The Stabilization of Monoatomic Hydrogen – a New Bose Gas

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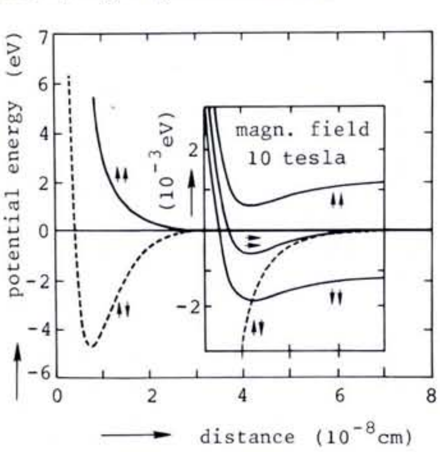
Monoatomic hydrogen (H), composed of one proton and one electron, is the lightest and simplest atom in the periodic system of the elements. In normal circumstances, a gas of H is highly unstable and recombines to form molecular hydrogen, H_2 but we have recently[1]) succeeded in stabilizing a gas of atomic hydrogen in a low temperature experimental cell and shown that at densities of $\sim 10^{14}$ atom/cm^3 the gas can be stabilized for periods measured in hours, with the main loss mechanism due to thermal diffusion (escape) out of the stabilization cell. In our latest experiments densities have been increased by more than two orders of magnitude.

In its spin polarised state (H↑), atomic hydrogen is expected to possess fascinating properties. When cooled towards $T = 0$ K all other substances liquify, then solidify, except for the quantum fluids ^{3}He and ^{4}He which remain liquid in equilibrium with their vapour pressures. H↑ is the extreme case of a quantum fluid and is predicted to have no many-body bound state, i.e. it remains a gas at $T = 0$ K[2]). Experiments at current temperatures and densities are not in contradiction with this prediction. This unique property will enable us to gain a deeper insight into the fundamental quantum nature and statistics of matter.

In gaseous hydrogen at low temperature, the density can be varied somewhat arbitrarily and thus the effect of interactions on ideal gas behavior can be studied. As an example, the only existing Boson superfluid is ^{4}He. Since the work of London, it has been believed that the superfluidity is associated with the phenomenon of Bose-Einstein condensation (BEC) i.e. the macroscopic population of the ground momentum state at a finite temperature. However at the temperature of the superfluid transition (2.17 K), ^{4}He is a liquid with a density such that the interactions plays a dominant role in the phenomena. Understanding the strongly interacting Boson superfluid has posed a difficult theroretical problem over several decades.

Fig. 1 — Interaction potentials of monoatomic hydrogen against distance.



Having an almost ideal Boson gas would be of great value to condensed matter physics. H is, in fact, a composite boson as the H atom has a nuclear spin, $I = \frac{1}{2}$, and electron spin, $s = \frac{1}{2}$, making the total spin either 0 or 1. It has been predicted [3]) that H will display Bose-Einstein condensation and superfluidity as a gas and at low density n, when interactions are unimportant, it should behave as an almost ideal Bose gas with a critical temperature for BEC of: $T_c = 3.31\, h^2 (n/g)^{2/3} / mk_B$ where g is the degeneracy, m the atomic mass and h and k_B Planck's and Boltzmann's constants. With $n = 10^{18}$/cm^3, T_c should be ~ 15 mK, accessible with current cryogenic techniques. In addition, a gas of H↑ should display many new phenomena. Since H↑ atoms carry magnetic moments, again at sufficiently low densities, the Bose condensate should be spatially localized[1]) and an interesting density — spin excitation spectrum has been predicted[4]).

One practical use of stabilized H↑ is as the active gas in a hydrogen maser which may provide substantial improvement over the room temperature H-maser as a time and frequency standard, due to a better control over wall problems, which are discussed later. H↑ would also provide an ideal fuel as a rocket propellant, although with densities achieved to date this remains a somewhat remote application.

