

# Chiral Complexes of Platinum Metals

## A NEW CLASS OF COMPOUNDS WITH LIGANDS DERIVED FROM NATURALLY OCCURRING TERPENES HAVING PROMISING PROPERTIES

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*Molecular isomerism has been known about for well over 100 years and forms a very important part of organic chemistry. It was one of the phenomena from which the Alsatian chemist, Alfred Werner, working, often with platinum group metals, at the University of Zürich, Switzerland (Nobel Prize for Chemistry 1918) derived his 'theory of co-ordination' in 1893 (1). However, more recently there has been a vast increase in the amount of work done on isomerism of co-ordination compounds, especially concerning chiral structures (2). The present paper describes some new developments on platinum metals complexes with chiral ligands derived from terpenes, where for the first time the chirality at metal centres can be controlled in a large number of compounds.*

Any discussion on such specialised topics as isomerism and chirality needs to be prefaced by a description of some of the terms used. Co-ordination compounds have a central atom surrounded by other atoms or molecular entities called ligands, which are bound or co-ordinated to it. Some compounds are isomeric, which means that they exist as two or more structures with the same molecular composition but with a different spatial composition or constitution.

### Background of Isomerism

Isomerism can occur in several ways: the simplest being constitutional isomerism, where the same atoms are connected in different ways. If, on the other hand two molecules contain identical atoms connected together in the same way, but with different spatial arrangement, one speaks of stereoisomers. Molecular stereoisomers can be divided unambiguously into two different classes: diastereoisomers and enantiomers.

Diastereoisomers are molecules that show the same connectivity, but differ in the spatial arrangement of the atoms. Internal co-ordinates (bond lengths and bond angles) will be in general different in different diastereoisomers, rendering them different chemical species in every

respect. A well-known example of diastereoisomers in platinum chemistry is *cis*- and *trans*-dichlorodiamino platinum(II), respectively. The former is the known anti-cancer agent cisplatin, whereas the latter has no therapeutic use (3).

The second class of stereoisomers are the so-called enantiomers (from the Greek word for opposite). The two molecular species of a pair of enantiomers differ from one another only in that they are non-superposable mirror images. From general symmetry considerations, it can be deduced that molecules which have neither planes of symmetry nor an inversion centre show enantiomerism (higher order so-called improper rotation axes must also be absent).

### The Concept of Chirality

Molecules that fulfil the conditions to show enantiomerism are said to be chiral (from the Greek word of handedness, a concept introduced by Lord Kelvin in 1893). Molecules, where the mirror image is identical to the molecule itself are designated as achiral. The two enantiomers of a pair behave in a chemically identical way, unless the interacting partner is also chiral. For example, enantiomers rotate the plane of incident, linearly-polarised, light of a certain wavelength by the same angle, but in

opposite directions, since such polarised light can be considered as a pair of enantiomers: one right- and one left-handed circularly polarised component.

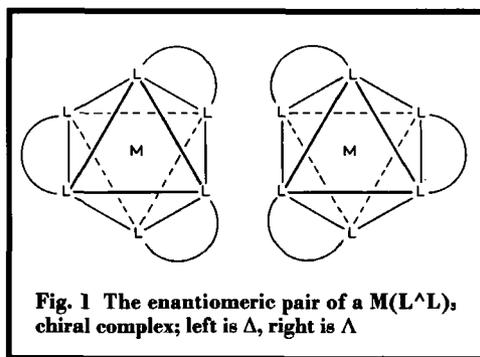
In general, enantiomers also behave very differently in real chemical reactions, if the reaction takes place between two chiral molecules. A substance composed of chiral molecules can occur either as an enantiomerically pure compound (EPC), or as a racemate, which is a 1:1 mixture of both enantiomers, or indeed as anything between these two limits. The enantiomeric purity is nowadays generally given as the so-called enantiomeric excess (ee), which is 1.0 (or 100 per cent) for an EPC and 0 (0 per cent) for a racemate.

Many molecules in living systems, such as amino acids or sugars, but also terpenes, are chiral and they occur as EPCs. Sometimes these naturally occurring enantiomerically pure compounds are referred to as the "chiral pool". It is unthinkable that biological systems could have developed without enantiomerically pure compounds, but it is still not completely explainable how nature achieved the single enantiomeric occurrence of most chiral compounds during early stages of evolution.

