PART B

Lanthanide (III) Complexes
INTRODUCTION

History of the Lanthanides

The history of the lanthanides[1, 2] began in 1787, when a young Swedish Army Officer, Carl Axel Arrhenius, a keen amateur geologist discovered a new black mineral near the town of Ytterby which he named Ytterbite. This aroused some curiosity and in 1794, a Finnish chemist Johan Gadolin analyzed it and found it to be a mixture of iron, beryllium and silicon along with a new earth which he named “Yttria”. A decade later, Martin Klaproth, Berzelius and Hisinger discovered another unusual earth, which was named “Ceria”. So now, there were two very similar rare earth oxides Yttria and Ceria. The next century was spent by chemists in trying to separate them into its chemically similar parts, which was difficult considering the similar properties these elements have. A great deal of painstaking work was to follow. In the 1830’s Charles Mosander discovered cerium, neodymium and Lanthanum. A few years later, three more earths Yttrium, Erbium and Terbium were isolated.

In the late 1870’s, armed with new techniques, chemists attacked the rare earths with renewed vigor. The isolation of the lanthanides was not completed until the 1908 - 1909 owing to the difficulties in separating them. Over nearly a century, chemists had analyzed these two oxides eventually discovering all the fifteen lanthanides known today.

Complexing Properties of Lanthanides

a) Electronic Configuration (f block elements) [3]

Lanthanides belong to f-block and have the general electronic configuration [Xe] 6s² 4fⁿ where n = 1 to 14. They generally appear trivalent by giving 5d¹ 6s² or outer electrons differing only in the number of inner electrons.

Each lanthanide ion presents to an approaching ligand a completely paired noble-gas atom type of outermost configuration where 4f electrons are largely or completely unavailable for bond formation due to the shielding by the 5s² 5p⁶ orbital. Higher energy orbitals alone can participate in hybridization. Ligand field stabilization energies in comparison to transition metals are very small (just 1 kcal mol⁻¹).
b) Towards Donor Atoms [4, 5, 6]

The lanthanide (III) ions may be classified as type “A” cations in the Ahrland, Chatt and Davies classification and as hard acids according to the Pearson classification. Hence, lanthanides have a strong preference for donor groups like oxygen. The binding preference is O > N > S. Lanthanide complexes with purely oxygen donors (e.g., oxalates, β-diketonates) have been synthesized. However Ln(III) chelates of 1,10 phenanthroline and 2,2'- bipyridyl indicate that nitrogen can also be a donor of some significance. Mixed oxygen – nitrogen donors (polyamino - polycarboxylic acids, oxines) were also synthesized. Other donor atoms like S, P, etc can also coordinate to lanthanides provided competition by other ligands is less.

c) Water and OH as donors [7]

Water molecules and hydroxide ions are strongly coordinating ligands. Since Ln\(^{13+}\) – ligand coordination occurs mainly through ionic bonding, it has a strong preference for negatively charged donor groups that are also “hard bases”.

Since water has a high dielectric constant and appreciable donor character towards lanthanides, it competes effectively with other ligands for coordination sites. A coordination site once occupied by a water molecule cannot be easily displaced by another ligand. Thus only strong chelating ligands are capable of forming complexes of sufficient thermodynamic stability to be isolable.

Lanthanide complexes prepared under anhydrous conditions are generally found to undergo at least partial hydrolysis in the presence of even small amounts of water.

d) Ionic Size of the lanthanides [7]

The lanthanides show a steady decrease in ionic size across the series as the nuclear charge increases. This phenomenon is known as lanthanide contraction. As the size of the tri positive lanthanide ion decreases from La(III) to Lu(III), the ligand – ligand repulsion goes on increasing for the heavy lanthanide complexes. At a point when repulsion becomes large enough so as to make a particular structure unstable, the coordination number, and therefore the geometry changes.
e) **Ligand Lability** [4]

Synthesis of lanthanide complexes indicates that ligand exchange reactions involving lanthanide species are very rapid when carried out in solution. The number of isolable complexes and isomerism are limited. A complex in solid state may have different composition compared to the same in solution.

f) **Coordination number and geometry** [7]

The Ln(III) - ligand interactions show little “directionality” so that primary coordination numbers and geometries are determined almost entirely by ligand characteristics (conformational properties, number, size and charged nature of door groups). Lanthanide complexes exhibit coordination numbers ranging from six to twelve with nine and eight being very common and coordination number six being rare. Coordination number eight and nine is characteristic of larger lanthanide ions, having square – antiprismatic (D$_{4d}$) and triangular dodecahedron (D$_{2d}$) geometry in case of former and symmetrical tricapped trigonal prismatic (D$_{3h}$) geometry in case of latter.

**Lanthanide Complexes and their Applications**

a) **In Medicinal field** [8]

Lanthanide complexes are used as in vivo diagnostic agents and therapeutic tools. Complexes of lanthanide radionuclide such as $^{158}$Sm and $^{166}$Ho are used for the treatment of primary bone cancer lesions. Lanthanides can induce perforation in cell membranes even in concentrations as low as $10^{-5}$ M, in contrast to Ca$^{2+}$ which works only at high concentrations, causing harm to host cells. This property promotes the transformation of plasmid in bacteria, which is a desirable way to enhance across membrane secretion and better uptake of drug molecules. The intracellular accumulation of cisplatin and the transformation of plasmid pBR 322 and the PUC 18 in E-Coli has been reported, further lending credence in permeability by Ln(III).

