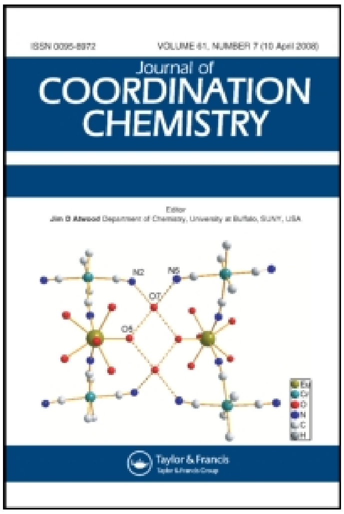


Journal of Coordination Chemistry
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713455674

Synthetic Methods in Supramolecular Chemistry

Marek Pietraszkiewicz[a]
[a] Institute of Physical Chemistry, Polish Academy of Sciences, Warsaw, Kasprzaka, Poland

To cite this Article Pietraszkiewicz, Marek(1992) 'Synthetic Methods in Supramolecular Chemistry', Journal of Coordination Chemistry, 27: 1, 151 — 199
To link to this Article: DOI: 10.1080/00958979209407951
URL: http://dx.doi.org/10.1080/00958979209407951

J. Coord. Chem. 1992, Vol. 27, pp. 151-199
Reprints available directly from the publisher
Photocopying permitted by license only

SYNTHETIC METHODS IN SUPRAMOLECULAR CHEMISTRY

MAREK PIETRASZKIEWICZ

Institute of Physical Chemistry, Polish Academy of Sciences 01-224 Warsaw, Kasprzaka 44/52, Poland

INTRODUCTION

Supramolecular chemistry is a relatively young branch of chemistry. The beginnings of this interdisciplinary science are associated with Dr. Charles Pedersen, father of crown ether chemistry. Twenty years after his pioneering work, the Nobel Prize was given to Prof. D. J. Cram, Prof. J.-M. Lehn, and Dr. Ch. Pedersen for their outstanding contributions to progress of supramolecular chemistry.

During this time many synthetic methods have been developed for the formation of macrocyclic molecular receptors, and a brief account on most popular strategies will be presented here.

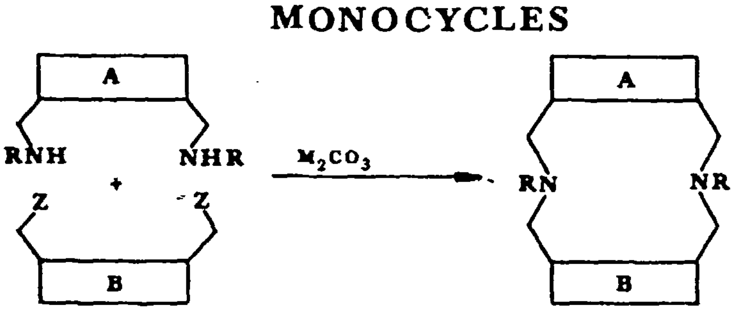
Readers are also encouraged to go through an original reviews, books, and monographs relevant to the field of supramolecular chemistry, cited at the end of this elaboration.

1. TEMPLATE SYNTHESIS OF MACROCYCLIC AND MACROPOLYCYCLIC SYSTEMS

1.1 Alkali Metal and Alkaline Earth Metal Ion-promoted Macrocyclizations

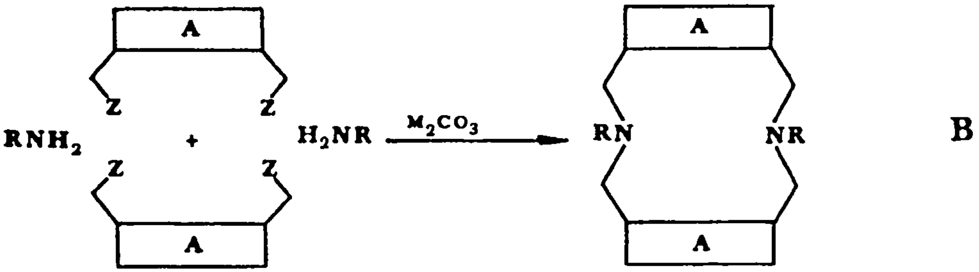
Although the first alkali ion-promoted macrocyclizations were found in the field of crown ethers, and are associated with Pedersen's discovery, they will not be discussed in this chapter. The scope of this presentation will be limited to macrocyclic and macrobicyclic structures possessing mixed donor atom sets, mainly nitrogen and oxygen atoms.

There are a few alternative strategies for the formation of monocyclic and bicyclic systems. They can be outlined as follows:



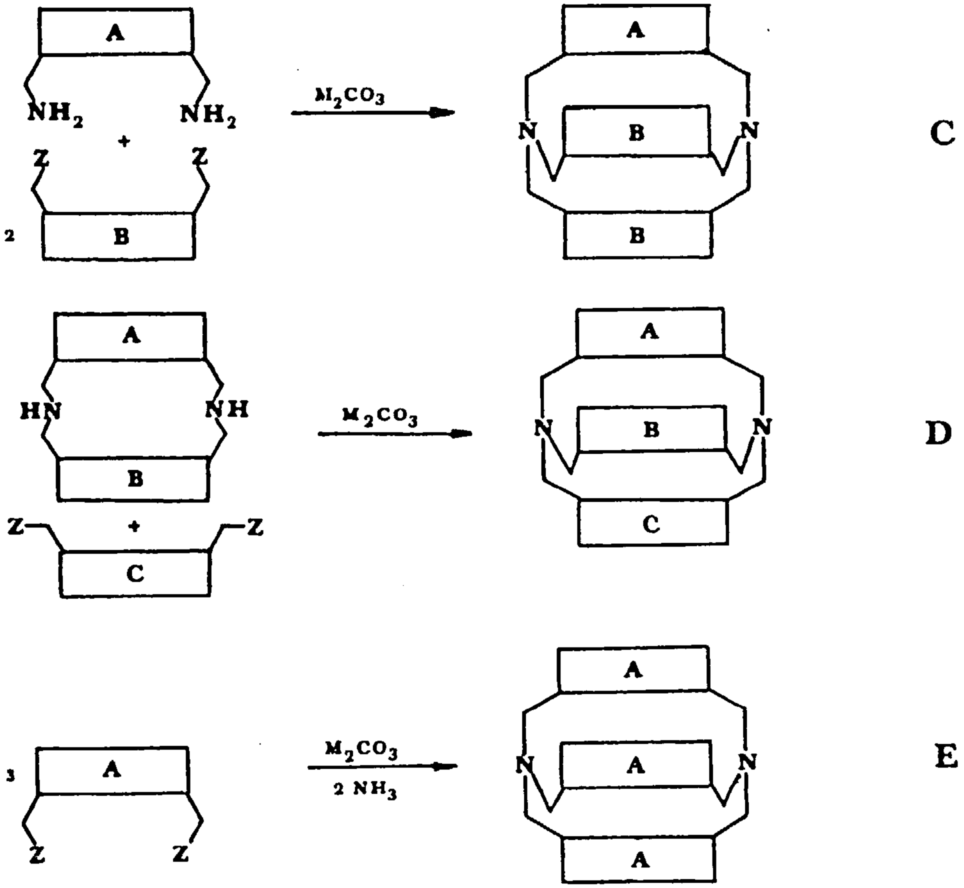
A

FIGURE 1.



X = Hal ; R = Alkyl, Aryl, Aralkyl

BICYCLES



Z = Hal

FIGURE 1. *continued*

Representative examples for all pathways A, B, C, D, E will be provided.

In general, alkali metal carbonates served as bases and templating agents, although there are a few examples with other carbonates. It has also been proven that addition of alkali metal halides to the reaction mixture had a significant impact on the overall yield, since the presence of metal ion is crucial for templated macrocyclization.

Strategy "A"

A classical example for the preparation of 4,13-diaza-18-crown-6 was described by Kulstad and Malmsten[1]:

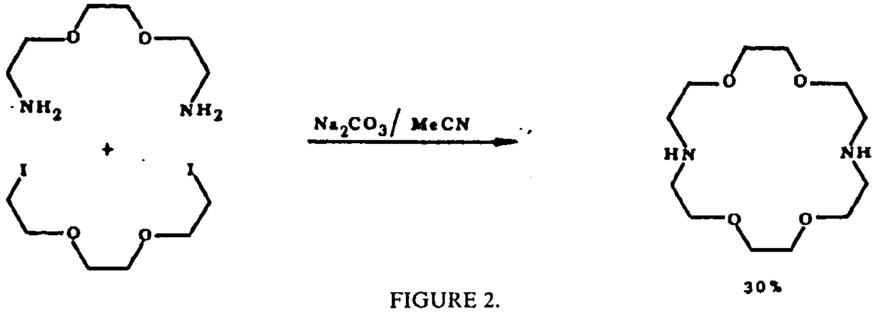


FIGURE 2.

It should be noted that in this, and in the majority of further examples, acetonitrile was solvent of choice, giving the best results in comparison with other aprotic solvents.

Gokel and co-workers have studied extensively various aspects of strategy "a". For example, a combination of diamine and diiodide components led to 15-membered ring in good yield[2]:

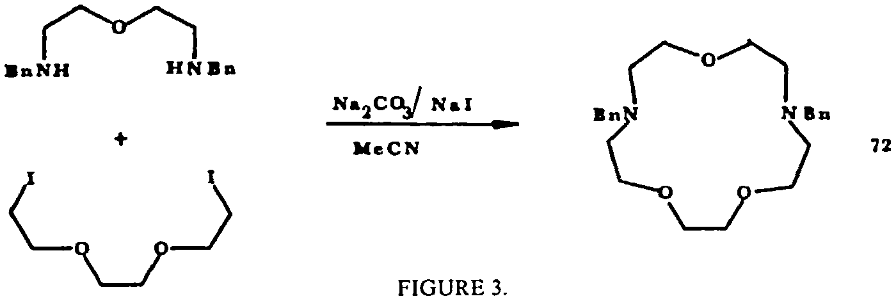


FIGURE 3.

More examples can be found in the literature.[3]

Strategy "B"

This path consists on "2+2" condensation of an appropriate dihalide component and a primary amine. Gokel and co-workers demonstrated the usefulness of this approach which can be shown as follows[4]:

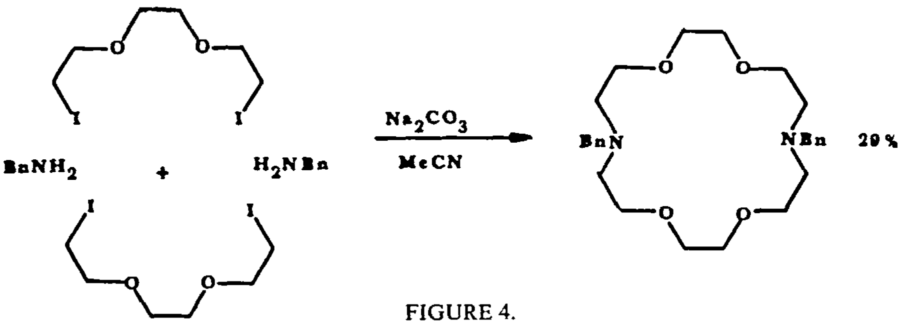


FIGURE 4.

Usually, yields for such cyclizations do not exceed 30%, however they seem to be quite satisfactory, since the reactions proceed in one step without need for preparation of diamine component.

Bicycles: strategy "C"

Early, the idea of combining two molecules of dihalide and one of diamine was demonstrated by Kulstad and Malmsten[5]:

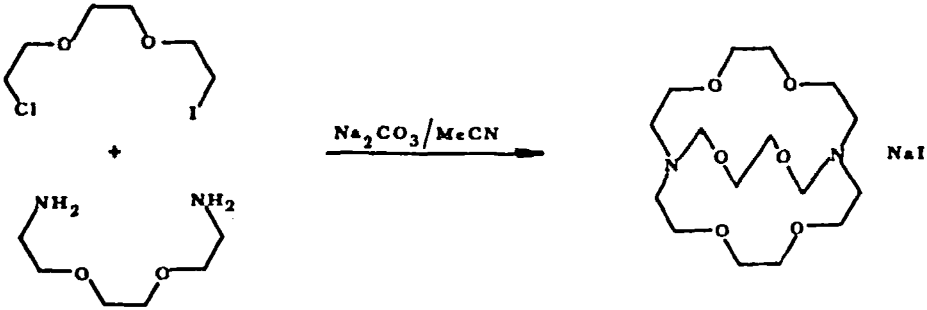


FIGURE 5.

In this way, cryptand (2.2.2) was prepared in 21% yield as its sodium cryptate. When potassium carbonate was used, no cryptand was detectable, indicating sodium template effect. It was important that mixed dihalide was used.

This strategy was further developed by Lehn and co-workers in the synthesis of cryptands incorporating heterobiaryls[6]:

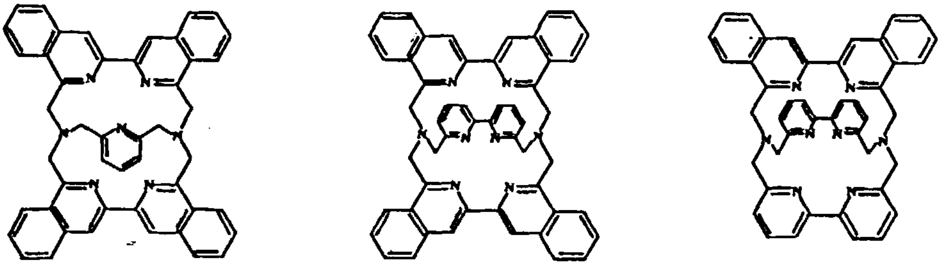

(biql)$_2$py Li$_2$CO$_3$: 30%
(biql)$_2$bpy Na$_2$CO$_3$: 10%
biql(bpy)$_2$ Na$_2$CO$_3$: 20%

FIGURE 6.

A very interesting feature was observed during the reaction course for $(biqi)_2py$; Li_2CO_3 turned out to be superior template than Na_2CO_3, giving higher yield of the product as its Li^+ cryptate. However, purification of this cryptate on silica gave a mixture of Li^+ and Na^+ cryptates as indicated by mass spectrometry. In fact, Li^+ in its cryptate of $(biqi)_2py$ could be easily exchanged for Na^+, when equilibrated with aqueous solution of NaBr. This example shows that the sodium cation forms the kinetically more stable complex, although as template is less efficient than lithium.

This fact can be explained in this way, that lithium acts as local template, and binds more efficiently than sodium two amino groups in 2,6-bis(aminomethyl)-pyridine in the following manner:

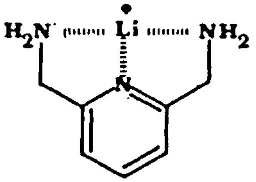


FIGURE 7.

Therefore, this configuration is more appropriate for bicyclization reaction.

Further exploration of this strategy indicated that this approach may be of importance in the large-scale preparation of bicyclic structures[7]:

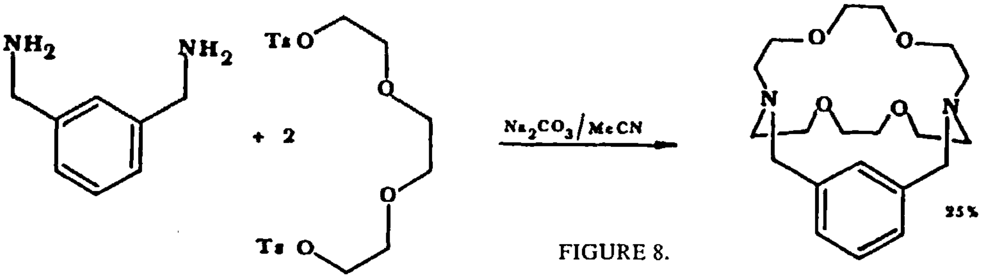


FIGURE 8.

Strategy "D"

This approach has also been studied by Lehn and co-workers and a pronounced template effect was demonstrated as shown in the scheme.[8]

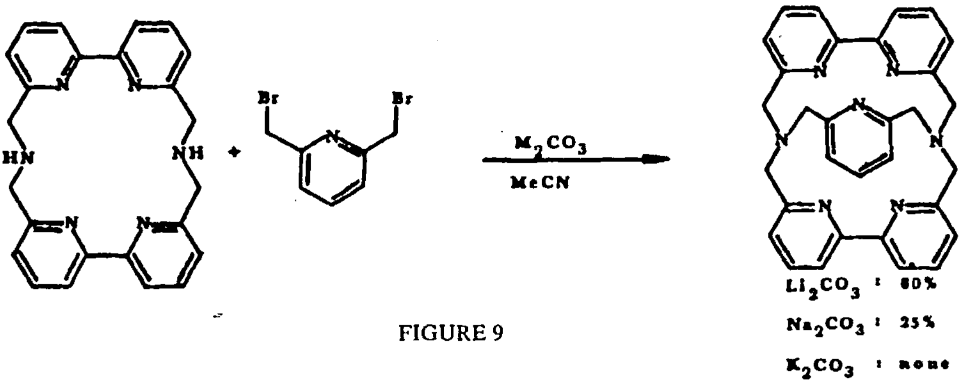


FIGURE 9

Similar macrobicyclizations may be found in earlier works of Lehn.[9]

Strategy "E"

This path seems to be the shortest access to bicyclic structures possessing the same three units linked by two nitrogen atoms, and has been elaborated by Lehn and co-workers. This method consists of reaction of dihalogeno component with ammonia at elevated temperature in a medium-pressure reactor in MeCN with Na_2CO_3 as a base. In this way, two sodium cryptates of the following formula have been obtained[10]:

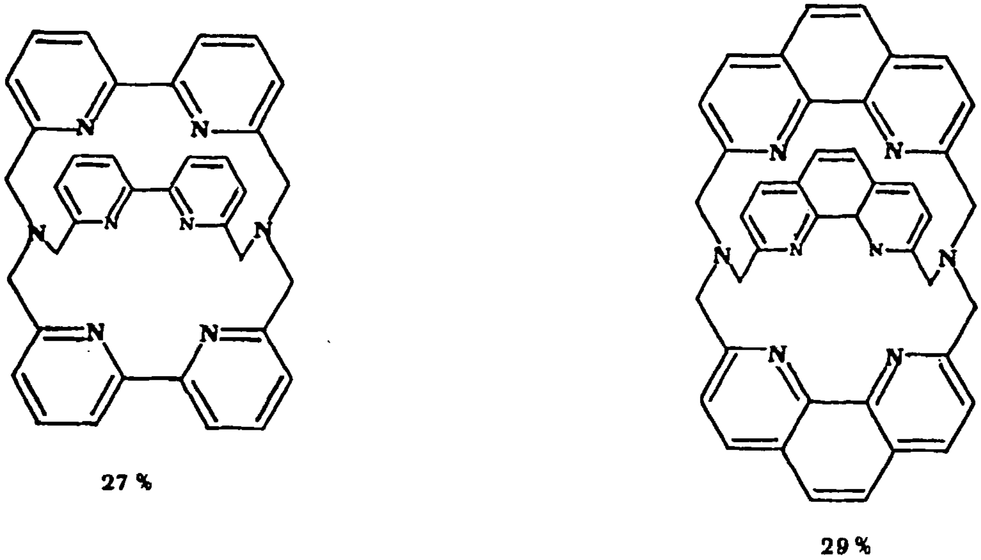


FIGURE 10.