### Racemates

Syntheses of chiral molecules starting from achiral precursors almost always yield racemates. A racemate can either crystallise as a macroscopic conglomerate of two kinds of crystals that themselves are mirror images of each other, or as uniform crystals where in each unit cell an equal number of each enantiomer is present. The latter case occurs more frequently and these solid phases are called racemic compounds or racemic modifications. The former case (occurrence of a conglomerate) gave rise, almost 150 years ago, to the discovery of molecular optical activity by Louis Pasteur (4).

Chiral descriptors are needed in order to distinguish between the two enantiomers of a pair. In principle one pair of symbols would suffice. For practical reasons, however, several conventions have been established. For organic compounds, the R/S convention (so named by Cahn,



Ingold and Prelog) is mostly used (from the Latin *rectus* and *sinister*, respectively), whereas in co-ordination chemistry the  $\Delta/\Lambda$  designation is often applied to right- or left-handed helical chiral molecules.

Using symmetry considerations, Alfred Werner had already predicted, in a paper published in 1899, that some types of octahedral co-ordination compounds should be chiral and hence, in principle, separable into enantiomeric compounds (5). In 1911, the first report of such a successful separation was published (6).

### Platinum Group Metal Co-ordination Sphere

The co-ordination sphere around many of the platinum group metal centres is octahedral, see Figure 1. In particular, the octahedral co-ordination spheres of ruthenium(II), osmium(II), rhodium(III), iridium(III) and platinum(IV), yield a large number of chiral complexes of the classical Werner type, that is  $M(L^{\wedge}L)_3$  or  $M(L^{\wedge}L)_2X_2$ , where  $L^{\wedge}L$  are bidentate ligands and X is a monodentate ligand, such as Cl<sup>-</sup>, etc. (2). The number of such complexes is almost limitless, since there are a very large number of bidentate ligands.

Interesting examples of such Werner-type complexes are the purely "inorganic" ions  $[PtS_{15}]^{2-}$  and  $[PtS_{17}]^{2-}$ , respectively (7). In these species, which should be written as  $[(Pt(S_5)_3]^{2-}$  and  $[Pt(S_6)_2S_5]^{2-}$ , the chelate rings around the central platinum atoms are formed by sulphur atoms (a chelate ligand is attached to the central atom through two or more co-ordinating atoms). For

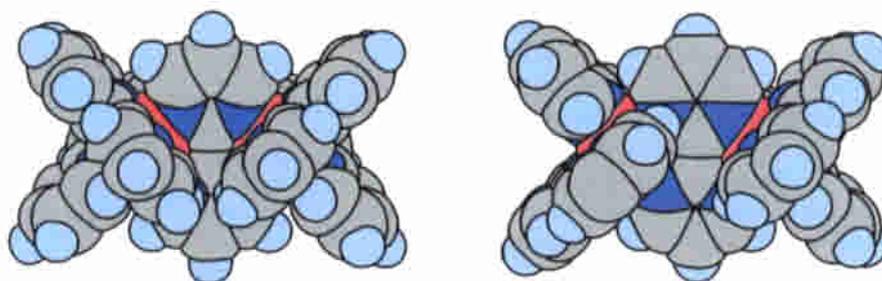


Fig. 2 Computer model representation of the two isomers of a dinuclear complex,  $[(Ru(bpy)_2)_2bpy]^{4+}$  with identical (homochiral), and with opposite chiralities (heterochiral), respectively, at the two ruthenium centres. To the left is  $\Delta,\Delta$ , to the right is  $\Lambda,\Delta$ . Here, ruthenium is coloured red, hydrogen pale blue, carbon grey and nitrogen dark blue

these species and for most other cases of chiral octahedral complexes, the chirality is a result of the helical arrangement of the chelate ligands. The symmetry group of these molecules ( $D_2$ ) does not contain any mirror plane or inversion centre, but only three-fold and two-fold rotation axes, see Figure 1.

