Preparation of Silica Gel-bound Macrocycles and their Cation-binding Properties

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Values of log K for the association of several metal cations with 15-crown-5, 18-crown-6, and N,N'-dibenzyldiaza-18-crown-6, each covalently bonded to silica gel, were found to be nearly the same as those for the association of the same cations with the unbound macrocycles; this observation indicates the possibility of building pre-determined cation selectivity into these permanent macrocycle-bound silica gel systems.

The high selectivity of certain macrocycles for particular cations is well known.[1] The chemical bonding of such macrocycles to a solid support would be expected greatly to enhance their usefulness. Earlier efforts to accomplish such chemical bonding involved the use of benzo-crown ethers, which have a lesser propensity for cation association than the parent crown ethers, and of amide bonding groups of relatively low stability.[2] We disclose here the first use of ether and alkyl chains to connect the carbon framework of the macrocycles to the siloxy component of silica gel.[3] The resulting bond is permanent and the system can be used indefinitely to perform separations, recoveries, and determinations without measurable loss of the crown. Furthermore, the bound macrocycles have approximately the same affinity as corresponding unbound macrocycles for metal ions in aqueous solution. Thus, new possibilities are presented for building pre-determined selectivity into separation systems.

The silica gel-bound macrocycles (1)—(3) were prepared as shown in Scheme 1. The allyloxymethyl-substituted macrocycle, a catalytic amount of chloroplatinic acid, and an excess of diethoxy(methyl)silane were heated at reflux temperature in benzene for 16 h. The macrocycle-containing diethoxysilane in dichloromethane was added to a weighed amount of 60—200 mesh silica gel (Aldrich) so that the macrocycle to gel ratio was about 1 : 10 (w/w). The solvent was removed under reduced pressure and the resulting silica gel was heated at 120 °C for 16—24 h to bring about the attachment reaction. The starting allyloxymethyl-18-crown-6 and -15-crown-5 were prepared as reported.[4] The preparation of the allyloxymethyl-substituted diaza-crown was similar to that of the non-benzyl-substituted diaza-crowns.[5,6]

The hydrocarbon and ether linkages of the new supported macrocycles are more stable in aqueous solutions than previously used amide linkage.[2,7] We have used the silica gel-bound macrocycles at varying aqueous pH values between −0.5 and 11.0 for 6 months without measurable decrease in crown activity. Lindoy and his co-workers have attached a macrocyclic oxygen–nitrogen donor ligand to silica gel through a hydrocarbon link.[8] However, their linkage was through a nitrogen donor atom on the macrocycle and the selectivity of the donor molecule for metal ions was different from that of the parent unbound macrocycle.

Values of log K for the interaction of the silica gel-bound macrocycles with various cations have been determined. Small amounts of the silica gel material were equilibrated with known concentrations of the cations studied. After equilib-

Table 1. Values of log K at various ionic strength (I) values for the interaction of M^{n+} with silica gel-bound and the analogous free (in parentheses) crown compounds (1)—(3).[a]

| Cation | log K | | |
	(1)	(2)	(3)
Sr²⁺		2.83 ± 0.01 ($I = 3$) (2.72)	2.4 ± 0.2 ($I = 0.5$) (2.57;[b] $I = 0.1$)
Ba²⁺		3.56 ± 0.01 ($I = 3$) (3.87)	
Cd²⁺			5.0 ± 0.2 ($I = 0.5$) (5.25;[b] $I = 0.1$)
Tl⁺	1.38 ± 0.01 ($I = 3$) (1.23)	2.01 ± 0.06 ($I = 3$) (2.2; $I = 0.1$)	
Ag⁺	0.90 ± 0.15 ($I = 1$) (0.94)	1.61 ± 0.09 ($I = 0.5$) (1.50, 1.60)	8.2 ± 0.2 ($I = 0.5$) (7.8;[b] $I = 0.1$)
K⁺		2.01 ± 0.01 ($I = 0$)[c] 1.79 ± 0.01 ($I = 1$) (2.03)	

[a] Ref. 1. [b] The values are for diaza-18-crown-6 in ref. 1. [c] Column was stripped with deionized water rather than EDTA or acid.

rium was reached, the amount of bound cation was measured by stripping the column with either a complexing agent such as ethylenediaminetetra-acetic acid (EDTA) or, for (3), an acidic solution. The metal cation concentration in the eluate was then determined by atomic absorption spectrophotometry. Binding of the cations by plain silica gel was determined similarly. Binding of the cations of interest to the silica gel sites was made negligible by including an excess of a cation (e.g. Mg^{2+}) which does not complex with the macrocycle but competes effectively with the cations of interest for plain silica gel as measured in the plain silica gel experiments. The equilibrium expression for 1 : 1 cation–macrocycle interaction is equation (1), where f is the fraction of ligand sites containing

