SUMMARY
SYNTHESIS, SPECTROSCOPIC AND ELECTROCHEMICAL STUDIES
OF METAL CHELATES OF MACROCYCLIC LIGANDS

The naturally occurring macrocyclic complexes like chlorophyll, vitamin B_{12}, haemoglobin, porphyrins etc. have been known for quite some time. These macrocyclic complexes perform vital functions in the various biological processes. It is important to note that the significant role played by metal ions in living systems depends on their confinement in an approximately planar, tetradentate, totally enclosed framework. The chemistry of the synthetic macrocyclic complexes, stems from the condensation reaction between ethylene diamine with acetone to give 5,7,7,12,14,14 hexamethyl 1,4,8,11 tetraazacyclotetradeca 4,11 diene generally abbreviated as Me_6[14] diene. A large number of such compounds are now known and they form an important class of compounds in themselves. These nitrogen donor synthetic macrocyclic complexes have close resemblance in their structure with their natural counterparts and can thus be considered as models for them.

Although a large amount of work has been done on the macrocyclic complexes during the last decade, evidently a large number of areas can be identified in this field which have received scant attention. Most of the work has been centered around the copper(II), nickel(II), cobalt(III) and iron(II) complexes of 12– to 14–membered macrocycles. Very little has been done either to prepare macrocycles with larger rings or to attach pendant groups to the already known macrocyclic structures. Preparation and characterization of macrocycles with large rings could be useful to generalize the characteristics which determine the stability of these complexes. Attachment of pendant groups (carrying different functional moieties) to the macrocyclic structure would be useful in investigating the effect of
such structures on the dynamic properties of the metal ion. In the present studies an attempt has been made to investigate both the above mentioned aspects to add to our existing knowledge on macrocyclic complexes. With this aim in view, the following studies on the chemistry of macrocyclic complexes were carried out.

a) Preparation and characterization of two new 16– and 17–membered macrocycles (capable of giving 8– and 9–membered chelate rings) and their complexes with copper(II), nickel(II), cobalt(III) and chromium(III). Some of their properties have also been investigated.

b) A few macrocycles with different attached pendant functional groups were synthesized and their metal complexes characterized. These studies have been extended to include a few bimetallic centered complexes.

Whole work divided into seven chapters.

**Chapter–I:** Contain General Introduction on the subject and related review of literature.

**Chapter–II: Copper(II), Nickel(II), Cobalt(III) and Chromium(III) Complexes of 1,4,8,11 cyclohexadecane and 1,4,8,11 cycloheptadecane**

A large number of tetraaza macrocycles and their metal complexes have been prepared and studied, during the last fifteen years. Most of the work has been done on 12– to 14–membered macrocycles which form the most stable complexes and it has been observed that the 14–membered cavity is a best fit for cobalt(III) and to a very large extent for nickel(II) as well. It has been observed that these complexes persist in acid solution for months, while in case of macrocycles carrying bigger chelate rings, the stability is markedly decreased. In order to investigate the effect of such larger chelate rings on the stability of the
macrocyclic complexes, two new 16– and 17–membered macrocycles have been prepared.

The tetratosylated linear tetramine was condensed with bistosylated diol (in case of 16–membered macrocycles, 1,5 pentane diol and in the case of 17–membered macrocycles 1,6 hexane diol was used) in DMF to give the cyclised product. The condensation product was then hydrolysed with conc.H\textsubscript{2}SO\textsubscript{4} to give the free macrocycle. Both the ligands undergo complexation quite easily with copper(II), nickel(II), cobalt(III) and chromium(III). The cobalt(III) complexes are quite stable and undergo axial ligand substitution reactions by the usual metathesis procedures.

The infrared spectra of copper(II) and nickel(II) complexes shows a sharp NH band around 3200 cm\textsuperscript{-1} and perchlorate band at 1100 and 620 cm\textsuperscript{-1}. Since there is no splitting in the \nu\textsubscript{asym} (Cl–O) band at 1100 cm\textsuperscript{-1}, it is concluded that perchlorate is present in the ionic state in the solid complex.

