Chirality in Transition Metal Chemistry: Molecules, Supramolecular Assemblies and Materials

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The cover picture represents a chiral two-bladed propeller cobalt complex $[(Co_2(CO)_4\mu,\eta^2,\eta^2\text{-}(—H_2CC\equiv CCH_2—)(\text{-}dppm)_2][BF_4]_2$ *(drawn by H. Amouri). This complex was prepared and resolved by the authors using a chiral auxiliary anion.* (Note: the carbonyl groups on the cobalt were removed for clarity.)

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Contents

Preface

This book deals with chirality in transition metal chemistry. Chirality is an ever-fascinating topic and is a field which occurs in various subjects of modern chemistry. Surprisingly, a check of the literature for textbooks on the topic yielded a series of titles that only partially covered the subject. To our knowledge *Stereochemistry of Coordination Compounds,* by Professor Alex von Zelewsky, is the only recent book which gives a specialized treatment of this subject and was published by John Wiley & Sons, Ltd, in 1996. In the last decade a great number of papers have been reported in the literature describing chirality in different fields of chemistry: organometallics, catalysis, coordination chemistry, supramolecular assemblies and nanomaterials. Therefore a new book devoted to this topic will no doubt provide a very interesting tool for students and researchers who are interested to this increasingly important field. We feel that a complementary book, *Chirality in Transition Metal Chemistry: Molecules, Supramolecular Assemblies and Materials,* which covers new discoveries in the field since 1996, and establishes the interesting connectivity between the various aspects of chirality in different fields of chemistry, will be a valuable work to advance research in this area. These different subjects are treated in Chapters 2 to 6 of this book. Chapter 1 represents the introduction and summary of the book. We have attempted to cite examples and key references which cover the full breadth of the field in all its diversity but, bearing in mind that the selection of references necessary for a textbook is always arbitrary to a certain degree, we apologize in advance to the many researchers whose work could not be included. No book is free from errors and this one will be no exception, so we would appreciate it if colleagues around the world would point out errors and mistakes and suggest any improvements. We hope this book will serve as a guide for students and researchers working in this area.

This work could not have been accomplished without the help, comments and advice of many people who agreed to read the chapters and contributed to improving the quality of the book and to whom we are very grateful. Thus we thank Professors Peter J. Stang (University of Utah) and Gérard Coquerel (University of Rouen) for reviewing Chapter 2. We also thank Professors Henri Brunner 'Emeritus' (University of Regensburg), John A. Gladysz (University AM-Texas) and Antonio Togni (University of Zurich-ETH) for Chapter 3. We are grateful to Professor Jacqueline K. Barton (California Institute of Technology) for Chapter 4. We also thank Professors Kenneth N. Raymond (UC-Berkeley) and Rolf W. Saalfrank (University of Erlangen) for reviewing Chapter 5. We are grateful to Professors Vincent L. Pecoraro (University of Michigan) and Gérard Coquerel (University of Rouen) for Chapter 6. We thank Debra and Simon Greenfield for translating Chapters 2 and 6, which were originally written in French by Dr Michel Gruselle, into English. Chapters 3, 4 and 5 were written in English by Dr Hani Amouri, while the introduction, (Chapter 1) was written by both authors.

We also thank the Wiley team at Chichester, West Sussex: Paul Deards, Richard Davies, Rebecca Ralf, and their colleagues for improving the quality and the presentation of the book and for the production, as well as Lyn Hicks for the copy-editing process, especially when the authors were writing in English, which is not our first language.

We are indebted to Professor Alex von Zelewsky who agreed to read the whole document and to write the Foreword to this book; these few words are not enough to express our gratitude and our immense respect to him. Finally, we would like to thank our life partners Jeannine and Anita for their support and patience throughout this period of writing.

