Magnetic Trapping of Spin-Polarized Atomic Hydrogen

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and

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(Received 6 May 1987)

We have confined over 5×10^{12} atoms of hydrogen in a static magnetic trap. The atoms are loaded into the trap by precooling with a dilution refrigerator. At operating densities near 1×10^{13} cm^{-3} the gas is observed to be electron and nuclear polarized in the uppermost hyperfine state. The long lifetime of the trapped gas (over 20 min) suggests that it is thermally decoupled from the wall and has evaporatively cooled to a temperature of about 40 mK. The residual decay of the gas density is consistent with spin relaxation induced by dipolar interactions between atoms.

PACS numbers: 67.65.+z, 32.80.Pj, 76.90.+d

One of the goals of spin-polarized hydrogen research is to achieve Bose-Einstein condensation, a phase transition in a noninteracting gas which takes place when the thermal de Broglie wavelength $\Lambda(T)\equiv(2\pi\hbar^2/MkT)^{1/2}$ becomes comparable to the mean spacing between atoms.[1] Two approaches have been tried. Compression experiments[2-4] decrease the mean spacing by increasing the density of the hydrogen. In such experiments the densities are limited by three-body recombination in the bulk gas. The second approach is to increase $\Lambda(T)$ by substantial cooling of the gas, but a practical limit again appears. The amount of hydrogen adsorbed on the helium-coated walls of the cell rapidly increases as the temperature is lowered below 0.3 K; ultimately three-body recombination on the film limits the lifetime of the sample.[2,5] To avoid this problem, wall-free confinement by static[6] or dynamic[7] magnetic field traps has been proposed.

The other goals of low-temperature hydrogen research lie in the areas of spectroscopy, atomic collisions, and surface studies. The study of free atoms at temperatures in the millikelvin and microkelvin regime has been spurred by laser techniques for atom trapping and cooling.[8,9] Because laser methods are not well suited to working with atomic hydrogen, hydrogen has so far been excluded from this line of research. In this Letter we demonstrate the trapping of spin-polarized hydrogen using a static magnetic field. Atoms have been observed after 20 min in the trap, suggesting that the temperature of the trapped gas is approximately 40 mK. A similar magnetic configuration has recently been used to trap sodium atoms by use of laser cooling methods.[10]

The apparatus is shown in Fig. 1. The hydrogen source and hyperfine resonator are similar to those described earlier in connection with our spin-polarized hydrogen maser.[11] The components shown, with the excep-

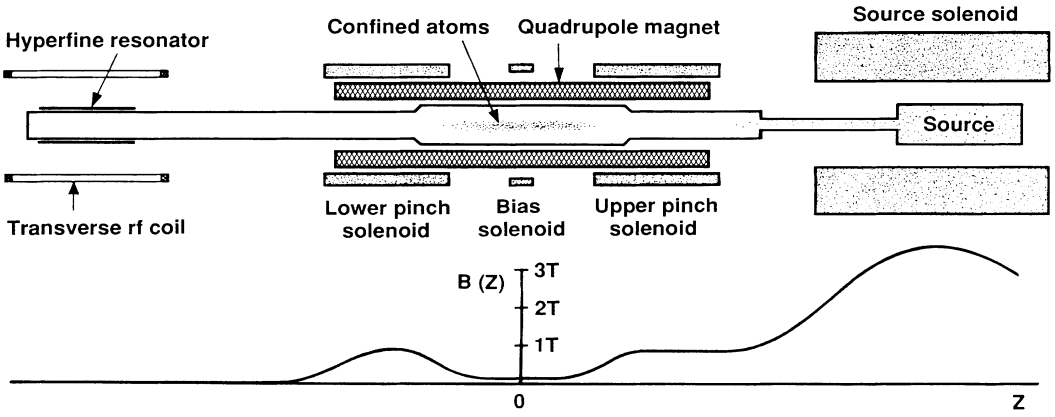

FIG. 1. Schematic diagram of apparatus. The magnitude of the on-axis magnetic field is indicated. The total length of the apparatus is 71 cm. The diameter of the trap region is 2.4 cm.

tion of the magnets, are cooled by a dilution refrigerator. The interior walls of the cell are coated with a thick ^{4}He film containing 30 ppm ^{3}He, more than enough to form a monolayer of ^{3}He on the surface of the film. The ^{3}He reduces the binding energy of the hydrogen to the walls. The hydrogen source is operated in a field of 3.5 T. The wall temperature in the source is below 200 mK, rising to nearly 1 K during the pulsed discharge. The discharge evaporates H_2 and He from the walls and dissociates the H_2. The resulting puff of He gas carries atomic hydrogen in all four hyperfine states toward the trap region.

