Optical Cooling of Atomic Hydrogen in a Magnetic Trap

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We present the first experimental demonstration of optical cooling of atomic hydrogen. Two methods are discussed: Doppler cooling, for which we report a minimum achieved temperature of 8 mK, and light-induced evaporation, a new cooling method by which we reached 3 mK.

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In the active field of optical cooling [1], atomic hydrogen (H), the simplest and theoretically most accessible atomic species, has until now defied experimental investigation. The reason is that H cannot be manipulated with the powerful techniques developed to optically cool and trap, e.g., Na and Cs [1–5]. The light source required for that purpose, a laser at wavelength $\lambda = 121.6$ nm to excite the $1^2S \rightarrow 2^2P$ transition in H (Lyman-α, L_α) is not available. H can, however, be loaded into a magnetic trap with a cryogenic filling technique exploiting interatomic collisions and heat exchange with liquid helium covered surfaces [6–10]. This approach is only possible with H because of its extremely small energy of physisorption (~ 1 K) on liquid helium. Long-lived samples of relatively high density ($n \gtrsim 10^{11}$ cm^{-3}) spin-up polarized gas (H$\uparrow$) are produced in this way, which offers the opportunity to study collisional phenomena and to apply evaporative cooling [6–10]; Doyle *et al.* [9] have reached temperatures down to ~ 100 μK, providing confidence that it should be possible to observe degenerate quantum behavior in gaseous H. Recently we introduced pulsed L_α radiation to enable *in situ* determination of the temperature and density of magnetically trapped H by a spectroscopic technique and to investigate the dynamics of evaporative cooling [10].

In this Letter we report the first demonstration of optical cooling of magnetically trapped H, using both Doppler cooling and light-induced evaporation (LIE). Optical cooling and spectroscopy of magnetostatically trapped Na atoms was demonstrated previously by Helmerson, Martin, and Pritchard [11] for the collisionless regime. In our experiments we use a *single* beam of *pulsed* radiation ($\sim 10^{-6}$ duty cycle) and rely on elastic collisions between the trapped atoms to maintain conditions close to internal thermal equilibrium. The cooling proceeds in minutes rather than milliseconds, slow in comparison to the interatomic collision rate ($\tau_c^{-1} \sim 0.1$–10 s^{-1}), but much faster than the sample decay rate due to spin-flip collisions ($\tau_d^{-1} \sim 10^{-5}$–10^{-3} s^{-1}).

The LIE method is complementary to Doppler cooling in that it is primarily suited for high density samples (optically thick regime) and starting temperatures close to the Doppler limit. As proposed in the literature [12,13], LIE is the optical analog of ordinary forced evaporative cooling [8,9] and as such is based on the preferential removal of atoms with higher than average potential energy. In LIE this is accomplished by optically pumping the low-field seeking H$\uparrow$ to nontrapped states (H$\downarrow$). The four $1S$ hyperfine states are labeled a and b (H$\downarrow$) and c and d (H$\uparrow$) in order of increasing energy [12]. Except immediately after loading the trap, the c-state population is typically much smaller than that of the d state as the former population decays preferentially due to rapid spin-exchange relaxation [14].

The magnetic trap used in the present experiments was developed previously in our laboratory [7,10]. The trapping field at position $\mathbf{r}$ is given by $B(\mathbf{r}) = (B_\perp^2 + B_z^2)^{1/2}$, where $B_\perp \approx \alpha\rho$ is the field component normal to the trap axis at radial distance ρ and $B_z \approx B_0 + \beta z^2$ is the parallel component. $B_0 \simeq 0.1$ T is the field at the trap minimum [15]. The trapping potential for H$\uparrow$ is given by $U_p(\mathbf{r}) \simeq \mu_B[B(\mathbf{r}) - B_0]$, where μ_B is the Bohr magneton. The H density is distributed according to $n(\mathbf{r}) = n_0 \exp[-U_p(\mathbf{r})/k_BT]$, where n_0 is the density at the trap center. The total number of particles $N = \int n(\mathbf{r})d^3r \equiv n_0 V_{1e}$. For our trap

$$V_{1e} \approx V_0[1 + \tfrac{3}{2}(T/T_0)](T/T_0)^{3/2} , \qquad (1)$$

where $V_0 = 2\pi^{3/2}B_0^{5/2}\alpha^{-2}\beta^{-1/2}$ and $T_0 = \mu_B B_0/k_B$ [15]. The internal energy of the gas is given by the expression $U = (\gamma + \frac{3}{2})Nk_BT$, where $\gamma Nk_BT = \int U_p(\mathbf{r})n(\mathbf{r})d^3r$ is the potential energy and $\frac{3}{2}Nk_BT$ is the kinetic energy. Notice that $\gamma = (T/V_{1e})(\partial V_{1e}/\partial T)$.

