

METAL ION COMPLEXATION BY
IONIZABLE CROWN ETHERS

by

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A THESIS

IN

CHEMISTRY

Submitted to the Graduate Faculty
of Texas Tech University in
Partial Fulfillment of
the Requirements for
the Degree of

MASTER OF SCIENCE

Approved

Accepted

August, 1984

1984
11/11/84
Y

ACKNOWLEDGMENTS

I wish to express my appreciation to my research supervisor, Professor R. A. Bartsch, for his patience and guidance in completing this research. Thanks are due to my committee, Drs. J. N. Marx and P. K. Dasgupta for their time and attention.

I am grateful to my colleagues, Drs. B. Czech and H. K. Lee, and Mr. B. Son for their cooperation.

Finally, I express my gratitude to my wife, Sandra, and the children for their support and sacrifices which allowed this work to be completed.

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CHAPTER I

INTRODUCTION

General Background

Discovery of Polyethers as Multidentate Ligands

Led by observations^{1a-c} of interactions between neutral polymers and ionic species, Lundberg and others² studied poly(ethylene oxide) and its interactions with inorganic salts. Association of potassium iodide with poly (ethylene oxide) was noted. The association was incorrectly attributed to an ion-dipole interaction of iodide anion and the ether oxygens of the poly(ethylene oxide).

In 1967, Pedersen³ reported the synthesis of several macrocyclic polyethers and their salt complexes. Noteworthy were the complexes which were formed between the macrocyclic polyethers and alkali and alkaline earth metal salts. The complexes were shown to be the result of an ion-dipole interaction between the metal cation of the salt and the negatively charged oxygen atoms of the polyethers. Pedersen coined the name "crown" ethers for these polyethers because of the appearance of their molecular model and their ability to crown the cation.

Shortly after Pedersen's report, Smid⁴ investigated a series of polyglycol dimethyl ethers, glymes, with re-

spect to their behavior in solvating alkali metal cations. The alkali metal cations were coordinated by the acyclic polyethers and formed 1:1 coordination complexes. Subsequently, numerous studies have further established the importance of polyethers, cyclic and acyclic, as a class of multidentate ligands.

Factors Controlling
Complexation of Metal
Cations by Acyclic and
Cyclic Polyethers

The complexation of metal cations by acyclic and cyclic polyethers is controlled by several important factors. Some factors apply only to complexation by acyclic polyethers and still others apply to both acyclic and cyclic polyethers.

Number of Binding Sites
for Acyclic Polyethers

Acyclic polyethers do not have cavities to nest cations but can build up appropriate crown ether-like cavities during complexation⁶. The number of binding sites helps to determine the size of the cavity which can be built upon complexation. Smid⁵ reported that 1:1 coordination complexes are formed between acyclic polyethers and metal cations when a certain minimum number of coordinating oxygen atoms are present. Increased complexation with an enhanced number of binding sites was found

but is not rigid and is only roughly true^{7,8}.

Flexibility of Acyclic Polyethers

Acyclic polyethers usually become less mobile upon complexation. A stiffening of the ligand backbone favors coordination⁹ because stiffened backbones are less mobile and the decrease in entropy upon complexation is less for polyethers with stiffened backbones than for more mobile polyethers¹⁰. Polyether chains are partly stiffened by inclusion of ortho-substituted aryl groups¹¹ into the molecule.

Terminal End Group Concept for Acyclic Polyethers

The stability of complexes between acyclic polyethers and metal cations is enhanced by certain terminal end groups¹². The enhancement due to the end groups was termed the "terminal end group concept." The enhanced stability is provided by rigid aryl end groups with additional donor sites attached. The end groups provide convergence of individual coordination sites which allows the formation of suitable cavities upon complexation.

Macrocyclic Effect for Cyclic Polyethers

Acyclic tetraamines 1 were compared to cyclic tetraamines 2 of similar molecular structure¹³ and the cyclic

structures were found to be significantly more stable complexes (Figure 1). The enhanced stability of the cyclic structures is termed the "macrocyclic effect." The effect was also observed for polyethers¹⁴. The enhancement is attributed to entropy factors because of the retention of the nature and geometry of donor atoms¹⁵ in the macrocyclic rings.

Cavity and Cation Diameter Ratio for Cyclic Polyethers

Upon discovering crown ethers, Pedersen suggested¹⁶ that more stable complexes were formed when the metal cation diameter and the polyether cavity diameter were such that the cation could fit into the polyether cavity. The x-ray crystal structure of a complex between dibenzo-18-crown-6 and rubidium thiocyanate showed the cation to be in the polyether cavity¹⁷ as suggested. Cation-to-cavity diameter ratios of 0.75 to 0.90 were found to provide the maximum interaction between the polyether and the metal cations¹⁸.

Solvent for All Polyethers

Effects of the solvent medium on the stability of a given complex are generally recognized. The solvent acts to stabilize or destabilize complexation in two ways. It competes with the ligand for the cation and it can inter-

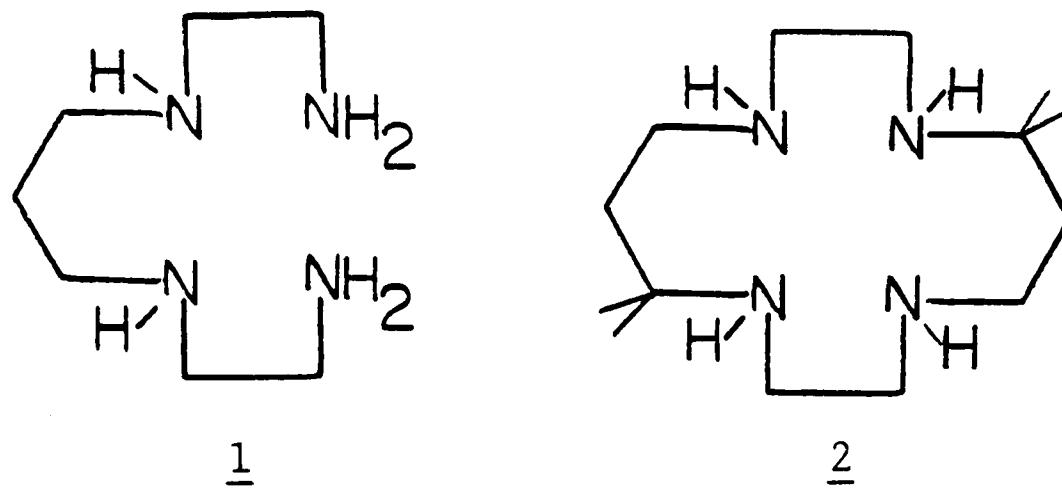


Figure 1: Formation Constants for Cu^{2+} - tetraamine Complexes

For 1 $\log K = 23.9$ and for 2 $\log K = 28.0$

act or not interact with the ligand¹⁹. The single most important solvent property is the dielectric constant. The dielectric constant measures the polarity of the solvent and determines its ability to solvate ions. Enhanced complexation was found with increased solvent polarity.

Identity of the Counter Anion for All Polyethers

Pedersen³ noted that for solubilization of polyether-cation complexes in non-polar solvents the counter anion played an important role. The solubilization of the polyether-cation complex was found to be a function of the counter anion and to decrease as the nucleophilicity of the anion decreased¹⁹. The counter anion which is associated with the polyether-cation complex can also have a steric effect if it is bulky. The steric effects can influence the complexation by affecting the bonding behavior and the conformation of the polyether.

Additional Binding Sites for All Polyethers

Polyethers which complex metal cations usually arrange their oxygen atoms equatorially around the metal cation. The arrangement of the oxygen atoms still allows for axial interactions with the metal cation by other molecules. Macrocyclic polyethers with side arms containing donor atoms have been synthesized and it was

noted that the side arm donor atoms could serve as additional axial binding sites for a complexed metal ion²⁰. The additional binding sites were found to be most effective when the complexation was not accompanied by freezing out of rotational degrees of freedom¹⁰. The studies of Bartsch²¹ and Gokel²² substantiate an increase in complexation for macrocyclic polyethers with axially disposed additional binding sites. In acyclic polyethers the additional binding site effect can be seen through the terminal end group concept.

Ionizable Polyethers as Multidentate Ligands

Background

The discovery of the antibiotic valinomycin and its alkali cation specificity led to the search for other biological ionophores²³. For the subsequently discovered acyclic ionizable biological ionophores, coupled counter-transport of cations and protons was observed^{23, 24}. Synthetic ionizable polyethers have been prepared and found to mimick the behavior of the biological ionophores^{24, 25}. The ionizable polyethers have two unique features that distinguish them from ordinary polyethers. They provide a counter anions as part of the host polyethers²⁰ and are pH sensitive complexing agents²⁵. The ionizable polyethers exhibit enhanced complexation of metal cations

compared with non-ionizable polyethers²⁵.

Complexation of Metal Cations

Ionizable polyethers, when compared to their neutral counterparts, show improved efficiency and selectivity in extracting (a measure of complexation) metal cations into organic media^{25,26}. The primary means of measuring this complexation is to assess the degree of transport of the metal cations into an organic phase from an aqueous phase. The polyether must be sufficiently lipophilic to remain in the organic phase for accurate complexation measurements²⁵. The structural relationship of the ionizable and lipophilic groups may enhance complexation²⁷. When the location of the lipophilic group sterically forces the ionizable group to occupy a position axial to the equatorial polyether oxygens²¹, complexation is enhanced greatly.

The complexation of ionizable polyethers is mediated by two factors, the polyether cavity and the internal counter anion. The polyether cavity effects are a function of the cation-cavity diameter ratio. The internal counter anions interact with the cations electrostatically. The cation-anion interaction for the carboxlate anion (COO^-) with alkali and alkaline earth metal cations decrease from cesium to lithium and from barium to magnesium,

respectively¹⁹.

Complexations of Lithium Metal Cations

Inherent Problems

Lithium metal cations are very small relative to the other alkali metal cations (see Table 1). The charge to radius ratio for lithium metal cations is very high²⁸ and they are "solvent philic"¹⁹. Lithium metal cations, because of their high charge to radius ratio, are very strongly hydrated in aqueous solution with an hydration energy of 122 kcal/mole²⁹. Lithium metal cations have a hydration number of approximately 25.3²⁸. The strong hydration sphere of the cations makes complexing them very difficult.

Table 1. Metal Ion Diameters (in Angstroms)

<u>Alkali Metal Cation</u>	<u>Diameter</u>	<u>Alkaline Earth Cation</u>	<u>Diameter</u>
Li ⁺	1.36	Mg ²⁺	1.56
Na ⁺	1.96	Ca ²⁺	2.12
K ⁺	2.66	Sr ²⁺	2.54
Rb ⁺	2.98	Ba ²⁺	2.83
Cs ⁺	3.30		

Historical Development and Status

Although there are numerous reports of complexation of most alkali metal cations, the number of reports for complexes of lithium cations are relatively limited²⁹. Lithium cation complexes of small ring crown ethers have been reported³. A very stable lithium cation complex with cryptand [2.1.1] was reported³⁰. Complexes of lithium with macrocyclic polyethers having 12-to 16-membered rings and 4 coordinating oxygen atoms have been reported^{31,32,29}. Complexes of lithium by acyclic dioxa diamides are also reported^{33,34}. The use of polyethers to separate lithium from other alkali metal cations depends upon the selectivity of the complexation. The normal means of assessing this selectivity is by Li^+/Na^+ selectivity ratios. Sodium, lithium's nearest periodic neighbor, would be the most likely cation to complex in a lithium selective system. Therefore the discrimination between lithium and sodium is a good measure of lithium specificity. The highest selectivity found for lithium is by complexation with [2.1.1] cryptand 3. However cryptands are impractical for use in large scale separations because they are very difficult to synthesize. Macrocyclic polyethers with Li^+/Na^+ selectivities of 2-10 are known^{29,32}. A high Li^+/Na^+ selectivity of 41.7 was

reported for an acyclic dioxa diamide 4 system³⁴. Lithium selective ionizable macrocyclic polyethers 5,6 with Li⁺/Na⁺ selectivity ratios of 1.9 and 2.5 have been reported recently³⁵ (Figure 2).

Statement of Research Plan

Research aimed at studying the complexation behavior of the alkali metal cations with small ring polyethers will be undertaken. The investigations are to focus on the lithium cation specificity in competitive alkali metal solvent extraction. The ionizable crown ether molecules will contain an ionizable COOH group in proximity of the polyether ring, a hydrocarbon group to impart lipophilicity, an aryl group for determining the concentration of the complexing agent in solution by UV spectrophotometry, and crown rings with 4 polyether oxygens arranged into varying 12- to 15- membered structures (Figure 3).