Several magnets are required to produce the trapping field.[6,12] A cylindrical quadrupole produces a radial trapping field whose magnitude increases linearly from zero on axis to 0.87 T at the wall. Pinch solenoids, also 0.87 T, at either end of the trap prevent atoms from escaping along the axis. This corresponds to a potential well which is 580 mK deep. The field of the lower pinch solenoid can be reduced rapidly to allow the atoms to flow out and be detected by zero-field hyperfine resonance. A bias solenoid prevents nonadiabatic spin flips that would otherwise occur in zero-field regions. The walls of the trap are cooled to temperatures between 60 and 200 mK.

Immediately after the source discharge is fired, all four hyperfine states (a, b, c, and d, in order of decreasing energy) are present in the trap region. The atoms become electronically polarized during the first second as the high-field-seeking states, a and b, are pulled back to the source. A fraction of the remaining atoms, those which lose energy during hydrogen-hydrogen collisions, are captured by the trap. Nuclear polarization to the d state occurs as the c-state atoms are eliminated through spin-exchange collisions: $c+c \rightarrow b+d$. The resulting b atoms are ejected from the trap by the field gradients. The characteristic time for nuclear polarization is 3 sec at a density of 10^{12} atoms cm^{-3} on axis.

After the atoms are held for a time t, the trap is emptied into the hyperfine resonator by a decrease of the lower pinch field linearly to zero in 4 sec. During this time the atomic density is monitored by a series of free-induction decays at the zero-field hyperfine resonance, 1420 MHz. The amplitude of the signal is proportional to $n_c - n_a$ and thus is not directly sensitive to the escaping d atoms. However, as a result of spin flips among the b, c, and d states induced by magnetic impurities on the walls. a resonance signal can be seen. This process gives a c-state density of the form[13]

$$n_c = \frac{N_d}{\sqrt{5}V_r}\left[\exp\left(-\frac{3-\sqrt{5}}{2}\frac{t}{\tau}\right) - \exp\left(-\frac{3+\sqrt{5}}{2}\frac{t}{\tau}\right)\right], \quad (1)$$

where N_d is the number of d-state atoms introduced into the resonance region at $t=0$, V_r is the volume of the resonator and its connecting tube, and τ is the time for an atom in the resonator to make a transition from d to c or from c to b. Our data yield $\tau=60$ sec. This value is consistent with the results of independent experiments with the trapping fields turned off.

The large initial d-state polarization of the atoms was confirmed by an alternative technique. The $d \rightarrow c$ transition can be induced in a controlled manner and at a more rapid rate than by surface relaxation by application of a 1-MHz transverse field which is resonant with the Zeeman splitting caused by the residual 0.6-G field in the resonance region. By comparison of the observed density n_c before and after this rf pulse, a lower bound on the d-state polarization is set. We find that n_c is strongly enhanced after the rf pulse indicating that at least 90% of the atoms leaving the trap are in the d state.

