Trapped Atomic Hydrogen

D. Kleppner
Research Laboratory of Electronics, MIT, Cambridge, MA02139, USA

1. INTRODUCTION

The rapid development of techniques for cooling and trapping atoms using laser light has created a new subfield of atomic physics. Research opportunities include the study of matter at ultra low temperature, ultra precise atomic spectroscopy and the study of light-matter interaction in a new quantum regime.

Unfortunately, the difficulty of generating UV light has so far excluded hydrogen from this research, though at least two groups are now undertaking to laser cool hydrogen. Nevertheless, interest in ultra cold hydrogen is considerable because of hydrogen's continuing appeal as a testing ground for theory. For example, the hydrogen constitutes an ideal candidate for studying low energy scattering phenomena and the weakly interacting Bose gas. As a candidate for ultra precise spectroscopy hydrogen remains pre-eminent for testing theory and evaluating the fundamental constants.

At MIT we have recently succeeded in trapping hydrogen and cooling it to the millikelvin regime using an approach far removed from laser cooling. Our method, which was developed in the course of research on spin-polarized hydrogen, is based on special cryogenic techniques, essentially low temperature "tricks" that one can play with hydrogen. These developments open the way to several new lines of research including very high resolution spectroscopy. Some consideration governing spectroscopy of the $1S \rightarrow 2S$ two-photon transition are discussed below, following a brief summary of the hydrogen trap.

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2. BACKGROUND: SPIN-POLARIZED HYDROGEN

Pursuit of the goal of observing Bose-Einstein condensation in atomic hydrogen has resulted in the creation of techniques for stabilizing hydrogen and storing it at temperatures below 1 K. Electronically spin-polarized hydrogen interacts by the predominately repulsive triplet potential and is consequently immune to the normal molecular recombination processes. The electron spins can be "pinned" by working in the temperature-field regime $\mu_o B > k_B T$, where μ_o is the Bohr magneton and k_B is the Boltzmann constant. At a field of 10 T, $\mu_o B/k_B = 6.6$ K. At a temperature of 0.3 K, the system is essentially 100% electron polarized. Spin-polarized hydrogen is formed by allowing cold atoms to flow into a high magnetic field. The "high-field seeking" states ("H$\downarrow$") are attracted, the "low-field seeking" states ("H$\uparrow$") are repelled.

Helium-covered surfaces are crucial for cryogenically cooling and trapping hydrogen. The binding energy of H on He^4 is only 1.0 K. This is so low that hydrogen can be cooled to 0.1K or less without undue adsorption. As the atoms flow into the magnetic field they are thermalized by surface collisions and cannot escape.

Unfortunately, the density of H$\downarrow$ is limited by a three body recombination process of the form $H\downarrow + H\downarrow \rightarrow H_2 + H\uparrow$. The highest density achieved under controlled conditions is 4.5×10^{18} atoms·cm^{-3}, at a temperature of 0.4 K. This is a factor of twenty too low for Bose-Einstein condensation.

A large body of experimental and theoretical literature exists on the properties of H$\downarrow$ in the temperature regime surrounding 0.3K. Because this information is well documented [1-3], we shall not review it here but turn instead to a new direction of the research.

The temperature for Bose-Einstein condensation varies with density as $n^{2/3}$. Because density is limited by three-body recombination, the search for the transition leads naturally to lower temperatures. Unfortunately, at temperatures below 0.1 K, adsorption rapidly becomes prohibitive. To avoid this problem, Hess [4] suggested confining the atoms in a magnetic trap without any surfaces. The states confined are the "low-field seeking" states, (H$\uparrow$, electron spin "up"). These are the hyperfine states $(F=1, m=1)$ and $(F=1, m=0)$.

3. THE HYDROGEN TRAP

The trap consists of a configuration of coils designed to produce a magnetic field minimum at its center, but without having a zero in the field. The geometry, which is essentially cylindrical, employs a configuration proposed by Pritchard [5]. Transverse trapping is provided by a quadrupole magnetic field. Longitudinal trapping is provided by a coaxial coil ("pinch solenoid") at each end which provides a barrier against leakage and a bias field at the center. The trap is loaded from a pulsed hydrogen discharge located in a high field. The gas "falls" into the potential well of the trap by inelastic collisions which isolate a population of atoms at a temperature significantly below the ambient temperature. In the first experiment [6], for instance, the gas was found to be at 40 mK when the ambient temperature was 70 mK. The temperature was inferred from the rate of escape as one of the pinch coils was lowered. The escaping atoms were monitored by a low-field hyperfine resonance detector. Further details are given in reference [6]. The geometry is shown in Fig. 1, and a pictorial view is provided in Fig. 2.

