11,12-octahydro-1,4,7,10,13-benzopentaoxacyclopentadecin.

† 1,11-Bis(toluenep-sulphonyloxy)-3,6,9-trioxaundecane.

‡ 18-Formyl-2,3,5,6,8,9,11,12,14,15-decahydro-1,4,7,10,13,16-benzohexaoxacyclo-octadecin and 12-formyl-2,3,5,6,8,9-hexahydro-1,4,7,10-benzotetraoxacyclododecin.

Table 1. Analytical data and accurate masses for the molecular ions of the bis(benzo-12-crown-4) Schiff bases (4; $m = 1$)

n	Empirical formula	Analysis (%) ^a			Mass ^a	Error in p.p.m.	M.p. ^b (°C)
		C	H	N			
3	C ₂₉ H ₃₈ N ₂ O ₈	63.4 (64.2)	8.50 (7.05)	4.55 (5.15)	542.2625 (542.2628)	0.3	113
4	C ₃₀ H ₄₀ N ₂ O ₈	63.45 (64.75)	8.65 (7.25)	4.65 (5.05)	556.2734 (556.2784)	5.0	108
5	C ₃₁ H ₄₂ N ₂ O ₈	64.25 (65.25)	9.00 (7.40)	4.75 (4.90)	570.2919 (570.2940)	2.1	111
6	C ₃₂ H ₄₄ N ₂ O ₈	64.5 (65.75)	9.10 (7.60)	4.70 (4.80)	584.3121 (584.3097)	2.4	103
7	C ₃₃ H ₄₆ N ₂ O ₈	65.4 (66.2)	9.30 (7.75)	4.75 (4.70)	598.3247 (598.3254)	0.7	69
8	C ₃₄ H ₄₈ N ₂ O ₈	64.75 (66.65)	9.30 (7.90)	4.30 (4.55)	612.3385 (612.3410)	2.5	92
9	C ₃₅ H ₅₀ N ₂ O ₈	62.85 (67.05)	9.30 (8.05)	4.05 (4.45)	626.3577 (626.3567)	1.0	78
10	C ₃₆ H ₅₂ N ₂ O ₈	66.05 (67.5)	8.65 (8.20)	4.15 (4.35)	640.3740 (640.3723)	1.7	95
12	C ₃₈ H ₅₆ N ₂ O ₈				668.4038 (668.4036)	0.2	84

^a Calculated values in parentheses. ^b Uncorrected (meniscus formation).

Table 2. Analytical data and accurate masses for the molecular ions of the bis(benzo-15-crown-5) Schiff bases (4; $m = 2$)

n	Empirical formula	Analysis (%) ^a			Mass ^a	Error in p.p.m.	M.p. ^b (°C)
		C	H	N			
2	C ₃₂ H ₄₄ N ₂ O ₁₀	62.5 (62.3)	7.40 (7.20)	4.50 (4.55)	616.3052 (616.2996)	5.6	128
3	C ₃₃ H ₄₆ N ₂ O ₁₀	62.4 (62.85)	7.30 (7.35)	4.45 (4.45)	630.3146 (630.3152)	0.6	108.6
4	C ₃₄ H ₄₈ N ₂ O ₁₀	62.45 (63.35)	7.20 (7.50)	4.20 (4.35)	644.3347 (644.3310)	3.7	129.5
5	C ₃₅ H ₅₀ N ₂ O ₁₀	63.7 (63.8)	7.60 (7.65)	4.25 (4.25)	658.3439 (658.3465)	2.6	105
6	C ₃₆ H ₅₂ N ₂ O ₁₀	65.15 (64.25)	7.65 (7.80)	4.10 (4.15)	672.3652 (672.3622)	3.0	124
7	C ₃₇ H ₅₄ N ₂ O ₁₀	64.7 (64.7)	8.05 (7.90)	4.15 (4.10)	686.3800 (686.3779)	2.1	97
8	C ₃₈ H ₅₆ N ₂ O ₁₀	64.65 (65.1)	7.90 (8.05)	3.95 (4.00)	700.3916 (700.3936)	2.0	109
9	C ₃₉ H ₅₈ N ₂ O ₁₀	65.05 (65.5)	8.15 (8.20)	3.90 (3.90)	714.4081 (714.4092)	1.1	100
10	C ₄₀ H ₆₀ N ₂ O ₁₀	66.35 (65.9)	8.55 (8.30)	3.90 (3.85)	728.4198 (728.4249)	5.1	109
12	C ₄₂ H ₆₄ N ₂ O ₁₀	67.4 (66.65)	8.55 (8.50)	3.75 (3.70)	756.4616 (756.4561)	5.5	110
c	C ₃₃ H ₄₆ N ₂ O ₁₀	62.5 (62.85)	7.05 (7.35)	4.35 (4.45)			120.5