H. Amouri
M. Gruselle
Paris, July 2008

Foreword

One hundred years before the present book was written by two colleagues in Paris, a giant of modern science Alfred Werner, who originated from Mulhouse (now in France), was heading a group of students from several countries at Zurich University. He was obsessed by the idea that coordination compounds should be able to exhibit optical activity, that is rotate the plane of polarized light in a way similar to purely organic compounds, as had been known for decades. Until 1893 stereochemistry was completely dominated by the ideas of Le Bel and van't Hoff already published in 1874. That meant limitation to a tetrahedral arrangement of neighbours around an atomic centre in a molecule. Werner's coordination theory of 1893, which generalized the arrangements of atoms in space, notably to octahedral but also to square planar geometries, opened up new possibilities for isomerism. The proof for the correctness of these ideas was consequently largely based on stereochemical arguments. In 1899 Werner realized that the ultimate confirmation for the hypothesis of octahedral coordination would be the experimental demonstration of optical activity in a compound which did not contain any 'asymmetric' carbon atoms. It was not until 1911 that L. King in Werner's laboratory showed that, indeed, this could be achieved with a certain cobalt complex, as described in Chapter 2. It is known that Werner lived his relatively short life according to the principle of 'hard work followed by great feasts' and the story tells that an exuberant party was celebrated in the laboratory when King reported the result to his boss.

In the twentieth century organic stereochemistry continued to develop at a rapid pace reaching a high degree of sophistication, especially in view of the synthesis of natural compounds, which often comprise a large number of stereogenic centres. Highly stereoselective reactions were designed and correct absolute configurations were often obtained starting from simple 'chiral pool' natural products. In the past almost 40 years enantioselective catalysis has been added to the arsenal of methods yielding many enantiopure compounds, especially those for pharmaceutical applications. The field of chiral drugs has become a multibillion euro business since the importance of the correct absolute configuration of compounds that interact with the chiral molecular environment in our body was realized some decades ago. It is not an exaggeration to say that 'chirality' has become one of the most central concepts in molecular sciences – a Google search yields 3.5 million hits for this entry.

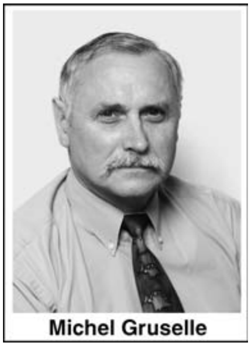
Despite these achievements in organic chemistry, stereochemistry of coordination compounds found much less attention. Textbooks of organic stereochemistry still do not generally cover coordination numbers higher than four, as realized in most carbon compounds. The stereochemistry of coordination compounds is basically a much more complex subject, due to the high number of possible arrangements of atoms in molecules containing one or several centres of higher coordination numbers. However, from a general point of view, all stereochemistry is based on the same principle: the geometrical properties of three-dimensional space. Today stereochemistry should no longer be strictly divided into the traditional branches of chemistry. In many cases stereochemical problems require considerations that combine principles from purely organic chemistry with those from coordination chemistry. This is especially true in enantioselective catalysis, where the active centre is often a metal, but also in organometallic chemistry.

It is the merit of the present book to treat chirality in a unified manner and to contribute in this way to bridging the gap between organic and coordination chemistry. One hundred years after Alfred Werner's fundamental work, *Chirality in Transition Metal Chemistry: Molecules, Supramolecular Assemblies and Material* is the definitive text about this important subject and it will serve as an introduction for students and as a reference for researchers for a long time to come.

Alex von Zelewsky


Hani, Haniel Amouri

Hani, Haniel Amouri, was born in Anapolis Goias (Brazil) and obtained his Ph.D. degree (1987) in chemistry from Université Louis Pasteur Strasbourg (France), with Professor John A. Osborn, on the subject of homogeneous catalysis (hydrogenation). In 1988 he spent one year at Gif-sur-Yvette (France) as a post-doctoral fellow with Dr Hugh Felkin where he studied C-H activation of saturated hydrocarbon with transition metal polyhydrides. In 1992–1993 he spent one year at UC-Berkeley (USA) with Professor K. Peter C. Vollhardt and was working on the synthesis of oligocyclopentadienyl metal complexes and their behaviour as electron transfer reagents. He is a Research Director in CNRS and is currently the director of the 'ARC' group (*Auto-assemblage, Reconnaissance et Chiralité*) of the IPCM at Université Pierre et Marie Curie Paris-6. His main research interests are chirality, organometallic and coordination chemistry, and he has had over 90 research papers and reviews published in international scientific journals.