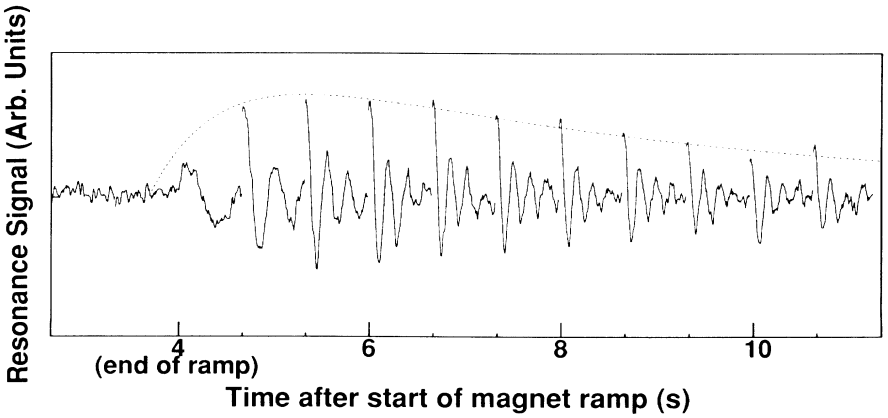

FIG. 2. Hyperfine resonance signal from c-state atoms in the resonant cavity in the period immediately after the trap is dumped. The time on the horizontal axis indicates the start of each free-induction decay. The time scale for individual decays, however, has been magnified to display only the first 6 msec. The density rises as d atoms relax to c atoms and falls with subsequent relaxation to b atoms. The dotted line, a fit by Eq. (1), allows us to determine the initial number of atoms in the trap.

This technique was not used for the primary detection because it required delicate control of the fields.

Figure 2 shows a sequence of free-induction decays taken for a trap that was dumped after a holding time of 20 sec. In Fig. 2 the first 6 msec of every second 333-msec interval is expanded to display the free-induction decays more clearly. The dashed curve shows a fit of Eq. (1) to the data with the initial number of d atoms, N_d, the relaxation time, τ, and the starting time as free parameters. The alternative detection technique with transverse resonance indicates that most of the atoms leave the trap during the last second before the lower pinch field reaches zero. Since the relaxation time in Eq. (1) is much longer than the time over which the atoms leave the trap, these measurements are not sensitive to details of the escape process. The relation of the resonance signal strength to the number of atoms was established through knowledge of the Q and the coupling losses of the resonance cavity. This calibration was cross-checked against the density dependence of T_2 for radiation damping. We estimate the precision of this calibration to be $\pm 50\%$.

The number of atoms in our trap, N_d, is related to the density on axis, n_0, by an effective volume, $N_d = n_0 V_{\text{eff}}$. By integrating the position-dependent density over the volume of the trap, we find

$$V_{\text{eff}} = 76(kT/\mu B)^{2.27}\ \text{cm}^3, \qquad (2)$$

where B is the field strength at the walls, and T is the gas temperature. (For an infinite cylindrical quadrupole trap, the exponent would be 2.) As an example, 1×10^{12} atoms at 40 mK, typical of atoms held in our trap for 6 min, give an on-axis density of $6\times10^{12}\ \text{cm}^{-3}$.

A series of identical fills was carried out and the atoms held for different lengths of time. Figure 3 shows the number of atoms in the trap as a function of holding time. Although the atoms leave the trap rapidly at first, the rate of loss decreases dramatically after 60 sec. Note that data taken at the wall temperatures of 70 and 110 mK show basically similar decays, particularly for long times. None of the decay mechanisms that were important in previous spin-polarized hydrogen experiments can explain this behavior. Spin exchange ($c+c \rightarrow b+d$) has already gone to completion, leaving a gas of d atoms that are immune to further spin exchange. Processes on the walls of the cell are not significant because trapped atoms touch the wall only infrequently and spin relaxation on the walls is strongly suppressed by the high fields.[14] Three-body and other high-order processes are entirely negligible at these densities. We believe that the major features of the observed decay are due to evaporative cooling[6] of the gas by energetic atoms which escape over the lower pinch field.

We have as yet no direct method of determining the temperature of the trapped gas. However, the time scale of the leakage from the trap strongly suggests that the gas temperature is substantially below that of the walls. If the gas remained in thermal equilibrium with the wall it would escape rapidly over the lower pinch field. The dotted curve in Fig. 3 shows the results of such an assumption for a wall temperature of 70 mK. Physically one expects that a flux of atoms over the barrier would result in a departure from equilibrium conditions: The energy distribution will be modified and the effective temperature will depart from that of the walls. The atoms which escape carry more energy than possessed by an average atom in the trap; therefore evaporational cooling occurs. The resulting energy distribution can be approximated by a Boltzmann distribution that is truncated well above kT at the threshold energy for escape.