The L_α source is based on nonresonant third-harmonic generation of frequency-doubled pulse-amplified light from a tunable cw dye laser operated at 729.4 nm [12,16]. Typically we produce 2×10^9 L_α photons per 10 ns pulse at a repetition rate of 50 Hz. In the present experiment the light power at the site of the sample is about 3×10^7 photons/pulse as inferred from optical pumping rates; this corresponds to an intensity a factor of 100 below saturation. Spectra are recorded by sweeping the frequency of the dye laser and monitoring the L_α transmission with a photodiode mounted at the end of the cell. From spectra taken at the lowest temperatures (~ 3 mK) we infer that the L_α bandwidth does not exceed ~ 100 MHz. Since the pulse is long compared to the radiative lifetime,

we consider the light to be cw, incorporating pulse-length effects [17] into the finite bandwidth.

To determine T and n_0 of the trapped gas, the transmission spectra are compared to calculated spectra. The propagation of the complex electric field amplitude $\mathbf{E}$ through the sample is described by

$$\frac{\partial \mathbf{E}(\mathbf{r})}{\partial z} = \frac{i}{2} k \overleftrightarrow{\chi}(\mathbf{r})\, \mathbf{E}(\mathbf{r}), \tag{2}$$

where

$$\overleftrightarrow{\chi} = i \frac{6\pi^{3/2}}{k^3} \sum_{j,l} n_l(\mathbf{r}) \frac{\mathbf{D}_{lj} : \mathbf{D}^*_{lj}}{\sum_f |\, \mathbf{D}_{fj}\,|^2} \frac{\Gamma}{2b} w(\zeta)\ . \tag{3}$$

Here $\overleftrightarrow{\chi}$ is the susceptibility tensor, $k = 2\pi/\lambda$, $b = k(2k_BT/m)^{1/2}$, Γ is the natural linewidth ($\Gamma/2\pi \sim$ 100 MHz), and $\mathbf{D}_{lj}$ is the transition dipole matrix element between hyperfine level l of the ground state and excited state j. Further, $n_l(\mathbf{r})$ is the density of l-state atoms and $w(\zeta) = e^{-\zeta^2}\mathrm{erfc}(-i\zeta)$ with $\zeta \equiv (\omega - \omega_{lj} + i\Gamma/2)/b$. The real part of $w(\zeta)$ is the Voigt profile describing a Doppler-broadened line. Three σ transitions and two π transitions are allowed in pure d-state gas [see Fig. 1(c)]. For $T \lesssim 20$ mK and $n_0 \gtrsim 10^{11}$ cm^{-3} the transmission is determined by the size of the shadow cast by the sample rather than by Doppler or Zeeman broadening. Even when the sample is optically thick, the detected signal is not zero as in this temperature regime the effective diameter of the sample is smaller than that of the incident L_α beam. Since the sample cross section is proportional to T, spectroscopic thermometry remains possible. Measuring a spectrum takes 10–30 s. To monitor processes occurring on a shorter time scale, we record the transmission at three frequencies (ν_1, ν_2, and ν_3) selected on a pulse-to-pulse basis using acousto-optic modulators [10,16]. For known L_α polarization and c-state population (determined from full spectra), these three values still allow us to infer T and n_0 by a fitting procedure.