Michel Gruselle

Michel Gruselle was born in Decazeville (France) and obtained his Ph.D. degree (doctorat d'Etat) in the CNRS laboratory of Thiais, a suburb of Paris, in 1975 with Dr Daniel Lefort where he worked on stereochemical problems in radical chemistry. In 1974 he joined Bianca Tchoubar's group and started working on nitrogen activation by organometallic complexes, and he spent some time collaborating with Prof. A. E. Shilov in Moscow. He is a Research Director in CNRS at Université Pierre et Marie Curie Paris-6 and was the director of the ARC group (*Auto-assemblage, Reconnaissance et Chiralité*) at the IPCM from 1996–2000. His main research interests are enantioselective synthesis in coordination chemistry and in material science and he has had over 110 research papers and reviews published in international scientific journals.

1 Introduction

Pasteur in his laboratory in Arbois (1864) by Callot, reproduced with the permission of the 'Société des Amis de Pasteur' (Dole France), from J. Jacques, La Molécule et son double, Hachette, Paris, 1992

'C'est se tromper entièrement que de croire qu'on fait de la dissymétrie quand on produit des racémiques'

'One is completely mistaken in believing that dissymmetry is created when racemates are produced'

Louis Pasteur[1]

This statement of Pasteur is free of any ambiguity, it is fundamental. Its interpretation simply implies that in order to create dissymmetry it is therefore necessary to separate physically the object in question from its mirror image; an object and image which, in the case of a chiral molecule, are by definition nonsuperimposable enantiomers and whose mutual association forms a racemate. Thus the goal of the chemist is not simply to record the geometric property of a molecular structure, but physically to obtain the possible enantiomers that result from this geometry. This clarification is necessary due to the

Chirality in Transition Metal Chemistry: Molecules, Supramolecular Assemblies and Materials H. Amouri and M. Gruselle

frequent confusion caused by the incorrect use of the concept of chirality, in particular the tendency to use it in place of the physical reality of the molecule. It is in this way that the absolute configuration, which unambiguously describes the geometry of a chiral molecule, is confused with chirality itself. The definition of the latter, which we will clarify in Chapter 2, concerns only the molecular symmetry and says nothing about the physical nature of the molecule under consideration. Is it a racemic derivative or an enantiomer? This question is essential, since the properties of a racemic or enantiomeric chiral molecule differ when placed in an asymmetric environment, whether this environment is produced by another chiral molecule or by polarized electromagnetic radiation.

One of the distinguishing features between a racemic compound and its enantiomers lies in their respective crystal organization, which are different for a racemate and an enantiomer, and which lead to specific properties for each.

The creation of dissymmetry at a molecular level, that is the preparation of enantiopure compounds, inevitably requires either the resolution of racemic compounds or asymmetric synthesis, so we shall pay particular attention to the problems associated with these two methods. The formation of enantiopure crystals by spontaneous resolution during crystallization, whether the crystals are separable or not, is of undeniable theoretical and practical importance to the technique of resolution by entrainment. In general, however, we will not consider this in itself as a technique for resolution.[2]

The importance of the topic of chirality is reflected by the large number of books, reviews and articles devoted to it. However, most of these books treat the stereochemistry in organic compounds.[3–8] Surprisingly the only recent book devoted to this topic in coordination compounds was published in 1996 by A. von Zelewsky[9] and therefore a new book is needed to update the recent evolution of this field. Our book is a continuation of von Zelewsky's book and is devoted to chirality in organometallic and coordination complexes as well as an introduction to chirality in molecular material science. In addition to the theoretical problems[10] raised by molecular asymmetry, in particular those relating to the origins of chirality in nature, the production of enantiopure molecules is an important issue in the fields of pharmaceutics and agriculture. Thus, the US Food and Drug Administration (FDA's policy statement for the development of new diastereomeric drugs, www.fda.gov./cder/guidance/stereo.htm) recommends that in the case of chiral molecules, the properties – particularly toxicity – of both enantiomers should be studied, which implies the total resolution of the racemates.

However, from the point of view of chirality, what is the specific role of organometallic and coordination chemistry? Is it merely a question of showing that the same general rules apply, or are there indeed concrete applications significant enough to stimulate research in this field?

