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Magnetic Confinement of Spin-Polarized Atomic Hydrogen

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Magnetic confinement is used to obtain spin-polarized atomic hydrogen ($H\uparrow$) in an open-ended helium-coated chamber, at densities up to 0.8×10^{17} atoms/cm^3. At a field of 10 T and temperature of 0.3 K, confinement times as long as 4 h are achieved. A quantitative study of the confinement times as a function of magnetic field is in excellent agreement with the expected escape from the magnetic potential well accompanied by a very slow loss process. Heat transport measurements confirm that the $H\uparrow$ is a gas and an upper limit is placed on the three-body recombination rate.

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Interest in spin-polarized hydrogen ($H\uparrow$) has accelerated, spurred by theoretical studies of its unique properties as a quantum fluid[1-3] and by growing awareness of experimental possibilities for its production.[4,5] An important experimental advance was achieved recently by Silvera and Walraven[6,7] who verified that the surface recombination of $H\uparrow$ could be avoided by using a helium-coated surface and demonstrated stabilization of small amounts of $H\uparrow$. We report here first results of a technique which allows much higher accumulation rate, density, and storage time than have yet been achieved, and which may open the way to study of $H\uparrow$ as a quantum fluid.[8]

The major experimental problems are to spin select the hydrogen atoms with essentially 100% efficiency, to stabilize them against spin relaxation, and to compress them to high density. Our approach rests on the use of a "magnetic bottle" to accomplish all three tasks simultaneously.[5] The "bottle" consists of a low-temperature chamber covered with a helium film in a high magnetic field. The entrance to the chamber, an open tube, leads to a high-flux source of low-temperature atoms outside of the field. Atoms in the upper hyperfine states are repelled but those in the lower hyperfine states are drawn into the chamber by the magnetic force. Their excess kinetic energy is rapidly lost to the walls and they become trapped in the "bottle." We should emphasize that confinement is effected purely by the magnetic field, in contrast to the helium-vapor–compressor (HEVAC) method of Silvera and Walraven which employs a flowing helium gas to help accumulate and confine the $H\uparrow$. In our initial efforts we have obtained a density of approximately 10^{17} atoms/cm^3, and have achieved confinement times of up to 4 h. Heat transport measurements confirm that the $H\uparrow$ is in the gas phase.

An important element of our technique is a high-flux source of atomic hydrogen at liquid-helium temperature. Such a source was developed and used to study the behavior of H on frozen H_2 surfaces in work reported earlier.[9]

Operation of our apparatus can be understood by referring to Fig. 1. Molecular hydrogen is dissociated in an rf discharge tube which is immersed in liquid nitrogen. The atoms pass through an orifice into a 4.2-K chamber whose walls are coated with frozen H_2. A baffle assures that the atomic hydrogen is thermalized at 4.2 K before it can proceed upwards to the cell. The cell is a 9.5-mm-diam hole in a 16-mm-diam copper rod. The hole ends near the midplane of the superconducting magnet, but the rod continues upwards to the mixing chamber of a dilution refrigerator. A gap of less than 1 mm separates the tip of the copper rod from the exit of the 4.2-K baffle. With this geometry the hydrogen atoms encounter only solid H_2 walls at 4.2 K or superfluid ^{4}He walls at about 0.3 K. Vacuum integrity is maintained by a concentric stainless-steel tube which connects

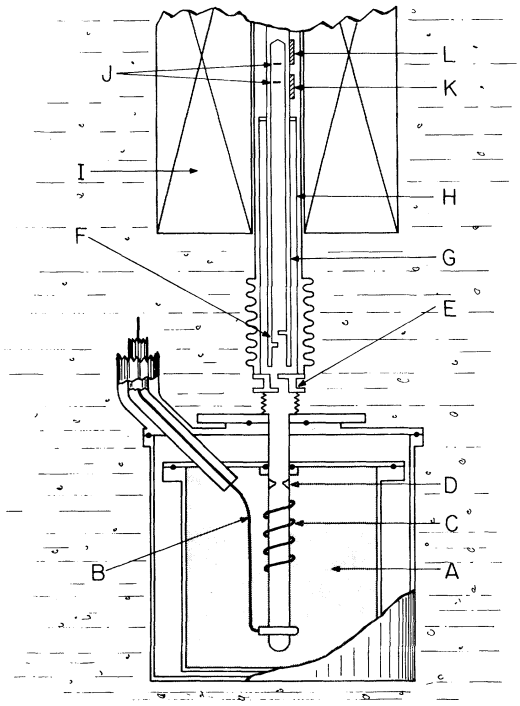

FIG. 1. Schematic diagram of the apparatus. *A*, liquid nitrogen bath; *B*, H_2-gas supply line; *C*, rf dissociator; *D*, orifice; *E*, 4.2-K baffle; *F*, 0.3-K baffle; *G*, hollow copper rod; *H*, stainless-steel tube; *I*, superconducting magnet; *J*, bolometer; *K*, thermometer; *L*, heater. The apparatus is immersed in liquid helium.