To observe Doppler cooling, the gas has to be thermally isolated from the walls of the sample cell. In the present experiments this is accomplished by cooling the cell to temperatures $T \lesssim 80$ mK at which the walls act as a sorption pump cooling the gas evaporatively to ~ 50 mK (for a trap depth of 0.6 K) [10]. Doppler cooling is demonstrated in Fig. 1(a). We show transmission data for the π_1 and σ_1 transitions as recorded before and after irradiating the sample for 15 min at the indicated frequency ν_1 corresponding to the position of maximum slope in the red wing of the σ_1 line. The σ_1 transition is selected because of the five allowed transitions it is the only one with a closed optical pumping cycle. The fitted curves indicate Doppler cooling from 80(10) mK to 11(2) mK accompanied by an increase of n_0 by a factor of 16. To monitor T and n_0 while the cooling is in progress, every 15 s the transmission is measured at frequencies ν_2 and ν_3 (for 0.5 s each). The resulting trajectory in the T-n_0 plane is shown in Fig. 2.

To compare these data with theory we calculated the Doppler cooling rate by considering the energy of an atom before and after scattering a photon. The energy difference, averaged over the direction of the scattered photon, is $\hbar\mathbf{k}\cdot\mathbf{v} + 2E_r$, where $\mathbf{v}$ is the initial velocity of the atom and $E_r = \hbar^2k^2/2m$ is the photon-recoil energy. After integrating over the thermal velocity distribution, we may write the rate of change of internal energy as

$$\dot{U}(\omega) = \int 2E_r \frac{I(\mathbf{r})}{\hbar\omega}\left(1 - \frac{k_BT}{\hbar}\frac{\partial}{\partial\omega}\right) n(\mathbf{r})\sigma(\omega,\mathbf{r})d^3r\,, \tag{4}$$

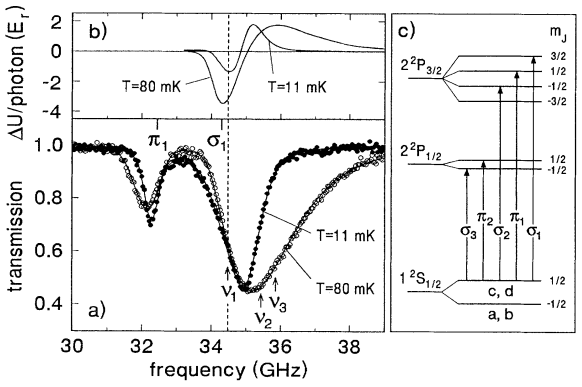

FIG. 1. (a) Transmission spectra before (open circles) and after (closed circles) Doppler cooling. The solid lines are calculated spectra for $T = 80(10)$ mK, $n_0 = 8(2)\times10^{10}$ cm^{-3} and $T = 11(2)$ mK, $n_0 = 1.3(4)\times10^{12}$ cm^{-3}, respectively. Resonant frequencies for the π_1 and σ_1 transitions at the trap minimum are indicated. (b) Energy change of the gas per incident photon in units of recoil energy (E_r). (c) Energy level diagram showing L_α transitions from H↑. Hyperfine splittings are not resolved on this scale.

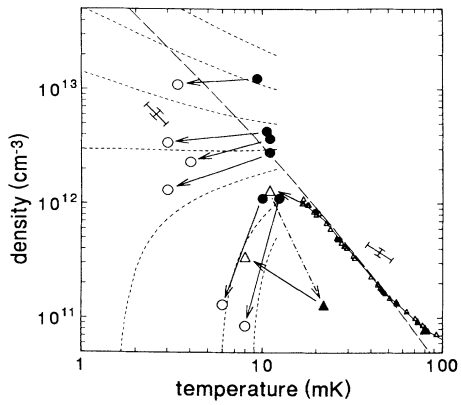

FIG. 2. Cooling trajectories in the T-n_0 plane. Triangles indicate Doppler cooling data, which are compared to a constant-atom-number trajectory (long-dashed line). Circles indicate starting and ending points of several LIE experiments. Also shown (short-dashed line) are LIE trajectories from a simple model (see text). The error bars indicate typical systematic errors.

where $n(\mathbf{r})\sigma(\omega,\mathbf{r}) = k\,\mathrm{Im}(\epsilon^* \cdot \overleftrightarrow{\chi} \cdot \epsilon)$ is the extinction coefficient, ϵ the polarization vector, and $I(\mathbf{r})$ the light intensity. A similar expression is given by Wineland and Itano [18]. The first term between parentheses describes the heating due to photon recoil and the second term the Doppler cooling. For optically thin samples I is constant and the cooling rate is proportional to the gradient in the transmission spectrum. To obtain $\dot{U}(\omega)$ for optically thick samples, Eq. (4) must be numerically integrated using Eq. (2). In Fig. 1(b) we show the energy change per incident photon versus frequency, calculated using n_0 and T obtained from the fits to the corresponding spectra.

