Studies in Supramolecular Chemistry: Synthesis and Host-Guest Interactions of some Oxygen Macrocycles and Podands

A Thesis
Submitted for the Degree of
Doctor of Philosophy

By

A. Manjula

School of Chemistry
University of Hyderabad
Hyderabad 500 046, India

April 1997

Dedicated
to My
Parents

CONTENTS

DECLARATION

I hereby declare that the **matter** embodied in this thesis is **the** result of investigations carried out by me in the School of Chemistry, University of Hyderabad, Hyderabad under the supervision of Prof. M. Nagarajan.

In keeping with the general practice of reporting scientific observations, due acknowledgements have been made wherever the work described is based on the findings of other investigators.

A. Manjula

A. MANJULA

CERTIFICATE

This is to certify that the work described in this thesis entitled **Studies in Supramolecular Chemistry: Synthesis and Host-Guest interactions of** some **Oxygen Macrocycles and Podands** has been carried out by *Ms. A. Manjula,* under my supervision and the same has not been submitted elsewhere for any degree.

M. NAGARAJAN
(THESIS SUPERVISOR)

DEAN

School of Chemistry,
University of Hyderabad,
Hyderabad - 500 046
INDIA

ACKNOWLEDGEMENTS

I express my heart-felt gratitude to Professor M. Nagarajan, whose inspiring guidance throughout my stay has helped me cultivate a systematic and philosophical approach towards research. I am indebted to him for his open-mindedness and the freedom he rendered me in doing the work of my choice. He has been a teacher in the true sense of the word. I also thank his wife, Ms. Manikarnika Nagarajan and his lovely daughter, Jahnavi, for the hospitality they extended.

I thank Professor P. S. Zacharias, Dean, School of Chemistry, for his support. I am very much grateful to Dr. M. Durga Prasad and Dr. A Samanta for their help at various stages. I would like to thank Dr. B. G. Maiya and Professor D. Basavaiah for their help. My due respects to all other faculty members of the school for their inspiring lectures and encouragement throughout Prof. T. N. Guru Row, IISc is acknowledged for providing the crystal structure.

The pleasant and co-operative atmosphere extended by my labmates throughout the stay is appreciated. I am grateful to my senior colleagues Drs. R. Murali, K. Narkunan, P. K. Vasudeva and B. L. A. Prabhavathi Devi for the help and support during the formative years. I am very much indebted to C. V. Ramana and A V. R. L. Sudha who have been a source of constant encouragement. They prevented me from getting stuck in the rut in the darkest moments. Their suggestions and proof-reading have been invaluable in the preparation of this thesis. The friendly association with Mr. K. R. Lakshmikanthan and Ms. Bhagyalakshmi is acknowledged.

I have been extremely fortunate in having some good friends who have made my stay at the school a memorable one. Amongst whom Hitler, Rakasi, G. F., Chandu, T. B., Sreelu and Souji deserve a special mention for never making me feel at home. Venkat, Saroja and Prasad have been extremely helpful during the thesis preparation. I thank T. A. R., Aneetha, Vijju, Sindhu, Ramalakshmi, Prasuna, Mangai, Brahmananda, Arounaguiri, Prasanna and all other friends for their help and co-operation. I appreciate the encouragement I received from my classmates, especially, Rajju. The homely atmosphere created by Rama and Rukku is appreciated.

Thanks are also due to the non-teaching staff of the School of Chemistry, especially to Mr. Shetty and family, Mr. R. Venkat Rao and family, Mr. Satyanarayana, Mr. Bhaskar Rao, Mrs. Vijayalakshmi, Mrs. Ayesha Begum, Mr. Venkataramana, Mr. Santosh Mr. Ramakrishna and Mr. Prasad for their assistance during the course of my research period.

The financial help from UGC is gratefully acknowledged. Gift samples of cyclodextrins and cesium carbonate from Amaize and Chemtall GMBH, respectively, are appreciated. Acknowledgements are due to CDRI, Lucknow for recording FAB mass spectra.

I am immensely indebted to my parents, brother and sister for their unflinching belief in my endeavours, but for whose motivation I would not have come this far.

I am at loss of words in expressing my gratitude to Naren, who practically sacrificed his wife to chemistry. I owe him a lot for his patience and support throughout. Support and encouragement from other members of the family is also acknowledged.

ABBREVIATIONS

A	Angstrom
AcOH	acetic acid
aq	aqueous
Bn	benzyl
CD	cyclodextrin
DMF	dimethylformamide
DDQ	2,3-dichloro-5,6-dicyano-1,4-benzoquinone
EtOH	ethanol
Et	ethyl
eq	equivalent
g	gram
h	hour(s)
Hz	hertz
Me	methyl
min	minute(s)
ml	millilitre(s)
mmol	millimole(s)
nm	nanometers
ns	nanosecond
Ph	phenyl
Pr	propyl

rt	room temperature
TCNQ	7,7,8,8-tetracyanoquinodimethane
THF	tetrahydrofuran
TMS	trimethylsilyl
Ts	*p*-toluenesulfonyl (tosyl)
UV	ultraviolet

ABSTRACT

This thesis is divided into three chapters, apart from a general introduction. Chapter 1 is concerned with the synthesis and complexation studies of a hitherto unknown naphthalene based oxygen macrocycle. The synthesis and cation binding capabilities of Troger's base based crown ethers are presented in chapter 2. Encapsulation of podands containing aromatic end groups by the hydrophobic cavities of cyclodextrins and the ensuing effect of the encapsulation on their photophysical properties is dealt with in chapter 3. Each chapter has an introduction, results and discussion and experimental sections, along with relevant references.

Chapter 1

In chapter 1, the study of supermolecules assembled by π-stacking and charge transfer interactions between the π-donor host, 1,4-dinaphtho-34-crown-10 (1,4-DN34C10, 27), and π-acceptor guests is detailed. 1,4-DN34C10 (27) apart from being an excellent host for π-acceptor guests, can also serve as a fluorescent cation detection probe.

The protocol adopted for the synthesis of 27 involved the sequential addition of two polyether chains to a differentially 1,4-disubstituted naphthalene. When 4-bromo-1-methoxynaphthalene 39 was utilised as starting material, the etherification gave two products of which the bis ether 41 was formed in 18% yield. However, cleavage of the methyl ether could not be realised under the conditions examined. The corresponding bis-benzyl ether 48 (obtained in 38% yield), however, cleaved readily with Pearlman's catalyst to yield the diol 43. This was then cyclised with tetraethylene glycol ditosylate to obtain 1,4-DN34C10 (27) in 32% yield. Earlier attempts at synthesising 27 from 1,4-dibromonaphthalene and 4-bromo-1-naphthol were unsuccessful.

Crystal structure data refined isotropically to an R value of 0.14 indicates that the host belongs to the monoclinic ($P2_1/n$) space group. The host supports a preorganised cavity for guest binding.

The UV-spectrum of 1,4-DN34C10 was found to be sensitive to metal ion presence. However, the changes were too small to quantify. 1,4-DN34C10 readily formed charge transfer complexes with 1,1'-dimethyl-4,4'-bipyridinium bis(hexafluorophosphate) (paraquat), 5,6-dihydropyrazino[1,2,3,4-lmn][1,10]phenanthrolinediium bis(hexafluoro phosphate) (phenquat) and 2,4,5,7-tetranitrofluorenone (TetNF). The stoichiometries of the solid complexes were 1 : 1 for both the quats and 1 : 2 for TetNF.

The binding constants of these complexes were evaluated by the NMR titration method. Both the quats show strong 1 : 1 binding. TetNF complex showed a 1 : 1 stoichiometry in solution with a low binding constant.

Chapter 2

The conformationally restricted Troger's base derivatives were utilised as rigid caps in the construction of large crown ethers 23a-c. Attempts to construct the macrocycle by fabricating the polyether framework first and then building the dibenzodiazocene were not fruitful.

Alternatively and successfully, the dibenzodiazocene unit was built first and the polyether frame attached later. The crown ethers 23a-c were thus assembled in 25, 32 and 20% yields, respectively.

Cation binding capacities were evaluated by Cram's picrate extraction method. The log Ka values indicated that all the macrocycles show reasonably good extraction capabilities and binding affinities with all the ions under consideration. There was, however, no selectivity towards any specific cation. This is reflective of the high flexibility and large cavity inherent in the complexation core of the macrocycles.

A theoretical calculation of the optimised conformations of macrocycles **23a-c** at AM 1 level also indicated that the sizes of the cavities are too large for any selective cation binding.

Chapter 3

In chapter 3, a study of the influence of metal cations and γ-cyclodextrin (CD) on the photophysical properties of isomeric podands is presented. All the podands chosen had the general frame of a tetraethylene glycol unit with aromatic end groups that were established to be good fluorophores **(17a-19b).** Synthesis of the podands was accomplished in a fairly straightforward manner by treating 2eq of the corresponding phenol with tetraethylene glycol ditosylate and NaH in DMF/THF.

Absorption spectra showed no appreciable changes on the addition of sodium perchlorate and potassium thiocyanate. The addition of metal salts to the solutions of podands only resulted in anion induced quenching of aromatic fluorescence.

On addition of *y-CD,* the absorption spectra of both the naphthyl podands **(17a** & 17b) exhibited an increase in the intensity of absorption with clear isosbestic points at 310 and 300 nm, respectively. The anthryl podands

(18a & **18b)** exhibited no changes on addition of y-CD, while the phenanthryl podands **(19a** & **19b)** showed a marginal enhancement in the absorption intensity.

The fluorescence spectra of naphthyl podands **17a** & **17b** exhibited excimer emissions at 410 nm and 414 nm, respectively, in the presence of y-CD. On addition of metal salts to the already y-CD loaded samples, both monomer and excimer emissions were completely quenched in **17a,** while only monomer emission was completely quenched in **17b.** When the sequence of additions was reversed, the long wavelength emissions appeared in both isomers, with no change in the peak maxima.

The fluorescence intensities of **18a** & **18b** were considerably enhanced on addition of y-CD. The reversal of the addition sequence resulted in the enhancement of the fluorescence already quenched by the addition of the metal salts. A similar trend was exhibited by the isomeric phenanthryl podands, 19a & **19b,** as well.

Indtrudction

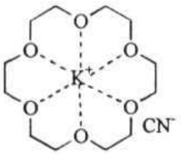
INTRODUCTION

Nature has played and continues to play a major role in the development of and progress in organic chemistry. All life processes are essentially achieved by arrays of molecules working together in synchronisation rather than by discrete molecules acting in isolation. In order to duplicate the diversity and complexity of the life processes, there is a need to understand the factors that control aggregation of molecules into assemblies performing specific functions. Thus, the quest for replicating even remotely similar systems to that of Nature led to the development of a totally new branch of chemistry called *Supramolecular Chemistry*, defined as 'the chemistry concerning the structures and functions of *Supermolecules* formed by association resulting from the molecular interactions between two or more molecules/chemical species, i.e., *chemistry beyond the concept of molecule*'. This branch of chemistry, though nominally organic chemistry with respect to the species involved, has revolutionised the concept of synthesis, for it is no longer concerned with forming covalent bonds to create molecules alone, but also in harnessing noncovalent forces to create supermolecules.

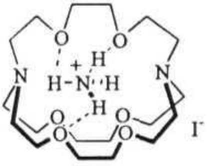
Conceptually, supramolecular chemistry can be broadly classified into host-guest chemistry and self-assembly. The former involves species combining with one another in small integer ratios, comprising a host that specifically accommodates a guest, thus leading to molecular recognition. The latter describes the building up of noncovalent arrays of defined geometry from specifically engineered molecular components. Supramolecular chemistry is, therefore, the chemistry of noncovalently bound species and noncovalent interactions play an important role in self-assembly and stabilisation of supermolecules. The forces encountered in supramolecular chemistry are electrostatic interactions, van der Waals interactions, hydrogen bonding and charge transfer interactions. Unlike covalent forces, the above mentioned forces are much weaker and are easily disrupted (a typical H-bond has 20 kJ mol^{-1} energy and a lifetime of the order of 10" sec). Despite their lability, many higher order structures are capable of discrete existence on the same time scale as covalent species due to the large number, and often co-operative nature, of the interactions involved, as also the high structural organisation produced through multiple binding. This organisation which is recognition directed, *i.e.*, directed by the capacity to distinguish one spatial relationship from another, requires the presence of information that is expressed at the molecular level as two types of fundamental complementarity: steric and functional. Steric complementarity plays a vital role in reaching an optimal geometry and interface for weak interactions. Functional complimentarity refers to the reciprocal functionality with which the subunits enter into noncovalent bonding relationships. To express a preferred molecular motif on a molecular scale, a species with the right kind of functional and steric information is required which could recognise and organise into the supermolecule desired.

Ever since the report of the discovery of the first synthetic ionophores by C. J. Pedersen in 1967, and more so since the awarding of the Nobel prize to C. J. Pedersen, D. J. Cram and J.-M. Lehn, the pioneers of this field, there has been an impetus to synthesise more and more novel structures with fascinating micro and macroscopic architectures endowed with novel functions. A concise description of supramolecular systems that exemplify the above mentioned noncovalent interactions is therefore in order.

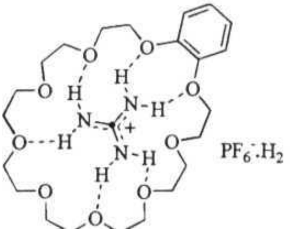
Multidentate macrocyclic compounds with heteroatoms, such as O, N, S, P and Se, having the ability to incorporate specific cations into their cavities were amongst the first to be synthesised. They are referred to by a general term, coronand. A multitude of them have been synthesised and categorised variously. The oxygen bearing macrocycles are called crown ethers, sulfur containing ones, thiacrown ethers and nitrogen bearing ones, azacrowns. Their acyclic counterparts, termed as podands, show very little selectivity, whereas their bicyclic counterparts with bridgeheads, called cryptands, display tetrahedral recognition. The most striking feature of these compounds is their selective complexation ability to bind the cationic portion of alkali, alkaline earth, transition metal, ammonium and guanidinium salts, incorporating them as guests into the cavity of the crown ring (host) through ion-dipole interactions (Fig. 1).



18 CROWN 6 (1)



|2.2.2] CRYPTAND (2)

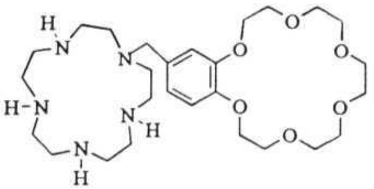


BENZO-27 CROWN 9 (3)

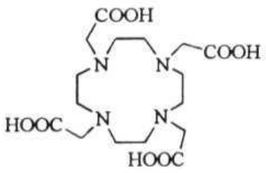
Figure 1

Selectivity in binding depends upon the size of the cavity of the host and diameter of the guest; the number of donor (hetero) atoms in the crown and topological effect; hardness of the host and the guest as well as the charge on the cation. These crowns and cryptands have been found to have a variety of analytical applications like separation, extraction, chromatography and electrophoresis of elements of the first and the second group. They have also been found to be excellent phase transfer catalysts.

The scenario underwent a complete transformation with the advent of bis crowns and multiloop crowns. More than one cation of same or different type could now be bound to the same host. This inspired the design and synthesis of novel hosts (eg. 4, Fig. 2) that could bind cations and anions simultaneously. A tighter binding of the guest could be achieved by a series of armed crown ethers or lariat ethers, wherein the co-operation between the ring and the side arm seals the guest tightly into the cavity. A typical example, azacrown ether 5 with side arms containing acetic acid moieties, encapsulates cations of lanthanide series of elements with an enhanced binding. Such systems are gaining popularity due to their applications in magnetic resonance imaging.



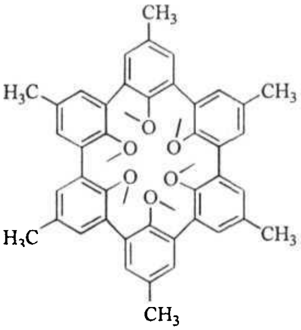
DITOPIC BINDER (4)



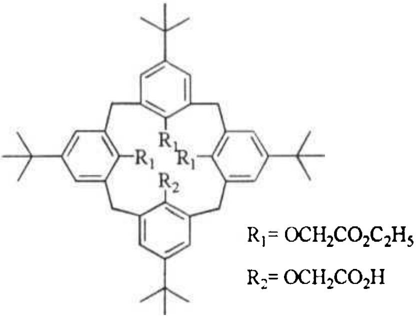
5

Figure 2

In all the above cases, conformational changes occur in the host during the complexation process, i.e., self organisation of the host takes place, which requires energy. In order to overcome this, Cram designed host molecules with rigid cavities in which conformational changes do not take place during the process of complexation. Thus, the host is now said to be preorganised to show more rigorous binding. The cavitands and spherands (6, Fig. 3) fall into this category. Among the preorganised hosts gaining prevalence of late are calixarenes, that also bind cations, selectivity being a function of cavity size and nature of binding groups **(7,** Fig. 3).



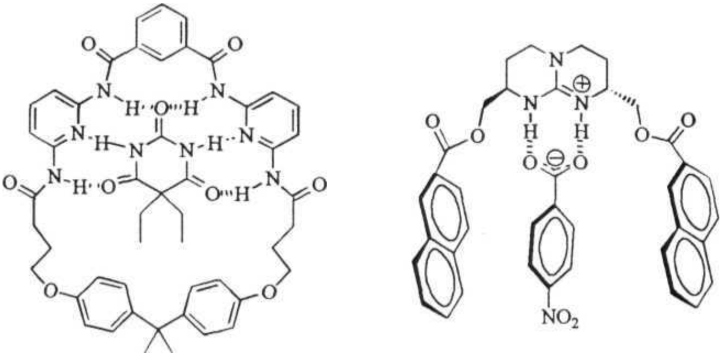
SPHERAND (6)



CALIXARENE (7)

Figure 3

Designing receptors for neutral molecules is still relatively a more challenging and less explored domain. Recently Hamilton reported a highly stable complex of the host 8 (Fig. 4) and a neutral guest by means of a designed network of hydrogen bonds.



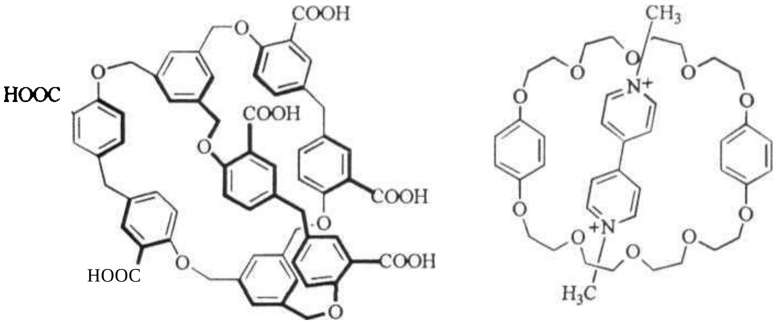
8

9

Figure 4

Very large, rigid cavities required to bind big molecules are very often difficult to construct. Moreover, it is observed that biomolecules like enzymes rarely have cavities that surround the substrate completely. This perception led to the designing of non-macrocyclic hosts with preorganised aromatic clefts, called molecular tweezers,[14] that contain two aromatic chromophores separated by a covalently linked spacer. They bind aromatic guests by forming a π-stacked, sandwich complex (9, Fig. 4).

Cyclophane type macrocycles containing aromatic units have a hydrophobic cavity of definite shape and dimensions. Molecular recognition study of a water soluble cyclophane host 10 (Fig. 5) synthesised by Lehn reveals that in aqueous medium the binding forces are both electrostatic and hydrophobic. The host 10 was found to bind to a variety of quaternary ammonium salts and acetylcholine.

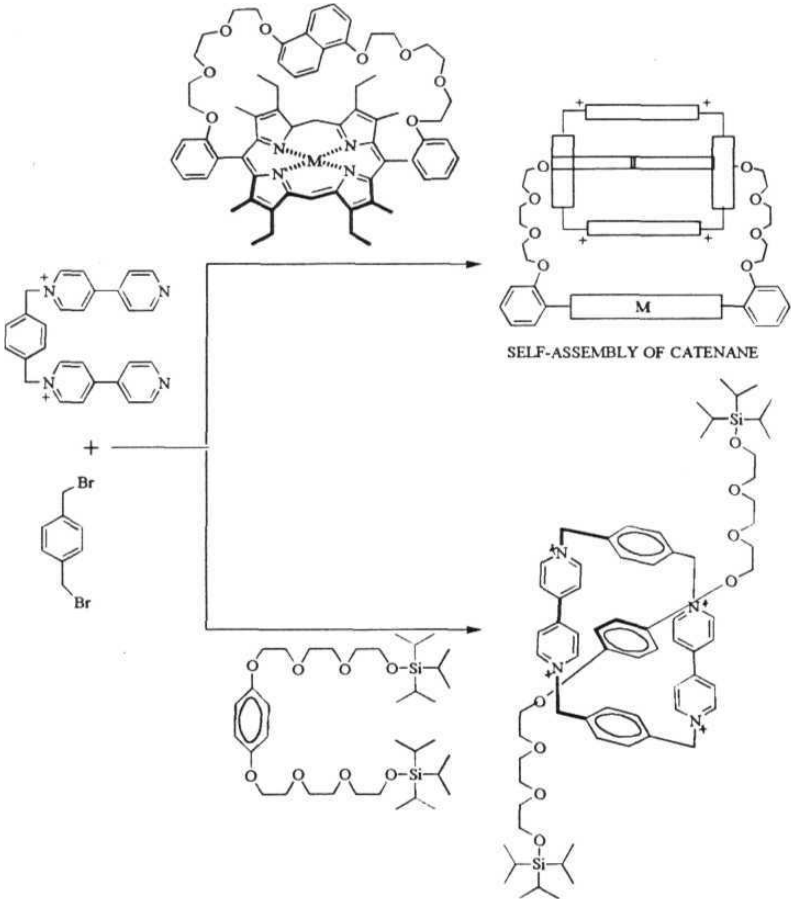


10

11

Figure 5

Cation-K and π-π-stacking interactions have been exploited in designing hosts for aromatic molecules (11, Fig. 5). The K-stacking and charge transfer interactions between K-electron rich and K-electron deficient systems function as templates for the one pot self assembly of interlocked rings or catenanes as well as beads on threads or rotaxanes (Fig. 6).

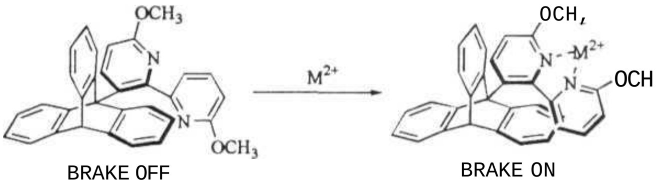


SELF-ASSEMBLY OF CATENANE

SELF-ASSEMBLY OF ROTAXANE

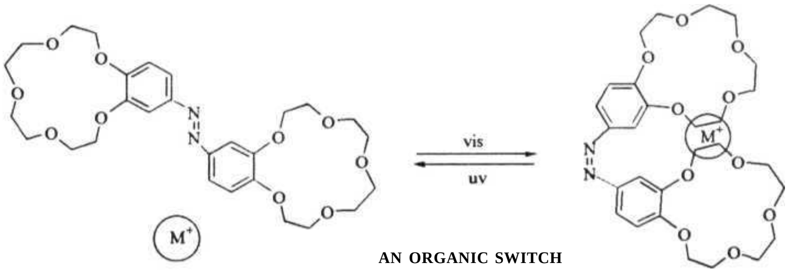
Figure 6

The knowledge gained by understanding the role played by noncovalent interactions in the self assembling processes of these simple artificial systems has led not only to a better understanding of physical organisation in biological systems, but has also inspired building of simple molecular devices, molecular machines (Fig. 7)[19] and molecular switches (Fig. 8).



A MOLECULAR BRAKE

Figure 7



AN ORGANIC SWITCH

Figure 8

From the brief description given above, it is clear that remarkable progress has been made in understanding host-guest interactions at the molecular level. However, there still exists a vast scope for further understanding the noncovalent interactions that hold the supramolecular structures together. An in-depth understanding of the structure-information-function relationship alone can lead to the development of supramolecular devices which can rival the ones that already exist in Nature. Central to this mission is the development of novel and simple chemical systems that can organise on their own due to their inherent recognition capabilities. In this context, we have undertaken the design, synthesis and study of some oxygen macrocycles and podands, each with a special kind of binding property involving different types of noncovalent interactions.

This thesis, dealing with some aspects of supramolecular chemistry is divided into three chapters. Chapter 1 is concerned with supermolecules assembled by 7r-stacking and charge transfer interactions involving a new naphthalene based macrocycle and suitable guests having π-stacking capabilities. Chapter 2 presents the synthesis of rigid molecular hosts based on Troger's bases and their cation binding abilities. Encapsulation of podands by hydrophobic cavities of cyclodextrins and the influence of this on their photophysical properties is discussed in chapter 3.

References:

1. J.-M. Lchn, *Angew. Chem. Int. Ed. Engl.,* **1988,** *27,* 89.
2. C. J. Pedersen, *J. Am. Chem. Soc,* **1967,** *89,* 2495 and 7017.
3. E. P. Kyba, R. C. Helgeson, K. Madan, G. W. Gokel, T. L. Tarnowski, S. S. Moore and D. J. Cram, J. *Am. Chem. Soc,* **1977,** *99,* 2564.
4. E. Blasius and K.-P. Janzen, *Top. Curr. Chem.,* **1983,** *98,* 163, Springer Verlag, Bcrlin.
5. E. Weber, *'Phase transfer catalysts, properties and applications ',* Merck-Schuchardt, Darmstadt, **1987.**
6. E. Kimura, *Crown ethers and analogous compounds',* in *'Studies in organic chemistry 45',* M. Hiraoka Ed., Elsevier, New York, **1992,** p. 381.
7. G. W. Gokel, *Chem. Soc. Rev.,* **1992,** 39.
8. W. Frank and H. Stetter, *Angew. Chem. Int. Ed. Engl.,* **1976,** *15,* 686.
9. H. Grics and H. Miklautz, *Physiol. Chem. Phys. Med. NMR,* **1984,** *16,* 105.
10. D. J. Cram, *Angew. Chem. Int. Ed. Engl,* **1988,** *27,* 1009.
11. F. A. Neu, V. Böhmer, L. Guerra, M. A. Mckervey, E. F. Paulus, A. Rodriguez, M. J. Schwin-weill, M. Tabatabai and W. Vogt, *J. Phys. Org. Chem.,* **1992,** *5,* 471.
12. S.-K. Chang and A. D. Hamilton, J. *Am. Chem. Soc,* **1988,** *110,* 1318.
13. C.-W. Chen and H. W. Whitlock, *J. Am. Chem. Soc,* **1978,** *100,* 4921.
14. A. Echaverren, A. Glan, J.-M. Lehn, and J. de Mendoza, *J. Am. Chem. Soc,* **1989,** *111,* 4994.
15. R. Meric, J. P. Vigneron and J.-M. Lehn, *J. Chem. Soc, Chem. Commun.,* **1993,** 129.

16. P. L. Anelli, P. R. Ashton, R. Ballardini, V. Balzani, M. Delagado, M. T. Gandolfi, T. T. Goodnow, A. E. Kaifer, D. Philp, M. Pietraskiewicz, L. Prodi, M. V. Reddington, A. M. Z. Slawin, N. Spencer, J. F. Stoddart, C. Vicent and D. J. Williams, *J. Am. Chem. Soc,* **1992,** *114*, 193.
17. M. J. Gunter, D. C. R. Hocless, M. R. Johnston, B. W. Sketon and A. H. White, *J. Am. Chem. Soc,* **1994,** *116*, 4810.
18. P. R. Ashton, M. Grognuz, A. M. Z. Slawin, J. F. Stoddart and D. J. Williams, *Tetrahedron Lett.,* **1991,** *32,* 6235.
19. T. R. Kelly, M. C. Bowyer, K. V. Bhaskar, D. Bebbington, A. Garcia, F. Lang, M. H. Kim and M. P. Jette, *J. Am. Chem. Soc,* **1994,** *116*, 3657.
20. S. Shinkai, T. Ogawa, Y. Jusano, O. Manabe, K. Kikukawa, T. Goto and T. Matsuda, *J. Am. Chem. Soc,* **1982,** *104*, 1960.

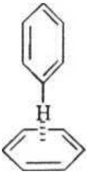
Chapter 1

Introduction

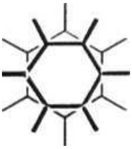
Interactions between aromatic molecules have been known and studied for over half a century. Strong attractive interactions between π-systems are a class of noncovalent intermolecular forces to reckon with in chemistry, biology and materials science as they control a range of recognition and self-assembly phenomena such as:

1. vertical base pair interactions which stabilise the DNA double helix and also intercalation of drugs into DNA,
2. the tertiary structure of proteins,
3. porphyrin aggregation,
4. the packing of aromatic molecules in crystals,
5. complexation in many host-guest systems especially with respect to conformational preferences and binding properties of polyaromatic macrocycles,
6. template directed synthesis.

Two major types of interactions are involved in π-systems, the edge-to-



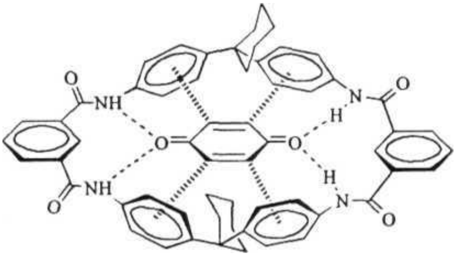
1



2

Figure 1

face and face-to-face interactions (Fig. 1). The former interactions involve the attraction of a proton of one aromatic molecule to the electron rich centre of the second (1, Fig. 1). This is a dominant motif in crystals of simple aromatics. Hunter[6] has designed a host that can complex guest molecules using edge-to-face interactions. The macrocycle selectively complexes *p*-benzoquinone (3, Fig. 2) with a high association constant $(K_a = 10^3\ M^{-1})$. Substitution of the benzoquinone unit with methyl group, chlorine, fluorine or fused aromatic rings for each of the quinone hydrogens, which would block the edge-to-face *n-n* interactions, inhibits the complexation $(K_a < 5$ M*).

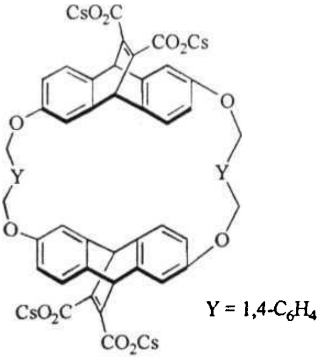


3

Figure 2

Face-to-face π-interactions (2, Fig. 1), the more common interactions, were observed by organic chemists even before the concept of aromaticity was clearly understood. The complexes between picric acid or trinitrobenzene, which are π-electron deficient (π-acceptors), with π-excessive or π-sufficient species {*n* -donors) were convenient derivatives for characterising aromatic hydrocarbons before the advent of modern spectroscopic techniques. These electron donor-acceptor (EDA) complexes were referred to as charge transfer complexes. Modern X-ray techniques reveal that the constituents of such a system lie parallel to each other. Although the exact nature of the forces involved in the formation of EDA complexes is a matter of debate, they are believed to be held together by van der Waals (dispersion as well as repulsion), electrostatic and polarisation (charge transfer) interactions.

Crown ethers and cyclophanes, especially the ones possessing aromatic moieties, are known to form charge transfer complexes with a variety of guests. Dougherty[a] designed a series of macrocycles, for example 4 (Fig. 3), incorporating two ethenoanthracene units, which provide a concave, rigid and hydrophobic surface for binding, connected by different spacers. These macrocycles were used to study complexation of diverse guests to provide new

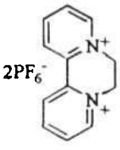


4

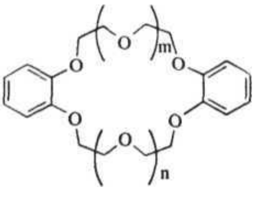
Figure 3

insights into the noncovalent binding interactions, chiefly cation-π interactions. These interactions involve the stabilisation of a positive charge by the face of an aromatic ring. The cation-π interactions are important binding forces in biological receptors like acetyl choline. Sufficiently electron deficient neutral molecules like nitro substituted aromatics and azulenes have also been shown to bind to the above set of hosts by *n* type interactions.

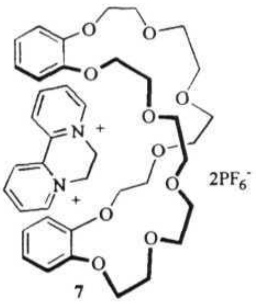
Stoddart has extensively investigated the interaction of dibenzo crowns 6 with the dipyridinium cations, diquat (S) and paraquat (15). A study of the complexation of a family of dibenzocrowns and diquat in acetone divulged that the association constants were sensitive to the polyether chain length (Table 1).[10] The data were interpreted by proposing a V- or U-shaped conformation for the macrocycle, with the aromatic rings lying parallel, providing a cavity for sandwiching the diquat. The X-ray crystal structure data authenticated the above contention.



5



6



7

Figure 4

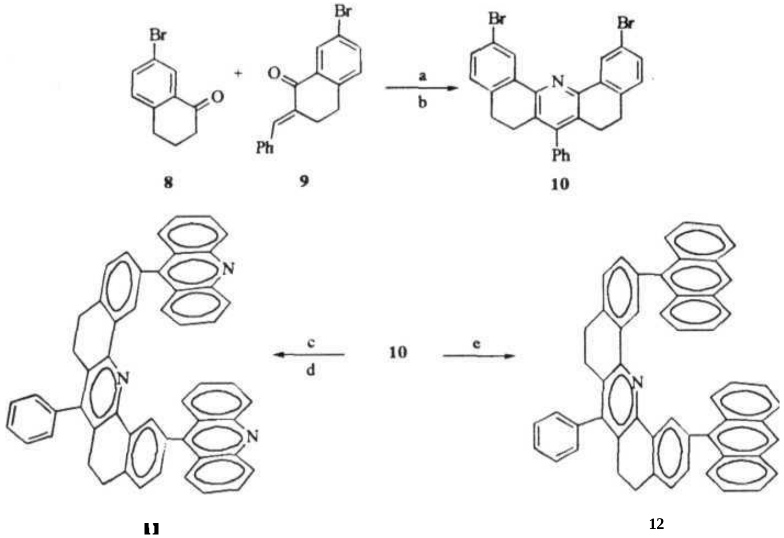
Another notable feature that the crystal structure revealed was that the aryl ether oxygens were each within van der Waals distance of nitrogen atoms of diquat, indicating a strong electrostatic component to complexation (7, Fig. 4).[11]

Table 1 Association constants for 1 : 1 complexes between diquat and dibenzocrown ethers 6 in acetone at 25 .

Receptor	m	n	
DB27C9	3	2	410
DB30C10	3	3	17500
DB33C11	4	3	10800
DB36C12	4	4	2000

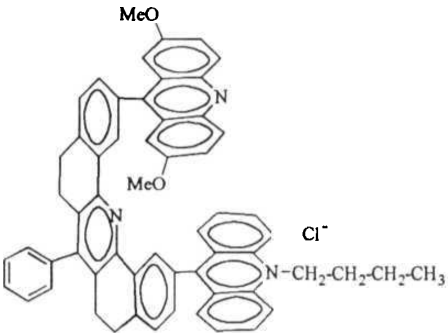
These π-sandwich complexes were the inspiration behind the synthesis of a variety of molecular clefts and tweezers.[12] Macrocycles with preorganised cavities were no longer seen as a prerequisite for efficient binding. Molecular tweezers, designed with a careful choice of complexing aromatic moieties and appropriate spacers to provide rigidity, have been shown to bind neutral guests with high binding affinities and selectivites. The binding was accomplished chiefly by π-stacking interactions and occasionally by H-bonding.

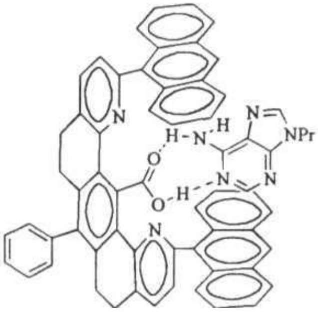
Based upon the above features, the tweezers 11, 12 and 13 were synthesised employing a general strategy (Scheme 1) and their binding capacities evaluated.[13] Only 13 (Fig. 5) containing both the donor and acceptor chromophores showed a tendency to aggregate in chloroform.



Scheme 1 *Reagents and conditions:* a) $BF_3{\cdot}OEt_2$, 100 ; b) NH_3, MeOH; c) *n*-BuLi, THF, -70 ; d) N-methoxyethoxymethylacridone; e) anthrylmagnesium bromide, $Ni(acac)_2$, PhH, Et_2O, reflux.

Binding studies with the tweezers **11** and 12 showed that they have no affinity towards rc-donor guests like naphthalene, but only towards re-acceptors **such** as 1,3,5-trinitrobenzene and 2,4,5,7-tetranitrofluorenone (TetNF). The binding with TetNF was monitored by both NMR and UV titration methods and complexation data (Table 2) indicate high binding affinities. Similarly, the tweezer 14 (Fig. 5) was found to show high binding affinity to 9-propyladenine. It is worth noting that the binding can further be enhanced by introducing additional binding sites on the tweezer, as now only 2 of the 5 H-bonding sites on adenine are used.