Macrobicyclization involving sodium cation as a template has been reported by Vögtle and co-workers.[11]

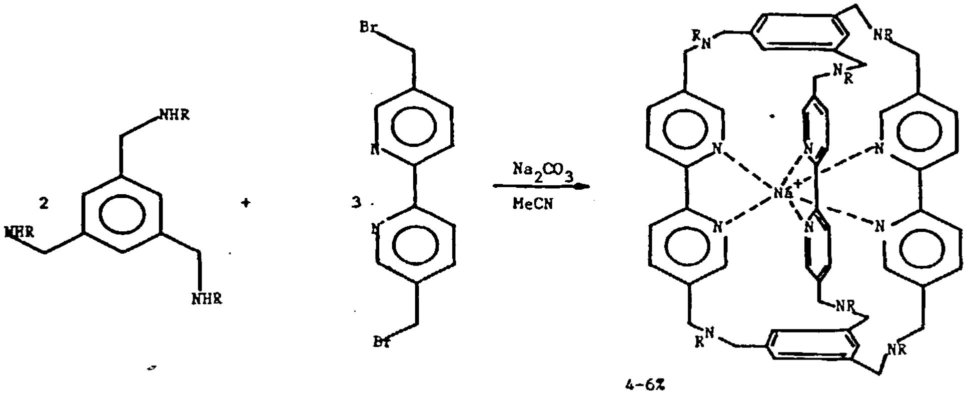


FIGURE 11.

Yield for this reaction was low (4–6%). So far, the discussion was limited to rather smaller cavities and cations such as lithium or sodium were sufficient as templates. There are also non-typical macrobicyclizations for much larger cavities in which cesium cations were found to be particularly good templates. Efficient cesium-promoted cyclizations are called "cesium effect".[12] Several examples will illustrate this concept.

Large macrobicyclic polyamines have been obtained by so-called "tripode-tripode" coupling, a one-pot procedure. The essential macrobicyclization step consists of the condensation of a tris-terminal tosylamine tripodal unit with a tris-terminal tripodal mesylate in hot DMF in the presence of large excess of Cs_2CO_3 or K_2CO_3[13].

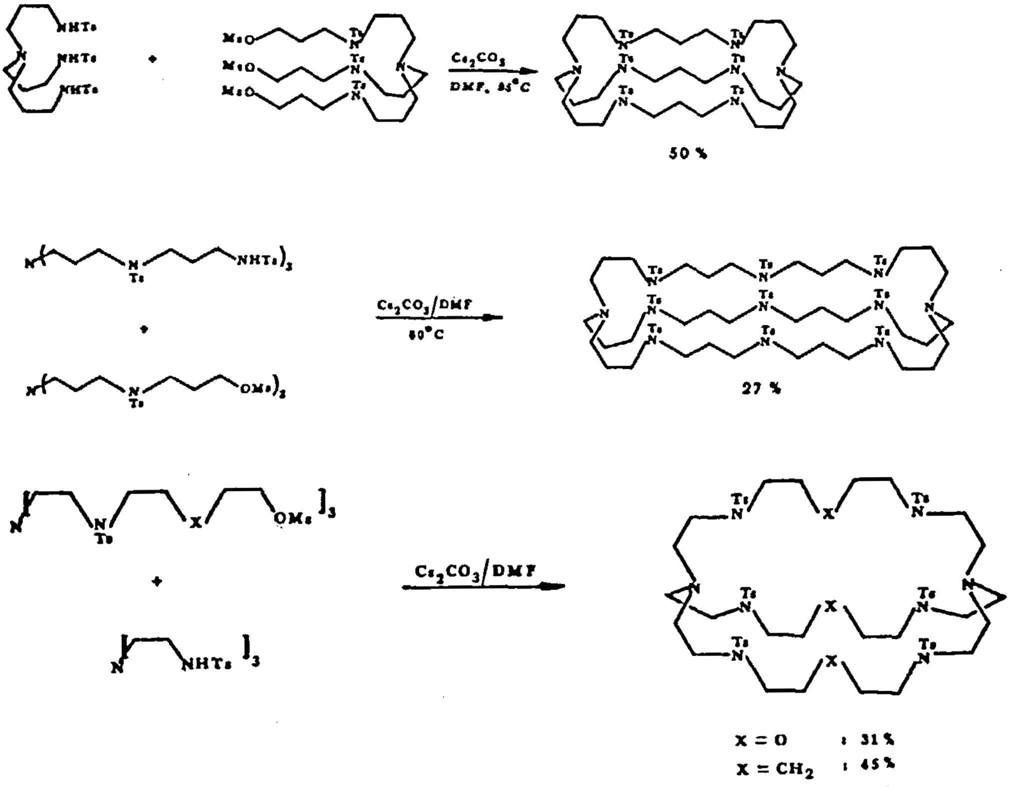


FIGURE 12.

A cesium effect was observed in case of macrocyclizations leading to polythia- and polyazaoxa macrocycles from respective terminal bis-tosylamides and dihalogeno derivatives. This concept was demonstrated by Kellogg and co-workers, and can be illustrated schematically[14]:

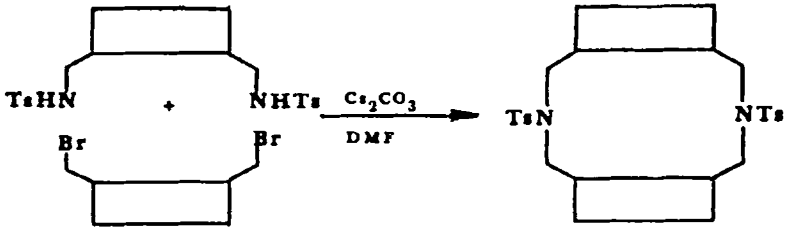


FIGURE 13.

It turns out that cesium carbonate is basic enough to ionize sulphonamides and thiols, enhancing therefore the nucleophilic character of nitrogen or sulphur atoms. Thus, the cesium effect can be regarded as a fusion of strongly basic character of Cs_2CO_3 and templating properties of Cs^+.

Template effect was observed during macrocyclization of ethylene-diamine ditosylate with bis(2-chloroethyl)ether[15]:

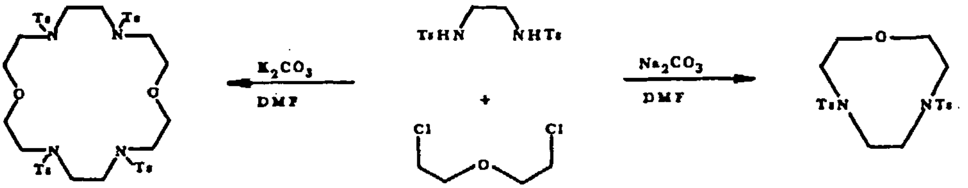


FIGURE 14.

When K_2CO_3 was used, the 18-membered macrocycle was found, whereas with sodium carbonate the diazaoxacyclononane derivative was the main product.

Dale and co-workers have elaborated one-step macrobicyclizations leading to small cryptands[16]:

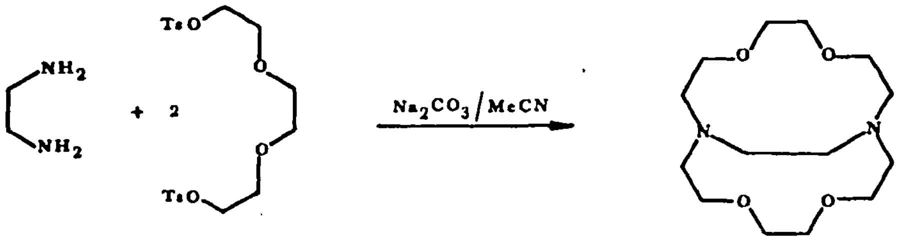


FIGURE 15.

Similarly, 1,4,7,10-tetraazacyclotetradecane was subjected to react with triethylene glycol ditosylate in the presence of Na_2CO_3 and Cs_2CO_3.[17] It is interesting to note that macrocyclization involving Na_2CO_3 led to 1,4-annelated and 1,7-annelated isomers in ratio 10:1, respectively, and reaction stopped at this stage because strong sodium complex prevented further annelation. Reaction in the presence of Cs_2CO_3 is the first and rare case of one-step macrotricyclization.

One-step macrotricyclization has been reported by Japanese chemists.[18] Potassium ion was involved in this case, probably as a template. The overall yield was rather low (2.4%). Similar condensations leading to macrobicyclic polyamines have been reported.[19]

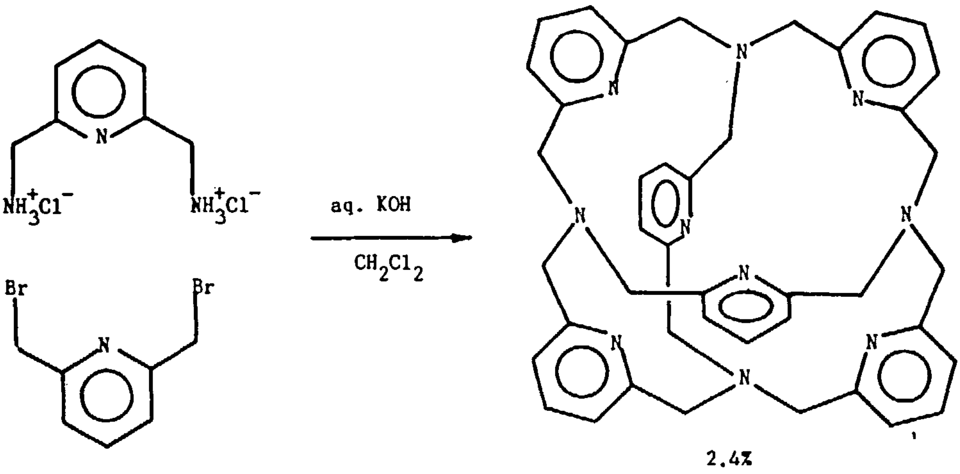


FIGURE 16.

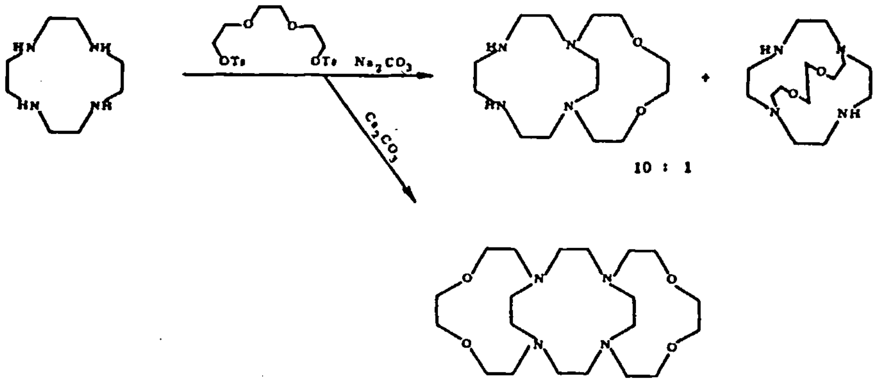


FIGURE 17.

Ingenous method for lithium- and sodium-templated macrocyclization has been recently reported by Bradshaw and co-workers.[20,21]

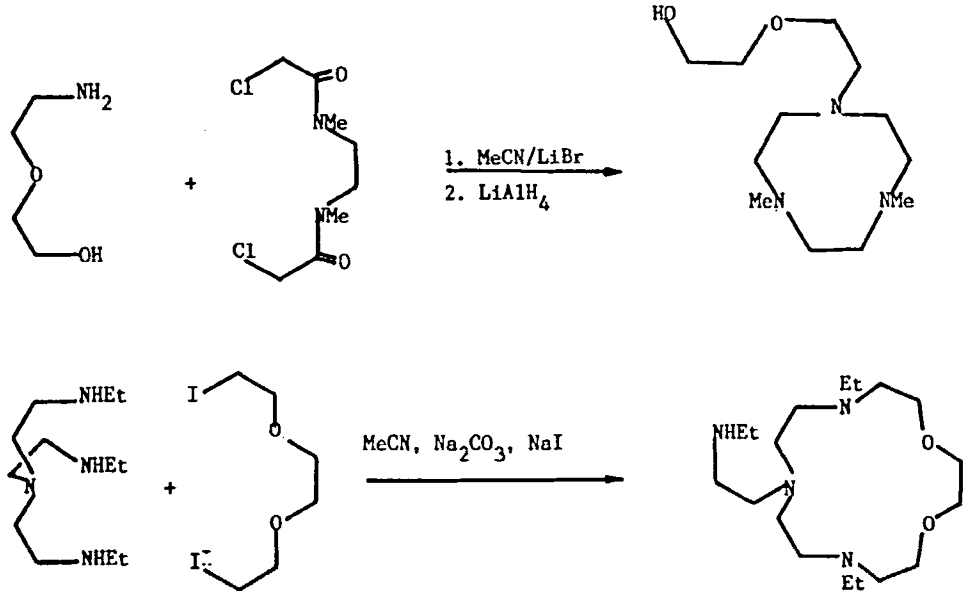


FIGURE 18.

Alkaline earth cations were mainly involved in the macrocyclic Schiff base condensations. A review on this subject appeared in 1980.[21]

Either 2,6-diacetylpyridine or furan-2,5-dicarboxaldehyde was condensed with 1,3-diamino-2-hydroxypropane or 1,5-diamino-3-hydroxypentane in the presence of Ba^{2+} and Sr^{2+} salts to form respective mononuclear macrocyclic complexes, as shown below[21]:

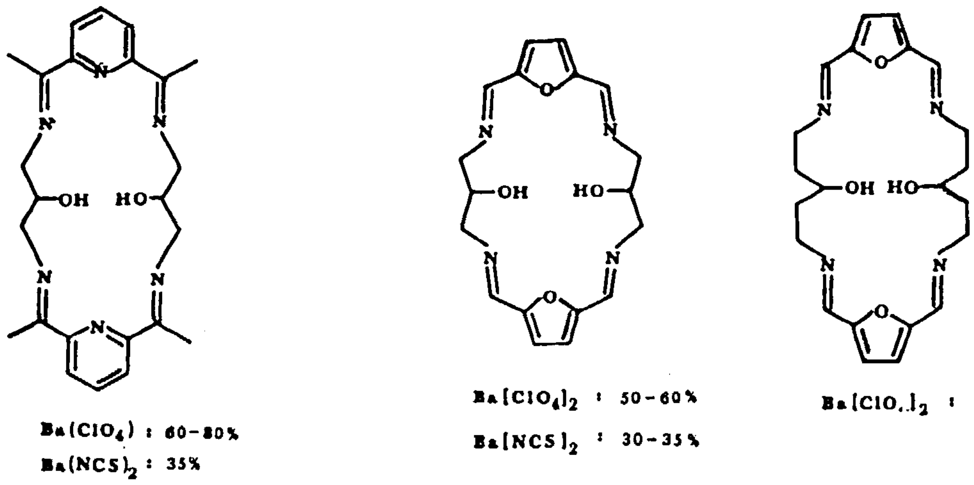


FIGURE 19.

Similar reaction was observed with 2,6-diacetyl-4-methyl phenol and 1,3-diamino-2-hydroxypropane[23]:

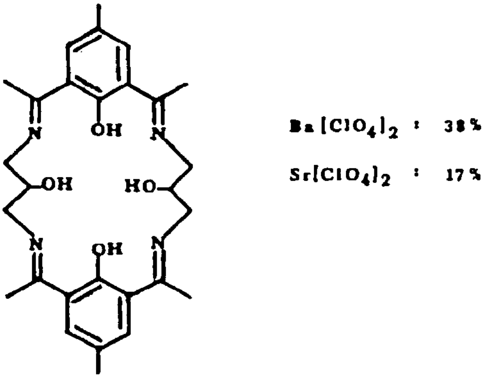


FIGURE 20.

Alkaline earth macrocyclic complexes with Schiff bases appeared to be kinetically labile, thus they could be transmetallated with transition metal cations to obtain transition metal complexes inaccessible by direct template method.

The "1 + 1" macrocyclizations have been observed on a few instances[25–28]:

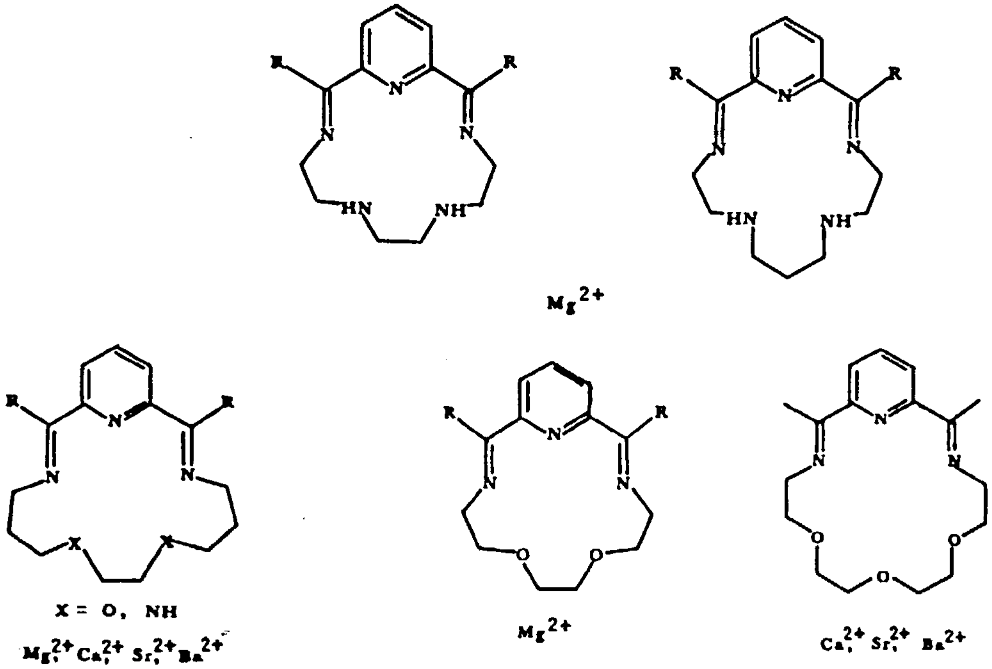


FIGURE 21.