^a Calculated values in parentheses. ^b Uncorrected (meniscus formation). ^c Propane-1,2-diamine derivative.

loose ion pairs with ϵ_{max} 22 600 \pm 500 dm³ mol⁻¹ cm⁻¹ at ca. 378 nm (except for the ligand with $n = 2$). ϵ_{max} for the caesium extract of the $n = 10$ ligand was 21 300 dm³ mol⁻¹ cm⁻¹. Extraction with bis(crown-4) ligands was less than 10% of the theoretical maximum, even when twice the clam concentration was used, and was in the order Na > Cs > Rb > K. Several bis(crown-6) ligands were examined. The amount of potassium picrate extracted was greater than 50% of the picrate present. Since 50% is the maximum possible extraction for a pocket complex, the extracted species could not be exclusively in this form. It had the characteristic spectrum of a

tight ion pair, ϵ_{max} at 361 nm. The corresponding λ_{max} for the extraction with 4'-formylbenzo-18-crown-6 and potassium picrate was 359 nm. The absorbance of the K, Rb, and Cs extracts of bis(crown-6) ligands showed that the Rb and Cs extracts had spectra more closely approximating to those expected for loose ion pairs, Rb having λ_{max} at 374 nm, Cs at 378 nm for the ligand with $n = 10$. Data for solvent extraction by the bis(crown-5) ligands are shown in the Figure.

Ultraviolet Absorption Spectra.—Typical u.v. absorption spectra of the bis(crown) ligands have a band characteristic of

Table 3. Analytical data and accurate masses for the molecular ions of the bis(benzo-18-crown-6) Schiff bases (4; $m = 3$)

n	Empirical formula	Analysis (%) ^a			Mass ^a	Error in p.p.m.	M.p. ^b (°C)
		C	H	N			
4	C ₃₈ H ₅₆ N ₂ O ₁₂	59.75	8.40	3.40	732.3740	9.3	105
		(62.3)	(7.70)	(3.80)	(732.3833)		
6	C ₄₀ H ₆₀ N ₂ O ₁₂	62.45	8.80	3.75	760.4126	2.0	95
		(63.15)	(7.95)	(3.70)	(760.4146)		
7	C ₄₁ H ₆₂ N ₂ O ₁₂	61.45	8.45	3.65	774.4290	1.2	68
		(63.55)	(8.05)	(3.60)	(774.4302)		
8	C ₄₂ H ₆₄ N ₂ O ₁₂	62.4	9.55	3.40	788.4400	5.9	102
		(63.95)	(8.20)	(3.55)	(788.4459)		
9	C ₄₃ H ₆₆ N ₂ O ₁₂	63.55	9.05	3.40	802.4641	2.6	75, 71
		63.95	8.70	3.35	(802.4615)		
		(64.3)	(8.30)	(3.50)			
10	C ₄₄ H ₆₈ N ₂ O ₁₂	63.2	9.00	3.30	816.4834	6.2	104
		(64.7)	(8.40)	(3.45)	(816.4772)		
12	C ₄₆ H ₇₂ N ₂ O ₁₂	64.85	9.30	3.20	844.4994	9.1	104
		(65.4)	(8.60)	(3.30)	(844.5085)		

^a Calculated values in parentheses. ^b Uncorrected (meniscus formation).