14

Figure 5

Table 2 Association constants of 11 and 12 with 2,4,5,7-tetranitrofluorenone and 14 with 9-propyladenine at 25

Receptor	**K_{assoc} (M^{-1})**	**-AG (kcal/mol)**
11	900	4.0
12	20000	5.9
14	120000	6.9

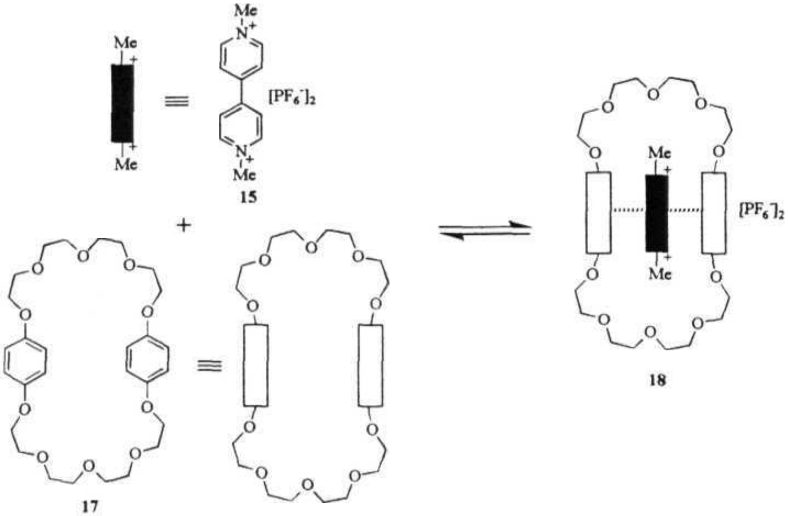
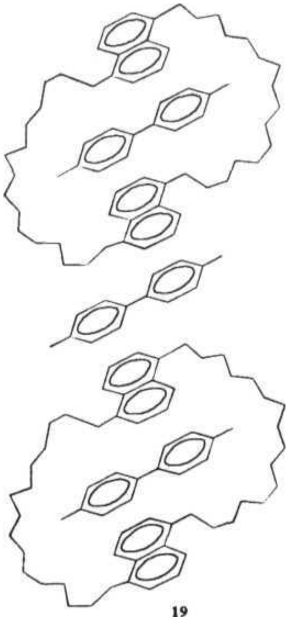


Figure 6

Another supramolecular system thoroughly exploited by Stoddart over the past decade involves 1,1'-dimethyl-4,4'-bipyridinium dication (15, trivial name paraquat) complexes with electron rich aromatic units. Paraquat is known to form complexes with aniline, *o*-phenylenediamine, catechol and hydroquinone. The crystal structure of the paraquat-hydroquinone complex reveals that the stacking is face-to-face with a separation of 3.38 A between *n*-planes. An extension of the complexation to the macrocyclic cavity bisparaphenylene-[34]-crown-10 (BPP34C10, 17, Fig. 6), generated a highly ordered superstructure in which the rod like paraquat lies in the cavity of BPP34C10 centrosymmetrically with the methyl groups facing the polyether linkages. (18, Fig. 6). The deep orange colour of the complex is indicative of charge transfer interactions. The crystal structure indicated extra stabilisation of the structure through C-H···O H-bonding interactions between the polyether oxygens and the methyl groups of the paraquat besides *n-n* stacking between the complementary π-systems.



19

Figure 7

A more noteworthy observation was made in the case of the paraquat and 1,5-dinaphtho-[44]-crown-12 (DN44C12) complex 19 (Fig. 7).[19a] It was found that the complex crystallises with 2 molecules of paraquat and not one as is the case with the rest of the dibenzo and dinaphtho crowns. One of the dications is included into the cavity and second is clatharated between the adjacent complexes in the crystal.

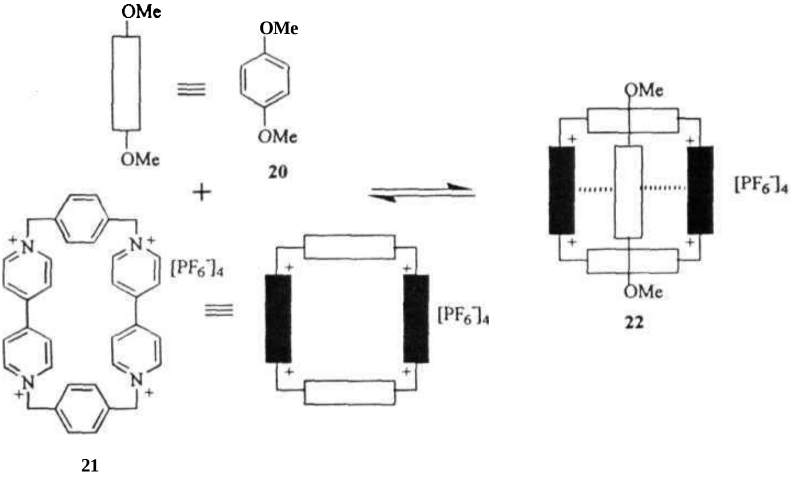
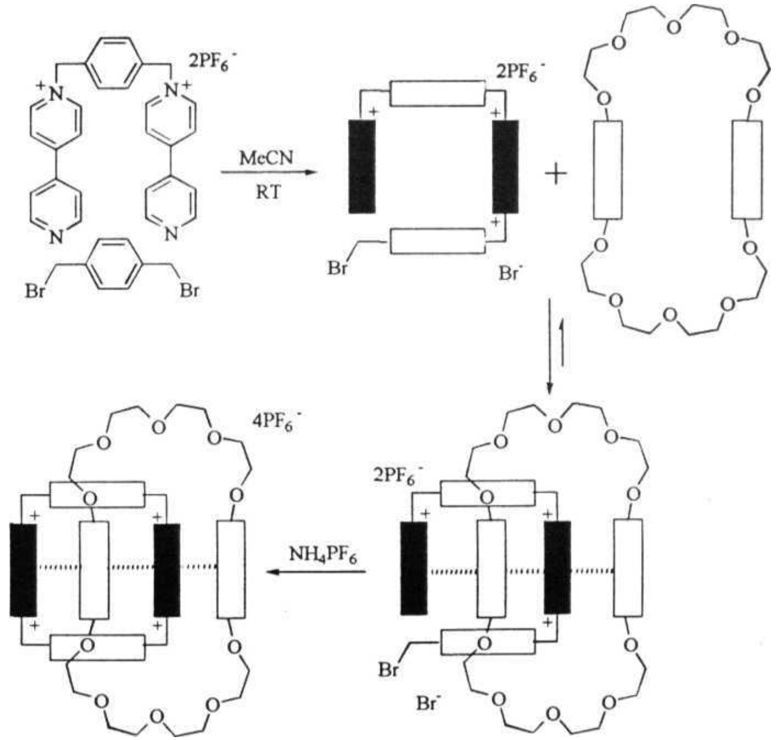


Figure 8

The roles of the π-donor and rc-acceptor can be reversed to produce a *n*-electron rich guest and π-electron deficient host. The tetracationic cyclophane host 21 (Fig. 8) is capable of binding a wide range of electron rich π-donors like catechol, hydroquinone dimethyl ether, aromatic aminoacids and 1,5-dialkoxy

naphthlenes within its rigid cavity, exclusively stabilized by n-stacking interactions. The crystal structures again revealed that the guest is centrosymmetrically threaded inside the host cavity.[20]

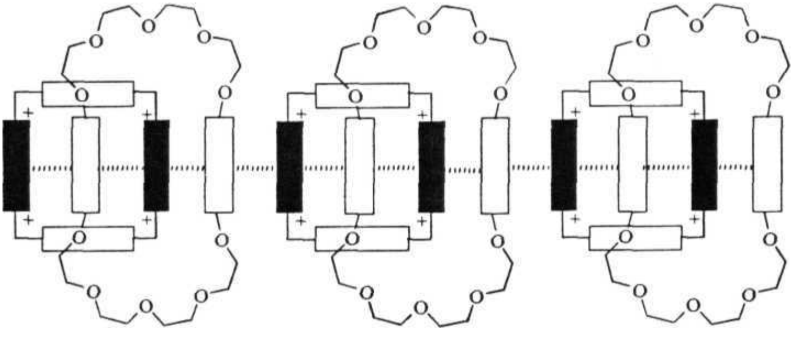


23

Figure 9

The above mentioned **centrosymmetrically** threaded structures form the building blocks for the self-assembly of supramolecular array of interlocked molecules the catenanes (23, Fig. 9) and rings trapped on the spindles of the dumbbell shaped components, the rotaxanes (the above structures are often referred to by the term pseudorotaxanes as they lack the bulky stoppers of a dumbbell, indicating that they are free to dissociate). [1]

Many examples of these archetypal interlocked molecules have been reported over the last decade, particularly after the concept of the chemical template based self-assembly became widely accepted as a useful paradigm in constructing chemical systems. The *n-n* interactions have been exploited to the fullest extent in the process of construction of the [2], [3] and [5] catenanes. The X-ray analysis of the crystal structure of the [2]-catenane 23



24

Figure 10

revealed that the mutual recognition between the appropriately located π-donors and π-acceptors is in action within and beyond the molecule forming a continuous π-donor/π-acceptor stack of [2]-catenane 24 (Fig. 10).[23]

Of particular interest to us were the results of a study made on the effect of the spacer unit of the π-donor macrocycle on the catenation yields. The study on the macrocycles ranging from BPP31C9 to BPP46C14 revealed the ideal framework for catenation to be BPP34C10 (70% yield). A smaller size of the cavity is too tight and discomforting for inclusion of the precursor and the larger ones have poor intercomponent recognition due to their inherent flexibility.

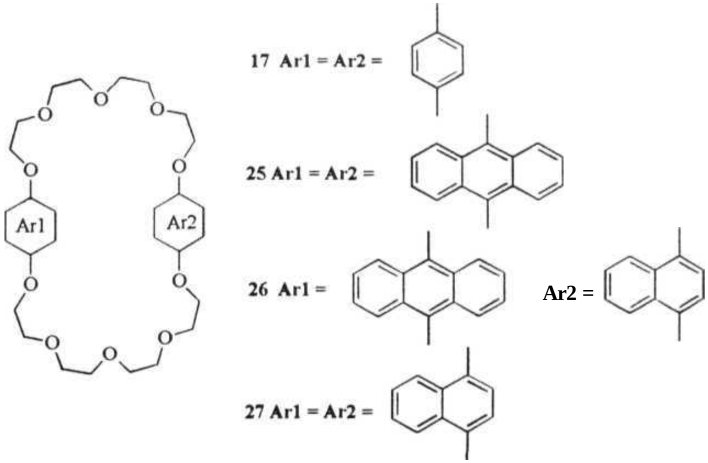
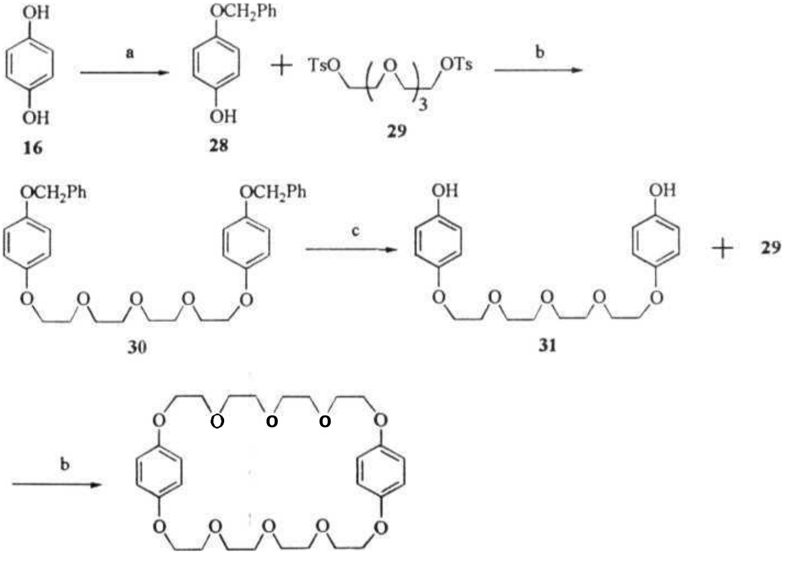


Figure 11

This provided the necessary impetus for us to synthesise the hitherto unreported 1,4-dinaphtho-34-crown-10 (1,4-DN34C10, (27)) and study its complexation capabilities with π-acceptor guests. In addition to providing an excellent framework for π-stacking complexation, 1,4-DN34C10 can also be an exceptionally good probe for cation detection. Desvergne has shown that BPP34C10,[25] its corresponding anthracene analog 25,[26] and a novel dissymmetric coronand 26,[27] display specific optical responses towards alkali and alkaline earth metal cations (Fig. 11). Thus, 27 can also serve as a fluorescent probe for cation detection. With this primary aim we set out to synthesise 1,4-DN34C10 and study its complexation properties.

Results and Discussion

With the crown ether 27 identified as the target molecule, we set out to plan a suitable strategy for its synthesis. A survey of the literature revealed that the most convenient starting materials for the construction of 1,4-crowns are the corresponding 1,4-diols. As exemplified by the synthesis of 17 (Scheme 2), partial **benzylation,** coupling with **a** ditosylate, deprotection,

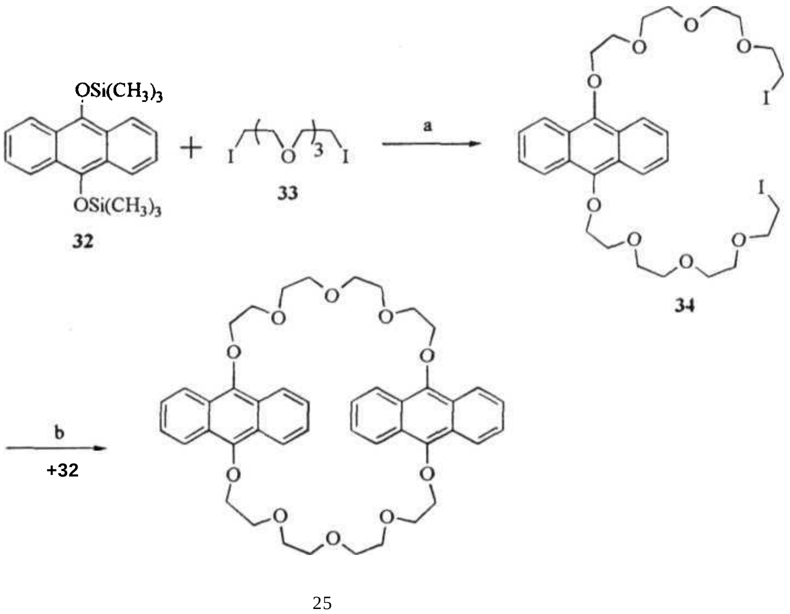


BPP34C10 17

Scheme 2 *Reagents and conditions:* **a)** $PhCH_2Cl$, K_2CO_3, DMF, rt, 18h; **b)** NaH, **DMF,** 80°, 24h; c) H_2, 10% Pd/C, $MeOH$-Et_2O.

followed by macrocyclisation with the same ditosylate provides **a** convenient **route to** such compounds. However, **1,4-naphthalenediol** is highly unstable and this rules out its utilisation in the above sequence.

Alternately, a 1,4-quinone was reduced to the hydroquinone which was **trapped** *in situ* as its bis silylether. This was further elaborated to the desired crown as depicted in Scheme 3.[26] In our case,



Scheme 3 *Reagents and conditions:* a) K_2CO_3, acetone, reflux, 5h; b) K_2CO_3, Cs_2CO_3, acetone, reflux, 4 days.

the undesirable properties of 1,4-naphthoquinone precluded its use as a starting material. Therefore, we felt the need for developing a different strategy for the synthesis of 1,4-DN34C10 (27).

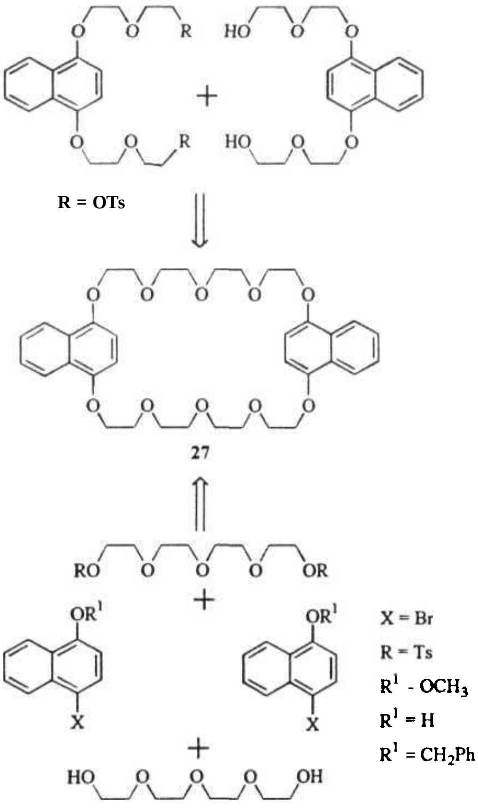
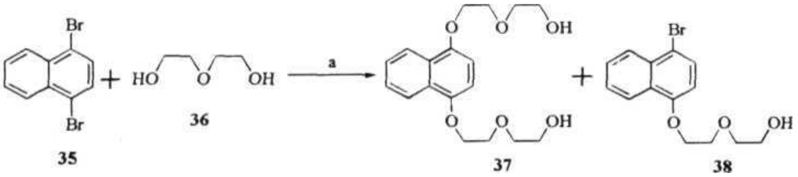


Figure 12

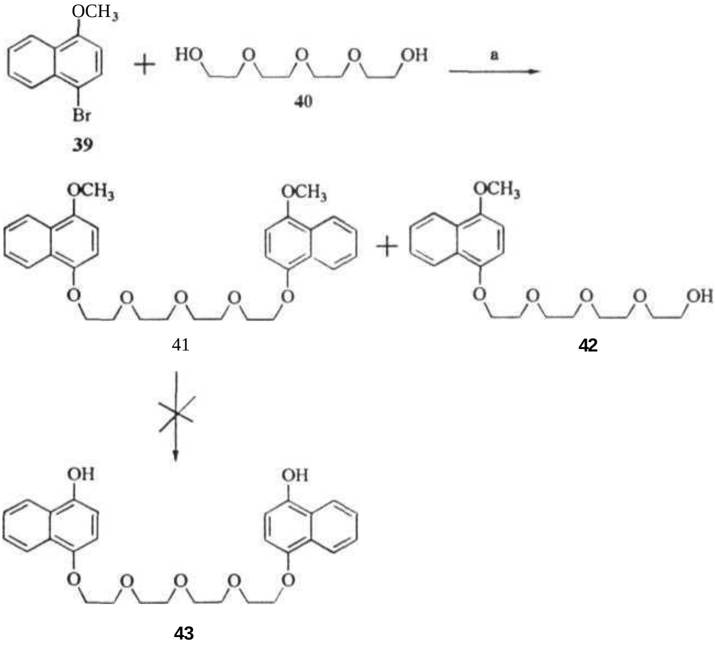
Synthesis of **1,4-DN34C10** can be envisaged in two ways (Fig. 12): either by coupling of 2 identical halves of the frame or by stepwise assembly of the glycol units.

The first strategy requires the use of a symmetrical starting material and therefore 1,4-dibromonaphthalene was chosen for this purpose. Copper(I) catalysed ether formation[30] of the sodium salt of diethylene glycol with 1,4-dibromonaphthalene was attempted to secure the desired diol. The reaction yielded two products, those of mono- and di-substitution. Disappointingly, the diol 37 was the minor product (7%), whereas the major product was the bromoalcohol 38. Various attempts to improve upon the yields of 37 including usage of a 10-fold excess of diethylene glycol were of no avail.



Scheme 4 *Reagents and conditions:* a) NaH, CuI, DMF, 120 , 48h.

Attention was next focussed on the sequential assembly protocol. Amongst the starting materials to be explored for this purpose, 4-halo-1-naphthols attracted our attention. Protection of the phenolic hydroxyl group followed by substitution of the halogen by the polyether chain, subsequent deprotection and macrocyclisation would yield the target molecule in a short and facile manner.



Scheme 5 *Reagents and conditions:* a) NaH, CuI, DMF, 120°, 48h.

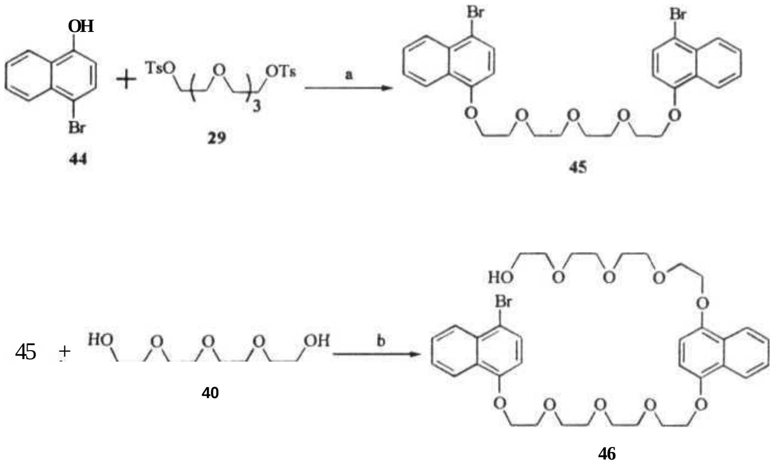
Accordingly, 4-bromomethoxynaphthalene was prepared and the copper(I) catalysed etherification of this aryl bromide with the dialkoxide derived from tetraethylene glycol was attempted in DMF. Not surprisingly, the reaction yielded more than one product. The bis ether 41 was obtained as a minor product (18%), while the monoether 42 was the major product, apart from a small amount of 1-methoxynaphthalene (reduced product). The products

41 and 42 were readily distinguishable by their IR spectra. The presence of a strong band at 1100 cm^{-1} was indicative of the presence of ether linkages in both products, while the monoether additionally displayed the OH stretching band at 3400 cm^{-1}.

The H NMR spectrum of the bis ether 41 showed 4 bunches of aliphatic signals from 8 4.25-3.72 in the ratio 1:2:1:1 while the naphthalene ring exhibited 3 equally integrating multiplets from 8 8.25-7.40. The ^{13}C NMR spectrum showed 9 carbons types in all. Lastly, the elemental analysis was satisfactory and the mass spectrum showed the M^+ ion at m/z 506. The yield of 41 could not be improved beyond this even on use of a large excess of the bromo compound 39. The monoether 42 was similarly characterised. Its ^1H NMR and ^{13}C NMR spectra exhibited the lack of symmetry unlike those of 41. An M^+ ion at m/z 350 and satisfactory elemental analysis proved beyond doubt that the major product was in fact the monoether 42. Attempts at etherification of the monoether for a second time under more drastic conditions did not meet with success.

Having thus successfully synthesized the bis ether, cleavage of the methyl ether was then attempted.[32] Simple acidic cleavage utilising HC1 or HBr in AcOH led to extensive decomposition and failed to give the required cleavage product. Subsequent attempts to cleave the ether with TMSCl/sodium iodide and lithium iodide/collidine were also found to be of no avail, with the ether 41 being recovered unchanged.

With the failure of the attempts to cleave the methyl ether, other options were investigated. In one approach, 1-naphthol was brominated at the 4-position using bromine in acetic acid and the product then coupled with tetraethylene glycol ditosylate in THF to give the corresponding bis bromonaphthyl ether 45 in 80% yield.

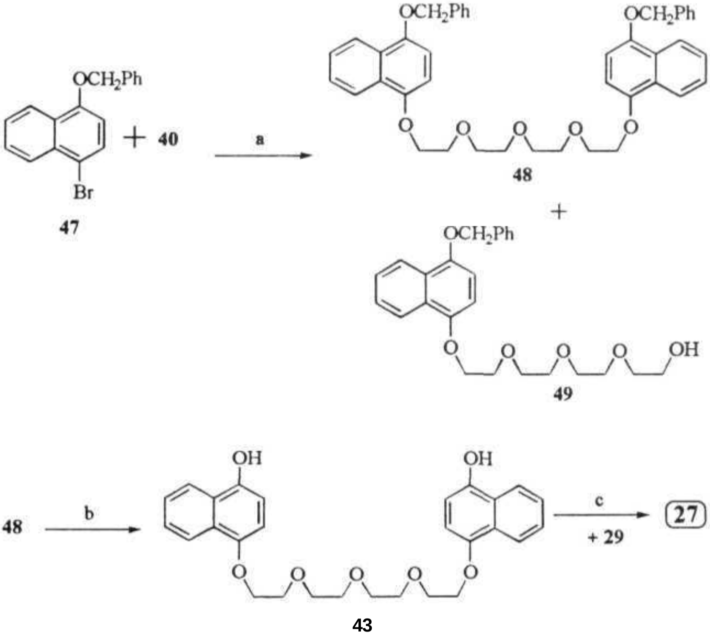


Scheme 6 *Reagents and conditions:* a) NaH, THF, reflux, 24h; b) NaH, CuI, DMF, 120°, 48h.

The disappearance of the hydroxyl band and appearance of a strong 1070 cm' band in the IR spectrum of 45 are indicative of the presence of the glycol unit. The 16 hydrogens of the glycol unit appeared in the range 5 4.32-3.78 in the ^{1}H NMR spectrum. The outer -CH$_2$- units closest to the aromatic rings exhibited the characteristic AA'XX' pattern, while the inner ones formed an AA'BB' group. The copper(I) catalysed etherification of 45 with tetraethylene glycol was then attempted in DMF. On chromatography of the crude product, a brown oil was obtained in 42% yield, based upon recovered starting material. The IR spectrum of this oil showed a clearly defined OH stretch at 3420 cm^{-1}. Its ^{1}H NMR and ^{13}C NMR spectra were fairly complex indicating that the molecule was unsymmetrical. Both the above factors indicated the fact that the desired ring closure had not occurred. The mass spectrum of the product provided the necessary conclusive evidence for this. An almost equal intensity M^{+} and (M+2) peaks at m/z 716 and 718 proved that the compound was 46. The result was a little surprising as the ring closure step, being intramolecular, should be more facile than the reaction leading to 46.

A careful analysis of both the above strategies (Scheme 5 and 6) at this stage clearly showed that though the copper catalysed etherification is simple and adaptable to various substrates, it cannot be used as the final cyclisation step owing to the formation of more than one product in addition to the poor yields obtained in the process.

The starting materials were therefore modified and 4-benzyloxy-bromonaphthalene (47) was now used (Scheme 7). Its reaction with tetraethylene glycol yielded two products once again. However, the yields of the desired bis ether 48 were higher (38%), when compared to that of 41, much to our gratification. The ^{1}H NMR spectrum of 48 showed the vicinal protons H-2 and H-3 of naphthalene ring at 5 6.73-6.64 as a quartet, whereas the other aromatic protons resonated at 8 8.30-7.36 (2 multiplets). The benzylic -CH$_2$- appeared at δ 5.17 as singlet and the glycol unit displayed the usual AA'XX' pattern. The ^{13}C NMR spectrum showed 11 aromatic signals and 5 aliphatic signals indicative of the symmetry present in the molecule. The elemental analysis of 48 was also in agreement with its structure. The mono-substituted product 49 was obtained in 50% yield and characterised routinely.



Scheme 7 *Reagents and conditions:* a) NaH, CuI, DMF, 120 , 48h; b) 20% $Pd(OH)_2/C$, EtOAc, H_2, 55psi, 6h; c) Cs_2CO_3, CsOTs, $n\text{-}Bu_4NI$, DMF, 110^0, 36h.

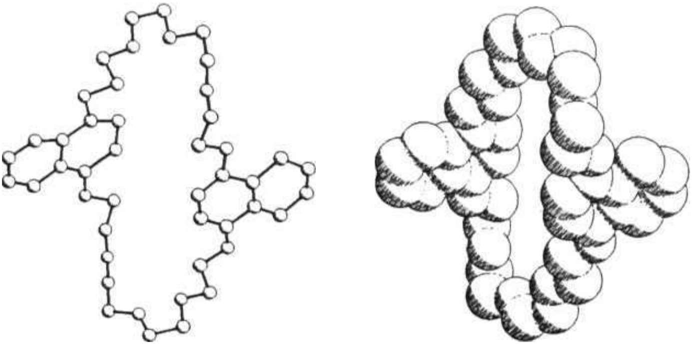
Cleavage of the benzyl ether was then taken up. Use of 10% Pd/C and H_2 in ethyl acetate resulted in incomplete and inconsistent cleavage of the benzyl ether. When 20% $Pd(OH)_2/C$ (Pearlman's catalyst)[34] in ethyl acetate at 55 psi H_2 pressure was employed, the benzyl ether cleaved readily and cleanly. The presence of the -OH stretch in the IR spectrum and the absence of benzylic signals in the H NMR spectrum of the product were clear indicators of the cleavage. Interestingly, the vicinal signals corresponding to H-2 and H-3 of the naphthyl ring were now seen as distinct doublets at 6 6.66-6.61 and 5 6.46-6.41. Since the dinaphthol 43 was unstable, it was processed immediately.

The dinaphthol 43 was then heated with tetraethylene glycol ditosylate and sodium hydride in DMF for 72h. The crude product obtained was chromatographed to yield a white solid in 9% yield. Its IR spectrum lacked the OH stretching frequency but displayed a very strong band at 1099 cm" for the ether linkage. The ^1H NMR spectrum was highly symmetrical. The aromatic signals showed two quartets at 5 8.18-8.14 and 7.38-7.33 and a singlet at 5 6.42, all integrating equally. The singlet represents the vicinal H-2 and H-3 protons. The high degree of symmetry is also a feature of the C NMR spectrum, where a total of 8 carbon signals appeared, 5 being aromatic and 3 aliphatic. All the above features are indicative of the formation of the desired macrocycle 27. The conclusive proof came from a satisfactory elemental analysis and a molecular ion in the mass spectrum at m/z 636.

Having achieved the synthesis of 27, attempts were now focussed towards improving its yield. Carrying out the reaction under high dilution conditions improved the yield to 27%, while a combination of cesium carbonate and high dilution pushed it up to 32%.[35] The reaction time was also reduced by half. These details are presented in the experimental section.

Crystal structure **of 1,4-DN34C1O**

The crystal structure of 1,4-DN34C10 determined by X-ray diffraction methods (isotropic, R = 0.14) at rt revealed that the host belongs to the monoclinic system and crystallises in the centrosymmetric space group, $P2_1/n$. The mean planes of the naphthalene rings are almost parallel with an interplanar angle of 2.64 . The two rings within the molecule are offset, the distance between the centroids of the two nearest rings being 7.3 A and the farthest 10.7 A. The crystal structure discloses that the host has a preorganised (14.5 × 4.5 A) cavity similar to that of the BPP34C10 (17) cavity.[28]



(a) (b)

Figure 13 *X-ray crystal structure of DN34C10* (a) A ball and stick representation (b) A space filling representation.

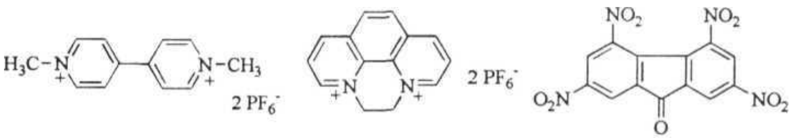
This is, however, not the case with 1,5-dinaphtho-crowns[19b] and the dissymmetric crown 26, which fill their own cavity as a result of the T-geometry adopted by the aromatic rings.

Translation related molecules are stacked along the b axis with the stacking distance between the aromatic rings being 5.12 A. The *2* screw related molecules exhibit herringbone interactions between the outer rings.

Complexation Studies

Invigorated by the simple and facile synthesis of 1,4-DN34C10, attention was now focussed on its complexing ability. The UV spectrum of 1,4-DN34C10 (in acetonitrile) was found to be sensitive to the addition of Na^+ ions. The changes in the spectra can be attributed to the conformational reorganisation due to complexation. However, the changes were small and therefore no attempts were made to determine the Na^+-crown association constants. Also, the cation complexes could not be isolated.

The complexation of 1,4-DN34C10 with organic cations and neutral guests was then explored. Since the host has electron rich naphthalene rings, the guests explored for complexation were the ones that were electron deficient. The guests examined were the quinones, TCNQ, aromatic cations and electron deficient aromatic nitrocompounds. Amongst the quinones investigated, only DDQ showed a clear charge transfer complex formation. However, the complex was not of a definite stoichiometry. All other quinones examined (9,10-anthraquinone, 1,4-benzoquinone, 9,10-phenanthrenequinone) and TCNQ did not show any influence on the UV spectrum of 27. The addition of quinones, however, showed a quenching influence on the naphthyl fluorescence. The preferred guests were those that were not only electron deficient and but also the ones that had good π-stacking capabilities like paraquat [1,1-dimethyl-4,4-bipyridinium bis(hexafluorophosphate), 50] a well tested classical example) phenquat [5,6-dihydropyrazino[1,2,3,4-lmn][1,10]phenanthrolinediium bis(hexafluorophosphate), 51] and TetNF (2,4,5,7-tetranitrofluorenone, **52) (Fig. 14).**



PARAQUAT 50 **PHENQUAT 51** **TetNF 52**

Figure 14

The complexes formed readily. Addition of a molar equivalent of 27 in chloroform to a molar equivalent of the quats in acetone immediately produced a change in the colour of the solution to purple in case of paraquat and brown for phenquat. The change in colour is attributable to charge transfer between the electron rich naphthyl units of 1,4-DN34C10 and the electron-deficient quats. The solutions were then set aside for crystallisation. Paraquat gave deep purple, and phenquat, brown coloured crystals. The host-guest stoichiometry was analysed and found to be 1 : 1 by elemental analysis. The FAB mass spectra of the paraquat and phenquat complexes gave the M peaks at m/z 1112 and 1134, respectively. The peaks corresponding to the [1,4-DN34C10·quatPF$_6$]$^+$ ion formed as a result of the loss of one PF$_6$ ion from the 1 : 1 complexes appeared at m/z 967 and 989, respectively.

Table 3 **H** NMR chemical shift data (5 values) in acetone-d_6

Compound /Complex	**Paraquat**			**1,4-DN34C10**		
	H-2,6	H-3,5	N^+Me	**H-5,8**	**H-6,7**	**H-2,3**
Paraquat	**9.36**	8.82	**4.71**			
DN34C10				**8.18**	7.39	6.53
Complex	8.87	7.80	4.68	7.80	7.42	6.23

The ^{1}H NMR spectra of both complexes were recorded in acetone-d_6 and the chemical shift data are listed in Tables 3 & 4. Comparison of the ^{1}H NMR spectral data of these complexes with those of the constituents indicated a dramatic upfield shift for the quat protons as well as the crown protons, particularly, the H-2, H-6 doublet in paraquat and the H-2, H-3 singlet of the naphthyl ring of the crown. The large chemical shifts induced by the macrocyclic host on the guests as well as by the guests on the host are indicative of the inclusion of the guest into the cavity of the host.

Table 4 ^{1}H NMR chemical shift data (5 values) in acetone-d_6

Compound /Complex	**Phenquat**				**1,4-DN34C10**		
	H-2,9	H-4,7	H-3,5,6,8	N^+-CH_2	**H-5,8**	**H-6,7**	**H-2,3**
Phenquat	9.97	9.80	8.97	6.05			
DN34C10					8.18	7.39	6.53
Complex	9.57	9.30	8.63	5.63	7.66	7.16	6.14

The 2,4,5,7-tetranitrofluorenone (TetNF) complex with 1,4-DN34C10 was prepared by mixing the host in chloroform with TetNF in ethanol. The colour of the solution changed to black on warming which was again an indication of the formation of a charge transfer complex. However, the elemental analysis of the fine black needles obtained did not match to a 1 : 1 host-guest stoichiometry and had a ratio of 2 : 1 (TetNF : 1,4-DN34C10). This was further substantiated by the FAB mass spectrum of the complex. The peak at m/z 1310 can only arise from a 2 : 1 (TetNF : 1,4-DN34C10) complex (M.W.1356) through the loss of a nitro group. Incidentally, the mass spectrum of TetNF also has a strong peak at m/z 314 corresponding to the loss of a nitro group. The H NMR spectrum of the complex showed small changes in chemical shifts of the host and guest protons, probably due to weak association of the host and guest (Table 5).

Table 5 ^{1}H NMR chemical shift data (5 values) in acetone-d_6

Compound /Complex	TetNF		**1,4-DN34C10**		
	H-3,6	**H-1,8**	**H-5,8**	**H-6,7**	H-2,3
TetNF	9.06	8.92			
DN34C10			8.18	7.39	6.53
Complex	9.04	8.68	8.07	7.36	6.45

Evaluation of Binding Constants

In order to further understand the host-guest interactions involved in the above complexes, we attempted to quantify them. ^1H NMR spectroscopy has been extensively employed to determine binding constants of complex formation in host-guest complexes. The method involves recording a series of spectra of the host after addition of incremental quantities of the guest over a wide concentration range, until there is no significant change in the chemical shift of a monitored signal in successive NMR spectra. To use the NMR method for studying the complexation process, atleast one proton (nucleus) in the uncomplexed host must give rise to a signal at a chemical shift that is significantly different from that of the same proton in the complexed host. The magnitude of the shift gives information about the nature of the complex. However, on the NMR time scale, it is often not possible to observe the chemical shift of the complex distinctly from that of the host, especially under the conditions of fast exchange. The observed chemical shift (δ_{obsd}) of the selected proton of the substrate is therefore a weighted average of the chemical shifts of the free and the complexed forms of the host.

$$\delta_{obsd.} = n_h \, \delta_h + n_c \, \delta_c \qquad (1)$$

where δ_h = chemical shift of the monitored proton in the uncomplexed host

δ_c = chemical shift of the same proton in the complex

n_h = mole fraction of the free host

n_c = mole fraction of the complex (and hence that of the complexed host)

Also, $n_h + n_c = 1$

$$\delta_{obsd} = (1 - n_c)\, \delta_h + n_c \, \delta_c$$

$$= \delta_h + n_c(\delta_c - \delta_h)$$

$$= \delta_h + n_c(\Delta\delta_{max}) \qquad (2)$$

$\Delta\delta_{max} = \delta_c - \delta_h$ = maximum chemical shift possible

For a host-guest complexation process represented as[38]

$$H + G \rightleftharpoons C$$

The equilibrium constant K is defined as

$$K = \frac{[C]}{([H_o] - [C])([G_o] - [C])} \qquad (3)$$

where $[H_o]$ = initial concentration of the host

$[G_o]$ = initial concentration of the guest

$[C]$ = concentration of the complex

$$[C] = n_c [H_o] \qquad (4)$$

Substituting equation 4 in equation 3, gives

$$K = \frac{n_c / [H_o]}{(1 - n_c)\ (R - n_c)}$$

where $R = [G_o] / [H_o]$.