The infrared spectra of cobalt(III) complexes show bands corresponding to the macrocycle and the appropriate axial ligands. The skeletal vibrations of the macrocycle in 750–1500 cm\textsuperscript{-1} region, reflect changes in the geometry of the macrocycle. A comparison of the spectra of [CoLY]\textsuperscript{3+} (Y=glycine or acac) with that of [CoL Cl\textsubscript{2}] reflects the difference between the folded geometry in the former cases and the planar geometry in the latter. Bands observed in the trans–chloro complexes are either shifted or not observed at all in the cis– complexes. The characteristic bands due to chelated acetyl acetone ligand appear around 1570 cm\textsuperscript{-1} and 1520 cm\textsuperscript{-1}. The glycine complex shows a broad band at 1340 cm\textsuperscript{-1} assigned to the asymmetric stretching vibration of the coordinated COO\textsuperscript{−} and another band at 1600 cm\textsuperscript{-1} due to symmetric stretching of COO\textsuperscript{−} group. The unidentate ligand
NO$_2^-$, which occurs in two complexes shows the characteristic bands due to $\nu_{\text{asym}}$(NO$_2$), $\nu_{\text{sym}}$(NO$_2$) and $\delta$(NO$_2$).

In the case of chromium(III) complexes, the cis– and trans– isomers can be easily distinguished on the basis of their infrared spectra. The pink coloured cis– isomer, cis–[CrLCl$_2$]Cl and cis–[CrLCl$_2$]ClO$_4$, show two $\nu$(NH) bands appearing around 3150 cm$^{-1}$ and 3200 cm$^{-1}$ while the light green coloured trans– isomer, trans–[Cr([16]ane N$_4$)Cl$_2$]Cl and trans–[Cr([16]ane N$_4$)Cl$_2$]ClO$_4$, show a single $\nu$(NH) band around 3200 cm$^{-1}$.

Conductometric measurement on copper(II) and nickel(II) complexes in aqueous solutions show that the complexes are 2:1 electrolytes.

The ultraviolet spectra of copper(II) complexes show a single band corresponding to N–Cu charge transfer. This shows that all the four nitrogens are equivalent in these complexes. The spectra of nickel(II) complexes show a broad band at 22222 cm$^{-1}$ for [Ni([16]ane N$_4$)](ClO$_4$)$_2$ and 21733 cm$^{-1}$ for [Ni([17]ane N$_4$)](ClO$_4$)$_2$ due to combination of $^3$A$_{2g} \rightarrow ^3$T$_{1g}$(P) transition of octahedral nickel(II), and $^1$A$_{1g} \rightarrow ^1$B$_{1g}$ transition of square planar nickel(II). The extinction coefficient of these two complexes are low and show temperature dependence, which suggests an octahedral planar equilibrium. The equilibrium is endothermic and shifts towards the planar form with increase in temperature or addition of inorganic salts like NaClO$_4$ which reduces the free water concentration

$$[\text{NiL(H}_2\text{O)}_2]^2+ \rightleftharpoons [\text{NiL}]^{2+} + 2\text{H}_2\text{O}$$

In the case of an analogous complex, c–meso–5,12 dimethyl 1,4,8,11 tetraazacyclotetradecane, only a single d–d band is observed at 21410 cm$^{-1}$ ($\varepsilon$=64 dm$^3$ mol$^{-1}$ cm$^{-1}$). For this complex, it has been evaluated that at 25°C, there is ca 65% of the octahedral species and 35% of the planar species. Such equilibria
exhibit values of $\Delta H^\circ$ in the range of 7.1 to 6.2 KJ mol$^{-1}$ and $\Delta S^\circ_{298}$ of the order of 20 to 140J mol$^{-1}$ over a temperature range of 20–50°C.

The electronic spectra of cobalt(III) complexes, trans– [CoLCl$_2$]ClO$_4$, show a typical d–d band corresponding to the CoN$_4$Cl$_2$ chromophore. A number of other trans–[CoLX$_2$]ClO$_4$ and cis–[CoLY](ClO$_4$)$_2$ complexes, prepared by ligand metathesis reactions show typical bands corresponding to CoN$_6$, CoN$_5$Cl, CoN$_5$O or CoN$_4$O$_2$ chromophores. The position of these bands supports the assignment of trans– and cis–configuration to these complexes. These values are comparable with other literature values for similar complexes.

The spectra of chromium(III) complexes can be used to distinguish the cis– and trans–geometry of these complexes. The more symmetrical trans– isomers have low extinction coefficients of <30 and the lowest d–d band appears in the 17500–16900 cm$^{-1}$ range, while the less symmetrical cis–isomers have much higher extinction coefficients (of the order of 80–120) and the lowest d–d band occurs at 18900–17500 cm$^{-1}$. The present complexes also show absorption bands in these regions in accord with their assigned geometries.