Studies of the complexation of acyclic polyether dicarboxylic acids with alkaline earth metal cations will also be undertaken. The acyclic polyethers will contain two ionizable COOH groups on rigid terminal groups, hydrocarbon lipophilic groups, and varying numbers of polyether oxygens (Figure 3). An assessment of the effects of the number of binding sites, cation to complexation induced

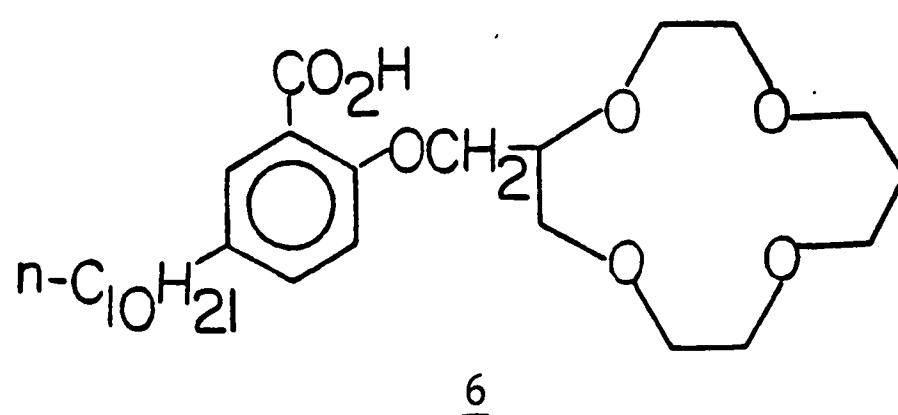
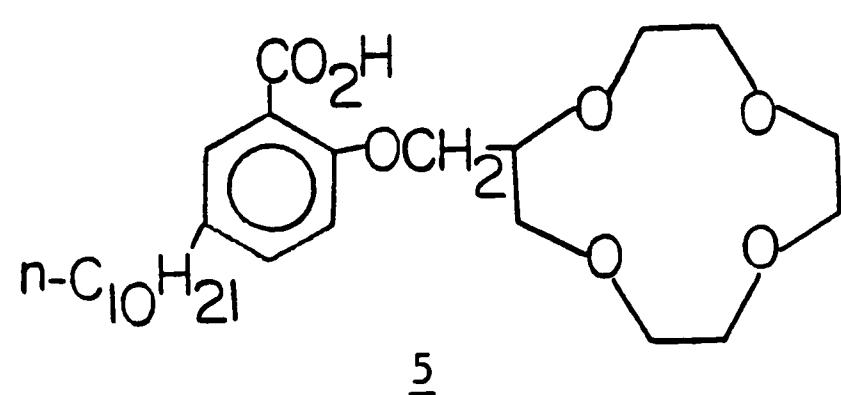
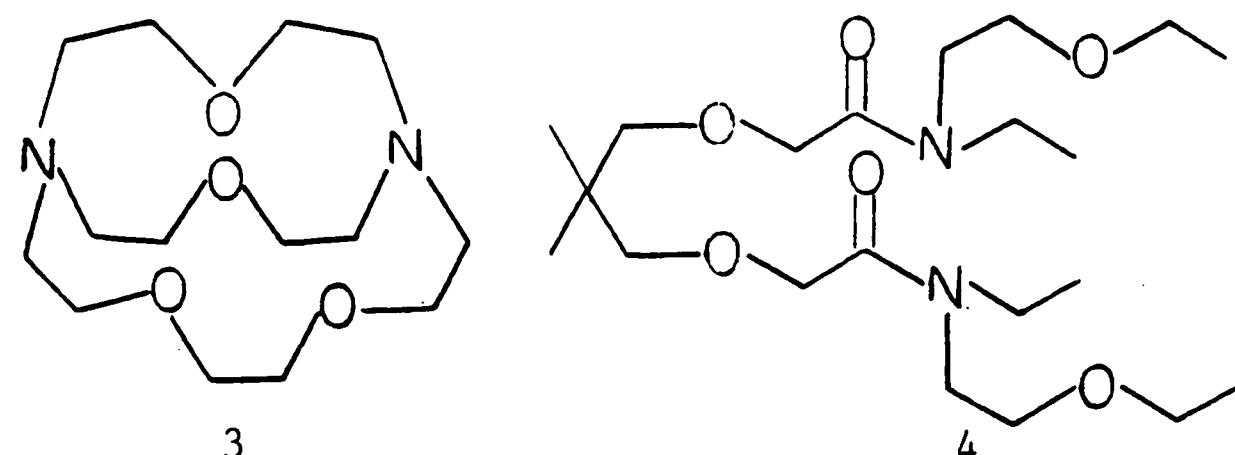


Figure 2: Lithium Ion Selective Ligands

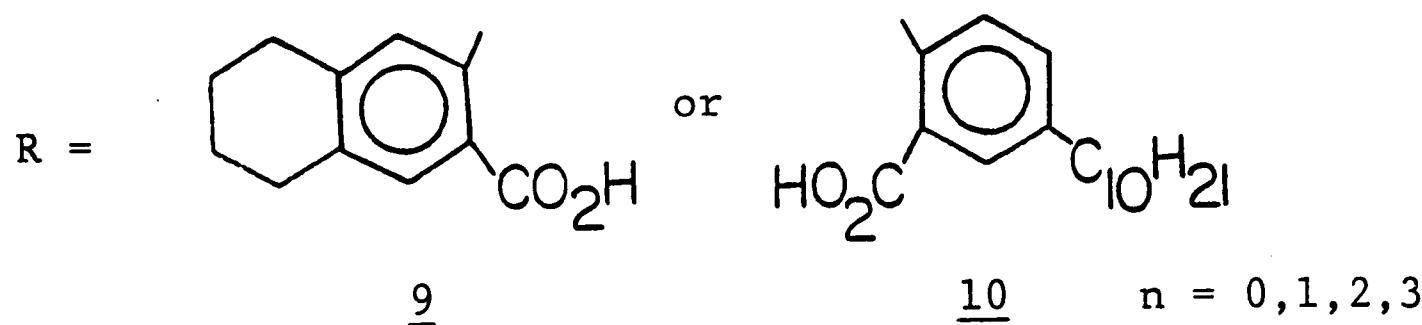
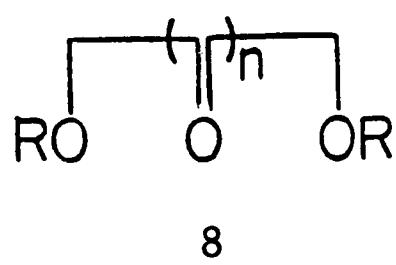
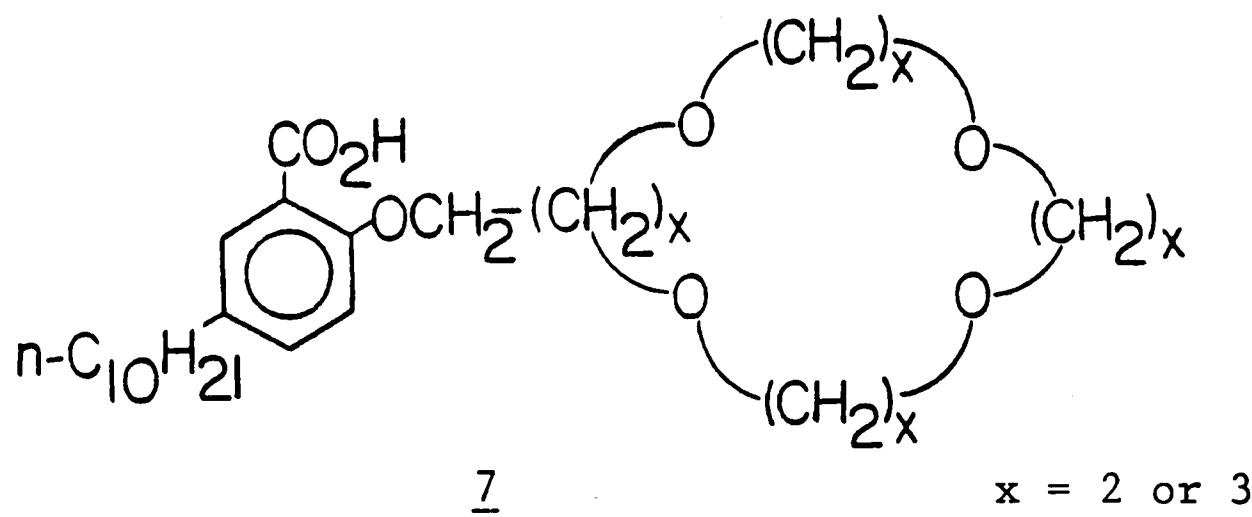


Figure 3: Small Ring Ionizable Polyethers and Polyether Dicarboxylic Acids

cavity size ratio, and type of lipophilic group will be made.

CHAPTER II

EXPERIMENTAL SECTION

Apparatus and Materials

Apparatus

Concentrations of alkali and alkaline earth metal cations in aqueous phases were determined with a Dionex Model 10 ion chromatograph and with a Perkin-Elmer Model 2380 atomic absorption spectrophotometer. Organic complexing agent concentrations in the chloroform phases were measured with a Cary Model 17 ultraviolet-visible spectrophotometer. Measurements of pH were made with a Fisher Accumet Model 620 pH meter using a Corning 476050 glass body combination electrode. For the solvent extraction studies samples were shaken on a Burrell Model 75 wrist action shaker.

Materials

The inorganic chemicals, CsCl, LiCl, CsOH, and RbCl were obtained from Aldrich (Milwaukee, WI). Sources of other inorganic chemicals include: Fisher (Fair Lawn, NJ), CaCl₂, NaOH, KCl, BaCl₂, HCl; MCB (Cincinnati, OH), MgCl₂; Merck (Rahway, NJ), SrCl₂; Mallinckrodt (Paris, KY),

NaCl. Demineralized water was prepared by passing distilled water through three Barnstead D8922 combination cartridges in series. Reagent grade chloroform from Fisher (Fair Lawn, NJ) was treated by shaking four times with demineralized water to remove the stabilizing ethanol and saturate the chloroform with water. Reagent grade toluene from MCB was used without further purification.

The complexing agents which were investigated were provided by other members of the Bartsch research group and are listed in Figure 4.

Procedure for Competitive Solvent Extraction

A chloroform solution (5.0 mL) of the complexing agent (0.05 M) and an aqueous solution of the metal chlorides (0.50 M each; Li⁺, Na⁺, K⁺, Rb⁺, and Cs⁺ for alkali metal cations; Mg²⁺, Ca²⁺, Sr²⁺, and Ba²⁺ for alkaline earth metal cations) and CsOH were shaken for 30 minutes in a 30 mL separatory funnel at room temperature (22-25°C). After allowing the two layers to settle for about 24 hrs., they were separated and the equilibrium pH of the aqueous phase was measured. A 4.0 mL sample of the chloroform phase was shaken with 4.0 mL of aqueous HCl (0.2 or 0.5 N) for 30 minutes to strip the metals from the organic phase into an aqueous medium for analysis by ion chromatography. A small sample of the organic

