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Summary: The synthesis, solubility enhancement, and phase-transfer catalysis properties of cyclic poly(alkyleneoxy)silanes are described. The compounds have the general structure $R^1R^2Si(OCH_2CH_2)_nO$ and are denoted silacrowns. Solubility enhancements of lithium, sodium, and potassium ions are a function of macrocycle and ion size. Phase-transfer catalysis of acetate, azide, cyanide, fluoride, and nitrite ions in displacement reactions are reported.

In the course of work on the immobilization of phase-transfer catalysts and in the transport of organic salts across liquid membranes, the ionophoric properties of silacrowns have been disclosed.[1,2] Silacrowns have the generalized structure $R^1R^2Si(OCH_2CH_2)_nO$. Specific examples are dimethylsila-17-crown-6 (I), dimethylsila-3,6,9-trimethyl-11-crown-4 (II), and [3-(*N*-(2-aminoethyl)amino)propyl]methylsila-14-crown-5 (III). We now

I   II   III
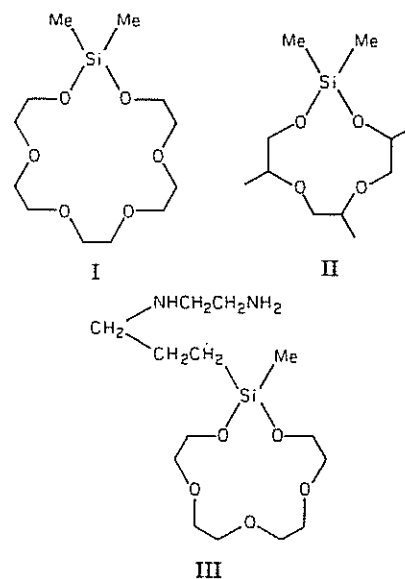
wish to report our preliminary findings on these materials. The silacrowns exhibit ionophoric properties that are

(1) Arkles, B.; King, K.; Peterson, W. In "Chemically Modified Surfaces in Catalysis and Electrocatalysis"; Miller, J. S., Ed.; American Chemical Society: Washington, D.C., 1982; *ACS Symp. Ser. No. 192.*

(2) Rico, E.; Pannell, K. H.; Arkles, B. "Transport of Na and K Picrates Across a Liquid Membrane Using New Silacrowns as Ionophores", presented 38th Southwest American Chemical Society, Meeting Dec 2, 1982.

comparable to crown ethers in both cation specificity and enhancement of anionic reactivities. The synthesis of silacrowns is facile. The presence of the silicon atom provides an opportunity to introduce organic moieties without precedent in other crown ether systems. The compounds have low levels of acute oral toxicity and appear to have at least substantially lower pseudoestrogenic effects than the simple crown ether analogues.

The lower members of the cyclic poly(ethyleneoxy)silanes have been previously reported.[3] They were produced in relatively poor yield by the interaction of chlorosilanes with lower ethylene glycols. Concomitant with our initial report silacrown structures with as many as 14 ring members were prepared by interaction of dimethylaminosilanes with lower ethylene glycols.[4] Dimethylsiladibenzo-14-crown-5 was produced in 15% yield by reaction of dimethyldichlorosilane with the disodium bis(phenolate) precursor.[5] In no cases were the ionophoric properties of these materials evaluated.

The silacrowns are readily prepared by transesterification of alkoxysilanes with polyethylene glycols. A typical reaction is $R^1R^2Si(OEt)_2 + HO(CH_2CH_2O)_nH \rightarrow \overline{R^1R^2Si(OCH_2CH_2)_nO} + 2EtOH$. The conditions of transesterification must be selected to promote cyclization in preference to polymerization. The reaction may be catalyzed by a variety of materials, but alkoxy titanates are generally preferred. A wide range of organic groups (R^1R^2) can be readily substituted to alter solubility, phase partition, and reactivity of the silacrowns. The reactants are combined, and approximately 80–95% of the alcohol is slowly distilled from the reaction mixture. The product is removed from the reaction mixture by distillation at reduced pressure. Rearrangement in the presence of transesterification catalysts during the course of distillation results in the preferential removal of the more volatile silacrowns from the equilibrating mixture. The silacrowns are generally colorless, odorless liquids of moderate viscosity. As expected, the electron-impact mass spectra of the compounds do not exhibit molecular ions; the highest mass ions correspond to the loss of radicals from the silicon atoms. Sila-14-crown-5, sila-17-crown-6, and sila-20-crown-7 structures have been prepared. Substituents on the silicon include methyl, vinyl, phenyl, ethyl, and methoxy groups. The compounds and yields are given in Table I. As an example, the synthesis of vinylmethyl-14-crown-5 is provided.