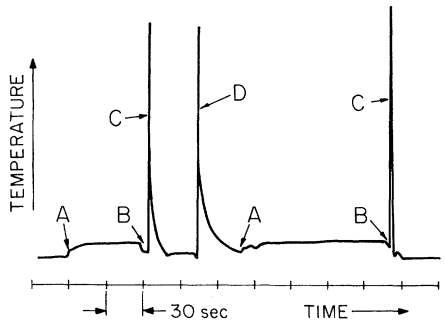

FIG. 2. A typical experimental trace of the cell temperature taken at 0.3 K and 8.0 T. The source is turned on at *A* and off at *B*. At *C* the atoms are made to recombine. At *D*, an electrical heating pulse is applied for calibration; its energy is equivalent to 3.0×10^{17} atoms. Peak amplitude is proportional to the energy released; variations in the return to the base line temperature are caused by the temperature controller.

the 4.2-K baffle to the copper rod 16 cm above the gap.

The helium, initially introduced into the cell through the H_2 supply line, coats the cell, the outside of the rod, and the upper part of the stainless tube. During operation the helium film continually flows down the stainless tube toward the 4.2-K chamber. At some point along the tube the film boils away. The vapor immediately condenses on the cold rod, replenishing the film. The stationary flow of the refluxing helium constitutes the primary heat load on the refrigerator, even when the discharge is operating. This geometry was chosen to avoid refluxing of ^{4}He in the cell itself, in contrast to the HEVAC method of Silvera and Walraven[6] which employs refluxing ^{4}He to help confine the $H\uparrow$.

Atomic hydrogen entering the cell is cooled to about 0.3 K by collisions with a baffle. As the cooled atoms flow upward they encounter the large field gradient of the magnet. Atoms in the upper two hyperfine states, which are repelled by the field, can return to the 4.2-K region, recombine at the mouth of the cell, or change their spin state and eventually enter the high field region of the cell where they thermalize by wall collisions and become trapped in the magnetic potential well. Spin selection is virtually perfect because of the enormous Boltzmann factor. Once the $H\uparrow$ has thermalized its density, $n(z)$, as a function of distance along the cell, z, is given by

$$n(z)=n_0\exp\{-\mu[B_0-B(z)]/kT\}. \quad (1)$$

The maximum density, n_0, occurs where the magnetic field attains its largest value, B_0.

Although we have observed stable $H\uparrow$ in fields as high as 10 T and at temperatures down to 0.15 K, most of our experiments were done at a field of 8 T and a temperature of 0.3 K. Central to all of our experiments is the measurement of the number of spin-polarized atoms, N, in our cell. We determine N precisely by measuring the energy liberated (4.48 eV per pair) when the atoms are made to recombine suddenly. The recombination is initiated by heating a small carbon bolometer, patterned after the design of Silvera and Walraven,[6] situated in the gas and only weakly coupled to the cell wall. Heating drives the superfluid film off the bolometer and allows the bare surface to catalyze the recombination reaction. Because of nonlinearities intrinsic to its design, however, we do not use the bolometer for quantitative measurement of the energy released. Rather, we measure the temperature rise of the copper rod itself as shown in Fig. 2.

The energy necessary to cause this temperature pulse is determined directly by using a heater wound around the outside of the copper rod at the midplane of the magnet. The largest signals that we have observed correspond to $N = 3.5 \times 10^{17}$ atoms. Using Eq. (1), the known cell geometry, and the measured field profile of the magnet, we find that this yields a maximum density n_0 of 0.8×10^{17} atoms/cm^3.

With our apparatus we have been able to demonstrate for the first time pure magnetic confinement of H↑. To investigate this process we have studied the lifetime as a function of magnetic field. In the absence of any recombination or relaxation mechanisms, a population of trapped H↑ will escape from the cell with time constant τ_B given by

$$\tau_B = t_0 \exp(\mu B_0/kT). \quad (2)$$

B_0 is the maximum field in the cell, T is the temperature at the entrance region of the cell, and t_0 is a characteristic escape time which can be shown to be given by $t_0 = 4l\kappa/v_m$. l is the length of the cell averaged over the density distribution function, Eq. (1), v_m is the mean velocity and κ is a geometrical factor determined by the exit geometry. τ_B is determined by measuring the number of atoms remaining after several different delay times and fitting the results to an exponential decay. The results of one set of measurements of τ_B as a function of B_0 are shown in Fig. 3. (Because l depends slightly on field, a plot of τ_B vs B_0 on a semilog scale will not be quite linear. The nonlinearity is very small, however.) For short lifetimes, Eq. (2) is obeyed quite accurately. In a similar set of measurements we have been able to verify Eq. (2) down to a field of 1.7 T. At high field, however, it is evident that some other process is limiting the lifetime. If we assume that this process is described by a decay constant τ_x, the observed time constant τ is given by

$$\tau^{-1} = \tau_B^{-1} + \tau_x^{-1}. \quad (3)$$

The solid line is a fit to this expression with $\tau_x = 8 \times 10^3$ sec. The relaxation time τ_x is sensitive to the amount and distribution of helium in the cell, but we have no direct evidence as to the nature of the relaxation mechanism. In one experiment we measured a time constant of 4 h at 10 T and 0.3 K for a sample whose density was 10^{16} atoms/cm^3.