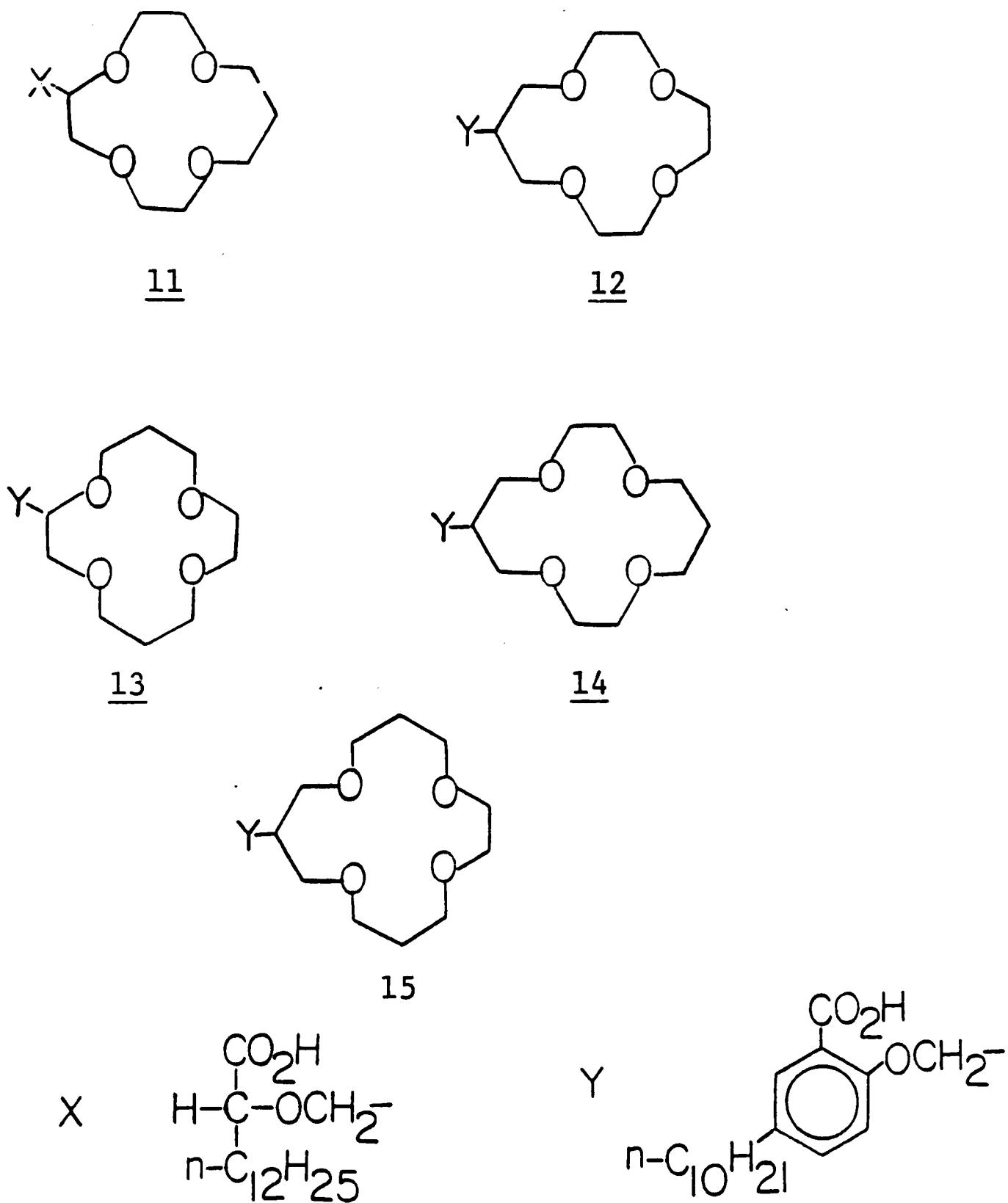


Figure 4: Complexing Agents Used in This Investigation

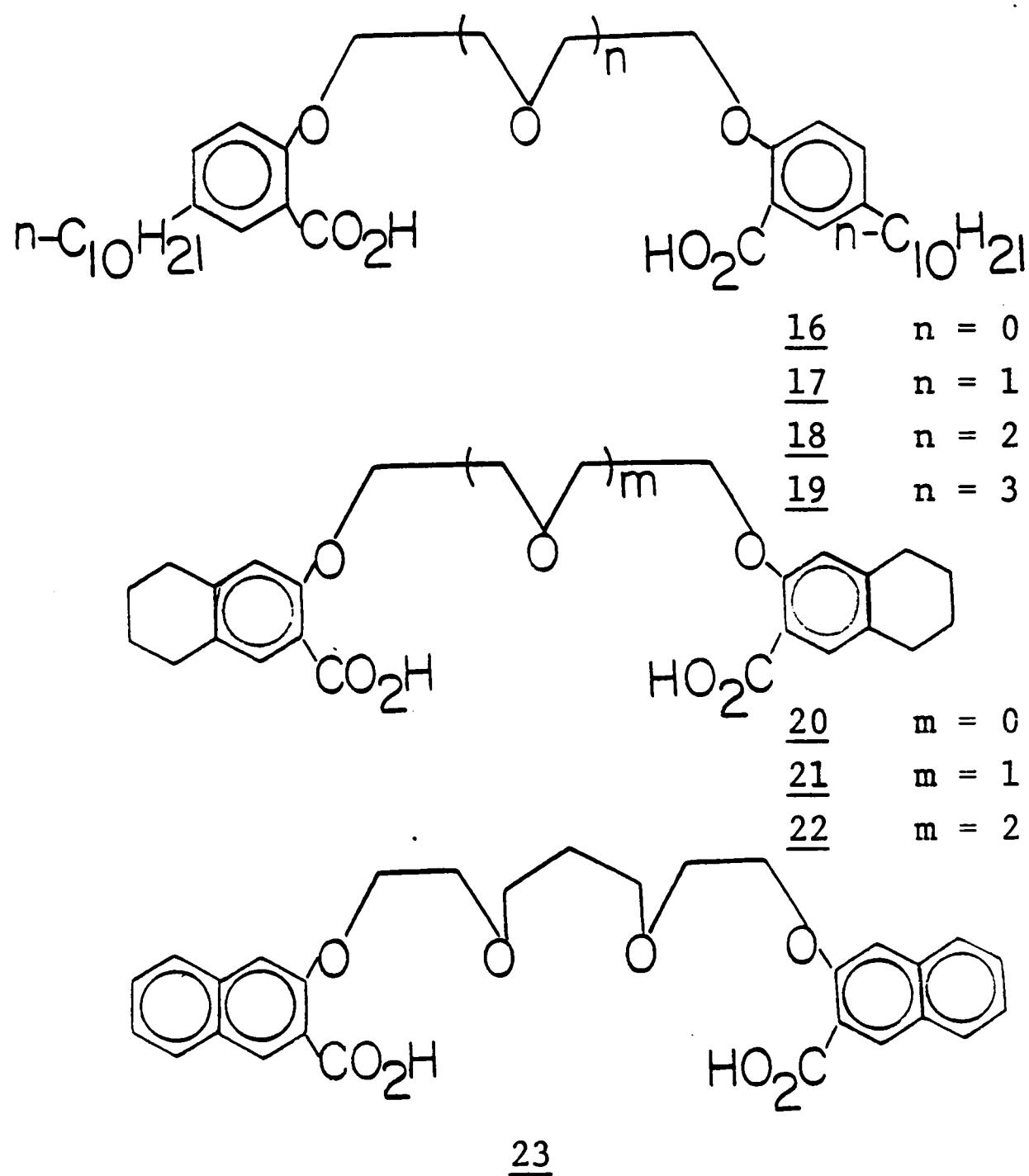


Figure 4: Continued

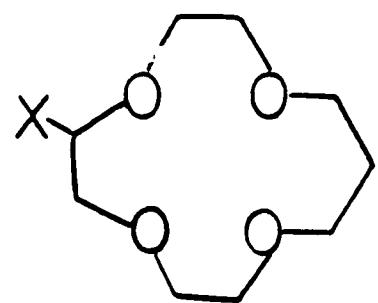
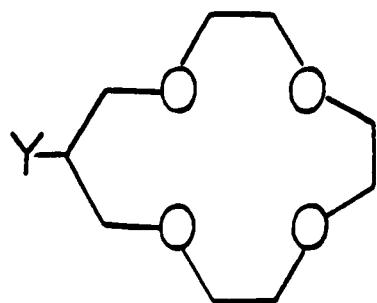
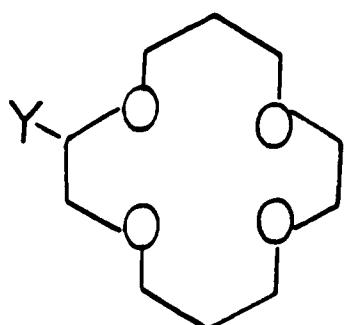
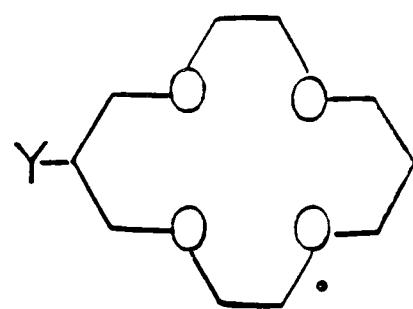
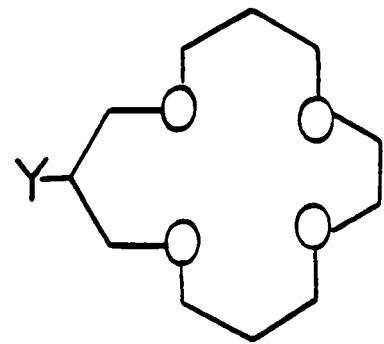
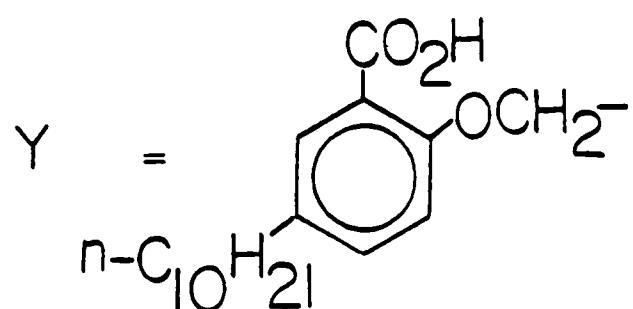
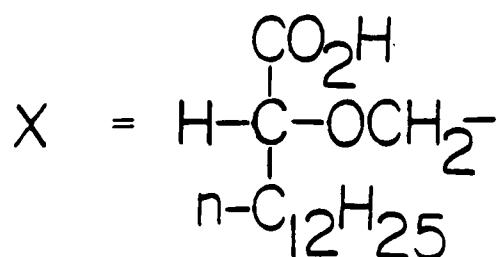
phase (usually 5-10 μL) was removed and diluted with chloroform in a 5.0 mL volumetric flask. Measurement of the absorption at the λ_{max} of each of complexing agent which contained a chromophore established its concentration in the organic phase. For the purpose of comparison, another sample was prepared from the stock chloroform solution of the complexing agent (0.05 M), and its absorbance was recorded. When the ionophore did not contain a chromophore, its concentration in the organic phase after stripping was determined by titration with 0.02 M methanolic NaOH in the presence of phenolphthalein as an indicator.

CHAPTER 3

RESULTS AND DISCUSSION

Complexation of Alkali Metal Cations by Small Ring Ionizable Polyethers

Reported lithium selective complexation by salicylic acid derivatives of 12-crown-4 and 13-crown-4³⁵ led to the examination of the solvent extraction of complexing agents 11-15 (Figure 5). This was a systematic effort to extend the investigation of lithium selective small ring crown ethers. The small ring ionizable crown ethers are a series of closely-related compounds in which the structures were systematically varied. Complexing agent 11 differs from complexing agents 12-15 in having an alkyl carbon attachment site for the lipophilic and the ionizable groups while the others have an aryl carbon. Complexing agents 11 and 12 differ from 13 and 14 which differ from 15 in having 13-, 14-, and 15-membered rings, respectively. Complexing agents 11-15 all have four ether oxygens. Complexing agents 11 and 13 differ from 12, 14, and 15 in the point of attachment of the lipophilic, ionizable moiety. For 11 and 13 the connection is made on a two carbon bridge while for 12, 14, and 15 attachment is at the center of a three carbon bridge.

1112131415Figure 5: Structures of Complexing Agents 11-15

The results of competitive alkali metal cation extractions from an aqueous phase to a chloroform phase for complexing agents 11-15 are recorded in Figures 6-8. From this data the effects of the mobility of the ionizable group, the cation-cavity size relationship, and the location of the lipophilic, ionizable moiety on the complexation efficiency and selectivity may be assessed.

The Effect of the Mobility of the Ionizable Group

The structures of complexing agents 11 and 6 (from reference 35, see Figure 9) differ only in the lipophilic ionizable moiety. Complexing agent 11 has its COOH group attached to a freely rotating alkyl carbon atom affording an ionizable function which is capable of assuming many positional relationships with respect to the polyether cavity. Complexing agent 6 has its COOH group attached to an aryl carbon atom which would restrict rotation and fewer positional relationships with the polyether cavity could be possible. Therefore the ionizable function of complexing agent 11 should have greater mobility.