In Fig. 2 the trajectory in the T-n_0 plane is compared to a curve obtained for constant particle number using Eq. (1) [15]. Cooling is accompanied by compression, since V_{1e} decreases with T. The initial deviation from the theoretical curve, above 50 mK, is caused by additional cooling due to evaporation. The final deviation is due to two loss mechanisms: spurious optical pumping to H$\downarrow$ and dipolar relaxation. Optical pumping to H$\downarrow$ occurs at the frequency ν_1 [see Fig. 1(a)] with an overall probability of $\sim 0.3\%$ per scattered photon via the blue wing of the π_1 transition. Dipolar relaxation is a two-body process and therefore prominent at high density [14]. Aside from particle loss, relaxation also gives rise to heating as it occurs preferentially near the center of the trap where the potential energy per atom is less than average. Both heating and particle loss are observed by letting the sample evolve in the dark for 37 min after the cooling period is terminated (see dash-dotted line in Fig. 2). By applying Doppler cooling once more, the sample is subsequently cooled to $T \approx 8$ mK.

For free atoms the lowest temperature achievable with Doppler cooling is $T = \frac{1}{2}\hbar\Gamma/k_B \approx 2.4$ mK. Due to Zeeman broadening in our inhomogeneous field, this Doppler limit is slightly increased to 3.1 mK. At high density the Doppler limit is further increased by multiple scattering and relaxation heating. To estimate the effect of multiple scattering we performed a Monte Carlo simulation which indicated that the photons escape after less than two scattering events, at least up to $n_0 \approx 10^{13}$ cm^{-3}. We attribute this to the highly anisotropic trapping potential (the length to width ratio of the gas cloud ~ 20). Nevertheless the simulation indicates that the Doppler limit is increased to about 5–7 mK, close to the lowest observed temperature. Dipolar heating leads to a further increase which depends on n_0.

To cool the gas below 10 mK we have used the new method of LIE. By irradiating the sample on the σ_2 transition, which has a branching ratio $f \approx 0.6$ for decay to H$\downarrow$ (untrapped), atoms are optically pumped out of the trap. In principle the Zeeman shifts could be used to excite the atoms selectively at high potential energy. However, this does not lead to efficient cooling as a result of long-range Lorentzian tails and the exponentially small density at high energy. Our method is primarily based on shielding of the atoms near the trap minimum by complete extinction of the light before it reaches the center of the gas cloud. Clearly this feature distinguishes the cooling technique from velocity-selective methods, as it relies on the fact that the sample is optically thick. We will show that if the density of the gas drops below a critical value, the cooling efficiency is quickly reduced but if the initial density is sufficiently high (for our trap $\gtrsim 10^{12}$ cm^{-3}), the cooling proceeds in a self-regulating manner. In principle LIE is suitable for achieving temperatures below the photon-recoil limit (0.6 mK).

In Fig. 3 we show that LIE indeed leads to cooling. Two spectra are shown, taken before and after optical pumping on the σ_2 transition. The sample is first precooled using regular evaporative cooling, by lowering the trap depth to 60 mK. Then the first spectrum is recorded, from which the initial values $T = 11(2)$ mK, $n_0 = 4.8(2.1) \times 10^{12}$ cm^{-3} are determined. The sample is then irradiated for 40 s with right circularly polarized light at a frequency which is continuously adjusted to remain close to the value which leads to optimal cooling (see below). After LIE another spectrum is taken which shows that the gas has cooled to $T = 3(1)$ mK. To confirm that the cooling was indeed due to LIE, a second sample was prepared in an identical manner but was left to evolve in the dark for 40 s. No significant changes in T and n_0 were observed in this case. To ensure high starting densities, the evaporative precooling is performed rapidly and as a consequence the c state is not yet fully depopulated when the LIE is initiated. This can be seen clearly in the 3 mK spectrum, where the hyperfine structure starts to be resolved. The line labeled σ_c^* corresponds to excitation to the $^2P_{3/2,m_J=-3/2}$ state and is strictly forbidden for d-state atoms but weakly allowed