Table 4. Ultraviolet absorption of some bis(crown) ligands

Ligand (4)		Solvent ^a	λ/nm	$\epsilon/\text{dm}^3 \text{ mol}^{-1} \text{ cm}^{-1}$	λ/nm	$\epsilon/\text{dm}^3 \text{ mol}^{-1} \text{ cm}^{-1}$
m	n					
2	4	MeOH	270	29 800	304	20 200
2	4	MeOH	268	28 300	299	17 900 ^b
3	4	MeOH	270	31 000	305	22 000
3	12	thf	265	29 800	301	17 000
2	6	CH ₂ Cl ₂			302	17 500 ^c
2	6	CH ₂ Cl ₂			299	15 000 ^c

^a thf = Tetrahydrofuran. ^b Solution equimolar in KBr and ligand. ^c Solution contains potassium picrate and ligand in *ca.* 0.8 : 1 mol ratio.

the aromatic *ortho*-diether portion at *ca.* 270 nm (ϵ *ca.* 30 000 $\text{dm}^3 \text{ mol}^{-1} \text{ cm}^{-1}$) and one characteristic of the azomethine at *ca.* 300 nm (ϵ *ca.* 20 000 $\text{dm}^3 \text{ mol}^{-1} \text{ cm}^{-1}$) as indicated in Table 4 for some systems. These typical absorptions change in shift and intensity when alkali-metal cations are added in methanol (bromide salts), methylene chloride (picrate salts), and tetrahydrofuran (picrate salts). The greatest change was observed for addition of equimolar KBr to $0.5 \times 10^{-4} \text{ mol dm}^{-3}$ ligand (4; $m = 2$, $n = 4$) in methanol, an isosbestic point being observed at 264 nm. Higher mole ratios of KBr to ligand altered the spectra appreciably further, and the resulting spectral traces did not go through the isosbestic point. When the cation employed was rubidium the spectra showed similar but smaller changes. Neither Na⁺ nor Cs⁺ altered the spectra by more than 2 or 3% in intensity, and the wavelength shift was imperceptible.

N.M.R. Spectra.—Sodium-23 n.m.r. spectra were measured for solutions of NaI (0.4 mol dm^{-3}) in methanol containing bis(crown-5) (4; $m = 2$, $n = 4$) (0.066 mol dm^{-3}), from room temperature down to 192 K. A single line was observed at all these temperatures, and the width of the line ($\Delta\nu_{\frac{1}{2}}$, taken as a measure of $1/\pi T_2$, where T_2 is the transverse relaxation time²¹) altered with temperature in a fashion characteristic of a sodium-exchange process.²¹ A typical Z-shaped curve was obtained for a plot of $\log \Delta\nu_{\frac{1}{2}}$ versus $1/T$ where T is the absolute temperature in K. The fast-exchange region was above 230 K, and the slow-exchange region was below 204 K. The exchange rate was evaluated from the intermediate-exchange region.

The ¹H n.m.r. spectra of bis(crown-5) (4; $m = 2$, $n = 7$) in

the presence of metal cations also indicated a quite different behaviour for K⁺ and Na⁺. Addition of equimolar NaI to a solution of the ligand 0.05 mol dm^{-3} in CD₃OD shifted ligand signals downfield (as when Na⁺ is complexed to a single benzo-15-crown-5²²). Equimolar KSCN shifted aromatic and ether signals spectacularly upfield, as has been found previously for sandwich complexes.²² Addition of a second equivalent of KSCN (which would provide one K⁺ per crown face) had little additional effect on the spectrum, which remained that of a sandwich complex. The spectra were unfortunately not well resolved and have not been analysed in detail. The signals of the polymethylene chain were little affected by the presence of the cation.

The n.m.r. spectra were all run on a Bruker Spectrospin, ¹H at 90 MHz and ²³Na at 23.81 MHz with a modification to permit Fourier transform, using a Fabritek 1074 signal-averaging computer interfaced to a DEC PDP8 E.