### Predetermined Helical Chirality

As already mentioned, the synthesis from achiral starting materials yields racemates, except for some very special cases (2). The two enantiomers are consequently formed in equal amounts, and applications for which EPCs are needed therefore require a separation procedure. Enantiomerically pure co-ordination compounds are relevant for several important applications:

- (i) The stereoselective step in enantioselective catalysis (a multi-billion pound sterling business) often takes place at the metal site.
- (ii) Multicentred supramolecular species of photochemically active co-ordination units often give rise to a large number of stereoisomers (which makes their detailed characterisation very difficult), unless enantiomerically pure building blocks are used.
- (iii) Enantiopure chiral metal complexes are potentially interesting species for solid state applications in non-linear optics (NLO), since such compounds must crystallise in non-centrosymmetric space groups.

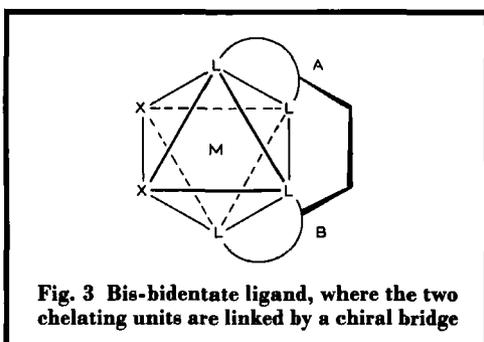
(iv) EPCs are needed in therapeutic applications of chiral co-ordination compounds, since enantiomeric purity is nowadays required for pharmaceutical molecules.

Thus, for all four types of applications, the platinum group metals constitute co-ordination centres of prime interest.

### Controlling the Chirality

The control of chirality at the metal centre can be achieved by various means. First, racemates can be separated into pure enantiomers which can then be used as chiral building blocks. This method has been applied for the synthesis of dinuclear ruthenium complexes with tris-diimine co-ordination spheres (8). Such complexes are the prototypes of species that can be functionalised to yield photochemical molecular devices (9). In Figure 2 two isomers of the ruthenium complex  $[(Ru(bpy)_2)_2bpy]^{4+}$ , where  $bpy$  is 2,2'-bipyridine and  $bpy$  is 2,2'-bipyrimidine, are shown. The isomers have different stereochemistry; one is a homochiral complex (having the same chirality  $\Delta,\Delta$  at both metal centres), and the other is a heterochiral complex (different chiralities  $\Delta,\Lambda$  at the metal centres), built from units which were obtained by classical resolution of a racemate (that is, separation of the two enantiomers).

However, there are two drawbacks to using enantiomerically pure building blocks obtained by resolution of a racemate. One drawback is



the inevitable loss of at least 50 per cent of the material, if one is only interested in a building block of a given chirality. The other, even more severe drawback is the possibility of racemisation (back-transformation to the 50:50 mixture of the two isomers) under certain reaction conditions. The latter effect is especially important for ruthenium complexes, which are known to racemise under the influence of light.

A second method, where complete control of chirality at the metal centre can be achieved using ligands that are themselves chiral, is therefore to be preferred. A chiral ligand is shown in Figure 3.

Here, two bidentate chelates are linked by a bridge that is anchored at the chiral centres (carbon atoms with four different substituents which were formerly called asymmetric carbon atoms, nowadays designated stereogenic carbon centres) A and B, respectively. The ligand mole-

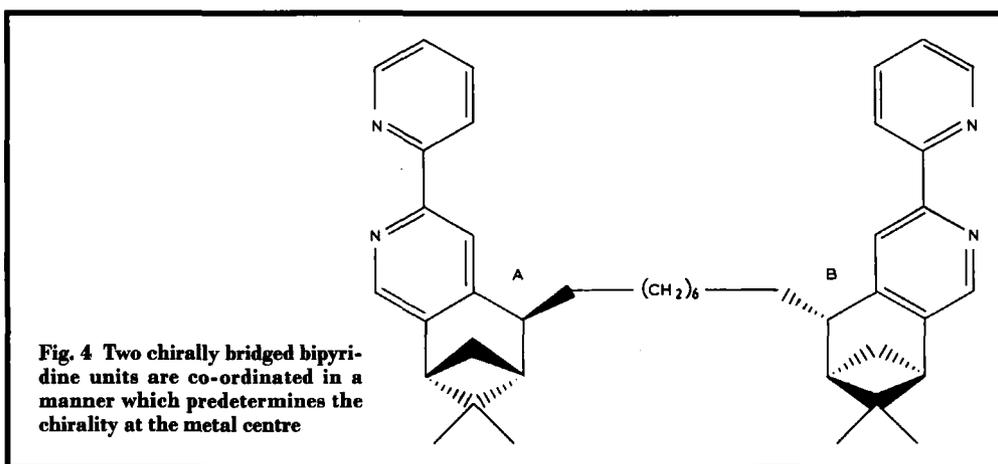
cule is now a tetradentate chelate, where two bpy units are permanently connected. The chirality at the metal centre can be predetermined completely by this method as we have shown, by designating a ligand, which fulfils these requirements.