The data in Fig. 3 indicate a temperature of 0.48 K, somewhat above the cell temperature

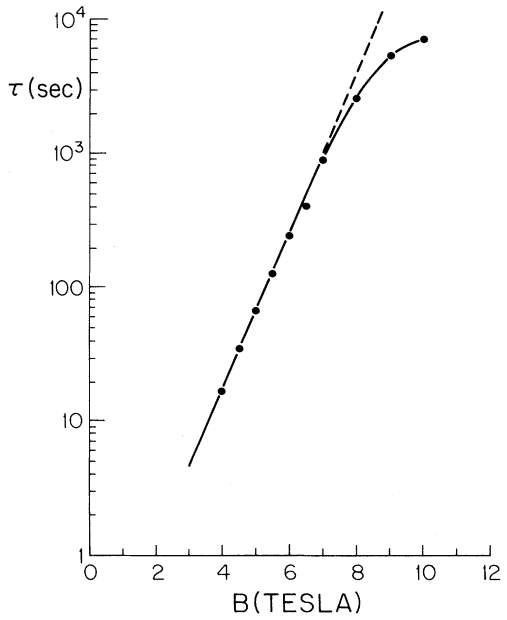

FIG. 3. Demonstration of pure magnetic confinement. Dots are experimental values for the magnetic confinement times at different magnetic fields. Solid line is given by Eq. (3) with $\tau_x = 8000$ sec. Dashed line is theoretical confinement time in the absence of extraneous loss mechanisms ($\tau_x = \infty$).

measured at the midplane of the magnet, 0.35 K. This temperature difference is consistent with the heat flow in the copper rod due to the refluxing helium. The characteristic time t_0 is 100 msec. This is longer by a factor of 4 than the value which we calculate from simple geometrical considerations, possibly indicating that the escaping atoms have a high probability of reentering the cell before they undergo recombination or spin relaxation.

We have monitored the accumulation of H↑ in the cell at high fields by operating the source for fixed periods of time and then immediately triggering recombination. The initial accumulation is linear in time and allows us to determine the flux, f, of cold, polarized atoms. We have obtained values of f at least as high as 5×10^{15} atoms/sec. The density eventually reaches a limiting value with a characteristic time typically in the range of 100–200 sec. This effect is evident in the experimental trace shown in Fig. 2. In general we find that thicker helium films give rise to higher densities of H↑. (It should be pointed out that the ^{4}He film may not be saturated and that it can include substantial amounts of molecular H_2 in an unknown configuration.) We have also studied the decay of the density in the cell af-

ter the source has been turned off. For high magnetic fields [where τ deviates from Eq. (2)] neither the accumulation nor the decay are purely exponential. If three-body recombination in the gas were the sole dissipative mechanism, the limiting density would be equal to $(f/\gamma V_{\mathrm{eff}})^{1/3}$ and the subsequent decay would be governed by the equation $dn/dt = -\gamma n^3(t)$. In these expressions γ is the rate constant for three-body recombination and V_{eff} is an effective volume. Although we have not studied the time evolution of $n(t)$ in sufficient detail to identify the dissipation processes involved, we are able to place an upper bound on γ of about 1×10^{-36} cm^6/sec at 10 T and 0.3 K.

The bolometer used to initiate recombination can also be used as a thermometer and this has allowed us to confirm directly that the H↑ is a gas. Since the bolometer is only weakly coupled to the cell wall, the process of measuring its resistance is accompanied by self-heating. When the cell contains a helium film, but no H↑, because of self-heating the temperature of the bolometer is typically 20 mK above that of the wall. As H↑ is accumulated, however, the bolometer temperature falls and approaches the wall temperature. Qualitative estimates show that this effect is consistent with heat transport away from the bolometer by a H↑ gas at the densities which we measure. We believe that this provides conclusive evidence that the H↑ is in a gaseous state in our cell.

We regard the results so far as most encouraging, particularly in view of the fact that they represent the very first application of the "magnetic-bottle" method. Not only are the density, accumulation rate, and confinement time considerably improved over other methods, the results can be understood quantitatively without resort to the somewhat roundabout arguments needed to interpret results with use of the HEVAC technique. Although the density so far achieved is only about 1% of that needed to start observing the quantum aspects of a Bose gas, it is already high enough for new lines of study of atomic interactions and chemical kinetics. In particular, the possibility of cooling hydrogen to very low temperature affords important new opportunities for hydrogen spectroscopy.

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