Kinetic Studies.—Kinetic studies were made by the temperature-jump method, using equipment from Messanlagen-Studiengesellschaft, Göttingen, W. Germany, with u.v. detection, the output from the photomultiplier being stored on a Tektronix 564B storage oscilloscope. The conditions of the experiment included heating by discharge of a 0.02- μF condenser charged to 35 kV; solutions of bis(crown-5) ligand (4; $m = 2$; $n = 4$, 9, or 10) were equilibrated with KBr or RbBr salts in methanol at 23 °C in a 6.5 cm^3 cell. The temperature rise was 2.6 °C, and the ligand and salt were equimolar in the range 10^{-4} – $10^{-3} \text{ mol dm}^{-3}$. The cavitation problem was less with a background electrolyte, LiCl, at 0.15 mol dm^{-3} concentration. Solutions were also degassed before equilibration to minimise this problem. Preliminary measurements on sodium and caesium salts discovered no relaxation within the range of the instrument. For the potassium and rubidium salts, single relaxation times in the range 20–120 ms were observed for changes in the absorption spectrum at 285 nm (on the minimum between two bands) or at 300 nm (near the maximum of one band). Relaxation times τ were measured for four to six different initial concentrations of reagents. Since $[M^+]_0 = [L]_0$ and the equilibrium (i) lies far to the right, the dependence of relaxation time on initial ligand concentration $[L]_0 (= [ML]_e$, where e = equilibrium) was investigated using the expression (ii).^{23,24} A plot of $1/\tau^2$ versus $[L]_0$ was a straight line, least-squares treatment of which yielded the

Table 5. Formation rate constants (k_1) and dissociation rate constants (k_{-1}) for the reaction (i), for ligand (4; $m = 2$) and MBR in methanol at 23 °C

Ligand	M	$k_1/\text{dm}^3 \text{ mol}^{-1} \text{ s}^{-1}$	k_{-1}/s^{-1}	$K/\text{dm}^3 \text{ mol}^{-1} = k_1/k_{-1}$
(4; $n = 4$)	K	3.7×10^5	24	1.5×10^4
(4; $n = 4$)	Rb	5.8×10^5	13	4.5×10^4
(4; $n = 9$)	K	5.4×10^5	12	4.5×10^4
(4; $n = 9$)	Rb	5.2×10^5	14	3.7×10^4
(4; $n = 10$)	K	1.2×10^5	10	1.2×10^4
(4; $n = 10$)	Rb	2.4×10^5	5	4.8×10^4
<i>a</i>	K	$6 \pm 2 \times 10^8$	1.6×10^4	3.7×10^4
<i>a</i>	Rb	$8 \pm 2 \times 10^8$	1.8×10^4	4.5×10^4
(2) ^b	K	4.7×10^8	1.8×10^{-2}	2.6×10^{10}
(2) ^b	Rb	7.6×10^8	8.0×10^{-1}	9.5×10^8

^a At 25 °C, data from ref. 30; ligand = dibenzo-30-crown-10 (6,7,9,10,12,13,15,16,23,24,26,27,29,30,32,33-hexadecahydro-dibenzo[*b,q*][1,4,7,10,13,16,19,22,25,28]decaoxacyclotriacontin).

^b At 25 °C, data from ref. 9.

slope and intercept.* The derived rate constants k_1 and k_{-1} are given in Table 5.

$$1/\tau^2 = k_1^2 + 4k_1k_{-1}[L]_0 \quad (\text{ii})$$

Discussion

A number of measurements outlined in the preceding Experimental section support the conclusion that K^+ is fully enclosed in a pocket site by bis(crown-5) Schiff bases (4; $m = 2$), and that Cs^+ forms a higher proportion of such pocket complexes with bis(crown-6) Schiff bases (4; $m = 3$). The pocket site can fully enclose a cation of optimum size, effectively screening it from solvent or anion interaction, but, while complexing smaller or larger cations, leaves these exposed to solvent or anion. It is generally believed that K^+ is sandwiched by ligand (1), while Na^+ forms only 1:1 complexes. However, recent crystal structures²⁵ indicate that sodium can also form a sandwich with ligand (1), but that the Na-O contacts are very long (2.4–3.0 Å) and the ion-dipole interaction consequently must be rather weak. It is thus possible that sodium can enter the pocket sites provided here by the bis(crown-5) ligands, and the structure of the tetraphenylborate complex with ligand (1),²⁵ which has the benzogroups close together, seems particularly relevant. The behaviour of the sodium complexes of the bis(crown-5) Schiff bases suggests that the most stable form in solution does *not* have a well screened sodium cation.