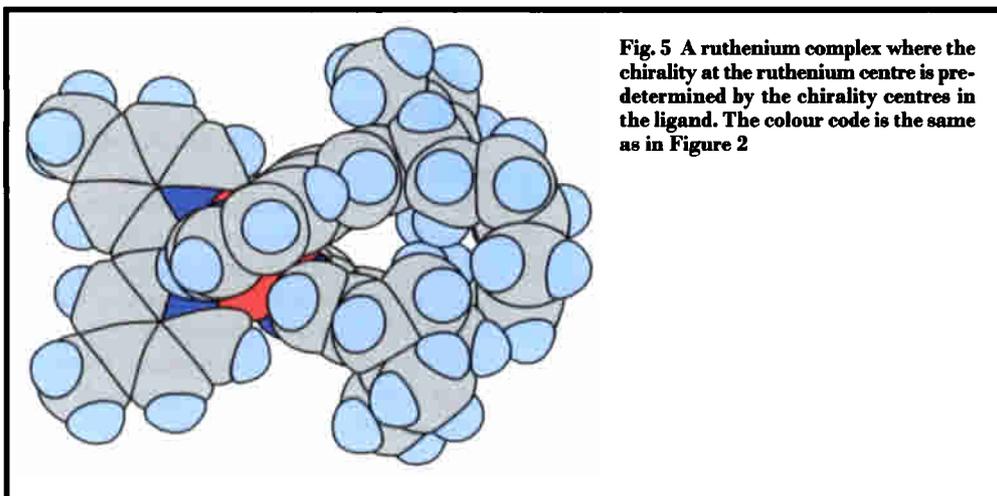
In Figure 3 the helical chirality is  $\Delta$ . An inversion of the chiral centres, A and B, leads to  $\Lambda$  chirality at the metal centre, whereas the ligand is not capable of co-ordinating to one metallic centre with both bpy moieties if only one of the chirality centres, A or B, is inverted. Since configurations at carbon centres are stable under most circumstances, inversion does not take place at all and the chirality at the metal centre is therefore completely fixed.

### Chiral Ligands

The first ligand of this type was CHIRAGEN[6], the ligand depicted in Figure 4; the number in square brackets, for instance [6] in this case, indicates the nature of the bridge, here six  $-\text{CH}_2-$  groups.

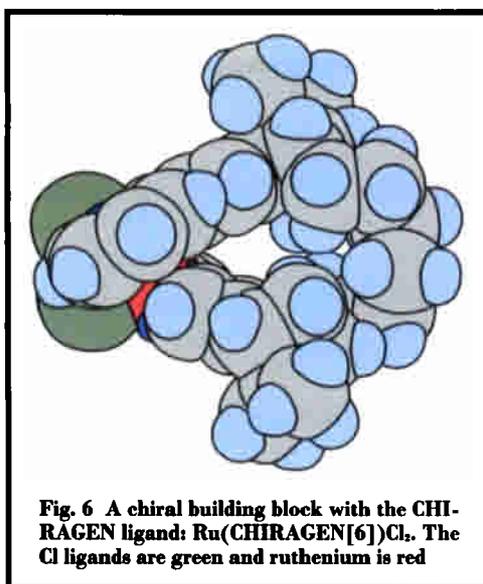
This type of ligand was called a CHIRAGEN ligand [6], since it generates chirality at the metal centre. The original source of the chirality in CHIRAGEN ligands is in the saturated part of the molecule, which is derived from naturally occurring pinene, a "chiral pool" molecule. The ruthenium(II) complex,  $[\text{Ru}(\text{CHIRAGEN}[6])\text{-(DMbpy)}]^{2+}$ , shown in Figure 5, where DMbpy is 4,4'-dimethylbipyridine, has been shown to





possess the expected  $\Delta$ -configuration, if the ligand is derived from (-)- $\alpha$ -pinene. The latter is a low priced naturally occurring terpene, which is commercially available in either configuration ((-)- $\alpha$ - or (+)- $\alpha$ -) in enantiomeric purity of about 80 per cent.

