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RECENT DEVELOPMENTS IN SPIN-POLARIZED HYDROGEN

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ABSTRACT

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 microKelvin and densities of 10^{14} cm^{-3}. These techniques allow a new approach to creating doubly polarized hydrogen for source or target applications [1].

1. Background

Much of the recent progress in atomic spin-polarized hydrogen sources is motivated by achieving flux and lower temperatures. This is paralleled by the groups pursuing the Bose-Einstein transition of spin-polarized hydrogen [2] which is primarily a search for high density and low temperature. The maximum density so far achieved, $4.5x10^{18}$ cm^{-3}, is limited by three-body recombination [3-5]. The lowest temperature is constrained by the 1K binding energy of hydrogen to the liquid helium surface. These limitations have recently directed attention toward new approaches which eliminate the liquid helium as a confining surface and rely instead on magnetic gradients to trap the atoms.

This article describes the general features of a new method for trapping, cooling, and compressing a gas of hydrogen atoms which are confined in a static magnetic trap. The upper hyperfine states $|1\rangle$ and $|2\rangle$ (to use the convention of the polarized source community) can be confined in a free space minimum of the magnetic field [6]. The confined gas is cooled by evaporation. The gas can be compressed by this cooling process or by changing the magnetic field gradients. Various cooling and compression strategies are made possible by suitably manipulating the trap parameters.

2. A Trap for Spin-Polarized Hydrogen

Fig. 1 shows the proposed experimental arrangement. The atomic hydrogen source operates at a temperature of 0.5K and is patterned after the liquid helium-temperature source of Hardy *et al* [7]. Molecular hydrogen initially frozen to the walls is vaporized and dissociated by a pulsed rf discharge. As can be een from the magnetic field profile in Fig. 1, the source is at a magnetic field maximum H_D. The $|1\rangle$ and $|2\rangle$ atoms are swept toward the confinement region by the field gradient. Since $kT << \mu H_D$, the lower hyperfine states $|3\rangle$ and $|4\rangle$ remain in the source. The production and transport of $|2\rangle$ atoms from the source was observed in our laboratory. Using zero field NMR as a detector, a flux of $3x10^{12}$ atoms/sec into the confinement region was observed. Larger polarized flux should be possible with better

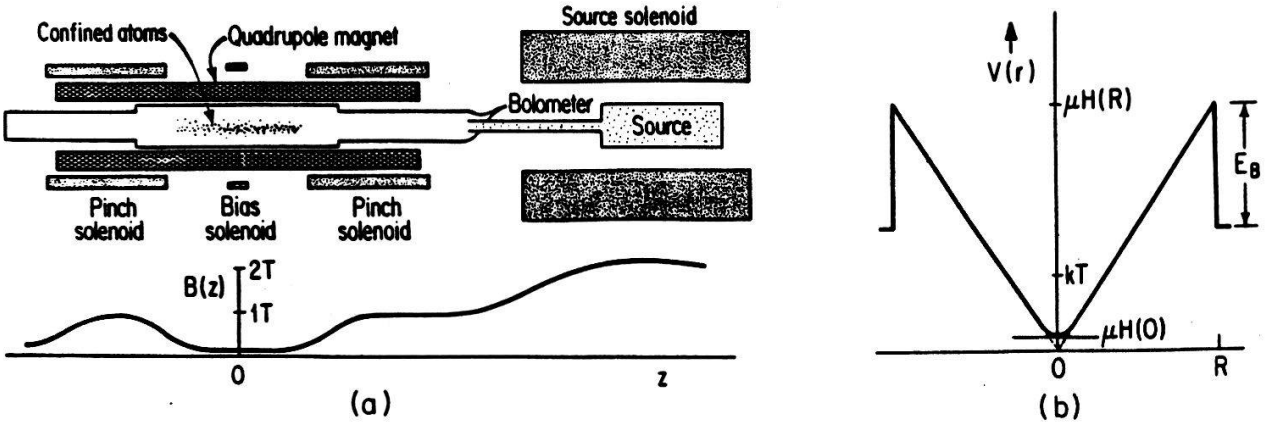

Fig. 1. a) Schematic diagram of apparatus for production, confinement and cooling of atomic hydrogen. The highest magnetic fields are at the source and the lowest in the confinement region, b) Potential energy of atoms as a function of radial distance from the axis. The dotted line near r = 0 applies 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.

thermalization and cooling of the hot atoms in the source.

The atoms flow to the trap through a helium coated tube and pass into the confinement cell whose surface temperature T_s is approximately 80 mK. As shown in Fig. 1a, 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 | H | never vanishes and prevents non-adiabatic spin flips due to the atom's motion. The radial potential profile is shown in Fig. 1b. The initial well depth of the trap is $\mu H(R) = 0.65K$, which corresponds to a maximum trapping field of approximately 1T. An important feature of Fig. 1b is the binding energy at the cell wall, E_b = 0.35K for a ^{3}He surface.