In organic and organometallic chemistry, asymmetric catalysts play an important role in enantioselective synthesis, and the majority of these are mononuclear organometallic compounds. It was for their work on asymmetric catalysis that W. S. Knowles, R. Noyori and K. B. Sharpless won the Nobel Prize for Chemistry in 2001,[11–13] and hence the study of chirality for this class of compounds is of the utmost importance. For this reason, following on from Chapter 2, which lays the necessary groundwork in organometallic and coordination chemistry, in Chapter 3 we will develop the study of the chemistry of chiral mononuclear organometallic complexes and asymmetric catalysis in brief.

We will focus in particular on those complexes where the chiral element is the metallic centre itself and also on those bearing a chiral ligand. Many of these compounds are asymmetric catalysts, thus enabling the chemist to make use of them in order to produce a large amount of enantiopure active molecules. In these reactions we encounter the phenomenon of 'chiral recognition', which is just as essential for synthesis as for the separation of enantiomers, but what exactly does this concept mean? It can perhaps be defined as follows: there is chiral recognition when a chiral compound of defined stereochemistry interacts differently with the stereoisomers of another chiral compound. Here it is, in fact, a matter of there being a distinction between diastereomeric forms that are more or less strongly associated via hydrogen bonds, or from electrostatic or van der Waals interactions between chiral molecules, but also from steric and/or electronic repulsion. These interactions may also result from an association between a cationic complex and a chiral anion to form an ion pair. The latter has been highlighted as the 'chiral anion strategy' and has a profound effect in the area of enantioselective catalysis and also in chiral discrimination in coordination chemistry and is evolving rapidly. In particular the interaction between cationic transition metal complexes and the optically pure chiral anions such as Δ-Trisphat and (*R*-)- or (*S*)-BNP anions (Figure 1.1).[14,15] Finally a brief introduction on chiral recognition between such cationic octahedral complexes and biological molecules, particularly DNA[16] will be discussed in Chapter 4.

While mononuclear complexes and those of low nuclearity represent an important part of organometallic and coordination chemistry, those of higher nuclearity obtained through self-assembly currently form an extremely active area, defined as metallosupramolecular chemistry. We will explore the self-assembly of building blocks of metal ions and bridging ligands, leading to various types of chiral supramolecular structures – an important field in which J. M. Lehn won the Nobel Prize for Chemistry in 1987.[17,18] We will attempt to unravel the forces that guide and control the chiral information in these self-assemblies leading to enantiopure structures. The transfer of the chiral information that is contained in the constituent bricks of the resulting supramolecular structure is, in general, under thermodynamic control. As Lehn has already remarked, this leads to great regio- and stereoselectivity for these reactions. We will see that the same is also true for the formation of enantiopure supramolecular compounds. While many of the parameters relating to the transfer of chiral information remain poorly defined, thus occasionally leading to unexpected results, rational synthesis is nevertheless progressively replacing

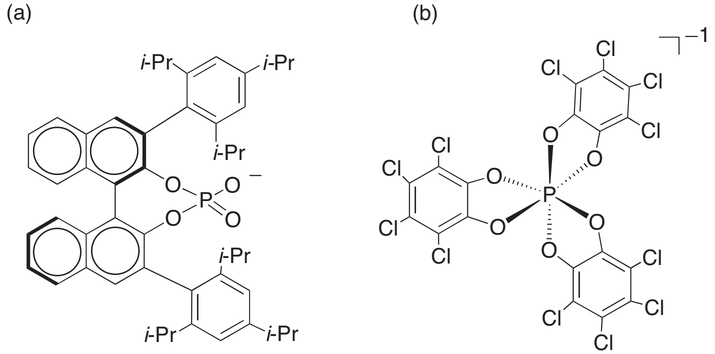


Figure 1.1
Gold asymmetric catalysis (Chapter 3) (a) (*R*)-BNP. Chiral recognition (Chapter 4) (a) (*R*)-BNP and (b) Δ-Trisphat.