Therefore, $n_c /K [H_o] = (1 - n_c)(R - n_c) = R - (R + 1) n_c + n_c^2$

or $n_c^2 - n_c(1 + R + 1/(K [H_o]) + R = 0 \qquad (5)$

and $n_c = (b - \sqrt{b^2 - 4R})/2 \qquad (6)$

where $b = (1 + R + 1/(K [H_o])$

Substituting equation 6 into equation 2 leads to

$$\delta_{obsd.} = \delta_h - (\Delta\delta_{max}/2)(b - \sqrt{b^2 - 4R}) \qquad (7)$$

or, $\Delta\delta = \delta_h - \delta_{obsd} = (\Delta\delta_{max}/2)(b - \sqrt{b^2 - 4R})$.

Equation 7 gives the observed chemical shift of the proton in the host induced by its complexation with the guest as a function of b (i.e., R and K). Variation of δ_{obsd} with respect to changes in the host-guest ratio (R) forms the basis of the NMR titration technique for the determination of K values. Equation 7 has two unknown parameters, $\Delta\delta_{max}$ and K. Using an iterative non-linear curve fitting technique, the values of K and $\Delta\delta_{max}$ that best simulate the experimental set of data (AS and R) can be determined. A simple BASIC programme, for doing these iterations, has been developed by Macomber.[38]

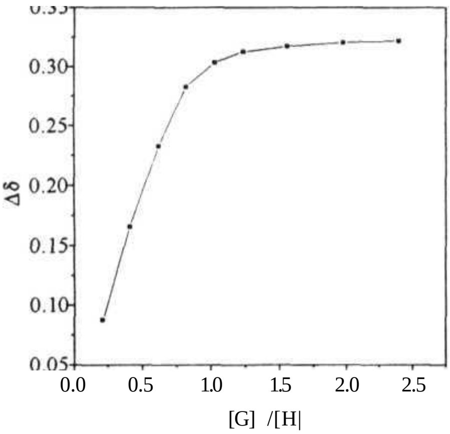


Figure 15 *Titration curve of paraquat.*$2PF_6$ *versus 1,4-DN34C10*

We chose to evaluate the binding constants of the complexes utilising the above methodology. The titration curves of 1,4-DN34C10 for interaction with guests paraquat 50 and phenquat 51 were obtained by plotting (A5 versus R) the data being obtained from the direct titration of a known concentration of the host with increasing amounts of the corresponding guest. As is evident from the titration curves (Fig. 15 and Fig. 16) both the quats show a break in the curve as the guest concentration equals that of the host. This is a strong indicator of 1 : 1 binding.[39]

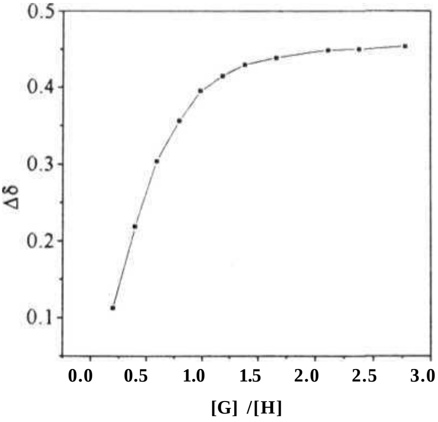


Figure 16 *Titration curve of phenquat.*$2PF_6$ *versus 1,4-DN34C10*

However, it was found that the data obtained were inadequate for the purpose of determination of the binding constants due to excessive saturation. So the alternative protocol of dilution was adopted.[39] An equimolar solution of the host and the guest was prepared and its spectrum was recorded. The solution was then progressively diluted and successive spectra were recorded. The ratio of the host to guest was thus constant throughout the experiment. Both the sets of data were combined and the binding constants were evaluated using equation 7, which was fitted employing the Sigma plot curve fitting routine (see experimental section for details). The binding constant K and $\Delta\delta_{max}$ thus obtained are listed in Table 6.

Table 6

Binding constants and $\Delta\delta$, values of 1,4-DN34C10 complexes

Guest	K (M^{-1})	
paraquat	$6.62 \pm 0.81 \times 10^3$	0.334 ± 0.007
phenquat	$2.27 \pm 0.33 \times 10^3$	0.465 ± 0.010
TetNF	9.71 ± 2.17	0.537 ± 0.082

As is evident from the K values, both the quats show strong binding and the host-guest stoichiometry is 1 : 1.

The titration curve of tetranitrofluorenone versus 1,4-DN34C10 obtained by the direct titration method did not show any signs of saturation even at a host : guest ratio of 1 : 4 (Fig. 17). Also, the changes in chemical shifts were lower than those obtained for the quats.

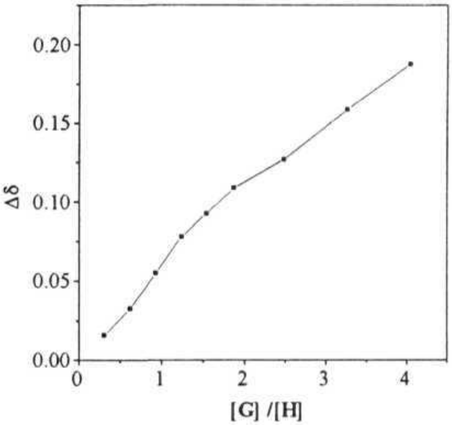


Figure 17 *Titration curve of* ***TetNF*** *versus 1,4-DN34C10*

The stoichiometry of the complex in solution could not be ascertained directly from the titration curve. It was therefore determined by using the method of continuous variations or Job's method.[40] The experimental procedure consists of preparing a series of host and guest solutions subject to the condition that the sum of the total host and guest concentration is a constant. The NMR spectra of these solutions were then recorded and a Job's plot made (Fig. 18). The plot indicated a host : guest stoichiometry of 1 : 1 in solution (see experimental section for details).

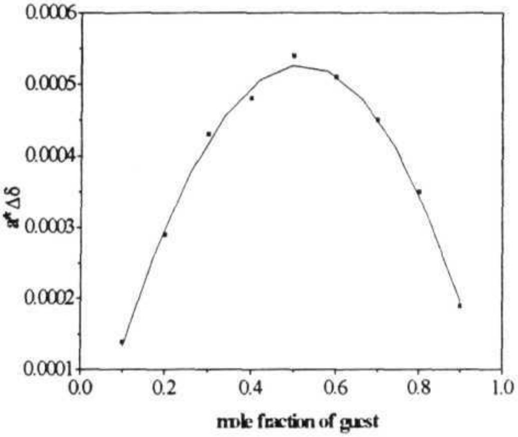


Figure 18

The NMR titration results mentioned earlier analysed by the curve fitting software assuming a 1 : 1 stoichiometry gave a **K** value of 9.71 ± 2.17 **M^{-1} and** the $\Delta\delta_{max}$ was 0.537±0.082. The low value of K and the non-saturating nature of the titration curve indicate that the binding is weak. The solution complexation stoichiometry was thus different from the solid complex, where **a** 2 : 1 guest to host ratio was found. This differential behaviour of **a** complex, formed between the same set of host and guest, in solution and the solid state is not an unprecedented observation. As mentioned in the introduction, it has been shown by **Stoddart**[19a] **that** the paraquat complex of **1,5-dinaphtho-44-crown-12** exhibits different stoichiometries in solution (1:1) and solid states (2 : 1).

Furthermore, it has been conclusively shown that of the two guests molecules involved, one of them is intramolecularly included into the cavity and the second is clatharated in between the adjacent 1 : 1 complexes (19, Fig. 7). An extrapolation of this argument to the TetNF complex would perhaps be in order. A similar structure may be visualised in this case wherein the guest is intramolecularly included and intermolecularly clatharated. However, despite our best efforts, we could not grow crystals of suitable quality for X-ray diffraction which could have provided the necessary evidence for the above hypothesis.

This chapter highlights a short and facile synthesis of the versatile host 1,4-DN34C10. From the preliminary crystal structure data, the host was found to support a preformed cavity for guest binding even in the solid state. Although it forms complexes with electron deficient neutral and charged organic guests, the complexes with charged guests are stronger than those with neutral guests.

Experimental Details

All solvents were dried by using appropriate drying agents prior to use. The reagents were purified by employing standard techniques. All moisture sensitive reactions were carried out under nitrogen atmosphere. Reagents were transferred using the standard septa-syringe techniques while carrying out dry reactions. 50% Sodium hydride was used for generating the corresponding phenoxide or alkoxide. It was generally washed with dry hexane prior to the addition of the substrate. After the appropriate workup, the organic extracts were washed with water, followed by brine and all organic extracts were dried over anhydrous $MgSO_4$.

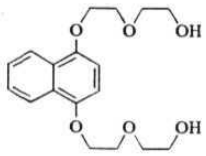
Solvents used for column chromatography were fractionally distilled. Column chromatography was performed using mixtures of hexane and ethyl acetate, unless otherwise stated. Acme silica gel (100-200 mesh) was used for column chromatography, unless otherwise mentioned. Analytical thin layer chromatography was performed on home made plates using ACME silica gel GF 254 grade containing 13% calcium sulphate as binder and were visualised by shining UV light and/or by exposure to iodine vapours.

Melting points were determined on a SUPERFIT melting point apparatus and are uncorrected. IR spectra were recorded on PERKIN-ELMER Model 1310 or JASCO FT-IR 5300 instruments. Solid samples were prepared as KBr wafers and liquid samples as a film between NaCl plates. H-(100, 200 and 500 MHz) and C-NMR (25 and 50 MHz) spectra were recorded on JEOL FX-100, BRUKER AF-200 and ACP 500 NMR spectrometers in chloroform-d solutions with tetramethylsilane (TMS) as an internal standard, unless otherwise stated. Chemical shifts are reported relative to tetramethylsilane as an internal standard (H and C). H NMR spectral assignments are as follows: (1) chemical shift on the 6 scale (2) multiplicity (3) number of hydrogens (4) coupling constants in hertz (Hz). Elemental analyses were obtained using PERKIN-ELMER model 240C-CHN analyser. The FAB mass spectra were recorded on JEOL SX-102 mass spectrometer at CDRI, Lucknow. Mass spectra were recorded on VG 70-70H instrument at IICT, Hyderabad.

Naphthalene was brominated using bromine in dioxane. The crude product was recrystallised (yield 32%, m.p 72-74°, lit. 78^{0})[29] to obtain **35.**

Reaction of 1,4-dibromonaphthalene (35) **with diethylene glycol:**

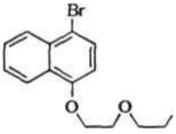
To a suspension of sodium hydride (1.92 g, 40 mmol) in DMF (15 ml), was added diethylene glycol (3.12 g, 20 mmol) and the mixture was stirred at room temperature for an hour. To this mixture 1,4-dibromonaphthalene (572 mg, 2 mmol) in 15 ml DMF was added, followed by cuprous iodide (380 mg, 2 mmol) and the reaction mixture heated at 120 for 48h. Usual workup followed by column chromatography yielded 37 (53 mg, 7 %) and 38 (320 mg, 48%) as oils.



37

IR(neat): 3416, 3068, 2938, 1595, 1507, 1455, 1424, 1132, 1087, 760 cm'^{1}.

^{1}H NMR (100 MHz) : 5 8.24-8.12 (m, 2H), 7.52-7.40 (m, 2H), 6.68 (s, 2H), 4.28-4.12 (m, 4H), 4.0-3.88 (m, 4H), 3.72 (bs, 8H), 2.0 (bs, 2H).



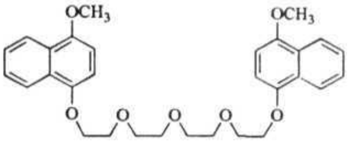
38

IR (neat): 3416, 3069, 2930, 1591, 1506, 1454, 1423, 1373, 1321, 1263, **1132,** 1087, 889, 806, 761, 736 cm^{-1}. ^{1}**H** NMR (100 MHz) : 5 8.28-8.08 **(m,** 2H), 7.64-7.42 **(m,** 3H), 6.68-6.60 (d, 1H), **4.32-4**.20 **(m,** 2H), 4.0-3.92 **(m,** 2H), 3.76 (s, 4H), 1.80 (bs, 1H).

1-Naphthol was methylated using dimethyl sulphate as **reported**.[41] The crude product was distilled in vacuum to obtain **1-methoxynaphthalene** (yield 81%, b. p. 85-87 at 1 mm). This was then brominated with Br_2 in CCl_4 and the crude product was distilled under reduced pressure to obtain **1-bromo-4-methoxynaphthalene** (39) (yield **67%)**.[31]

1,11-Bis(4-methoxynaphthyloxy)-3,6,9-trioxaundecane (41)

To a stirred suspension of sodium hydride (96 mg, 2 **mmol)** in DMF (8 ml) was added tetraethylene glycol 40 (194 mg, 1 mmol) and the mixture stirred at **rt** for an hour. Then a solution of 4-bromomethoxynaphthalene (948 **mg,** 4 mmol) in 7 ml DMF was added followed by cuprous iodide (380 mg, 2 mmol). The reaction mixture was heated under reflux for 65h. The reaction mixture was then poured into ammonia solution and extracted with ether. The crude product obtained after the evaporation of the solvent was chromatographed to separate the following (500 mg of 4-bromomethoxynaphthalene was recovered):



41

Yield: 90 mg, 18%, oil.

IR (neat): 3060, 2900, 2860, 1600, 1470, 1400, 1285, 1250, 1100, 1050, 810, 770 cm'^{1}.

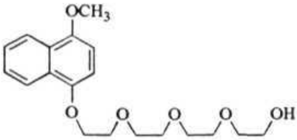
^{1}HNMR (500 MHz) : 5 8.25-8.18 (m, 4H), 7.50-7.46 (m, 4H), 6.71-6.65 (q, 4H), 4.25-4.22(t, 4H), 3.98-3.95 (m, 10H), 3.80-3.78 (m, 4H), 3.75-3.72 (m, 4H).

^{13}C NMR (25 MHz):149.78, 148.72, 126.65, 126.42, 125.90, 122.01, 121.88, 104.89, 103.18, 70.95, 70.77, 69.89, 68.30, 55.59 ppm

Analysis: Calc. for $C_{30}H_{34}O_7$: C,71.12; H,6.77,

Found: C,70.95; H,6.81.

Mass: M^+ ion at m/z 506.



42

Yield: 300 mg, 59%, oil.

IR (neat): 3400, 3060, 2880, 1600, 1460, 1400, 1280, 1240, 1110, 1050, 780 cm^{-1}.

^{1}HNMR (500 MHz) : 5 8.25-8.19 (m, 2H), 7.51-7.47 (m, 2H), 6.75-6.68 (q, 2H), 4.28-4.25(t, 2H), 4.01-3.96 (m, 5H), 3.82-3.73 (m, 2H), 3.72-3.67 (m, 8H), 3.61-3.58 (m, 2H), 2.89 (s, 1H).

^{13}C NMR (25 MHz): 149.18, **148.60,** 126.60, 126.37, 125.83, 121.95, 121.77, 104.89, 103.18, 72.48, 70.83, 70.59, 70.24, 69.89, 68.30, 61.59, **55.59 ppm**.

Analysis: **Calc. for $C_{19}H_{26}O_6$:** **C,65.12; H,7.48,**
Found: C,65.26; **H,7.47**.

Mass: **M^+** ion at **m/z** 350.

When the monoarylated product was subjected to further etherification under similar conditions, the bis arylated product was obtained in poor yields (5%). Further attempts to improve the yields failed.

Attempted cleavage of **the naphthylmethyl ether**[32]**:**

a) HCl/acetic acid or HBr/acetic acid: To a solution of 41 (100 mg, 0.20 mmol) in 1 ml of acetic acid was added 3 ml of 47% HBr (or 37% HCl) and the reaction mixture was heated under reflux for 1h. It was then poured into water and extracted with ether. The combined extracts were washed with water to remove traces of acetic acid, dried and the solvent evaporated. The tlc showed **a** complex mixture indicating that the cleavage was not clean.

b) TMSC1 and sodium **iodide:** To **a** solution of 41 (80 mg, 0.16 mmol) and sodium iodide (48 mg, 0.32 mmol) in acetonitrile (1 ml) chlorotrimethylsilane (35 mg, 0.32 mmol) was added and the resulting mixture heated to reflux under N_2 for 48h. The reaction mixture was then quenched with water and extracted with ether. The combined extracts were washed with saturated sodium thiosulphate solution before drying and evaporation. The residue was found to be uncleaved 41.

c) Lithium iodide and **2,4,6-collidine**: A stirred mixture of 41 (100 mg, 0.20 mmol) and lithium iodide (95 mg, 0.7 mmol) in 1 ml of 2,4,6- collidine was heated at 180 for 10h. The reaction mixture was then poured into water and extracted with ether. The combined organic layers were washed with saturated sodium thiosulphate solution before drying and evaporation. Starting material was recovered without any cleavage.

1-Naphthol was brominated using Br_2/AcOH and the crude product was recrystallised from CCl_4 to obtain 4-bromo-1-naphthol (52%, m.p. 122° lit 121-122^{0}).[33]

1,11-Bis(4-bromonaphthyloxy)-3,6,9-trioxaundecane (45)

To a stirred suspension of sodium hydride (259 mg, 5.4 mmol) in 5 ml of THF was added dropwise a solution of 4-bromonaphthol (1.21 g, 5.4 mmol) in 5 ml THF. The resulting solution was warmed to 45 for 1h to accelerate anion formation. To this mixture, tetraethylene glycol ditosylate (1.28 g, 2.7 mmol) dissolved in 5 ml of THF was added dropwise over 25 min. The reaction mixture was heated under reflux for 18h. The reaction mixture was cooled to rt and quenched by the addition of water. The aqueous layer was extracted with chloroform. After the evaporation of the solvent the crude product was subjected to chromatography to obtain 45 as a brown coloured oil.

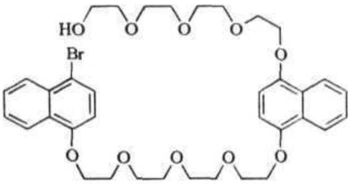
Yield: 1.30 g, 80%.

IR(neat): 3060, 2836, 1580, 1350, 1250, 1120, 1070, 800, 750 cm"^{1}.

^{1}HNMR (100 MHz): S 8.32-8.08 (m, 4H), 7.68-7.48 (m, 6H), 6.68-6.60 (d, 2H), 4.32-4.20 (t, 4H), 4.02-3.92 (t, 4H), 3.78 (s, 8H).

Attempted synthesis of DN34C10 (27)

To a stirred suspension of sodium hydride (82 mg, 1.7 mmol) in 2 ml DMF was added tetraethylene glycol (144 mg, 0.75 mmol) dropwise. The mixture was then stirred for an hour at rt and 45 (450 mg, 0.75 mmol) was added in 2 ml DMF followed by cuprous iodide (145 mg, 0.75 mmol). The reaction mixture was then refluxed for 24h. It was then poured into aqueous ammonia solution and extracted with dichloromethane. The crude product obtained on evaporation of the solvent was chromatographed. The separated components were analysed and found to contain the starting material (250 mg) and a brown coloured oil which was characterised as 46.



46

Yield: 100 mg, 42% (based on recovered starting material).

IR(neat): 3420, 3040, 2836, 1580, 1450, 1350, 1260, 1230, 1090, 940, 760 cm"^{1}.

^{1}H NMR (100 MHz): 5 8.32-8.21 (m, 4H), 7.56-7.44 (m, 6H), 6.68 (s, 2H), 4.36-4.18 (m, 6H), 4.20-3.92 (m, 6H), 3.76 (bs, 12H), 3.68 (bs, 8H), 2.84 (bs, 1H).

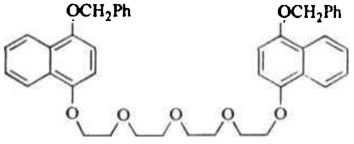
^{13}C NMR (25 MHz): 154.60, 148.83, 129.42, 127.72, 127.36, 126.71, 126.51, 126.36, 125.22, 125.12, 122.65, 122.45, 121.95, 120.60, 104.72, 72.47, 70.83, 70.65, 70.53, 70.24, 69.77, 69.53, 68.76, 67.94, 67.72, 61.53 ppm.

Mass: M$^+$ and (M + 2)$^+$ ions at m/z 716 and 718.

4-Bromonaphthol was benzylated by treating it with benzyl chloride and potassium carbonate in DMF for 18h to obtain 47 (yield 83%, m.p. 78-80°).

1,11-Bis(4-benzyloxynaphthyloxy)-3,6,9-trioxaundecane (48)

To a stirred suspension of sodium hydride (3.38 g, 70 mmol) in DMF (50 ml), was added tetraethylene glycol (6.82 g, 35 mmol) and the mixture was stirred at room temperature for an hour. To this mixture, 4-bromobenzyloxynaphthalene (47) (22.0 g, 70 mmol) in 50 ml DMF was added, followed by CuI (5.90 g, 31 mmol) and the reaction mixture heated at 120° for 60h. Usual workup followed by column chromatography yielded 48 (8.80 g, 38%) as a solid and 49 (7.50 g, 50 %) as an oil.



48

M. p.: 62^0 (MeOH).

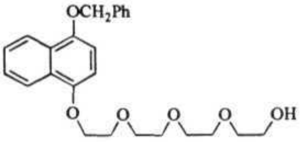
IR (KBr): 3040, 2836, 1580, 1450, 1360, 1270, 1240, 1100, 1050, 800, 770 cm^{-1}.

^1H NMR (200 MHz) : δ 8.30-8.21 (m, 4H), 7.69-7.36 (m, 14H), 6.73-6.64 (q, 4H), 5.17 (s, 4H), 4.24-4.18 (t, 4H), 3.98-3.92 (t, 4H), 3.80-3.71 (m, 8H).

^{13}C NMR (25 MHz): 148.89, 148.72, 139.54, 128.60, 127.89, 127.42, 126.65, 125.95, 122.01, 104. 89, 104.77, 70.89, 70.77, 70.36, 70.56, 69.89, 68.24 ppm.

Analysis: Calc. for $C_{42}H_{42}O_7$: C,76.57; H,6.43,

Found: C,76.55; H,6.43.



49

IR (neat): 3400, 3060, 2836, 1590, 1450, 1370, 1270, 1240, 1070, 800, 750, 720 cm^{-1}.

^{1}H NMR (200 MHz): 6 8.31-8.21 (m, 2H), 7.53-7.32 (m, 7H), 6.78-6.67 (q, 2H), 5.19 (s, 2H), 4.29-4.21(t, 2H), 4.0-3.92 (t, 2H), 3.82-3.72 (t, 2H), 3.69-3.66 (m, 8H), 3.63-3.60 (t, 2H).

1,11-Bis(4-hydroxynaphthyloxy)-3,6,9-trioxaundecane (43)

The dibenzyl ether 48 (500 mg, 0.76 mmol) was hydrogenated with 20% $Pd(OH)_2/C$ (Pearlman's catalyst)[34] (180 mg) in ethyl acetate at 55 psi pressure in a Parr apparatus for 6h. The catalyst was then filtered off and washed thoroughly with ethyl acetate. After evaporation of the solvent, the crude product was subjected to flash chromatographic purification to obtain 43 as a brown oil.

43

Yield: 290 mg, 80%.

IR (neat): 3260, 3060, 2860, 1580, 1440, 1320, 1260, 1060, 940, 750, 720 cm'^{1}.

^{1}H NMR (200 MHz): 5 8.24-8.13 (m, 4H), 7.50-7.44 (m, 4H), 6.66-6.61 (d, 4H), 6.46-6.41(d, 2H), 4.13-4.08(t, 4H), 3.94-3.89 (t, 4H), 3.72-3.69 (d, 8H).

^{13}C NMR (25 MHz): 148.24, 145.95, 126.48, 122.59, 122.06, 121.83, 108.06, 105.86, 70.65, 70.01, 67.89 ppm.

Synthesis of DN34C10(27)

a) To a stirred suspension of sodium hydride (80 mg, 1.68 mmol) in DMF (2 ml) was added dinaphthol 43 (400 mg, 0.84 mmol) dropwise in 2 ml DMF. The mixture was stirred at rt for 30 min. To this tetraethylene glycol ditosylate (472 mg, 0.84 mmol) in 2 ml DMF was added and the reaction mixture was heated at 80 for 72h. It was then quenched with water and extracted with dichloromethane. The dried organic layer was evaporated and the crude product was chromatographed to obtain DN34C10 as a white solid.

Yield: 50 mg, 9%.

b) The dinaphthol (455 mg, 0.95 mmol) and tetraethylene glycol ditosylate (477 mg, 0.95 mmol) in 60 ml of DMF were added over a period of 3h to a stirred and heated suspension of sodium hydride (100 mg, ~2 mmol) in 50 ml DMF. The reaction mixture was heated at 110^0 for a period of 72h. The solvent was then removed from the reaction mixture under vacuum and water was added to quench the reaction mixture. The organic components were extracted with chloroform. The crude product mixture obtained on the evaporation of the solvent was chromatographed to give pure 27.

Yield: 165 mg, 27%.

c) To a stirred mixture of Cs_2CO_3 (2.60 g, 8 mmol), CsOTs (245 mg, 0.80 mmol) and $n\text{-}Bu_4NI$ (20 mg) in 80 ml of DMF at 110^0 was added a mixture of dinaphthol 43 (380 mg, 0.80 mmol) and tetraethylene glycol ditosylate (400 mg, 0.80 mmol) in 40 ml DMF dropwise over 3h.[35] The reaction mixture was further heated for 48h at 110^0. DMF was removed from the reaction mixture under reduced pressure and the resultant residue was partitioned between chloroform and water, the organic layer dried and concentrated. The crude product was chromatographed to furnish pure 27.

Yield: 165 mg, 32%.

M. p.: 100-101° (MeOH).

IR (KBr): 3049, 2870, 1595, 1466, 1452, 1392, 1275, 1240, 1099, 1022, 952,794,765,750 cm^{-1}.

^{1}H NMR (200 MHz): 5 8.18-8.13 (m, 4H), 7.37-7.26 (m, 4H), 6.42 (s, 4H), 4.10-4.04 (t, 8H), 3.93-3.88 (t, 8H), 3.75-3.74 (d, 16H).

^{13}C NMR (25 MHz): 148.83, 126.60, 125.77, 121.94, 104.95, 70.89, 69.83, 68.30 ppm

Analysis: Calc. for $C_{34}H_{44}O_{10}$: C,67.90; H,6.97,
Found: C,67.82; H,6.91.

Mass: M^+ ion at m/z 636.

Complexation studies - Preparation of the guests

l,l'-dimethyl-4,4'-bipyridinium diiodide or paraquat diiodide

To a stirred solution of 4,4'-bipyridyl (150 mg, 0.96 mmol) in 1 ml MeOH under nitrogen was added methyl iodide (545 mg, 3.84 mmol) and the reaction mixture stirred overnight at rt. The bright orange coloured crystals obtained were filtered off. It was then recrystallised from acetone-water (crystallises on cooling).

Yield: 384 mg, 90%.

Analysis: Calc. for $C_{12}H_{14}N_2I_2$: C,32.75; H,3.21; N,6.36,
Found: C,33.00; H,3.35; N,6.38.

1,1'-dimethyl-4,4'-bipyridinium bis(hexafluorophosphate) or paraquat bis(hexafluorophosphate) (50):

Paraquat diiodide (230 mg, 0.523 mmol) was dissolved in water (15 ml) and ammonium hexafluorophosphate (170 mg, 1.04 mmol) was added. The contents were warmed to obtain a clear solution and allowed to cool. The hexafluorophosphate salt crystallised out as pale yellow needles.

Yield: 200 mg, 80%.

^{1}HNMR (200 MHz, acetone-d_6): 5 9.36-9.33 (d, 4H), 8.82-8.79 (d, 4H), **4.71** (s, 6H).

5,6-dihydropyrazino|l,2,3>4-lmn][l,10]phenanthrolinediium dibromide

1,10-Phenanthroline (900 mg, 5 mmol) was refluxed in excess of 1,2-dibromoethane for 30 min. The reaction mixture was then cooled to rt and water added to it. The product, which passed into the aqueous layer, was separated and evaporated. The residue was recrystallised from EtOH.

Yield: 392 mg, 20%.

5,6-dihydropyrazino[1,2,3,4-lmn][1,10]phenanthrolinediium bis(hexafluorophosphate) (51)

The dibromide (184 mg, 0.5 mmol) was dissolved in 10 ml of water and to this a solution of ammonium hexafluorophosphate (170 mg, 1.04 mmol) was added. The resulting solution was boiled and then filtered to remove any undissolved material. It was then set aside to allow crystallisation. The salt crystallised as pale brown needles.

Yield: **190** mg, 76%.

^{1}HNMR (200 MHz, acetone-d_6): 5 9.97-9.94 (d, 2H), 9.80-9.76 (d, 2H), 8.97-8.86 (m, 4H), 6.05 (s, 4H).

Analysis: Calc. for $C_{14}H_{12}N_2P_2F_{12}$: C,34.85; H,2.33; N,5.42,
Found: C,33.75; H,2.42; N,5.62.

2,4,5,7-Tetranitrofluorenone (52)

Fluorenone was nitrated using fresh fuming nitric acid as reported in the literature.[44]

M.p.: 244-46^{0} (lit. 249-253^{0})[44]

^{1}H NMR (200 MHz): 5 9.06-9.04 (d, 2H), 8.92-8.91 (d, 2H).

Preparation of paraquat **bis(hexafluorophosphate)** (SO) and DN34C10 complex

Paraquat bis(hexafluorophosphate) (17 mg, 0.0357 mmol) in 3 ml of acetone was added to a solution of DN34C10 (23 mg, 0.0357mmol) in 1 ml chloroform and the resulting purple coloured solution was filtered to remove any insoluble material. Pentane was layered on top of this solution and the dark purple coloured crystals obtained on standing were filtered off. A weak charge transfer absorption band is observed at *X* = 504 nm.

Yield: 30 mg, 75%.

^{1}HNMR (200 MHz, acetone-d_6): 5 8.87-8.30 (d, 4H), 7.80-7.75 (m, 8H), 7.42-7.37 (m, 4H), 6.23 (s, 4H), 4.68 (s, 6H), 3.87-3.85 (m, 32H).

Analysis: Calc. for $C_{48}H_{58}O_{10}N_2P_2F_{12}$: C,51.79; H,5.25; N,2.52,
Found: C,51.50; H,5.24; N,3.03.

FAB mass: m/z 1112, 967, 636.

Preparation of 51 and DN34C10 complex

To a solution of 51 (18 mg, 0.0357 mmol) in 3 ml of acetone was added a solution of DN34C10 (23 mg, 0.0357 mmol) in 2 ml of chloroform. After ensuring that the resulting solution was clear, pentane was layered on top and the dark brown coloured crystals obtained were filtered off. A weak charge transfer absorption band was observed at λ = 450 nm.

Yield: 25 mg, 61%.

^{1}H NMR (200 MHz, acetone-d_6): 5 9.57-9.55 (d, 2H), 9.30-9.26 (d, 2H), 8.63-8.56 (m, 2H), 8.10-8.09 (d, 2H), 7.66-7.61 (m, 4H), 7.16-7.11 (m, 4H), 6.14 (s, 4H), 5.63 (s, 4H), 3.91-3.90 (d, 32H).

Analysis: Calc. for $C_{50}H_{56}O_{10}N_2P_2F_{12}$: C,52.91; H,4.97; N,2.47,
Found: C,52.48; H,5.15;N,1.99.

FAB mass: m/z 1134, 989, 636.

Preparation of 2,4,5,7-tetranitrofluorenone (52) and DN34C10 complex

A solution of DN34C10 (25 mg, 0.039 mmol) in 4 ml of chloroform was added to a solution of tetranitrofluorenone (14 mg, 0.039 mmol) in 4 ml of ethanol-benzene (1 : 1). The resultant solution was warmed to dissolve all the solids. The solution was left at rt to allow it to crystallise. The fine black needles obtained were filtered. The analysis of the complex was found to correspond to the 2 : 1 ratio of TetNF to host. A weak charge transfer absorption band is observed at λ = 485 nm.

Yield: 15 mg, 50%.

^{1}HNMR (200 MHz, acetone-d_6): 5 9.04-9.03 (d, 2H), 8.68-8.08 (d, 2H), 8.01-8.02 (m, 4H), 7.36-7.31 (m, 4H), 6.45 (s, 4H), 4.10-4.01 (m, 8H), 3.99-3.89 (m, 8H), 3.72-3.66 (m, 16H).

Analysis: Calc. for $C_{62}H_{52}O_{28}N_2$: C,54.87; H,3.86; N,8.25,
Found: C,55.10; H,4.08; N,7.55.

FAB mass: m/z 1310,636.

Experimental procedure for NMR titration:

All H NMR titration experiments were recorded on a BRUKER AF-200 NMR spectrometer in acetone-d6 at 25°. The titrations were done by both methods *i.e.,* by saturating the host solution with the guest and by the dilution protocol.

A sample containing a known amount of the host in a known volume of the solvent was taken in an NMR tube and the spectrum recorded. To this sample, a known quantity of the guest was added and the spectrum recorded again. The process was repeated. Typically eight to ten spectra were recorded for each determination of the association constant K. The host concentration was of the order of 10" M and the guest concentrations ranged from 10" to 10" M. The A8 values were calculated by subtracting the chemical shift of the mixture from that of the pure host. The aromatic signal of the host monitored for the determination of the $\Delta\delta$ values was the H-2, H-3 singlet which was well separated from other resonances and convenient to monitor. The titration curve of the $\Delta\delta$ vs the guest to host ratio was plotted, to obtain information about the stoichiometry of the complexes.

For the dilution protocol, an equimolar solution of the host and the guest was made by carefully weighing out the two and dissolving them in a known volume of acetone-d_6. The NMR spectrum of the sample was recorded. The solution was then diluted by adding a known volume of acetone-d_6 and the spectrum recorded again. The process was continued by progressively diluting the mixture. A5 values were calculated by taking the difference between the chemical shift of interest in the mixture and the same resonance in the spectrum of the pure host. Both the sets of data were combined and the binding constants evaluated.

Equation 7, given in the results and discussion, was slightly modified for this purpose as follows:

$$\delta_{h} - \delta_{obsd} = (\Delta\delta_{max}/2)\,(b - \sqrt{b^2 - 4R})$$

$$\Delta\delta = (\Delta\delta_{max}/2)\,(b - \sqrt{b^2 - 4R}) \qquad (8)$$

Thus, the data were fitted to this non-linear expression using the Sigma plot software routine and the parameters K and $\Delta\delta_{max}$ were obtained. The sample data and the output for the titrations are given in the tables below.

Table 7 Titration data of paraquat vs DN34C10

S.No	Conc. of Host (x 10^{-3} M)	Conc. of Guest (x 10^{-3} M)	AS
1	1.195	1.195	0.2254
2	0.880	0.880	0.2148
3	0.702	0.702	0.2106
4	0.582	0.582	0.2038
5	0.497	0.497	0.1979
6	0.330	0.330	0.1647
7	0.249	0.249	0.1514
8	0.199	0.199	0.1453
9	0.166	0.166	0.1443
10	17.0	3.50	0.0878
11	17.0	7.01	0.1656
12	17.0	10.5	0.2331
13	17.0	14.0	0.2830
14	17.0	17.5	0.3033
15	**17.0**	21.0	0.3127
16	17.0	26.6	0.3169
17	17.0	33.6	0.3204
18	17.0	40.6	0.3216

$K = 6.62 \pm 0.81 \times 10^{3}\ M^{-1}$

$\Delta\delta_{max} = 0.334 \pm 0.007$.

Table 8 Titration data of phenquat vs DN34C10

S.No	Conc. of Host (x 10^{-3} M)	Conc. of Guest (x 10^{-3} M)	A8
1	17.0	3.35	0.1128
2	17.0	6.69	0.2191
3	17.0	10.0	0.3040
4	17.0	13.4	0.3565
5	17.0	16.7	0.3951
6	17.0	20.0	0.4149
7	17.0	23.4	0.4295
8	17.0	28.1	0.4390
9	17.0	35.8	0.4488
10	17.0	40.5	0.4498
11	17.0	47.2	0.4531
12	2.04	1.94	0.2453
13	1.36	1.29	0.2401
14	1.02	0.97	0.2289
15	0.82	0.78	0.2223
16	0.41	0.39	0.1593
17	0.27	0.26	0.1521
18	0.21	0.20	0.1507

$K = 2.27 \pm 0.33 \times 10^{3}\ M^{-1}$

$\Delta\delta_{max} = 0.465 \pm 0.010$.

Table 9 Titration data of TetNF vs DN34C10
(at host conc. of 1.49 x 10^{-2} M)

S.No	**Conc.** of **Guest** (x 10^{-2} M)	A5
1	0.463	0.0160
2	0.925	0.0330
3	1.39	0.0550
4	1.85	0.0780
5	2.30	0.0930
6	2.78	0.1090
7	3.70	0.1270
8	4.86	0.1590
9	6.02	0.1880

$K = 9.97 \pm 2.17 \times 10^{3}\ M^{-1}$

$\Delta\delta_{max} = 0.537 \pm 0.082$.

