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Rapid Communications

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Evaporative cooling of magnetically trapped and compressed spin-polarized hydrogen

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A gas of spin-polarized atomic hydrogen can be prepared in the upper hyperfine states and loaded into a static magnetic trap. Evaporative cooling and magnetic compression of such a gas can produce temperatures of 30 μK and densities of 10^{14} cm^{-3}. Under these conditions a Bose-Einstein condensate may form.

The search for the Bose-Einstein transition has been the central goal of research on spin-polarized hydrogen.[1] However, the highest density so far achieved under controlled conditions,[2] 4.5×10^{18} cm^{-3}, is a factor of 50 less than the critical density at the typical operating temperature of 570 mK. The density is limited by a three-body recombination in the gas:[2–4] Attempts to reduce the value of the critical density by lowering the temperature are thwarted by three-body recombination on the surface. To achieve Bose-Einstein condensation in hydrogen under controlled conditions, some method must be found for eliminating the helium-lined walls of the confinement cells that have been employed in all of the research up to date. This Rapid Communication describes the general features of a method for cooling and compressing a gas of atoms which are confined in a static magnetic trap.

Atoms used in previous experiments have been in the lower two hyperfine states a and b, which are attracted to high magnetic fields. Those atoms cannot be confined solely by a static magnetic field since it is not possible to generate a magnetic field maximum in a current free region of space. The new method operates with the "low-field seekers," atoms in the upper two hyperfine states, c and d. These atoms are confined in a minimum of a magnetic field.[5] Energetic atoms ($E \geq E_{\rm th}$) are generated by collisions and are allowed to evaporate out of this potential minimum over the edge of this well with a threshold energy $E_{\rm th}$. The remaining confined gas is cooled. If $E_{\rm th}$ is much larger than the thermal energy or k_BT then the evaporation of a small fraction of the atoms will result in a large temperature drop. The gas may also be compressed. Both the temperature and density of the gas can be controlled by varying both the threshold potential energy and the volume of space with lower potential energy.

Figure 1 shows the proposed experimental arrangement. The atomic hydrogen source operates at a temperature of 0.5 K and is patterned after the helium-temperature source of Hardy, Morrow, Jochemsen, and Berlinsky.[6] Molecular hydrogen initially frozen to the walls is vaporized and dissociated by rf pulses. A sustained flux greater than 10^{14} atoms/sec has been achieved with such a design.[7] As can be seen from the magnetic field profile in Fig. 1, the strongest magnetic fields are at the source. Baffles first reduce the temperature of the atoms to T_s before they encounter a field gradient which sweeps the c and d atoms to the confinement region.

The atoms flow to the trap through a helium-coated tube and pass into the confinement cell whose initial surface temperature T_s is approximately 90 mK. As shown in Fig. 1(a), the magnetic trap consists of a quadrupole magnet and two pinch solenoids.[8] The quadrupole confines the atoms radially; the pinch solenoid confines the atoms axially. The bias solenoid assures that $|\mathbf{H}|$ never vanishes and prevents nonadiabatic spin flips due to the atom's motion. The radial potential profile is shown in Fig. 1(b). The initial well depth of the trap is $\mu H(R)=0.65$ K, which corresponds to a maximum trapping field of approximately 1 T. An important feature of Fig. 1(b) is the binding energy at the cell wall, $E_B=0.35$ K for a ^{3}He surface.

The entering hydrogen atom thermalizes with the cell surface at temperature T_s. This thermalization rate is $\Gamma_s=\alpha v/2R$, where v is the mean speed, $R=1.5$ cm is the cell radius, and α is the accommodation coefficient. Estimates for α range from 0.01 to 0.6.[9] The gas kinetic thermalization resulting from collisions between two atoms in free space occurs at a rate $\Gamma_g=\sqrt{2}nv4\pi a^2$, where