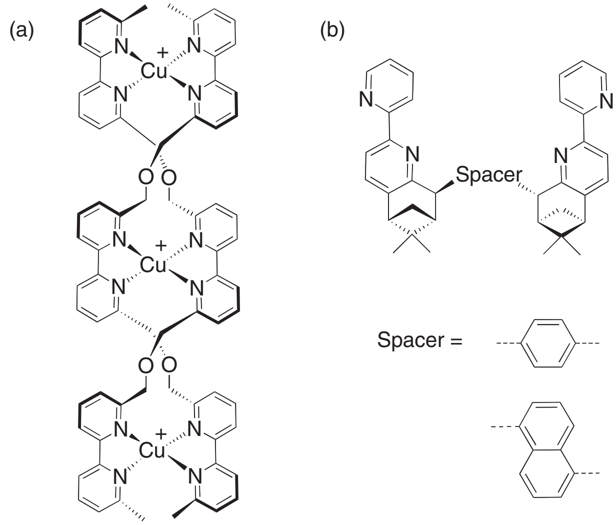


Figure 1.2
Chirality in supramolecular coordination chemistry (Chapter 5). (a) Double-stranded helicates;[19] (b) chiragen ligands.[20]

the role of chance in these matters. This theme will be addressed and developed in Chapter 5 (Figure 1.2).

The process of self-assembly not only occurring in solution but also on metallic surfaces leads to supramolecular structures with specific properties which lie at the root of what we term ‘molecular materials’ or nanometer scale materials. Those that will be described here are enantiopure, and we will explore their principal features. This chemistry is in its infancy, and while concrete results in terms of properties are still modest, the rapid growth in these chiral materials is such that their applications are becoming promising. An appraisal of the chemistry of chiral molecular materials is the subject of Chapter 6 (Figure 1.3).

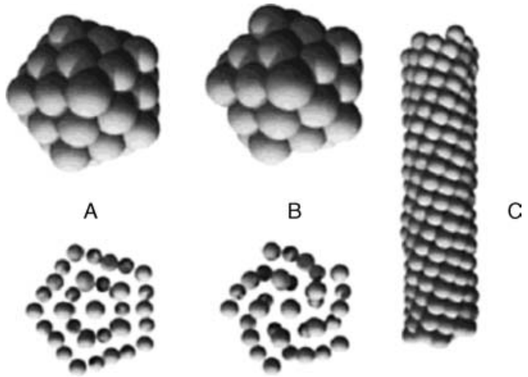


Figure 1.3
Achiral and chiral structural motifs for nanoscale metal structures: A represents an achiral 39-atom structure; B represents the chiral 39-atom structure of D5 symmetry; C illustrates a compact helical nanowire (Chapter 6) (reproduced with permission from reference[21], copyright American Chemical Society).

One of the important aspects of this chemistry is the ability of the materials to be multifunctional. From this, multifunctionality properties can emerge that are more than the simple addition of the individual effects.

To close this brief introduction, we hope this book will be useful to readers not currently working in chirality, as well as informative to those who are more familiar with this subject. We would also expect to stimulate further interest and experiments in order to push the horizon of the chirality field further since Pasteur's and Werner's first discoveries up to the present day and beyond.

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2 Chirality and Enantiomers

2.1 Chirality

2.1.1 Brief Historical Review

2.1.1.1 Alfred Werner and the First Resolved Cobalt (III) Coordination Complex

It is fitting to begin this brief historical overview of chirality in organometallic and coordination chemistry with the name of Alfred Werner (1866–1919) who, as far back as 1893, applied van't Hoff and Le Bel's stereochemical ideas of the tetrahedral nature of the carbon atom to the structure of hexacoordinated metal complexes.[1] He established their octahedral structure and predicted that some could exist in an enantiomeric form with the power of optical rotation. This prediction was followed in 1911 by the resolution of the two enantiomers of the complexes $[Co^{III}(en)_2(NH_3)X]X_2$ ($X = Cl, Br$) **(2.1)-X$_2$** (en = ethylene diamine) (Figure 2.1).[2,3] This overall work won him the Nobel Prize for Chemistry in 1913, following which he then went on to resolve the inorganic complex $\{Co^{III}(OH)_6[Co^{III}(NH_3)_4]_3\}Br_6$ **(2.2)-Br$_6$** (Figure 2.2).[4]