The macrocycles are capable of forming a novel sequence of chelate rings 5,6,5,8 and 5,6,5,9 on undergoing complexation. The complexes of these ligands carry four chiral nitrogen centres, which can yield as many as ten N–diastereoisomers. Molecular models show that out of the possible ten diastereoisomers, only four are virtually free from torsional strain as well as have minimum hydrogen–hydrogen interaction in the chelate rings. The ligands are expected to exist in their most stable trans– form (cyclam form) with an R,S,S,R configuration.

Kinetic of acid–catalysed dissociation of copper(II) complexes have also been studied. The present copper(II) complexes undergo very rapid dissociation in
acidic solutions. A plot of $k_{\text{obs}}$ vs hydrogen ion concentration shows that initially there is a linear dependence of $k_{\text{obs}}$ on $[H^+]$ but at higher hydrogen ions concentrations the reaction becomes independent of $[H^+]$ concentration. The plots show an intercept corresponding to a solvolytic path associated with these dissociation reactions. The acid–catalyzed path leading to dissociation is consistent with the following kinetic scheme.

$$\begin{align*}
[CuL]^2+ + H^+ & \rightleftharpoons [CuLH]^3+ \\
[CuLH]^3+ & \xrightarrow{k} Cu^{2+} + [LH]^2+
\end{align*}$$

The overall rate expression for this mechanism can be represented as

$$k_{\text{obs}} = k_o + \frac{kK[H^+]}{1 + K[H^+]}$$

where $k_o$ is the solvolytic route. The above equation can be written as

$$\frac{1}{(k_{\text{obs}} - k_o)} = \frac{1}{kK[H^+]} + \frac{1}{K}$$

which means that a double reciprocal plot of $1/(k_{\text{obs}} - k_o)$ vs $1/[H^+]$ should be linear. The present results show that this plot is linear for both the complexes.

A general mechanism proposed for the acid–catalysed dissociation of linear polyamine complexes may be adopted for these complexes. It is observed that the macrocyclic complexes dissociate at a lower rate as compared to the linear tetraamine complexes. The dissociation mechanism involves some angular expansions of the bond angles in the chelate rings. This is followed by a slow cleavage of the second copper nitrogen bond, which is assumed to be rate determining. Breaking of subsequent copper nitrogen bonds resulting in complete dissociation is a very rapid process.
Copper(II) complexes usually show square planar or tetragonally distorted octahedral structure, for which broad bands are observed due to overlap of $a_{1g} \rightarrow b_{1g}$, $b_{2g} \rightarrow b_{1g}$ and $b_{2g} \rightarrow b_{1g}$ transitions in the visible region. The $\lambda_{\text{max}}$ for these broad bands gives an approximate value of 10Dqxy and the value of $\lambda_{\text{max}}$ corresponds to the field created by the macrocycles in the square plane. The position of this absorption band can therefore be used as a measure of the ligand field. It has been observed that the ligand experiences a strain in arranging itself at the corners of a square plane around the copper(II) ion when the 15– and 16–membered rings are considered. Spectral data studies on a variety of copper(II) complexes have shown that cyclam, with the 5,6,5,6 chelate ring sequence forms the most stable complex. A comparison of the $\lambda_{\text{max}}$ values for a large number of copper(II) complexes shows that the 5,6,5 chelates ring sequence is the most favoured geometry for complexation as it places the four nitrogens in a preoriented geometry favourable for coordination. Similar conclusions can be drawn for the nickel(II) complexes.

Polarographic studies on the copper(II) complexes in aqueous media shows that the complexes undergo a one electron, reversible reduction at the d.m.e. The reversible reduction of these complexes can be assigned to $\text{Cu}^{2+} \rightarrow \text{Cu}^{+1}$ couple. A comparison of $E_{1/2}$ values of the copper(II) complexes shows a systematic variation in their values with ring size. The values clearly show that the reduction potential decreases with increase in ring size.

**Chapter–III: Copper(II), Nickel(II), Cobalt(II), Cobalt(III) and Palladium(II) complexes of macrocycles carrying pendant functional groups**

The naturally occurring macrocyclic complexes carry pendent functional groups which act as structural components to the coordination sites. In order to
synthesis the macrocyclic complexes with pendent groups, the simplest route is to first synthesise the simple macrocyclic ligand and then attach suitable functional groups. The pendent functional group can be substituted either at carbon or nitrogen atoms. Both types of reaction have been observed and they give distinctly different types of complexes. In the present studies an attempt has been made to attach the CS$_2$ group to the appropriate carbon on the macrocyclic frame work to give 1,1 dithiolate derivative of macrocycle. The 1,1 dithiolate is capable of reacting with metals like copper(II), nickel(II), palladium(II) and metal bipyridyl complexes and diazotized aniline and benzidine.