Vinylmethylsila-14-crown-5. A 250-mL single-necked flask equipped with a magnetic stirrer and heating mantle was charged with 0.5 mol (93 mL) of vinylmethyldiethoxysilane, 0.5 mol (86 mL) of tetraethylene glycol and 0.5 mL of tetrabutyl titanate. The mixture was stirred at 50–60 °C for 16 h with a cold finger distillation head in place. The pot temperature was increased to 85–100 °C, and about 50 mL of ethanol was removed. The mixture was then distilled under vacuum. The fraction boiling at 129–131 °C at 0.5 mm was collected. Approximately 62 g of vinylmethylsila-14-crown-5 was isolated. The compound was identified by infrared and organic mass spectroscopy. The compound did not exhibit a molecular ion but exhibited $(M - CH_3)^+$ at 247 and $(M - CH=CH_2)^+$ at 235.

Solubility enhancement data for various inorganic salts in acetonitrile was determined under conditions similar

Table I. Silacrowns Prepared by Transesterification

compd	bp, °C (p, mmHg)	yield, %
dimethylsila-8-crown-3[a]	90 (50)	
dimethylsila-11-crown-4[a]	96 (9)	85
dimethylsila-14-crown-5	125–130 (0.5)	79
dimethylsila-17-crown-6	168–170 (0.3)	78
dimethylsila-20-crown-7	240–244 (0.2)	73
ethylmethylsila-14-crown-5	130–133 (0.5)	81
vinylmethylsila-14-crown-5	129–131 (0.5)	47
phenylmethylsila-14-crown-5	180–185 (0.1–0.15)	43
vinylmethylsila-17-crown-6	169–172 (0.3)	54
methoxymethylsila-17-crown-6	170–172 (0.3)	32
dimethylsila-3,6,9-trimethyl-11-crown-4	125–129 (0.2–0.3)	69
[3-(N-(2-aminoethyl)amino)-propyl]methylsila-14-crown-5	221–228 (0.1)	35

[a] Reported in ref 3.

to those reported by Liotta and Dabdoub.[6] Data for the silacrowns are in Table II. On first approximation it is attractive to compare silacrowns to the simple crown ethers. Although there is one less member in the ring of the silacrown, the longer silicon–oxygen bonds result in an O–Si–O unit that is 75% of the length of an O–CH₂CH₂–O unit. Summation of bond lengths indicate an overall macrocycle circumference reduction of 4.5% when sila-14-crown-5 is compared to 15-crown-5. This simplistic comparison does not take into account the puckered multidentate structure that the crown ethers assume in cation complexes. Specificities and solubility enhancements appear to be similar for the silacrowns and crown ethers. One interesting result is that the greatest solubility enhancement for KBr is achieved with sila-20-crown-7 rather than sila-17-crown-6. The enhancement value of the sila-20-crown-7 is comparable to that of 18-crown-6. Potassium ions are often considered to have the "just right" diameter to enter the cavity of 18-crown-6. In fact, the complex, while nearly planar, does exhibit slight puckering.[7] Since the potassium ion is slightly larger than the cavity of 18-crown-6, steric factors must account for a substantial part of the difference in solubility.

The silacrowns depart from ideal crown ether structure in that the oxygens are not uniformly distributed and that they are not uniformly basic. In the case of the cyclic siloxanes that contain alternating silicon and oxygen atoms, efforts to facilitate simple anionic reactions gave negative results. The use of cyclic siloxanes under more extreme conditions to promote anionic polymerization give both negative and positive results.[8,9] This is consistent with the observation that cyclic siloxanes are weak ionophores with stability constants far lower than those of crown ethers.[10,11] Nevertheless, the work suggests that the re-

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(5) Liptuga, R. I.; Irodionova, L. F.; Lozinskii Zh. Obshch. Khim. 1978, 48, 1185.

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(8) Yuzhelevskii, Yu; Pchelintsev, V.; Fedoseeva, N. Vysokomol. Soedin., Ser. B 1975, 18 (11), 873; Chem. Abstr. 1975 86, 73181.
(9) Karger-Kocsis, J.; Szafner, A. Makromol. Chem. 1978, 179, 519.
(10) Olliff, C.; Pickering, G.; Rutt, K. J. Inorg. Nucl. Chem 1980, 42, 288.