Since only ligands that are homochiral (having the same configuration at both centres A and B, respectively) can co-ordinate to one metallic centre, a considerable chiral amplification is obtained upon complexation, yielding



a species of about 96 per cent enantiomeric excess. If more expensive pinene derivatives (for example myrtenal) with high enantiomeric purity are used, the ee-value (enantiomeric excess) of the product is very close to 100 per cent.

The methods used for the synthesis of CHIRAGEN ligands are easy to vary (10), and consequently ligands for different purposes can be designed. For example, when osmium is the co-ordination centre, it prefers a longer bridge than ruthenium between the bpy units. Thus,  $\text{Os}(\text{CHIRAGEN}[7])$ , a ligand with a link of seven  $-\text{CH}_2-$  groups between the two bpy moieties, is more stable than one with only six  $-\text{CH}_2-$  groups.

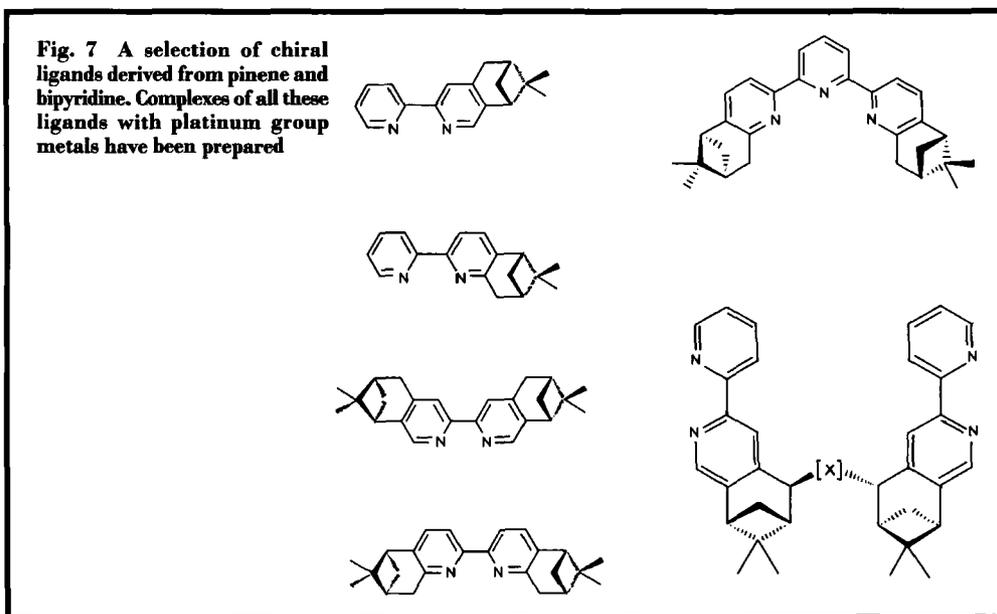
Also the remaining ligands at the metal centre can be varied. For example, in  $\text{Ru}(\text{CHIRAGEN}[6])\text{Cl}_2$  the fifth and sixth co-ordination sites are occupied by chloride ligands that can be easily substituted, see Figure 6.

In Figure 7 a survey is given of synthesised ligands derived from bipyridine and pinene as the chiral group. With all these ligands chiral octahedral complexes of the platinum metals, so far mainly of ruthenium(II), osmium(II) and rhodium(III), have been synthesised.

### Chiral "Planar" Complexes

As discussed above, octahedral complexes (OC-6 complexes according to IUPAC nomenclature) with two or three bidentate ligands

**Fig. 7** A selection of chiral ligands derived from pinene and bipyridine. Complexes of all these ligands with platinum group metals have been prepared



are intrinsically chiral. The  $d^8$  platinum group metals – rhodium(I), iridium(I), palladium(II) and platinum(II) – form complexes with square planar (SP-4) co-ordination geometry. A large number of such complexes has been investigated and they play an important role as catalysts, or at least as intermediates in many catalytic reactions. The SP-4 geometry is inherently achiral, but it can become chiral under special circumstances. This was observed for the first time in a ligand which has large substituents, as shown in Figure 8 (11). It is noteworthy that the strong *trans*-influence of the carbon-bonded ligand always directs these ligands into the *cis*-position.