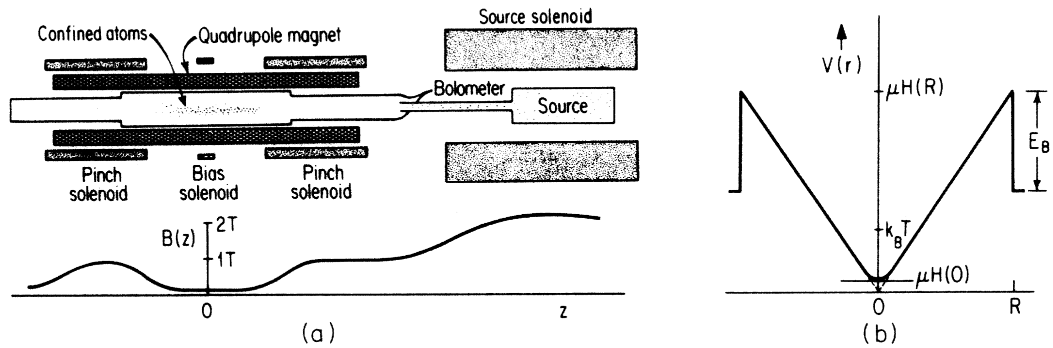

FIG. 1. (a) Schematic diagram of apparatus for production, confinement, and cooling of atomic hydrogen. The highest magnetic fields are at the source, and the lowest in the confinement region. (b) Potential energy of atoms as a function of radial distance from the axis. The dotted line near $r=0$ applies to a pure quadrupolar magnetic field. The bias solenoid produces a field $H(0)$ at $r=0$ to prevent nonadiabatic transitions to the lower hyperfine states. When the trap is emptied, $H(0)$ is reduced to zero.

the s-wave scattering length a is taken to be 0.7×10^{-8} cm,[10] and n is the density. Together these processes lead to the settling of atoms onto the potential energy minimum at the center of the trap.

The thermalization and trap loading process can be sabotaged in the initial stages by losses due to recombination and, more important, by the recombination heat load. The recombination heat load per unit area is given by the expression $\dot{q}=\varepsilon_R K_s \sigma_\uparrow \sigma_\downarrow$, where ε_R is the energy of recombination, the rate constant K_s is calculated[11] to be 1.2×10^{-5} cm^{2}sec^{-1} and $\sigma_\uparrow,\sigma_\downarrow$ represent the surface density of the upper and lower hyperfine states. The local surface densities in turn are related to the local bulk density by $\sigma=n\Lambda\exp(E_B/k_BT_s)$ where Λ is the deBroglie wavelength. In order for the temperature rise at the helium-cell boundary to be less than 50%, the initial density must be limited to 10^{13} cm^{-3} at $T_s=0.09$ K. This assumes worst case initial conditions with $n_\uparrow=n_\downarrow$, a uniform initial distribution of density, and a Kapitza resistance of $5\times10^{-6}/T^3$ (cm^2 K^{4}s/erg). At this density the values of Γ_s and Γ_g indicate that the gas takes 0.1 s to thermalize and expel the high field seekers. As the field gradients separate the two hyperfine species, the recombination rate rapidly decreases. Simultaneously, the gas density on axis will increase toward 10^{14} cm^{-3} as the gas settles into the trap minimum.

In order to cool the gas far below T_s, thermal contact with the surface must be broken. This contact is maintained by the flux of atoms that evaporate from the surface. By cooling the confinement cell to 30 mK or lower, surface evaporation is effectively stopped.

Once the trapped gas is isolated, it can be cooled by slowly reducing the height of the magnetic trap. The hot atoms escape and stick to the cold surface.[12] As this evaporation process proceeds, the gas temperature T falls.

The maximum rate of cooling is limited by the time needed to regenerate the population of energetic atoms in the Boltzmann tail. These atoms evaporate if their total energy is greater than the well depth $\mu(H(R)-H(0))\equiv\eta_{ev}k_BT$ where $\eta_{ev}\gg1$. In order to have successful cooling there must be many s-wave collisions among the less energetic atoms for every high energy evaporating atom that is produced. The number of collisions per evaporating atom can be parametrized by $S\exp(s\,\eta_{ev})$, where estimates give $S=1.3$ and $s=0.8$ in the range of interest.[13]

Aside from evaporation, the major process contributing to a loss of atoms is spin exchange between c-state atoms followed by dipolar electron-spin relaxation. The dominant spin-exchange collisions are of the type $c+c\rightarrow b+d$ and lead to the creation of a doubly polarized gas of d atoms as the b atoms are expelled. Subsequently spin-exchange plays no further role. The lifetime of the d atoms is limited by dipolar electron-spin relaxation. The leading process is $d+d\rightarrow a+a$, where the a atoms are promptly expelled from the trap. The relaxation rate can be written Gn, where G is 1×10^{-15} cm^{3}s^{-1} (Refs. 4 and 14) at 300 g. A figure of merit for thermalization versus relaxation is the ratio of the s-wave collision rate to the dipolar relaxation rate: $\Gamma_g/Gn\equiv g\sqrt{T}$. At 100 mK $g\sqrt{T}$ has a value of approximately 4000 s-wave collisions per relaxing atom. Relaxation becomes an increasingly important consideration at low temperatures since this figure decreases with the square root of temperature. The fraction of atoms f which escape from the trap by evaporation can now be expressed by