The pH profiles for complexing agents 6 (Figure 9) and 11 (Figure 6) are quite similar except for the efficiency of lithium complexation and Li^+/Na^+ selectivity

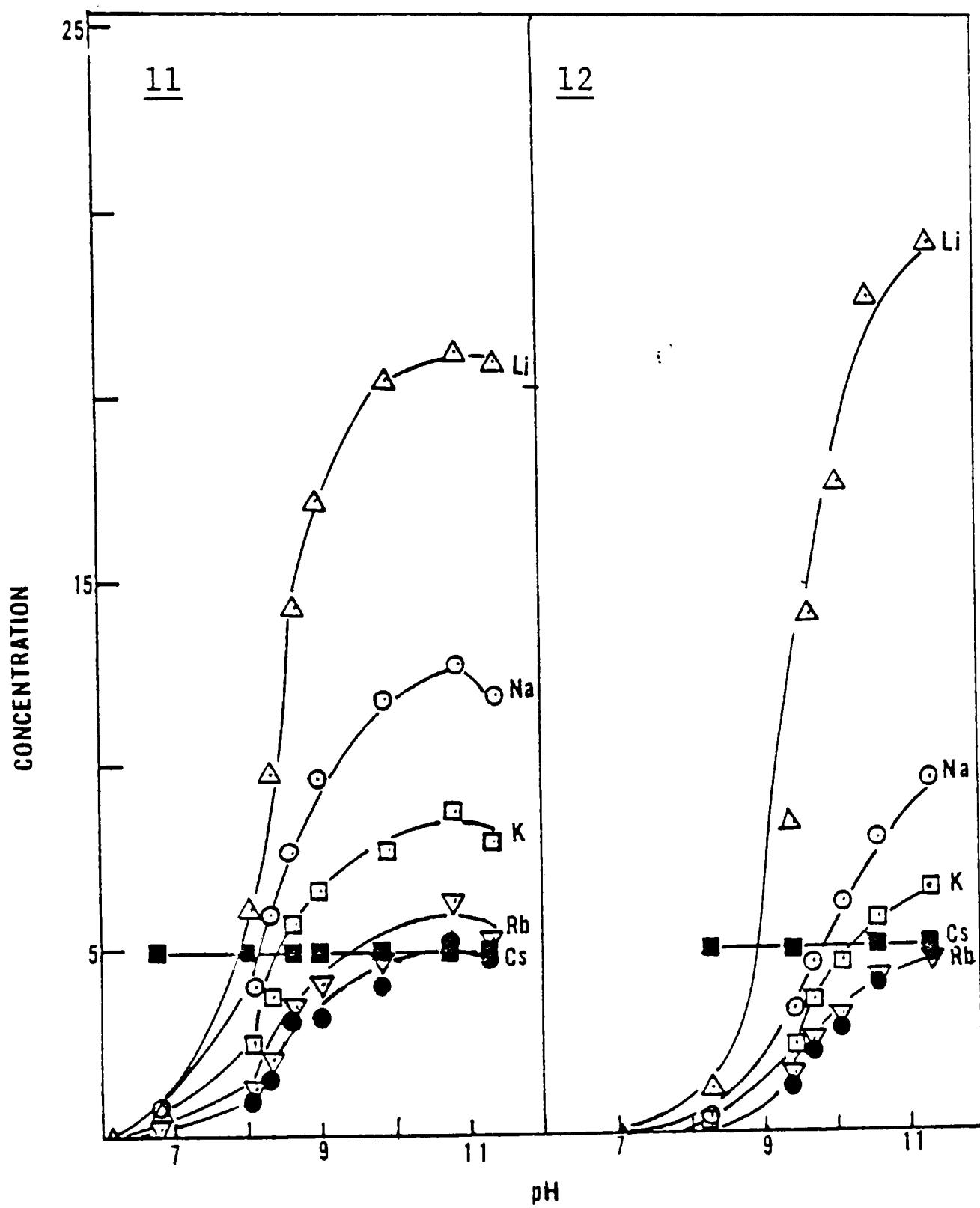


Figure 6: Solvent Extraction of Alkali Metal Ions by Ionizable Crown Ethers 11 and 12. Concentration of metals ($M \times 10^3$) and complexing agent ($M \times 10^2$) in the organic phase versus the equilibrium pH of the aqueous phase.

■ = complexing agent

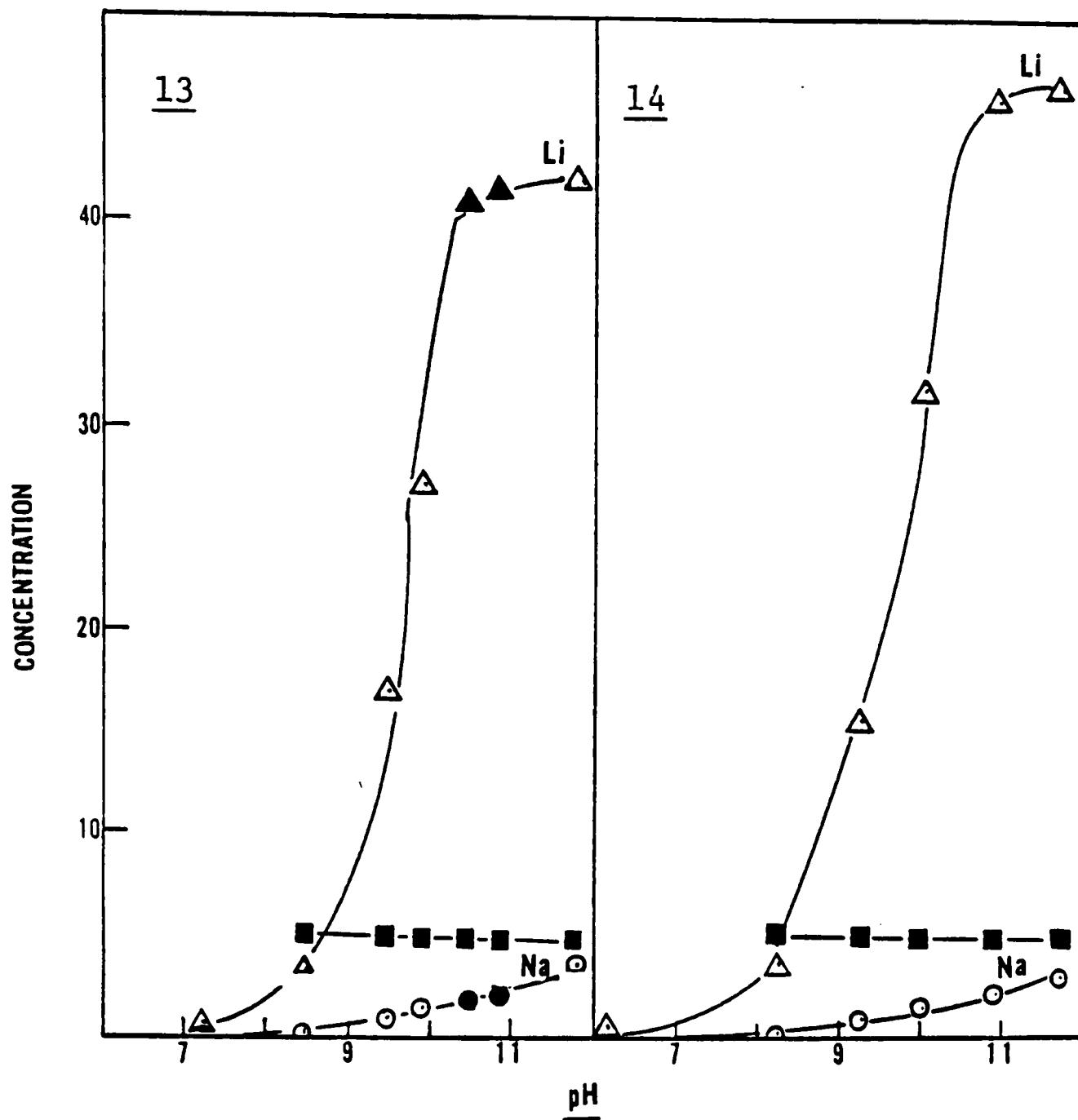


Figure 7: Solvent Extraction of Alkali Metal Ions by Ionizable Crown Ethers 13 and 14. Concentration of metals ($M \times 10^3$) and complexing agent ($M \times 10^2$) in the organic phase versus the equilibrium pH of the aqueous phase. The filled symbols are from a later experiment conducted with a new sample of the crown ether.

■ = complexing agent

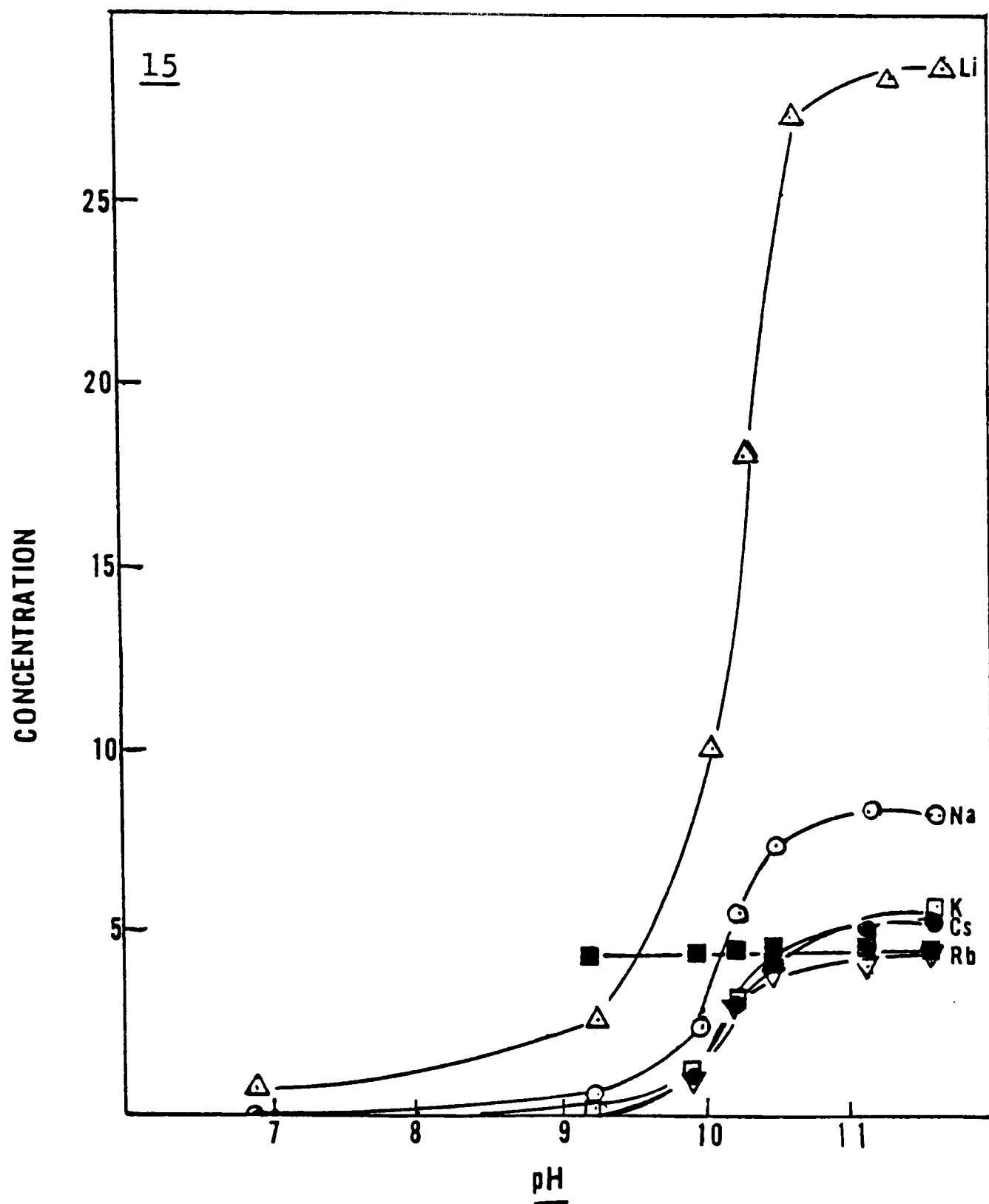


Figure 8: Solvent Extraction of Alkali Metal Ions by Ionizable Crown Ether 15. Concentration of metals ($M \times 10^3$) and complexing agent ($M \times 10^2$) in the organic phase versus the equilibrium pH of the aqueous phase.