Bell and co-workers have reported the synthesis of a hexaazamacrocycle from 2,6-dicarbonylpyridine and 1,2-diaminobenzene[29]:

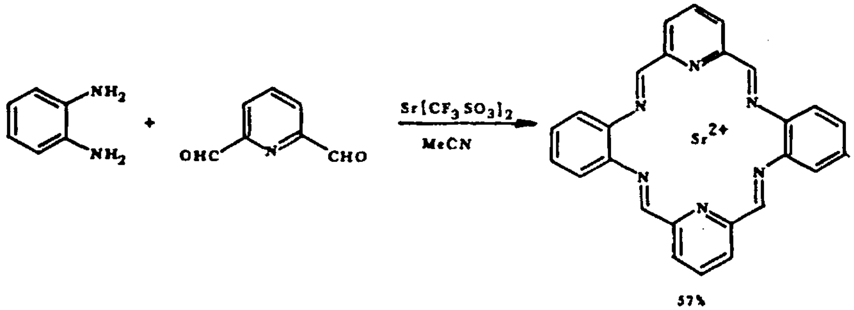


FIGURE 22.

Tetraazamacrocycles were recently obtained by magnesium-template "2+2" reaction between 1,2-diketones and range of diamines[30]:

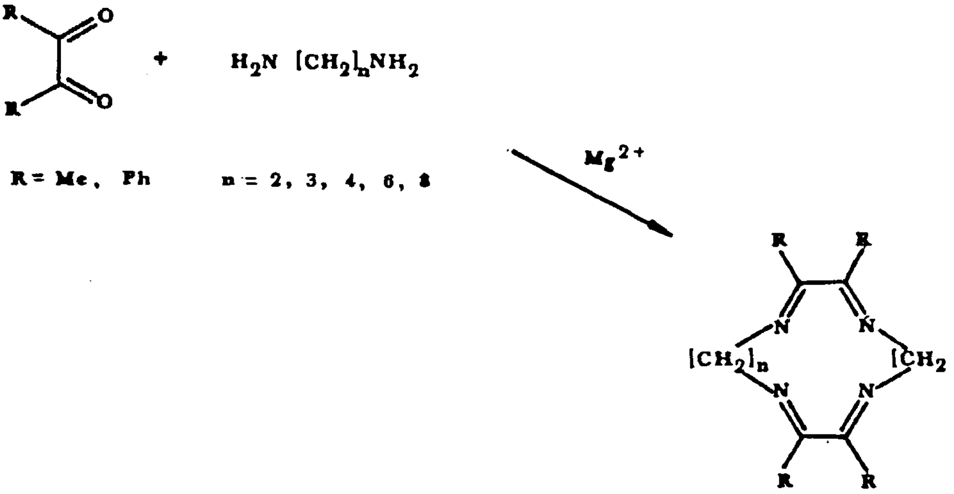


FIGURE 23.

Barium-template has been found recently to be effective in the macrocyclic Schiff base formation[31]:

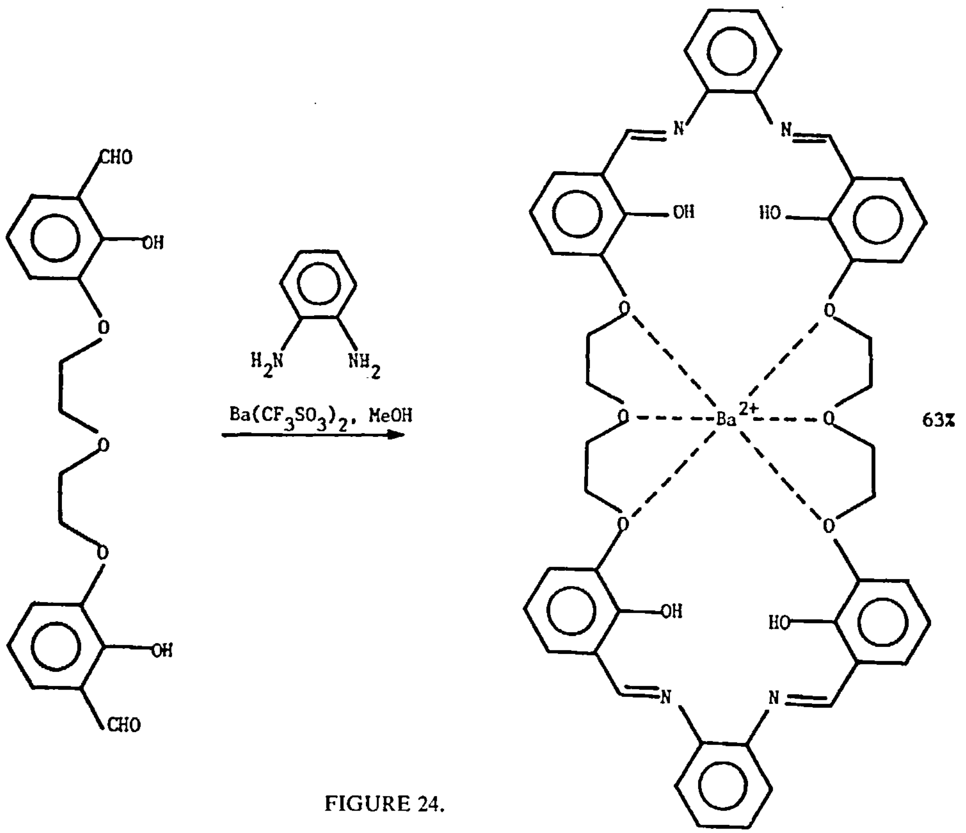
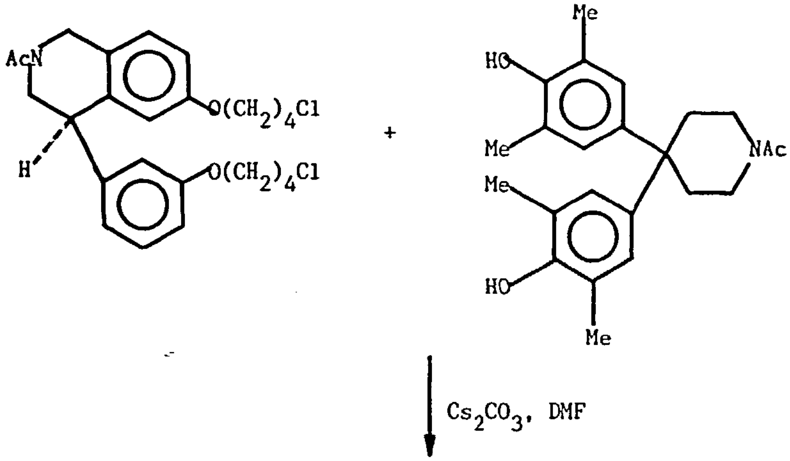


FIGURE 24.

Cesium-promoted macrocyclization has been used in the synthesis of a large hydrophobic receptor molecules[32]:



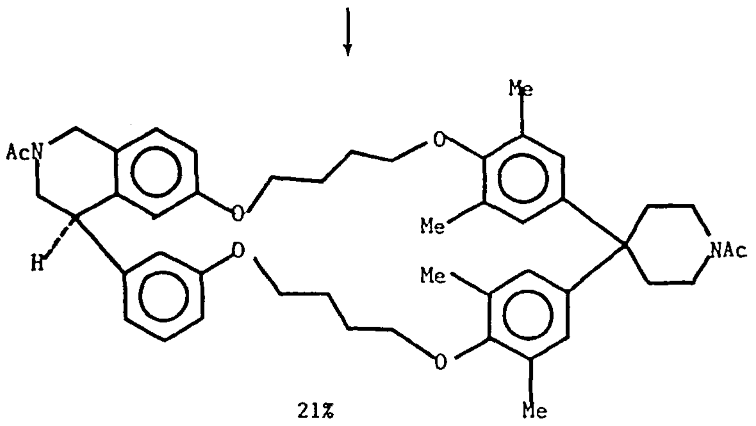


FIGURE 25.

1.2 *Transition Metal Ion Templates*

The number of macrocyclic compounds prepared by template reactions involving transition metal ions is so enormous, that it is far beyond the scope of this account. The reader is advised to go through books and reviews on this subject and respective references are collected at the end of this Chapter.

First examples of templated macrocyclization with Ni^{2+} begun in 1961, when Curtis demonstrated the reaction of $Ni(en)_3(ClO_4)_2$ ($en = NH_2CH_2CH_2NH_2$) with acetone, yielding isomeric tetraazamacrocyclic compounds.[1]

In 1964 Thompson and Busch described a template synthesis of macrocyclic compound as its Ni^{2+} complex[2]:

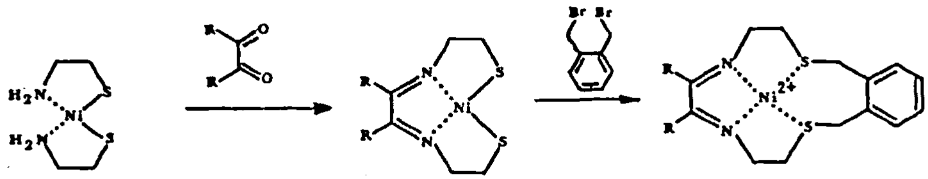


FIGURE 26.

Macrocyclizations involving 1,2-dicarbonyl compounds and a range of terminal diamines will not be discussed, since vast numbers of examples can be found in original books ("Coordination Chemistry of Macrocyclic Compounds", Ed. G. A. Melson, Plenum, N.Y., 1979).

Emphasis will be placed on more recent works in this area, providing less typical host structures.

A number of macrocyclic Schiff bases has been prepared using transition metal ions as templates. Tetranuclear, mixed-valence manganese complex was obtained by

Mn^{2+} template reactions between 2,6-diformyl-4-methylphenol and 1,5-diamino-3-hydroxypropane[3]:

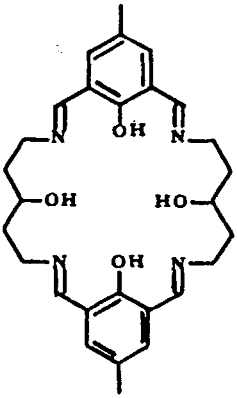


FIGURE 27.

Similarly, a tetracopper complex was obtained by the same authors (t-Bu instead of Me) in the same way.[4]

The "4+4" Schiff base macrocyclic ligand was prepared by template rearrangement of an appropriate barium complex[5]:

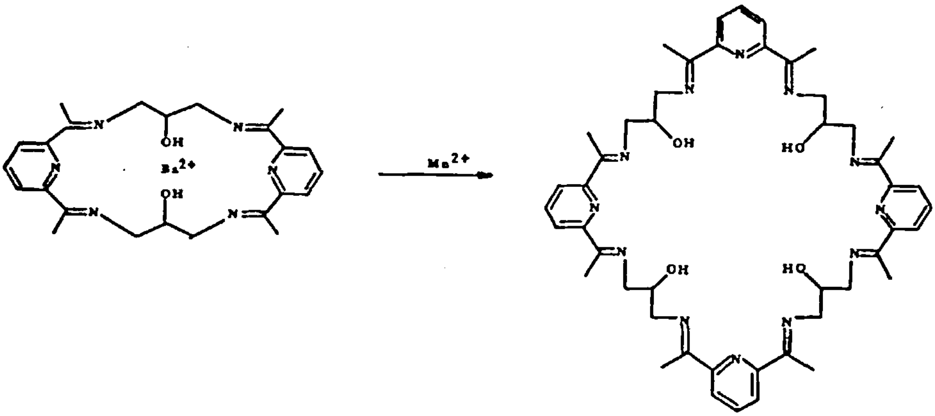


FIGURE 28.

A wide range of pentadentate macrocyclic Schiff bases has been obtained from easily accessible components, templated by various transition metal ions. They are summarized briefly as follows[6–11]:

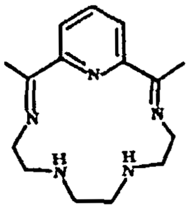


FIGURE 29.

Larger rings were obtained in similar manner[12]:

FIGURE 30.

Many other examples of pentadentate macrocyclic Schiff bases of general formula N_5, N_4X, N_3X_2, N_2X_3, and N_4X have been presented extensively in a review article.[12]

Black and co-workers have studied in a great detail transition metal ion templated macrocyclizations. One of the examples can be shown as follows[13]:

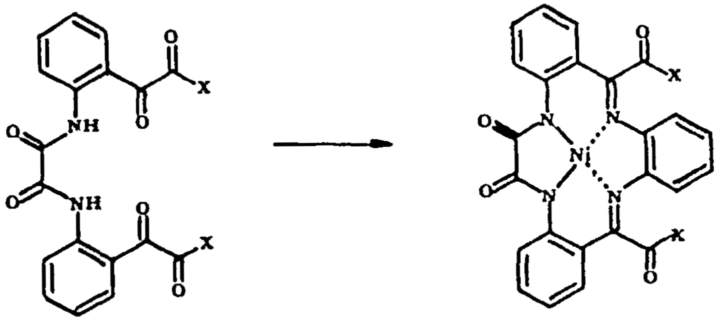


FIGURE 31.

Along with macrocyclic Schiff base formation, an alternative approach based on polyamines, formaldehyde and carbon acids, has been elaborated.

Generally, metallic complexes of macrocyclic Schiff bases can be easily reduced with $NaBH_4$ to saturated systems, containing metal ion when complexation is strong, or eventually, the metal ion is also reduced (Pb^0 for instance).

Saturated macrocycles may be formed in the condensations involving formaldehyde, CH-acids and linear aliphatic polyamines. This type of synthesis has been elaborated extensively by Lawrance and co-workers. Several examples will illustrate this concept[14]:

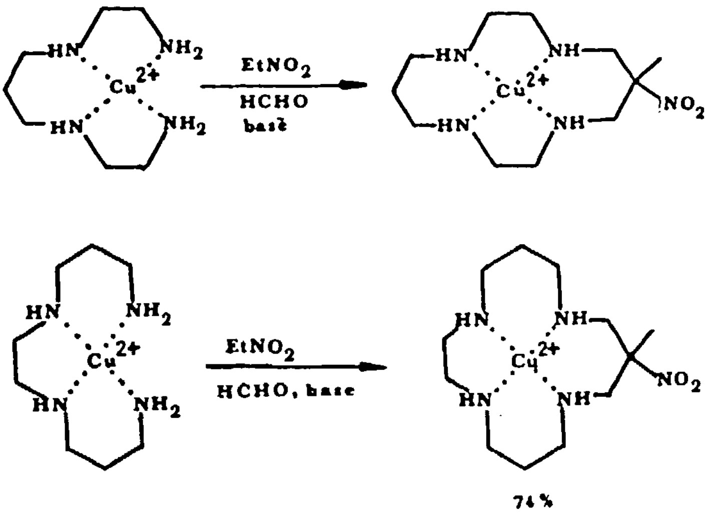


FIGURE 32.

In the second example shown above large-scale preparations were possible.[15] Also, the N2S2 macrocycle was obtained in the same way[16]:

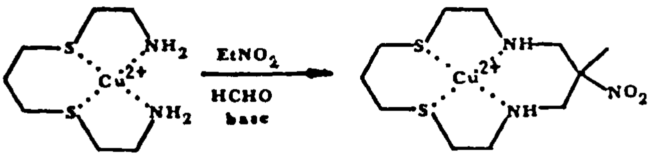


FIGURE 33.

One-step macrobicyclization was observed with octaamine, formaldehyde and nitrometane[17]:

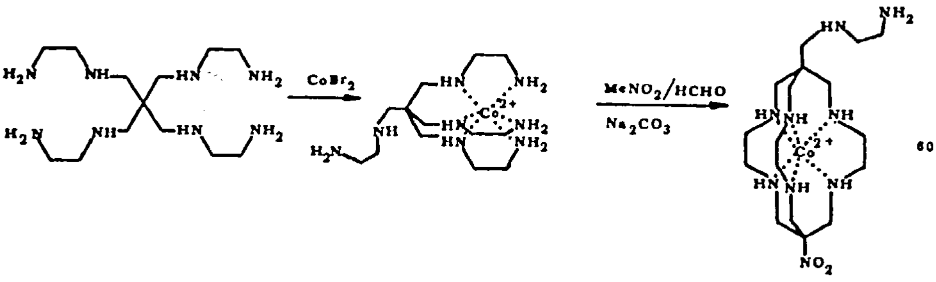


FIGURE 34.

Bicyclic ligands have been a subject of extensive investigations since the late sixties. Boston reported the synthesis of a clathrochelate containing cobalt from dimethylglyoxime, boron trifluoride and Co^{3+} [18]:

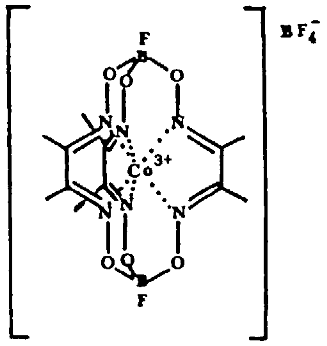


FIGURE 35.

Sargeson has conducted a broad studies on macrobicyclic polyamines in the form of their metal complexes from very simple components[19,20]:

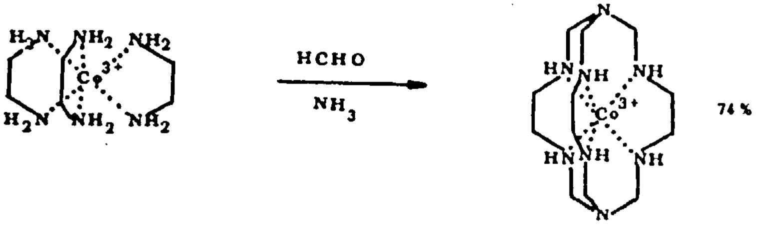


FIGURE 36.

Instead of ammonia, nitromethane could be used. Cobalt III complexes of sepulchrate type have been proven extremely strong and kinetically inert.

Macrotricyclic ligand have been prepared recently by a Nickel(II) template condensation of linear triamines with formaldehyde[21]:

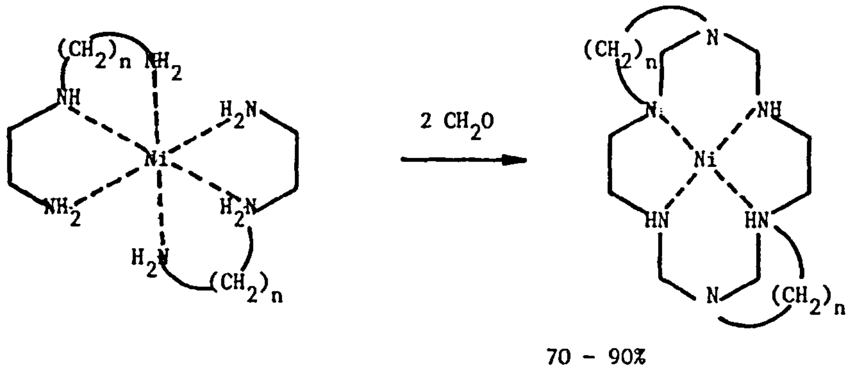


FIGURE 37.