Job's plot for TetNF-DN34C10 complex:

The complex stoichiometry was determined by using Job's method of continuous variations. The method involves preparation of standard solutions of TetNF and DN34C10 (0.013 M in each) in acetone-d_6. In 9 separate NMR tubes, the solutions of the host and guest were mixed in different proportions such that the ratio of each component varied but the total volume of the mixture was kept constant (500 µl), i.e., [H] + [G] was kept constant while varying [H] /

[G]. The solutions prepared were such that the mole fraction of the guest varied from 0.1 to 0.9. The NMR spectrum of each sample was recorded and the A5 values were obtained by subtracting the chemical shift of interest in the sample from that of the same resonance in the pure host.

For the purpose of plotting the Job's curve the following derivation was used based on equation 9:

$$\delta_{obsd} = (a\delta_a + c\delta_c)/a_o \qquad \textbf{(9)}$$

where δ_{obsd} = chemical shift of the sample

a = conc. of the free host and c = conc. of the complex

δ_a = chemical shift of the free host

δ_c = chemical shift of the complex

and, a_o = initial concentration of the host.

$$\Delta\delta = \delta_a - \delta_{obsd} = \delta_a - ((a\delta_a + c\delta_c)/a_o) \qquad (10)$$

$$\Delta\delta = ((a + c)\,\delta_a - a\delta_a - c\delta_c)/a_o$$

$$\Delta\delta = c(\delta_a - \delta_c)/a_o \qquad \text{or}$$

$$(a_o \times \Delta\delta) = c \times \Delta\delta_{max}$$

Thus, the concentration of the complex is shown to be proportional to the product (a_o x A6) as $\Delta\delta_{max}$ is a constant. A plot of the product of the host concentration and A6 vs the guest mole fraction was made. This peaked at the guest mole fraction of 0.5 (the complex concentration would also be maximum at this mole fraction), indicating that the complex has a stoichiometry of 1 : 1 in solution.[40b] The data used for plotting the Job's curve is listed in Table 10.

Table 10 Job's plot data for TetNF complex

Conc. of Host (×10^{-2} M)	**Conc.** of guest (×10^{-2} M)	Mole fraction of guest	A5	a_0 x A5 (×10^{-4} M)
1.31	0	0	-	-
1.18	0.13	0.99	0.0117	1.38
1.05	0.26	0.2	0.0278	2.92
0.92	0.39	0.3	0.044	4.30
0.79	0.52	0.4	0.061	4.78
0.66	0.66	0.5	0.083	5.40
0.52	0.79	0.6	0.098	5.14
0.39	0.92	0.7	0.115	4.50
0.26	1.05	0.8	0.133	3.48
0.13	1.18	0.9	0.146	1.91
0	1.31	1	-	-

Structural data:

The structure was solved by direct methods and refined isotropically to an R value of 0.14 using 384 above 4 sigma of 1762 reflections. The quality and the quantity of the data was not sufficient for further refinements.

Crystal structure analysis indicated that the host crystallised in the space group $p2_1/n$, monoclinic, Z = 2; Cell dimensions: a = 13.108(3)A, b = 5.120(4)A, c = 25.201(7)A and β - 102.79°(2), p $_{(cell)}$.= 1.19 g / c.c., $V_{(cell)}$= 1649.3 A^3. The coordinates are listed in Table 11.

Table 11

Atom	Fractional coordinates		
	X	Y	Z
027	0.45534	0.09721	0.15052
O1	-0.06168	-0.81094	0.03274
04	-0.17237	-1.18402	-0.08173
C33	0.06029	-0.47977	0.02226
021	0.67391	-0.44852	0.08679
C48	0.34990	-1.25084	-0.18972
030	0.24872	-0.09626	0.12318
C16	0.45690	-1.18140	-0.00433
010	0.04428	-1.70611	-0.14676
C36	0.11513	-0.42891	0.12909
C35	0.03707	-0.60797	0.10908
C44	0.46128	-1.02701	-0.10454
C40	-0 01828	-0.80440	0.13768
C2	-0.08687	-0.91033	-0.02245
C6	-0.25039	-1.41888	-0.15989
C11	0.13180	-1.86247	-0.12465
C31	0.16985	-0.26838	0.09296
O13	0.26149	-1.56190	-0.12297
024	0.66099	0.00467	0.14748
018	0.57498	-0.85334	-0.03113
07	-0.17151	-1.54342	-0.15500
C46	0.46579	-0.89858	-0.20022

C34	0.00546	-0.63915	0.05058
C19	0.38070	-1.19077	-0.13174
C8	-0.12794	-1.73180	-0.19619
C99	0.57571	-0.79068	0.02912
C32	0.13517	-0.28128	0.04022
C3	-0.18387	-1.06533	-0.03498
C29	0.29032	0.04623	0.08757
C25	0.64122	-0.00902	0.19968
C12	0.21269	-1.73784	-0.08522
C5	-0.26115	-1.31201	-0.10448
C17	0.48987	-1.03601	-0.04497
C23	0.75179	-0.17966	0.16441
C9	-0.03696	-1.91136	-0.16977
C15	0.37031	-1.34654	-0.03510
C20	0.67161	-0.57111	0.03227
C14	0.33696	-1.38678	-0.10138
C22	0.76330	-0.31302	0.11188
C45	0.49003	-0.85578	-0.14577
C26	0.54712	0.22217	0.17954
C28	0.36501	0.27525	0.13074
C47	0.39230	-1.06397	-0.22216
C37	0.15817	-0.37671	0.19169
C39	0.02139	-0.75082	0.19548
C38	0.09456	-0.56916	0.22026

References

1. a) W. Saenger, '*Principles of Nucleic Acid Structure*' Springer-Verlag, New York, **1984, p.** 132; **b) L. P.** G. Wakelin, *Med.Res. Rev.*, 1986, *6,* 275.
2. a) S. K. Burley and G. A. Petsko, *Science*, **1985**, *229*, 23; b) R. J. Abraham, F. Eivazi and H. Pearson, *J. Chem. Soc, Chem. Commun.*, **1976,** 698.
3. G. **R.** Desiraju and A. Gavezzotti, *J. Chem. Soc, Chem. Commun.*, **1989,** 621.
4. a) C. **A.** Hunter and J. K. M. Sanders, *J. Am. Chem. Soc*, 1990, *112*, 5525; b) C. A. Hunter, *Chem. Soc. Rev.*, 1994, 101 and references cited therein.
5. a) S. Anderson, H. L. Anderson and J K. M. Sanders, *Acc. Chem. Res.*, 1993, *26*, 469, b) J. F. Stoddart, *'Template-Directed Synthesis of New Organic Materials'*, in *'Frontiers in Supramolecular Organic Chemistry and Photochemistry'*, H. J. Schneider and H. Dürr, Ed., VCH., New York, **1991, p.**251.
6. C. A. Hunter, *J. Chem. Soc, Chem. Commun.*, 1991, 749.
7. R. Foster, '*Organic Charge Transfer Complexes'*, Academic Press, New **York, 1969, p.** 238.
8. **a) D. A.** Dougherty, **D. A.** Stauffer, *Science*, **1990,** *250,* 1558; b) P. C. Kearney, L. S. Mizoue, R. A. Kumpf, J. E. Forman, A. McCurdy and D. A. Dougherty, *J. Am. Chem. Soc*, **1993,***113*, 9907; c) D. A. Dougherty, D. A. Stauffer and R. E. Barrens, J. *Org. Chem.*, **1990,** *55*, 2762.
9. J. F. Stoddart, *Pure andAppl. Chem.*,**1988,***60*, 467.

10. H. M. Coloquhoun, E. P. Goodings, J. M. Maud, J. F. Stoddart, J. B. Wolstenholme, D. J. Williams, *J. Chem. Soc, Perkin Trans. II,* **1985,** 607.

11. J. F. Stoddart, et al, *J. Chem. Soc, Chem. Commun.,* **1987,** 1054, 1058, **1061, 1064, 1066.**

12. S. E. Zimmerman, '*Rigid Molecular Tweezers as hosts for the Complexation of Neutral Guests*' in '*Topics in Current Chemistry-Supramolecular Chemistry I -Directed Synthesis and Molecular Recognition,*'E. Weber, Ed., Springer-Verlag, Berlin, **1993, p**.**71**.

13. a) S. C. Zimmerman and C. M. Vanzyl, *J, Am. Chem. Soc,* **1987,** *109,* 7894; b) S. C. Zimmerman, G. S. Hamilton and C. M. Vanzyl, *J. Am. Chem. Soc,* **1989,** *111***,** 1373.

14. S. C. Zimmerman, M. Mriksich, M. Baloga, *J. Am. Chem. Soc,* **1989,** *111***,** 8528.

15. S. C. Zimmerman and W. Wu, *J. Am. Chem. Soc,* **1989,** *111*,8054.

16. M. M. Mahmond and S. C. Wallwork, *ActaCrystallogr. Sect. B.,* 1976, *32,* 440.

17. A. M. Z. Slawin, N. Spencer, J. F. Stoddart and D. J. Williams, *J. Chem. Soc, Chem. Commun.,* **1987,** 1070.

18. a) B. Odell, M. V. Reddington, A. M. Z. Slawin, N. Spencer, J. F. Stoddart and D. J. Williams, *Angew. Chem. Int. Ed. Engl.*, **1988,** *27,* 1547; b) P. R. Ashton, M. V. Reddington, A. M. Z. Slawin, B. Odell, J. F. Stoddart and D. J. Williams, *Angew. Chem. Int. Ed. Engl.*, 1988, 27, 1550.

19. a) J.-Y. Ortholand, A. M. Z. Slawin, N. Spencer, J. F. Stoddart and D. J. Williams, *Angew. Chem. Int. Ed. Engl.,* **1989,** *28,* 1394; **b) P. R.** Ashton,

E. J. T. Chrystal, J. P. Mathias, K. P. Parry, A. M. Z. Slawin, N. Spencer, J. F. Stoddart and D. *i.* Williams, *Tetrahedron Lett.,* **1987,** *28,* 6367.

20. D. B. Amballino and J. F. Stoddart, *Chem. Rev.,* 1995, *95,* 2725.
21. D. Philp and J. F. Stoddart, *Angew. Chem. Int. Ed. Engl.*, **1996,** *35,* 1154; b) G. J. Owen and P. Hodge, *Chem. Commun.*, **1997, 11**; c) J. F. Stoddart, M. Asakawa, P. R. Ashton, R. Ballardini, V. Balzani, M. Belohradsky, M. T. Gandolfi, O. Kocian, L. Prodi, F. M. Raymo and M. Venturi, *J. Am. Chem. Soc,* 1997, *119*, 302 .
22. P. R. Ashton, T. T. Goodnow, A. E. Kaifer, M. V. Reddington, A. M. Z. Slawin, N. Spencer, C. Vicent, J. F. Stoddart and D. J. Williams, *Angew. Chem. Int. Ed. Engl.,* **1989,** *28,* 1396; b) C. L. Brown, D. Philp, N. Spencer and J. F. Stoddart, *Isr. J. Chem.*, 1992, *32,* 61.
23. D. Philp, C. L. Brown and J. F. Stoddart, *Synlett.,* 1991, 459, 462; b) P. L. Anelli, P. R. Ashton, A. E. Kaifer, D. Philp, M. V. Reddington, A. M. Z. Slawin, N. Spencer, L. Prodi, M. Pietraszkiewicz, C. Vicent, J. F. Stoddart and D. J. Williams, *J. Am. Chem. Soc,* 1992, *114,* 193; d) M. Asakawa, P. R. Ashton, S. E. Boyd, C. L. Brown, R. E. Gillard, O. Kocian, F. M. Raymo, J. F. Stoddart, M. S. Tolley and A. J. P. White, *J. Org. Chem.,* **1997,** *62,* 26.
24. **P. R.** Ashton, A. E. Kaifer, D. Philp, A. M. Z. Slawin, N. Spencer, D. B. Amballino, M. T. Rutland, S. P. Newton, F. M. Raymo, C. L. Brown, M. Pietraszkiewicz, C. Vicent, J. F. Stoddart and D. J. Williams, *J. Am. Chem. Soc,* **1995,** *117*, 1271.
25. H. B. Laurent, A. Castellan, M. Daney, J. P. Desvergne, P. Guinand, P. Marsau and M. H. Riffaud, *J. Am. Chem. Soc,* **1986,** *108*, 315.

26. D. Marquis, J. P. Desvergne and H. B. Laurent, *J. Org. Chem.*, 1995, *60,* 7984.
27. D. Marquis, J. P. Desvergne, P. Marsau, B. Heinze and M. Cotrait, *Tetrahedron Lett.*, 1996, *37,* 5499.
28. J. F. Stoddart, D. J. Williams, N. Spencer, B. L. Allwood and H. S. Zavareh, *J. Chem. Soc, Chem. Commun.*, 1987, 1061 and 1064.
29. E. J. O'Reilly and R. B. Bayer, *J. Org. Chem.*, 1958, *23,* 311.
30. R. G. R. Bacon and S. C. Rennison, *J. Chem. Soc. (C)*, 1969, 312.
31. a) E. C. Spaeth and T. A. Geiss, *J. Org. Chem.*, 1946, *11,* 399; b) L. F. Feiser and V. Desreux, J. *Am.* Chem. Soc, 1938, 60, 2255.
32. M. V. Bhatt and S. U. Kulkarni, *Synthesis,* 1983, 249.
33. W. Militzer, *J. Am. Chem. Soc,* 1938, 60, 256.
34. W. M. Pearlman, *Tetrahedron Lett.*, 1967, 1663.
35. P. R. Ashton, C. L. Brown, E. J. T. Chrystal, K. P. Parry, M. Pietraszkiewicz, N. Spencer and J. F. Stoddart, *Angew. Chem. Int. Ed. Engl.*, 1991, *30,* 1042.
36. O. Hutzinger and W. D. Jamieson, *Anal. Biochem.*, 1970, *35,* 351.
37. T. Wang, J. S. Bradshaw and R. M. Izatt, *J. Heterocyclic Chem.*, 1994, *31,* 1097.
38. R. S. Macomber, *J. Chem. Ed.*, 1992, *69,* 375.
39. C. S. Wilcox, *Efficacious Functional Group Dyad. NMR in Host-Guest Interactions,* in *Frontiers in Supramolecular Organic Chemistry and Photochemistry,* H. J. Schneider and H. Diirr, Ed., VCH, New York, 1990, p. 123.

40. a) A. Job, *Annales de chimie* (10th series), **1928,** *9,* 113; b). **K. A.** Connors, *Binding Constants,* Wiley, New York, **1987;** c) **V. M. S.** Gil **and N. C.** Olivira, ***J.*** *Chem. Ed.,* **1990, *67,*** 473.

41. *A Textbook of Practical Organic Chemistry,* A. I. Vogel, 4th edition Longman, London, **1978, p**.755

42. M. Haring, ***Helv.*** *Chim.* ***Acta*.,1963,** *46*, 2970.

43. J. E. Dickeson **and L. A.** Summers, ***Aust.*** *J. Chem.*.,**1970,** *23* 1023.

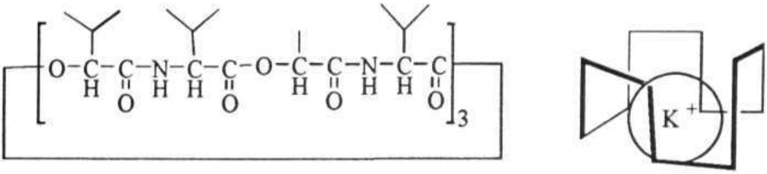
44. M. S. Newman and H. Boden, *Org. Synth. Coll. Vol. V,* **1973, p.** 1029.

Chapter 2

Introduction

Selective complexation of inorganic cations is by far the most important and well developed aspect of supramolecular chemistry. Research in this area that began with Pedersen's[1] preparation of crown ethers possessing superior complexation properties towards alkali metal cations, received a boost with the advent of Cram's '*spherands*' and Lehn's '*cryptands*'. With the progress of time, several chemical modifications were made: nitrogen, sulphur and phosphorous were introduced into the rings for specific control on cation-binding selectivity; rings of varying size and heteroaromatics were incorporated, to achieve the objective of selective binding. Today the field has gained considerable practical significance, particularly in the area of analytical applications.

The most striking feature of the crown compounds is their specific cation complexation ability which is dependent upon the number and type of donor atoms, dimensions of the cavity and preorganisation of the host. Apart from ring size, rigidity of the ring also plays a role in the selectivity. Small and rigid crown compounds often show pronounced selectivity for the small metal cations and large and flexible crown compounds effectively complex larger metal and molecular cations. One advantage is that conformations are easily adjustable in the case of flexible crown compounds, though this leads to low stabilities of their complexes in solution. Another very important factor controlling stabilities of complexes is the topology of the ligand. It determines the way in which the cation and ligand interact and defines the complex formed as podate, coronate or cryptate depending upon whether the ligand is a podand, coronand (crown ether) or cryptand. On going from open-chain to monocyclic crown to cryptand, the stabilities of the complexes increase significantly. The ligand that replaces the solvation shell better, would be the one which would envelop the cation better and bind stronger. Such recognition is a basic feature in biological systems. Valinomycin (1, Fig. 1), for example, is a well known biological ion-carrier specific for K^+ transport.[5] It is however remarkable, because, despite its apparently very large ring (36-depsipeptide ring), it forms a stable, dynamic complex with K^+.



VALINOMYCIN 1

Figure 1

It can therefore be said that the often assumed matching of ion diameter and cavity size (apart from usual inductive and polarisability effects) is no more a sufficient condition for selectivity in binding. This has been shown conclusively by Hancock and Martell.[6] They observed that the simple rules of size matching break down with flexible crown ethers of type 2 and 3 (Fig. 2). The smaller macrocycles (2a, 3a) show greater selectivity towards larger cations than the larger analogs (2b, 3b).

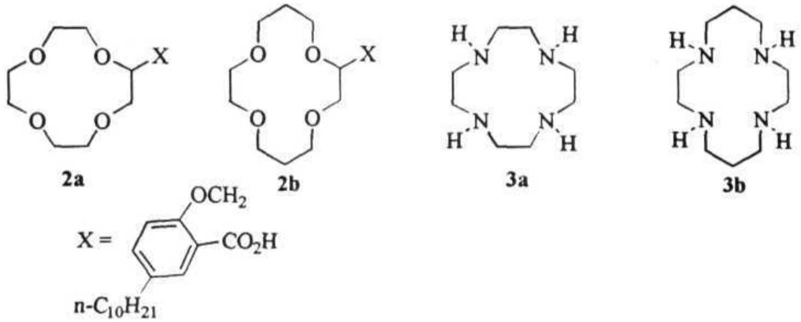
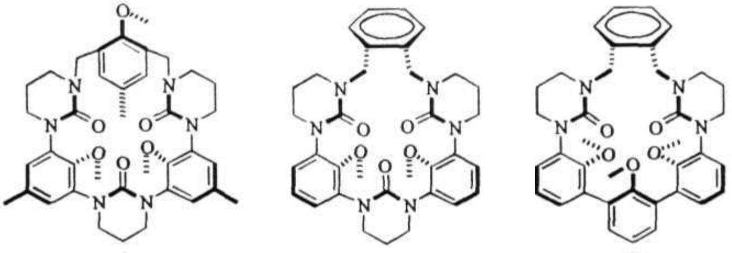


Figure 2

The above observation clearly indicates that the complementarity of hole and cation size concept has serious limitations, especially with respect to crown ether derivatives that are more flexible.



	4a	4b	4c
Li^+	50.6	76.5	69.4
Na^+	64.4	68.1	64.4
K^+	65.2	51.8	45.1

Figure 3 Free energies of complexation (in **kJ/Mol.,** extraction method)

A way out of this difficulty is to utilise Cram's preorganisation principle and introduce some rigidity in the flexible crown ethers. He has shown that within one family of ligands, it is possible to construct hosts of the type 4a-c (Fig. 3) with large cavities and flexible binding arrangements capable of adapting to various guest sizes.

Inspired by this idea, we decided to extrapolate this to a totally flexible and sufficiently large crown ether system. The idea was to make large rings with a rigid cap/handle connected by a flexible loop that is capable of cation uptake.

A survey of the literature reveals that a large number of such molecules have been reported. A few interesting cases are discussed below. Shinkai, during the course of his studies on azobenzene as a photoswitch, synthesised an interesting family of compounds 5a-c, Fig. 4.

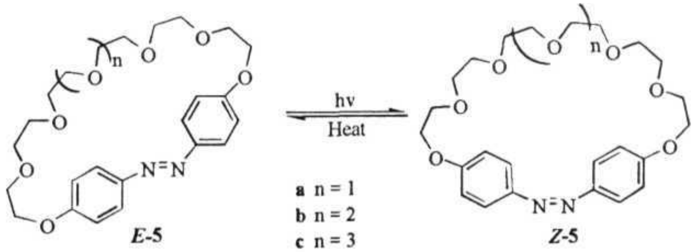


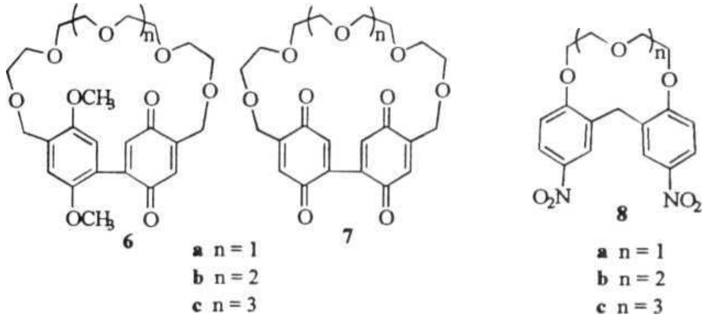
Figure 4

These compounds are of interest in more than one way. First, *E-Z* isomerisation in them can be achieved both thermally and photochemically. Secondly, the *E*-isomers showed absolutely no extracting ability towards metal cations, due the to stretched arrangement of the polyethylene glycol unit. In the

Z-isomer, the distance between *p*-positions (those that are para to the N=N) decreases from 0.9 to 0.55 nm leading to the formation of crown ether type macrocycles. Binding studies show that 5a binds $Na^+ > K^+$, Rb^+ but not Cs^+, 5b binds $K^+ > Na^+ > Rb^+$ and Cs^+, and 5c binds all cations, with Rb^+ being the strongest . A feature observed in the above case is that specificity to a particular cation is no longer present.

A similar kind of observation was made by Tsukube after a study of novel macrocyclic quinonoid compounds bearing ion-binding polyether moieties (6a-c and 7a-c, Fig 5). Addition of $NaClO_4$ and $KClO_4$ to an acetonitrile solution of the macrocycle 6a enhanced the intensity of the quinonoid absorption band at 430-440 nm, while no change was observed on addition of $LiClO_4$. Though absorption intensities were found to rise with increasing amounts of metal (Na^+, K^+) perchlorate additions, the deviations were too small to be quantitatively analysed. The same effect was observed in all other quinonoid crowns. These macrocycles seem to bind Na^+ and K^+ in a selective but loose manner. This is to be expected, for the elongated polyether rings do not efficiently form a spherical cavity to bind the cations as observed in normal crown ethers. Also, not all the polyether oxygen atoms bind to the guest simultaneously.

Kilic[10] prepared the macrocyclic polyethers containing nitro group on the aromatic ring by reacting 2,2'-methylene bis(4-nitrophenol) and oligoethylene glycol ditosylates (8, Fig. 5). The structures of these compounds were unambiguously established. However, these compounds did not form stable complexes with alkali or alkaline earth metal cations.



6

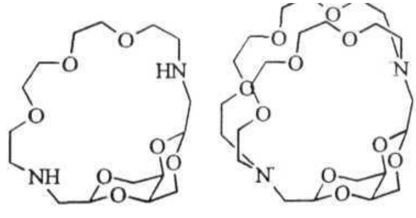
7

8

a n = 1
b n = 2
c n = 3

Figure 5

Reduction in basicity of the ether oxygens due to nitro group carrying benzene rings and distortion due to the benzylic $-CH_2$ were the reasons attributed for the non-complexing behaviour.



9a

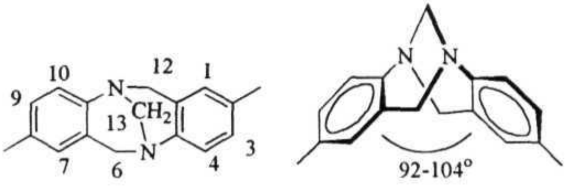
9b

Figure 6

More recently, Fuchs[11a] reported the synthesis of novel diacetal podands, diaza crowns and cryptands bearing *cis*-1,3,5,7-tetraoxadecalin as the rigid frame (Fig. 6). These diaza crowns were shown to have good alkali and alkaline earth cation inclusion behaviour.

The above studies with stretched crowns indicate that large flexible cavities are effective in binding cations though not with high selectivities. This substantiates the fact that recognition is a dynamic process involving distinct chemical interactions and not a mere fitting of the hole and ion. Our concern in this context was to choose an appropriate rigid cap that would not inhibit the complexation of the loop as in case of the 2,2'-methylene bis-4-nitrophenol crowns. The choice naturally was the Troger's base unit.

2,8-Dimethyl-6H,12H-(5,11)-methanodibenzo[b,f][1,5]diazocene (10, Fig. 7), first prepared by Troger in 1887, has recently been attracting the attention of chemists in the area of biomimetic and bioorganic chemistry involved in the construction of new synthetic receptors. It is a rigid and very easily available molecule, obtained by acid promoted condensation of p-toluidine and formaldehyde. Historically, it was the first amine proven to have a

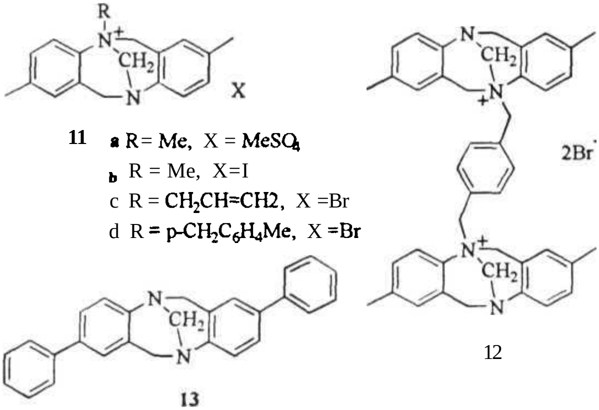


10

Figure 7

rate of configurational inversion slow enough to allow resolution into its enantiomeric components. The methanodibenzodiazocine unit has a hinge region in the form of the five saturated atoms of the central rings and the phenyl rings of the base are oriented approximately at right angles to each other.[14] There is however a moderate flexibility in the mcthanodibenzodiazocine ring system (a 10 difference in the dihedral angle is observed by X-ray structure analysis of racemate and (+)-enantiomer, obviously from the packing effects associated with crystal structures). Incorporation of this unit within the macrocycle can afford water soluble, rigid, chiral synthetic receptors. This sharply folded molecule is therefore a well-suited key component for synthesis of macrocycles, molecular clefts and helices.

A variety of synthetic receptors incorporating Tröger's base have already been reported in the literature, a brief survey of which would substantiate the views presented above. The studies have mostly focussed on the addition of recognition sites on either side of the hinge of the dibenzodiazocine unit to bring out subtle recognition of different guests. Most of the early studies were concerned with the inclusion of solvent molecules and clathrate formations. Weber[16] synthesized onium salts of Troger bases. A clathrate inclusion study of these salts (**11** and 12, Fig. 8) revealed that all the onium salts displayed a remarkable preference for aromatic solvents as guests. 1,4-Dioxane was found to be selectively included in the crystals of **11b**, when it was crystallised from a 1 : 1 mixture of either benzene-dioxane or toluene-dioxane in the ratio dioxane : **11b** equal to 1 : 2. The bis Troger base salt **12** shows a 1 : 1 clathrate stoichiometry exclusively and a marked preference for less voluminous guests.



13

Figure 8

It is noteworthy that most clathrate formations reported are with quaternised Tröger's bases analogues. However, Bond and Scott have shown **that** 13 (Fig. 8) clathrates dioxane in a host-guest ratio of 1 : 0.33 in a non-quaternised form.

Pioneering work has been done by Wilcox with Troger's bases. He has synthesized several derivatives of Troger's bases that are of potential value as conformationally restricted 'armatures' to build on.[1 ft] Based on these analogs, he has designed a variety of macrocycles and clefts for specific binding of hosts (Fig. 9). The macrocyclic receptor 14 has been reported to form complexes with benzenoid substrates in aqueous solutions[19] and the receptor 15 with H-bonding guests. It was shown to be an excellent binder of biotin. The crystal structure of the molecular cleft 16 (Fig. 9) has been shown to include two ethanol molecules within the cleft defined by the ester groups.[21]

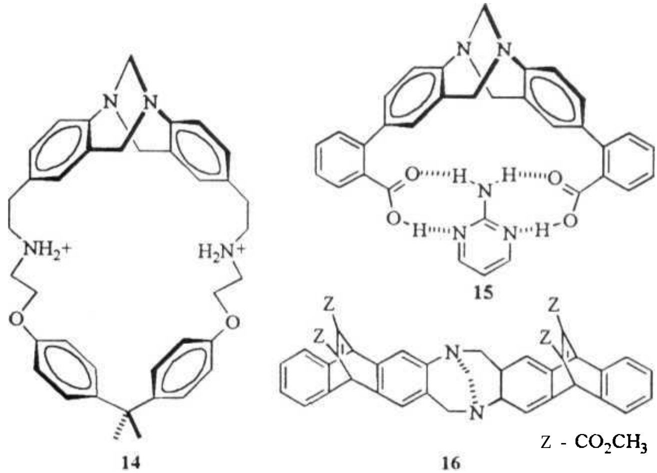


Figure 9

The rigidity of the dibenzodiazocine unit has been aptly used in constructing a bisporphyrin substituted Troger's base armature. It was shown that this molecule displays high binding affinities with several α,ω-diamines.

Lately, a lot of interest has been shown in synthesising derivatives of Troger's bases bearing aromatic substituents that could be potential DNA intercalators (17, 18 and 19, Fig. 10).[23] These probes would be a unique class of DNA intercalators, especially because of their chirality.

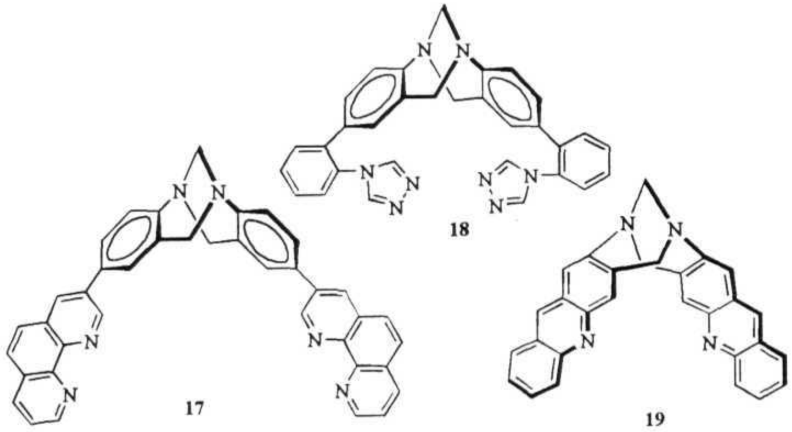
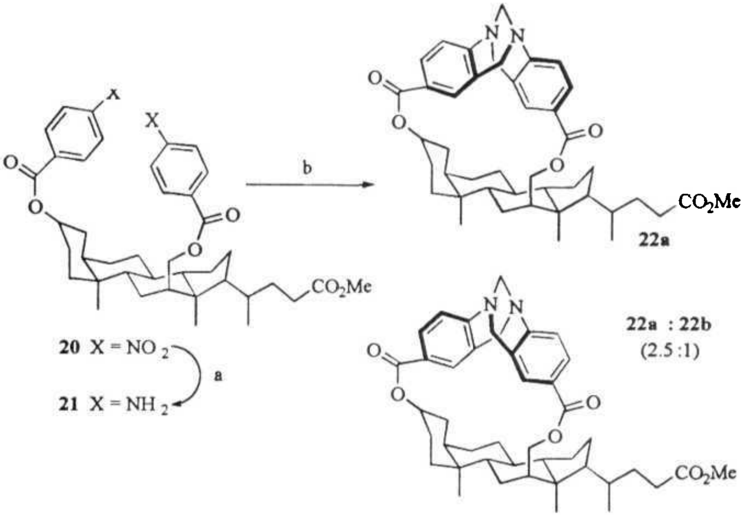


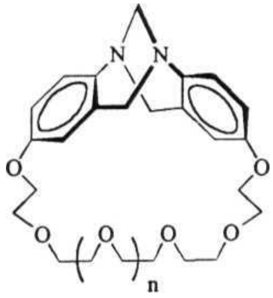
Figure 10

Asymmetric synthesis of Troger's bases have always been a challenge since the enantiomers racemise rapidly under the acidic conditions required to build the dibenzodiazocine ring. The first diastereoselective synthesis by Maitra, was based on using 17-deoxycholic acid as a chiral template (Scheme 1). Removal of the steroid unit then resulted in a chiral product. The same group has also reported the synthesis of novel Troger's base analogues functionalised with two carboxyl groups. [4]



22b

Scheme 1 *Reagents and Conditions:* a) $SnCl_2.2H_2O$, EtOH, 70 , 3h; b) $CH_2(OCH_3)_2$, CH3SO3H, reflux, 48h.



23a (n=1)

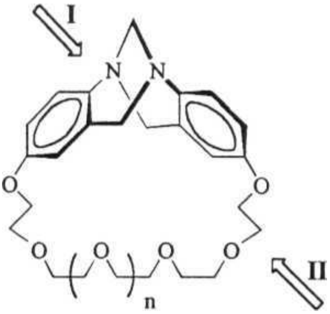
23b (n=2)

Figure 11

As is clear from the above examples, Troger's base derivatives provide a rigid chiral framework for construction of novel chelating and biomimetic systems. This moiety was therefore our natural choice as a rigid cap in construction of polyether macrocycles. These molecules would form a class of novel synthetic receptors that could be potential cation binders. A simple and facile synthesis of novel oxygen macrocycles bearing the Troger's base moiety (23a-c, Fig. 11) is discussed in the next section.

Results and Discussion

The aim was to construct oxygen macrocycles bearing the Troger's base moiety in a simple, facile and shortest possible route. The synthesis of the macrocycles can be envisaged in two ways (Fig. 12). The polyether framework can be assembled first and then the macrocycle formed by tying up the amine ends by condensation (I). Alternately, the Troger's base frame can be fabricated first followed by closure of the macrocycle with the appropriate polyether chain **(II)**.



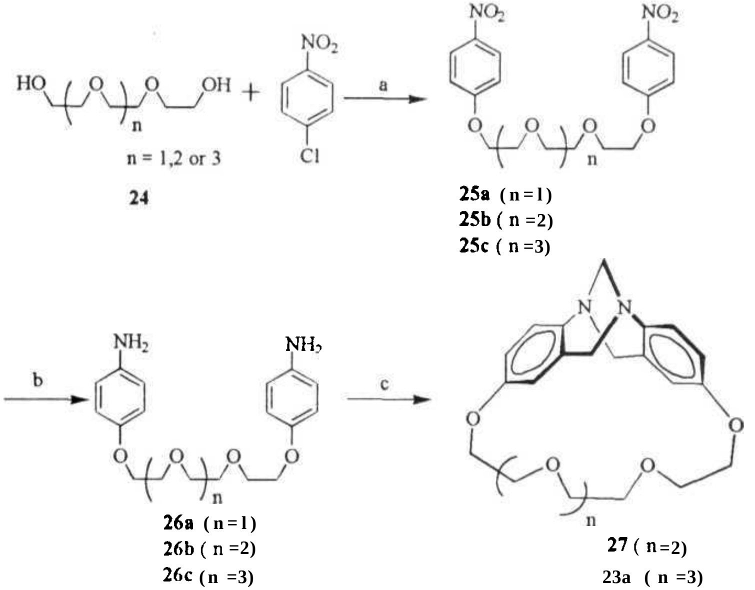
n= 1,2,3

Figure 12 **I** and **II** indicate the final steps in the synthesis.

Adopting the first strategy, we set out to synthesise the polyether frame (Scheme 1). The bis(4-nitrophenoxy) ethers **(25a-c)** of the corresponding glycols 24 were made either by nucleophilic substitution of the 4-nitrophenoxide ion on the corresponding ditosylate or by nucleophilic substitution of the glycol dianion on 4-nitrochlorobenzene. The products were all solids having a characteristic yellow colour and sharp melting points. All three compounds exhibited the same general pattern in their H NMR spectra: a pair of well separated doublets in the aromatic region (5 8.19-8.11 and 7.00-6.91) and a characteristic AA'XX' pattern in the aliphatic region (5 4.20-3.60) corresponding to the glycol unit.

