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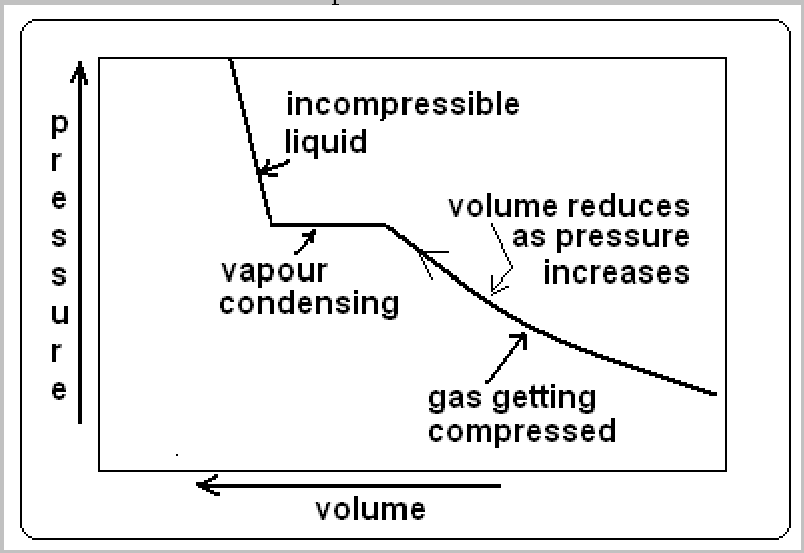
The metallurgy of hydrogen

There are conditions in which hydrogen, the stuff that we fill in gas balloons, can exist as a metal, says S.Ananthanarayanan.

Well, there are conditions where any metal would exist as a gas. Obviously, when things are hot enough and the metals have melted and then vaporized. But the reverse is not true, not everything can become solid, or liquid, simply by getting cool enough – the pressure also needs to be right. And conversely, no pressure is any good if the temperature is not low enough.

The minimum temperature

The first instance of man-made change of state of things, outside the ordinary, was in liquefaction of gases. It was seen that gases got steadily compressed as the pressure was increased, but at one pressure, when the gas began to liquefy, the pressure stayed the same, while the gas rapidly became liquid, till the gas was all liquid. Then, no end of increasing the pressure could compress the liquid to any measurable extent. This can be shown in the form of this picture:



But this happened only below a certain temperature for each gas. When the temperature fell below this level, the gas could be liquefied with less and less pressure, but above the given temperature, not all the pressure applied could liquefy the gas.

This behaviour was understood as arising from the fact that the gas consisted of tiny particles, the molecules, which were in incessant motion, moving faster as the gas got warmer. If the molecules were pressed close enough together, forces of attraction could get active, to form bonds between molecules, to bring about the liquid state – but this could happen only when the thermal motion was below a certain 'floor' level, or when the gas was below its 'critical temperature'.

The freezing limit

The next step after liquefaction was to freeze the liquid, or to form solids. This was usually done with further cooling and also more pressure. The case of water is an exception, or ‘anomalous’, because water which expands when it freezes and what it needs to freeze, at first, is not more pressure but ‘less’ pressure. But generally, for liquids to ‘freeze’ into the compressed crystal structure of solids, what is needed is lower temperature and higher pressure.

And in this way, even the most stubborn gases have been got to condense and then to freeze.

Hydrogen is extreme

Hydrogen the simplest element, consists of just a positively charged ‘proton’ with a relatively tiny, negatively charged ‘electron’ in orbit around it. The word ‘orbit’ is to be understood with some reservations – the reason the proton and electron do not just meet and neutralize, is that the rules of physics of very small particles do not allow two particles to be at the same place – as they get closer, they experience a force of repulsion. This ‘repulsion’ expresses itself as the revolving behaviour, which creates a ‘centre fleeing’ force, like in the earth-moon system and hence the word, ‘orbit’.

Now, in ordinary atoms and molecules, where there are several electrons around the central protons, or in a group of atoms sharing electrons, the large central charge is somewhat ‘shielded’ and the particle groups can approach, form bonds and ‘share the outer electrons. When elements do this, they form crystals, and in the case of electrons being ‘shared’ and ‘set free’, the solid has ‘metallic’ properties – it is shiny, hard, etc. It is also a conductor, because of the ‘free’ electrons, which can react to fields and whose motion is what an electric current is made of.

Except that in the case of hydrogen, the structure is so simple that there is hardly any shielding and two protons cannot form bonds or allow the electrons to float, in the form of a metal. Hydrogen, accordingly, remains a gas till very low temperatures and its metallic form is yet to be realized.

Superconductivity

Theoretical work has shown that hydrogen should exist in metallic form at very high pressures – of the order of 5 million times the atmospheric pressure – more than the pressure at the centre of the earth! The theoretical work also shows that in this state, the lattice the hydrogen atoms form and the conducting electrons would so relate that electrical resistance would disappear – we would have a superconductor at normal temperatures. It is also suggested that we would find a superfluid state of a nature that is different from what has been encountered so far!

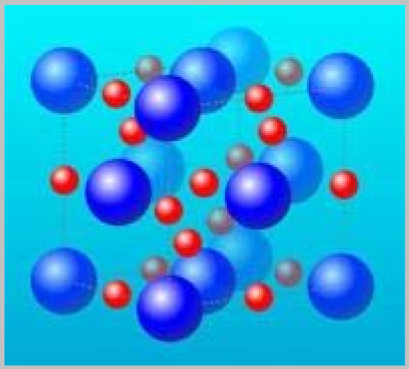
It is believed that hydrogen exists in these forms at the core of giant planets like Jupiter and Saturn. This may explain in part the very powerful magnetic field of Saturn, the strongest in the Solar System.

H metal in the lab

In 1996, the Lawrence Livermore Laboratory created a metallic form of hydrogen for a fleeting microsecond at a temperature of a thousand degrees and a pressure of about a million atmospheres. Other attempts to create metallic hydrogen, at low temperatures, had failed at even 2.5 million atmospheres.

While the pressures that it takes to form metallic hydrogen may be too challenging, it is possible to use compounds of hydrogen with other metals, for get a glimpse of metallic hydrogen under more practical conditions. A compound of hydrogen and silicon, for instance, yields a dense form of hydrogen which becomes a metal at a pressure of about 1 million atmospheres.

Timothy Strobel and others at the Carnegie Institution, Washington DC have presented in ***Physical Review Letters*** their work with a mixture of a silicon-hydrogen compound and hydrogen. They have discovered a new compound which forms at a pressure of less than 100 thousand atmospheres, which is very rich in hydrogen and with bonds so weak that it may become metallic without the need for very high pressures.



It is the objective of such research to find forms of hydrogen that could be metallic and thus superconducting at practical pressures and temperatures.