In 1897 Werner began the search for a definitive proof of his hypothesis of the octahedral structure of chiral cationic Co^{III} complexes, and to do so he required an efficient anionic resolving agent. Whether or not he himself was familiar with the work of Pope[5–7] on the resolving power of the (+)-3-bromo-camphor-9-sulphonate anion (**2.3**) (Figure 2.3), it was his student L. King who chose to use this anionic agent to resolve the complexes $[Co^{III}(en)_2(NH_3)X]X_2$ ($X = Cl, Br$) **(2.1)-X$_2$**.[8]

To give an idea of the difficulty of his task, King recalls that, prior to achieving this resolution by crystallization of one of the diastereomeric salts resulting from the combination of (**2.1**) with the (+)-3-bromo-camphor-9-sulfonate, he had attempted no fewer than 2000 unsuccessfully experiments.[9] His eventual choice of the anion **(2.3)** was due to its large power of optical rotation, which he believed made it the most capable of increasing the dissymmetry of the resulting diastereomers. Werner also observed that the solubility of the oxalato(bis)ethylenediamine cobalt bromides **(2.4)-Br** (Figure 2.4) differed between the racemic and optically active forms.[10] He therefore successfully attempted their resolution by starting with a supersaturated aqueous solution, slightly enriched in one of the enantiomers, and initiating crystallization by the addition of methanol (Scheme 2.1).

Addition of methanol results in the crystallization of the (+)-**(2.4)-Br** salt.

Chirality in Transition Metal Chemistry: Molecules, Supramolecular Assemblies and Materials H. Amouri and M. Gruselle

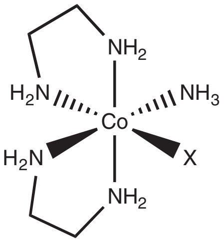
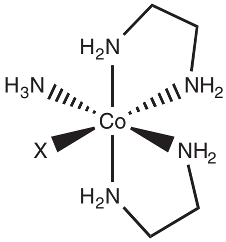



Figure 2.1
View of the cationic part of the two enantiomers of **(2.1)-X$_2$**.

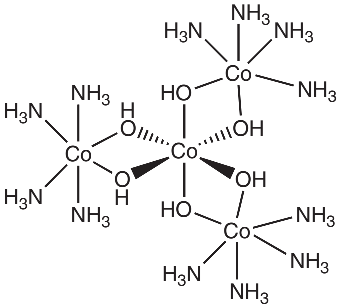
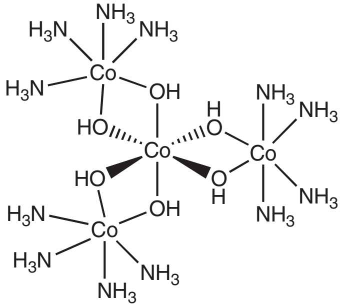



Figure 2.2
View of the cationic part of the two enantiomers of **(2.2)-Br$_6$**.

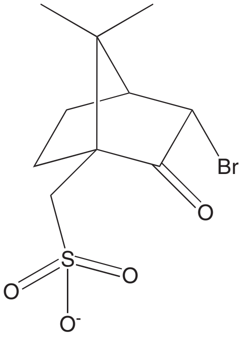


Figure 2.3
View of the (+)-**(2.3)** anion.

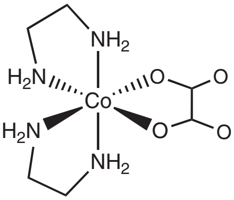
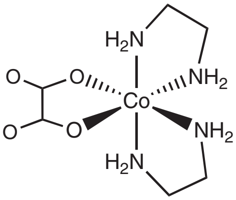
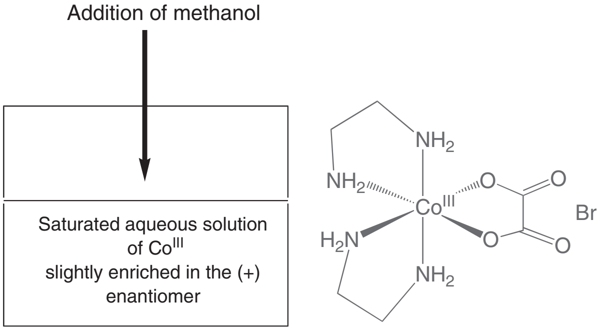



Figure 2.4
View of the cationic part of the two enantiomers of **(2.4)-Br**.