In normal circumstances, the lifetime of a gas of atomic hydrogen is limited by volume recombination at a rate K_V, as well as surface recombination at a rate K_S. The decay of the density n is governed by the rate question: $-dn/dt = K_V n^3 + K_S n$ (1). At room temperature $K_V \cong 1.2 \times 10^{-32}$ cm^6/atom s for unpolarized H[5]). Volume recombination begins to become important for densities $n \cong 10^{16}$ atom/cm^3, but it is the surface term which usually sets the lifetime. This decay rate can depend quadratically or linearly (as in eq. 1) on density, depending on the surface and temperature. The best known surface for suppressing recombination at room temperature is teflon, on which an atom of H can have 10^4 to 10^5 bounces before recombination. For a spherical gas cell of volume 1 cm^3 this leads to $K_S \cong 10$ cm^3/atom s or a surface limited lifetime $\tau \cong 0.1$ s, which is independent of density. However, to stabilize H it is necessary to cool the cell to T $\lesssim$ 1 K, when on almost all known surfaces the H will condense out and rapidly recombine. If we assume that the lifetime of the H is determined by the diffusion of the H to the cell surface, then $\tau \cong 50\ \mu$s for our 1 cm^3 spherical cell.

The way through this limitation leads from the fact that the two atoms of the resultant H_2 molecule are bound by a potential with a well depth $\varepsilon \cong 4.75$ eV (~ 55000 K). This stable bound state is a spin singlet state, $^1\Sigma_g^+$, i.e. the electronic spins are coupled antiparallel. However, if the electron spins of the two H atoms are coupled parallel in the triplet state, $^3\Sigma_u^+$, the interatomic interaction is only weakly attractive with $\varepsilon/k_B \cong 6.45$ K. Due to the light mass and consequent large zero-point energy, triplet hydrogen has no bound state. A gas of H atoms with all pairs interacting via the $^3\Sigma_u^+$ potential is called spin polarized hydrogen, and the hydrogen gas that we have stabilized is spin polarized (using the world stabilization to mean that we have increased the lifetime of the gas by many orders of magnitude by suppressing surface and volume recombination).

In order to stabilize H, then the spins have to be polarized, and must be maintained so. In zero magnetic field, H is absolutely unstable. This can be seen from the interaction potential in Fig. 1. We see that at all distances the unstable $^1\Sigma_g^+$ potential lies lower in energy than the $^3\Sigma_u^+$. Magnetic dipole-dipole or hyperfine interactions are sufficient to cause spin flips in H↑, relaxing the $^3\Sigma_u^+$ to the $^1\Sigma_g^+$ state which will result in subsequent recombination. The triplet state can be transformed into the ground state by applying a magnetic field, as shown in the inset of Fig. 1. Here, the $m_s = -1$ of the $^3\Sigma_u^+$ state is now lower in energy than the $^1\Sigma_g^+$ state beyond a certain range. This two-particle picture can be carried over to a may-particle picture and motional averages can be included to provide a relationship between applied magnetic field and the maximum density for "static" stability, n_m[6]). Even for $n << n_m$ the temperature must be low to reduce the Boltzmann probability for spin-flipped states; for a field of 10 T, T $\lesssim$ 1 K.

The low temperature requirement creates another problem. Due to long range attractive London type forces, hydrogen will condense out on almost every conceivable surface and will rapidly recombine due to the second term in eq. (1). We have found that the one surface on which H will not condense with any important coverage is that of liquid helium, so

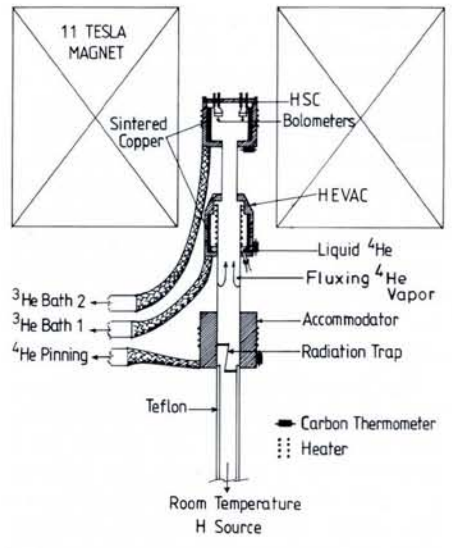


Fig. 2 — Schematic of the experiment.

that all surfaces of the confining stabilization cell must be covered with this liquid (helium is a superfluid at these low temperatures).

Experimental Set-up

The hydrogen stabilization cell (HSC) that we used is shown in Fig. 2, centred in a superconducting solenoidal magnet of maximum field, 11 T. The HSC and a device called HEVAC (HElium VApour Compressor) are cooled to below 1 K by means of (single-shot) ^{3}He evaporation refrigerators. A small amount of ^{4}He is condensed in the HEVAC reservoir and a saturated film of superfluid ^{4}He covers the walls of the HSC and HEVAC. Atomic hydrogen which is made in a conventional room temperature microwave discharge is led into the cryostat via a teflon tube. The hot H gas is cooled to ~ 4 K by contact with the accommodator [7]), prior to injection into the HSC which operates at temperatures as low as 270 mK.