Dicopper(II) imidazolate complex was found to be a bimetallic template for the macrocyclic Schiff base formation[22]:

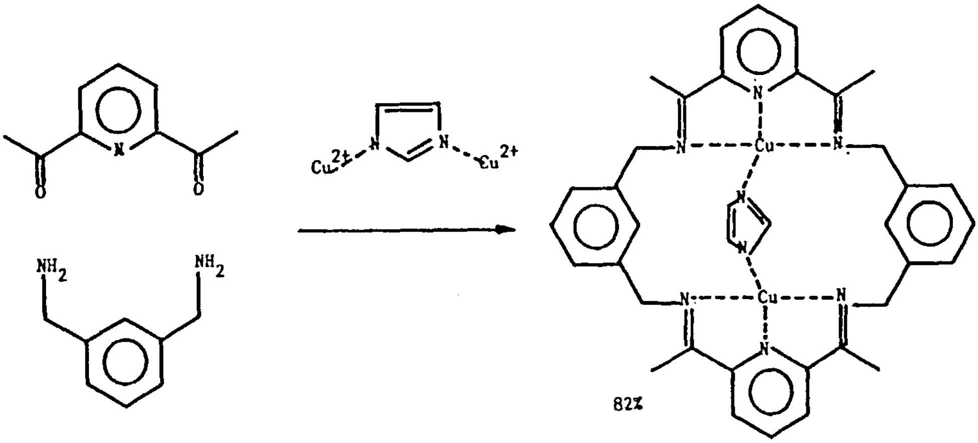


FIGURE 38.

Very elegant chemistry has been invented by Sauvage and coworkers. Their concept is based on the design and synthesis of interlocked systems known as catenands.

There are two general strategies for the formation of catenands[23]:

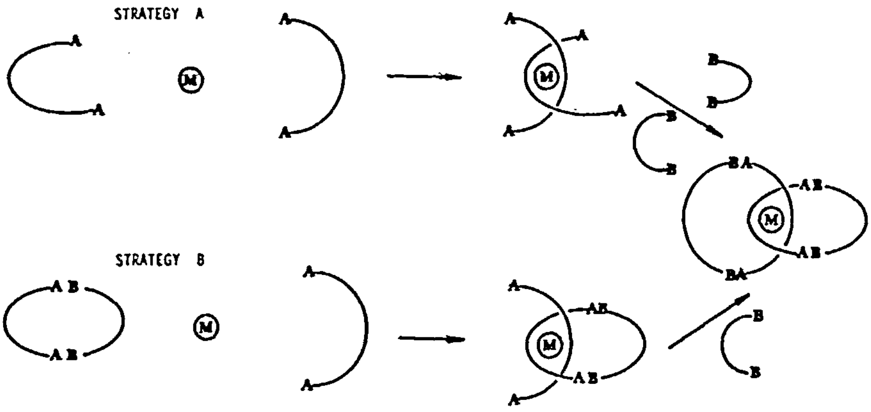


FIGURE 39.

Template effect is induced by a transition metal cation. Stragety "A" provides systems with the same rings, whereas "B" delivers two various interlocked rings[24]:

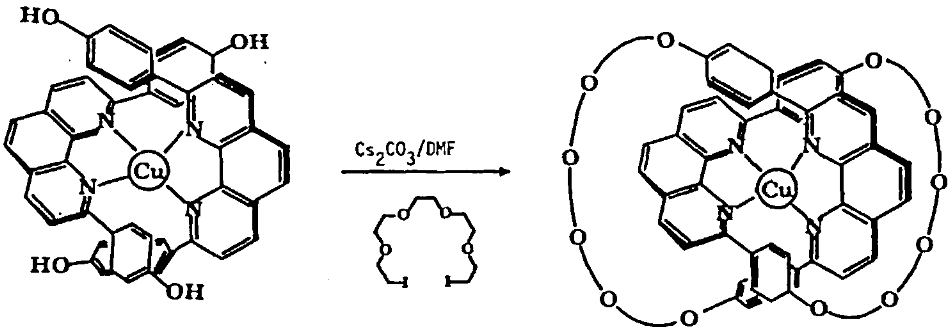


FIGURE 40.

Cesium carbonate may be considered also as auxiliary templating agent.

An excellent review on catenands chemistry has been published recently.[23] Further development of the template strategy led to more sophisticated design of an unusual ligand possessing a topology of trefoil knot, and has been synthesized by template synthesis in combination with high dilution technique in 3% yield[25]:

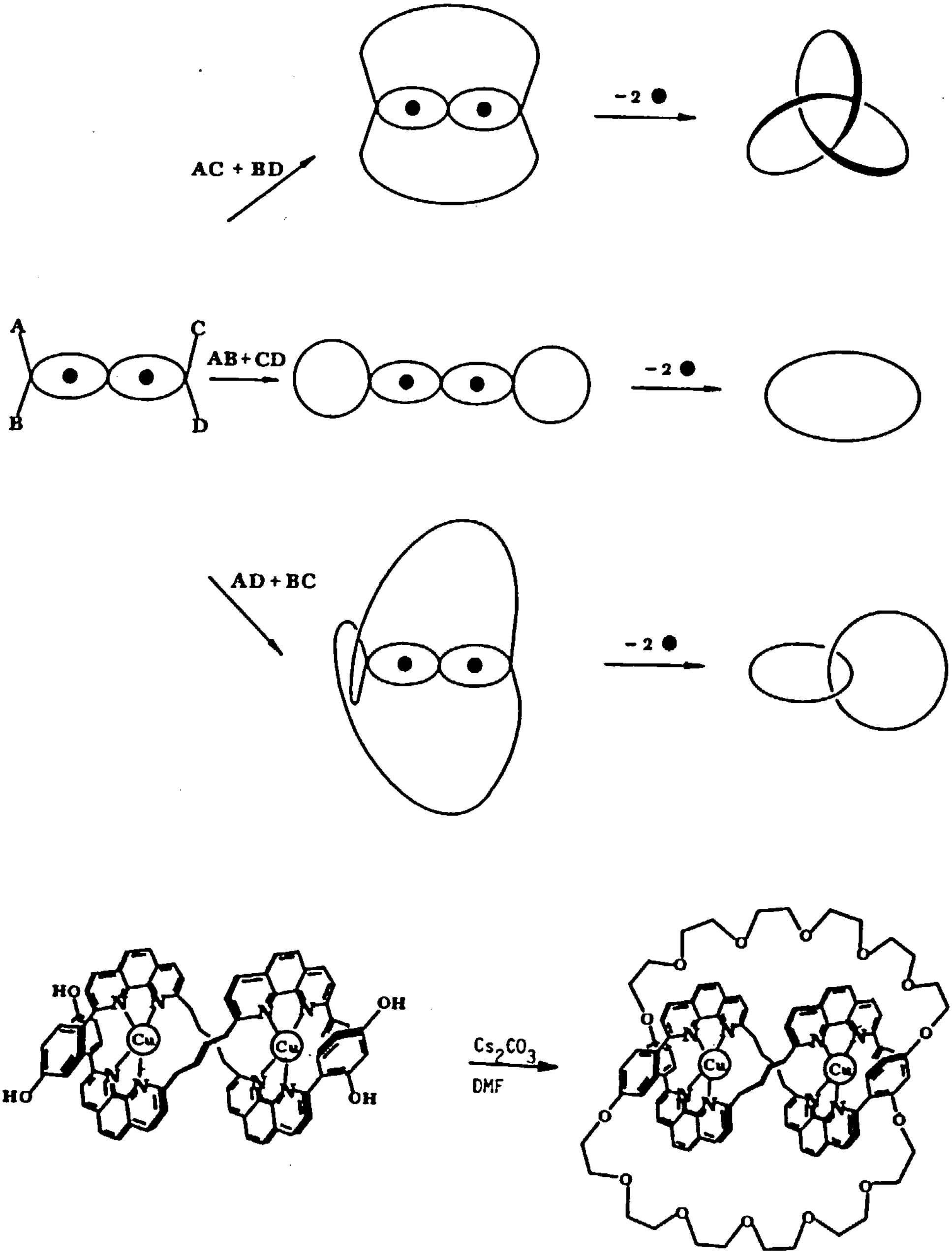


FIGURE 41.

Direct alkylation of amino-nickel complex led to facile synthesis of P_2N_2 macrocycle[26]:

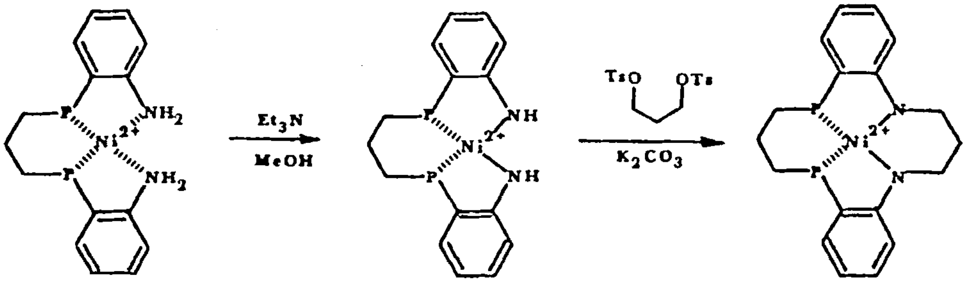


FIGURE 42.

One step macrobicyclization templated by Fe^{3+} cation proceeded in remarkable yield[27]:

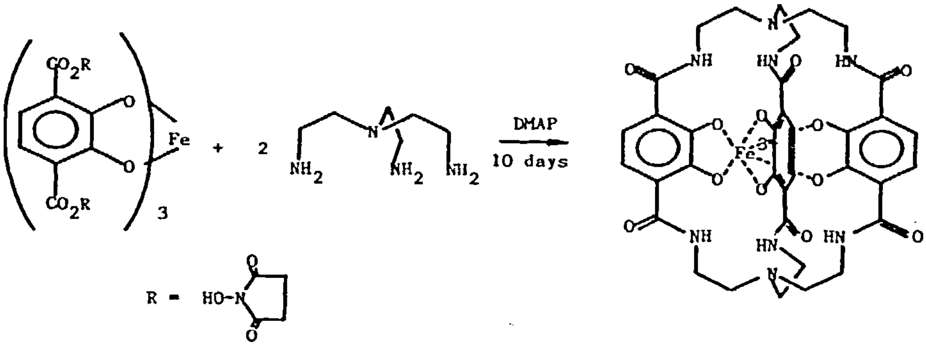
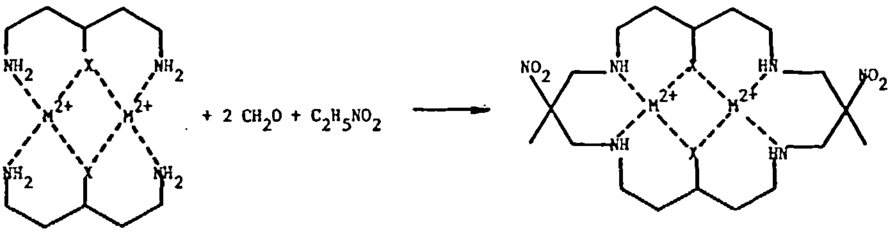


FIGURE 43.

Binuclear transition metal template has been reported recently in one-step macrocyclizations involving formaldehyde, nitroethane and polyamine complexes[28,29]:



M = Ni, X = S, 42%

M = Cu, X = O, 35%

FIGURE 44.

1.3 Rare Earth Metal Ion Templates

The essential reason for using lanthanide ions as templates in the synthesis of macrocyclic systems is an access to their macrocyclic complexes possessing a number of important characteristics, such as NMR and ESR contrast agents, luminescent probes, energy-transfer devices, stereochemical probes, *etc.*

Most of these syntheses consist on the Schiff base condensations involving aromatic, or heteroaromatic dialdehydes and aliphatic or aromatic diamines. Depending on the mode of condensation, four groups of condensations can be distinguished; "1+1", "2+2", "3+3", and "4+4" additions. So far, the "4+4" type of condensation has not been accomplished with lanthanide cation, although tetranuclear manganese complex formation has been obtained (see reference 5, Section 1.2).

The "1+1" Condensations

The 2,6-diacetylpyridine reacts with a range of di- and polyamines in the presence of $La(NO_3)_3$ with the formation of the complexes $(La(M)(NO_3)_3).nH_2O$ for 1 and 2, and $(La(M)(NO_3)_2OH).nH_2O$ for 3 and 4[1],[2]:

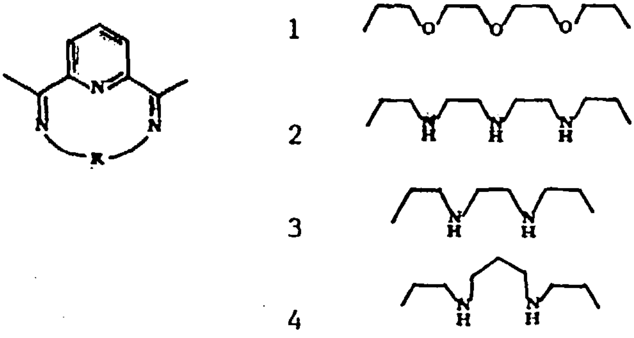


FIGURE 45.

The "2+2" Condensations

Diacetylpyridine and 1,2-diaminoethane were condensed in a "2+2" mode in the presence of La^{3+} and Ce^{4+} ions to form macrocycle 5[3]:

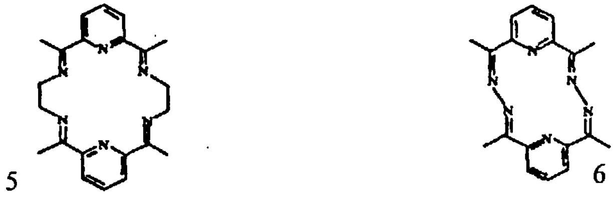
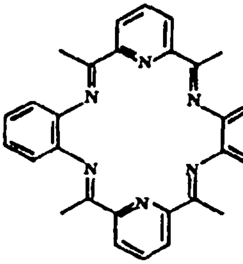


FIGURE 46.

The heavier lanthanides were not found to be effective as templates. They were effective however, in template reactions for 14-membered macrocycle 6 incorporating hydrazine lateral units.[4]

More recent studies of the template potential of the lanthanide ions indicated their greater potential in the template synthesis of the macrocycle 7:



7

FIGURE 47.

Complexes of 7 were obtained with all lanthanides except prometium.[5] Template synthesis of 8 and complexes with Ce, Pr and Nd have been reported.[6] Similar "2+2" complexes were prepared from 2,5-diformylfuran and aliphatic diamines.[7] An excellent review on template "1+1" and "2+2" Schiff base syntheses has been published recently.[8]

The "3+3" Condensations

There has been recently a report on the synthesis of a macrocyclic Schiff base from 1,3-diamino-2-hydroxypropane and 2,2-diacetylpyridine in the "3+3" mode. This reaction was templated by lanthanum nitrate. The product 9 appeared to be a complex with three La^{3+} cations[9]:

9

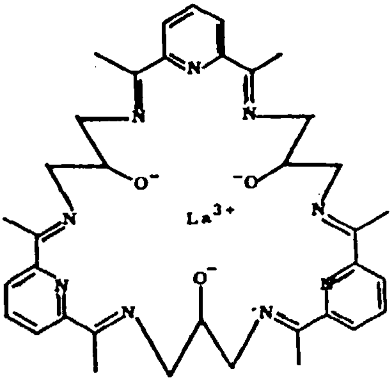
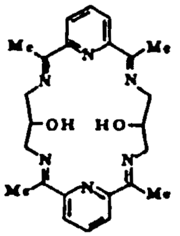


FIGURE 48.

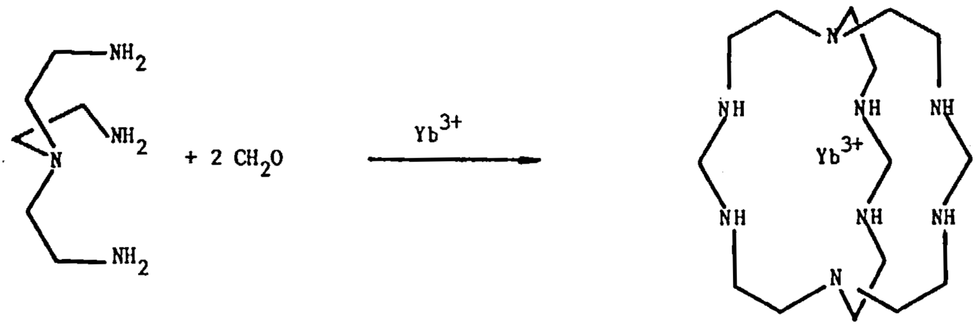
It should be noted that "2+2" condensation with the same reactants and lanthanide templates have also been reported[10] (Formula 10):



10

FIGURE 49.

Macrobicyclization involving Yb^{3+} as a template has been reported[11]:



1.4 Platinum Metal Ion Templates

Platinum salts are used as templates when their particular complex is desired, but not the free ligand itself. Therefore, only limited number of platinum metal complexes has been synthesized.

Ruthenium II has been used as a template in the following synthesis[1]:

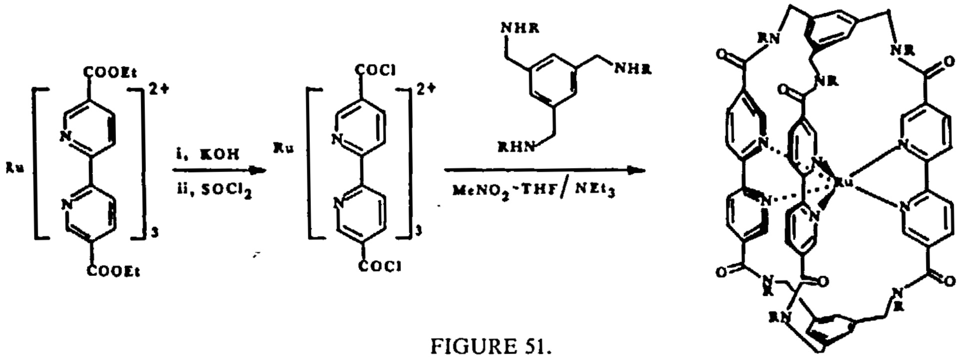


FIGURE 51.

Grzybowski and co-workers reported the synthesis of Ru clathrochelate obtained from 1,2-cyclohaxanedione and phenylboronic acid[2]:

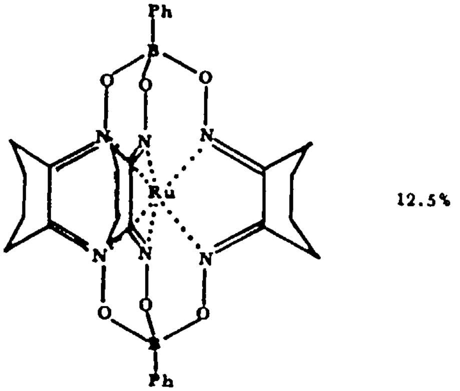


FIGURE 52.