■ = complexing agent

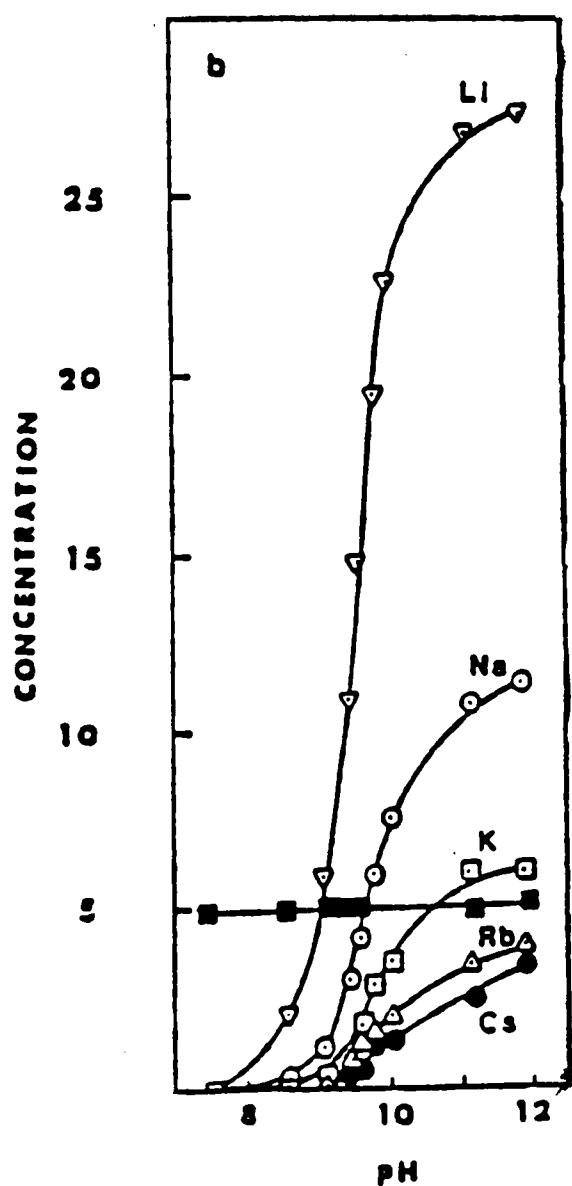
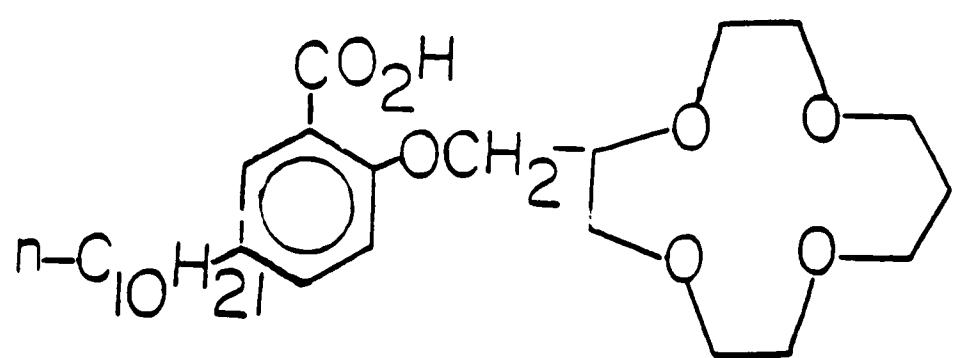


Figure 9: The Structure and pH Profile of Complexing Agent 6

ratios. The efficiency of lithium complexation for complexing agent 6 is higher than for complexing agent 11. The Li^+/Na^+ selectivity ratio for complexing agent 6 is 2.5 while for complexing agent 11 it is 1.9. The increase in the efficiency and the specificity of lithium complexation for complexing agent 6 suggests the more positionally restricted COOH group helps to increase cavity-mediated complexation. A rationale for the increase in lithium complexation efficiency and specificity is that a more restricted COOH group is more likely to be positioned axial to the polyether cavity and can serve as an additional binding site thus increasing complex stability. Interaction of the cation with the carboxylate anion without concomitant interaction with the polyether cavity should be enhanced by the mobility of the anion. The decrease in lithium selectivity of complexing agent 11 which has the less restricted ionizable function suggests less cavity-mediated complexation for this ligand.

The Effect of the
Attachment Site of the
Lipophilic, Ionizable
Moiety

The proximity of the COOH group to the crown ether cavity might play a significant role in determining the degree of complexation in the small ring ionizable crown

ethers. The complexing agents isoneric pair of 13 and 14 and of 6 and 12, are identical except for the attachment site of the lipophilic, ionizable moiety which changes the proximity of the ionizable function to the crown ether cavity. The extraction data show similar behavior for complexing agents 13 and 14 (Figure 7) which include pH dependence, lithium complexation efficiency and Li^+/Na^+ selectivity ratios. The lithium concentration in the chloroform phase is $4.10 \times 10^{-2}\text{M}$ for 13 and $4.60 \times 10^{-2}\text{M}$ for 14. The Li^+/Na^+ selectivity ratios are 19.9 and 18.8 for complexing agents 13 and 14, respectively. The lithium complexing efficiency for complexing agents 6 (Figure 9) and 12 (Figure 6) are also comparable and the Li^+/Na^+ selectivity ratios are 2.5 for both complexing agents. These data clearly show that the differences in the attachment sites of the lipophilic, ionizable moiety do not significantly affect the complexation behavior. Therefore the structural changes are not sufficient to produce significant differences in complexation properties.

The Effect of the Cation-cavity Diameter Ratio

The cavities of the small ring ionizable polyethers 5, 6, 11-15, increase in diameter in the order; 5 (12-crown-4) 6, 11, 12 (13-crown-4) 13, 14 (14-crown-4) 15 (15-crown-4). The diameters of the aforementioned polyethers are between 1.2 and 1.7 angstroms. The cation-cavity diameter ratios for lithium and the polyethers lie between 0.80 and 1.13. A maximum lithium complexation efficiency and lithium specificity should be observed when the optimum cation-cavity diameter ratio is attained.

The extraction data reveal organic phase concentrations above pH = 9 of 2.1×10^{-2} M, 2.4×10^{-2} M, 4.1×10^{-2} M and Li^+/Na^+ selectivity ratios of 1.8, 2.5, 19.9 for complexing agents 5, 6, 13, respectively. The complexation results for the series of complexing agents 12, 14, 15 reveal organic phase lithium concentrations of 2.3×10^{-2} M, 4.6×10^{-2} M, 2.8×10^{-2} M and the Li^+/Na^+ selectivity ratios of 2.8, 18.8, 3.5, respectively. The trends for lithium loading and specificity show increases in going from 12-crown-4 to 13-crown-4 and then to 14-crown-4 cavity diameters with a subsequent decrease for larger

size ring diameters. These trends suggest that the cation-cavity diameter ratio is at an optimum for Li^+ and the 14-crown-4 polyethers. By implication, the 13-crown-4 polyethers have less than optimal cavity size for Li^+ and the 15-crown-4 polyether has greater than optimal cavity size for Li^+ .

The selectivity orders are $\text{Li}^+ > \text{Na}^+ > \text{K}^+ > \text{Rb}^+ > \text{Cs}^+$ for complexing agents 5, 6, 12, and 15 and $\text{Li}^+ > \text{Na}^+$ with no K^+ , Rb^+ , Cs^+ detected for complexing agents 13 and 14. The selectivity orders suggest cavity-mediated complexation because the selectivity order would be $\text{Cs}^+ > \text{Rb}^+ > \text{K}^+ > \text{Na}^+ > \text{Li}^+$ for cation-carboxylate interaction based extraction.

Complexation of Alkaline Earth Metal Cations

The complexation of alkaline earth metal cations should be facilitated by complexing agents which are di-anions. The acyclic polyether dicarboxylic acids 16-23 (Figure 10) used in this study contained the kind of internal anion necessary for good alkaline earth metal cation complexation. The internal anions are generated at basic pH's for the polyethers 16-23 and consist of two carboxylate anions. This study is an effort to extend the investigation into this type of ligand from previous work³⁵ in the Bartsch research group.

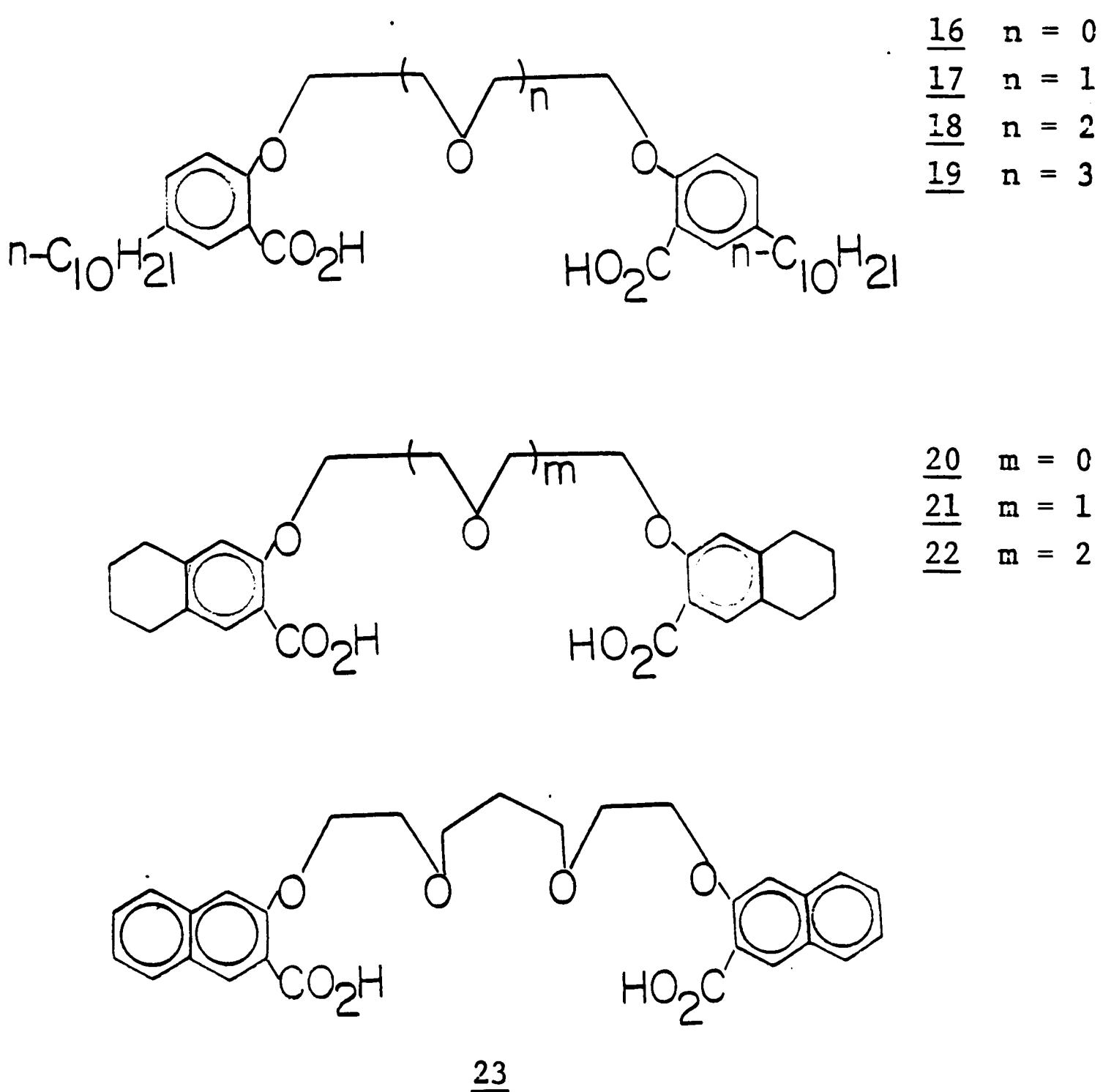


Figure 10: The Structures of Complexing Agents 16-23

The aim of this study is to examine the effects of structural changes in the polyether dicarboxylic acid ligands and different solvents on alkaline earth metal cation complexation. The ligands differ in the lipophilic group nature and the number of polyether oxygens. The differences in lipophilic group are complexing agents 16-19 contain two n-decyl salicyl groups, complexing agents 20-22 contain two tetralin groups, and complexing agent 23 contain two naphthalene groups. The number of polyether oxygens is two for complexing agents 16 and 20, three for complexing agents 17 and 21, four for complexing agents 18, 22, and 23, and five for complexing agent 19. The extraction studies were done mainly with chloroform solvent, but complexing agent 17 was utilized for solvent extractions into toluene also. The results of competitive alkaline earth metal cation extractions from an aqueous phase to an organic phase for complexing agents 16-23 are recorded in Figure 11-16.