The infrared spectra of these complexes shows the presence of C=C, C=S and N=S bands corresponding to 1600 cm$^{-1}$, 1100, 840 and 620 cm$^{-1}$ and 390 cm$^{-1}$ respectively. It is evident that the macrocycle is bound to the added metal ion through the two 1,1 sulphur atoms. In case of bipyridyl complexes the infrared spectra shows absorption in the 1600–1400 cm$^{-1}$ region corresponding to the ring stretching vibration. The infrared spectra of aniline and benzidine complexes shows bands for N=N and the aromatic groups in addition to the C=S, C=N and NH groups of the macrocycles.

The results of magnetic measurements show that nickel(II) and palladium(II) complexes are diamagnetic while the copper(II) complex is paramagnetic corresponding to one unpaired spin. The magnetic data of bipyridyl complexes is in accord with the octahedral geometry of the bipyridyl part of the complex. The spectral data is an accord with these geometries. The complexes with aniline and benzidine are also diamagnetic. The electronic spectra shows bands in the visible region due to the diazotized moieties.
The results of these studies show that diazonium ions can be conveniently attached to the methylene sites of macrocyclic complexes as reported by Goddard. The reaction is very fast even at the low temperatures used for diazotization reaction.

It is observed that the macrocyclic complex \([\text{NiMe}_2[13]\text{diene}]\)I reacts with diazotized aniline and diazotized p–aminobenzoic acid in the ratio of 1:1. The infrared spectra of these complexes shows the \(v(N=\text{N})\) band in 1600–1580 cm\(^{-1}\) region. In addition, both complexes show bands assignable to \(v(\text{C–H}), v(N=\text{N})\) and ring vibrations due to C–C and C=C stretchings of the phenyl groups. The \(^1\text{H}\) n.m.r. spectra shows typical bands corresponding to \(-\text{CH}_3, -\text{CH}_2\text{N}=, -\text{NH}–\) and the aromatic moieties of the complex.

Further investigations under this section deal with complexes derived from cyclam and C–rac and C–meso Me\(_2\)cyclam. The synthesis of tetra cyanoethylcyclam was first referred to briefly by Barefield but detailed investigations on the nickel(II) complex of tetra cyanoethylcyclam was reported by Wainwright who observed the weak coordinative interaction of the four cyano groups with the metal. Thus in effect a high spin five coordinated nickel(II) complex is formed.

The cyanoethylation of both C–rac and C–meso Me\(_2\)cyclam proceeds quantitatively on refluxing with acrylonitrile as reported for cyclam. Infrared spectra of these ligands show no band for \(v(\text{NH})\) and show a sharp single band around 2240 cm\(^{-1}\) due to C≡N. Both these ligands readily yield complexes with copper(II), nickel(II), cobalt(II) in methanolic/ethanolic solutions. A cobalt(III) complex has also been successfully isolated with tetra cyanoethyl cyclam.
The infrared spectra of the nickel(II) complex of cyanoethyl cyclam shows two bands corresponding to C≡N at 2250 cm\(^{-1}\) (same as in the free ligand) and another weak band at 2282 cm\(^{-1}\) which shows the coordination of four nitrile groups with the nickel(II) ion and this leads to the formation of high spin five coordinate complex, while in the case of C–meso and C–rac, the infrared spectra shows a sharp single C≡N band at 2240 cm\(^{-1}\). This shows that there is no ligation of the nitrile groups with the central metal ion. The infrared spectra of C–rac complex shows the splitting of perchlorate band at 1080, 1110 and 1120 cm\(^{-1}\) in addition to the sharp ClO\(_4^–\) band at 620 cm\(^{-1}\) which corresponds to presence of coordinated ClO\(_4^–\) in the solid state. In the case of C–meso complex, the infrared spectra does not provide any evidence for coordinated perchlorate due to steric effects of the two C–meso methyl groups. Both the complexes are 2:1 electrolyte in CH\(_3\)CN.

Both copper(II) complexes of C–rac and C–meso show a single infrared band for C≡N at around 2240 cm\(^{-1}\). There is no shifting of this band in comparison to the free ligand, indicating that there is no ligation of the nitrile groups with copper(II). These complexes also show the splitting of perchlorate band at 1100 cm\(^{-1}\) which indicates the presence of coordinated perchlorate in the solid state. Both the copper(II) complexes are 2:1 electrolyte in CH\(_3\)CN. The polarographic waves of the copper(II) complexes show reversible reduction through a one electron transfer process in which copper(II) is reduced to copper(I).