Sargeson and co-workers demonstrated that some platinum ions may serve as templates in the synthesis of cage macrobicylic polyamines from ethylenediamine metal complexes, formaldehyde and ammonia or nitromethane[3,4]:

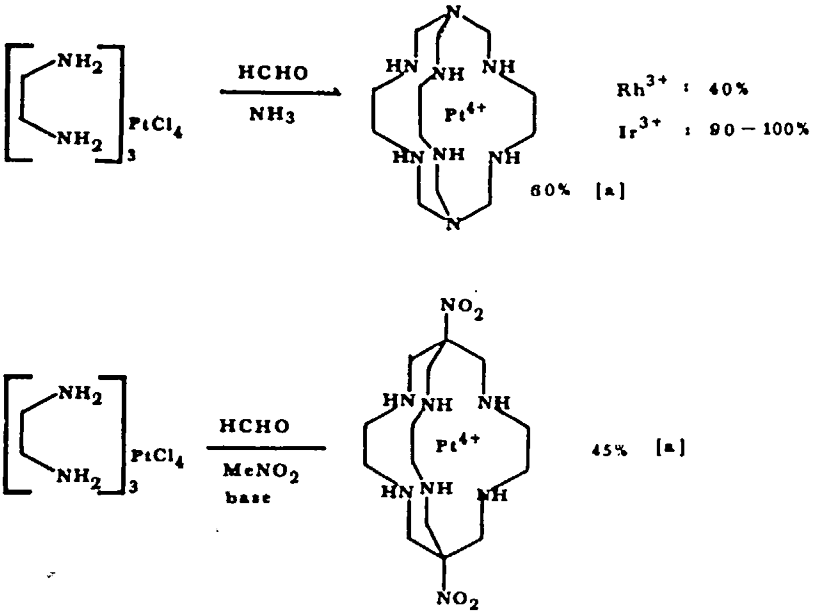


FIGURE 53.

1.5 Other Metal Ion Templates

Many macrocyclic Schiff bases have been obtained by Sn IV or Pb II template condensations, and representative examples are collected in this Section.

For example, 2,6-diacetylpyridine was condensed with various aliphatic polyamines, as shown below[1,2]:

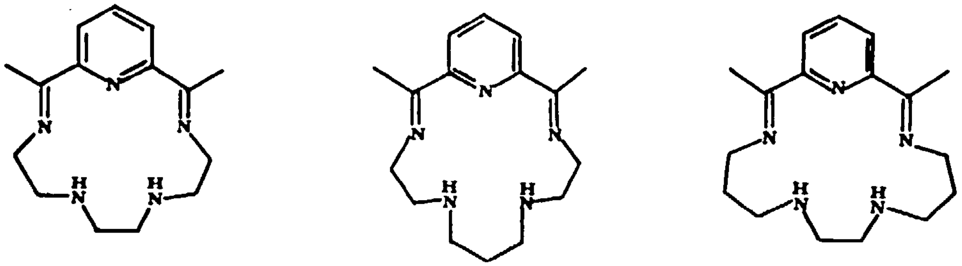


FIGURE 54.

Reaction of 2,6-diacetylpyridine with 1,3-diamino-2-hydroxy-propane in the presence of $Pb(ClO_4)_2$ led to the formation of macrocyclic mononuclear complex with contracted cavity[3]:

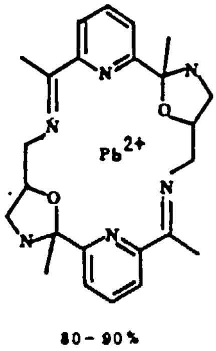
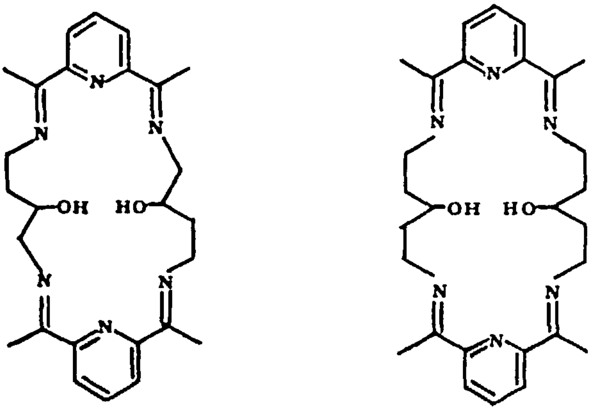


FIGURE 55.

Lead ions were most extensively used as metal ion template. The same work reports on Pb II effective macrocyclization of dicarbonyl components, as shown below:



Pb(ClO$_4$)$_2$: 75%

Pb(ClO$_4$)$_2$: 95%
Pb(NCS)$_2$: 55%

FIGURE 56.

Similarly, 2,6-diacetylpyridine condensed with 1,6-diaminohexane in the presence of lead thiocyanate[4]:

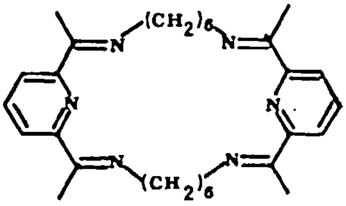


FIGURE 57.

Lead-driven macrocyclization was observed for 1,3-diaminopropane and 2,6-diacetyl-4-methylphenol[5]:

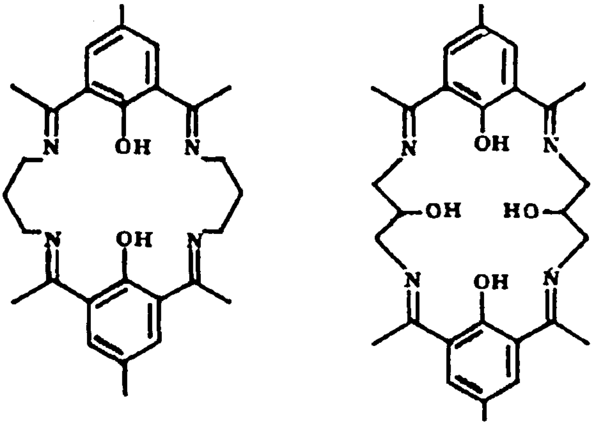


FIGURE 58.

Lead-templated synthesis of binucleating tetrapyrrole ligand has been reported[6]:

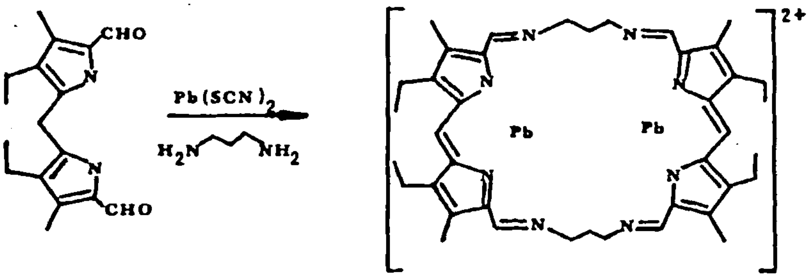


FIGURE 59.

1.6 *Non-Metallic Templates*

Templates that cannot be fitted into former categories are collected here. There are boron and hydrocarbon species as templating agents.

Very recently there has been report on the synthesis of host molecules with π-acceptor properties[1] (see Figure 60).

It was demonstrated that the synthesis on 1d proceeded in 16% yield when an excess of phenanthrene was present, whereas in its absence—only 3–5% of 1d was formed. Thus, the authors suggest a hydrocarbon template effect.

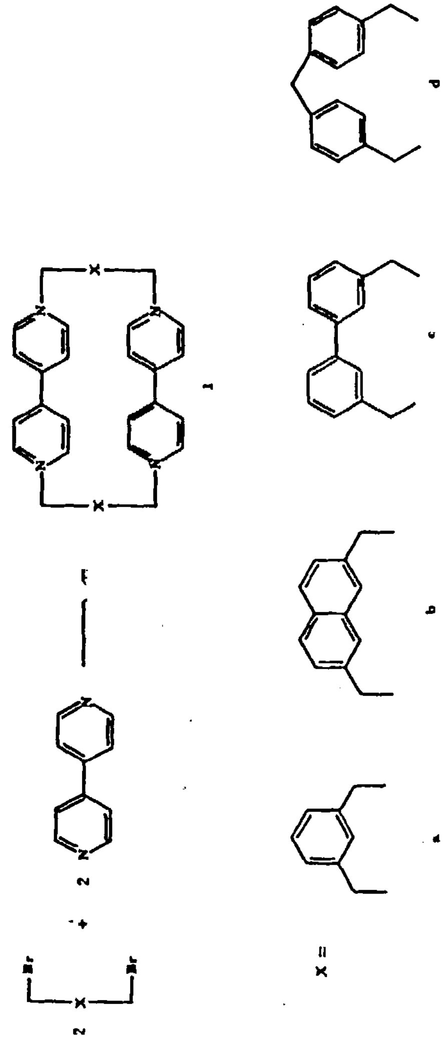


FIGURE 60.

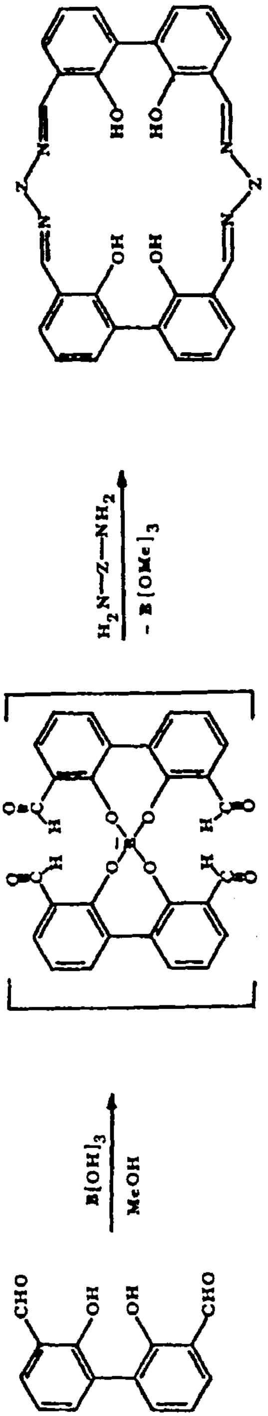


FIGURE 61.

A boron transient template was postulated during the following macrocyclization[2] (see Figure 61).

The boron intermediates were not isolated, but boron was essential for good yield of the macrocycle. Metallic templates were not effective at all.

An interesting example of templated formation of [2]catenane has been reported by Stoddart and co-workers.[3] The driving force of this reaction is π-donor π-acceptor interaction between reactants (see Figure 62).

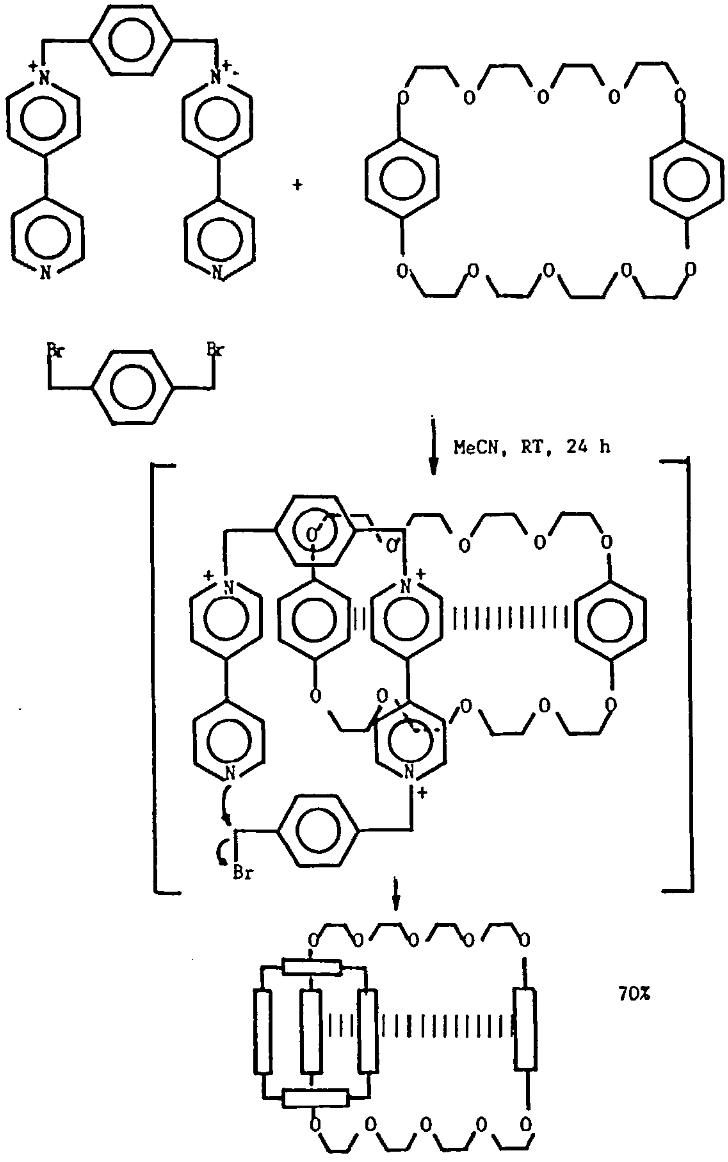


FIGURE 62.

2. HIGH DILUTION TECHNIQUES

The essential feature of this method is the reaction between two components in an inert solvent at concentration around 10^{-5} M. This requirement emerges from the fact that at higher concentration linear polymerization will be a predominant process, whereas at low concentration intramolecular cyclization has a better chance to happen.

In general, two or sometimes three components are added *via* syringe pump to vigorously stirred solvent. The rate of addition can be adjusted in order to maintain a low concentration of reactants constant. There are two classes of substrates: fast reacting (for instance diacid dichlorides and diamines) and slow reacting (bis-tosylamides and dihalogeno derivatives). In the first case, there is no need to run the reaction at elevated temperature, whereas in the second case elevated temperature is essential to accelerate the rate of reaction to avoid the polymeric product formation. An excellent review on high dilution macrocyclizations has been published.[1]

Discussion here will be limited to macrocyclic aza-oxa macrocycles, or macrocyclic polyamines, although the above-mentioned review covers also syntheses of oxa-thia macrocycles, cyclophanes, macrocyclic lactones, *etc.*

2.1 Slow Reacting Components

Here we will discuss macrocyclizations involving terminal bis-N-tosylamides and terminal dihalogeno derivatives. Several examples will illustrate the utility of this approach for the synthesis of cyclic polyamines.

It has been generally found that unprotected diamines when condensed with dihalogeno derivatives form the desired macrocycles in fairly low yield. Better results were obtained when N-ditosylamides reacted with respective dihalogeno compounds[2]:

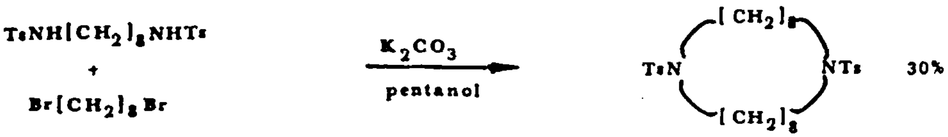


FIGURE 63.

1,7-Dibromoheptane and p-toluenesulphonamide were dissolved in methylethylketone and dropped into the same solvent with 72 h, containing K_2CO_3. The yield of the cyclic product was 17%[3]:

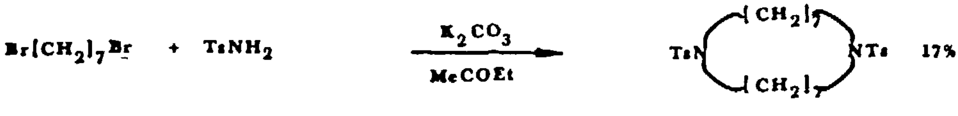
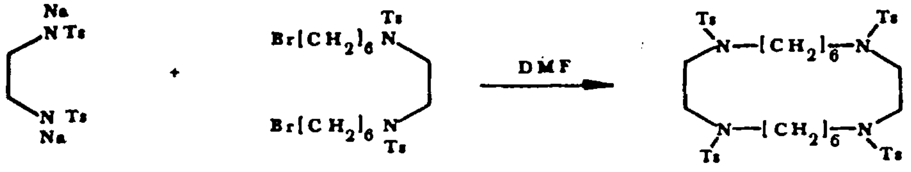


FIGURE 64.

Macrocyclic polyamine containing four nitrogen atoms has been synthesized in the following way[4]:



3

FIGURE 65.

Azaphanes were prepared in the same way from respective bistosylamides and dihalogeno compounds. DMF was found to be the best solvent for macrocyclization, although pentanols and DMSO have been used as well.

An example of a phane synthesis is shown below[5]:

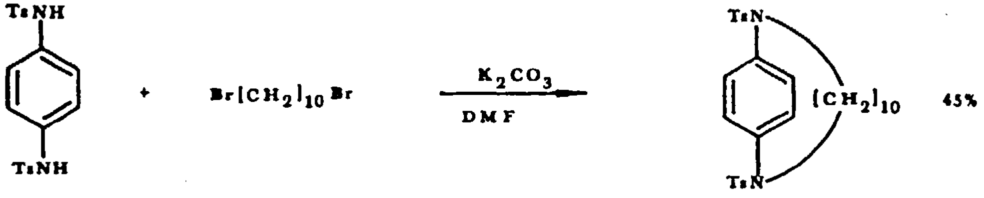


FIGURE 66.

The reaction conditions were the following: 20 mmol of each reactant were dissolved in DMF (350 mL) and added over 21 h to 350 mL of DMF + K_2CO_3 at 130 ± 5°C.

The sodium salts of bis-tosylamides can be used in the formation of large rings[4]:

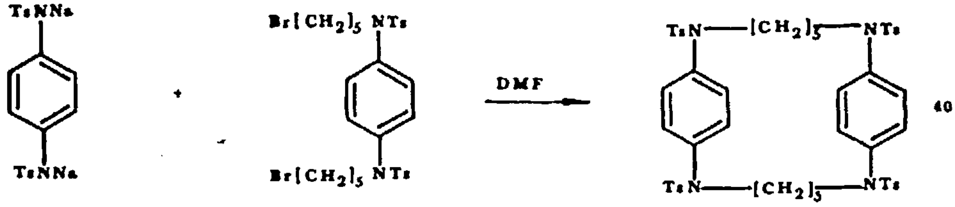


FIGURE 67.

A large paracyclophane was obtained in DMF/K_2CO_3 mixture[6]:

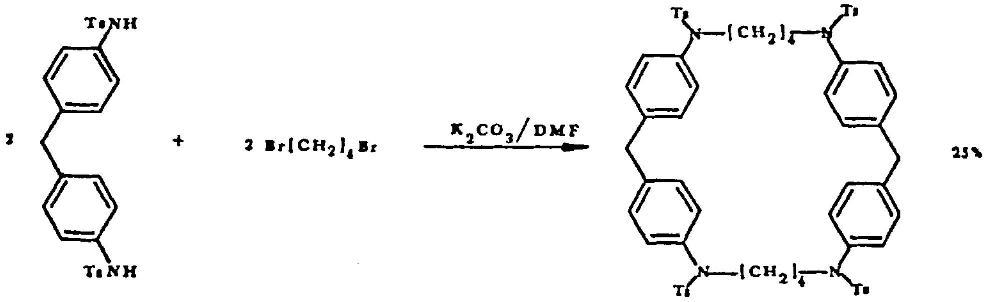


FIGURE 68.