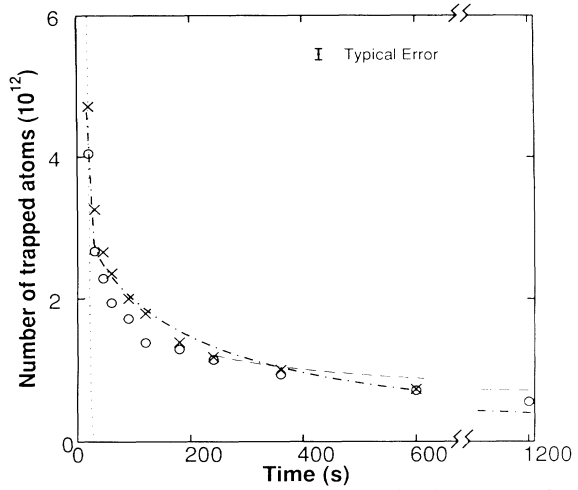

FIG. 3. Number of trapped atoms vs holding time of trap. Crosses and circles indicate data taken at wall temperatures of 70 and 110 mK, respectively. The dotted curve indicates the time dependence of N_d expected if the gas temperature were fixed at the wall temperature. The dot-dashed curve indicates the evolution of N_d taking into account evaporative cooling and spin relaxation. Both of these curves were calculated for a wall temperature of 70 mK and have been normalized to the first 70-mK datum point. The dashed curve shows the long-time behavior in the absence of spin relaxation.

Within the trap, the "tail" of the Boltzmann distribution tends to be replenished by collisions of two atoms of lesser energy that generate an escaping atom. Knowledge of this collision rate and the associated energy flow allows one to model the evolution of the density and temperature. The dot-dashed curve in Fig. 3 shows the result of such a calculation.[15] The model gives a gas temperature of 43 mK after 5 min and 41 mK after 10 min. Heat flow from the walls to the gas occurs only through wall collisions and becomes negligible compared with the evaporative cooling when the gas temperature drops sufficiently below the trapping energy of 580 mK. Thus the temperatures that are predicted by the model after 30 sec are approximately independent of the wall temperature and the sticking coefficient.

The slow decay of the trapped atoms at longer times, when the gas has become decoupled from the wall, is consistent with dipole-dipole relaxation in the gas. For such a process $\dot{n}/n = -gn$, where g is the two-body rate constant. Integration over our trap geometry gives $\dot{N}/N = -0.21gN/V_{\text{eff}}$. Using the $\dot{N}$ and N from Fig. 3 at 6 min and assuming a temperature of 41 mK, we obtain $g = (1.2 \pm 0.5) \times 10^{-15}$ sec^{-1} cm^3. This agrees with the rate constant for the principal relaxation channels $(d+d \rightarrow a+a$ and $d+d \rightarrow d+a)$, $g = (2G_{dd,aa} + G_{dd,aa}) = 1 \times 10^{-15}$ sec^{-1} cm^3, that was calculated for $T=0$ by Lagendijk, Silvera, and Verhaar.[16] Such spin-flip processes are an important limitation on the densities and hold times achievable in static magnetic traps.[6,16] The dashed curve in Fig. 3 shows how the density would behave after 200 sec if the spin relaxation were turned off.

In conclusion, we have trapped atomic hydrogen in a static magnetic trap. The atoms are in the uppermost hyperfine state. This gas appears to be thermally isolated from its environment and at a lower temperature which is determined by evaporation over a magnetic potential barrier. We observe a loss mechanism associated with dipolar relaxation of the trapped atoms. This experiment demonstrates that the limitations imposed by surface processes on the temperature of a hydrogen gas can be avoided. Further evaporative cooling should be able to lower the temperature below 100 μK. Once the gas becomes this cold, quantum effects will become important.

This research is supported by the National Science Foundation under Grant No. DMR-85-13769. The experiments were carried out in the Center for Materials Science and Engineering at Massachusetts Institute of Technology. One of us (G.P.K.) would like to acknowledge the support of the AT&T Bell Laboratories Ph.D. Scholarship Program.

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