3. Filling the Trap

The entering hydrogen atom thermalizes with the cell surface at temperature T_s at a rate Γ_s. The gas kinetic thermalization resulting from s-wave collisions between two atoms in free space occurs at a rate Γ_g. Together these processes lead to the settling of atoms onto the potential energy minimum at the center of the trap. The competition between thermalization and the losses due to recombination and to relaxation plays a decisive role in determining the fraction of the atoms that are trapped. The principal loss mechanisms are surface processes; surface electronic relaxation, with rate Γ_{rel}, and surface recombination, with rate Γ_{rec}. To capture a large fraction of the atoms we require that $\Gamma_{rec}, \Gamma_{rel} < \Gamma_s, \Gamma_g$. These inequalities can be satisfied by maintaining the initial surface temperature T_s above 80 mK and having an initial gas density of 10^{13} cm^{-3}. The density on axis will increase toward 10^{14} cm^{-3} as the gas

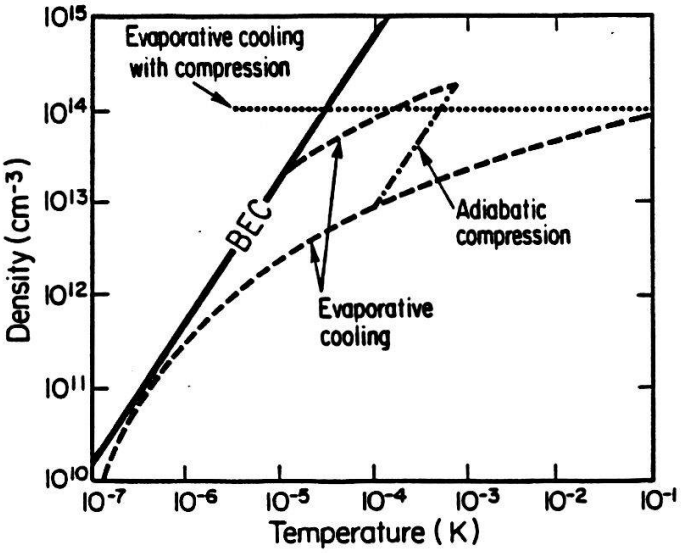

Fig. 2. Possible cooling paths. For evaporation without compression $\eta_{ev} = \eta_{opt}$ the path is indicated with a dashed line. A cooling process with compression is indicated with the dotted line. The densities and temperatures required for Bose condensation is indicated by the solid line.

thermally 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.

4. Cooling and Relaxation

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 [9]. 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 $\mu(H(R)-H(0))$. 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 $S\exp(s\,\eta_{ev})$. The barrier height to temperature ratio is defined by $\eta_{ev} \equiv \mu(H(R)-H(0))/kT$. Detailed modeling for the parameters S and s give S = 1.3 and s = 0.8 in the range of interest [10].

Aside from evaporation, the major process contributing to a loss of atoms is spin exchange between | 2> state atoms followed by dipolar electron spin relaxation. The dominant spin-exchange collisions are of the type | 2> + | 2> → | 1> + | 3> and lead to the creation of a doubly polarized gas of | 1> atoms as the | 3> atoms are expelled. Subsequently spin-exchange plays no further role. The lifetime

of the | 1> atoms is limited by dipolar electron spin relaxation. The leading process is | 1> + | 1> → | 4> + | 4> where the | 4> atoms are promptly expelled from the trap. The two body electron dipole relaxation rate can be written Gn where G = $1x10^{-15}$ cm^3 s^{-1} [5,11] at 300 gauss.

A figure of merit for thermalization vs. 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

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

5. Evolution of Density and Temperature

Energy is removed from the trapped gas by evaporation at a rate $(\eta_{ev}+2kT)fN$ where fN is the rate that atoms evaporate. Additional energy is removed by the escape of relaxed atoms and also by external work associated with changing magnetic fields. It can be shown that these cooling processes lower the temperature of the remaining trapped gas according to

$$\frac{d\ln N}{d\ln T}=\frac{d\ln n}{d\ln T}=\frac{1}{\gamma} \tag{2}$$

$$\gamma=\frac{2}{3}[\eta_{ev}-\frac{3}{2}]f \tag{3}$$

This assumes no compression of the trapped gas. If the cooling exponent γ is sufficiently large, the evaporation of a small fraction of atoms results in a large temperature drop. For constant γ an integration of Eq. 2 gives

$$\frac{T}{T_o}=(\frac{N}{N_o})^{\gamma} \tag{4}$$

6. Optimal Conditions for Cooling

The cooling exponent γ is a function of η_{ev} and T. In order to obtain optimum cooling γ must be maximized at each temperature. The condition $\frac{\partial\gamma}{\partial\eta_{ev}}|_T=0$ fixes the barrier height to temperature ratio, η_{opt}, and thus determines 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 for a two dimensional quadrupole trap are $\gamma_{opt}\sim4.5$ and $\eta_{opt}\sim10$. 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 $\frac{\mu H' R}{kT} = \eta^{opt}$. An integration of Eq. 2 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. 3 by adiabatic compression or expansion. Raising the trapping field gradient H' quickly would stop evaporation and adiabatically heat and compress an ideal gas. This path, where $\frac{d\ln n}{d\ln T} = \frac{3}{2}$, 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.

Cooling and compression can actually occur simultaneously. Several experimental strategies are possible. A cold absorbing surface can be physically moved toward the trap minimum. Alternatively, the magnitude and spatial position of the pinch magnetic fields can be changed to control evaporation and compression along the axis. In addition, radial evaporation and compression can be controlled by superimposing an octopolar or dipolar field on the quadrupolar trapping field.

One possible cooling path where constant density is maintained, $\frac{d\ln n}{d\ln T} = 0$, is indicated by the horizontal line in Fig. 2. A gas of 10^{13} atoms with a density of 10^{14} cm^{-3} and a temperature of 1 mK can be achieved. The lifetime of these atoms, is limited by electron relaxation, to about 20 seconds. This cold gas is easily confined by magnetic fields of 200 gauss.

7. Conclusion

The strategies proposed here for achieving Bose condensation are rather complex, but the basic principles of magnetic confinement and evaporative cooling are straightforward. Experimental work is in progress. The possibility of confining polarized hydrogen in free space may have eventual applications to polarized targets and sources.

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