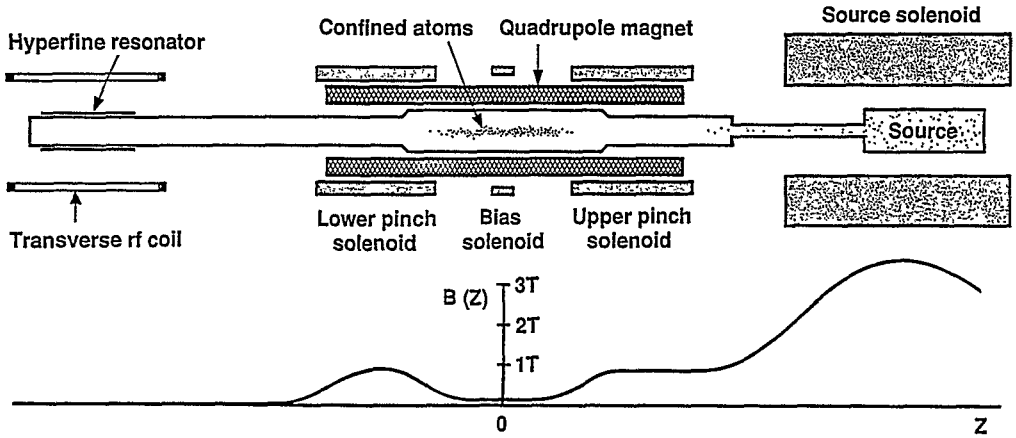

Figure 1. Schematic diagram of the MIT hydrogen trap, with magnetic field profile. (From ref. 7.)

The trapped gas can be further cooled by controlled evaporation as proposed by Hess [4]. The process is relatively efficient because the evaporating atoms have to surmount a high potential barrier and carry off energy substantially greater than the average thermal energy. Furthermore, the density in the trap stays approximately constant during the evaporation process because the loss of atoms is compensated by a decrease in temperature and the consequent decrease of the effective volume.

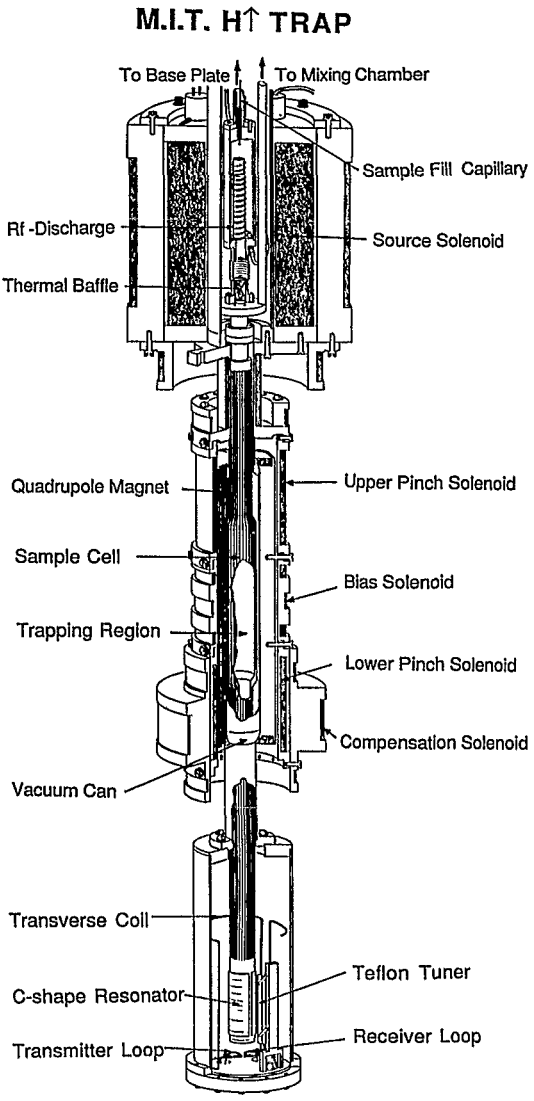

Figure 2. Pictorial diagram of the hydrogen trap. The magnets are immersed in liquid helium: the inner region of the trap is connected to a dilution refrigerator.