It should be noted that smaller macrocycles can be formed in good yield without high dilution conditions (see: Richman-Atkins syntheses).

2.2 Fast Reacting Components

In this section, cyclizations involving diamines and dicarboxylic acids will be discussed. Carboxylic groups have to be activated prior to reaction to ensure fast reaction with diamines. Usually, due to high reactivity of acid chlorides there is no need for elevated temperature, although in the case of aromatic amines elevated temperatures are essential for a desired high rate of condensation.

Usually, a double amount of the diamine component is used because the second molecule serves as HCl-receptor. Alternatively, to save diamine, which sometimes is expensive, other amines, such triethylamine, pyridine can be used conveniently as HCl-traps. Toluene or benzene are frequently used as a solvent.

An early example of macrocyclic bisamide formation can be exemplified as follows[7]:

FIGURE 69.

Instead of acid chlorides, activated carboxyl derivatives can be used alternatively, such as para- and orthonitrophenyl esters,[8] phosphoric acid esters,[9] or tertiary amide of the thiazolidene-2-thione.[10] It is interesting that less reactive acyl derivatives display apparent selectivity upon macrocyclization with mixed primary/secondary amino components. This fact can be illustrated by the following example[10]:

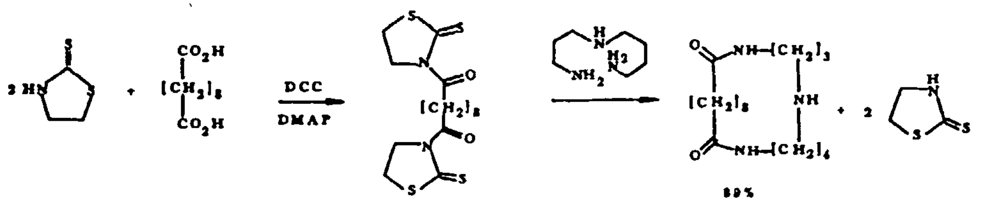


FIGURE 70.

There were no detectable amounts of other cyclic products present.

High dilution technique has been applied successfully in various syntheses of diaza crown ethers and cryptands. most of them have been prepared with diacid dichlorides. Details can be found in numerous reviews.[11–15]

A typical procedure for the synthesis of macrocyclic diamines is shown below:

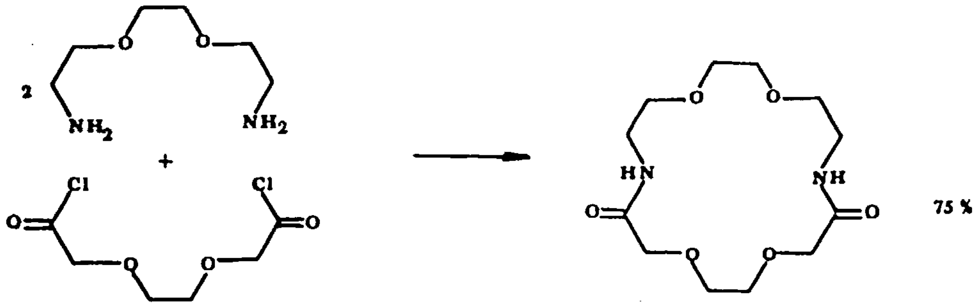


FIGURE 71.

The reaction conditions were the following: diamine—99.8 mmol in benzene (500 mL), dichloride—44.4 mmol in benzene (500 mL); solvent—benzene (1.2 L), reaction temperature—10–20°C; addition time 8 h.

More complicated hosts are also possible to be formed by high dilution technique. Cyclotriveratrylene speleands have been obtained from CTV-triacid trichloride and (18)-N_3O_3 triaza-crown ether[17]:

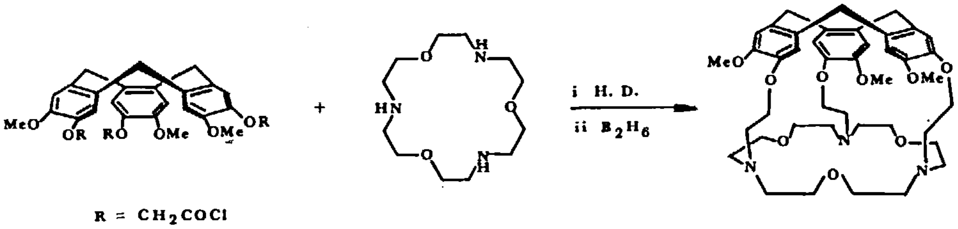


FIGURE 72.

3. NON-TEMPLATE MACROCYCLIZATIONS AND POLYCYCLIZATIONS

3.1 Schiff Base Formation

There are interesting examples of macrocyclizations and macrobicyclizations involving dialdehydes and diamines without any template agent. This alternative is superior to similar ion-promoted syntheses, since it provides metal-free macrocycles. It should be noted also that the metal ion may be removed from the complex with difficulties.

There are examples of macrocyclizations using aromatic or heteroaromatic dicarbonyl compounds and linear aliphatic polyamines[1–3]:

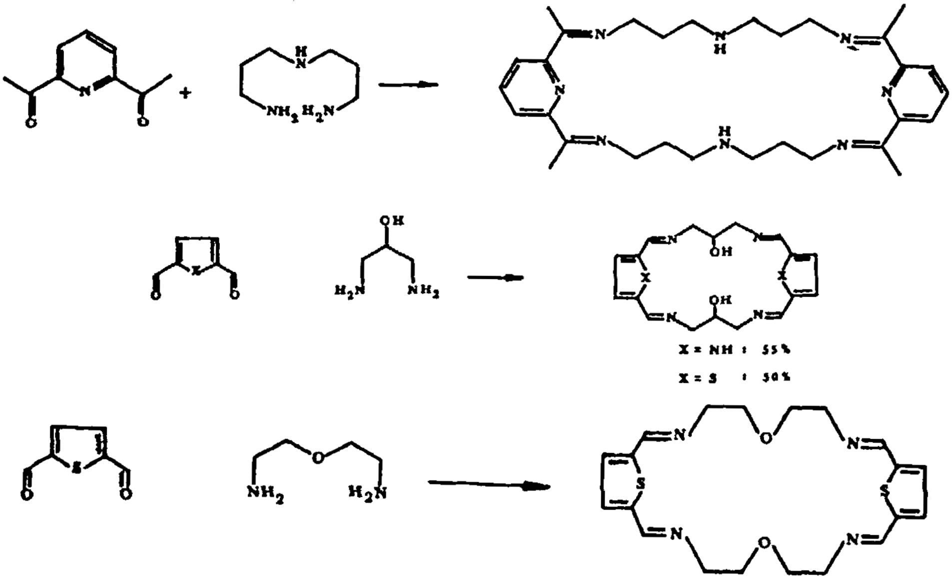


FIGURE 73.

Similar macrocyclizations were observed between terephtalic aldehyde and bis-(3-aminopropyl)amine or 1,1-bis-(3-aminopropyl)ethylenediamine in high yield[4]:

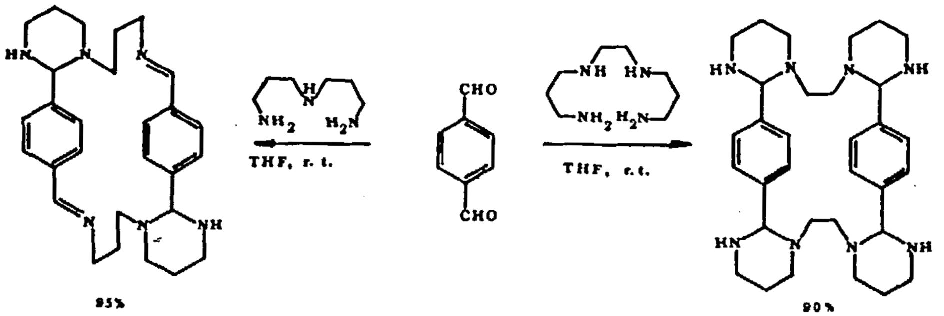


FIGURE 74.

It seems that the driving force for these cyclizations lies in the formation of six-membered aminal rings. Using shorter amines, such as bis(2-aminoethyl)amine led to polymeric product only.

An ingenous method for macrobicyclization has been developed independently by two groups. This method consists on "2+3" Schiff base condensation between tris(2-aminoethyl)amine with a range of aromatic or heteroaromatic dialdehydes without template. Schematically, this type of condensation is shown below[5,6]:

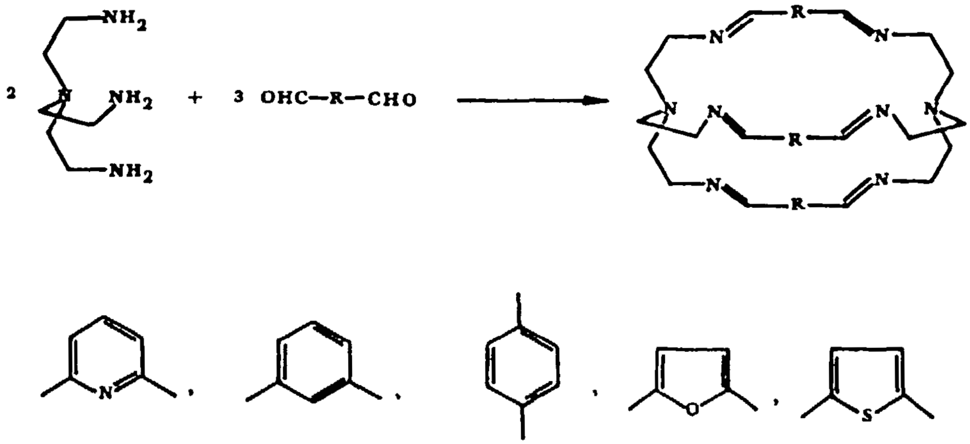
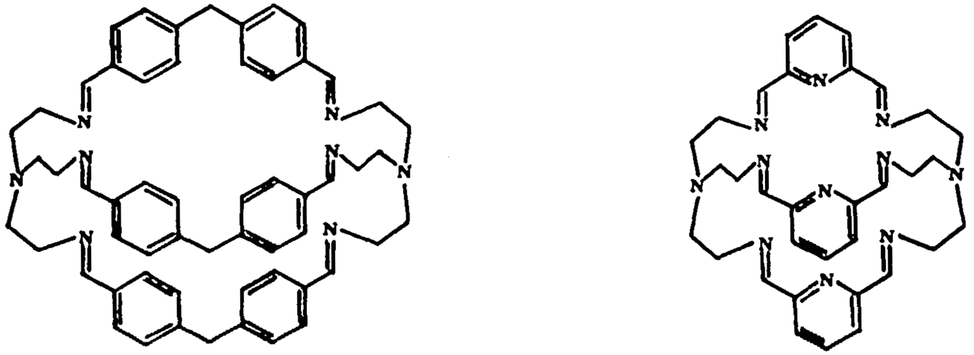


FIGURE 75.

Lehn and co-workers reported similar synthesis[7]:



70%

80%

FIGURE 76.

Such macrocyclic or macrobicyclic Schiff bases can be reduced easily with $LiAlH_4$ to polyamines.

3.2 Cyclooligomerizations

There are many types of hydrophobic host molecules capable of binding the neutral guests by means of van der Waals forces. Inclusion of neutral species may have a variety of further commercial applications, for instance as a sensing materials for coatings in piezoelectric sensors.

Three classes of hydrophobic receptors will be discussed here: calixarenes, cyclotriveratrylene derivatives and cavitands. It should be also emphasized at this point that these cyclic oligomers can be easily derivatized further to form much more elaborated architectures that are able to perform more complicated tasks, such as a simultaneous binding of several substrates, supramolecular catalysis, signal transduction, light conversion, transport, *etc.* Although the other types of hosts, such as macrocyclic cyclophanes also bind a neutral molecules, their syntheses will not be discussed here, since they are synthesized by high dilution technique, whereas macrocyclic oligomers are formed by condensation of phenol-type compounds with aliphatic or aromatic aldehydes. The chemistry of water-soluble cyclophanes has been reviewed.[8]

Essential advantage of macrocyclic oligomers is their accessibility by straightforward preparation from commercially available phenols and aldehydes. Such condensations are run in an acidic conditions.

Cyclotriveratrylene Compounds

Cycloveratrylenes are compounds formed from veratrol and formaldehyde, or its polymers in acid-catalysed reaction:

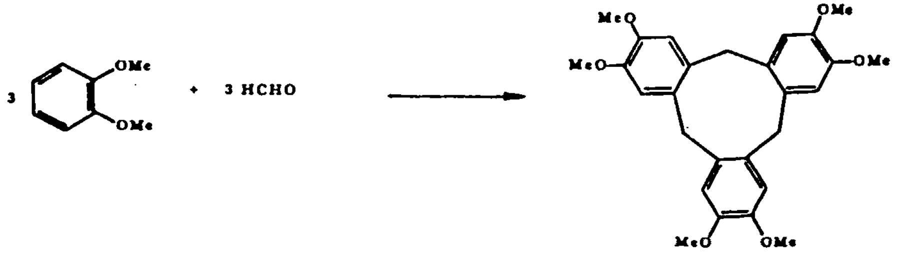


FIGURE 77.

Not only mineral acids are effective as catalysts, but also Lewis acids. Cyclic trimer is the major product, accompanied by small amount of cyclotetramer.

Cyclotriveratrylene forms crystalline inclusion complexes with hydrocarbons, chlorohydrocarbons, ketones, carboxylic acids, esters, alcohols, ethers and heterocyclics. On the other hand, host-guest interactions have not been observed in the solution, probably due to weak interactions.

Cyclotriveratrylene can be further derivatised. Of particular interest is a development of so-called cryptophanes comprising two cyclotriveratrylene fragments linked together by supporting units (pillars) to form a three dimensional void capable of forming stable complexes in solution.

The chemistry of cycloveratrylenes and their derivatives has recently been reviewed.[9]

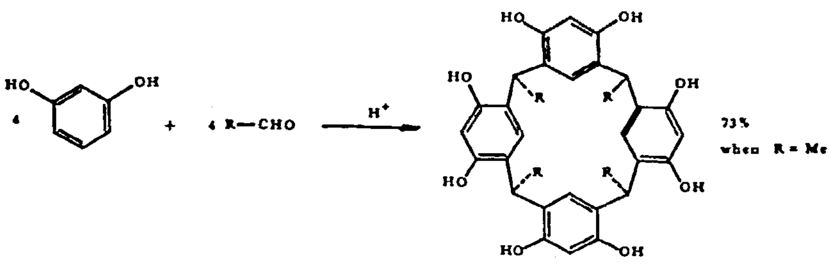


FIGURE 78.

Cavitands

Cavitands are the class of cyclic tetramers originating from resorcinol and aldehydes, either aliphatic or aromatic. The first synthesis was reported in 1940.[10]

Substituents R possess all-cis configuration. The greater stability of the hydrogen bonds is possible only in all-cis configuration, but not in other isomers. Oligomers containing more than four resorcinol units have not been observed. A great variety of possible functionalizations for cavitands can be envisioned.

Calixarenes

Calixarenes are hydrophobic cyclic oligomers obtained by controlled base-catalysed reaction between p-alkylphenols and formaldehyde.[12] The best known is calix(4)arene comprising four aromatic units:

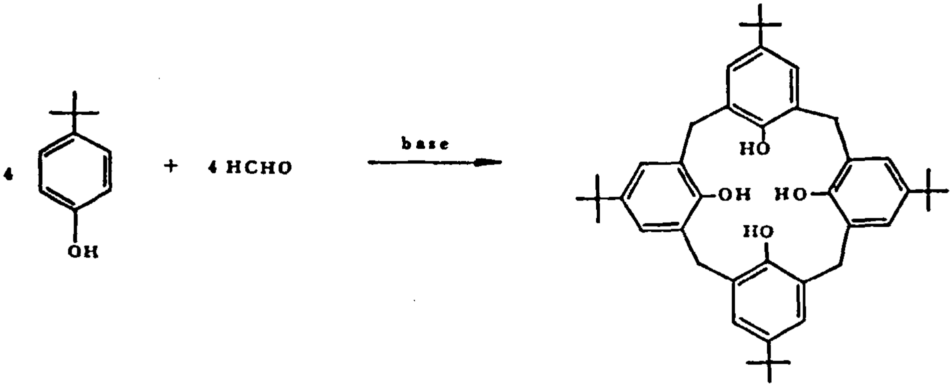


FIGURE 79.

Larger oligomers consisting of five, six or eight units are more conformationally mobile and their chemistry is less elaborated than for the calix(4)arene.

Calixarenes form a great variety of inclusion complexes with neutral molecules, such as aromatic hydrocarbons, ketones, alcohols, halogeno-alkyls, *etc.* Many possibilities exist to functionalise calixarenes. They involve alkylation and acylation of oxygen atoms, removal of t-butyl group and introduction of functional groups, for instance sulphonyl, aminoalkyl (Mannich reaction) *etc.*

Therefore, calixarenes remain a group of hydrophobic hosts that offers a lot of interesting objects, as enzyme mimics, supramolecular catalysts, energy transducers and selective complexing agents.

4. MISCELLANEOUS METHODS OF PREPARATIVE SIGNIFICANCE

4.1 Richman-Atkins Method

An alternative access to macrocyclic polyamines has been developed by Richman and Atkins.[1,2] In these works tosylated polyamines were allowed to react with respective dihalogeno- or ditosyl components in the presence of base, such as NaH in DMF at elevated temperatures. For example, tritosyl triamine sodium salt condensed with appropriate second component, as shown below:

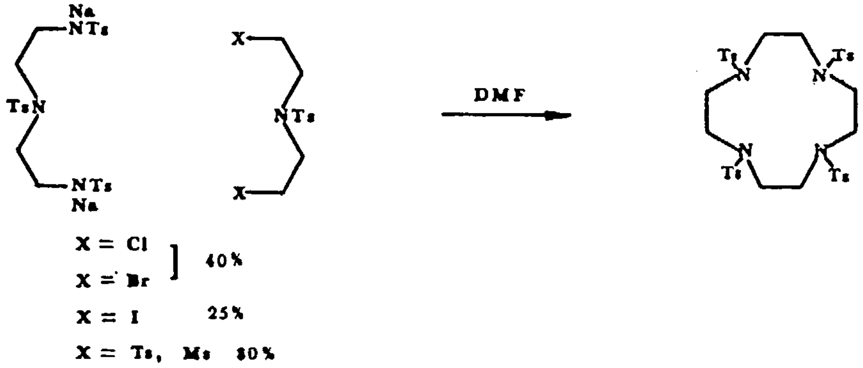


FIGURE 80.