Achiral ligands, such as those shown in Figure 8, again of course, yield racemates. The same type of synthesis that produced the pinene derivatives of bipyridine, shown in Figure 7, can be used to obtain cyclometallating ligands (with C<sup>N</sup> co-ordination). In this case predetermination of the chirality at the metal centre is achieved. For example, in the complex shown in Figure 9, where the ligand is chiral owing to the pinene substituents, chirality is predetermined at the metal centre (12). The chirality of the complex can again be described by the

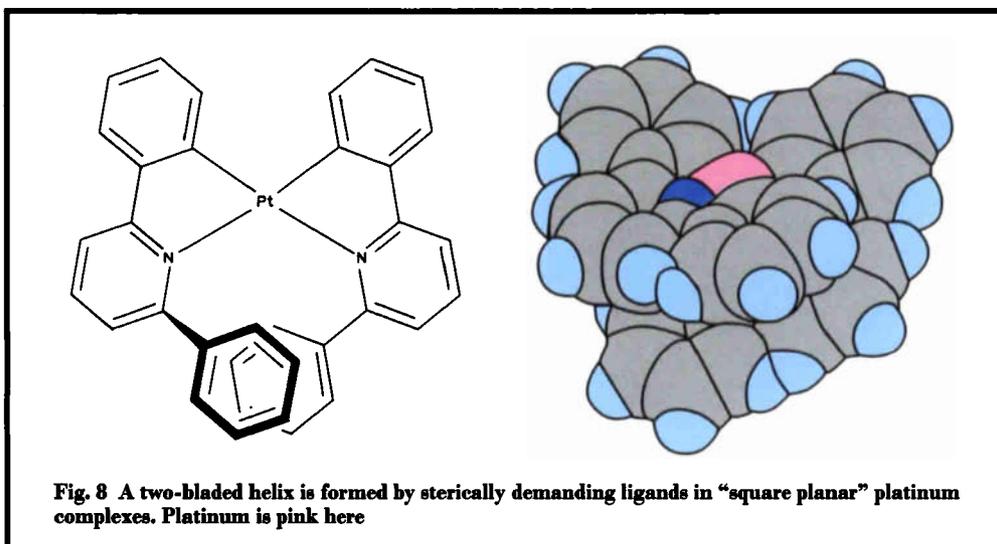
descriptors used for octahedral complexes, because the two ligands form a two-bladed helix. In Figure 9, the  $\Delta$ -form of the complex is depicted.

### Oxidative Addition Reactions

There are many possible reactions for these types of complexes. Oxidative addition is one interesting type of reaction that square planar, SP-4, platinum(II)-compounds undergo. Here the oxidation number of the metal is increased from +II to +IV, and simultaneously, the co-ordination number changes from four to six, yielding again an octahedral species. In the case of SP-4 complexes with predetermined chirality at the metal centre, an octahedral species is obtained which preserves the chirality in the resulting bis-bidentate OC-6 complex (12).

### Conclusions

A large number of chiral octahedral and a few chiral “square planar” complexes of the platinum metals have been known for a long time. These complexes have hitherto always been prepared as racemic compounds. A newly developed synthesis of pyridine and bipyridine ligands with attached groups derived from



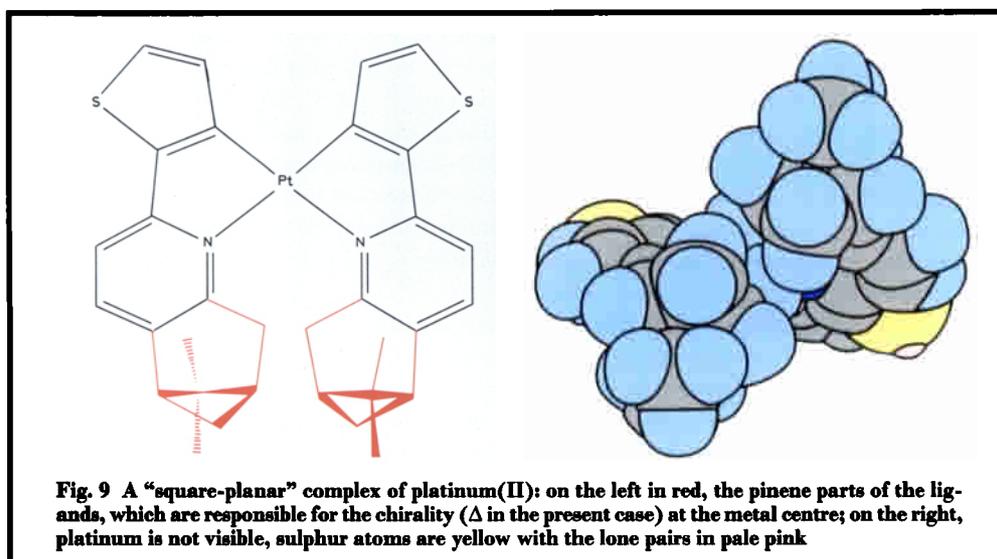
naturally occurring terpenes, such as pinene or carene, leads to chiral ligands, and these direct the chirality at the metal centre into a predetermined configuration. Thus, in many instances, only one helical form of the complex is obtained.