Scheme 2.1
Enantioselective crystallization of the (+)-**(2.4)-Br** salt starting from a slightly enriched (+)-**(2.4)-Br** solution by addition of methanol.

This experiment was in fact a rediscovery, several years later, of the work of Gernez (a student of Pasteur) on the crystallization of one of the enantiomeric tartrates from a supersaturated solution by seeding with a pure enantiomeric crystal.[11] This method is known as resolution by entrainment.

We will return later to the first resolution of octahedral complexes as it embodies numerous concepts, which we will need to explain the general principles of chirality in the field of coordination chemistry. Meanwhile, we will quickly retrace the long route, which led to the concept of molecular asymmetry and chirality.

These concepts, which seem so familiar today, only became clear with the atomic theory of Le Bel and van't Hoff[12,13] which provided a solid theoretical basis for the understanding of the three-dimensional structure of molecular objects.

2.1.1.2 Polarized Light and Rotation of the Polarization Plane

At the origin of the concept of dissymmetry lies the work of the physicists who studied the interaction of polarized light with crystalline minerals. The work of Bartholin (1625–1698), who discovered the phenomenon of double refraction in Iceland spar ($CaCO_3$), forms the basis of the wave theory of light that was developed by Huygens (1629–1698). The discovery of polarized light by Malus (1775–1812) rapidly led to intense research by physicists in this area. In 1811, Arago (1786–1853) introduced the concept of optical rotation by showing that pieces of quartz placed in the path of polarized light could turn the plane of polarization in one sense or the other depending on the crystal. Biot (1774–1862), in 1812, went further, as he was able to prove that the rotation of polarized light is not exclusive to certain crystals. It is also shown, for example, by solutions of natural camphor and oil of turpentine, as well as tartaric acid. In 1817, he proved that the vapour from oil of turpentine was able to rotate the plane of polarized light. This was a decisive step since, whether in solution or the gas phase, the observed phenomenon could not be due to the molecular arrangement in the crystal, but rather to an intrinsic molecular property.

2.1.1.3 Hemihedrism and Enantiomorphism

At this time, whereas the physicists had developed a theory of light to account for its interactions with highly organized crystalline matter, the chemists did not yet have a theory of molecular structure, but were themselves also interested in crystals. It was to be the studies of the latter group that would play a decisive role in the understanding of the phenomenon of structural asymmetry, whether this originated from the actual organization of the crystal or from the molecular structure itself.

In this context it was the discovery of hemihedrism that proved to be critical. The most important works in this area are those of Haüy (1743–1822) and Mitscherlich (1794–1863), and from their studies emerged the idea that the morphology of a crystal reflects the underlying form of its constituents. Haüy hypothesized that the exterior form was just a consequence of a periodic arrangement of matter in the solid. This idea was of great importance, even if it appeared to contradict Mitscherlich's discovery of isomorphism, that is the possibility of different substances having identical crystalline forms.

At this point we should recall that there are seven crystal systems. All crystals of the same crystal system have lattices with the same orientation symmetry. In each of the seven crystal systems, the group which defines it is the one with the highest order, and is termed holohedral. Within the same system, all the groups which are not holohedral are termed merihedral and, in particular, hemihedral for the case where the group order is half that of the holohedral. Those which possess a centre of symmetry are called centrosymmetric hemihedral, whilst those which lack an inversion centre are enantiomorphic hemihedral.

To summarize, there is a hemihedral form which, while having a reduced level of symmetry, nevertheless conserves the planes of symmetry in the crystal. There is also a 'nonsuperimposable' hemihedral form for which truncation of the crystal faces or edges gives rise to objects that are nonsuperimposable with their mirror image. Thus, certain crystals with the same chemical composition are mirror images of each other and are nonsuperimposable. Herschel (1792–1871) showed that Haüy's right-handed and left-handed quartz *plagièdre* were able to rotate the plane of polarized light in opposite senses.