The operational distinction between loose ion pairs (with a screened cation) and tight ion pairs (with a cation partially exposed to counter ion) as formed by different cation-ligand combinations has been made initially in this work from the u.v.-visible spectra of their solvent-extracted metal picrate complexes^{15,16} in methylene chloride and has been amplified in selected cases by a similar u.v.-visible distinction for the metal picrate and ligand in tetrahydrofuran. Further u.v. studies of the spectrophotometric titration of ligand (4; $m = 2$, $n = 4$) with KBr in methanol solution have shown that both crown and azomethine bands undergo considerable change, with an isosbestic point at 264 nm, on addition of KBr up to equimolar, consistent with formation of a 1:1 or pocket complex of the type (5). The ¹H n.m.r. spectra

* Standard errors in the intercept were $\pm 10\%$ in the worst case giving $\pm 2 \text{ s}^{-1}$ in the k_1 values, which were carried through to the k_{-1} values, also subject to an error in slope of $\pm 10\%$.

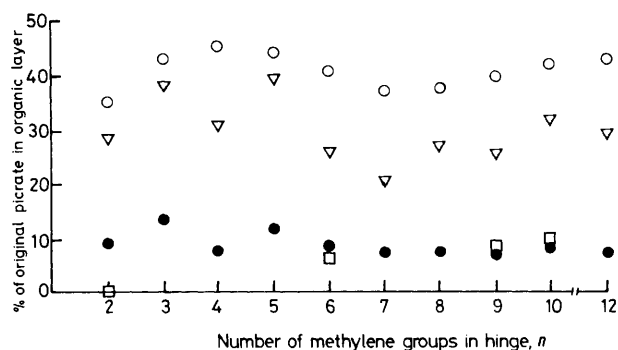


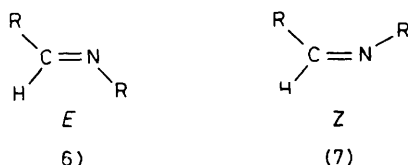
Figure. Solvent-extraction ability of the ligands (4; $m = 2$) for solutions in CH_2Cl_2 ($7 \times 10^{-5} \text{ mol dm}^{-3}$) extracting picrate ($1.4 \times 10^{-4} \text{ mol dm}^{-3}$) in 0.1 mol dm^{-3} metal hydroxide. Cations: K (○), Rb (▽), Na (●), and Cs (□)

corroborate that different types of complex occur for Na^+ and for K^+ in a solution in deuterated methanol of (4; $m = 2$, $n = 7$). Diagnostic spectra for complexing of Na^+ with just a single crown face of the ligand, and of K^+ with the full potential pocket site, were observed. A kinetic discrimination of bis(crown-5) ligands between Na^+ and K^+ is also apparent. From our ²³Na n.m.r. studies of NaI solutions in methanol containing the ligand (4; $m = 2$, $n = 4$), the reciprocal exchange lifetime of sodium at 212.8 K is $1/\tau \approx 900 \text{ s}^{-1}$ for exchange between free and bound sites. This is of the same magnitude as observed for simple crown ligands complexed to sodium²¹ at the higher temperatures 260–270 K, and so this exchange is deemed even faster. In contrast, in the temperature-jump studies, a very slow dissociation rate is observed for the pocket complexes of K^+ or Rb^+ with bis(crown-5) ligands (4; $m = 2$; $n = 4, 9$, or 10), again in methanol solution, and shown in Table 5.

Solvent-extraction results are shown in the Figure for the ligand series (4; $m = 2$), the bis(crown-5) compounds. The effect of changing n , the number of CH_2 groups in the hinge, could be examined. The optimum size for the hinge was at $n = 4$, while a minimum in extracting power was found at $n = 7$, and the effectiveness of the ligands improved again as the connecting hinge lengthened. The ligand with $n = 4$ provided the best distribution ratio, $D_{\text{M(pic)}} = [\text{M(pic)}]_{\text{org}} : [\text{M(pic)}]_{\text{aq}}$,²⁶ for potassium picrate (0.78) and the best separation factors, $\text{S.F.} = D_{\text{M}'} : D_{\text{M}''}$,²⁶ for K:Na (9.5), K:Rb (1.9), and K:Cs (9.5). The ligand with $n = 2$ did not appear to form exclusively a pocket complex, and it was not a strong extractant.