Table II. Dimethylsilacrown Solubility Enhancements[a]

crown	salt				
	LiCl	NaBr	KBr	KN$_3$	KCN
11-4	2:1–4:1	2:1–3:1	4:1–5:1		
14-5	6:1–8:1	5:1–6:1	9:1–11:1		
17-6	3:1–4:1	4:1–5:1	11:1–14:1	18:1–20:1	10:1–11:1
20-7			45:1–50:1		

[a] Solubility enhancements are expressed as ratios of the saturation solubility in 0.15 M silacrown in acetonitrile vs. acetonitrile.

Table III. Silacrown Solid/Liquid Phase-Transfer Catalysis of Cyanide Substitution[a]

reactant	cation	catalyst	time, h	yield, %	
benzyl chloride	K		48	29	
benzyl chloride	K		75	25	1
benzyl chloride	K	18-6	1	99	1
benzyl chloride	K	17-6	16	100	
benzyl bromide	K		4	1	
benzyl bromide	K		48	54	
benzyl bromide	K	18-6	6	100	1
benzyl bromide	K	D$_5$	16	20	2
benzyl bromide	K	17-6	16	100	
benzyl bromide	Na		4	1	
benzyl bromide	Na	14-5	16	100	
benzyl bromide	K	14-5	4	3	
allyl bromide	K		16	1	3
allyl bromide	K	14-5	16	1	3
allyl bromide	K	17-6	16	74	3
hexyl bromide	K	18-6	40	100	1, 4
octyl bromide	K	17-6	48	63	
octyl chloride	K		48	19	4
octyl chloride	K	17-6	48	63	4
[(p(m)-(chloromethyl)phenyl)ethyl)]-trimethoxysilane (mixed isomers)	K	17-6	48	100	6
trimethylsilyl chloride	K	17-6	72	85	5

[a] All reactions run at room temperature with 0.05 M of reactant in 25 mL of acetonitrile and 0.13 M catalyst with a 100% molar excess of CN unless otherwise noted. Reaction times and conditions were not optimized; analysis by GC: (1) literature value from ref 6; (2) decamethylcyclopentasiloxane; (3) mixture of allyl cyanide and crotononitrile; (4) at reflux; (5) 20% excess only of KCN at reflux; (6) [((cyanomethyl)phenyl)ethyl]trimethoxysilane bp 122–125 °C (0.4 mmHg); 94% recovered.

placement of a single OCH$_2$CH$_2$O unit for an OSiO unit in a crown ether would not eliminate its ability to form cation complexes. The reduced basicity of oxygen atoms in alkoxysilanes compared to those in ethers is greater than would be expected by comparison of dipole moments. In general, the dipole moments of Si–O–C bonds are greater than those of Si–O–Si bonds and similar to those of C–O–C bonds.[12] Although it is difficult to draw analogy between the Si–O and C–O bond due to the more electropositive nature of silicon and the nonbonding orbital interaction of silicon and oxygen atoms, it is at least plausible to suggest that dipole interactions of silacrowns should be comparable to those of crown ethers.

The substitution reaction of cyanide with benzyl, allyl, alkyl, and silyl halides was evaluated with and without silacrown-promoted catalysis (Table III). Reaction conditions and times were not optimized. Despite the difference in solubility enhancement, dimethylsila-17-crown-6 appeared to be equivalent to 18-crown-6. The specificity of the dimethylsila-14-crown-5 for sodium ions and not potassium ions demonstrated in the solubility enhancement data is substantiated in the catalysis data.

(11) Olliff, C.; Pickering, G.; Rutt, K. *J. Inorg. Nucl. Chem.* 1980, 42, 1201.