The trap is loaded in a time of a few seconds, and after a preselected delay its contents are dumped into the resonator region by lowering the field of one of the pinch solenoids. The signal from the hyperfine resonance detector provides a measure of the total number of atoms N in the trap. The stored atoms decay by dipole relaxation (described below) with a rate that is proportional to the density n. From values of N and n one can find the effective volume of the trap. The effective volume depends on the field geometry and the temperature. This roundabout route is

used to find the temperature. In a recent experiment [7] the gas was cooled to a temperature of 3 mK at a density of $7.6\times10^{12}\,cm^{-3}$. Further cooling to 1 mK was inferred from the data. It is evident, however, that a more direct method for studying the atoms is essential. A laser-based approach is attractive.

An important feature of laser cooling and/or trapping is the built-in diagnostic process method provides: the fluorescence constitutes a sensitive probe of the trapped gas. A number of schemes have been proposed for laser cooling hydrogen using the Lyman-α transition. However, the conventional Doppler cooling limit for this transition, $T = h\Gamma/2k_B$, is relatively high, approximately 15 mK (though it is now recognized that this does not constitute a fundamental limit). The recoil energy limit, $(h\gamma)^2/(2M_pc^2)$, is also high due to the high energy of the photon and the low mass of the atom: it corresponds to a temperature of 0.5 mK. Thus, laser cooling into the μK regime is a formidable task though, as Walraven has pointed out [8], there may be advantage to combining laser cooling with evaporation.

We have chosen optical excitation of the $1S \rightarrow 2S$ two-photon transition to study the trapped gas. Because the natural linewidth for this transition is only a few cycles, it is capable of yielding enormous spectral resolution. Consequently, two-photon excitation is capable of providing excellent momentum resolution for the gas and has the added attraction of offering a new possibility for carrying out ultra high resolution spectroscopy on hydrogen. It is the latter application which we discuss here. We note in passing that the two-photon transition is not well suited to laser cooling schemes: the 246 nm radiation is so effective at photoionizing the 2S state that the gas would be ionized before it is significantly cooled.

4. ULTRA HIGH RESOLUTION SPECTROSCOPY OF TRAPPED HYDROGEN

We summarize here some considerations affecting the potential accuracy of a spectroscopic measurement of the $1S \rightarrow 2S$ transition. We shall not dwell on the challenging problems of laser stabilization and optical frequency metrology, but only on the atomic considerations. In particular, we shall consider the major sources of line broadening and possible systematic shifts. We discuss below some of the factors which govern the accuracy of $1S \rightarrow 2S$ spectroscopy in the hydrogen trap.

NATURAL LINE WIDTH

The lifetime of the metastable state is $\tau_o = 1/7$ s. The "Q" of the transition is 2.2×10^{15}. In principle, the resonance can be located to a small fraction of the linewidth.

LIFETIME IN THE TRAP

The trapped hydrogen is in the hyperfine state F=1, m=1. The gas can decay by dipole relaxation to a lower-lying hyperfine state and escape from the trap. The decay rate is given by $\Gamma_d = nG$, where n is the total density and the factor G is approximately temperature independent. Lagendijk, Silvera and Verhaar [9] have calculated $G = 1 \times 10^{-15}$ cm^3·s^{-1}, which is in agreement with the observed value [7] $G = (1.2 \pm 0.5) \times 10^{-15}$ cm^3·s^{-1}. With a density of 10^{12} cm^{-3}, the lifetime is 10^3 s^{-1}. Dipole decay imposes a requirement on the supply rate of hydrogen to maintain the density, but does not limit the spectral resolution.

DOPPLER SHIFTS

First order Doppler broadening can be eliminated by using a standing wave geometry (i.e. oppositely running waves) to excite the two-photon transition. The fractional second order Doppler shift, $v^2/2c^2$, is less than 2×10^{-16} at a temperature of 1 mK.