The infrared spectra of cobalt(II) complexes of C–rac shows a single band for C≡N which clearly shows the non–coordination of the nitrile groups. The complexes are non–electrolytes in CH\(_3\)CN which indicate that both the bromides
occupy the two axial sites. The magnetic data shows that the complexes are high spin with three unpaired spins. A green coloured cobalt(III) complex of tetra cyanoethyl cyclam has been isolated which shows a single absorption band for $\text{C} \equiv \text{N}$ at 2250 cm$^{-1}$ and is diamagnetic. The visible spectra of the complex shows a broad band at 15384 cm$^{-1}$ which is consistent with a cobalt(III) species a $\text{N}_4\text{Br}_2$ chromophore.

**Chapter–IV: Synthesis and Spectral Studies of transition metal complexes with 3,6,9,12,15,18 Hexa aza bicyclo[15.3.1]henicosa–1(21) 2,15,17,19–Pentane:**

In this chapter we report the synthesis and characterization of transition metal complexes with 3,6,9,12,15,18 hexa aza bicyclo[15.3.1]henicosa–1(21) 2,15,17,19 Pentane ($C_{15}H_{24}N_6$)(L$_1$) complexes of transition metal ions. All the complexes were found to have the composition $\text{ML}^1\text{Cl}_2$ where $\text{M} = \text{Mn}^{\text{II}}$, $\text{Co}^{\text{II}}$, $\text{Ni}^{\text{II}}$ and $\text{Cu}^{\text{II}}$ or $\text{M}^1\text{L}^1\text{Cl}_3$ where $\text{M}^1 = \text{Cr}^{\text{III}}$ and $\text{Fe}^{\text{III}}$. Molar conductance measurements of $\text{Mn}^{\text{II}}$, $\text{Co}^{\text{II}}$, $\text{Ni}^{\text{II}}$ complexes in DMSO correspond to 1:1 electrolytes, where as $\text{ML}^1\text{Cl}_3$ and $\text{CuL}^1\text{Cl}_2$ are 1:2 electrolytes. Therefore complexes may be formulated as $[\text{ML}^1\text{Cl}]\text{Cl}$, $[\text{M}^1\text{L}^1\text{Cl}]\text{Cl}_2$ and $[\text{CuL}^1]\text{Cl}_2$. All the complexes were characterized through elemental analysis, molar conductance and magnetic susceptibility measurements, IR, electronic and EPR–spectral studies.

**Chapter–V: Synthesis of Macrocyclic Schiff base ligand its interaction with Mn(II), Co(II), Ni(II) and Cu(II) and biological screening:**

The synthesis of a tetradeutate ligand 3,4,12,13–tetraphenyl–2,5,11,14,19,20–hexa aza tricyclo [13.3.1, 6–10] cosa 1(19), 2,4,6,8,10(20) 11,13,15,17–decene (L) ($C_{36}H_{24}N_8$) and its complexes with Mn(II), Co(II), Ni(II) and Cu(II) have been reported. The complexes are characterized by elemental analysis, molar
conductance measurements, magnetic susceptibility measurements mass spectra, $^1$H–NMR, IR electronic and EPR–spectral studies. On the basis of molar conductance the complex may be formulated as $[M(L)X_2]$ [where $M=\text{Mn}^{\text{II}}$, $\text{Co}^{\text{II}}$, $\text{Ni}^{\text{II}}$ and $\text{Cu}^{\text{II}}$ and X=Cl$^-$, NO$_3^-$] due to non electrolyte nature in dimethyl formamide (DMF). All the complexes are of high spin type and found to be six coordinated.

On the basis of IR, electronic, and EPR–spectral studies an octahedral geometry was proposed for Mn$^{\text{II}}$, Co$^{\text{II}}$, and Ni$^{\text{II}}$ complexes and tetragonal geometry for Cu(II) complexes. The antimicrobial activities of the ligand and complexes have been screened in vitro against many bacteria and pathogenic fungi to study their growth inhibition capacity.

**Chapter–VI: Tetra aza Macrocyclic Nickel(II) Complexes: Synthesis and Spectral Studies:**

Tetraazamacroyclic Ni(II) complexes $[\text{NiCl}_2(L)]$ (where $L=\text{N}_4$ donor macrocyclic ligands have been synthesized by the reactions of metallic salt with some of macrocyclic Schiff base ligands containing $\text{N}_4$–donor groups. The complexes were characterised by elemental analysis, IR, $^1$H, $^{13}$C–NMR, mass spectra, electronic molar conductance and magnetic susceptibility measurements. An octahedral geometry has been proposed for all complexes.