$$f=[1+S\exp(s\,\eta_{ev})/g\sqrt{T}]^{-1}\ . \tag{1}$$

The trapped gas of N atoms has a total energy that is the sum of the kinetic energy $\frac{3}{2}k_BTN$ and the potential energy $\mu\langle H\rangle N=Ck_BTN$. Atoms in the field of an infinite two-dimensional quadrupole for which $|H|=H'r$ would have $C=2$. For the present geometry, where the length is much larger than the diameter, $C\sim2$. As the magnetic field is lowered, energy is removed from this gas by the evaporating and relaxing atoms, and also by the changing fields themselves. The energy flow is described by

$$d/dt\,(\tfrac{3}{2}+C)k_BTN=\dot{Q}_{ev}+\dot{Q}_{rel}+\dot{Q}_H\ . \tag{2}$$

Atoms which evaporate by escape over a potential barrier of height $\mu H_{ev}=\eta_{ev}k_BT$ will typically have an excess kinetic energy of $2k_BT$. The evaporative cooling power is $Q_{ev}=(\eta_{ev}+2)k_BT\,fN$, where fN is the rate that atoms escape by evaporation. Similarly, atoms which relax will typically remove much less energy: $Q_{rel}=(\frac{3}{2}+C)k_B\times T(1-f)N$, where $(1-f)N$ is the rate of escape by relaxation. Energy is also changing due to external work, MdH. The PdV external work can be neglected if the size of the trapped gas cloud is constant, and H_{ev} and T follow one another so that η_{ev} is constant. Lowering the trapping field then results in a lower potential energy of the gas. For the quadrupole field this contributes a cooling term $\dot{Q}_H = \mu H' \langle r \rangle N = CkTN$. It follows that Eq. (2) can be reexpressed as

$$\frac{d\ln N}{d\ln T} = \frac{d\ln n}{d\ln T} = \frac{1}{\gamma} , \tag{3}$$

$$\gamma = \tfrac{2}{3}(\eta_{ev} + 2 - \tfrac{3}{2} - C) f , \tag{4}$$

when compression is neglected. If the cooling exponent γ is sufficiently large, the evaporation of a small fraction of atoms results in a large temperature drop.

The cooling exponent γ is a function of η_{ev} and T. In order to obtain optimum cooling it is important to maximize γ at each temperature. The condition $\partial\gamma/\partial\eta_{ev}|_T = 0$ defines the optimum barrier height to temperature ratio, η_{opt}, and therefore the optimum magnetic field. Values of $\eta_{ev} < \eta_{opt}$ result in inefficiencies since a larger flux of atoms with low energy evaporate. A higher value of η_{ev} results in excessive losses from the electron relaxation process. Typical initial values are $\gamma_{opt} \sim 4.5$ and $\eta_{opt} \sim 10$ for a two-dimensional quadrupole trap. η will tend to increase and become nonoptimum as the temperature falls. To prevent this it is necessary to lower the evaporation threshold $\mu H' R$ in proportion to the temperature. If the atoms are removed by sticking to fixed walls, the trapping field gradient must be lowered so that $\mu H' R / k_B T = \eta^{opt}$. The electron spin-flip cross section increases at lower temperature and reduces the value of γ_{opt}. Under these conditions, the spatial distribution changes very little during the cooling process. An integration of Eq. (3) yields the relationship between density and temperature. Such a cooling path is indicated by the dashed line in Fig. 2.

An alternate path can be followed on the n-T diagram of Fig. 2 by adiabatic compression or expansion. Raising the trapping field gradient H' quickly would stop evaporation and adiabatically heat and compress an ideal gas. This

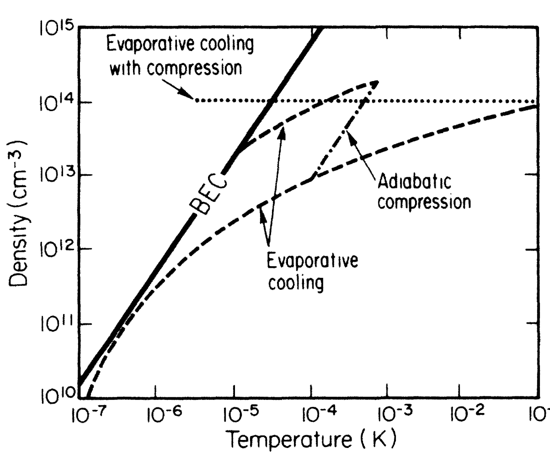

FIG. 2. Possible cooling paths. For evaporation without compression $\eta_{ev} = \eta_{opt}$ the path is indicated with a dashed line. A cooling process with compression is indicated with the dotted line. The densities and temperatures required for Bose condensation are indicated by the solid line.

path, where $d\ln n / d\ln T = \tfrac{3}{2}$, is indicated by the dot-dashed line in Fig. 2. A subsequent evaporation cycle onto a cold fixed wall at smaller radius can take the gas to lower temperatures of yet higher densities.