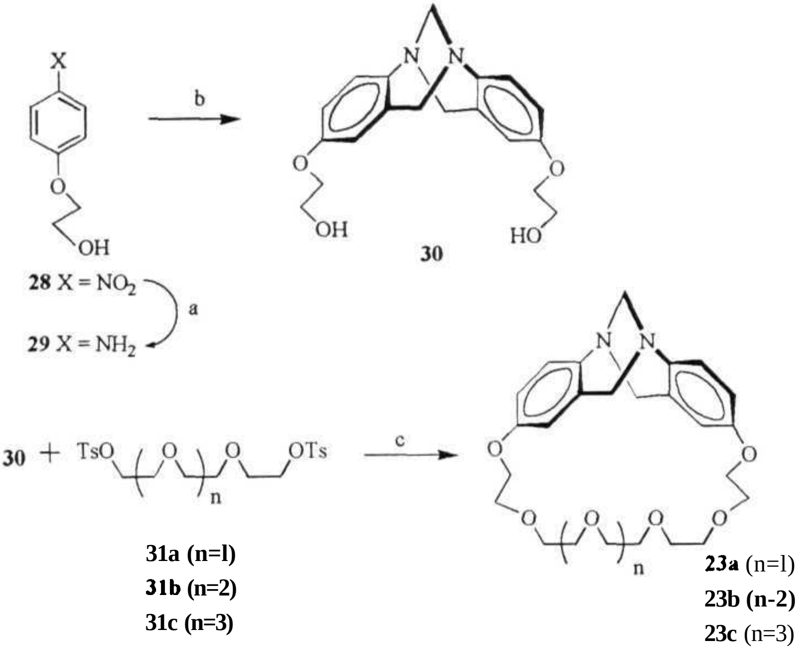
The nitro group of these ethers was then reduced under non-acidic and non-aqueous conditions using $SnCl_2 \cdot 2H_2O/EtOH$ in an inert atmosphere. The corresponding diamines (26a-c) which were obtained in good yields, rapidly changed colour on exposure to air. The primary amine stretching frequencies (3420 and 3320 cm$'^{1}$) were very distinct in the IR spectra. In the ^{1}H NMR spectra, no specific changes were observed in the glycol pattern from those of the dinitro compounds. However, the well separated pair of doublets in the aromatic region merged to a quartet like pattern at 5 6.70 to 6.50.

Attempts were made to construct the 1,5-diazocene ring by employing the acid promoted condensation of formaldehyde with the diamines.[15] Efforts to condense the diamine 26a (n = 1) with formaldehyde, in order to obtain the corresponding macrocycle were not successful. This could be due to the shorter ether chain in 26a. The condensations of 26b and 26c with formaldehyde were then tried under the same conditions. The reactions yielded a complex mixture of products. The crude H NMR spectra of the reaction mixtures displayed signals characteristic of the 1,5-diazocene unit. However, attempts to purify the mixtures were unsuccessful due to the presence of inseparable polar by-products.



Scheme 2 *Reagents and conditions:* a) NaH, DMF, reflux, 24h; b) $SnCl_2 \cdot 2H_2O$, EtOH, reflux. **12h;** c) HCHO, HC1, EtOH. rt, 48h.

Having failed to obtain the macrocycles in pure condition by the first strategy, we then concentrated our efforts on the alternative route. Accordingly, **2-(4 -nitrophenoxy)ethanol** (28) was synthesised as reported in the literature, from **2-chloroethanol** and **4-nitrophenol**. The reduction to 2-(4-aminophenoxy)ethanol (29) employing the same conditions as above, proceeded smoothly (Scheme 3). The acid catalysed condensation of the **amine with** formaldehyde, under the same conditions as above, was successful, yielding 30 in 25% yield.



Scheme 3 *Reagents and conditions:* a) $SnCl_2 \cdot 2H_2O$, EtOH, reflux, **12h;** **b) HCHO,** HCl, EtOH, rt, 48h; c) NaH, Cs_2CO_3, DMF, reflux, 36h.

The IR spectrum of 30 showed the absence of the primary amine stretching frequencies. The H **NMR** spectrum exhibited the distinguishing signals of the 1,5-diazocene unit. All the three aromatic protons appeared as discrete signals. The methylene protons of N-CH_2-N appeared as a singlet at 6 4.29 while the two C-CH_2-N signals formed an AB pattern with doublets at 5 4.68-4.59 (J = 16.7 Hz) and at 5 4.10-4.02 (J = 16.8 Hz). The ^{13}C NMR spectrum showed 10 carbons signals in all, six in the aromatic and four in the aliphatic (C-C-N signal doubling up), which is in agreement with the symmetry inherent in the molecule. The compound gave a satisfactory elemental analysis.

With 30 in hand, the macrocyclisation was undertaken employing tri-, tetra- and pentaethylene glycol ditosylates (**31a-c**) for the purpose. At the outset, 30 was heated with the ditosylates **31a-c** and NaH in DMF. The crude reaction mixtures again exhibited the typical signals of the 1,5-diazocene unit.

The crude reaction mixture was then purified by column chromatography on basic alumina. The corresponding macrocycles 23a-c were obtained in pure form in 25, 32 and 20% yields, respectively.

The absence of the hydroxyl band and the appearance of the characteristic strong ether band at 1100 cm^{-} in the IR spectrum marked the macrocyclisation. The H NMR spectrum showed no significant changes in the 1,5-diazocene unit. The polyether signals were distinct at 5 4.09-3.63 in all the macrocycles. In the C NMR spectrum, the disappearance of the signal at 61.55 ppm (C-C-OH), was again indicative of ring closure. The C NMR spectra of all the macrocycles were fully in consonance with the symmetry present in these molecules. Lastly, all compounds gave satisfactory elemental analyses.

Encouraged by this, the synthesis of the macrocycles was done under various conditions in order to improve the yields in the macrocyclisation step. The conditions used and the yields obtained under these conditions are listed in

Table 1. As is clear from the table, the addition of cesium carbonate improves the yields, but not to a very large extent.

Table 1

S.No	**Ditosylate used**	**Reaction conditions**	**Time** (h)	**Yield** (%)
1.	Triethylene glycol ditosylate	a	**72**	25
		b	**72**	g
		c	**36**	26
		d	**72**	26
2.	Tetraethylene glycol ditosylate	a	**72**	32
		b	**72**	20
		c	**36**	41
		d	**72**	32
3.	Pentaethylene glycol ditosylate	a	**72**	20
		b	**72**	18
		c	**36**	24
		d	**72**	27

Conditions under which macrocyclisation was carried out. a) NaH, DMF, 120°; b) NaH, Cs_2CO_3, DMF, rt; c) NaH, Cs_2CO_3, DMF, 120°; d) NaH, DMF, 120°, CS2CO3, dilution.

Having thus achieved a simple and straightforward synthesis of a novel class of oxygen macrocycles, efforts were addressed to study their binding abilities, especially their cation complexation affinities. With a reasonable assumption that the oxygen macrocycles 23a-c are potentially capable of coordinating alkali metal cations, we chose to work with Li^+, Na^+, K^+ and Cs^+ ions. A tetrahedral ion, NH_4 ion was also added to the list to see if it shows any special binding affinities. Evaluation of the cation binding properties was done by using Cram's picrate extraction method. The chloroform solutions of the macrocycles 23a-c were used to extract aqueous solutions of the metal picrates by a technique described in the experimental section. After the extraction, the UV absorption of the organic phase was measured at 380 run and from these, the molar ratios of the picrate to the host (R) were determined at rt. The association constants K_a were then calculated using the equation 1, written for the equilibrium represented below:

$$[H_i]_{CHCl_3} + [G_i^+]_{H_2O} + [X^-]_{H_2O} \rightleftharpoons [G^+.H.X^-]_{CHCl_3}$$

$$K_a = \frac{R}{(1\text{-}R)\,K_d\,[\,(G_i)_{H_2O} - R\,(H_i)_{CHCl_3}\,V_{CHCl_3}/V_{H_2O}]^2} \qquad (1)$$

where, R = Molar ratio of the picrate to the host in $CHCl_3$

(Gi) H_2O = Initial picrate concentration

(Hj) CHCB = Initial concentration of the host

V CHCB = Volume of $CHCl_3$

V H_2O = Volume of H_2O

In equation 1, the term K_d represents the distribution constant of the picrate between chloroform and water layers in the absence of the host. These values were not determined by us, but the K_d values reported by Cram were used for all our calculations.

The log K_a values obtained from the extraction studies are presented in Table 2. The K_a values were of the order of 10^4 - 10^3. From the data it is clear that all the macrocycles show reasonably good extraction capabilities and binding affinities with all the cations studied. However, no specific selectivity towards any particular cation was observed. The particularly low selectivity of the hosts towards cations of different sizes reflects on the high flexibility present in the macrocycle. This kind of low discrimination between cations of different radii is characteristic of stretched macrocycles ' and podands.

Table 2 Log K_a values

Cation	Host 23a	Host 23b	Host 23c
Li^+	4.65	5.13	4.82
Na^+	4.61	5.02	4.98
K^+	4.70	4.97	5.09
Cs^+	4.52	4.96	4.80
NH_4^+	4.60	4.84	4.83

In order to further understand the extraction data and cavity sizes of the macrocycles 23a-c, their optimised conformations were determined at AM1 level using HYPERCHEM for windows software. The optimised structures are shown in Figure 13.

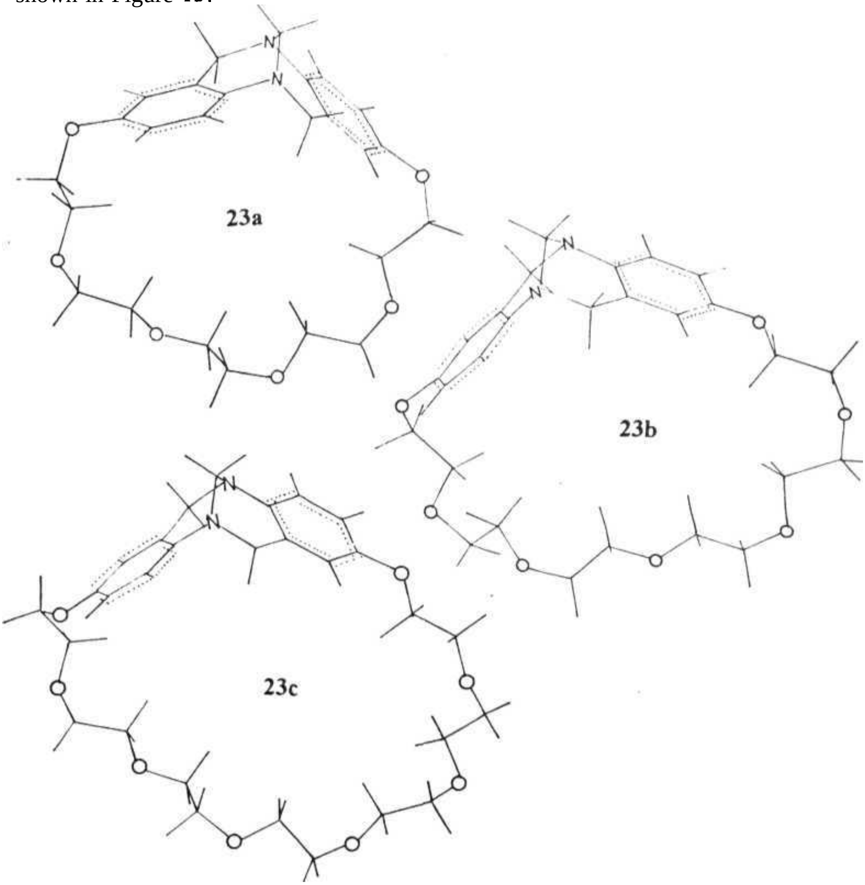


Figure 13 AM 1 Optimised Structures of 23a-c

The objective was to determine the cavity dimensions. The two planes containing the hinge of the Troger's base are at an angle of 113 . This rules out the participation of the phenolic oxygens in the complexation. The distance between the next set of diagonal oxygen atoms was taken as a measure of the effective cavity size offered for complexation. This distance was found to vary from 9.34-11.78 A. As is clear from the above distances, the incorporation of Troger's base unit distorts the macrocycle to the extent that the ether oxygens are forced into a non-optimal orientation for complexation. The binding can therefore not be selective. The experimental results are in agreement with this.

A simple and straightforward synthesis of a novel class of supramolecular hosts was realised in this chapter. The complexation studies however revealed that the macrocycles are too flexible to be efficient cation binders. The ideal guests for complexation with these kind of macrocycles would be the ones that could take advantage of the stretched cavity of the macrocycle. We therefore attempted to study the complexation of some α,ω-diammonium salts to realise this. Keeping in view the cavity sizes of the macrocycles, a sufficiently long chain was chosen for this purpose. Complexation of the macrocycle 23c with 1,6-hexanediammonium ditosylate was taken up since the macrocycle is the largest and the diamine was found have an end to end distance of 7.82 A that could comfortably fit into the macrocycle. A H NMR spectrum was recorded in methanol-d_4 (a mixture of the host and the salt in 1 : 1 ratio). It was found that the signals of both the macrocycle as well as the diammonium salt were affected. However, the signals were broadened heavily making it difficult to judge the extent to which the shifts occurred. Work on these lines is currently in progress in our laboratory.

Experimental Details

Commercially available glycols were used directly without further purification for all the reactions. The ditosylates of tri-, tetra- and pentaethylene glycol were prepared as reported in the literature.[29] All the ditosylates were adequately purified and gave satisfactory physical data. 4-Nitrochlorobenzene and 4-nitrophenol (Merck, AR grade) were recrystallised from appropriate solvents before use. 2-Chloroethanol was freshly distilled before use. All the solvents for dry reactions were distilled using appropriate drying agents. All reactions involving sodium hydride were carried out under nitrogen atmosphere. All the ^{1}H NMR spectra were recorded on 200 MHz (and ^{13}C NMR on 50 MHz), unless otherwise mentioned.

General procedure for the preparation of bis 4 -nitrophenoxy ethers

The ethers can be prepared by nucleophilic displacement of either the tosyl group of ditosylate by 4-nitrophenoxide ion or by dianion of the corresponding glycol on 4-nitrochlorobenzene. Although both the procedures were equally facile, the latter was adopted more often.

To a stirred suspension of sodium hydride (2 eq.) in DMF was added the glycol (1 eq.) dropwise and the resulting mixture was stirred at rt for 30 min. Once a clear solution was obtained, 4-nitrochlorobenzene (2.5-3 eq.) was added in DMF over a period of 15 min and the resulting reaction mixture heated for the appropriate time. It was then cooled and quenched by adding water and then extracted with dichloromethane. After evaporation of solvent, the crude products were subjected to chromatography to remove excess of **4-nitrochlorobenzene** and then recrystallised from ethanol.

1,8-Bis(4-nitrophenoxy)-3,6-dioxaoctane (25a)

Triethylene glycol (1.50 g, 10 **mmol)** was added to a stirred suspension of sodium hydride (960 **mg,** 20 mmol) in 5 ml DMF. To this mixture, 4-nitrochlorobenzene (4.70 g, 30 mmol) in 5 ml DMF was added slowly. Since the addition of **4-nitrochlorobenzene** proved to be exothermic, the reaction mixture was stirred at rt initially for 12h and then heated at 120 for 6h and worked up. After purification, 25a was obtained as a yellow solid.

Yield: 3.0 g, 76%.

M.p.: 91-92°.

IR (KBr): 3080, 2860, 1602, 1500, 1340, 1260, 1105, 840, 760cm^{-1}.

^{1}HNMR : 6 8.21-8.16 (d, 4H), 6.99-6.95 (d, 4H), 4.25-4.20 (t, 4H), 3.92-3.88 (t, 4H), 3.76 (s, 4H).

1,11-Bis (4-nitrophenoxy)-3,6,9-trioxaundecane (25b)

To a stirred suspension of sodium hydride (1.20 g, 25 mmol) in DMF, tetraethylene glycol (2.25 g, 12 mmol) was added, followed by 4-nitrochlorobenzene (4.70 g, 30 mmol) in 9 ml DMF. The resulting mixture was heated overnight at 120°. The product 25b was obtained as a yellow coloured solid.

Yield: 4.13 g, 80%.

M.p.: 62°.

IR(KBr): 3080, 2860, 1600, 1510, 1340, 1265, 1110, 850, 760cm^{-1}.

^{1}H NMR (100 MHz): 6 8.19-8.11 (d, 4H), 6.99-6.91 (d, 4H), 4.27-4.17 (t, 4H), 3.93-3.83 (t, 4H), 3.71 (s, 8H).

^{13}C NMR (25 MHz): 164.01, 143.66, 125.89, 114.65, 70.89, 70.65, 69.42, 68.24 ppm.

Analysis: Calc. for $C_{20}H_{24}O_9N_2$: C, 55.04; **H,** 5.54; N, 6.42,
Found: C, 54.98; **H,** 5.52; N, 6.40.

1,14-Bis (4 -nitrophenoxy)-3,6,9,12-tetraoxatetradecane (25c)

To a stirred suspension of sodium hydride (1.50 g, 30 mmol) in 15 ml of DMF was added pentaethylene glycol (3.60 g, 15 mmol), followed by 4-nitrochlorobenzene (7.0 g, 45 mmol) in 15 ml of DMF. The reaction mixture was heated for 24h at 120 and processed in the usual manner to obtain **25c** as a yellow coloured solid.

Yield: 3.68 g, 50%.

M.p.: 80-81°.

IR(KBr): 3086,2916, 2876, 1595, 1502, 1331, 1302, 1255, 1105, 1051, 947,846 cm^{-1}.

^{1}H NMR: 5 8.19-8.16 (d, 4H), 7.00-6.97 (d, 4H), 4.24-4.20 (t, 4H), 3.90-3.86 (t, 4H), 3.70-3.66 (m, 12H).

General procedure for reduction of the nitro group

In a typical reduction using $SnCl_2 \cdot 2H_2O$ and 95% ethanol, 5 eq. of $SnCl_2 \cdot 2H_2O$ was used for each nitro group present in the substrate.

To the solution of the substrate in ethanol, $SnCl_2 \cdot 2H_2O$ was added as a solid all at once and the reaction mixture was heated at reflux overnight (10-

12h) under nitrogen. The reaction mixture was then poured into ice. The solution was made basic with saturated sodium bicarbonate solution (pH 8) and then extracted with ethyl acetate (occasionally the solutions had to be filtered through a sintered runnel to remove the tin impurities that caused formation of heavy emulsions). The organic extracts were evaporated to obtain the diamines (26a-c) as a brown oils. Activated charcoal treatment was employed to further purify the compound.

1,8-Bis(4 -aminophenoxy)-3,6-dioxaoctane (26a)

Substrate 25a (1.0 g, 2.55 mmol) and $SnCl_2 \cdot 2H_2O$ (5.76 g, 25.5 mmol) were refluxed in 10 ml of 95% ethanol for 12h. The crude product was boiled with charcoal in ethyl acetate and filtered to yield a pale brown oil.

Yield: 750 mg, 88%.

IR(neat): 3425, 3320, 3010, 2830, 1600, 1510, 1430, 1350, 1240, 1160, 1060,930,820 cm^{-1}.

^1H NMR: 5 6.78-6.74 (d, 4H), 6.66-6.60 (d, 4H), 4.07-4.02 (t, 4H), 3.84-3.79 (t, 4H), 3.73 (s, 4H).

1,11-Bis (4 -aminophenoxy)-3,6,9-trioxaundecane (26b)

Substrate **25b** (735 mg, 1.685 mmol) was dissolved in 6 ml of 95% ethanol and $SnCl_2 \cdot 2H_2O$ (3.80 g, 16.85 mmol) was added and heated under reflux for 10h. The usual work up gave 26b.

Yield: 470 mg, 75%.

IR(neat): 3420, 3320, 3020, 2830, 1610, 1510, 1450, 1350, 1240, 1150, 1060, 930, 830 cm^{-1}.

^{1}H NMR (100 MHz): 6 6.78-6.71(d, 4H), 6.61-6.53 (d, 4H), 4.03-3.96 (t, 4H), 3.83-3.75 (t, 4H), 3.67 (s, 8H).

1,14-Bis (4 -aminophenoxy)-3,6,9,12-tetraoxatetradecane (26c)

$SnCl_2.2H_2O$ (2.71 g, 12 mmol) and the substrate 25c (570 mg, 1.2 mmol) in 6 ml of EtOH were refluxed for 12h and processed in the above manner to yield 26c.

Yield: 385 mg, 74%.

IR(neat): 3420, 3326, 3010, 2850, 1600, 1510, 1450, 1340, 1250, 1150, 1050, 920, 840 cm^{-1}.

^{1}H NMR: 5 6.79-6.74 (d, 4H), 6.65-6.61 (d, 4H), 4.08-4.03 (t, 4H), 3.84-3.71 (t, 4H), 3.70-3.67 (m, 12H).

Attempted synthesis of the Tröger's base [15]

To a mixture of the diamines 26a-c (1 eq.) in 10 ml of 95% ethanol was added 37% formaldehyde solution (6 eq). The stirred mixture was then cooled to 0° and 5 eq. of conc. HCl was added dropwise. The solution was stirred at rt under N_2 for 48h. The volatile components of the reaction mixture were removed under reduced pressure and the reaction mixture was reduced to half the original volume. It was poured into a solution of aqueous ammonia. The product was extracted with dichloromethane (3 * 50 ml), the combined extracts were washed with saturated sodium bicarbonate solution and then brine. The solvent was removed and the crude product was subjected to column chromatography on basic alumina.

Even after repeated purification, the ^1H NMR spectra of the samples showed that impurities were present. The Troger's base's signals, especially the methylene signals of the diazocene unit, were very clearly seen. However, attempts to further purify them to the required level were unsuccessful.

2-(4 -nitrophenoxy)ethanol (28)

To a stirred solution of sodium hydroxide (2N, 58 g in 700 ml), 4-nitrophenol (100 g, 0.72 mol) was added as a solid in portions and a high speed of stirring maintained. After the dissolution of the phenol, 2-chloroethanol (115 g, 1.44 mol) was added and the reaction mixture heated for 4h at 110 . During the course of the heating, the product slowly oiled out. After 4h, the reaction mixture was cooled and the solid thus formed filtered. The pale yellow solid was recrystallised from ethyl acetate

Yield: 91.0 g, 70%.

M.p.: 80-82° (lit. 92°).[26]

IR (KBr): 3277, 1597, 1506, 1342, 1271, 1078, 1039, 841, 752cm^{-1}.

^1H NMR: 5 8.25-8.20 (d, 2H), 7.02-6.97 (d, 2H), 4.22-4.17 (t, 2H), 4.07-4.02 (m, 2H).

2-(4 -aminophenoxy)ethanol (29)

2-(4 -Nitrophenoxy)ethanol (13.0 g, 0.07 mol) and $SnCl_2\cdot 2H_2O$ (80.0 g, 0.35 mol) were heated to reflux in 80 ml ethanol for 18h under N_2. The reaction mixture was poured into ice and neutralised. It was then filtered through a sintered funnel, taking adequate care to wash the residue with ethyl acetate. The solution was then extracted with ethyl acetate (3 × 150 ml). The product crystallised as soon as the solvent was removed.

Yield: 8.50 g, 75%.

M.p.: 68-70° (lit. 72°).[26]

IR(KBr): 3400,3050, 1600, 1510, 1240, 1100, 810 cm^{-1}

^{1}H NMR: 6 6.79-6.75 (d, 2H), 6.67-6.63 (d, 2H), 4.02-3.99 (t, 2H), 3.94-3.91 (t, 2H).

2,8-bis(2'-hydroxy)ethoxy)-6H,12H-5,11-methanodibenzo [b,f| [1,5] diazocene (30)

The amine 29 (2.0 g, 13.1 mmol) and 37% solution of formaldehyde (7.4 ml) in 18 ml of ethanol were cooled to 0 and then conc. HC1 (6.5 ml) was added . The mixture was stirred at rt for 48h. The reaction mixture was then reduced to half the volume in vacuum and poured into 150 ml water. To this, 25 ml of 25% aq. ammonia was added. The reaction mixture was extracted with dichloromethane (3 * 100 ml). The organic layers were washed with saturated sodium bicarbonate solution (3 × 50 ml). The solvent was removed under reduced pressure. The crude product was chromatographed on a silica gel column with ethyl acetate as the eluent. The solid product obtained was crystallised from ethanol.

Yield: 610 mg, 25%.

M.p.: 162-164°.

IR (KBr): 3379, 2930, 1614, 1576, 1495, 1454, 1277, 1230, 1159, 1080, 922,837,760 cm^{-1}.

^{1}H NMR: 6 7.09-7.05 (d, J =8 Hz, 2H), 6.78-6.72 (m, 2H), 6.45-6.44 (d, 2H), 4.68-4.60 (d, J = 16.7 Hz, 2H), 4.29 (s, 2H), 4.10-4.02 (d, J = 16.8 Hz, 2H), 3.99-3.94 (t, 4H), 3.91-3.86 (t, 4H), 3.15 (bs, 2H).

^{13}C NMR: 155.26, 141.33, 128.76, 126.11, 114.68, 112.0, 69.55, 67.30, 61.55, 58.94 ppm.

Analysis: Calc. for $C_{19}H_{22}O_4N_2$: C, 66.65; H, 6.48; N, 8.18,
Found: C, 66.72; H, 6.46; N, 8.20.

Synthesis of the macrocycles 23a, **23b** and 23c

a) The dibenzodiazocene 30 (200 mg, 0.58 mmol) was dissolved in 4 ml of DMF and added dropwise to a stirred suspension of sodium hydride (60 mg, 1.17 mmol) in 2 ml of DMF. The reaction mixture was then stirred at rt for 1 h. To this mixture, the corresponding ditosylate (0.58 mmol) was then added in 4 ml of DMF. The resulting solution was heated at 120 for 72h. The reaction concoction was quenched with water and extracted with dichloromethane (3 × 50 ml). At the outset, purification by silica gel column chromatography was attempted. However, nothing could be eluted from the column in substantial amounts due to very strong adsorption on to the column. The chromatography was therefore performed on basic alumina. First, ethyl acetate was eluted to remove any unreacted diol and the product was collected by eluting with 5-10% methanol in ethyl acetate. Often, the products of required purity were obtained only after a second chromatography. All the products were obtained as gums.

Yields: 23a = 67 mg, 25%
23b = 94 mg, 32%

23c = 63 mg, 20%

b) The dianion of the dibenzodiazocene 30 (200 mg, 0.58 mmol) was prepared using sodium hydride (60 mg, 1.17 mmol) in DMF. Cesium carbonate (380 mg, 1.17 mmol) was added to the reaction mixture and stirred for 10 min. Following this, the ditosylate (0.58 mmol) was added. This reaction mixture was either stirred at rt or heated at 120° for 36h. Cesium carbonate was filtered off from the reaction mixture and the reaction worked up in the usual manner. The yields obtained were better in the latter case.

Yields: at rt 23a = 21 mg, 8% at 120^0 23a = 70 mg, 26%
23b = 58 mg, 20% **23b** = 120 mg, 41%
23c = 52 mg, 18% 23c = 70 mg, 25%

c) The reaction was carried out as in the case of (b), but under high dilution conditions. Thus, the dianion of the dibenzodiazocene (200 mg, 0.58 mmol) was prepared as before, to which cesium carbonate was added (380 mg, 1.17 mmol) and stirred for 10 min. The ditosylate (0.58 mmol) in 30 ml of DMF was added from a pressure equalising funnel over 4 h. The reaction mixture was heated at 120° for 36h. The **DMF** was removed under reduced pressure and the reaction mixture worked up in the usual manner.

Yields: **23a** - 70 mg, 26%
23b - 93 mg, **32%**
23c = 80 mg, 27%

Physical data for the macrocycle 23a

IR(neat): 3052, 2880, 1613, 1493, 1246, **1128,** 964, 833, 735 **cm**$^{\cdot 1}$.

^{1}**H NMR**: 5 7.06-7.01 (d, J • 8.80 Hz, 2H), **6.78-6.73 (m,** 2H), 6.43 (s, 2H), **4.67-4.59 (d,** J = 16.80 **Hz,** 2H), 4.24 (s, 2H), 4.06-3.98 **(m,** 6H), 3.72 (bs, 4H), 3.63 (bs, 12H).

^{13}**C NMR**: 155.30, 141.18, 128.66, 126.0, **114.72,** 111.98, 70.87, 70.70, 69.81, 67.75, 67.26, 58.95 **ppm**.

Analysis: **Calc.** for $C_{25}H_{32}O_6N_2$: C, 65.77; H, 7.06; N, **6.14,**

Found: C, 65.82; H, 7.12, N, 6.18.

Physical data for the macrocycle 23b

IR (neat): 3053, 2880, 1612, 1493, 1271, 1097, 964, 833, 735 cm$^{'1}$.

^{1}**H NMR**: 5 7.05-7.01 (d, J = 8.60 Hz, 2H), 6.76-6.72 (d, **2H),** 6.43 (s, 2H), **4.67-4.58** (d, J = 17.06 Hz, 2H), 4.27 (s, 2H), 4.09-4.01 **(m,** 6H), 3.77 **(m,** 4H), 3.63 (bs, 16H).

^{13}**C** NMR: 155.27, 141.12, 128.72, 125.90, **114.61, 111.88,** 70.76, 70.60, 70.56, 69.61, 67.64, 67.23, 58.87 ppm.

Analysis: Calc. for $C_{27}H_{36}O_7N_2$: C, 64.78; H, 7.25; N, 5.60,

Found: C, 64.65; H, 7.21; N, 5.55.

Physical data for the macrocycle 23c

IR(neat): 3053, 2878, 1612, 1575, 1493, 1271, 1246, **1186,** 1109, 964, 735 cm$^{'1}$.

^{1}H NMR: 5 7.05-7.01 (d, J = 8.6Hz, 2H), 6.77-6.71 (m, 2H), 6.43-6.42 (d, 2H), 4.66-4.57 (d, J = 16.73 Hz, 2H), 4.26 (s, 2H), 4.07-3.98 (m, 6H), 3.79-3.74 (t, 4H), 3.63 (bs, 20H).

^{13}C NMR: 155.31, 141.15, 128.65, 125.96, 114.68, 111.94, 70.80, 70.62, 69.76, 67.68, 67.27, 58.91 ppm.

Analysis: Calc. for $C_{29}H_{40}O_8N_2$: C, 63.95; H, 7.40; N, 5.15,
Found: C,64.12; H, 7.38; N, 5.25.

Complexation studies of 23a-c with unipositive cations: determination of the association constants by UV method

The association constants were determined using picrate salts of Li$^+$, Na$^+$, K$^+$, Cs$^+$ and NH$_4^+$. All the picrate salts were prepared as reported in the literature[30] by the action of picric acid on the corresponding metal hydroxides or carbonates. The salts were recrystallised from appropriate solvents and dried in high vacuum prior to use. All UV measurements were made on a UV-160A Shimadzu Spectrophotometer at $26\text{-}30^0$. Spectral grade solvents were used throughout. Aqueous solutions of the picrate salts were made in distilled and deionised water. The molar extinction coefficients of the picrate salts were determined (in concentration range 10^{-6} - 10^{-4} M) and were found to be consistent with those reported by Cram (Table 3) The solutions of Li$^+$, Na$^+$, K$^+$ and NH$_4^+$ picrates were 0.015 M and that of Cs$^+$ was 0.010 M (relatively poor solubility in water) for the extraction experiments. The host solutions were prepared in chloroform and were 0.075 M. Typically, four complexation experiments were run simultaneously for each cation with a given host.

Table 3

Picrate salt	e (M^{-1} cm^{1})	K_d × 10^3 M^{-1}
Li^+	17100	1.42
Na^+	16910	1.74
K^+	16920	2.55
Cs^+	17080	5.41
NH_4^+	16940	4.02

In a centrifuge tube, 0.5 ml of the metal picrate was transferred using a Gilson micropipettor, followed by 0.2 ml of the host solution. The centrifuge tube was then closed by a septum to prevent evaporation. The contents of the tube were then thoroughly mixed by means of a vortex mixer for 2 min. The solutions were subjected to high speed centrifugation for 10 min. to obtain a clear bilayer separation. An aliquot (0.05 ml) of the chloroform layer was transferred by a microlitre syringe into a 5 ml volumetric flask and diluted upto the mark by adding acetonitrile. The UV absorption of each aliquot was measured against the blank at 380 nm. The concentration of the picrate salt in the chloroform layer was calculated based on Beer's law. From this, the molar ratios of the host to picrate in the chloroform layer (R) were determined. The distribution coefficients (K_d), representing the distribution of the picrate salt between chloroform and water in the absence of the host, reported by Cram were used in all calculations. The association constants were calculated employing equation 1 mentioned in the results and discussion. The values obtained are listed in the tables given below.

Table 4 **R** and K_a, values of Host **23a**

Picrate salt	**R** x 10^{-2}	$K_a \times 10^4\ M^{-1}$
Li^+	2.17	4.43
Na^+	1.51	4.34
K^+	2.66	5.00
Cs^+	2.58	3.38
NH_4^+	3.12	4.00

Table 5 **R** and K_a, values of Host **23b**

Picrate salt	**Rx** $10^{''2}$	$K_a \times 10^5\ M^{-1}$
Li^+	3.70	1.27
Na^+	3.53	**1.05**
K^+	5.00	**1.04**
Cs^+	3.51	0.97
NH_4^+	4.91	0.68

Table 6 **R** and K_a, values of Host **23c**

Picrate salt	**Rx** 10^{-2}	$K_a \times 10^4\ M^{-1}$
Li^+	2.07	6.66
Na^+	3.23	9.51
K^+	5.59	12.10
Cs^+	2.97	6.35
NH_4^+	4.90	6.83

References

1. C. J. Pedersen, *J. Am. Chem. Soc*, 1967, *89*, 2495.
2. D. J. Cram, T. Kaneda, R. C. Helgeson and G. M. Lein, *J. Am. Chem. Soc*, 1979, *101*, 6752.
3. B. D. Dietrich, J.-M. Lehn and J.-P. Sauvage, *Tetrahedron Lett.*, 1969, 2885.
4. a) J. J. Christensen, D. J. Eatough and R. M. Izatt, *Chem. Rev.*, 1974, *74*, 351; b) G. W. Gokel and S. H. Korzeniowski, '*Macrocyclic Polyether Synthesis*', Springer, Berlin, 1982; c) R. M. Izatt and J. J. Christensen, '*Progress in Macrocyclic Chemistry*', Vol. 1-3, John Wiley, New York, 1979, 1981, 1987.
5. H. Tsukube in '*Crown Ethers and Analogous Compounds*', M. Hiroaka, Ed., Elsevier, Amsterdam, 1992, p. 100.
6. R. D. Hancock and A. E. Martell, *Chem. Rev.*, 1989, *89*, 1875.
7. a) D. J. Cram, *Angew. Chem. Int. Ed. Engl.*, 1986, *25*, 1039; b) D. J. Cram, I. B. Dicker, M. Lauer, C. B. Knobler and K. N. Trueblood, *J. Am. Chem. Soc*, 1984, *106*, 7150.
8. a) S. Shinkai, T. Minami, Y. Kusano and O. Manabe, *Tetrahedron Lett.*, 1982, *23*, 2581; b) S. Shinkai, T. Minami, Y. Kusano and O. Manabe, *J. Am. Chem. Soc*, 1983, *105*, 1851.
9. H. Tsukube, H. Sohmiya and K. Maruyama, *J. Chem. Soc, Perkin Trans. I*, 1986, 2069.
10. Z. Kilic and N. Gunduz, *Tetrahedron*, 1986, *42*, 137.

U.K. Frische, M. Greenwald, E. Ashkenasi, N. G. Lemcoff, S. Abramson, L. Golender and B. Fuchs, *Tetrahedron Lett.,* 1995, *36,* 9193.

12. J. Troger, *J. Prakt. Chem.,* 1887, *36,* 225.
13. a) M. A Spiclman, *J. Am. Chem. Soc,* 1935, *57,* 583; b) V. Prelog and P. Wieland, *Helv. Chim. Acta.,* 1944, *27,* 1127.
14. I. Sucholeiski, V. Lynch, L. Phan and C. S. Wilcox, *J. Org. Chem.,* 1988, *53,* 463.
15. I. Sucholeiski, V. Lynch, L. Phan and C. S. Wilcox, *J. Org. Chem.,* 1988, *53*, 98.
16. E. Weber, U. Miiller, D. Worsch, F. Vogtle, G. Will and A. Kirfel, *J. Chem. Soc, Chem. Commun.,* 1985, 1578.
17. D. R. Bond and J. L. Scott, *J. Chem. Soc, Perkin Trans. II,* 1991, 47.
18. (a) C. S. Wilcox, *Tetrahedron Lett.,* 1985, *26,* 5749; (b) M. D. Cowan, I. Sucholeiki, R. R. Bukownik and C. S. Wilcox, *J. Am. Chem. Soc,* 1988, *110,* 6204; (c) J. C. Adrian and C. S. Wilcox, *J. Am. Chem. Soc,* 1991, *113,* 678; (d) J. C. Adrian, T. H. Webb, F. Zawacki and C. S. Wilcox, *J. Am. Chem. Soc,* 1992, *114*, 10189.
19. C. S. Wilcox and M. D. Cowart, *Tetrahedron Lett.,* 1986, *27,* 5563.
20. J. C. Adrian and C. S. Wilcox, *J. Am. Chem. Soc,* 1989, *111,* 8055.
21. C.S. Wilcox, L. M. Greer and V. Lynch, *J. Am. Chem. Soc,* 1987, *109,* 1865.
22. M. J. Crossley, T. W. Hambley, L. G. Mackay, A. C. Try and R. Walton, *J. Chem. Soc, Chem. Commun.,* 1995, 1077.
23. (a) E. Yashima, M. Akashi and N. Miyauchi, *Chem. Lett.,* 1991, 1017; (b) L. Cerrada, J. Cudero, J. Elguero and C. Pardo, *J. Chem. Soc, Chem.*

Commun., 1993, 1713; (c) H. Salez, A. Wardani, M. Demeunynck, A. Tatibouet and J. Lhomme, *Tetrahedron Lett.,* 1995, *36,* 1271.