The antioxidant effect of Ln(III) on Reactive Oxygen Species (ROS), which are the mediators of degenerative diseases, has been reported. Small doses of SmCl$_3$ and PrCl$_3$ (0.05 mg kg$^{-1}$ body weight, ip) inhibits lipid peroxidation in rat lung. High doses of Ln(III) are known to induce apoptosis in tumour cells and inhibit their growth. Apoptosis of rat skin fibroblasts and incubated macrophagocytes of rat teeth
was induced by Ce\(^{3+}\) and Gd\(^{3+}\) respectively. Lanthanides enhance pulmonary absorption of insulin and are also used in analysis of drugs. Hence the integrated effects comprising ROS scavenging effects, cell protection, cytoskeleton stabilizations and immunological enhancement together act as multiple target systems in anticancer therapy.

**b) As catalysts: Organolanthanide Chemistry [9]**

The chiral heterobimetallic lanthanide complexes have proved to be a fascinating aspect of organolanthanide chemistry. First developed by Shibasaki *et al*, it has shown countless applications in asymmetric catalysis. These catalysts used in the stereoselective synthesis of a broad variety of functional ligands are not limited to a single reaction but catalyze a broad spectra of organic reactions, viz., nitroaldol reaction, Michael addition, Aldol reaction and so on.

Polymerization reactions involving rare-earth metals are well known. Polymerisation of methyl methacrylate (MMA), alkyl acrylates, thermoplastics, elastomers, lactones, etc are all initiated by rare-earths. La[CH(SiMe\(_3\))\(_2\)](C\(_2\)Me\(_5\)) initiator was used to polymerize acrylonitrile and alkylisocyanates, and Ln(acac)\(_3\)/AIR/H\(_2\)O for oxiranes respectively. Nafion-based rare earth catalysts, polyacrylonitrile-based rare-earth catalysts and microencapsulated Lewis acids are a few rare earth catalysts, which have been used successfully in many reactions.

Equally important are the rare earth reagents, whose applications cover a wide spectrum of areas ranging from Inorganics to organometallics; diidosamarium, Ln(NTf\(_2\))\(_3\) (H\(_2\)O); NTf = bis(trifluoromethyl) sulfonyl amide and Ln[BNP]\(_3\); BNP = (R) 1,1'-binaphthyl-2,2'-diyl phosphato, are some of the rare earth metal reagents used in organic synthesis.

**c) As NMR Shift reagents [10, 11]**

NMR is one of the most powerful analytical techniques used for elucidating structures of organic compounds. Depending upon the chemical shifts of signals, their coupling constants and intensities of signals, the stereochemistry of the molecule is arrived at. However in certain organic molecules, the signals remained unresolved with chemical shifts of hydrogen atoms being insensitive to changes in chemical and stereochemical environment. To overcome these, the shift-inducing agents were developed in order to resolve the signals.
Eu(thd)₃, a dipyridine adduct was the first reported lanthanide shift agent by Hinckley in 1969, which successfully induced shifts in NMR of Cholesterol. Ever since many more shift agents have been reported. Lanthanide complexes of two enolic β- diketones dipivaloyl methane (DPM), heptafluorodimethyl octanedione (FOD) and decafluoroheptanedione (FHD) are being used as shift reagents. The use of europium and other lanthanide complexes as chemical shift reagents has enabled the NMR studies of even very complex molecules.

d) As Contrast Agents [12]

The rapid development of magnetic resonance imaging (MRI) has been of great importance to medical diagnosis. MRI is a medical diagnostic technique, which allows a detailed non - invasive image of the body to be generated. Consequently the development of MRI contrast agents has also increased rapidly due to their capacity to enhance contrast of images thereby allowing an easier recognition of abnormal tissue.

The gadolinium complexes of DTPA (Diethylene triamine penta acetic acid) and DOTA (1, 4, 7, 10- tetrazacyclododecanetetra acetic acid) along with a few variants of these ligands are being widely used. Their ideal properties like low toxicity, high thermodynamic stability (pGd = 20.3), kinetic inertness and an inner – sphere water molecule which exchanges rapidly with the bulk water in the body makes them the ideal candidates for imaging agents.

Their application as a diagnostic tool has opened broad possibilities for the solutions of many biological and medical problems. The greatest promise lies in synthesizing more diverse agents, which can both remain in the body longer and be targeted towards specific tissues.

e) In Industries

Lanthanide(III) complexes are promising as efficient light conversion molecular devices having potential applications as luminescent labels in fluoroimmunoassays, light concentrators for photovoltaic devices, antennas in photosensitive bioinorganic compounds and high – technology optics. Alloys of lanthanides with iron, cobalt and nickel are used in the production of very powerful magnets. Industrial utilization of the lanthanides received its initial impetus from the automatic lighter flint industry. Cerium oxide is used in the manufacture of glasses for x-ray work. Lanthanum is used in optical glasses due to its high refractive property.
Neodymium and praseodymium oxides are used in the production of artificial gemstones. Addition of lanthanides to Fe\textsubscript{3}Al alloys makes it corrosion resistant. Lanthanide ions are used as dopants for Lasers. This is just a miniscule account of the various uses of lanthanides.

It is to be expected and desired therefore that the near future will bring more detailed, systematic and exact studies with the general framework of interests delineated here. This hopefully will lead to a better understanding of the characters and parameters and also to a better understanding of their nature.

During the last few years, lanthanides and their complexes have been studied in great detail. There are however many more areas that are availing its applications and much more remains to be done in this regard.
References