Actually cooling and compression can take place simultaneously if both the value of the evaporation threshold energy $\mu H_{ev} = \mu H' R$ and its spatial position R are under independent experimental control. Such schemes allow both η_{ev} and $\langle r \rangle \propto (N/n)^{1/2}$ to be independently optimized. The relationship between T, η_{ev}, the effective volume $V = N/n$, and the density at the center n can be expressed as

$$\frac{d\ln n}{d\ln T} = \frac{1}{\gamma}\left[1 + (\tfrac{2}{3} - \gamma)\frac{d\ln V}{d\ln T}\right] = \frac{d\ln N}{d\ln T} - \frac{d\ln V}{d\ln T} . \tag{5}$$

This is identical to Eq. (3) except that compression is now included.

There are many experimental ways to achieve simultaneous compression and cooling: A cold absorbing surface can be physically moved toward the trap minimum. Both the magnitude and spatial position of the pinch magnetic fields can be changed to control evaporation and compression along the axis. Similar control of radial evaporation and compression is feasible by superimposing an octopolar or dipolar field on the quadrupolar trapping field.

One possible cooling path where constant density is maintained, $d\ln n / d\ln T = 0$, is indicated by the horizontal line in Fig. 2. A gas of 10^{12} atoms with a density of 10^{14} cm^{-3} and a temperature of 30 μK can be achieved.

The simplest way to demonstrate trapping is to measure the number of atoms that can be released from the trap long after it has been filled. To expel atoms, nonadiabatic electron spin-flip transitions (Majorana flop) are induced by lowering the bias magnetic field until the residual field at the bottom of the trap [$H(0)$ in Fig. 1(b)] is less than 1 G. Field gradients cause the spin-flipped atoms to leave either end of the trap. Half of the atoms flow back toward the source where they are funneled and magnetically compressed into the end of a closed glass capillary. The density on this small surface area increases rapidly until recombination occurs. This bolometer is maintained at ~ 20 mK. A sensitivity of 10^8 atoms should be readily achievable.

Measurements of the total number of trapped atoms will be useful to determine the optimum conditions for filling and operating the trap. They can also serve to check the evaporative cooling process. The temperature of the gas can be deduced by studying how the number of escaping atoms varies with the height of the potential well μH_{ev}. Independent estimates of the gas temperatures can be deduced from the Majorana flop rate or the time required to detrap the atoms.

A more detailed study of the equation of state of hydrogen at low temperatures, requires more sophisticated diagnostic techniques. The highly nonuniform magnetic fields can be exploited to study the density profile of the gas.[15] Optical and electron spin-resonance imaging of this profile are convenient probes, for they can be applied to the magnetically confined gas without mechanical intrusion.

So far, the description of the cooling process is based upon classical Boltzmann statistics. These assumptions indicate that one can easily approach the quantum regime. Once close to the Bose-Einstein transition, the stability of a very degenerate atomic gas against electron relaxation must be reexamined. Whether a condensate can be produced with evaporative cooling and compression remains a tantalizing open question.

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[12]Although the probability for sticking per collision is small, the important parameter is the probability of sticking before colliding with another atom in the trap. At low densities the probability that an energetic atom sticks to the wall compared with the probability that it collides with another atom can be large. Under these conditions a wall can be considered highly absorbing.

[13]This estimate is based on the rate at which a Boltzmann distribution in the trap potential, truncated at $\eta_{ev} k_B T$ will generate atoms with energy greater than $\eta_{ev} k_B T$.

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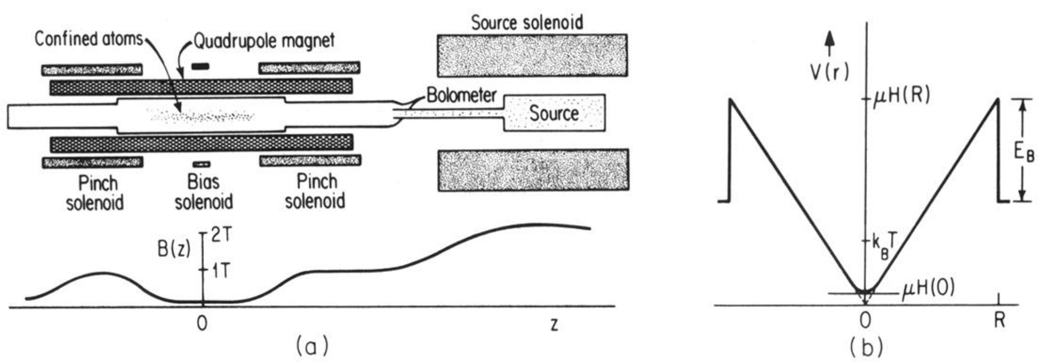

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