Potential applications for such platinum group metal species lie in the field of enantioselective catalysis, the design of stereochemically well-defined large functionalised structures for

molecular devices, as materials with interesting non-linear optical properties and finally as chiral pharmaceuticals.

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# Palladium Facilitates Optical Switching

## HYDROGEN ADSORPTION ALTERS PROPERTIES OF RARE EARTH FILMS

Hydrogen gas can permeate palladium, diffuse through it and be stored in it. This property has been known for many years, and has been discussed in this journal on numerous occasions; see (1–3) and references therein. Similarly, the effects resulting from the alloying of palladium with rare earth metals have been reported here (4). Now, physicists at Vrije University in The Netherlands have combined these properties to produce thin yttrium and lanthanum films coated with palladium, which display an optical switching phenomenon as they adsorb hydrogen (J. N. Huiberts, R. Griessen, J. H. Rector, R. J. Wijngaarden, J. P. Dekker, D. G. de Groot and N. J. Koeman, "Yttrium and Lanthanum Hydride Films with Switchable Optical Properties", *Nature*, 1996, 380, (6571), 231–234).

Thin films of yttrium and lanthanum (500 nm) were evaporated under UHV and then coated with a thin layer of palladium (5 to 20 nm). The palladium film acts as a support for the films, forms an oxidation barrier, and allows hydrogen to permeate through and be adsorbed by the rare earths. It also enables various physical properties to be measured.

Films were examined by electrical resistivity and light transmission measurements. At the start of the experiment hydrogen, at room temperature and  $0.9 \times 10^5$  Pa pressure, was introduced into the apparatus and began to diffuse through the palladium overlayer. The yttrium film adsorbed hydrogen and changed to yttrium hydride,  $\text{YH}_x$ , which remained metallic up to  $x \sim 2$ , but as more hydrogen was adsorbed, the  $\text{YH}_x$  changed to a semiconductor, corresponding to  $\text{YH}_{2.86}$ .

The films also undergo optical changes as hydrogen is taken up. After 17 seconds of expo-

sure to hydrogen, an initially perfectly reflecting yttrium film, begins to precipitate the dihydride phase, with resistivity  $\sim 5$  times lower than that of pure yttrium. After 65 seconds the resistivity increases rapidly and for a few seconds there is increased optical transmission, shown by a partially reflecting film, close to the dihydride composition. As hydrogen adsorption increases, optical transmission drops to zero, but after 80 seconds there is an abrupt and drastic increase in the optical transmission intensity, shown by a non-reflecting, transparent yellow film. This corresponds to  $\text{YH}_{2.86}$  to the trihydride,  $\text{YH}_3$ .

For a lanthanum-palladium film the pattern is similar, but without the transparency window which occurred around 67 seconds; optical switching in  $\text{LaH}_x$  is more gradual than in  $\text{YH}_x$ .

Thus, there is a continuous, reversible metal-insulator transition in thin yttrium films supported and protected by a palladium overlayer, which can be brought about at room temperature by changing the hydrogen pressure, between hydrogen : yttrium ratios of 1.8 and 2.9. As hydrogen pressures increase, the films change from a reflective, shiny, mirror-like state to a yellow transparent state.

It is suggested that this technique could be used to investigate other rare earth films which undergo similar changes, and that such a significant optical phenomenon might find wide technological applications.

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