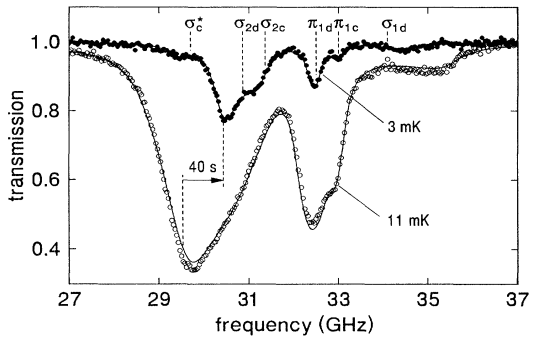

FIG. 3. Transmission spectra before (open circles) and after (closed circles) LIE cooling. The solid lines are calculated spectra for $T = 11(2)$ mK, $n_0 = 4.8(2.1)\times10^{12}$ cm^{-3} and $T = 3(1)$ mK, $n_0 = 3.9(1.7)\times10^{12}$ cm^{-3}, respectively. The subscripts c and d refer to transitions from the corresponding ground states. The c-state fraction $n_{c0}/n_0 \sim 0.1$. For the various lines the transition frequencies at $B = B_0$ are indicated.

for c-state atoms.

To clarify the LIE method, we will use a simple model. Removing the atoms (optically) at potential energy $\eta k_B T$ and at a rate τ_e^{-1} chosen such that $\tau_c \ll \tau_e \ll \tau_d$, the internal energy changes according to $\dot{U} = \eta \dot{N} k_B T$ and the rate of change of the gas temperature is given by

$$\frac{\dot{T}}{T} = \frac{\eta - \gamma}{\gamma + T(\partial\gamma/\partial T) + \frac{3}{2}} \frac{\dot{N}}{N} . \tag{5}$$

We calculate η for given n_0 and T by retaining the potential energy bookkeeping while propagating the light through the sample using Eq. (2). The results of this calculation can be represented by the following semiempirical expression in the temperature range 1–10 mK:

$$\eta_m = \ln[n_0/n_1 + \exp(\gamma)] . \tag{6}$$

Here η_m is the value of η when the frequency is tuned to the point of minimum transmission on the σ_2 line. The characteristic density $n_1 \approx 1.6 \times 10^{11}$ cm^{-3} is independent of temperature and of the order of the density at which the resonant extinction length equals the sample length $l_s \equiv (\pi k_B T/\mu_B \beta)^{1/2}$. The physical basis for Eq. (6) is that for $n_0 \gg n_1$ (which is well satisfied in the LIE experiments) most of the light is absorbed in a narrow shell of positions $\mathbf{r}$ satisfying $n_1 \approx n_0 \exp[-U_p(\mathbf{r})/k_B T]$. Then, $\eta_m k_B T$ is just the potential energy of atoms in this shell. Using Eqs. (5) and (6), converting N to n_0 using Eq. (1), and eliminating time, we obtain the trajectories in the T-n_0 plane. In Fig. 2 these trajectories are shown and compared with experimental data. Clearly there is qualitative agreement between the data and the simple model. Particularly, the feature that the cooling proceeds more efficiently (fewer atoms lost) for higher starting density is prominent. The predicted increase of n_0 at higher densities is not observed. This can be traced back to atom loss due to intrinsic decay, i.e., $\tau_e \ll \tau_d$ no longer holds.

The ultimate limits of either of the two cooling methods discussed have not been fully explored in this work. The maximum achievable density is determined by competition between compression due to optical cooling and atom loss due to dipolar decay. A moderate increase in light intensity will enable achievement of higher densities and render Doppler cooling a suitable method for precooling to the regime where LIE becomes effective. With 10 times higher power, it seems entirely feasible that LIE can be employed to reach temperatures below the photon-recoil limit at densities in excess of 10^{14} cm^{-3}. To investigate the microkelvin regime transmission spectroscopy is not suitable as the samples become very small. We therefore intend to turn to fluorescence measurements.

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