When sodium was replaced by tetramethylammonium cation, the yield dropped to 50% which was a bit surprising result. It has been suggested that large sulphonyl groups tend to restrict free rotation in the starting materials. As a consequence, there is a small internal entropy loss on cyclization, allowing for macrocyclization to occur in quite good yield even when no apparent organization is involved by a templating ion. On the other hand, the difference in 50% and 80% yield depending on the nature of the cation involved reflects some template effect of the sodium cation.

In this technique high dilution is not required. Rather concentrated solutions of reactants appear to give the best yields.

The nature of components may give different results when two alternative pathways exist leading to the same target molecule[3]:

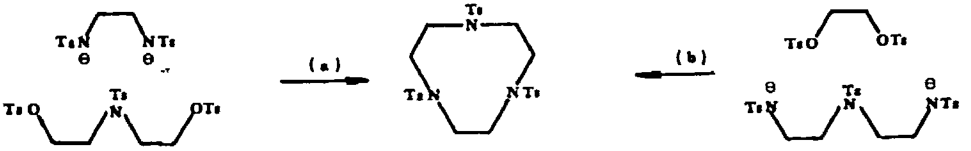


FIGURE 81.

It turned out that lower yield result in pathway "a". Similar approach has been published recently[4] for the preparation of a range of polytosyl polyaza macrocycles. Appropriate components were coupled in DMF solution in the presence of cesium carbonate at room temperature.

The Richman-Atkins procedure was extended by Lehn and co-workers towards larger, 24-, 27-, and 32-membered macrocyclic polyamines[5]:

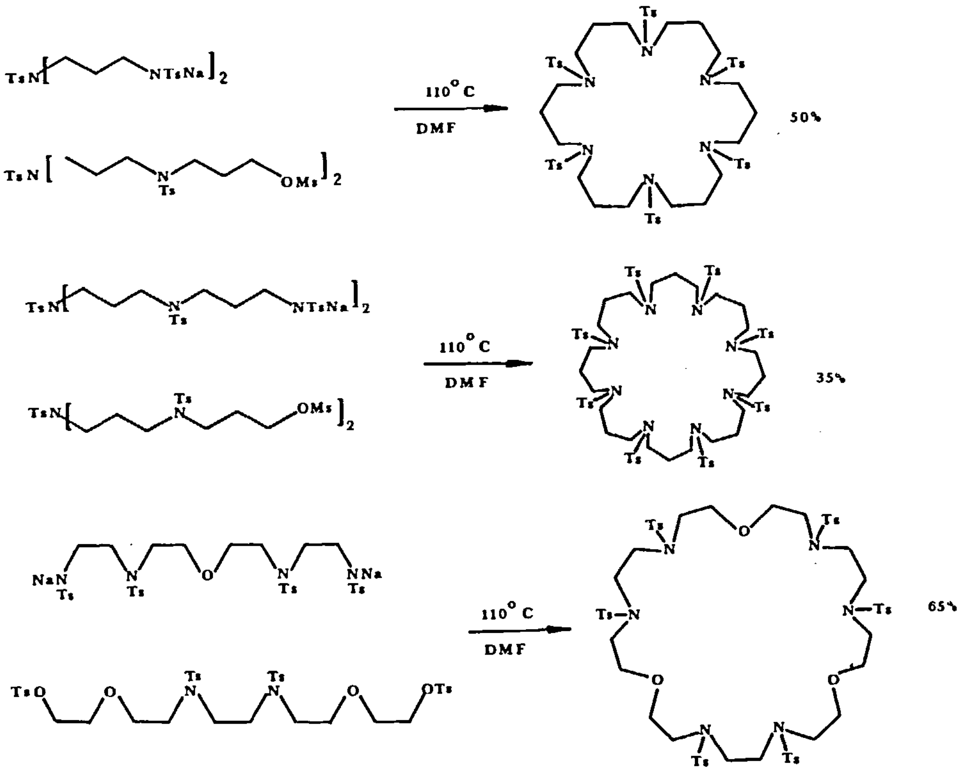


FIGURE 82.

Yields for all macrocyclizations are remarkably good and considered of general importance for the formation of large rings. DMF has always been a solvent of choice and should be dried carefully prior to use.

4.2 Double Quaternization

Lateral macrobicycles can be synthesized by the method elaborated by Newkome and co-workers.[6] N,N'-Dimethyl diaza macrocycle is doubly quaternized on nitrogen atoms with bis(2-iodoethoxy)ethane in refluxing MeCN to form the bis-quaternary salts that can be demethylated with L-Seletride[6]:

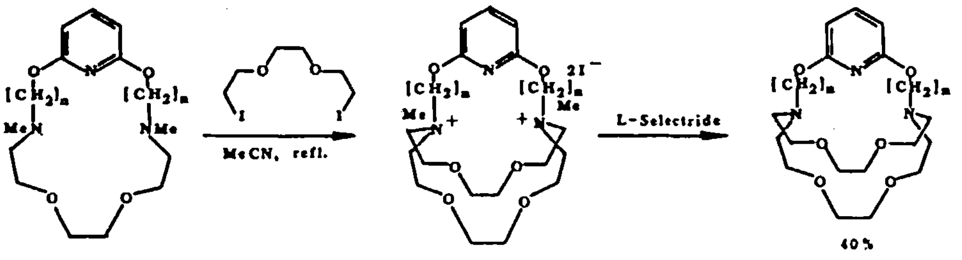


FIGURE 83.

The bis-quaternization in thermal conditions has not been further explored.

4.3 High-Pressure Method

Newkome's findings have been adopted as high-pressure modification based on the fact that well known Menshutkin reactions under high pressure are greatly accelerated by pressure, due to highly negative volume of activation. Indeed, this approach turned out to be very successful in respect to yield of bis-quaternization. A general scheme for this method may be outlined as follows[7]:

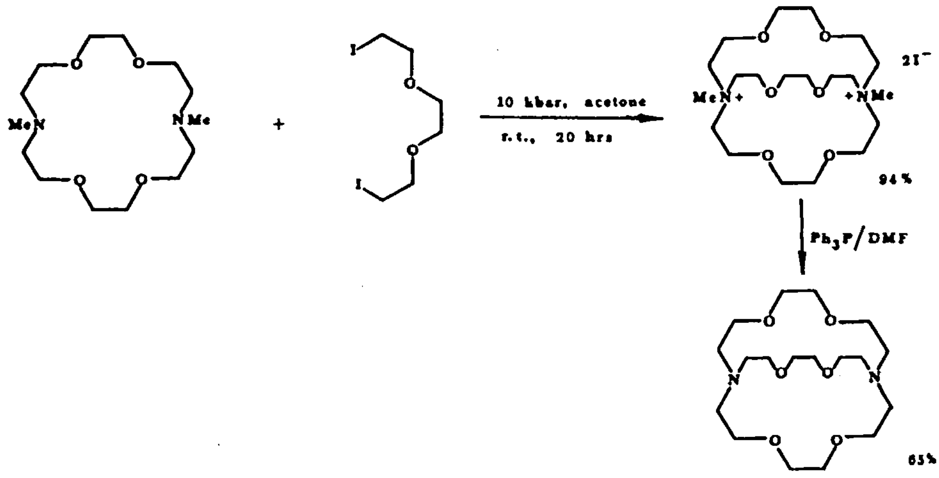


FIGURE 84.

Typically, these reactions were carried out in dry acetone under 10 kbar pressure at room temperature for 20 h. Usually, a white percipitate of bis-quaternary salt deposited during the reaction course. Yields were generally high (81–100%).

Demethylation was achieved by heating the bis-quaternary salt in boiling DMF with triphenylphosphine. In this way, a range of cryptands have been prepared: (1.1.1), (2.1.1), (2.2.1), (2.2.2), and (2B.2.2) in excellent yield.

Systematic studies on the influence of aliphatic bridging unit (linking nitrogen pivot atoms) have been done by the same group.[8] It turned out that chains consisting of ten methylene units can be incorporated into 4,13-diaza-18-crown-6 framework in only 55% yield. Shorter units gave much better yields. This result demonstrated a practical scope of this method.

Along these lines, the influence of leaving group, solvent and reaction time have been investigated in order to optimize the reaction conditions for practical purposes.[9] These studies demonstrated a usefulness of highly polar solvents as a reaction medium (the shortest reaction time) and bisiodides appeared to be the best bridging components among chlorides, bromides or tosylates.

High-pressure technique has been applied successfully in Diels-Alder macrocyclization to form an exotic host molecule from readily available materials[10]:

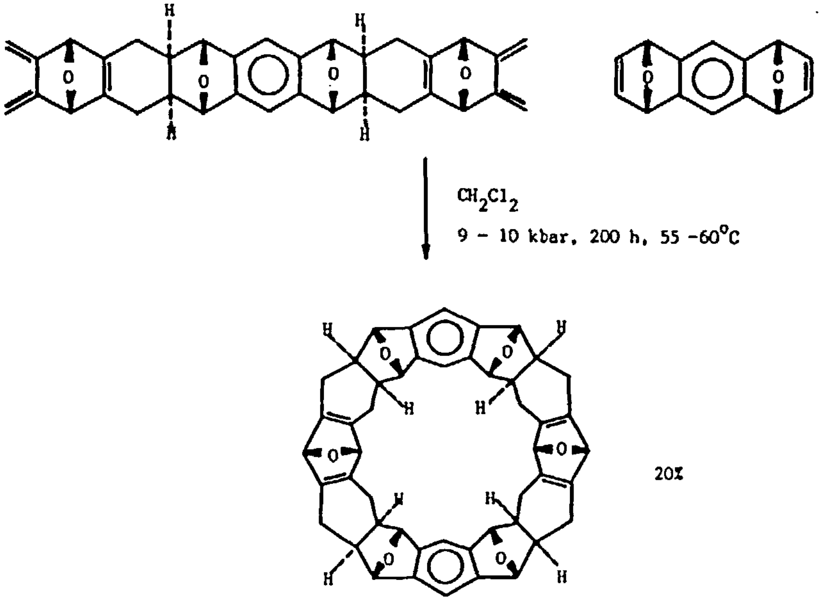
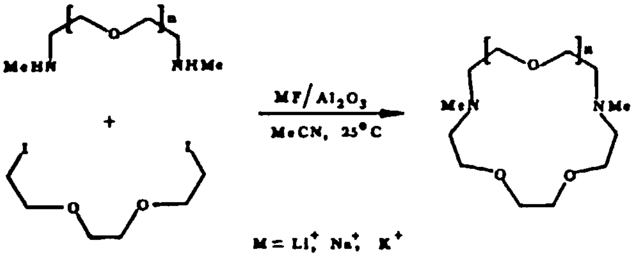


FIGURE 85.

Also, a few chiral cryptands incorporating carbohydrates have been synthesized in this way, being inaccessible by classical procedures.[11–13]

4.4 *Macrocyclizations on Solid Supports*

Yamawaki and Ando demonstrated the utility of alumina coated with KF as a solid support for the synthesis of "all-oxygen" crown ethers.[14] This method proved to be useful also in the case of synthesis of diaza crown ethers incorporating carbohydrates.[15] Simple diaza crown ethers can be obtained in this way from easily available starting materials: N,N′-dimethyldiamines and triethylene glycol diiodide[16]:



		YIELD %	
		A	B
n = 1, 2	Li	32	23
A: n = 1	Na	30	30
B: n = 2	K	48	55

FIGURE 86.

Components are stirred with the solid support at room temperature in MeCN for 72 h. Filtration, evaporation and high-vacuum distillation led to appropriate diaza crown ethers in acceptable yields. There is no need for protection-deprotection of nitrogen atoms which is obvious advantage.

4.5 Okahara's One-Step Cyclization Method

This method consists in preparation of aminodiol which is subsequently monotosylated at oxygen atom and cyclized in a basic conditions to form N-alkyl-monoaza crown ether. This concept can be illustrated as follows[17,18]:

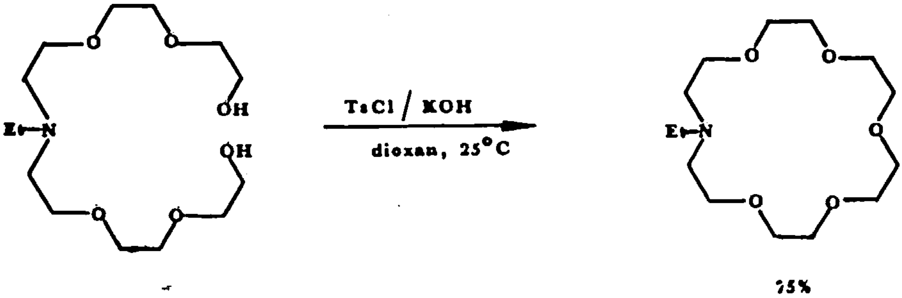


FIGURE 87.

4.6 Kimura's Method

Kimura and co-workers have developed a method for preparation of phenol pendant cyclams from commercially available linear polyamines and coumarin derivatives[19]:

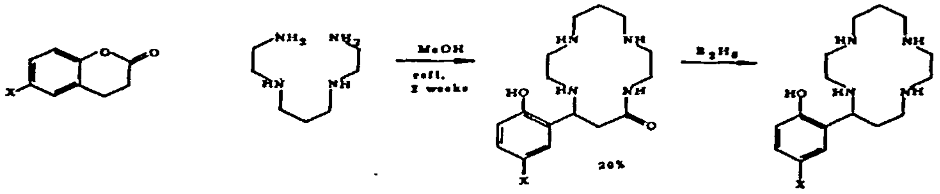


FIGURE 88.

The components are refluxed in methanol for 2 weeks to afford the monocyclam in 20% yield. The product can be reduced typically with diborane. Although the yield is not very high, this strategy may be the only choice as far as pendant phenol side arms are to be incorporated into macrocyclic polyamine backbone. This subject has been reviewed recently.[19]

REFERENCES FOR SECTIONS 1–4

Section 1.1

1. S. Kulstad and L.A. Malmsten, *Acta Chem. Scand.*, B33, 469 (1979).
2. V. Gatto, K.A. Arnold, A.M. Viscariello, S.R. Miller and G.W. Gokel, *Tetrahedron Lett.*, **27**, 327 (1986).
3. V.J. Gatto, K.A. Arnold, A.M. Viscariello, S.R. Miller, Ch.R. Morgan and G.W. Gokel, *J. Org. Chem.*, **51**, 5373 (1986).
4. V.J. Gatto and G.W. Gokel, *J. Am. Chem. Soc.*, **106**, 8240 (1984).
5. S. Kulstad and L.M. Malmsten, *Tetrahedron*, **36**, 521 (1980).
6. B. Alpha, E. Anklam, R. Deschenaux, J.-M. Lehn and M. Pietraszkiewicz, *Helv. Chem. Acta*, **71**, 1042 (1988).
7. M. Pietraszkiewicz, R. Gasiorowski and M. Kozbial, *J. Incl. Phenom. and Molecular Recogn. in Chem.*, **7**, 309 (1989).
8. See reference 6.
9. J.-C. Rodriguez-Ubis, B. Alpha, D. Plancherel and J.-M. Lehn, *Helv. Chim. Acta*, **67**, 2264 (1984).
10. See reference 9.
11. F. Ebmeyer and R. Vogtle, *Chem. Ber.*, **122**, 1725 (1989).
12. W.H. Kruizinga and R.M. Kellogg, *J. Am. Chem. Soc.*, **103**, 5183 (1981).
13. B. Dietrich, M.W. Hosseini, J.-M. Lehn and R.B. Sessions, *Helv. Chim. Acta*, **68**, 289 (1985).
14. B.K. Vriesema, J. Butler and R.M. Kellogg, *J. Org. Chem.*, **49**, 110 (1984).
15. J.F. Biernat and E. Luboch, *Tetrahedron*, **40**, 1927 (1984).
16. T. Alfheim, J. Dale, P. Groth and K.D. Krautwurst, *J. Chem. Soc., Chem. Commun.*, 1502 (1984).
17. S. Buoen and J. Dale, *Acta Chem. Scand.*, B40, 141 (1986).
18. H. Takemura, T.·Shinmyozu and T. Ilaazu, *Tetrahedron Lett.*, **29**, 1789 (1988).
19. T. Alfheim, S. Buoen, J. Dale and K.D. Krautwurst, *Acta Chem. Scand.*, B40, 40 (1986).
20. J.S. Bradshaw, K.E. Krakowiak and R.M. Izatt, *Tetrahedron Lett.*, **30**, 809 (1989).
21. K.E. Krakowiak, J.S. Bradshaw, N.K. Daley, W. Jiang and R.M. Izatt, *Tetrahedron Lett.*, **30**, 2897 (1989).

22. S.M. Nelson, *Pure & Appl. Chem.*, 52, 2461 (1980).
23. H. Adams, N.A. Bailey, D.E. Fenton, R.J. Good, R. Moody and C.O. Rodriguez de Barbarin, *J. Chem. Soc., Dalton Trans.*, 307 (1987).
24. N.A. Bailey, D.E. Fenton, P.B. Roberts and A.M. Walford, *J. Chem. Soc., Dalton Trans.*, 1865 (1987).
25. M.G.B. Drew, A.H. bin Othman, S.G. McFall and S.M. Nelson, *J. Chem. Soc., Chem. Commun.*, 818 (1975).
26. D.H. Cook and D.E. Fenton, *J. Chem. Soc., Dalton Trans.*, 266 (1979).
27. D.H. Cook, D.E. Fenton, M.G.B. Drew, S.G. McFall and S.M. Nelson, *J. Chem. Soc., Dalton Trans.*, 446, 1977.
28. D.H. Cook and D.E. Fenton, *J. Chem. Soc., Dalton Trans.*, 810 (1979).
29. T.W. Bell and F. Guzzo, *J. Chem. Soc., Chem. Commun.*, 769 (1986).
30. R.N. Prasad and M. Jain, *Book of Abstracts, 13th Int. Symp. on Macrocyclic Chemistry*, p. 238 (1988).
31. F.C.J.M. van Veggel, M. Bos, S. Harkema, W. Verboom and D.N. Reinhoudt, *Angew. Chem. Int. Ed. Engl.*, 28, 746 (1989).
32. R. Dharanipragada and F. Diederich, *Tetrahedron Lett.*, 28, 2443 (1987).