24. a) U. Maitra and B. G. Bag, *J. Org. Chem.,* 1992, *57,* 6979; b) U. Maitra **and** P. Rao, *Tetrahedron Lett.,* **1996,** *37,* 5791.
25. F. D. Bellamy and K. Ou, *Tetrahedron Lett.,* **1984,** *25,* 839.
26. **a) S. B.** Binkely and C. S. Hamilton, *J. Am. Chem. Soc,* **1937,** *59,* 1716; **b)** A. **J.** Shukis and C. R. Tallman, *J. Am. Chem. Soc,* **1944,** *66,* 1716.
27. S. S. Moore, T. L. Tarnowski, M. Newcomb and D. J. Cram, *J. Am. Chem. Soc,* **1977,** *99,* 6398.
28. B. Tummler, G. Maass, F. Vogtle, H. Sieger, U. Heimann and E. Weber, *J. Am. Chem. Soc,* **1979,***101,* 2588.
29. M. Ouchi, Y. Inoue, Y. Liu, S. Nagamune, S. Nakamura, K. Wada and T. Hakushi, *Bull. Chem. Soc. Jpn.,* 1990, *63,* 1260.
30. O. Silberrad and H. A. Philips, *J. Chem. Soc,* 1908, *93,* 474.

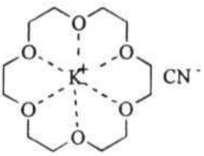
Chapter 3

Introduction

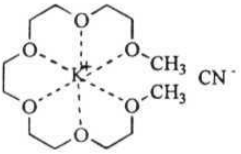
Molecular devices have been defined as structurally organised and functionally integrated chemical systems.[1] The elementary acts performed by the specific components add on to give the function performed by the device. The components of a device may be photoactive, electroactive or ionoactive, depending upon whether they operate with photons, electrons or ions. Supramolecular entities containing photoactive components display novel properties with respect to isolated species. Photoresponsive supramolecular systems of this type are of great interest, particularly because of their potential applications in designing nanoscale devices for cation detection, photoreversible cation traps, light directed ionic switches and light energy devices.[2] Synthesis of molecules with photoactive subunits combined with complexing centres for the uptake of ions or molecules, is of current interest. Amongst the photoactive subunits, aromatic hydrocarbons have been examined for their fluorescent properties and for their photochemical reactivity. For example, anthracenocryptands that combine the strong complexing ability of the cryptand with the intense fluorescence emission of the anthracene group, have been known to display drastic changes in fluorescence emission on cation complexation.[3] A study of the effect of cation binding on the photophysical properties of macrocyclic systems with aromatic units is well documented in the literature,[4] but the same with podands is a relatively unexplored realm.

Podands by definition are open chain analogs of macrocyclic systems, containing heteroatoms with no preformed cavities for guest bindings. They are inherently flexible because the two ends of the molecule are not tied together.

Thus, they form a class of molecules that have an intermediate position with respect to non-specific solute-solvent interactions (i.e., cation solvation) on the one hand and to the highly selective uptake of metal cations into intramolecular cavities by macrocyclic host molecules on the other.



18 CROWN 6(1)
log K = 6.08

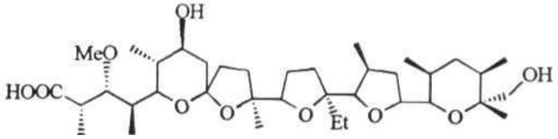


2
log K = 2.3

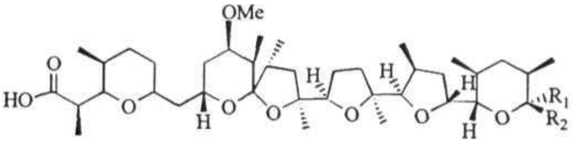
Figure 1

In general, it is observed that podands form complexes of lower stabilities than their corresponding macrocyclic counterparts (Fig. 1). The enormous difference in binding results from a 'macrocylic effect'. Guest complexation needs a lot of organisation in podand structure, i.e., changes to a more ordered conformation and consequently, lowering of entropy, which, in turn, is responsible for the large difference in binding.

A source of inspiration for studying these open chain systems was derived from the fact that a variety of natural polycyclic antibiotics bear a structural resemblance to podands (Fig. 2).[5] These antibiotics contain cation binding sites consisting of oxygen atoms and show ionophoric properties. The antibiotics grisorixin and nigericin that differ amongst themselves by a single substituent show K ion selectivity whereas monensin, (with one less heterocyclic ring than the other two), shows Na^+ selectivity.[5]



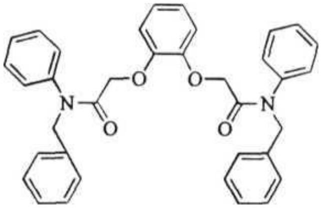
3 Monensin



4 **Grisorixin** R1=OH, R2=Me
5 Nigericin R1=CH2OH, R2=OH

Figure 2

A pioneering effort to develop podand type structures of utility in the development of ion selective electrodes was initiated by Simon.[6] Podands of the type 6 were synthesised and were shown to be Ca^+ binders (Fig. 3).



6

Figure 3

This was closely followed by Vogtle and Weber's synthesis of a variety of podands possessing quinoline end groups (Fig. 4). These were shown to form crystalline complexes with a wide variety of metal salts (eg., KSCN, NH_4SCN, RbI, $AgNO_3$ and $Ba(SCN)_2$), with varying stoichiometries.[7]

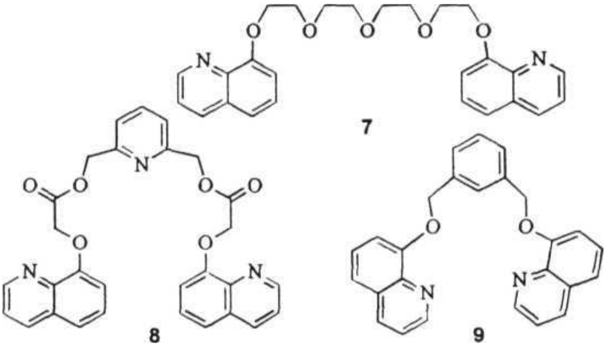
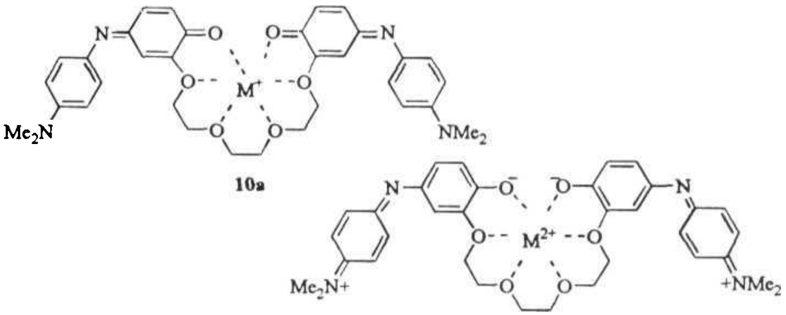


Figure 4

Podands that can selectively bind metal cations and indicate this accomplishment by spectral changes, such as a change in wavelength of absorbed light, as in the case of 10, have been of great interest. A greater spectral shift is exhibited by 10 for binding with divalent cations when compared to monovalent cations (Fig. 5).[8]

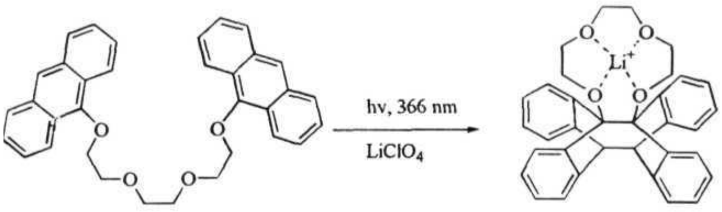


10a

10b

Figure 5

The first photochemically generated cation locked crown ether is, interestingly, a product of photocycloisomerisation of **11a**. Desevergne has shown that **11a** reacts when photolysed in the presence of an excess amount of lithium perchlorate to give its cation locked thermally stable isomer **11b** (Fig 6).[9] It is interesting to note that though **11a** photocycloisomerises in the absence of lithium salts, the product being thermally unstable, reverts back to 11a.

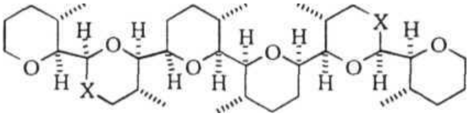


11a

11b

Figure 6

Inspired by the naturally occuring antibiotics, Still designed podand ionophores of C_2 symmetry containing conformationally locked pyran rings, where conformational locking ensures a high degree of preorganisation. Hexacyclic podands 12a and 12b (Fig. 7) have been prepared and shown to have a cation binding site with six oxygens arranged in the geometry found in the crystal structure of potassium 18-crown-6.[10] Utilising Cram's picrate extraction method, it has been shown that these podands have K^+ ion selectivity.

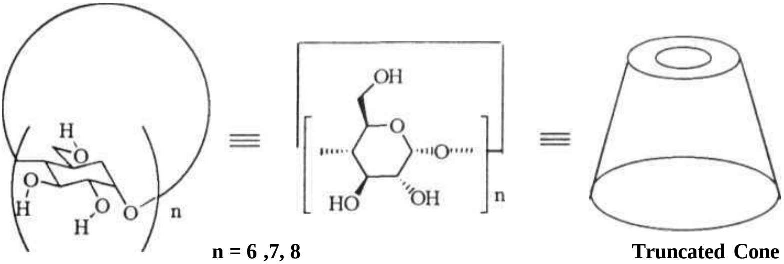


12a X = O
12b X = S

Figure 7

From the above examples, it is clear that despite the lack of preorganised cavities, podands show reasonable cation binding capacities. Podands, owing to their cation complexing properties and also due to their inexpensive nature, have found a wide variety of applications, especially as phase transfer catalysts.[5]

A study of the influence of metal cations on the absorption and emission properties of podands was undertaken with the assumption that they would form a pseudocavity to nest the cation. This would then alter the photophysics of the system. Of particular interest would be the response of this organised system to the addition of a third component. The choice of the third component should be such that it would now host the podand. This would form an interesting system with the cation being a guest to the podand which itself is a guest in another host. The choice of the third component would be crucial, since this component should host the podand in such a way that the podand-cation complex is unaffected. The choice naturally was cyclodextrins.



n = 6 ,7, 8

Truncated Cone

Various Representations of Cyclodextrins

Figure 8

Cyclodextrins are cyclic oligoniers composed of glucopyranose units. Joined together in a toroidal fashion, they form a homologous series of water soluble host molecules, containing 6, 7 and 8 D-glucose residues per molecule, designated as a, p and γ-cyclodextrins, respectively (Fig 8). They have a lipophillic (hydrophobic) cavity with varying inner diameters, ranging from 4.5 to 8 A." These molecules are shaped like truncated cones with smaller and larger openings at the primary and secondary hydroxyl faces, respectively. The interior of the cavity is encircled by ether oxygen atoms, and is therefore hydrophobic, providing an ideal microenvironment to host hydrophobic molecules in aqueous media. Since the exterior of the cyclodextrin molecule is hydrophilic, it can also form adducts with guests in aqueous solutions. The supramolecular aggregates formed with guests in the cavity are termed as inclusion compounds (A, Fig. 9) and the adducts as association compounds (B, Fig. 9). They are easily distinguishable from one another as the inclusion complexes have greater stability than association compounds.

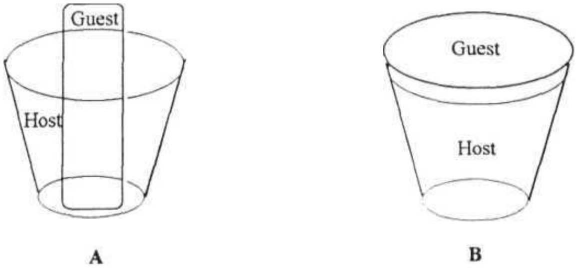


Figure 9

Cyclodextrins (CDs) form a large number of crystalline inclusion compounds with alkyl halides, paraffins and aromatic compounds.[13] The unbranched chain fits best into α-CD.[14] The stability constants of the cyclodextrin-alkyl halide complexes increase with increasing chain length, indicating that the primary driving force is the hydrophobic interaction. Neutral end groups at the end of the alkyl chains do not change the stability of the complexes. However, charged terminal groups do lower the stability. Evidence for the complexation process as well as the effect of the end groups comes from NMR spectral data.[14]

The benzene molecule is already too large to be included into the cavity of a-CD. Nevertheless, some simple derivatives of benzene are known to form complexes. Planar structures like azobenzene were found to form stable inclusion complexes with a-CD in comparison to noncoplanar structures like biphenyls.[16]

P-CD provides a better fit to bulkier benzene derivatives[17] as well as naphthalene derivatives.[18] However, the p-CD cavity is better satiated by molecules with a cylindrical shape, like for example adamantane,[19] than flat arenes. It is interesting to note that although P-CD does form inclusion complexes with linear alkyl chains, virtually no spectral changes could be detected perhaps due to loose packing.

y-CD, being the largest amongst the three, can take up polyannelated arenes such as pyrenes.[21] It is known to complex steroids[22] and even form sandwich type complexes of 2 : 1 stoichiometry with C_{60} More interestingly, y-CD is known to include more than one guest into the cavity simultaneously.

As is clear from the above paragraphs, CDs are versatile hosts forming a wide variety of inclusion complexes with numerous guests of different shapes and sizes depending upon their cavity size. The photophysics and the photochemistry of the included species is modified due to the hydrophobic microenvironment and constrained conformation/orientation enforced by the host. Molecular photophysics can be modified in a complexation process either by simply influencing the relative populations of the ground state conformers available for excitation or by changing the environment experienced by the excited species. Changes in the conformation also have a direct bearing on the photophysics of the system. The original structure of the molecule defines the conformational isomers in equilibrium that are available for complexation.

Many aromatic compounds exhibit enhanced fluorescence emission in the presence of CDs. Aromatic excimers or fluorescence excited dimers, produced by collisional interaction between the excited and unexcited monomers, are readily formed when two molecules are assimilated into the cavity of CDs. Ueno observed enhanced formation of the excimer of 1-naphthylacetic acid included in y-CD, which was attributed to the ability of y-CD to include two molecules of 1-naphthylacetic acid. The perturbations produced by cyclodextrin alone on the included guests have been well documented. An enhanced longer wavelength emission, which was distinctive of an intramolecular excimer, was reported in the case of 1,3-bichromophoric propanes in aqueous y-CD solution. Some examples are 1,3-dinaphthylpropanes (13),[27] 2,2-bis(1-naphthylmethyl)-1,3-dithiane (14)[28] and bis(l-naphthylmethyl)ammonium chloride (15). These molecules are forced to take up a particular conformation where the two chromophores lie parallel to each other in the cyclodextrin cavity. Thus, the conformational control offered by the y-CD cavity is highlighted in the above examples.

The podand type bichromophore 16 studied by Ueno shows only monomer fluorescence in the absence of cyclodextrin. However, on addition of y-CD it reveals mainly excimer emission suggesting that the two naphthalene moieties are trapped with their long axes parallel to each other. Except for the above example, very little has been known about the inclusion and the effect of inclusion on the photophysics of podands, into the cyclodextrin cavity. Even in the case of 16, though the two naphthyl units are separated by 16 atoms, the presence of the benzoic acid unit offers some rigidity to the system.

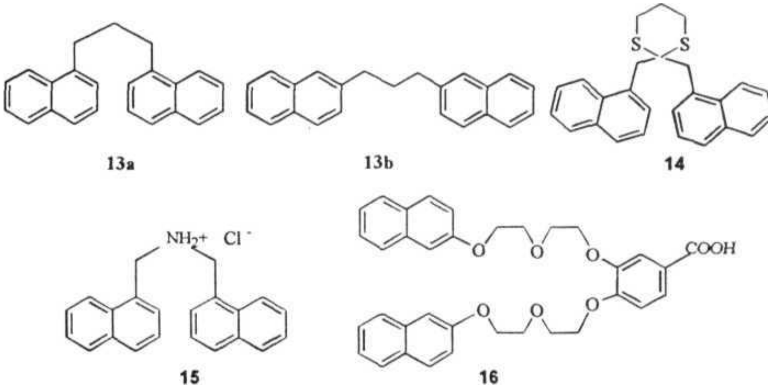


Figure 10

We, therefore, chose to work with podands that were totally flexible. A tetraethylene glycol unit with suitable aromatic end groups would befit the requirements of a totally flexible and sufficiently long chain. The aromatic groups of choice were naphthyl, anthryl and phenanthryl units, all good fluorophores displaying dual fluorescence under appropriate conditions. The arenes mentioned above have also been shown to be included into the cyclodextrin cavities of relevant size. We therefore took up a study of podands having terminal naphthyl, anthryl and phenanthryl groups and the results obtained are described in the next section.

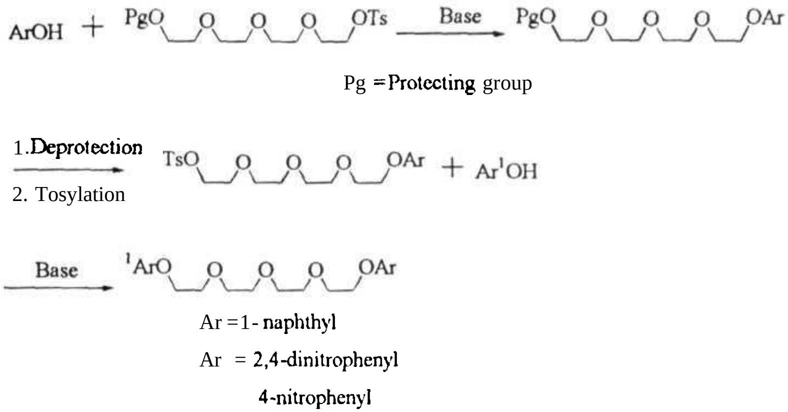
Results and Discussion

As mentioned in the introduction, the general framework chosen for the podands is a tetraethylene glycol chain terminated by identical or different arenes as end groups. Synthesis of podands with the same arene end groups is fairly simple and straightforward once the corresponding phenol is available. Two equivalents of phenol on reaction with an equivalent of tetraethylene glycol ditosylate would afford the corresponding podand (Scheme 1).

Ar = 1- and 2- naphthyl
2- and 9-anthryl
2- and 9-phenanthryl

Scheme 1

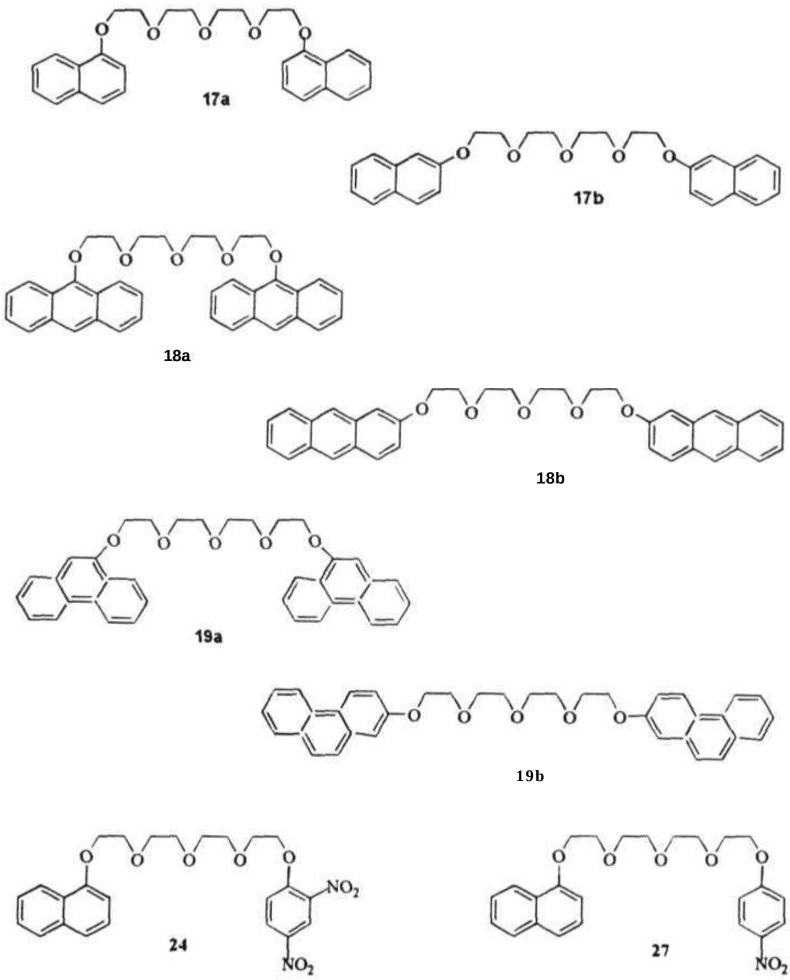
Synthesis of podands with different arene end groups on the other hand would involve sequential addition of one arene to a protected glycol unit followed by deprotection and addition of the second arene unit (Scheme 2).



Scheme 2

With these strategies in hand we then set out to synthesise the podands **17a, 17b, 18a, 18b, 19a** and **19b** with the same arene end groups as well as 24 and 27, with different end groups (Fig. 11).

Synthesis of the podands with 1-naphthyl[33] and 2-naphthyl[34] units was achieved in a single step by refluxing the corresponding naphthols with tetraethylene glycol ditosylate in the presence of sodium hydride and THF in 70% and 50% yields, respectively.[35]



17a

17b

18a

18b

19a

19b

24

27

Figure 11

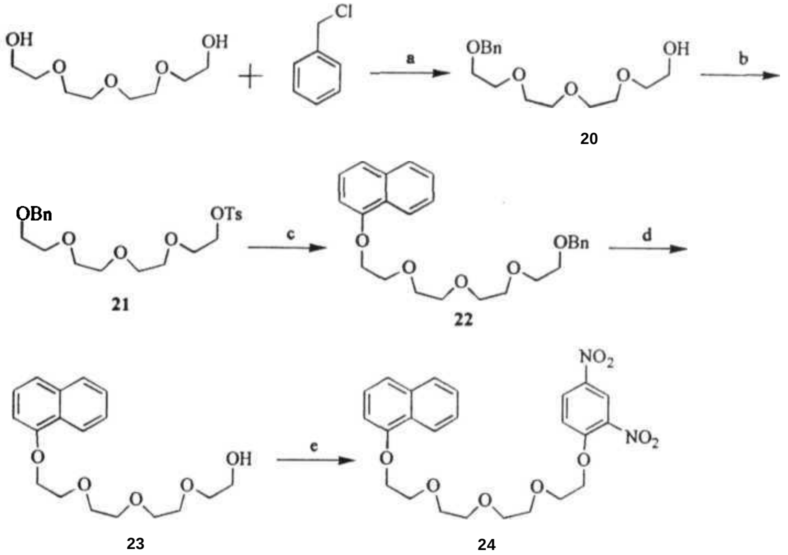
The IR and H NMR spectra showed the absence of the tosyl group signals. The aromatic proton on the ortho carbon was shifted upfield quite distinctly. In the case of **17a,** the doublet at 5 6.82-6.78 (J = **7.7** Hz) in the ^{1}H NMR spectrum was assigned to the proton on the C-2 carbon. The C-2 carbon was distinct in the ^{13}C NMR spectrum at 104.81 ppm. The 2-substituted naphthalene unit in **17b** has two protons adjacent to oxygen bearing carbon. They gave rise to **a** complex pattern in the ^{1}H NMR spectrum while the ^{13}C NMR spectrum displayed signals at 110.01 and 106.77 ppm, indicative of their presence. The ^{1} C NMR spectrum of **17a** showed only 9 carbons while that of **17b** showed all 10 carbons of the arene unit.

In the case of **18a,** however, since 9-anthrol is highly unstable, the corresponding phenoxide was generated in situ by treating 9-anthrone with 20% sodium hydroxide solution in 2-propanol and immediately reacting it with tetraethylene glycol ditosylate in the same pot.[36] **18a** was attained as a yellow coloured solid in 20% yield. The anthryl ring showed four sets of protons in the ^{1}H NMR spectrum in a 2 : 1 : 2 : 4 pattern, while the glycol unit retained its characteristic AA'XX' pattern. The ^{13}C NMR spectrum showed only 8 carbon atoms in the aromatic area, indicating the high degree of symmetry present in the molecule.

All the other phenols (2-anthrol, 2- and 9-phenanthrols) were not readily available and were synthesised by reported procedures. **18b** was obtained in 40% yield from 2-anthrol by the usual ditosylate coupling reaction as an off-white solid. The ^{1}HNMR spectrum showed **a** 2 : 2 : 3 : 2 pattern for the arene ring while the glycol unit had the same splitting pattern as before. The protons and the carbons next to the substituent bearing carbon made their distinctive appearances in the respective spectra. A singlet at 5 7.16 and a doublet at 5 7.21-7.20 (J = 2.14 Hz) accounted for the protons at C-1 and C-3. The C-1 and C-3 carbons resonated at 104.59 and 120.77 ppm in the C NMR spectrum. The ^{13}C NMR spectrum, however, showed 13 carbons of the arene ring with one carbon signal doubling up.

9-Phenanthrol was subjected to the coupling reaction with tetraethylene glycol ditosylate in DMF to provide 19a in 35% yield as a gummy syrup. The syrup crystallised over a period of time and gave rise to a white coloured solid. The ^{1}H NMR spectrum displayed four groups of protons in the aromatic region integrating in the ratio 2 : 1 : 5 : 1 . The ^{1}H NMR spectrum contained the C-10 proton as a singlet at 8 6.98 and the corresponding carbon at 103.12 ppm. The ^{13}C NMR spectrum again exhibited 13 carbons in the aromatic zone with one signal accounting for two carbons.

The podand 19b was procured in very high yields (95%) from the routine coupling reaction of 2-phenanthrol with tetraethylene glycol ditosylate. The ^{1}H NMR and ^{13}C NMR spectra showed the total lack of symmetry in the arene ring. The ^{1}H NMR spectrum did not display any distinct signals. However, the ^{13}C NMR spectrum showed signals at 117.44 and 109.63 ppm corresponding to the C-l and C-3 carbons. The lack of symmetry was demonstrated very clearly in the ^{13}C NMR spectrum by the appearance of all the 14 carbons in the aromatic region.

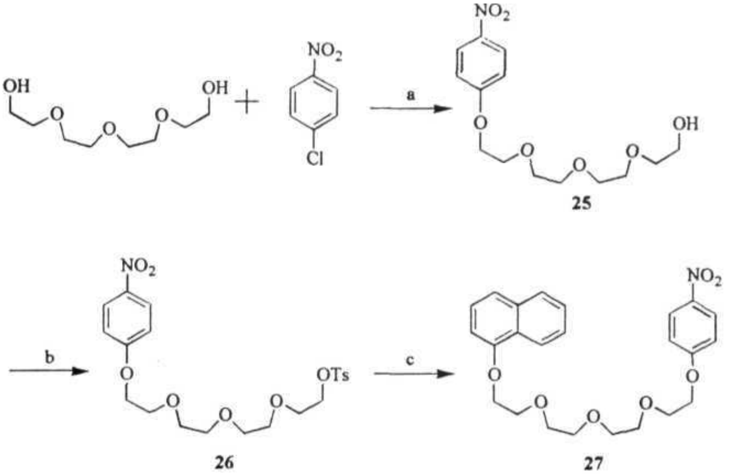


Scheme 3. *Reagents and conditions:* a) NaH, DMF, rt, 12h; b) NaOH, *p*-TsCl, H_2O-THF, 0°, 1h; c) NaH, 1-naphthol, THF, reflux, 16h; d) H_2, 10% Pd/C, EtOH, 6h; e) NaH, 2,4-dinitrochlorobenzene, THF, reflux, 24h.

Having thus accomplished the synthesis of the homomeric podands, attention was focussed on the synthesis of 24 and 27. As mentioned earlier, the preconceived strategy (Scheme 3) involves first the protection of the glycol. Tetraethylene glycol was therefore monoprotected using either benzyl chloride or p-methoxybenzyl chloride under otherwise similar conditions in 50% and 40% yields, respectively. The objective behind the choice of the reagents is obviously the fact that the deprotection proceeds in a facile manner with good yields (90% and 65%, respectively) and under fairly mild conditions (H_2 & 10% Pd/C for the former and ceric ammonium nitrate, CH_3CN-H_2O for the latter). The monobenzylated glycol was then tosylated in order to obtain **21** in 65% yield. Coupling with 1-naphthol proceeded smoothly in 88% yield as did the cleavage of the benzyl group.

It has been known for a long time that 2,4-dinitrochlorobenzene reacts with sodium salts of phenols to yield crystalline 2,4-dinitrophenyl ethers. The extrapolation of this coupling to the aliphatic sodium salts would thus complete the synthesis of the podand 24. Accordingly, the sodium salt of 23 was prepared in THF employing sodium hydride and 2,4-dinitrochlorobenzene added to it in situ to yield 24 as a yellow coloured solid. The H NMR spectrum displayed all the three 2,4-dinitrophenyl protons separately as doublets while the naphthyl ring protons were split in 2 : 1 : 4 ratio. The characteristic symmetrical pattern of the polyether unit was also lost. The protons were now in 4 : 2 : 2 : 2 : 6 ratio. The ^{1} C NMR spectrum also reflected the lack of symmetry, displaying 21 of the 24 carbons as distinct signals.

Reorienting the synthesis, podand 27 was obtained in three steps (Scheme 4). The utilisation of the above ether coupling reduces the number of steps in the synthesis. Characterisation of 27 was uneventful.



Scheme 4. *Reagents and conditions:* a) NaH, THF, reflux, 24h; b) NaH, TsCl, THF, 0°, 4h; c) NaH, 1-naphthol, DMF, 140°, 24h.

The study of photophysical properties of the podands was then undertaken. Before embarking on this task, extreme care was taken to purify the podands for the study. All products were first chromatographically purified. All the solids were further purified by repeated recrystallisations from appropriate solvents. All compounds used for the studies had satisfactory elemental analyses.

Absorption spectra of the podands were recorded in CH_3CN. The molar extinction coefficients are listed in Table 1. The absorption spectra were then recorded in the presence of the metal salts both in CH_3CN and 1 : 9 (v/v) EtOH-

H_2O. The metal salts of choice for this purpose were sodium perchlorate and potassium thiocyanate, since these cations are efficient binders for a polyether system with 5 oxygens, the former being better. An added factor in their favour is their excellent solubilities in organic solvents. The concentrations of the metal salts used ranged from 0.1 M to 0.5 M in organic solvents and 0.5 M to 7 M in aqueous solutions. The absorption spectra of all the podands exhibited no significant changes on addition of the metal salts.

Table 1 UV data of podands 17a-19b & 24 in acetonitrile

Compound	X (nm)	e (dm^3 mol^{-1} cm^1)	Compound	λ (nm)	e (dm mol* ^{1} cm^1)
17a	282.5	8300	**18b**	350	10900
17b	329	3480		335	5700
	319	3000	**19a**	352	2400
18a	389	7390		336	2300
	370	7900	**19b**	351	1300
	348	8870		334	1400
	330	7700		319	900
	315	4600	**24**	215	48090
18b	388	11600		231	41090
	368	14400		293	22800

The fluorescence spectra of the podands were recorded in CH_3CN by exciting them at appropriate wavelengths as mentioned in Table 2. To these solutions, metal salts were added and the spectra recorded again. To our disappointment, the changes in the fluorescence spectra were nothing of the kind hoped for. An overall quenching of the aromatic fluorescence was observed in response to the addition of metal salts. This was not a totally unpredicted result, since the quenching of aromatic fluorescence by inorganic anions has been the subject of many investigations.[38] It was inferred that the quenching occurs due to electron transfer wherein a single electron jumps from the occupied orbital of the anion to the unoccupied orbital of the arene to produce aromatic radical anions. The anticipation that the complexation of the podands with the metal ions and the ensuing effect of the complexation in bringing the arene ends together, thus altering the photophysics of the system, could not be realised. Podands being weak complexing agents, especially so in solutions, are unable to wrap the cations adequately enough.

Table 2 Fluorescence data of podands 17a-19b & 24 in acetonitrile

Compound	$\lambda_{excitation}$ (nm)	$\lambda_{emission}$ (nm)
17a	300/310	324(s),343,354(s)
17b	300	364
18a	370	410(s),426,447(s)
18b	370	429
19a	335	364,380
19b	335	360,375
24	290	347

The effect of cyclodextrin addition on the absorption spectra of the podands varied. All the spectra involving the addition of cyclodextrins were recorded in 1 : 9 (v/v) $EtOH\text{-}H_2O$.

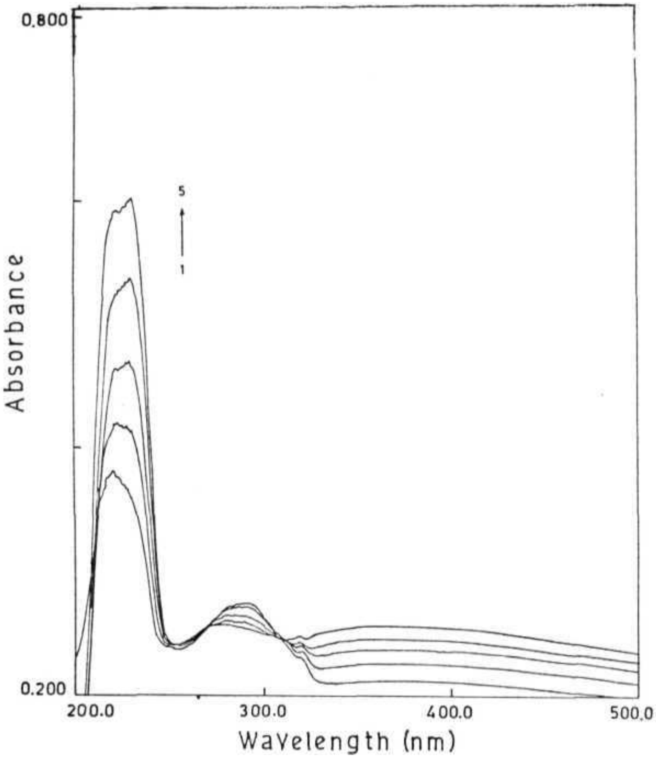


Figure 12. *Absorption spectra of17a in 1 : 9 (v/v) ethanol-water with various amounts ofy-CD.* (1) γ-CD = 0 M; (2) 8.94 x10^{-4} M; (3) 1.72 x 10^{-3} M; (4) 2.85 x 10''^{3} M; (5) 3.82 x 10^{-3} M.

In the case of **17a** (Fig. 12), the addition of y-CD produced an increase in the intensity of absorption with a clear isosbestic point at 310 nm. Similar changes were noticed in the absorption spectra of the isomeric podand **17b.** The isosbestic point in this spectrum was at 300 nm. In both the above instances, the occurrence of an isosbestic point clearly testified to the presence of two absorbing species. p-CD addition did not produce any evidence for the above kind of phenomenon. Its additions only triggered an enhancement in the intensity of absorption.

In both the anthryl podands, the absorption spectra remained uninfluenced by the addition of y-CD. On the other hand, a slight rise in the absorption intensity was observable in the case of the isomeric pair of phenanthryl podands. Only γ-CD studies were attempted in both the above pairs of samples as P-CD is too small to efficiently encapsulate anthracene and phenanthrene rings. The absorption spectrum of the mixed podand 24 also showed only a rise in the absorption intensity, on y-CD addition, with no spectral shifts or isosbestic points being detected.

The fluorescence spectra of podands **17a** and **17b** exhibited marked changes on the addition of y-CD. Even a small amount of y-CD added led to the emergence of a longer wavelength emission at 410 nm along with a significant rise in fluorescence emission intensity at 340 nm in the podand **17a** (Fig. 13). CD concentrations of the order of 10 M were sufficient to induce the appearance of the 410 nm wavelength emission. The enhancement in the emission intensity and emanation of the longer wavelength emission are unambiguous indicators of the fact that the probe resides in the hydrophobic cavity of the cyclodextrin. Furthermore, the structureless emission at 410 nm can **be** ascribed to an intramolecular excimer emission.[40] Increasing concentrations of cyclodextrin only served to increase the intensity of emission without further altering the spectra.

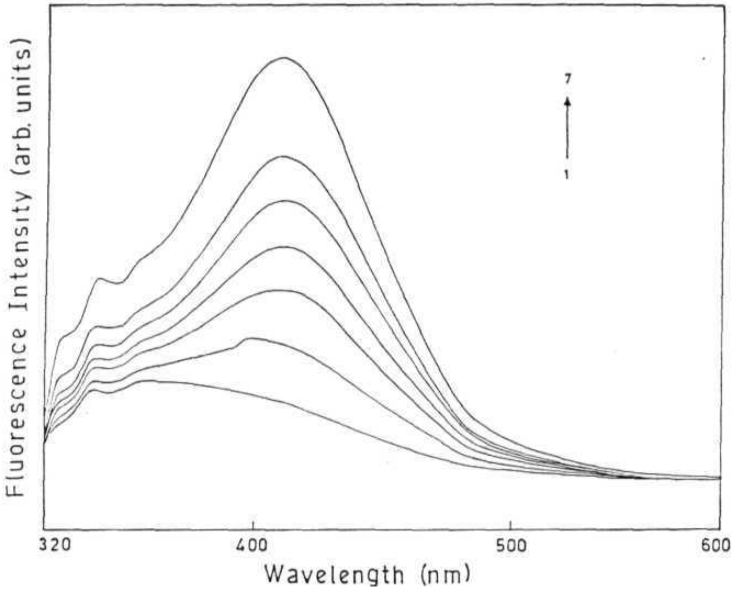


Figure 13. *Fluorescence spectra of* ***17a*** *in I : 9 (v/v) ethanol-water with various amounts of γ-CD*: (1) y-CD = 0 M; (2) 6.68 x 10^{-4} M; (3) 2.16 x 10° M; (4) 4.16 x 10^{-3} M; (5) 6.8 x 10^{-3} M; (6) 1.02 x 10^{-2} M; (7) 1.69 x 10^{-2} M.