The Effect of the Lipophilic Group

The three lipophilic groups investigated were the n-decyl salicyl group, the tetralin group, and the naphthalene group. The n-decyl salicyl group is the most lipophilic and flexible, the tetralin group is intermediate in lipophilicity and flexibility, while the nap-

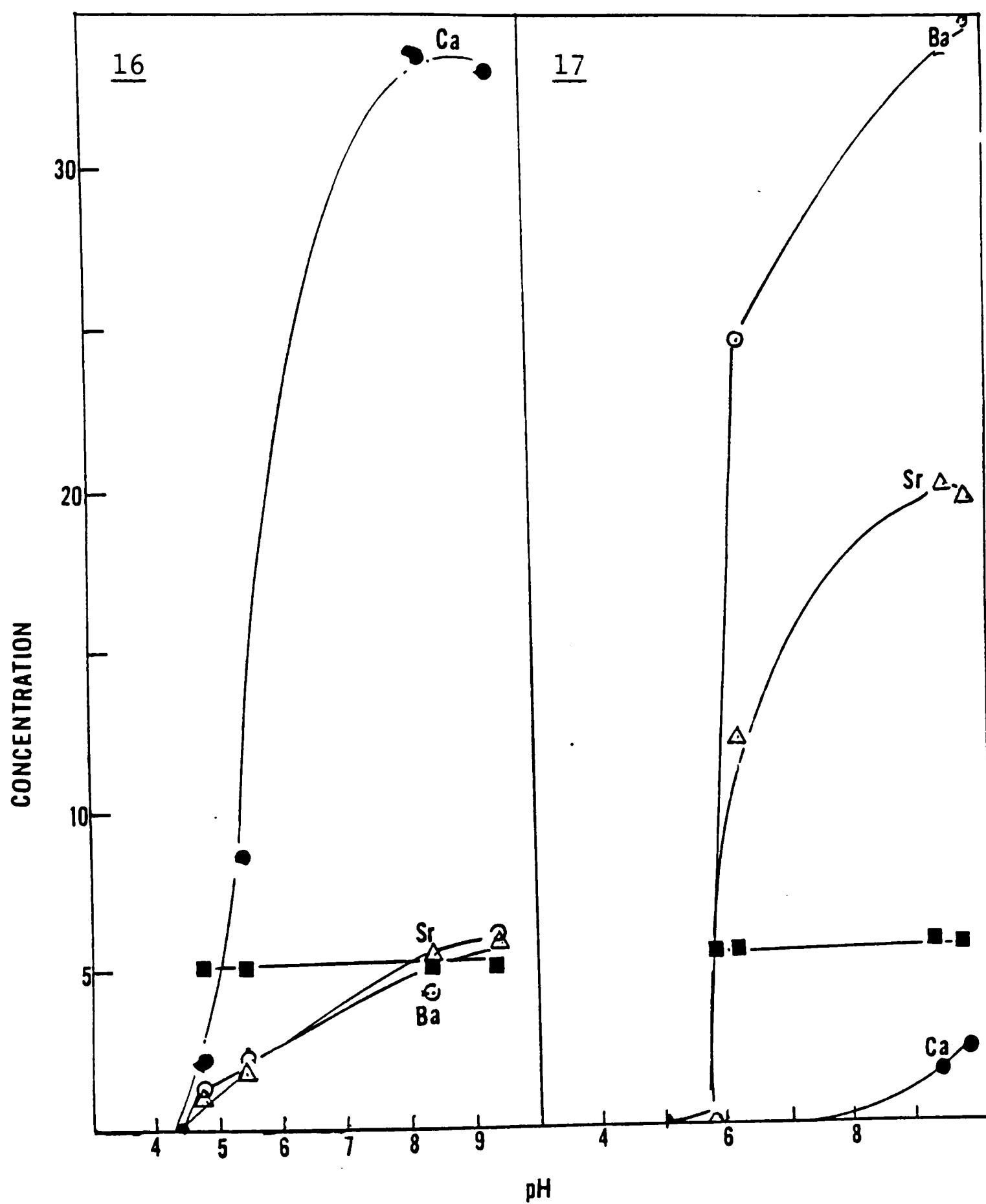


Figure 11: Solvent Extraction of Alkaline Earth Metal Ions by Acyclic Polyether Dicarboxylic Acids 16 and 17. Concentration of metals ($M \times 10^3$) and complexing agent ($M \times 10^2$) in the organic phase versus the equilibrium pH of the aqueous phase.

■ = complexing agent

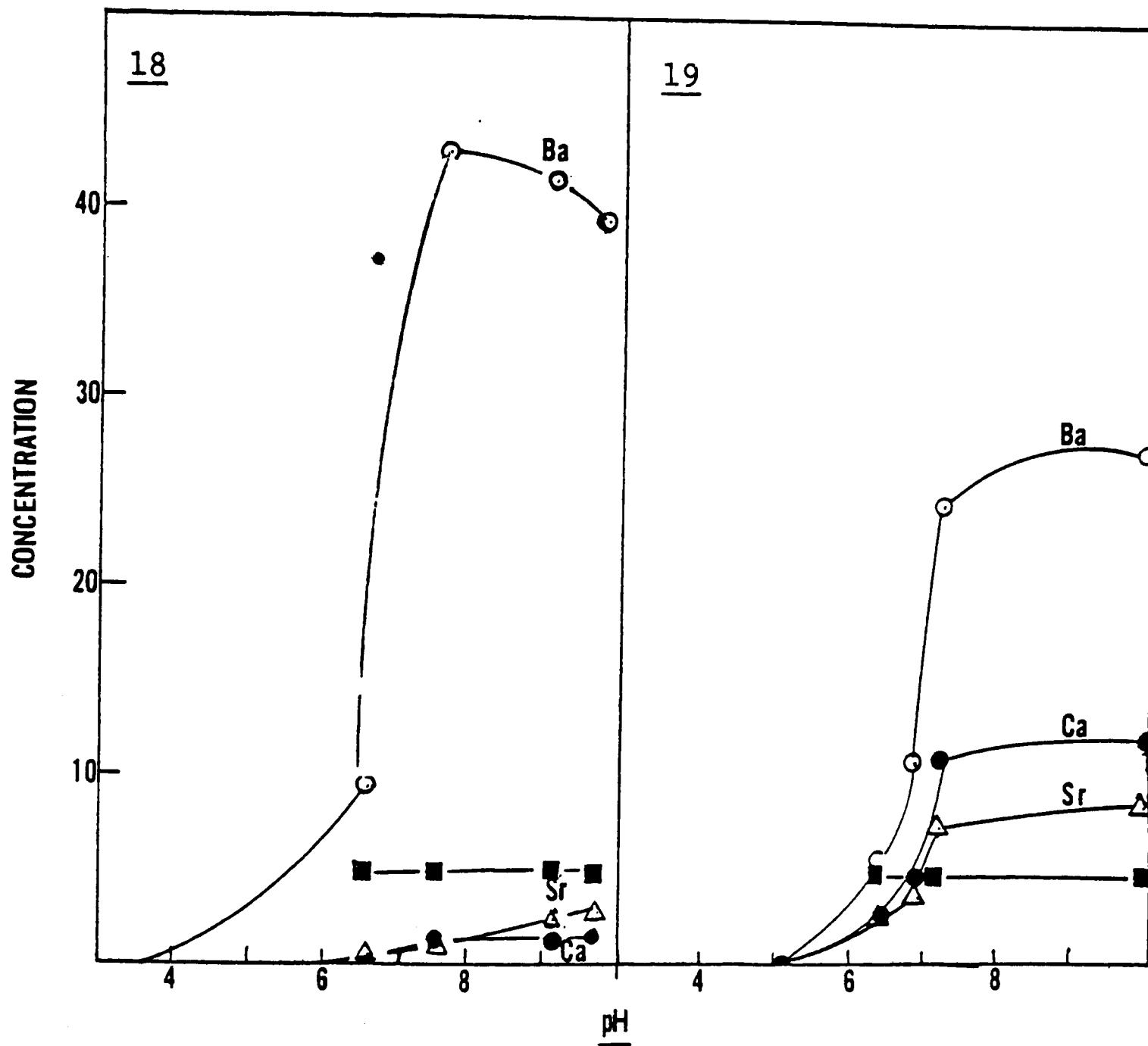


Figure 12: Solvent Extraction of Alkaline Earth Metal Ions by Acyclic Polyether Dicarboxylic Acids 18 and 19. Concentration of metals ($M \times 10^3$) and complexing agent ($M \times 10^2$) in the organic phase versus the equilibrium pH of the aqueous phase.

■ = complexing agent

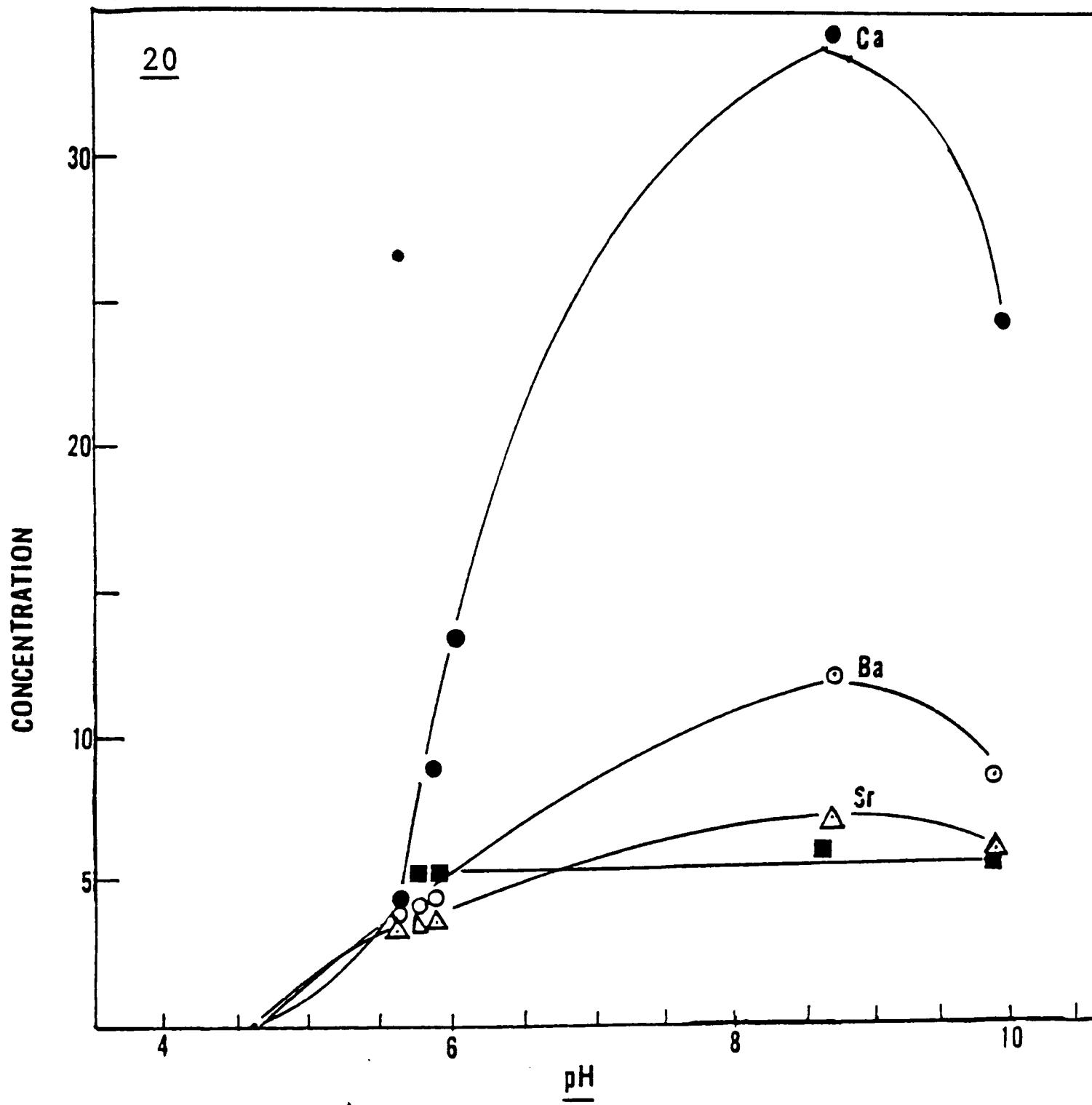


Figure 13: Solvent Extraction of Alkaline Earth Metal Ions by Acyclic Polyether Dicarboxylic Acid 20. Concentration of metals ($M \times 10^3$) and complexing agent ($M \times 10^2$) in the organic phase versus the equilibrium pH of the aqueous phase.