2.1.1.4 Pasteur and Tartaric Acid

It was the observation of the hemihedral crystals of sodium ammonium tartrate tetrahydrate that enabled Pasteur (1822–1895) to make a decisive step forward in stereochemistry. The problem he encountered was the contamination of the potassium salt of tartaric acid with that of another acid (which Gay-Lussac (1778–1850) called the racemic acid) that made it unsuitable for commercial use. The two acids had the same chemical composition, and Biot showed that whereas tartaric acid and its salts could rotate the plane of polarized light, the racemic acid itself was inactive. In 1848, Pasteur found the solution to this problem.[14] He noticed that crystals of tartaric acid, like its salts, have hemihedral faces, but that the racemic sodium ammonium tartrate exists as two distinct crystals in which the hemihedral faces are mirror images of each other. One of these crystalline forms is identical to the optically active tartrate. In solution, it rotates the plane of polarized light in a dextrorotatory manner, while the other form (a mirror image of the first) is levorotatory, that is in solution it rotates the plane of polarization towards the left (Figure 2.5).

The sense of rotation is termed right if an observer placed behind the object through which the light passes sees the plane of polarization turn in a clockwise sense; rotation in the inverse sense is termed left.

Pasteur noted that the crystal forms were enantiomorphic, and he supposed that the molecules that comprised them would be also and called them dissymmetric. It was

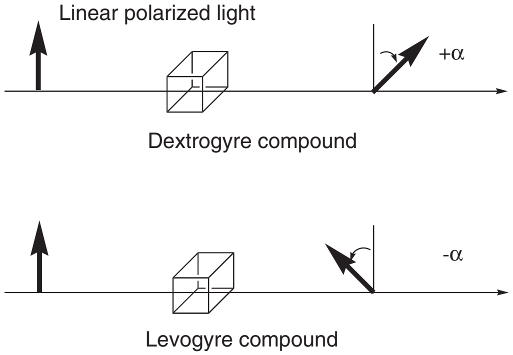


Figure 2.5
Right and left rotation of polarized light through a dextrogyre or levogyre compound.

widely agreed that Pasteur was lucky to observe what, in reality, was a spontaneous resolution of the enantiomorphic crystalline forms of racemic sodium ammonium tartrate **(2.5)-NaNH$_4$.4H$_2$O** (Figure 2.6).

However, this fundamental discovery had nothing to do with chance, but rather with Pasteur's insight and knowledge of both chemistry and crystallography.[15] Following Pasteur, the work of his student Gernez revealed the properties of conglomerates and

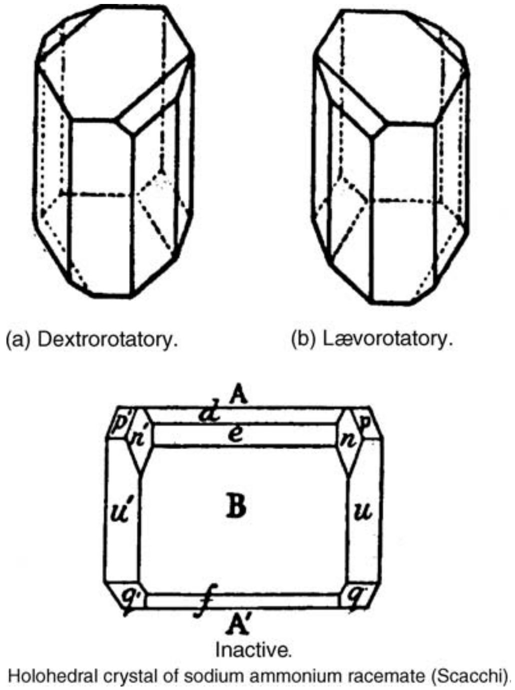


Figure 2.6
Enantiomorphous crystals of (+)-**(2.5)NaNH$_4$.4H$_2$O** and (−)-**(2.5)NaNH$_4$.4H$_2$O**. Crystal of the (*rac*)-**(2.5)NaNH$_4$.4H$_2$O** (reproduced with permission from reference[15]).