Section 1.2

1. D.A. House and N.F. Curtis, *Chem. Ind.*, 1708, (1961).
2. M.C. Thompson and D.H. Busch, *J. Am. Chem. Soc.*, 86, 3651 (1964).
3. V. McKee and S.S. Tandon, *J. Chem. Soc., Chem. Commun.*, 1335 (1988).
4. V. McKee and S.S. Tandon, *J. Chem. Soc., Chem. Commun.*, 386 (1988).
5. S. Brooker, V. McKee, W.B. Sheperd and L.K. Pannell, *J. Chem. Soc., Dalton Trans.*, 2555 (1987).
6. M.D. Alexander, A. van Heuvelen and H.G. Hamilton, *Inorg. Nucl. Chem. Lett.*, 6, 445 (1970).
7. J.C. Dabrowiak, L.A. Nafie, P.S. Brian and A.T. Torkelson, *Inorg. Chem.*, 16, 540 (1977).
8. M.G.B. Drew, A.H. bin Othman, W.E. Hill, P.D.A. McIlroy and S.M. Nelson, *Inorg. Chim. Acta*, 12, L25 (1975).
9. E. Fleischer and S. Hawkinson, *J. Am. Chem. Soc.*, 89, 720 (1967).
10. C. Cairns and S.M. Nelson, unpublished results.
11. M.G.B. Drew, S.G. McFall and S.M. Nelson, *J. Chem. Soc., Dalton Trans.*, 575 (1979).
12. R. Bhula, P. Osvath and D.C. Weatherburn, *Coord. Chem. Rev.*, 91, 89 (1988).
13. D.St.C. Black and G.I. Moss, *Austr. J. Chem.*, 40, 129 (1987).
14. G.A. Lawrance, M. Rossignoli, B.W. Skelton and A.H. White, *Austr. J. Chem.*, 40, 1441 (1987).
15. G.A. Lawrance and M.A. O'Leary, *Polyhedron*, 6, 1291 (1987).
16. P. Comba, G.A. Lawrance, M. Rossignoli, B.W. Skelton and A.H. White, *Austr. J. Chem.*, 41, 773 (1988).
17. A.A. Achilleos, L.R. Gahan, K.A. Nicolaidis and T.W. Hambley, *J. Chem. Soc., Chem. Commun.*, 912 (1988).
18. D.R. Boston and N.J. Rose, *J. Am. Chem. Soc.*, 90, 6859 (1968).
19. I.I. Creaser, J.MacB. Harrowfield, A.J. Herlt, A.M. Sargeson, M.R. Snow and J. Springborg, *J. Am. Chem. Soc.*, 99, 3181 (1977).
20. I.I. Creaser, R.J. Geue, J.MacB. Harrofield, A.J. Herlt, A.M. Sargeson, M.R. Snow and J. Springborg, *J. Am. Chem. Soc.*, 104, 601 (1982).
21. M.P. Suh, W. Shin, S.-G. Kang, M.S. Lah and T.-M. Chung, *Inorg. Chem.*, 28, 1602 (1989).
22. C.A. Salata, M.-T. Youinou and C. Burrows, *J. Am. Chem. Soc.*, 111, 9278 (1989).
23. Ch.O. Dietrich-Buchecker and J.-P. Sauvage, *Chem. Rev.*, 87, 795 (1987).
24. Ch.O. Dietrich-Buchecker, J.-P. Sauvage and J.M. Kern, *J. Am. Chem. Soc.*, 106, 3043 (1984).
25. Ch.O. Dieterich-Buchecker and J.-P. Sauvage, *Angew. Chem. Int. Ed. Engl.*, 28, 189 (1989).
26. Ch.W.G. Ansell, M.K. Cooper, K.P. Dancey, P.A. Dukworth, K. Henrrick, M. McPartlin and P.A. Tasker, *J. Chem. Soc., Chem. Commun.*, 440 (1985).
27. K.N. Raymond, *J. Incl. Phenom. & Mol. Recogn. In Chem.*, 7, 169 (1989).
28. G.A. Lawrance, M. Maeder, T.M. Manning, M.A. O'Leary, B.W. Skelton and A.H. White, *J. Chem. Soc., Dalton Trans.*, 2491 (1990).
29. P. Comba, G.A. Lawrance, T.M. Manning, A. Markiewicz, K.S. Murray, M.A. O'Leary, B.W. Skelton and A.H. White, *Austr. J. Chem.*, 43, 69 (1990).

30. G.A. Melson (Ed.), *Coordination Chemistry of Macrocyclic Compounds*, Plenum Press, New York, London (1979).
31. D.St.C. Black and A.J. Hartshorn, *Coord. Chem. Rev.*, 9, 219 (1972).

Section 1.3

1. G. Wang and L. Miao, *Guodeng. Xuexiao Hua Xua Xuebao*, **5**, 28 (1984).
2. A.M. Arif, C.J. Gray, F.A. Hart and M.B. Hursthouse, *Inorg. Chim. Acta*, **109**, 179 (1985).
3. J.D.J. Backer-Dirks, C.J. Gray, F.A. Hart, M.B. Hursthouse and B.C. Schoop, *J. Chem. Soc., Chem. Commun.*, 774 (1979).
4. W. Radecka-Paryzek, *Inorg. Chim. Acta*, **52**, 261 (1981).
5. K.K. Abid and D.E. Fenton, *Inorg. Chim. Acta*, **95**, 119 (1984).
6. W. Radecka-Paryzek, *Inorg. Chim. Acta*, **109**, L21 (1985).
7. K.K. Abid and D.E. Fenton, *Inorg. Chim. Acta*, **82**, 223 (1984).
8. D.E. Fenton and P.A. Vigato, *Chem. Soc. Rev.*, **17**, 69 (1988).
9. D.E. Fenton, S.J. Kitchen, C.M. Spencer, S. Tamburini and P.A. Vigato, *J. Chem. Soc., Dalton Trans.*, 685 (1988).
10. M. Sakamoto, *Bull. Chem. Soc. Jpn.*, **60**, 1546 (1988).
11. K.N. Raymond, *J. Incl. Phenom. & Mol. Recogn. in Chem.*, **7**, 169 (1988).

Section 1.4

1. P. Besler, L. De Cola and A. von Zelewsky, *J. Chem. Soc., Chem. Commun.*, 1058 (1988).
2. J.G. Muller, J.J. Grzybowski and K.J. Takeuchi, *Inorg. Chem.*, **25**, 2665 (1986).
3. H.A. Boucher, G.A. Lawrance, P.A. Lay, A.M. Sargeson, A.M. Bond, D.F. Sangster and J.C. Sullivan, *J. Am. Chem. Soc.*, **105**, 4652 (1983).
4. J.MacB. Harrowfield, A.J. Herlt, P.A. Lay and A.M. Sargeson, *J. Am. Chem. Soc.*, **105**, 5503 (1983).

Section 1.5

1. S.M. Nelson, *Pure & Appl. Chem.*, **52**, 2461 (1980).
2. D.H. Cook, D.E. Fenton, M.G.B. Drew, A. Rodgers, M. McCann and S.M. Nelson, *J. Chem. Soc., Dalton Trans.*, 414 (1979).
3. H. Adams, N.A. Bailey, D.E. Fenton, R.J. Good, R. Moody and C.O. Rodriguez de Barbarin, *J. Chem. Soc., Dalton Trans.*, 207 (1987).
4. B.P. Murphy, J. Nelson, M.G.B. Drew, P. Yates and S.M. Nelson, *J. Chem. Soc., Dalton Trans.*, 123, 1987.
5. N.A. Bailey, D.E. Fenton, P.B. Roberts and A.M. Walford, *J. Chem. Soc., Dalton Trans.*, 1865 (1987).
6. F.V. Acholla and K. Bowman Mertes, *Tetrahedron Lett.*, **25**, 3269 (1984).

Section 1.6

1. M. Bühner, W. Geuder, W.-K. Gries, S. Hning, M. Koch and T. Poll, *Angew. Chem. Int. Ed. Engl.*, **27**, 1553 (1988).
2. W. Moneta, P. Baret and J.-L. Pierre, *J. Chem. Soc., Chem. Commun.*, 899 (1985).
3. P.R. Ashton, T.T. Goodnow, A.E. Kaifer, M.V. Reddington, A.M.Z. Slawin, N. Spencer, J.-F. Stoddart, C. Vincent and D.J. Williams, *Angew. Chem. Int. Ed. Engl.*, **28**, 1396 (1989).

Section 2

1. L. Rossa and F. Vogtle, *Topic Curr. Chem.*, **113**, 1 (1983).
2. A. Muller and L. Kindlmann, *Ber. Dtsch. Chem. Ges.*, **74**, 416 (1941).
3. A. Muller, E. Srepel, E. Funder-Fritzsche and F. Dicher, *Monatsch. Chem.*, **83**, 386 (1952).
4. H. Stetter and E.-E. Ross, *Chem. Ber.*, **87**, 566 (1954).
5. T. Doornbos and J. Starting, *Org. Prep. Proc.*, **101**, 1970.
6. H. Setter and E.-E. Ross, *Chem. Ber.*, **88**, 1390 (1950).
7. H. Setter and J. Marx, *Liebigs Ann. Chem.*, **607**, 59 (1957).
8. M. Rothe, *Angew. Chem.*, **74**, 725 (1962).

9. M. Rothe, I. Rothe, H. Brning and K.D. Schwenke, *Angew. Chem.*, 71, 700 (1959).
10. Y. Nago, K. Seno, T. Miyasaka and E. Fujita, *Chem. Lett.*, 159 (1980).
11. D.A. Laidler and J.F. Stoddart, in "Synthesis of Crown Ethers and Analogues" (S. Patai Ed.); *The Chemistry of Functional Groups*, Supl. part 1, J. Wiley and Sons, Chichester–New York–Brisbane–Toronto (1980).
12. N.K. Dalley, in "Synthesic Multidentate Macrocyclic Compounds", (R.M. Izatt and J.J. Christensen Eds.), Academic Press, New York–San Francisco–London, 1973, Chapter 4, p. 207–243.
13. J.-M. Lehn, *Struct. & Bonding*, 16, 1 (1973).
14. R.M. Izatt and J.J. Christensen, *Progress in Macrocyclic Chemistry*, J. Wiley, New York (1979).
15. J.J. Christensen, D.J. Eatough and R.M. Izatt, *Chem. Rev.*, 74, 351 (1974).
16. B. Dietrich, J.-M. Lehn and J. Blanzat, *Tetrahedron*, 29, 1629 (1973).
17. J. Canceill, A. Collet, J. Gabard, F. Kozyba-Hibert and J.-M. Lehn, *Helv. Chim. Acta*, 65, 1894 (1982).

Section 3

1. N.W. Alcock, R.G. Kingston, P. Moore and C. Pierpoint, *J. Chem. Soc., Dalton Trans.*, 1937 (1984).
2. N.A. Bailey, M.M. Eddy, D.E. Fenton, S. Moss, A. Mukhopadhyay and G. Jones, *J. Chem. Soc., Chem. Commun.*, 628 (1981).
3. D.E. Fenton and R. Moody, *J. Chem. Soc., Dalton Trans.*, 219 (1987).
4. M. Pietraszkiewicz and R. Gasiorowski, *Chem. Ber.*, 123, 405 (1990).
5. D. McDowell, J. Nelson, V. McKee and M.G.B. Drew, *Book of Abstracts, 13th Int. Symp. on Macrocyclic Chem.*, Hamburg 1988, p. 200.
6. D. McDowell and J. Nelson, *Tetrahedron Lett.*, 385 (1988).
7. J. Jazwinski, J.-M. Lehn, D. Lilienbaum, R. Ziessel, J. Guilhem and C. Pacsard, *J. Chem. Soc., Chem. Commun.*, 1691 (1987).
8. I. Tabushi and K. Yamamura, *Topics Curr. Chem.*, 113, 145 (1983).
9. A. Collet, *Tetrahedron*, 43, 5725 (1987).
10. J.B. Niederl and J.H. Vogel, *J. Am. Chem. Soc.*, 62, 2512 (1940).
11. D.J. Cram, S. Karbach, H.-E. Kim, C.B. Knobler, E.F. Maverick, J.L. Ericson and R.C. Hegelson, *J. Am. Chem. Soc.*, 110, 2229 (1988).
12. D. Gutsche, in "Calixarenes", *Monographs in Supramolecular Chemistry Series*, Ed. J.F. Stoddart, *Royal Soc. Chem.*, 1989, UK.

Section 4

1. J.E. Richman and T.J. Atkins, *J. Am. Chem. Soc.*, 99, 2268 (1974).
2. J.E. Richman, T.J. Atkins and F.W. Oettle, *Org. Synth.*, 58, 86 (1978).
3. G.H. Searle and R.J. Geue, *Austr. J. Chem.*, 37, 959 (1984).
4. M. Iwata and H. Kuzuhara, *Bull. Chem. Soc. Jpn.*, 62, 198 (1989).
5. B. Dietrich, M.W. Hosseini, J.-M. Lehn and R.B. Sessions, *Helv. Chim. Acta*, 66, 1262 (1983).
6. G.R. Newkome, V.K. Majestic and F.R. Fronczek, *Tetrahedron Lett.*, 3039 (1981).
7. M. Pietraszkiewicz, P. Salanski and J. Jurczak, *Bull. Polish Acad. Sci.*, 33, 432 (1985).
8. M. Pietraszkiewicz, P. Salanski and J. Jurczak, *Heterocycles*, 23, 547 (1985).
9. M. Pietraszkiewicz, P. Salanski, R. Ostaszewski and J. Jurczak, *Heterocycles*, 24, 1203 (1986).
10. F.H. Kohnke, A.M.Z. Slawin, J.F. Stoddart and D.J. Williams, *Angew. Chem. Int. Ed. Engl.*, 26, 892 (1987).
11. M. Pietraszkiewicz, P. Salanski and J. Jurczak, *Tetrahedron*, 40, 2971 (1984).
12. M. Pietraszkiewicz, P. Salanski and J. Jurczak, *J. Carbohydr. Chem.*, 4, 429 (1985).
13. J. Jurczak and M. Pietraszkiewicz, *Topics Curr. Chem.*, 130, 183 (1985).
14. J. Yamawaki and T. Ando, *Chem. Lett.*, 533 (1980).
15. M. Pietraszkiewicz and J. Jurczak, *J. Chem. Soc., Chem. Commun.*, 132 (1983).
16. M. Pietraszkiewicz, *J. Incl. Phenom.*, 2, 195 (1984).
17. P.-L. Kuo, M. Miki, I. Ikeda and M. Okahara, *J. Am. Oil Chem. Soc.*, 227 (1980).
18. H. Maede, Y. Nakatsuji and M. Okahara, *J. Chem. Soc., Chem. Commun.*, 471 (1981).
19. E. Kimura, *Pure & Appl. Chem.*, 58, 1461 (1986).

Monographs

1. G.A. Melson (Ed.), *Coordination Chemistry of Macrocyclic Compounds*, Plenum Press, New York, London (1979).
2. G.W. Gokel and S.H. Korzeniowski (Eds.), *Macrocyclic Polyether Syntheses*, Springer-Verlag, Berlin, Heidelberg, New York (1982).
3. R.M. Izatt and J.J. Christensen (Eds.), *Synthetic Multidendat Macrocyclic Compounds*, Academic Press, San Francisco, London (1978).
4. R.M. Izatt and J.J. Christensen (Eds.), *Progress in Macrocyclic Chemistry*, Vol. 1, Wiley, New York (1979).
5. R.M. Izatt and J.J. Christensen (Eds.), *Progress in Macrocyclic Chemistry*, Vol. 2, Wiley, New York (1981).
6. R.M. Izatt and J.J. Christensen (Eds.), *Progress in Macrocyclic Chemistry*, Vol. 3, Wiley, New York (1987).
7. F. Vogtle (Ed.), *Host-Guest Complex Chemistry I, Top. Curr. Chem.*, **98**, Springer-Verlag, Berlin, Heidelberg, New York (1981).
8. F. Vogtle (Ed.), *Host-Guest Complex Chemistry II, Top. Curr. Chem.*, **101**, Springer-Verlag, Berlin, Heidelberg, New York (1982).
9. F. Vogtle and E. Weber (Eds.), *Host-Guest Complex Chemistry III, Top. Curr. Chem.*, **121**, Springer-Verlag, Berlin, Heidelberg, New York (1984).
10. F. Vogtle and E. Weber (Eds.), *Biomimetic and Bioorganic Chemistry, I–III, Top. Curr. Chem.*, **128, 132, 136**, Springer-Verlag, Berlin, Heidelberg, New York (1985).
11. F. Vogtle and E. Weber (Eds.), *Host-Guest Complex Chemistry–Macrocycles-Synthesis, Structures, Applications*, Springer-Verlag, Berlin, Heidelberg, New York, Tokyo (1985).

Reviews

1. D.St.C. Black and A.J. Hartshorn, "Ligand Design and Synthesis", *Coord. Chem. Rev.*, **9**, 219 (1972).
2. J.S. Bradshaw and J.Y.K. Hui, "Macrocyclic Sulphide Syntheses: A Review", *J. Heterocyc. Chem.*, **11**, 649 (1974).
3. J.J. Christensen, D.J. Eatough and R.M. Izatt, "The Synthesis and Ion Binding of Synthetic Multidentate Macrocyclic Compounds", *Chem. Rev.*, **74**, 351 (1974).
4. D.J. Cram, "Synthetic Host-Guest Chemistry", in *Application of Biochemical Synthesis in Organic Systems Part II*, J.B. Jones, C.J. Sih, D. Perlmann (Eds.), Techniques of Chemistry, Vol. X, Wiley, New York, 1976, p. 815.
5. G.R. Newcome, J.D. Saner, J.M. Roper and D.C. Hager, "Construction of Synthetic Macrocyclic Compounds Possessing Subheterocyclic Rings, Specifically Pyridine, Furan and Thiophene", *Chem. Rev.*, **75**, 513 (1977).
6. J.S. Bradshaw, G.E. Maas, R.M. Izatt and J.J. Christensen, "Synthetic Macrocyclic Di- and Tetraester Compounds", *Chem. Rev.*, **79**, 37 (1979).
7. J.-M. Lehn, "Macrocyclic Receptor Molecules: Aspects of Chemical Reactivity, Investigations into Molecular Catalysis and Transport Processes", *Pure & Appl. Chem.*, **51**, 979 (1979).
8. G.W. Gokel, D.M. Dishong, R.A. Schultz and V.J. Gatto, "Syntheses of Aliphatic Azacrown Compounds", *Synthesis*, 997 (1982).
9. S.T. Jolley, J.S. Bradshaw and R.M. Izatt, "Synthetic Chiral Macrocyclic Crown Ligands: A Short Review", *J. Heterocycl. Chem.*, **19**, 3 (1982).
10. V.K. Majestic and G.R. Newcome, "Pyridinophanes, Pyridinocrowns and Pyridinocryptands", *Top. Curr. Chem.*, **106**, 79 (1982).
11. R. Bhula, P. Osvath and D.C. Weatherburn, "Complexes of Tridendate and Pentadentate Macrocyclic Ligands", *Coord. Chem. Rev.*, **91**, 89 (1988).
12. P. Chaudhuri and K. Wieghardt, "The Chemistry of 1,4,7-Triazacyclononane and Related Tridendate Compounds", *Progr. Inorg. Chem.*, **35**, 329 (1987).
13. K.E. Krakowiak, J.S. Bradshaw and D.J. Zaniecka-Krakowiak, "Synthesis of Aza-Crown Ethers", *Chem. Rev.*, **89**, 929 (1989).