■ = complexing agent

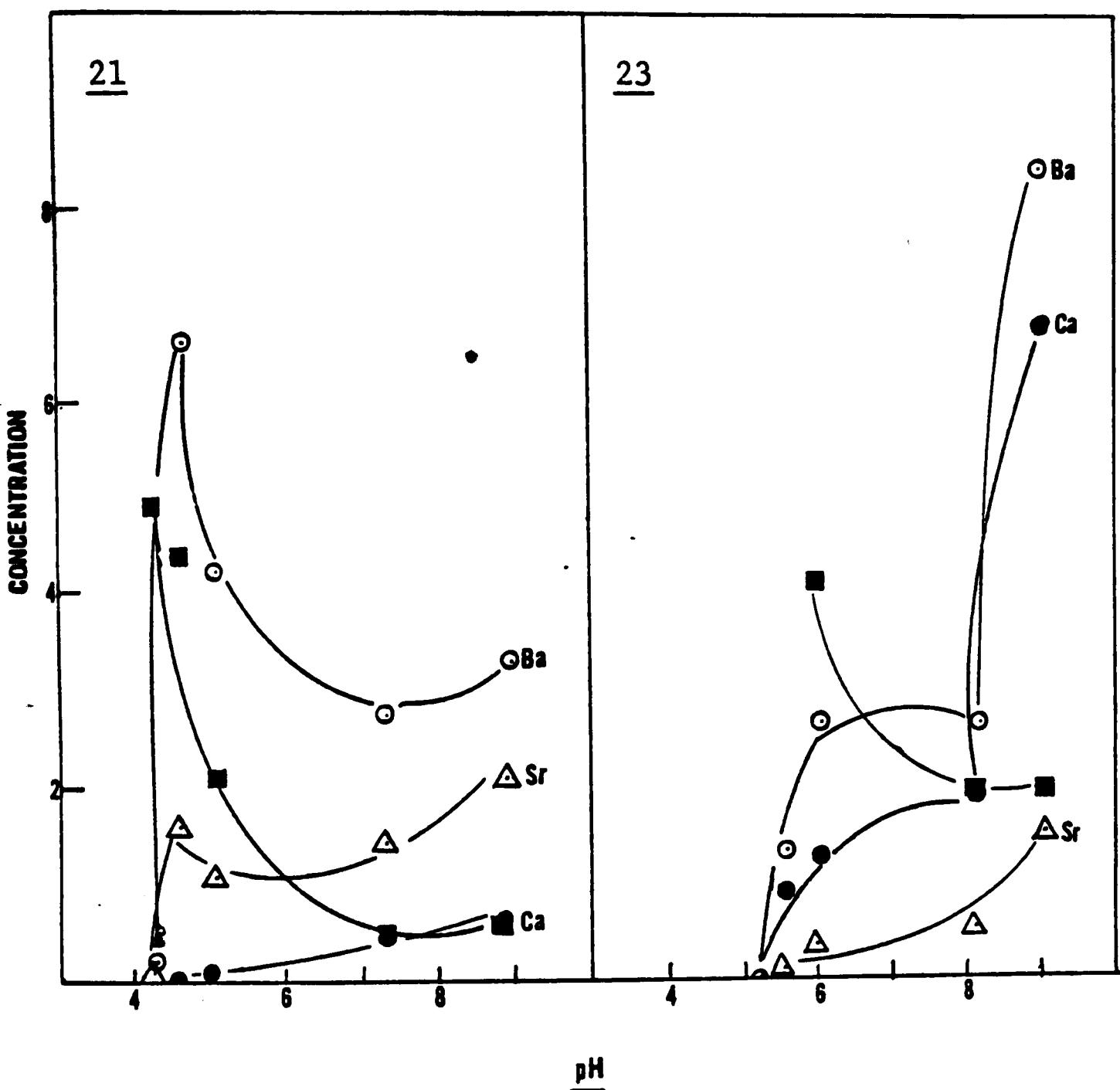


Figure 14: Solvent Extraction of Alkaline Earth Metal Ions by Acyclic Polyether Dicarboxylic Acids 21 and 23. Concentration of metals ($M \times 10^3$) and complexing agent ($M \times 10^2$) in the organic phase versus the equilibrium pH of the aqueous phase.

■ = complexing agent

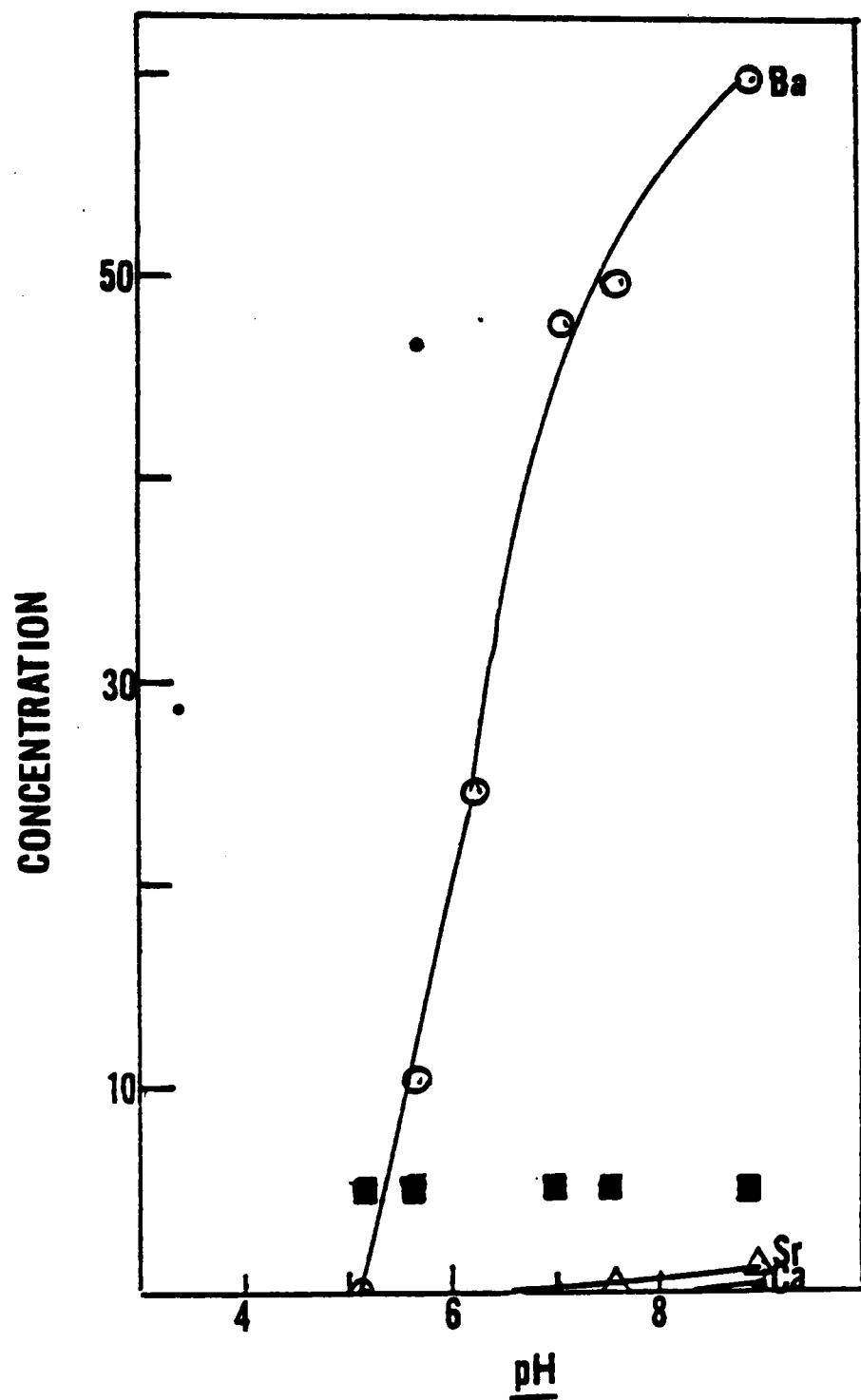


Figure 15: Solvent Extraction of Alkaline Earth Metal Ions by Acyclic Polyether Dicarboxylic Acid 22. Concentration of metals ($M \times 10^3$) and complexing agent ($M \times 10^2$) in the organic phase versus the equilibrium pH of the aqueous phase.

■ = complexing agent

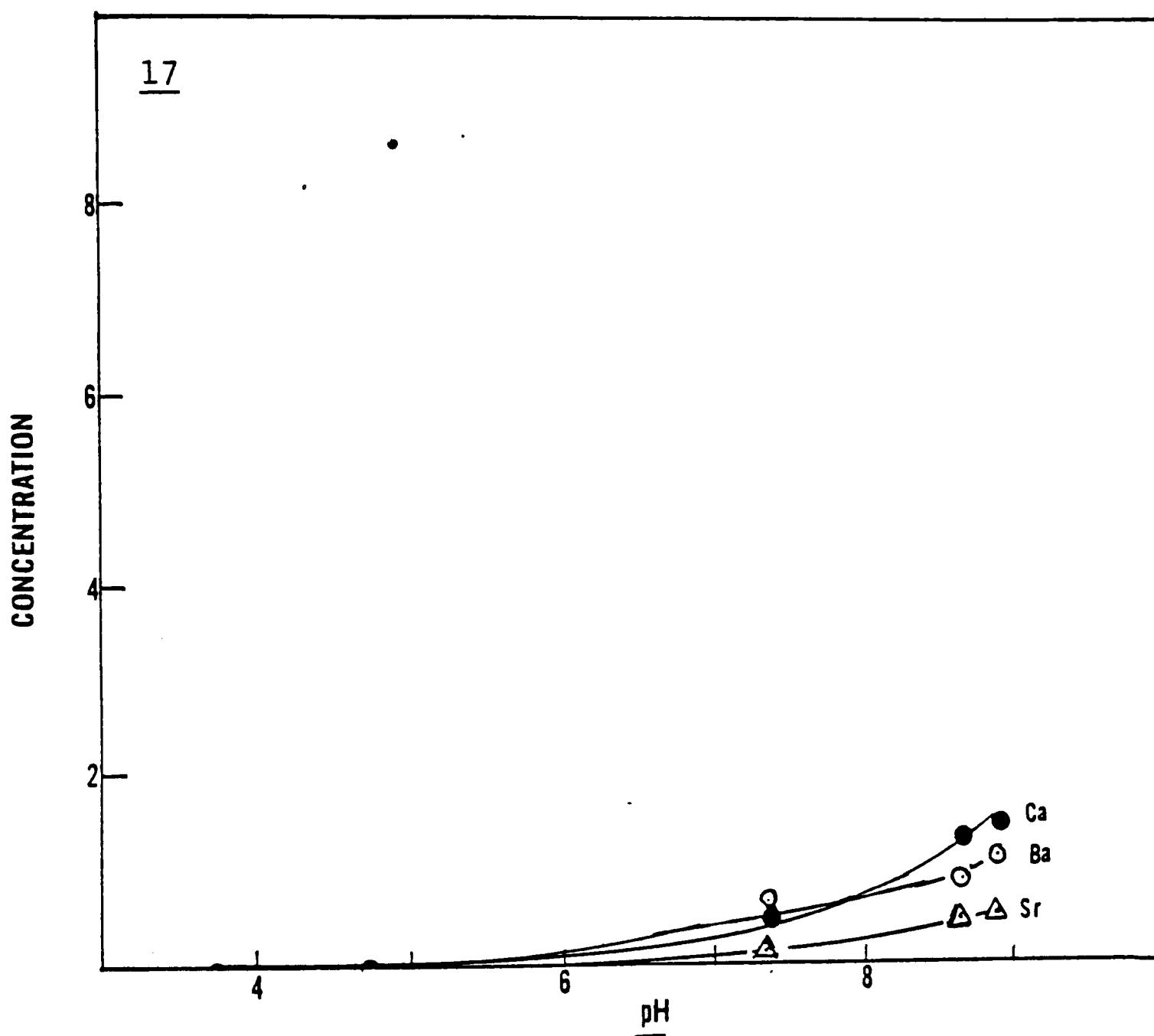


Figure 16: Solvent Extraction of Alkaline Earth Metal Ions by Acyclic Polyether Dicarboxylic Acid 17 in Toluene Solvent. Concentration of metals ($M \times 10^3$) and complexing agent ($M \times 10^2$) in the organic phase versus the equilibrium pH of the aqueous phase.

thalene group is least lipophilic and flexible.

The results of UV analysis of the chloroform phase after stripping show no loss of complexing agent to the aqueous phases for complexing agents 16-20 and 22, while complexing agents 21 and 23 show significant losses of complexing agent concentration from the chloroform phase when the aqueous phases are basic. The losses in complexing agent concentration for complexing agent 23 were to the aqueous phases which suggests insufficient lipophilicity in the structure of this complexing agent. The losses in complexing agent concentration for complexing agent 21 were due to precipitation of the cation-polyether complex during extraction.

A comparison of the extraction data for the complexing agent pairs, 16 and 20, 18 and 22, which differ only in the lipophilic group, show similar pH profiles. The principle ion extracted for complexing agents 16 and 20 was Ca^{++} with organic phase Ca^{++} concentrations of $3.3 \times 10^{-2}\text{M}$ and $3.4 \times 10^{-2}\text{M}$, respectively. The principle ion extracted by complexing agents 18 and 22 was Ba^{++} with organic phase Ba^{++} concentrations of $4.1 \times 10^{-2}\text{M}$ and $5.0 \times 10^{-2}\text{M}$, respectively. These results suggest that with respect to alkaline earth cation complexation there are only small differences between the extraction behavior of complexing agents which differ only in lipophilic

group.

The Effect of the Number of Polyether Oxygens

The size of the pseudo-cavities formed upon complexation by acyclic polyethers are determined by the number of polyether oxygens. The number of polyether oxygens present in the acyclic polyether dicarboxylic acids studied varied from two to five. The pseudo-cavity size along with the cation size should determine the complexation efficiency and specificity in the same manner as with crown ethers for cavity-mediated complexation.

Comparisons of the complexation data for the two series of ligands where the number of polyether oxygens is the only variable within the series show a ligand cavity size to cation size relationship. Complexing agents 16 and 20, which have two polyether oxygens each and would form the smallest cavity of the ligands studied, extract Ca^{++} most efficiently in a competitive alkaline earth cation system. The Ca^{++} selectivity of complexing agents 16 and 20 is clearly indicative of cavity-mediated complexation. The selectivity orders for complexing agents 16 and 20 were $\text{Ca}^{++} > \text{Sr}^{++} = \text{Ba}^{++}$ with no Mg^{++} detected, and $\text{Ca}^{++} > \text{Ba}^{++} > \text{Sr}^{++}$ with no Mg^{++} detected, respectively. The most likely selectivity order for cavity-mediated complexation of alkaline earth metal cations by complex-

ing agents 16 and 20 is $\text{Ca}^{++} > \text{Sr}^{++} > \text{Ba}^{++}$ with no Mg^{++} detected. The selectivity order for complexing agent 16 differs from this anticipated ordering for cavity-mediated complexation selectivity order with Ba^{++} being extracted as well as Sr^{++} which indicates that cation-anion interactions are also important. The selectivity order for complexing agent 20 shows Ba^{++} extraction even greater than Sr^{++} which suggest an even greater contribution from cation-anion interactions. The overall differences in selectivity orders suggest that there is a difference in the degree of cavity-mediated complexation between complexing agents 16 and 20.