$$K = \frac{f(1 + K_1[H^+] + K_1 K_2[H^+]^2)}{(1 - f)[M^{n+}]} \quad (1)$$

bound cations, K_1 and K_2 are the protonation constants applicable to (3), and $[M^{n+}]$ and $[H^+]$ are the equilibrium molar free cation and proton concentrations, respectively. The total number of moles of ligand sites is known from the organic synthesis and was checked by quantitatively loading every macrocycle site with a strongly binding cation at sufficiently high concentrations. The pK_a values for (3) (8.9 ± 0.2 and 7.5 ± 0.2) were determined by repeating the experiment for Ag^+ and Cd^{2+} at several pH values and curve-fitting the results according to equation (1). Representative log K values for the association of cations with the silica gel-bound and analogous free macrocycles are compared in Table 1. The agreement between the two sets of log K values is excellent.

The similarity of the log K values for the bound and unbound macrocycle–cation interactions suggests that both types are effectively solvated by the aqueous solution. Thus, the silica gel-bound macrocycles form complexes in the same manner as do the free macrocycles in water. On the other hand, the bonding of macrocycles to hydrocarbon polymers, such as polystyrene, causes a considerable modification in metal-ion-binding properties in both organic solvents and aqueous solutions. In particular, aqueous solutions cannot be treated effectively because the hydrocarbon polymers are not wetted by water.[2,9] The similarity of the log K values determined in the present study to those involving the unbound macrocycle also suggests that prediction of metal separations by other silica gel-bonded macrocycles should be
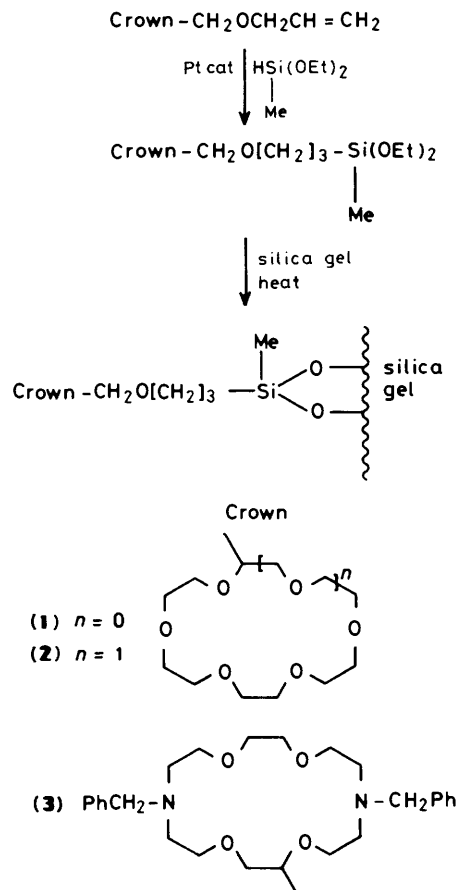
Scheme 1. Preparation of silica gel-bound crown compounds.

possible. Thus, one has a powerful means to predict separations from available data compilations.[1] In addition, the immobilization of expensive macrocycles on silica gel or other hydrophilic supports opens the way to use similar systems for specific metal ion separations and/or determinations.[10] Since the system results in removal of the metal ion with its accompanying anion(s) and is not an ion-exchange process, it

has the potential for removal of metal ions from dilute aqueous solutions, producing pure water. An important application of this procedure could be the removal of metals from dilute aqueous solutions at the source of pollution, which would be a great step towards a trace-metal-free environment.

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References

1 See R. M. Izatt, J. S. Bradshaw, S. A. Nielsen, J. D. Lamb, and J. J. Christensen, *Chem. Rev.*, 1985, **85**, 271 for a compilation of log *K* values for ligand–cation association.

2 See M. Takagi and H. Nakamura, *J. Coord. Chem.*, 1986, **15**, 53 for a recent review.

3 J. S. Bradshaw, R. M. Izatt, J. J. Christensen, and R. L. Bruening, U.S. Pat. Appl. 093 544/1987.

4 I. Ikeda, S. Yamamura, Y. Nakatsuji, and M. Okahara, *J. Org. Chem.*, 1980, **45**, 5355.

5 J. Stetter and J. Marx, *Liebigs Ann. Chem.*, 1957, **607**, 59.

6 D. A. Babb, B. P. Czech, and R. A. Bartsch, *J. Heterocycl. Chem.*, 1986, **23**, 609.

7 M. Nakajima, K. Kimura, and J. Shono, *Anal. Chem.*, 1983, **55**, 463.

8 V. Dudler, L.F. Lindoy, D. Sallin, and C. W. Schlaepfer, *Aust. J. Chem.*, in the press.

9 R. S. Paredes, N. S. Valera, and L. F. Lindoy, *Aust. J. Chem.*, 1986, **39**, 1071.

10 J. S. Bradshaw, R. L. Bruening, R. M. Izatt, J. J. Christensen, and R. L. Alldredge, U.S. Pat. Appl. 093 543/1987.