The results in the Figure show that the optimum extraction is for a ligand with n , the number of methylene groups, even, and that there is a curious alternation † with odd, even chain length for the percentage extraction. The ligand with $n = 4$ must have the best compromise conformation for the separation of the crown rings. Molecular models indicate that the ligand 4 has many possible conformations, with *E* or *Z* forms [see formulae (6) and (7)] possible for the azomethine links,^{27–29} rotation about each methylene link in the polymethylene hinge, and the possibilities inherent in the crown rings. The two crown rings are required to be approximately parallel for a pocket complex of type (5) to form; the optimum distance apart for the approximate plane of the ether oxygens in one ether ring from that in the other for known sandwich complexes of ligand (1) seems to be 3.34 Å for the potassium iodide¹⁴ complex, while the sodium perchlorate complex²⁵

† Indeed, the physical properties of polymethylene chains often show this alternation. See the m.p.s in Tables 1–3.



is isostructural. The best separation of the two planes would be expected to be somewhat less for a stable sodium complex, and somewhat greater for rubidium and caesium analogues. The number of conformations for ligand (4; $m = 2$) which could achieve this is large. It does seem that the ligand with $n = 2$ cannot have the two ether rings parallel; they are forced to a V shape [*cf.* the bis(crown) linked by an azobenzene¹²]. This is not necessary for longer hinges. The question of whether the CH=N links are *E* or *Z* was considered. Both are possible in models. The only relevant evidence came from the perturbation of the u.v. band associated with the CH=N link (see Table 4). In tetrahydrofuran solutions of several ligands (4) with metal picrates the CH=N band was split at low [ligand]:[picrate] mole ratios (*ca.* 0.2–1.0), a shoulder at 304 nm being strongest at low ratios, one at 297 nm being strongest at higher ratios. This suggests that the band at 304 nm could be associated with a ligand complexing to two or more cations, while that at 297 nm is associated with the pocket complex. Since the azomethine group (either *E* or *Z*) lies some distance away from the donor groups of the macrocyclic rings and is unlikely to be bonded to the cation, these changes must signify a change in environment or conformation. Methods of determining whether the CH=N has the *E* or the *Z* form^{27–29} depend on empirical interpretation of spectroscopic features which either were unavailable or non-existent for these compounds. The ¹H n.m.r. signal of the CH=N proton appeared as one line for the free ligands and for the metal complexes (although shifted), but it was not well enough resolved to facilitate the assessment or assignment of coupling and conformation, and the question remains open.

The rate process observed in the ²³Na n.m.r. spectra was very fast and probably corresponds to sodium exchanging between its free solvated cation and a complex involving only one crown face, since it is as fast as, or faster than, similar processes observed for other crowns.²¹ The temperature-jump measurements showed that the corresponding reactions of potassium and rubidium ions were slower than for crowns. Measurements were made for several bis(crown-5) ligands and K or Rb cations which indicated only a single relaxation time within the range of the instrument. This was assumed to correspond to the relaxation of the step in equation (i), whence rate constants for the forward and reverse steps were evaluated using equation (ii) (Table 5). Data have been obtained by others for the single step (i) for the crown ligand dibenzo-30-crown-10³⁰ and for cryptand (2) in methanol^{6,7} and a comparison can be made (Table 5). The reactions for dibenzo-30-crown-10 are 10³ times faster in both directions; although the cryptand (2) forms its cryptate 10³ times faster, that cryptate dissociates *ca.* 10³ times more slowly than for the bis(crown-5) ligands. Insufficient data are available to justify a detailed discussion of these intriguing results in terms of mechanism at this stage. It is hoped to examine the reaction further by alternative kinetic methods in a search for possible faster steps in the reaction path.

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