The extraction data for complexing agents 17 and 21, which have three polyether oxygens, show Ba^{++} as the most extractable ion. The selectivity orders for complexing agents 17 and 21 are the same i.e. $\text{Ba}^{++} > \text{Sr}^{++} > \text{Ca}^{++}$ with no Mg^{++} detected. These selectivity orders are the same as the cation-anion interaction order for alkaline earth metal cations and the carboxylate anion¹⁹. The possible cavity-mediated complexation is not evident based on the data but it should not be ruled out because the selectivity orders and the cation-anion interaction order may be the same by coincidence.

The extraction data for complexing agents 18 and 22, which have four polyether oxygens, show Ba^{++} as the most

extractable ion. The selectivity orders are the same, i.e., Ba^{++} as the most extractable ion. The selectivity orders are the same i.e. $\text{Ba}^{++} > \text{Sr}^{++} = \text{Ca}^{++}$ with no Mg^{++} detected. The $\text{Ba}^{++}/\text{Sr}^{++}$ selectivity ratios for complexing agents 18 and 22 are 45 and 50, respectively. The fact that Ba^{++} is extracted much more than Sr^{++} and Ca^{++} , which are extracted about equally well, show the selectivity orders of complexing agent's 18 and 22 to be different from the cation-anion interaction order indicating cavity-mediated complexation for complexing agents 18 and 22. The high Ba^{++} selectivity suggests that the pseudo-cavity is the correct size for Ba^{++} to complex within the polyether framework.

The percent metal loadings (the percent of ligand associated with the metal cations) were quite different for these two ligands. Complexing agent 18 showed 91% loading at pH = 7.5 while complexing agent 22 exhibited 120% loading near the same pH. Loading greater than 100% suggests formation of complexes with cation to ligand ratios greater than one. The observed requirement of more than one cation per ligand also would require concomitant transfer of counter anions which are not a part of the ligand. The other anions, ones not a part of the ligand, available during extraction are only Cl^- and OH^- . In an attempt to assess possible Cl^- transfer into the

organic extraction phase, a sample of the organic extraction phase was added to an equal volume sample of aqueous silver nitrate solution and shaken. After standing, the solution was inspected for silver chloride precipitate. The fact that no silver chloride precipitate was observed suggest Cl^- was not present. Therefore no Cl^- was being transferred with the complex. A plausible explanation for the observed high loading would be the formation of some two cation to one ligand complexes with the transfer of OH^- counter anions. A possible structure for this complex is illustrated in Figure 17.

When compared to the extraction data for complexing agents 18 and 22 that for complexing agents 19 and 23 show Ca^{++} complexation efficiency higher than expected. The higher Ca^{++} complexation efficiency suggest a different cavity-mediated phenomena is probably responsible. A possible explanation lies in a helical wrapping of the cation by the complexing agent. The helical wrapping which completely encapsulates the cation requires a longer complexing agent backbone for its formation.

The extraction data for complexing agents 16, 17, 18, 20, 21, and 22 when taken together show the very significant role played by the number of polyether oxygens in determining the cation complexation of the host ligands through cavity-mediated complexation phenomena.

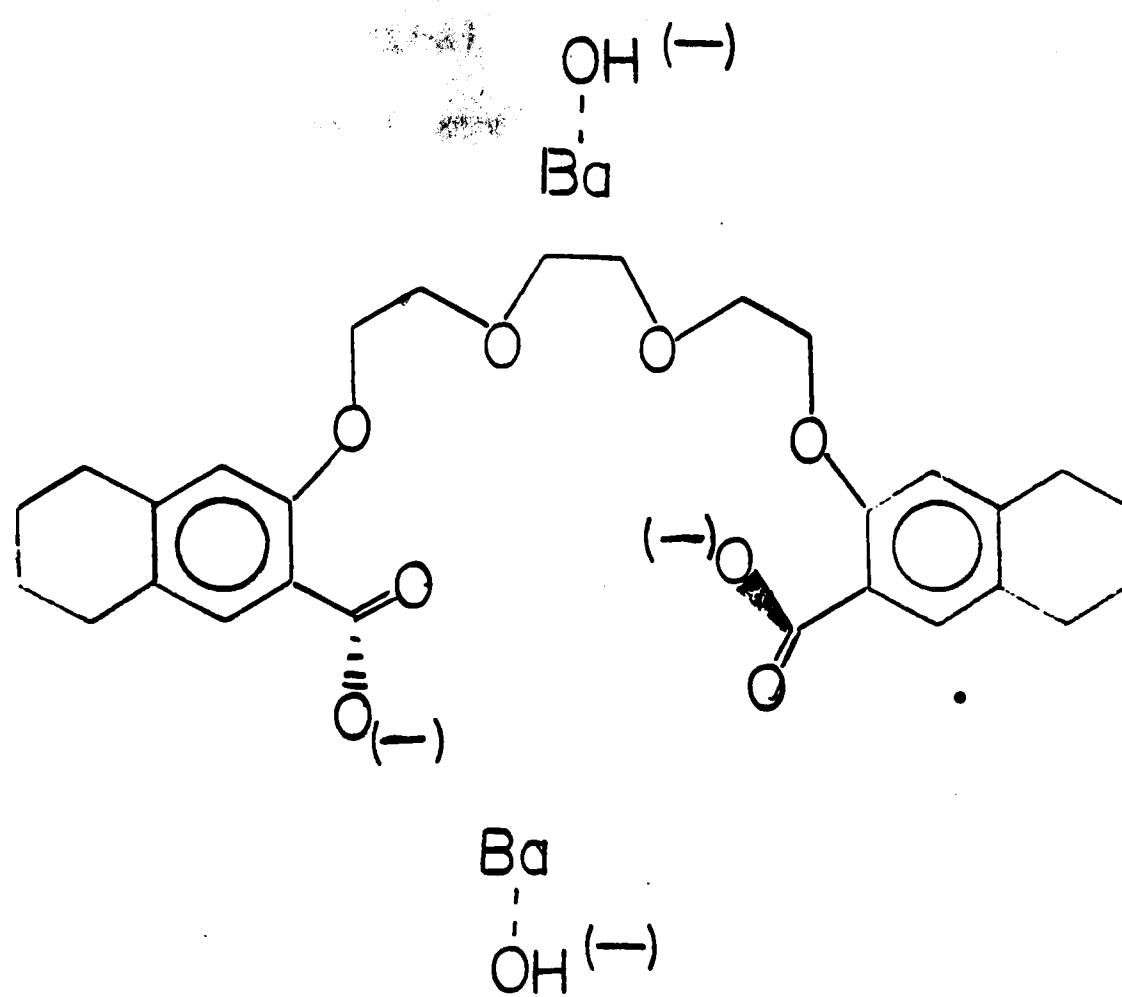


Figure 17: Possible Structure for a 2 to 1 Barium Ion to Complexing Agent Complex

The Effect of Solvent

Solvent extraction with complexing agent 17 was carried out in both chloroform and toluene solvents. The chloroform solvent system is a good organic extraction medium for theoretical studies in the laboratory, while the toluene solvent system is a good practical system because it is similar to the cheap kerosene solvent used commonly on an industrial scale. The extraction behavior of complexing agent 17 in chloroform and toluene are very different. The selectivity orders in the two solvents are different. The percent loading above pH = 9 for the two solvents, chloroform and toluene, are 100% and 6%, respectively. The selectivity order in chloroform is $Ba^{++} > Sr^{++} > Ca^{++}$ with no Mg^{++} detected, while the order in toluene is $Ca^{++} > Ba^{++} > Sr^{++}$ with no Mg^{++} detected. The large difference in percent metal loading for complexing agent 17 in chloroform and toluene solvents results from severe precipitation of the complex from the toluene extraction solution. The complex was stripped from the organic phase into an aqueous phase and subsequently analyzed, but only the complex that was in solution would be detected. The complex that precipitates out of solution, as in the toluene system, is not a part of the metal cations extracted.

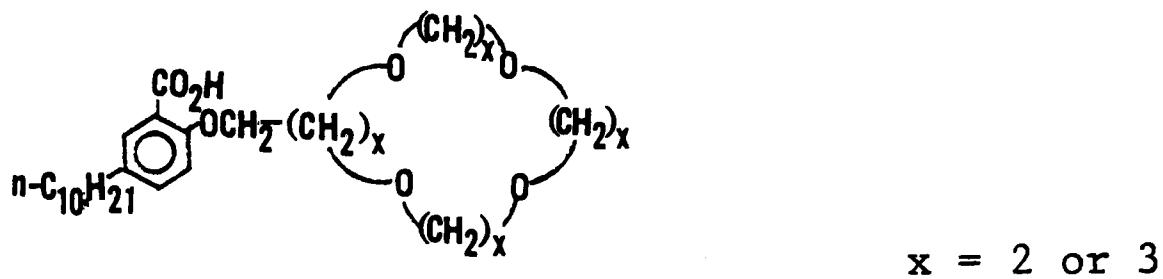
CHAPTER 4

SUMMARY

The extraction selectivity for lithium cations was found to be optimal for crown ethers with the 14-crown-4 size cavity (Table 2). The lithium selectivity of the 14-crown-4 type molecules is greatly facilitated by the incorporation of an ionizable group held in close proximity to the crown ether cavity. The Li^+/Na^+ selectivity of slightly more than 18 is the highest yet found for ionizable macrocyclic polyethers. It also represent the highest reported lithium selectivity in a competitive metal cation extraction system.

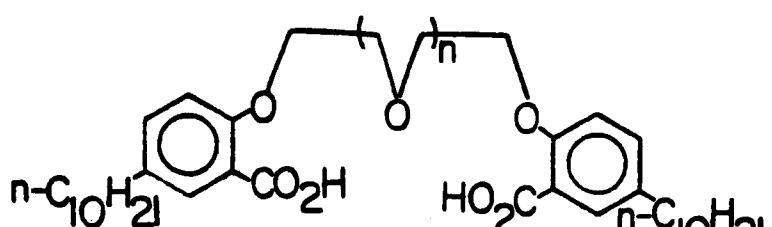
Extraction of alkaline earth metal cations by acyclic polyether carboxylates was shown to contain a pseudo-cavity mediated component. The complexing agents with one ethyleneoxy unit were Ca^{++} selective (Table 3 and 4). The complexing agents with three ethyleneoxy units were highly Ba^{++} selective. The high Ba^{++} selective observed in chloroform could not be transferred to the more practical solvent toluene due to low solubility of the metal ion complexes in this solvent.

Table 2: Selectivity for Small Ring Ionizable Polyethers
with Alkali Metal Cations. General Structure
for compounds 11-15.



Compound Number	Li^+/Na^+ Selectivity
11	1.9
12	2.5
13	19.9
14	18.8
15	3.5

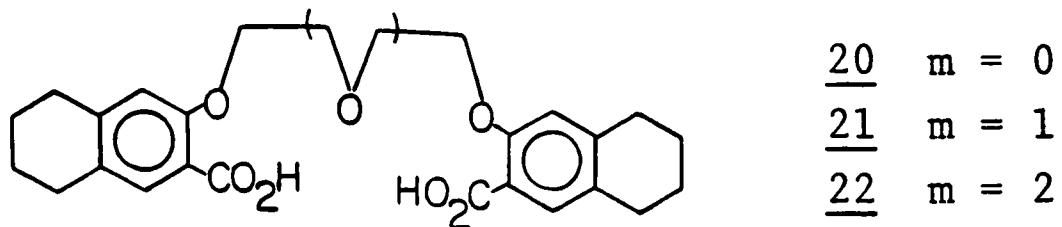
Table 3: Extraction Data for Complexing Agents 16-19.
Generalized Structure for Complexing Agents 16-19.



16 n = 0
17 n = 1
18 n = 2
19 n = 3

Compound	Most Extracted Ion	Selectivity
16	Ca^{2+}	6.2
17	Ba^{2+}	2.0
18	Ba^{2+}	45.0
19	Ba^{2+}	2.0

Table 4: Extraction Data for Complexing Agents 20-22.
 Generalized Structure for Complexing Agents
20-22.



Compound Number	Most Extracted Ion	Selectivity Ratio
20	Ca^{2+}	3.0
21	Ba^{2+}	3.5
22	Ba^{2+}	50.0

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