(12) Dipole moments of compounds with C–O–C, Si–O–C, and Si–O–Si bonds, from compiled sources (Handbook of Chemistry and Physics, and Voronkov, The Siloxane Bond):

MeOMe 1.30   Me$_3$SiOMe 1.18   Me$_3$SiOSiMe$_3$ 0.78
EtOEt 1.15   Me$_2$Si(OMe)$_2$ 1.33   (Me$_2$SiO)$_5$ 1.35
         Me$_2$Si(OEt)$_2$ 1.15

Table IV. Sila-17-crown-6-Catalyzed Reactions of Benzyl Bromide with KX[a]

reactant	product	yield, %
KCN	benzyl cyanide	100
KOAc	benzyl acetate	100
KF	benzyl fluoride	5–10
KF at reflux 48 h	benzyl fluoride	35
KN$_3$	benzyl azide	99
KNO$_2$	benzyl nitrite	0
KNO$_2$ at reflux 24 h	benzyl nitrite[b]	5–10

[a] Reactions after 16 h at ambient temperature with 0.13 M dimethylsila-17-crown-6. [b] Includes isomers.

Substitution reactions of halogens, pseudohalogens, and organic anions were evaluated (Table IV). Displacements by acetate and azide proceeded similarly to cyanide. The weaker nucleophiles, fluoride and nitrite required more vigorous conditions. In the case of the fluoride it is possible the silacrown is destroyed in the course of the reaction.

The most conspicuous difference in reactivity of the silacrowns compared to the simple crown ethers is the susceptibility of the Si–OC bond to hydrolysis, particularly at pH extremes. In liquid/liquid phase-transfer reactions utilizing concentrated aqueous KCN, no substantial differences in displacement reactions were observed.

The difference in silacrown hydrolytic stability compared to the simple crown ethers may account for their reduced acute oral toxicity. Toxic effects of crown ethers are observed in doses as low as 100 mg/kg, initially affecting the central nervous system.[13] They exhibit unusual

long–term pseudoestrogenic effects even at low levels resulting in testicular atrophy.[14]   The acute oral toxicity (LD50) of dimethylsila-14-crown-5 for rats is 9900 mg/kg, compared to 1020 mg/kg for 15-crown-5.[15]   During the course of the studies histologic examination indicated no significant changes in testicular function.[16]

Registry No. I, 83890-22-6; II, 84332-76-3; III, 84332-77-4; LiCl, 7447-41-8; NaBr, 7647-15-6; KBr, 7758-02-3; KN_3, 20762-60-1; KCN, 151-50-8; KOAc, 127-08-2; KF, 7789-23-3; KNO_2, 7758-09-0; dimethylsila-14-crown-5, 70851-49-9; dimethylsila-20-crown-7, 83890-23-7; ethylmethylsila-14-crown-5, 84332-75-2; vinylmethylsila-14-crown-5, 83890-24-8; phenylmethylsila-14-crown-5, 83890-27-1; vinylmethylsila-17-crown-6, 83890-25-9; methoxymethylsila-17-crown-6, 83890-26-0; vinylmethyldiethoxysilane, 5507-44-8; tetraethylene glycol, 112-60-7; benzyl chloride, 100-44-7; benzyl bromide, 100-39-0; allyl bromide, 106-95-6; hexyl bromide, 111-25-1; octyl bromide, 111-83-1; octyl chloride, 111-85-3; [(p-(m)-(chloromethyl)phenyl)ethyl]trimethoxysilane, 68128-25-6; trimethylsilyl chloride, 75-77-4; benzyl cyanide, 140-29-4; allyl cyanide, 109-75-1; crotononitrile, 4786-20-3; hexyl cyanide, 629-08-3; octyl cyanide, 2243-27-8; [((cyanomethyl)phenyl)ethyl]trimethoxysilane, 84332-74-1; cyanotrimethylsilane, 7677-24-9; benzyl acetate, 140-11-4; benzyl fluoride, 350-50-5; benzyl azide, 622-79-7; benzyl nitrite, 935-05-7.

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(13) Leong, B. K. J. *Chem. Eng. News* **1975**, *53* (4), 5.

(14) Leong, B. K. J.; Ts'o, T. O. T.; Chenoweth, M. B. *Toxicol. Appl. Pharmacol.* **1974**, *27*, 342.

(15) Hendrixson, R. R.; Mack, M. P.; Palmer, R. A.; Ottolenghi, A.; Ghirardelli, R. G.; *Toxicol. Appl. Pharmacol.* **1978**, *44* (2), 263.

(16) Toxicology performed by Springborn Institute for Bioresearch at Spencerville, OH, under direction of Richard Hiles. Two survivors of the highest dose level (12 300 mg/kg) showed lowest teste weight, although at lower levels no correlation was observed. The significance of this result is uncertain, but testicular function was normal in the animals. The lowest lethal dose observed (LDLO) was 4300 mg/kg.