Spin polarization is accomplished as follows. The magnetic field gradient at the end of the magnet will draw electron spin-down atoms into the high field region and repel spin-up atoms. As the latter cannot escape the guide tube, they either recombine or relax to the spin-down state and enter the HSC. The atoms accelerated into the HSC gain kinetic energy which is relaxed to the helium covered walls of the HSC: the gas is then at the temperature of the HSC and trapped in the cell by the magnetic field gradient.

The HEVAC serves two purposes: it is an H compressor and it enables thermal isolation of the HSC. The superfluid helium film is driven by the fountain effect towards the accommodator. As the film comes into the warmer region it vaporizes; the dense vapour fluxes back and condenses out again in the HEVAC. Since the helium mass is four times that of H, He-H collisions result in an efficient transfer of momentum and the H is compressed into the HSC. The HEVAC is a miniature, self driven, vapour diffusion pump which uses superfluid helium as its pump "oil". The fluxing vapours have a detrimental aspect; they actually operate as a heat pipe. Without the HEVAC, they would exist between the accommodator and HSC, leading to serious warming of the latter and limited times of operation at low temperature. Thus the HEVAC also serves to break the thermal link between the accommodator and the HSC.

The presence of $H\uparrow$ was detected by means of a bolometer. Such a device relies on a strong dependence of its electrical resistance on temperature. Normally the bolometer, which is suspended by fine wires in the HSC, is covered with helium. By passing an electrical current through the bolometer it is heated and the helium is evaporated from its surface faster than it can be replenished along the wires. When the surface is bare of helium it becomes an active area for catalyzing surface recombination, resulting in rapid conversion of $H\uparrow$ to H_2. The released recombination energy causes heating and a change of resistance of the bolometer which is easily measured. The density of H is determined by measuring the temperature rise of the HSC after recombination is triggered.

Using the techniques described above, the cell has been loaded with $H\uparrow$ which remained stable for periods extrapolated to hours at temperatures as low as 0.27 K. Densities greater than 10^{16} atoms/cm^3 have been achieved, although, at higher densities the lifetimes tend to become shorter. It is not yet clear if we are approaching a fundamental limitation due to recombination of if the decreasing lifetimes are related to the present geometry, magnetic field, and temperature of our system. If densities one to two orders of magnitude greater can be achieved, we may be able to study some of the fascinating aspects associated with the Bose nature of the gas.

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STELLA

On 6 March, the European Stella experiment concerned with the transmission of scientific data between high energy physics laboratories via the European satellite, OTS, was inaugurated at CERN with the additional participation of ESA, the European Space Agency, and the European Communities.

Through Stella, a large amount of experimental data can be transmitted rapidly and accurately from CERN to other high energy physics laboratories in Europe, notably: DESY FRG, Saclay France, Rutherford U.K., Pisa Italy, Dublin IRE and Graz Austria. Real data transmission speeds of up to 1 megabit/s will be possible via the geostationary satellite which was launched in May, 1978.

Stella was conceived about five years ago as a cooperation between the Commission of the European Communities, seeking ways to improve communication networks in western Europe, and ESA which is responsible for establishing satellite communication links in the region. CERN played the rôle of "guinea pig" user, in view of its requirement to transmit large amounts of data collected in high energy physics research. The experiment will provide pilot information for a network that is hoped can serve the communication needs of remote sites, facilitate remote newspaper printing, the distribution of environmental data, as well as being a real-time link between computers located in different countries.

Specific aims include the exploration of error rates (hopefully 10^{-9} or better) when using small earth receivers operating in the 11-14 GHz frequency band and employing special coding techniques, as well as an evaluation of the system for the transmission of high energy physics data as such. To determine the efficiency of transmission and methods of error detection under all weather conditions, a system of signal acknowledgement is incorporated which will permit re-transmission in the event of a failure to respond or an indication of error by the redundancy check.

Due to the very high capacity of the satellite communication channel (2 Mb/s), the real data can still be transmitted at high speed whilst introducing high redundancy in the transmission, so allowing powerful error correction techniques to be used.