

one of few three-legged piano-stool type hydride systems<sup>9,12,13</sup> that has been completely structurally characterized.

The Hembre group studied the electrochemical oxidation of their model complex by cyclic voltammetry and found that the process was reversible! In presence of electron acceptors such as ferrocinium ion or methyl viologen ( $MV^{2+}$ ), the complex releases an electron resulting in a 17-electron stable, isolable hydride cation which can be reduced back to its parent hydride by cobaltocene. The researchers found that ferrocinium ion or methyl viologen ( $MV^{2+}$ ) can also be reduced by  $H_2$  in the presence of a base (tetramethyl piperidine) and a catalytic amount of their model complex. Their studies show that the splitting of  $H_2$  into electrons and protons takes place as follows: a proton is released once  $H_2$  is bound to Ru followed by transfer of electrons of  $H_2$  to electron acceptors mediated by the metal and finally the release of the remaining proton (Scheme 1).

They refer to their system as a 'redox switch' catalyst because the Fe-Ru model acts as a template for the conversion of a two-electron reducing agent,  $H_2$ , into one-electron equivalents in a catalytic manner (8.5 turnovers/min at ambient temperature and pressure) mimicking the hydrogenase enzyme.

Hembre's  $Cp^*(dppf)RuH$  is the first example of the hydrogenase model complex that has hydrogen-splitting ability. Fuel cells are the subject of a great deal of research, and may in the future be used as sources of industrial and domestic electricity. Service<sup>14</sup> predicts that if Hembre's compounds perform just as efficiently as platinum catalysts, ruthenium, a much cheaper metal may as well replace Pt from fuel cells, thus reducing the cost and making them good model power sources. We can anticipate further new developments in this direction especially incorporating much less expensive metals in the models but having close resemblance to the real protein in terms of its activity.

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## Metallization of hydrogen – Everest conquered?

One of the dreams of the condensed matter physicist, of making the element hydrogen into a metal seems to have been achieved by a group led by W. J. Nellis, who has been working on this problem for some time. S. T. Weir, A. C. Mitchell and W. J. Nellis of the Lawrence Livermore National Laboratory in an article in the March issue of *Physical Review Letters* (1996, **76**, 1860) have claimed having produced metallic hydrogen. For more than six decades scientists have been speculating and theorists have been predicting the metallization of hydrogen. But this simplest of elements has ignored the theorists and has resisted becoming a metal for a long time; and when it did, the transformation was from the liquid

state and not from the solid state as predicted. Further it took place at temperatures and pressures very different from those expected!

There are two routes to obtain high pressures. The first is to create very high static pressures in a diamond anvil cell (see *Curr. Sci.*, 1991, **61**, 710) in which pressures in the range 2.5 megabars have been achieved. The second route, the one taken by the Lawrence Livermore group, is by a high pressure shockwave produced by a hypervelocity impactor fired from a two-stage gas gun. In the final experiments reported, the impactor, a 25 mm disc struck the front face of an aluminium sample holder at a speed of 7.33 km/s. The sample holder contained a thin

layer (0.5 mm), liquid hydrogen (or liquid deuterium) sandwiched between two insulating sapphire anvils (see Figure 1). The shock wave passes through the anvils into the hydrogen, reverberates between the anvils and builds up pressures of 93-180 gigapascals (or megabars). The temperature too rises but the cryogenic system keeps it down to between 2200-4400 K, which is low enough to prevent the hydrogen molecule from dissociating. The high pressures are reached within  $10^{-9}$  seconds of the impact and persist for almost 500 nanoseconds giving sufficient time for the fast electronic system to measure the resistivity of the sample.

The resistivity is measured through 1 mm electrodes inserted through the

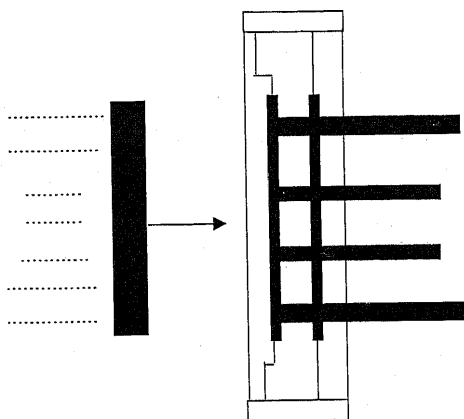


Figure 1.

rear walls, flush with the liquid hydrogen– $\text{Al}_2\text{O}_3$  interface. The two or the four probe method is used (the electrodes are shown Figure 1). Minor corrections are made for the resistivity of  $\text{Al}_2\text{O}_3$ . The resistance of 1 ohm cm at 93 megabars decreases exponentially to  $5 \times 10^{-4}$  ohm cm at 140 megabars after which it levels off. The resistance of the metallic fluid hydrogen is close to that of liquid caesium or liquid rubidium at 2000 K.

As the resistivity can be directly measured in the shock wave method, it has a distinctive advantage over the diamond anvil cell where only optical and spectroscopic methods can be used

(*Curr. Sci.*, 1989, **58**, 1111). There would be much interest, if the static studies could be extended to high temperatures. There are suggestions of using microlithography on diamonds to make resistivity measurements possible inside diamond anvil cells. However newer techniques may have to be developed to prevent the tendency of hydrogen at high temperatures to penetrate and break the diamond anvils.

Condensed molecular hydrogen is a wide gap insulator ( $E_g = 15$  eV) at ambient pressure. At high pressures the electronic energy gap is expected to close to zero when an insulator–metal transition should take place. Neil Ash-

croft, the recognized expert in this field, predicted that at very high pressures and high temperatures,  $\text{H}_2$  in the solid state should undergo a phase transition to a molecular metallic state (becoming probably  $\text{H}_2^+$ ). The transition takes place at about 1.4 megabars between 2200 and 4400 K, but in the *liquid phase* and not the solid phase as predicted. Further the temperatures are significantly higher and the pressures are significantly lower than expected.

There are many far-reaching implications of this work. These experiments measure the density dependence of the band gap under conditions similar to those of fuel pellet irradiation in laser fusion. Since in the fuel pellets hydrogen would absorb more energy than was thought of previously, higher laser fusion yields may be expected (see *Physics Today*, May 1996, page 17). It is certain that the larger planets like Jupiter and Saturn have metallic hydrogen in them. The onset of metallization at pressures lower than those expected implies that the dynamo generating the magnetic fields is located much closer to the surface. Since the dipole field generated decays approximately as the inverse cube of the distance, a near surface dynamo need not generate unreasonably large fields.

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## CSIR Tutorial Workshop on Complex Systems (Chaos) June 26–30, 1996

A few seats are still available for the above workshop on Chaos to be held at C-MMACS. Those interested in joining may contact Dr T. R. Krishna Mohan, C-MMACS, National Aerospace Laboratories (Belur Campus), Bangalore 560 037 (Tel: 5274649; FAX: 526 0392) giving a brief statement of their interest in the subject along with their bio-data before 10th June, 1996.