The fluorescence spectrum of **17b** (Fig. 14) in the presence of γ-CD displayed a structured part corresponding to locally excited species, the monomer, at 346 run and a red shifted non-structured band of naphthyl excimer

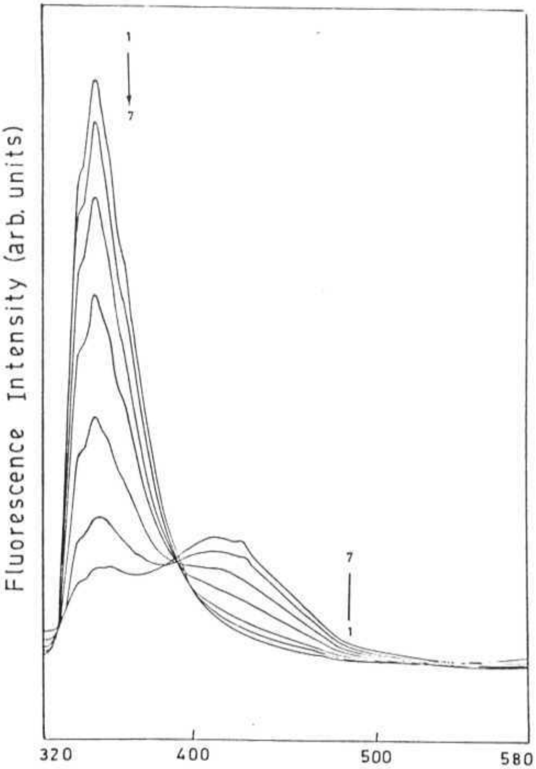


Figure 14. *Fluorescence spectra of 17b in 1 : 9 (v/v)* ***ethanol-water*** *with various amounts ofy-CD.* (1) y-CD = 0 M; (2) 5.14 x 10^{-4} M; (3) 1.28 x 10^{-3} **M; (4) 3.85 x** 10^{-3} M; (5) 7.20 x $10^{''3}$ M; (6) 1.20 x 10^{-2} **M; (7) 1.75** x 10^{-2} M.

at 414 **nm**. Further supplements of y-CD quenched the 346 run emission while enhancing the 414 nm emission. The isosbestic point at 390 nm and the dual fluorescence are again clear indicators of encapsulation by y-CD as well as the presence of two fluorescing species. Although the addition of P-CD in both the cases **(17a** and b) resulted in no shifts in the fluorescence maxima, an enhancement in the intensity of the emission was noticeable. This is an anticipated result since p-CD is too small to encapsulate both the rings.

At this stage, the addition of metal salts to already γ-CD loaded samples produced diverse changes in 17a and **17b.** While both monomer and excimer emissions were quenched in **17a,** only monomer emission was effectively quenched in the podand **17b.** This variation in the response to metal salts can explained only by invoking differential encapsulation of the podands. There have been scattered reports in the literature on the difference in encapsulation of the naphthyl isomers by p-CD. As early as 1975, Harata presumed that the variations in the absorption spectra of the 1- and 2-substituted naphthyl compounds in the presence of p-CD was attributable to the difference in the structure of the two complexes. According to him, the 2-substituted naphthyl ring is encapsulated only in an equatorial manner, while the 1-substituted naphthyl ring could be included in either axial or equatorial modes (Fig. 15). Either way, the 1-substituent does not allow efficient encapsulation. This was substantiated by Tee[42] in a recent study on the cleavage of 1- and 2-naphthyl acetates catalysed by cyclodextrins in basic media. The study endorses the findings of Harata and suggests further that 2-naphthyl acetate binds better with all the cyclodextrins when compared with its 1-isomer. Extending this analogy to the podands it can now safely be said that **17b** fits better into the cyclodextrin cavity and is completely engulfed into it, thus being totally shielded from the external environment. **17a** is partially exposed to the changes in the surrounding environment and its fluorescence is therefore quenched by the metal salts. As is clear from the above findings, a mere change in the position of the substituent on the aromatic ring produces a considerable change in the photophysical response of **the** molecules to the addition of y-CD as well as metal salts. The purpose behind the study of the structural isomers is thus justified.

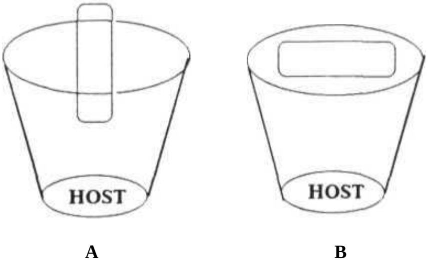


Figure 15 Two models of the complex (A) Axial inclusion and (B) equatorial inclusion

The reversal of the sequence of additions, i.e., metal salts first followed by γ-CD resulted in the appearance of the longer wavelength emissions in both the isomers. The peak maxima of the emissions were unaltered. The emissions increased in intensity on further increasing the concentrations of y-CD. Once again, the monomer emissions were not detected in **17b**.

Lifetime measurements were performed on both neat and y-CD loaded samples of both the podands. The fluorescence decay of the long wavelength emission was analysed and was found to be double exponential. Considerable enrichment of one of the species on addition of y-CD was observed. The lifetimes of the excimers were found to be 27 ns for 17a and 31 ns for 17b (lit. 32 ns for naphthalene).

The fluorescence intensities were enhanced considerably when y-CD was added to solutions of the podands 18a and 18b. The fluorescence enhancement was found to be linear with respect to the increase in the γ-CD concentrations in the range studied. This indicates that at any given instance, more molecules were in the uncomplexed form than in the complexed form. Another noticeable feature was the absence of any shifts in the emission peak maxima. This kind of enhancement in the fluorescence emission intensity on the addition of y-CD is a well documented observation in the literature. The primary conclusion that can be drawn from this enhancement is the inclusion of the probe into the cavity of y-CD. Various interpretations have been offered to account for the rise in intensity of emission. Encapsulation of the probe into the cavity of y-CD results in the exclusion of water molecules from the medium surrounding the probe, thus eliminating their quenching effect. Apart from this, the encapsulation also serves to reduce the rotational freedom of the probe, thus increasing the radiative rate.[26] The addition of metal salts served only to quench the emission. When the metal salts were added followed by y-CD, the fluorescence already quenched due to the addition of metal salts was enhanced.

The above observations lead to the following conclusions: 1) a loose complex is formed between the fluorophore and y-CD which is amenable to the quenching effects of metal salts; 2) only one ring of the probe is encapsulated by one y-CD unit. This is in agreement with the findings of Sanemasa whose analysis infers that the complex formed between the cyclodextrin and anthracene is a 1 : 1 complex with anthracene included axially into the cavity.

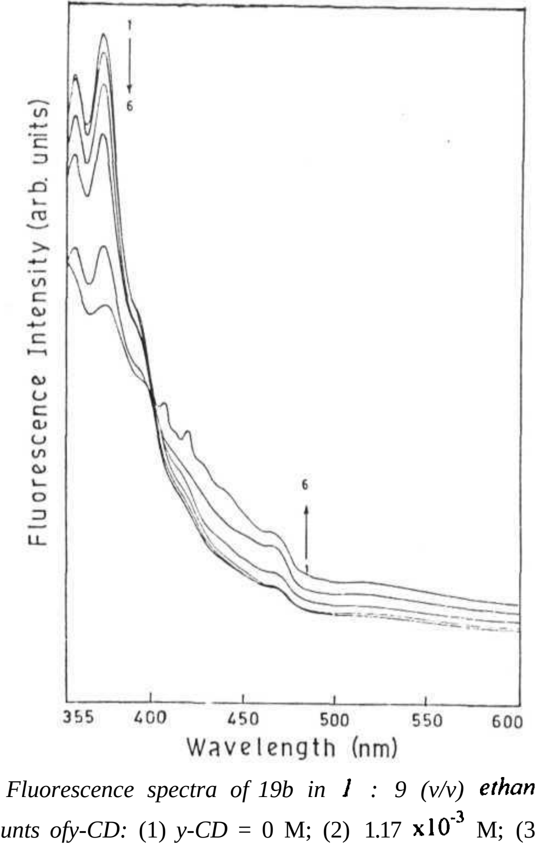


Figure 16. *Fluorescence spectra of 19b in 1 : 9 (v/v) ethanol-water with various amounts ofy-CD:* (1) *y-CD* = 0 M; (2) 1.17×10^{-3} M; (3) 4.12×10^{-3} M; (4) 1.20×10^{-2} M; (5) 2.50×10^{-2} M; (6) 3.50×10^{-2} M.

The isomeric pair of podands, 19a and 19b, differed in the way they fluoresced on addition of y-CD. While 19a (Fig. 16) displayed only an enhancement in fluorescence intensity, 19b exhibited quenching of the shorter wavelength emission and formation of a hump around 470 nm. Increasing concentrations of y-CD continued the trend, with a clear isosbestic point at 402 nm for **19b.** Addition of metal salts quenched all the emissions in both 19a and **19b.** When metal ions were added first followed by y-CD, the fluorescence was enhanced after being initially quenched by the salts in the case of 19a. Interestingly, with 19b, no enhancement took place and no humps were found in the spectrum at 470 nm. This could probably mean that the earlier observed hump at 470 nm in the case of 19b is due to a weak π-stacking interaction between the phenanthryl rings in the y-CD cavity.

The mixed podand 24 showed only an enhancement in absorption when y-CD was added in increasing amounts. The fluorescence spectrum of the podand in 1 : 9 (v/v) ethanol-water displayed an absorption maximum at around 400 nm and not at 347 nm as in acetonitrilc This peak showed further increase in the intensity of emission on incremental addition of y-CD.

The work described in this chapter shows that the inclusion of organic chromophores into the cavity of cyclodextrins alters the response of the chromophore to light. Podands with naphthyl end groups exhibit intramolecular excimer formation. As is well documented, a pair of naphthyl rings get accommodated into the cavity of the γ-CD which has the ideal dimensions for this (Fig. 17).[25]

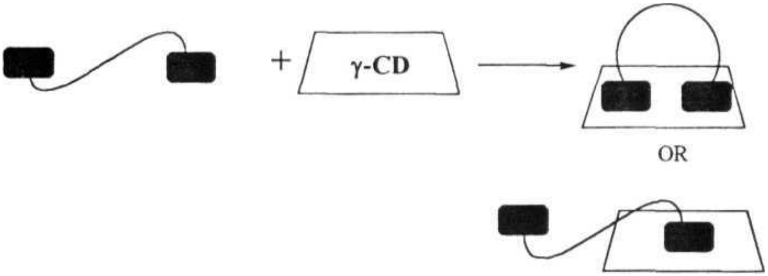


Figure 17

The anthryl and phenanthryl moieties are too large to get encapsulated in pairs into the cavity of y-CD and therefore no excimers are observed. They are also prone to changes in the surrounding medium indicating that they are probably included in an axial manner, atleast partially.

Though the metal cations have by themselves not proved to be sufficient and efficient to yield any extraordinary changes in both absorption and emission spectra, they have helped in understanding the photophysical behaviour of these podands in the presence of y-CD.

Experimental Details

The UV-visible spectra were recorded with either **SHIMADZU** model **UV160A** or **JASCO** model 7800 spectrophotometers. The fluorescence spectra were recorded either on HITACHI model F-3010 or JASCO model FP 777 Spectrofluorometers using a 1 cm ($3cm^3$) quartz cell. Lifetime measurements were done on an IBH 5000 instrument with a H_2 discharge coaxial nanosecond flash lamp as the excitation source. Unless other wise mentioned H NMR and C NMR spectra were recorded on a Bruker AF-200 instrument.

Cyclodextrins (American Maize-Products Company) were used without further purification. Sodium perchlorate monohydrate and potassium thiocyanate (Merck AR grade) were used without further purification. Triply distilled water was used for all measurements. All other solvents were thoroughly purified using standard procedures. The probes were all purified repeatedly by crystallisation or chromatography, and only samples with satisfactory elemental analyses were employed for photophysical studies.

Only dilute solutions were used for fluorescence studies. The spectra involving CD studies were recorded in 1 : 9 (v/v) ethanol-water and solubilities of the podands under study were poor in this solvent system. The solutions were sonicated for an hour and then allowed to settle for 30 min. This was then followed by repeated filtrations to obtain clear solutions. The solutions were then diluted sufficiently to give an O.D. of around 0.2 at the longest wavelength absorption maximum. Consequently, the exact concentrations of the solutions in question could not be determined. The spectra were recorded in the following manner. A known volume of the probe solution was taken up into the cell and its spectrum recorded. All additions were done to the known volume of probe in the cell and the spectra recorded after ensuring that the solution was clear.

The required phenols were obtained as described below. Commercially available 1- and 2-naphthols were recrystallised from CCl_4 and used. 2-Anthrol was obtained in a two step sequence from 2-methoxyanthrone. Sodium borohydride reduction in diglyme-methanol of 2-methoxyanthrone to 2-methoxyanthracene (77%; m.p. 176-178°, lit. 178^{0})[43] followed by an ether cleavage reaction[44] in 48% aq. HBr and acetic acid yielded 2-anthrol (50%; decomposes at 200). When 9-methoxyphenanthrene was subjected to the same cleavage, 9-phenanthrol was obtained (94%; m.p. 150-2°, lit 152-4^{0}).[44] 2-Methoxyphenanthrene was obtained by photocyclisation of *trans* m-methoxystilbene in cyclohexane containing iodine (42%; m.p. 96 , lit. 97-98)[4] The usual cleavage of the methyl ether afforded 2-phenanthrol (72% ; m.p. 166°, lit. 167-8^{0}).[46]

General procedure **for** synthesis of podands 17a, 17b, 18b, 19a and **19b**

The corresponding phenol (2eq.) dissolved in dry THF or DMF was added at room temperature under nitrogen to a stirred suspension of sodium hydride (2eq.) in the same solvent. After stirring the mixture for an hour at 45° to facilitate anion formation, tetraethylene glycol ditosylate (1eq.) in the same dry solvent was added and the reaction mixture was heated under reflux (110 for DMF) until the starting material disappeared. The reaction mixture was then quenched with water and extracted with dichloromethane. The combined extracts were washed with water, brine and then dried. The crude product was subjected to column chromatography on silica gel using mixtures of hexane and ethyl acetate for elution.

1,11-Bis(1-naphthyloxy)-3,6,9-trioxaundecane (17a)[34]

1-Naphthol (1.44 g, 10 mmol) and tetraethylene glycol ditosylate (2.50 g, 5 mmol) were refluxed for 16h in THF and worked up in the usual manner to yield **17a** as a pale yellow oil.

Yield: 1.57 g, 70%.

IR(neat): 3040, 2860, 1590, 1470, 1260, 1100, 1020, 960, 800, 770, 740cm^{-1}.

^{1}H NMR: 8 8.32-8.27 (m, 2H), 7.82-7.77 (m, 2H), 7.51-7.31 (m, 8H), 6.82-6.78 (d, 2H), 4.31-4.29 (t, 4H), 4.01-3.97 (t, 4H), 3.82-3.73 (m, 8H).

^{13}C NMR (25 MHz): 154.60, 134.54, 127.82, 126.82, 125.89, 125.12, 122.18, 120.42, 104.81, 70.89, 70.66, 69.66, 67.77 ppm.

Analysis: Calc. for $C_{28}H_{30}O_5$: C, 75.31; H, 6.77,
Found: C, 75.37; H, 6.79.

1,11-Bis(2-naphthyloxy)-3,6,9-trioxaundecane (17b)[35]

2-Naphthol (1.44 g, 10mmol) and tetraethylene glycol ditosylate (2.50 g, 5 mmol) after a 16h reaction in THF, gave 17b as a white solid which was recrystallised from methanol.

Yield: 1.10 g, 50%.

M.p.: 60-61°.

IR (KBr): 3050, 2900, 2860, 1610, 1520, 1480, 1400, 1225, 1195, 1120, 1060,840,760 cm^{-1}.

^{1}H NMR: 6 7.77-7.70 (t, 4H), 7.46-7.20 (m, 6H), 7.19-7.13 (m, 4H), 4.26-4.22(t, 4H), 3.94-3.90 (t, 4H), 3.74-3.73 (d, 8H).

^{13}C NMR (25MHz): 156.83, 134.54, 129.36, 129.07, 127.66, 126.73, 126.37, 122.66, 110.00, 106.77, 70.71, 70.59, 69.59, 67.79 ppm.

Analysis: Calc. for $C_{28}H_{30}O_5$: C, 75.31; H, 6.77,
Found: C, 75.30; H, 6.79.

1,ll-Bis(9 **-anthryloxy)-3,6,9-trioxaundecane** (18a)[36]

Anthronc (1.50 g, 7.7 mmol) was dissolved in 2-propanol (5 ml) and 20% sodium hydroxide (1.00 g in 5 ml water) solution was added and the mixture heated under reflux. To the boiling mixture was added tetraethylene glycol ditosylate (1.95 g, 3.88 mmol) and the refluxing was continued further for an hour. The reaction mixture was then diluted with water and extracted with ethyl acetate. The combined extracts were washed with water, dried and the crude product was chromatographed. 18a was obtained as an yellow solid on recrystallisation from methanol-dichloromethane.

Yield: 381 mg, 20%.

M.p.: 90-91°.

IR (KBr): 3053, 2874, 1558, 1440, 1336, 1089, 1037, 842, 738 cm"^{1}.

^{1}H NMR: 5 8.40-8.35 (m, 4H), 8.21 (s, 2H), 7.99-7.94 (m, 4H), 7.46-7.41 (q, 8H), 4.40-4.35 (t, 4H), 4.03-3.98 (t, 4H), 3.88 (s, 8H).

^{13}C NMR: 151.20, 132.67, 128.53, 125.66, 125.32, 125.01, 122.80, 122.42, 75.08, 71.31, 71.18, 70.88 ppm.

Analysis: Calc. for $C_{36}H_{34}O_5$: C, 79.09; H, 6.27,
Found: C, 79.02; H, 6.28.

1,11-Bis(2 -anthryloxy)-3,6,9-trioxaundecane (18b)

2-Anthrol (325 mg, 1.70 mmol) and tetraethylene glycol ditosylate (426 mg, 0.85 mmol) were heated for 48h in DMF to obtain **18b** as an off-white solid. The product was crystallised from methanol-dichloromethane.

Yield: 190 mg, 40%.

M.p.: 144-146°.

IR (KBr): 3049, 2870, 1581, 1209, 1132, 885, 742 cm^{-1}.

^{1}H NMR: 5 8.31-8.21 (m, 4H), 7.92-7.88 (m, 6H), 7.43-7.27 (m, 4H), 7.21-7.20 (m, 4H), 4.29-4.25 (t, 4H), 3.98-3.93 (t, 4H), 3.78-3.70 (m, 8H).

^{13}C NMR: 156.34, 132.66, 132.20 130.42, 129.81, 128.23, 127.59, 126.19, 125.51, 124.45, 124.22, 120.77, 104.59, 70.92, 70.79, 69.74, 67.42 ppm.

Analysis: Calc. for $C_{36}H_{34}O_5$: C, 79.09; H, 6.27,
Found: C, 79.15; H, 6.25.

1,11-Bis(9 -phenanthryloxy)-3,6,9-trioxaundecane (19a)

The reaction of 9-phenanthrol (529 mg, 2.72 mmol) and tetraethylene glycol ditosylate (682 mg, 1.36 mmol) was carried out in DMF for 24h and the crude product on chromatographic purification gave a gummy syrup. This was taken up in ether and thoroughly scratched to induce crystallisation. The product **19a** was procured as a white solid.

Yield: 260 mg, 35%.

M.p.: 92-94°.

IR(KBr): 3059,2874, 1626, 1601, 1452, 1313, 1118, 1041,767 cm^{-1}.

^{1}H NMR: 6 8.64-8.57 (m, 4H), 8.41-8.39 (m, 2H), 7.80-7.52 (m, 10H),6.98 (s, 2H), 4.42-4.39 (t, 4H), 4.10-4.04 (t, 4H), 3.82-3.75 (m, 8H).

^{13}C NMR: 152.77, 132.98, 131.42, 127.43, 127.19, 126.92, 126.76, 126.66, 126.38, 124.37, 122.82, 122.56, 103.12, 71.08, 70.90, 69.82, 67.80 ppm.

Analysis: Calc. for $C_{36}H_{34}O_5$: C, 79.09; H, 6.27,
Found: C, 78.70; H, 6.35.

1,11-Bis(2 -phenanthryloxy)-3,6,9-trioxaundecane (19b)

2-Phcnanthrol (400 mg, 2.05 mmol) and tetraethylene glycol ditosylate (517 mg, 1.03 mmol) werc heated in DMF for 24 h to yield **19b** as a white solid. It was recrystallised from mcthanol.

Yield: 540 mg, 95%.

M.p.: 86-88°.

IR (KBr): 3050, 2874, 1614, 1466, 1358, 1257, 1107, 1059, 856 cm"^{1}.

^{1}H NMR: 8 8.57-8.52 (d, 4H), 7.88-7.84 (d, 2H), 7.73-7 .S3 (m, 8H), 7.32-7.24 (m,4H), 4.30-4.26(t, 4H), 3.97-3.92, (t, 4H), 3.82-3.72 (m, 8H).

^{13}C NMR: 157.52, 133.42, 131.10, 130.45, 128.57, 127.51, 126.67, 126.47, 125.61, 124.78, 124.26, 122.17, 117.44, 109.63, 70.93, 70.79, 69.82, 67.62 ppm.

Analysis: **Calc. for $C_{36}H_{34}O_5$**: C, 79.09; H, 6.27,
Found: C, 79.25; **H,** 6.25.

2-(2-{2-[2-(Benzyloxy)ethoxy]ethoxy}ethoxy)-l-ethanol(20)

To a stirred suspension of sodium hydride (246 mg, 5.15 mmol) in 10 ml **of** DMF was added tetraethyelene glycol (1.0 g, 5.15 mmol) dropwise, under nitrogen. After completion of the addition, the reaction mixture was stirred further for an hour to facilitate anion formation. To this mixture, benzyl chloride (690 mg, 5.15 mmol) was added in 2 ml DMF, slowly and dropwise over a period of 15 min. The resulting mixture was stirred overnight at room temperature. It was quenched with water and extracted with dichloromethane. The combined extracts were washed with water, brine and then dried. The crude product obtained on evaporation of solvent was subjected to chromatographic separation to obtain 20 as a pale yellow coloured oil.

Yield: 700 mg, 48%.

IR (neat): 3340, 3000, 2840, 1450, 1240, 1060, 920, 730 cm"^{1}.

^{1}HNMR (100 MHz): 5 7.52 (s, 5H), 4.72 (s, 2H), 3.88 (s, 16H), 2.25 **(b, 1H).**

2-(2-{2-[2-(Benzyloxy)ethoxy]ethoxy}ethoxy)ethyl 4 -methylbenzene sulfonate (21)

Sodium hydroxide (150 mg, 3.75 mmol) was dissolved in 4 ml water and to it the monobenzyl ether (700 mg, 2.46 mmol) in 4 ml THF was added. The mixture was then cooled to 0 . To this mixture, tosyl chloride (470 mg, 2.46 mmol) in 4 ml **THF** was added at a slow pace, while the reaction temperature was maintained strictly between 0-5 all through the addition. The reaction mixture was stirred vigorously and maintained at 0 for another hour. It was then poured into ice cold water. The contents were brought to room temperature before being extracted with dichloromethane. The extracts were combined, washed with water and brine, dried and evaporated to obtain the tosylated product 21 as an oil.

Yield: 890 mg, 83%.

IR(neat): 2840, 1580, 1440, 1360, 1170, 1090, 920, 720 cm^{-1}.

^{1}HNMR(100 MHZ): 6 7.84-7.76 (d, 2H), 7.40-7.24 (m, 7H), 4.60 (s, 2H), 4.24-4.12 (t, 2H), 3.68-3.62 (d, 14H), 2.48 (s, 3H).

1-[2-(2-{2-[2-(Benzyloxy)ethoxy]ethoxy}ethoxy)ethoxy]naphthalene (22)

To a stirred mixture of sodium hydride (144 mg, 3 mmol) in 2 ml THF was added dropwise a solution of 1-naphthol (432 mg, 3 mmol) in 2 ml of THF and the reaction mixture stirred at rt for about 30 min. 21 was then added to this mixture and the progress of the reaction monitored by tlc. At the end of 16h when no starting material was left, the reaction mixture was quenched with water and extracted with dichloromethane. The crude product was subjected to column chromatography to obtain 22 as a clear oil.

Yield: 825 mg, 88%.

IR(neat): 3050, 2850, 1590, 1460, 1280, 1240, 1120, 800, 780 cm^{-1}.

2-(2-{2-[2-(1 -Naphthyloxy)ethoxy]ethoxy}ethoxy)-l-ethanol (23)

22 (425 mg, 1.05 mmol) was dissolved in 3 ml of ethanol and a catalytic amount of 10% Pd/C was added to it. This mixture was hydrogenated in a Parr hydrogenator at 45psi for 6h. Subsequently, the catalyst was filtered

off and thoroughly washed with ethanol to obtain 23 on evaporation of the solvent which was used as such for the next reaction.

Yield: 301 mg, 94%.

IR(neat): 3450, 3050, 2900, 1580, 1460, 1400, 1270, 1240, 1110, 800, 780 cm^{-1}.

^{1}HNMR (100 MHz): 6 8.38-8.28 (m, 1H), 7.92-7.80 (m, 1H), 7.58-7.42 (m, 4H), 6.92-6.82 (m, 1H), 4.44-4.32(t, 2H), 4.12-4.00(t, 2H), 3.82-3.68 (m, 12H).

1-(2 ,4 -Dinitrophenoxy)-11-(1 -naphthyloxy)-3,6,9-trioxaundecane (24)

To a stirred mixture of sodium hydride (100 mg, 2 mmol) in 2 ml THF was added 23 (570 mg, 1.78 mmol) in 2 ml THF. After stirring the solution for 30 min at rt, 2,4-dinitrochlorobenzene (440 mg, 1.98 mmol) was added and the reaction mixture heated under reflux for 24h. Following this, the reaction mixture was quenched with water and worked up in the usual manner. The crude product was chromatographed to obtain a yellow coloured solid. The product was recrystallised from a mixture of ethyl acetate and hexane.

Yield: 380 mg, 44%.

M.p.: 74-76°.

IR (KBr): 3050, 2800, 1600, 1510, 1340, 1260, 1080, 940, 780 cm"^{1}.

^{1}H NMR: 5 8.67-8.64 (d, 1H), 8.32-8.24 (m, 2H), 7.88-7.76 (m, 1H), 7.48-7.34 (m, 4H), 7.12-7.08 (d, 1H), 6.82-6.80 (m, 1H), 4.33-4.24 (m, 4H), 4.03-3.98 (t, 2H), 3.92-3.87, (m, 2H), 3.81-3.79 (m, 2H), 3.73-3.67 (m, 6H).

^{13}C NMR: 156.69, 154.60, 141.76, 134.56, 128.67, 127.40, 126.36, 125.80, 125.09, 122.07, 121.54, 120.47, 114.97, 105.07, 71.10, 70.99, 70.76, 70.53, 69.83, 69.07, 68.03 ppm.

Analysis: Calc. for $C_{24}H_{26}O_9N_2$: C, 59.25; H, 5.38; N; 5.75,
Found: C, 59.43; H, 5.59; N; 5.34.

2-(2-{2-[2-(4 -Nitrophenoxy)ethoxy]ethoxy}ethoxy)-1-ethanol (25)

The anion of tetraethylene glycol (3.88 g, 20 mmol) was generated in 5 ml of DMF containing sodium hydride (960 mg, 20 mmol). To this solution was added 1-chloro-4-nitrobenzene (1.60 g, 10 mmol) dissolved in 5 ml of DMF and the reaction mixture heated at 140 overnight. After the usual workup, the crude product was chromatographed to obtain a pale yellow oil.

Yield: 1.40 g, 45%.

IR(neat): 3450, 3050, 2900, 1610, 1420, 1350, 1270, 1180, 1120, 1080, 860, 750 cm^{-1}.

^{1}H NMR (100 MHz): 6 8.20-8.12 (d, 2H), 7.0-6.82 (d, 2H), 4.28-4.18 (t, 4H), 3.92-3.82 (t, 4H), 3.72-3.64 (d, 8H).

^{13}C NMR (25 MHz): 207.37, 125.89, 116.13, 114.65, 72.59, 70.77, 70.53, 70.42, 70.12, 69.24, 68.12, 61.53 ppm.

2-(2-{2-[2-(4 -Nitrophenoxy)ethoxy]ethoxy}ethoxy)ethyl 4 -methylbenzenesulfonate (26)

To the stirred mixture of sodium hydride (200 mg, 4.16 mmol) in 3 ml THF was added 25 (1.30 g, 4.12 mmol) in 3 ml THF and the contents cooled to 0° in an ice bath. At this temperature, tosyl chloride (800 mg, 4.2 mmol) in 4

ml THF was added dropwise over **a** period of 20 min. The reaction **mixture** was **stirred** at 0° **for** an hour after the completion of addition and quenched by adding ice cold water. The usual workup and chromatographic purification gave **26** as **a pale yellow oil.**

Yield: 1.30 g, 68%.

IR(neat): 3050, 2850, 1600, 1500, 1340, 1260, 1180, 1120, 920, 840, 760 cm"^{1}.

^{1}H NMR (100 MHz): 5 8.24-8.12 (d, 2H), 7.84-7.78 (d, 2H), 7.38-7.24 (d, 2H), 7.02-6.92 (d, 2H), 4.28-4.12 (m, 4H), 3.94-3.84 (m, 4H), 3.72-3.58 (d, 8H), 2.44 (s, 3H).

1-(4 -Nitrophenoxy)-11-(1 -naphthyloxy)-3,6,9-trioxaundecane (27)

To a stirred solution of sodium hydride (72 mg, 1.5 mmol) in 1 ml DMF was added 1-naphthol (216 mg, 1.5 mmol) in 2 ml DMF and stirred at rt for 30 min. **26** (469 mg, 1 mmol) was added in 2 ml of DMF and the reaction mixture was heated at 140 for 24h. After the usual workup **and** chromatographic purification, 27 was obtained as a gum.

Yield: **140** mg, 32%.

IR(neat): 3050, 2836, 1600, 1520, 1420, 1250, 1110, 810, 790 cm^{-1}.

^{1}H **NMR** (100 MHz): 5 8.28-8.20 (m, 1H), 7.80-7.68 (m, 1H), 7.48-7.20 (m, 8H), 6.80-6.68 (m, 1H), 4.32-4.20 (t, 4H), 4.0-3.88 (t, 4H), 3.80-3.74 (m, 8H).

Tables of UV and Fluorescence Data

1. Changes in the Absorption Spectra

(a) Effect of γ-cyclodextrin on **17a**

Conc. (x 10^{3} M) of Cyclodextrin	**Absorption at**	
	220 nm	282 nm
0	0.258	0.382
0.894	0.419	0.262
1.72	0.465	0.266
2.85	0.517	0.271
3.82	0.592	0.274

(b) Effect of β-cyclodextrin on **17a**

Conc. (x **10^{-3} M)** of Cyclodextrin	Absorption at	
	225 nm	285 nm
0	0.134	0.252
1.17	0.148	0.282
3.82	0.180	0.381
6.17	0.232	0.491

(c) Effect of γ-cyclodextrin on **17b**

Conc. (x 10^{-3} M) of Cyclodextrin	Absorption at 223 nm	266 nm	320 nm
0	0.239	0.116	0.109
0.77	0.380	0.121	0.108
1.77	0.437	0.127	0.108
2.62	0.524	0.134	0.107

2. Changes in the fluorescence spectra (the fluorescence intensities reported are relative intensities i.e., I/I_o, Where I_o = fluorescence intensity of the probe and I = fluorescence intensity in the presence of the additive)

(a) Effect of γ-cyclodextrin on **17a**

Conc. (x 10^{3}M) of Cyclodextrin	Fluorescence Intensity at 342 nm	410 nm
0.67	1.03	1.87
2.16	1.07	2.60
4.16	1.13	3.18
6.8	1.22	3.81
10.2	1.28	4.40
16.9	1.90	5.74

(b) Effect of P-cyclodextrin on 17a

Conc. (x **10^{-3} M)** of Cyclodextrin	Fluorescence **Intensity** at 340 urn
0.26	1.06
0.77	1.28
3.85	**1.73**
11.6	3.65

(c) Effect of **γ-cyclodextrin** on **17b**

Conc. (x **10^{3} M)** of Cyclodextrin	Fluorescence **Intensity** at	
	346 **nm**	414 nm
0.51	0.92	1.06
1.28	0.80	**1.12**
3.85	0.64	1.37
7.20	0.43	1.71
12.10	0.26	2.04
17.52	0.17	2.26

(d) Effect of P-cyclodextrin on **17b**

Conc. (x **10^{3} M)** of Cyclodextrin	Fluorescence Intensity at	
	346 nm	414 nm
0.51	0.98	1.01
3.08	0.91	1.04
5.65	0.89	1.09
8.20	0.87	**1.21**
13.41	0.85	1.50

(e) Effect of **γ-cyclodextrin** and potassium thiocyanate addition on **17a**

Conc. of		Fluorescence Intensity at	
y-CD (x 10^{-3}M)	KSCN (M)	340 nm	410nm
M)	0.52	0.81	
0	2.06	0.63	
0	5.53	0.46	
2.31	5.53	0.69	2.38
6.17	5.53	0.84	3.01
13.61	5.53	1.21	4.25

Conc. of		Fluorescence Intensity at	
y-CD (x 10"^{3} M)	KSCN (M)	340 nm	410nm
3.08	0	1.38	1.82
10.3	0	2.39	2.85
15.4	0	4.09	4.03
15.4	1.3	2.73	3.90
15.4	2.03	2.27	3.08
15.4	5.46	1.95	2.33

(f) Effect of y-cyclodextrin and potassium thiocyanate addition on **17b**

Conc. of		Fluorescence Intensity at	
γ-CD (x 10^{-3} M)	KSCN (M)	346 nm	414 nm
5.14	0	0.82	1.60
10.3	0	0.45	2.12
15.4	0	0.31	2.55
15.4	1.37	0.22	2.39
15.4	2.4	0.19	2.30
15.4	3.43	0.14	2.08

Conc. of		Fluorescence Intensity at	
y-CD (x 10^{-3} M)	KSCN (M)	340 nm	410nm
0	1.2	0.61	
0	2.4	0.54	
0	3.4	0.44	
5.14	3.4	0.23	1.25
10.3	3.4	0.20	1.51
15.4	3.4	0.19	1.65

(g) Effect of γ-cyclodextrin and potassium thiocyanate addition on **18a**

Conc. of		Fluorescence Intensity at		
γ-CD (x 10^{-3} M)	KSCN (M)	410 nm	426 nm	447 nm
1.69	0	1.07	1.08	1.09
4.78	0	1.13	1.12	1.18
12.9	0	1.25	1.21	1.34
12.9	1.0	1.22	1.17	1.30
12.9	3.0	1.03	1.07	1.19
12.9	6.0	0.84	0.82	0.88

Conc of		Fluorescence Intensity at		
y-CD (x 10^{-3} M)	KSCN (M)	410nm	426 nm	447 nm
0	1.4	1.01	0.97	0.99
0	3.3	0.80	0.81	0.90
0	6.5	0.69	0.67	0.73
3.08	6.5	0.63	0.64	0.72
7.84	6.5	0.70	0.67	0.78
15.8	6.5	0.81	0.8	0.94

(h) **Effect** of **γ-cyclodextrin** and potassium thiocyanate addition on 18b

Conc.		Fluorescence Intensity at	
Y-CD (x 10^{-3} M)	KSCN (M)	430 nm	511 nm
2.11	0	1.06	1.03
6.22	0	1.15	1.08
14.8	0	1.38	1.28
20.7	0	1.72	1.47
20.7	1.15	1.56	1.28
20.7	3.15	1.45	1.09
20.7	6.6	1.14	0.58

Conc.		Fluorescence Intensity at	
Y-CD (x 10^{-3} M)	KSCN (M)	430 nm	511 nm
0	1.65	0.96	0.90
0	3.8	0.89	0.78
0	6.73	0.70	0.66
5.35	6.73	0.73	0.68
13.95	6.73	0.77	0.72
20.1	6.73	0.84	0.80

(i) Effect of y-cyclodextrin and potassium thiocyanate addition on **19a**

Conc.		Fluorescence Intensity at	
γ-CD (x 10^{-3} M)	KSCN (M)	362 nm	380 nm
1.54	0	1.29	1.06
6.68	0	1.38	1.26
12.6	0	1.87	1.57
12.6	1.24	1.42	1.16
12.6	2.4	1.33	1.10
12.6	3.39	1.19	0.98

Conc. of		Fluorescence Intensity at	
y-CD (x $10^{"3}$ M)	KSCN (M)	362 nm	380 nm
0	0.62	0.83	0.99
0	1.06	0.80	0.90
0	1.64	0.78	0.88
5.14	1.64	0.89	0.96
9.30	1.64	0.92	0.99
11.9	1.64	0.95	1.02

(j) Effect of y-cyclodextrin on 19b

Conc. (x 10^3 **M**) of **Cyclodextrin**	Fluorescence Intensity at 359 nm	374 nm	470 nm
1.16	0.98	0.97	1.05
4.14	0.93	0.91	1.12
12.1	0.86	0.83	1.20
24.8	0.70	0.65	1.75
35.4	0.59	0.55	2.00

(k) Effect of y-cyclodextrin and potassium thiocyanate addition on 19b

Conc. of		Fluorescence Intensity at	
y-CD (x 10^{-3} M)	KSCN **(M)**	359 nm	374 nm
0	1.23	0.91	0.90
0	2.73	0.79	0.76
0	3.97	0.69	0.67
2.72	3.97	0.62	0.61
9.97	3.97	0.58	0.58
16.4	3.97	0.51	0.52

Conc. of		Fluorescence Intensity at	
y-CD (x 10^{-3} M)	KSCN (M)	359 nm	374 nm
2.75	0	0.99	0.99
9.33	0	0.85	0.87
15.8	0	0.80	0.78
15.8	1.33	0.69	0.62
15.8	2.91	0.65	0.56
15.8	4.44	0.53	0.43

References

1. J.-M. Lehn, *Angew. Chem. Int. Ed. Engl.*, 1988, *27,* 89.
2. a) J.-M. Lehn, *Angew. Chem. Int. Ed. Engl.*, 1990, *29,* 1304; b) *'Supramolecular photochemistry',* V. Balzani Ed., D. Reidel, Dordrecht, 1987; c) J.-M. Lehn, in *'Frontiers in Supramolecular Organic Chemistry and Photochemistry',* H-J. Schneider and H-Diirr Ed., VCH Publishers, Weinheim, 1991, p. 1; d) R. A. Bissel, A. P. De Silva, H. N. Q. Gunaratne, P. L. M. Lynch, G. E. M. Maguire and K. R. A. Sandanayake, *Chem. Soc. Rev.,* 1992, 187; e) S. Shinkai, *Top. Curr. Chem.,* 1984, *121,* 67.
3. a) J.-P. Konopelski, F. Kotzyba-Hibert, J.-M. Lehn, J.-P. Desvergne, F. Fages, A. Castellan and H. Bouas-Laurent, *J. Chem. Soc, Chem. Commun.*, 1985, 433; b) F. Fages, F. Kotzyba-Hibert, J.-P. Desvergne, H. Bouas-Laurent, P. Marsau, J.-M. Lehn, A.-M. Albrecht-Gary and M. Al-Joubbeh,./. *Am. Chem. Soc,* 1989, *111*, 8672.
4. a) P. Marsau, H. Andrianatoandro, T. Willms, J. P. Desvergne, H. Bouas-Laurent, H. Hopf and R. Utermöhlen, *Chem. Ber.,* 1993, *126,* 1441; b) D. Marquis and J. P. Desvergne, *Chem. Phys. Lett.,* 1994, *230,* 131.
5. G. W. Gokel, in *'Comprehensive Supramolecular Chemistry',* J.-M. Lehn Ed., *Vol. 1,* Pergamon, Oxford, 1996.
6. W. E. Morf, D. Ammann, R. Bissig, E. Pretsch and W. Simon, *Prog. Macrocycl. Chem.,* 1978, /, 1.
7. E. Weber and F. Vogtle, *Tetrahedron Lett.,* **1975**, *16*, 2415.
8. J. P. Dix and F. Vogtle, *Chem. Ber.,* **1980**, *113*, 457.