ZEEMAN SHIFT

The $1S \rightarrow 2S$ transition obeys the selection rule $\Delta F = 0$, $\Delta m = 0$ and is almost field-independent. However, the g-factor for the bound electron is slightly less than for free space due to relativistic effects, and this gives the transition a small first-order field dependence. In the 1S state the g-factor is $g(1S) = g_e\,(1 - \alpha^2/3)$ [10]. The relativistic term is proportional to the binding energy so that $g(2S) = g_e\,(1 - \alpha^2/12)$. Thus, the field-dependence of the transition $1S \rightarrow 2S$, (F=1, m=1; ΔF=0, Δm=0) leads to a frequency shift

$$\nu_z = \frac{g_e}{2}\,\frac{\alpha^2\,\mu_o\,B}{4h} = 1.8 \times 10^5 \text{ Hz·B(tesla)} .$$

If the mean field can be determined to 10^{-5}T (0.1 gauss), ν_z is known to 1.8 Hz and the frequency uncertainty due to ν_z can be expected to be small. However, the trapping process demands that the atom sample a spatially varying field, and that can result in line broadening.

The characteristic spread in magnetic field is given by $\Delta B = k_B T/\mu_o$. For a temperature of 1 mK, $\Delta B = 1.6\times10^{-3}$ T, and the spread in ν_z is $\Delta\nu_z = 300$ Hz. For a temperature of 30 μK the linewidth is 10 Hz. Thus, Zeeman-broadening in the trap is potentially significant. However, as described below, it is reduced by motional averaging effects.

The 2S state has a large electron polarizability due to the proximity of the 2P state. Motion through the magnetic field produces an electric field $E_m \cong (v/c)B$. This field can lead to the quenching of the 2S state, and a Stark shift. The quenching rate is $\Gamma_s \cong |V|^2/\Gamma_{2p}$, where $B^2 = |\langle 2S|ezE|2P\rangle|^2$, and Γ_{2P} is the radiative decay rate of the 2P state. At a temperature of 1 mK, $\Gamma_s \cong 10^{-3}\,s^{-1}$. The Stark shift is smaller by a factor of approximately ten, and is also negligible.

MOTIONAL AVERAGING

Zeeman broadening can be reduced by motional averaging providing that the rate at which the atom transverse the trap is large compared to the Zeeman frequency spread. The average linewidth is given by

$$\Delta\nu_z' \cong 2\pi(\Delta\nu_z)^2\tau_c$$

where τ_c is the correlation time in the field. We can regard $\eta = (2\pi\Delta\nu_z\tau_c)^{-1}$ as a narrowing factor. For a harmonic (but anisotropic) trap, $\tau_c \cong \omega_t^{-1}$, where ω_t is the natural frequency in the trap. Taking $B(r) = B_o\, r^2/a^2$, where B_o is the magnetic field at some characteristic radius r = a, measured with respect to the trap minimum, then

$$\tau = (Ma^2/2\mu_o B_o)^{1/2},$$
$$\eta^{-1} = (\pi\alpha^2/2\sqrt{2})(a/h)(M\mu_o B_o)^{1/2}.$$

If we choose a to be the effective radius of the trapped sample, then $\mu_o = k_B T$. and we have $\eta^{-1} = (\pi\alpha^2 a/2\sqrt{2}\,h)(Mk_B T)^{1/2} = 4.3\,a\sqrt{T}$, where a is the radius in cm, and T is the temperature in mK.

Motional averaging puts a high premium on a small trapping volume - i.e. a "stiff" trap. For a = 0.1 cm, the narrowing factor is 2.5 at 1 mK, and 15 at 30 μK. In the latter case, the contribution to the linewidth due to the Zeeman effect is 0.7 Hz, which is unimportant.

OTHER CONSIDERATIONS

The ideal conditions for studying an atom is to have it at rest in free space, or in free fall as in a "fountain" experiment. Any process which confines an atom perturbs it. However, as has been shown, at ultra low temperatures the perturbations of hydrogen due to a magnetic trap are small. Furthermore, the trap provides an enormous advantage in density compared to atomic beams or fountains: density of $10^{11} \sim 10^{12} cm^{-3}$ is readily available. Thus, the trap is particularly attractive from the point of view of signal to noise ratio.

A number of schemes are available for observing optical resonance in the trap. A straightforward technique is to quench the 2S state with a small electric field (or possibly by collisional quenching) and observe the Lyman-α emission. Most of the quenched atoms will escape from the trap, but the loss rate is so small that its effect on the density would be negligible.

5. SUMMARY

The recently developed hydrogen trap provides an opportunity to extend the precision of hydrogen spectroscopy into new regimes of accuracy. Carrying forward such a program, however, requires developing methods for introducing laser light into the trap— not a simple matter in the ultra low temperature regime— and for observing the fluorescence. It also puts great demands on optical metrology, but since advancing the art of metrology is a central goal for this enterprise, and so such a struggle is not only inevitable, it is healthy.

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