9. a) J. P. Desvergne, A. Castellan and R. Lesclaux, *Chem. Phys. Lett.*, 1980, *71*, 228; b) J. P. Desvergne and H. Bouas-Laurent, *J. Chem. Soc, Chem. Commun.*, **1978**, 403.
10. G. Li and W. C. Still, *Tetrahedron Lett.*, 1993, *34*, 919.
11. A. Ueno and T. Osa, in *'Photochemistry in Organised and Constrained Media'*, V. Ramamurthy, Ed.,VCH Publishers, New York, 1991 p. 739 and references cited therein.
12. G. Wenz, *Angew. Chem. Int. Ed. Engl.*, 1994, *33*, 803.
13. M. L. Bender and M. Komiyama, in *' Cyclodextrin Chemistry'*, Springer Verlag, New York, 1978.
14. a) M. Watanabe, H. Nakamura and T. Matsuo, *Bull. Chem. Soc. Jpn.*, 1992, *65*, 164; b) A. Aversa, W. Etter, R. I. Gelb and L. M. Schwartz, *J. Inclusion Phenom. Mol. Recognit. Chem.*, 1990, *9*, 277; c) H. Saito, H. Yonemura and H. Nakamura, *Chem. Lett.*, 1990, 535.
15. K. A. Connors and D. A. Pendergast, *J. Am. Chem Soc*, 1984, *106*, 7607.
16. K. Harata, *Bull. Chem. Soc. Jpn.*, 1976, *49*, 1493.
17. Y. Matsui, T. Nishioka and T. Fujita, *Top. Curr. Chem.*, 1985, *128*, 61.
18. a) N. Kobayashi, S. Minato and T. Osa, *Makromol. Chem.*, 1983, *184*, 2123; b) Y. Yamashoji, M. Tanaka and T. Shono, *Chem. Lett.*, 1990, 945.
19. R. I. Gelb and L. M. Schwartz, *J. Inclusion Phenom. Mol. Recognit. Chem.*, 1989, *7*, 537.
20. A. Buvari, J. Szejtli and L. Barcza, *J. Inclusion Phenom.*, **1983**, *1*, 151.
21. A. M. de la Pena, T. Ndou, J. B. Zung and I. M. Warner, *J. Phys. Chem.*, 1991, *95*, 3330.
22. A. Ueno and I. Suzuki, *Anal. Chem.*, 1990, *62*, 2461.

23. **T.** Andcrsson, K. Nilsson, M. Sundahl, G. Wcstman and O. Wennerstroem, *J. Chem. Soc, Chem. Commun.*, **1992,** 604.

24. **A.** Ueno, K. Takahashi, Y. Hino and T. Osa, *J. Chem. Soc, Chem. Commun.,* **1981,** 194.

25. **D. F.** Eaton, *Tetrahedron,* 1987, *43,* 1551

26. a) A. Ueno, K. Takahashi, Y. Hino **and** T. Osa, *J. Chem. Soc, Chem. Commun.,* **1981,** 194; b) M. Hoshino, M. Imamura, K. Ikehara and Y. Hama, *J. Phys. Chem.,* **1981,** *85,* 1820.

27. a) N. J. Turro, T. Okuba and G. C. Weed, *Photochem. Photobiol.,* **1982,** *35,* 325; b) M. Itoh and Y. Fujiwara, *Bull. Chem. Soc. Jpn.,* **1984,** *57,* 2261.

28. R. Arad-Yellin and D. F. Eaton, *J.Phys. Chem.,* **1983,** *87,* 5051.

29. J. Emert, K. Dharmarao and R. Catena, *J. Chem. Soc, Chem. Commun.,* **1981,758.**

30. **N.** Kobayashi, Y. Hino, A. Ucno and T. Osa, *Bull. Chem. Soc Jpn.,* **1983,** *56,* 1849.

31. '*Photophysicsof Aromatic Molecules*',J. B. Birks Ed., Wiley Interscience, London, **1970.**

32. **I.** Sanemasa, T. Takuma and T. Deguchi, *Bull. Chem. Soc. Jpn.,* **1989,** *62,* 3098.

33. H. M. Colquhoun, E. P. Goodings, J. M. Maud, J. F. Stoddart, J. B. Wolstenholme and D. J. Williams, *J. Chem. Soc, Perkin Trans. II,* **1985**, 607.

34. **J. H. Jung,** S. **B.** Cho, **J.** Kim, **J.** S. Kim and S. **S.** Lee, *Anal. Sci. Technol.*, **1993,** *6,* 29.

35. E. P. Kyaba, R. C. S. Helgeson, K. Madan, G. W. Gokel, T. L. Tarnoswski, S. S. Moore and D. J. Cram, *J. Am. Chem. Soc,* 1977, *99,* 2564.

36. a) J. S. Meek, P. S. Monroe and C. J. Bouboulis, *J. Org. Chem.,* **1963,** *28,* 2572; b) J. -P. Desvergne, A. Castellan and R. Lesclaux, *Chem. Phys. Lett.,* **1980,** *71,* 228.

37. *A Text Book of Practical Organic Chemistry,* A. I. Vogel, 3rd edition, Longman, London, 1968, p.684.

38. a) A. R. Watkin, *J. Phys. Chem.,* **1974,** *78,* 1885; b) H. Shizuka, M. Nakamoto and T. Morita, *J. Phys. Chem.,* 1980, *84,* 989.

39. M. Mac, J. Wirz and J. Najbar, *Helv. Chim. Acta,* 1993, *76,* 1319 and references cited therein.

40. A. Ueno, K. Takahashi and T. Osa, *J. Chem. Soc, Chem. Commun.,* 1980, 921.

41. K. Harata and H. Uedaira, *Bull. Chem. Soc. Jpn.,* **1975,** *48,* 375.

42. O. S. Tee and M. J. Boyd, *J. Chem. Soc, Perkin Trans. II,* 1995, 1237.

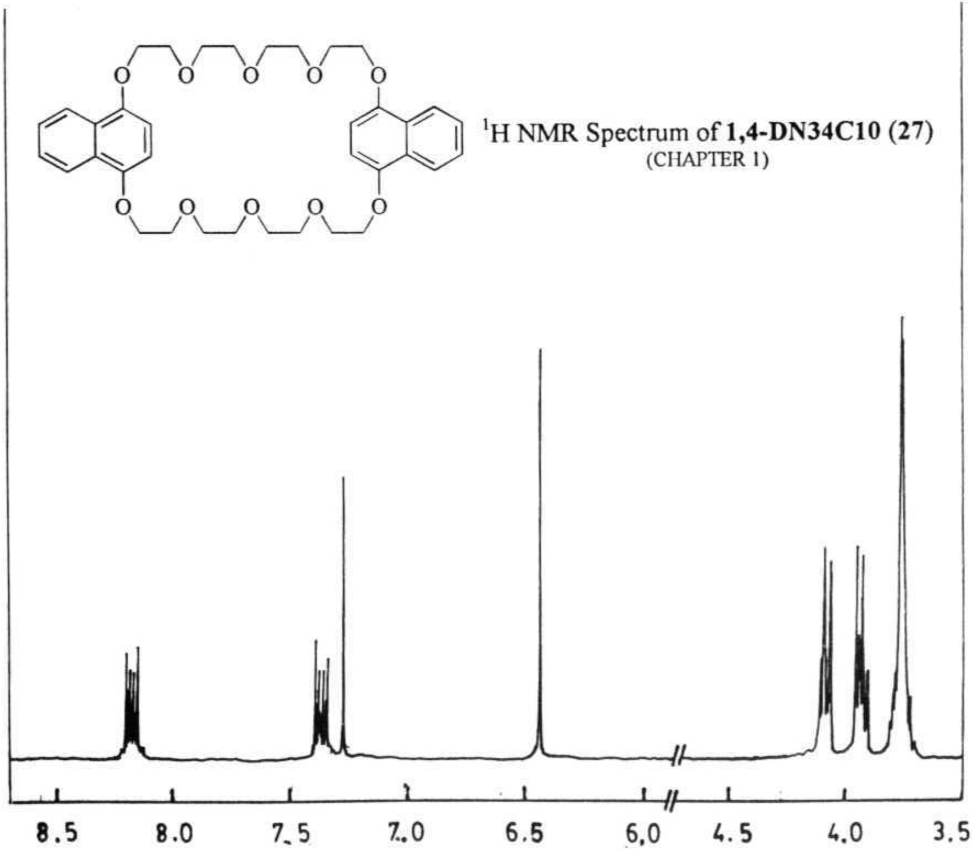
43. D. J. Marquardt and F. A. McCormick, *Tetrahedron Lett.,* 1994, 35, 1131.

44. R. G. R. Bacon and S. C. Rennisson, *Chemistry and Industry,* 1966, 812.

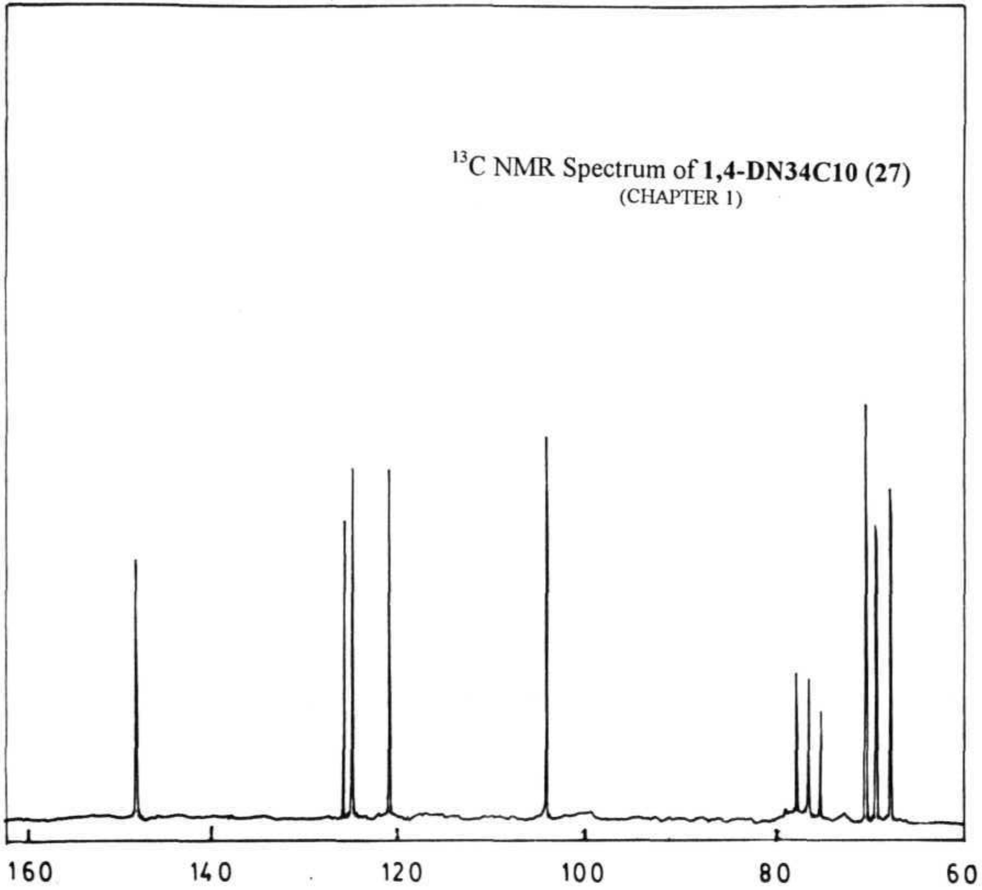
45. F. B. Mallory and C. S. Mallory, *J. Am. Chem. Soc,* 1972, *94,* 6041.

46. L. F. Fieser, *J. Am. Chem. Soc,* 1929, *51,* 2466.

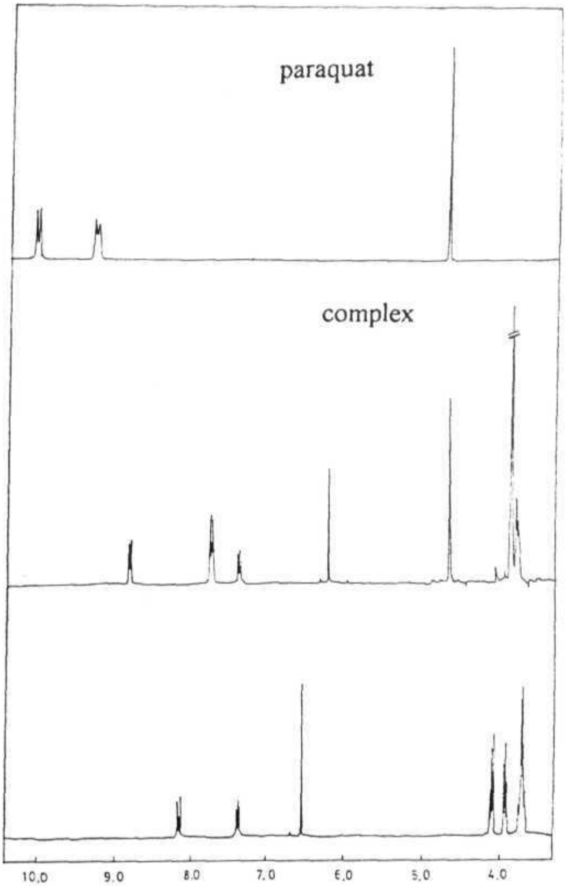
Spectra



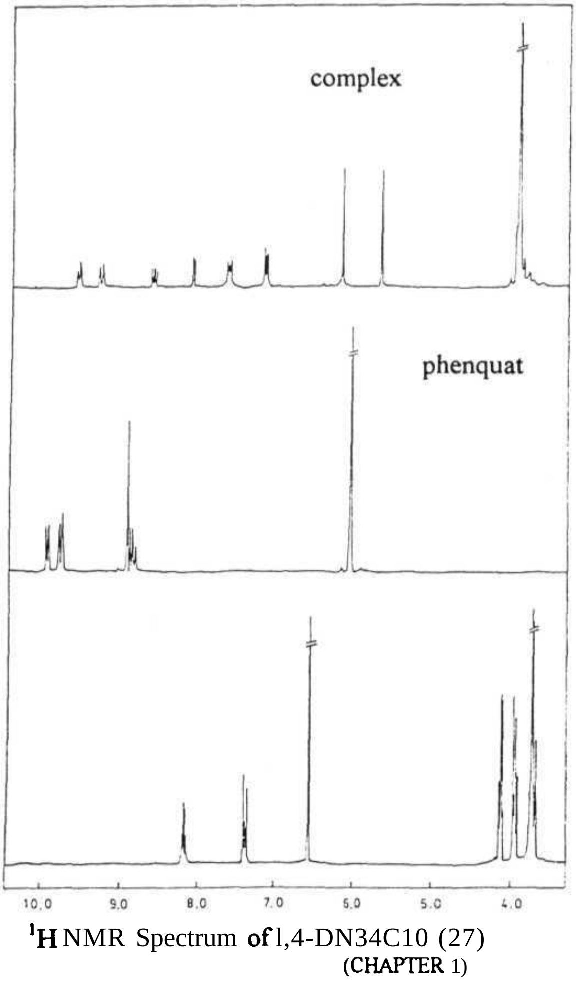
^{1}H NMR Spectrum of **1,4-DN34C10 (27)**
(CHAPTER 1)



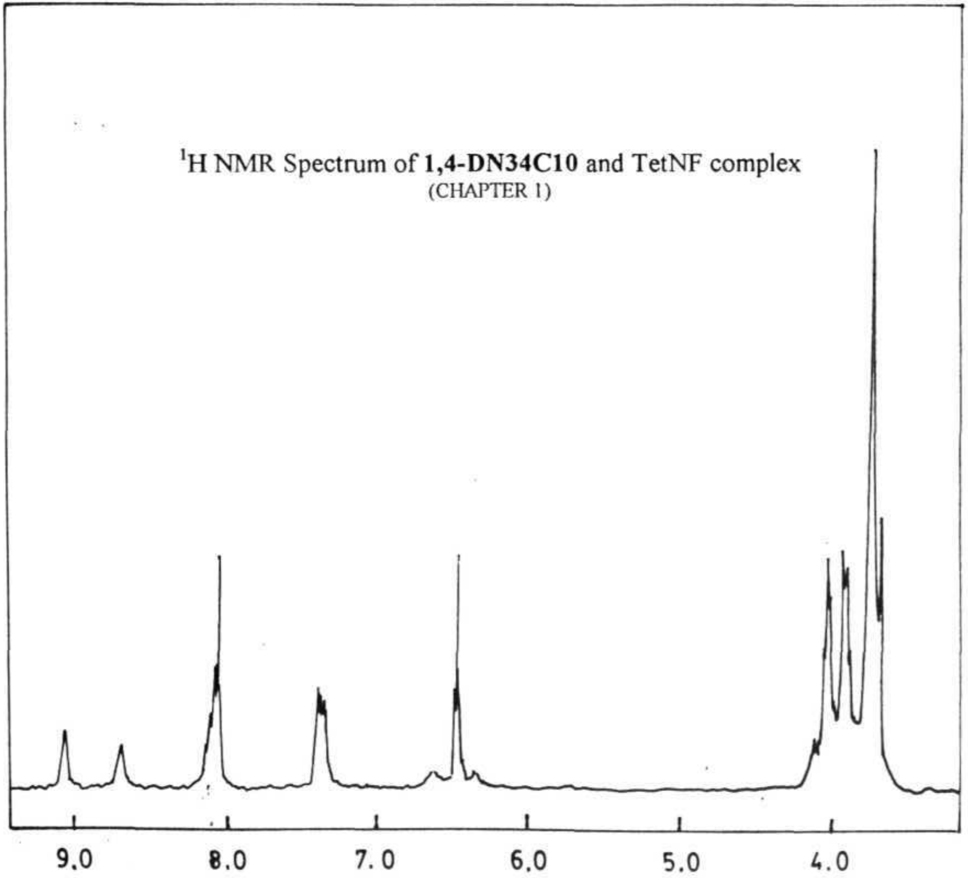
^{13}C NMR Spectrum of **1,4-DN34C10 (27)**
(CHAPTER 1)



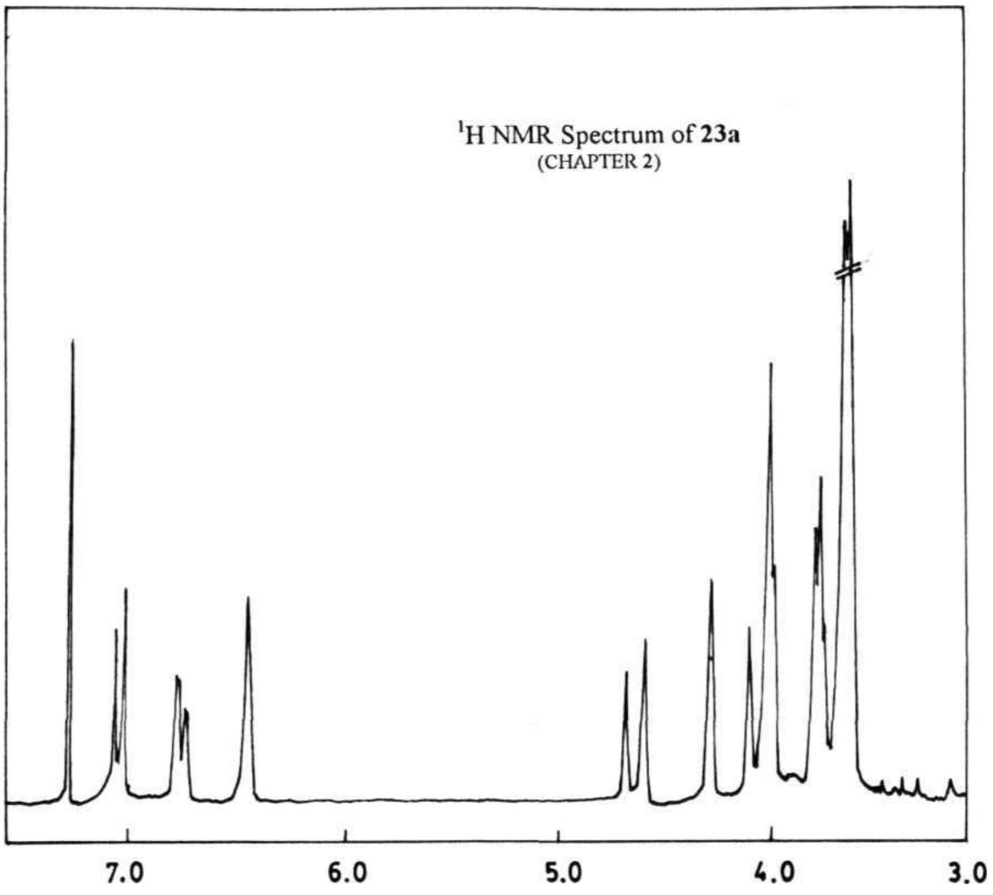
^1H NMR Spectrum of l,4-DN34C10 (27)
(CHAPTER 1)



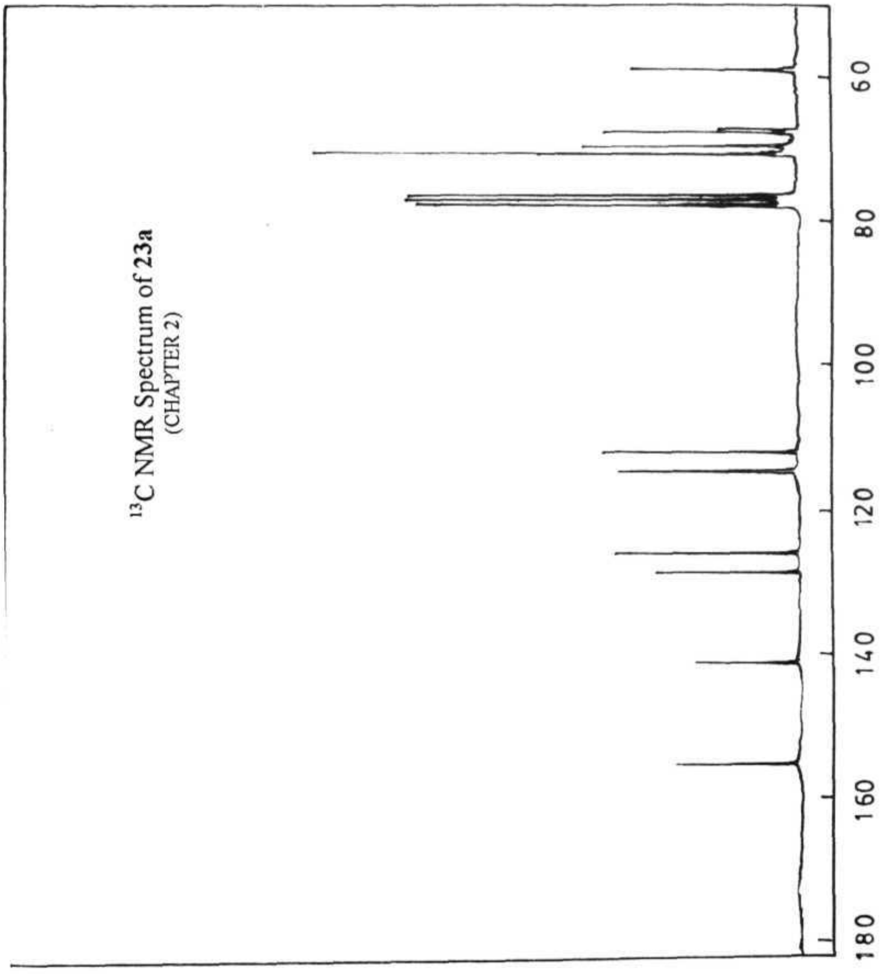
^1H NMR Spectrum of 1,4-DN34C10 (27)
(CHAPTER 1)



^{1}H NMR Spectrum of **1,4-DN34C10** and TetNF complex
(CHAPTER 1)

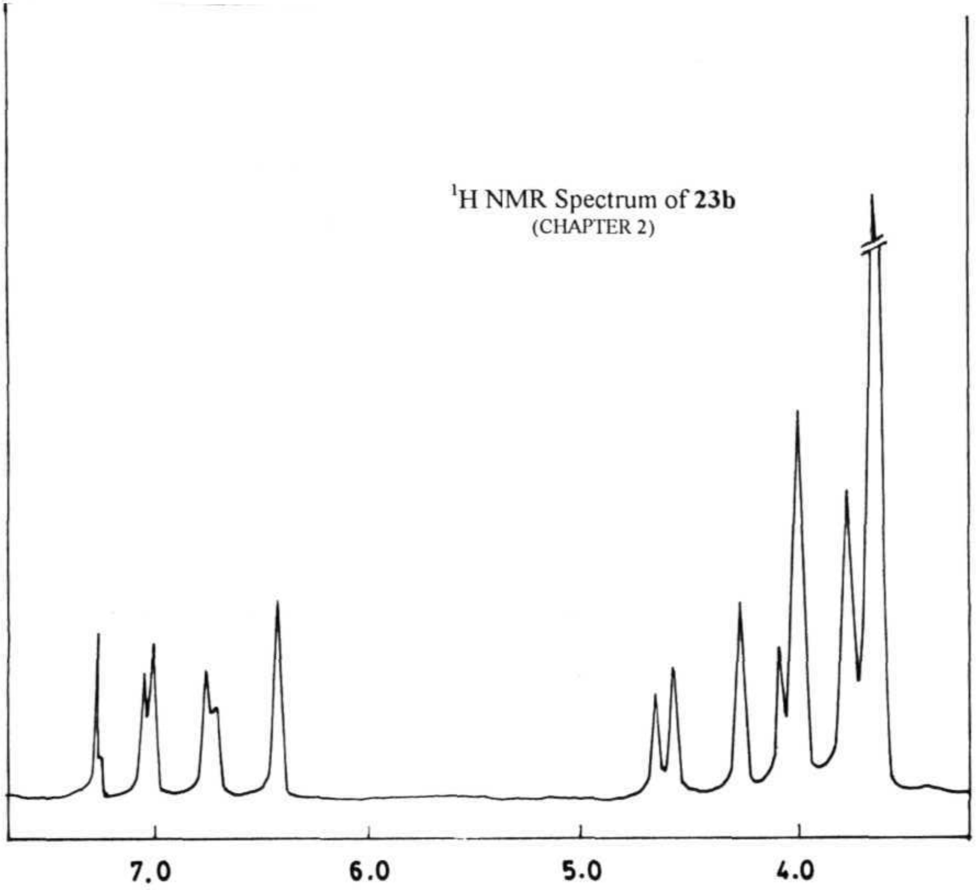


^{1}H NMR Spectrum of **23a**
(CHAPTER 2)



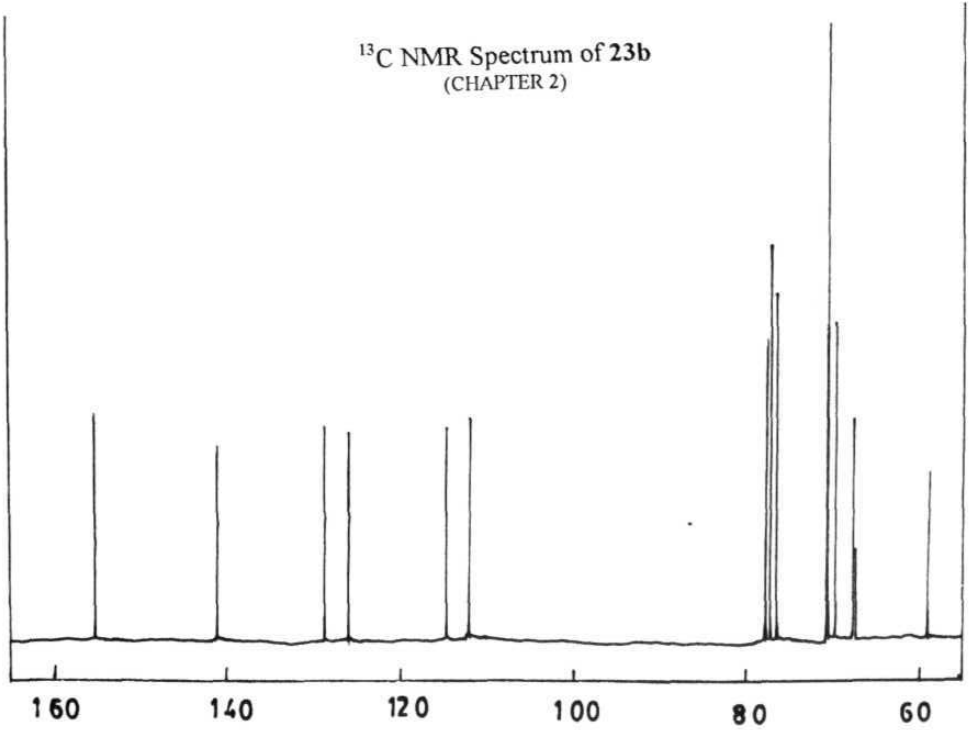
^{13}C NMR Spectrum of **23a**

(CHAPTER 2)

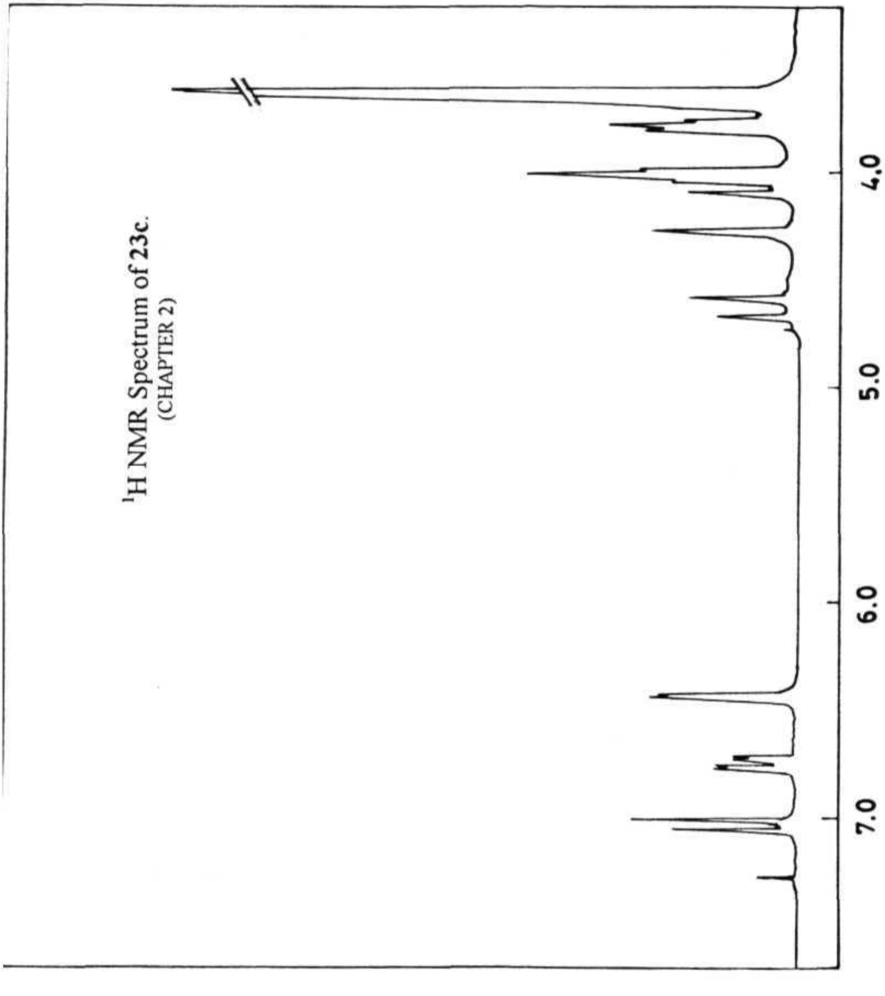


^{1}H NMR Spectrum of **23b**

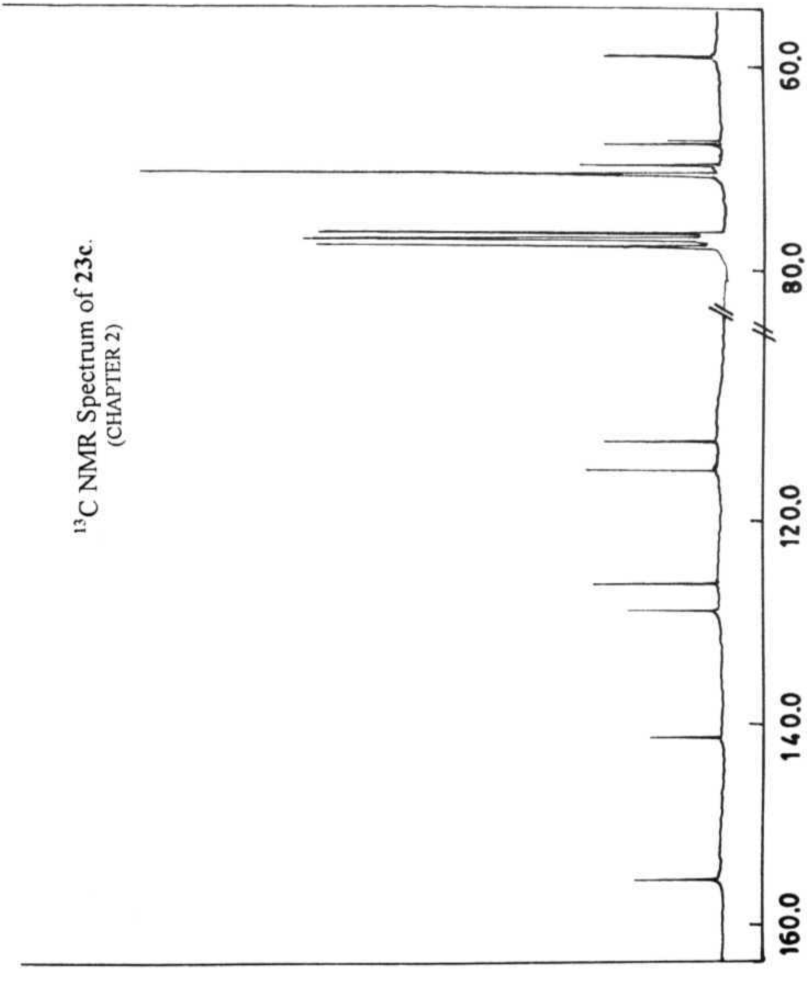
(CHAPTER 2)



^{13}C NMR Spectrum of **23b**
(CHAPTER 2)



^{1}H NMR Spectrum of **23c**.
(CHAPTER 2)



^{13}C NMR Spectrum of **23c**.
(CHAPTER 2)