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PHYSICA B

Evaporative cooling of magnetically trapped atomic hydrogen

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We present a new model describing the dynamics of the evaporative cooling of a sample of trapped particles. We compare the results of the model with recent optical measurements of the evolution of the density and the temperature of magnetically trapped atomic hydrogen during evaporative cooling.

Evaporative cooling of magnetically trapped atomic hydrogen, first proposed by Hess [1], is considered a very promising technique for attaining Bose-Einstein condensation. Recently we performed Lyman-α spectroscopy of magnetically trapped H enabling *in situ* determination of the density and the temperature of the trapped gas [2]. We applied this new optical technique to study the dynamics of evaporative cooling under very well defined conditions. In this contribution we present a model for the evolution of density and temperature which contains no adjustable parameters, and compare it with the experimental data.

Consider a gas of particles trapped in a potential well $U_p(\vec{r})$. The gas is surrounded by an adsorptive wall which coincides with a surface of constant potential energy: $U_p(\vec{r}) = \epsilon_t$. Particles with a total energy $U_p(\vec{r}) + p^2/2m$ less than ϵ_t are trapped in the potential well whereas particles colliding with the wall, which have an energy greater than ϵ_t, adsorbe and are lost from the sample forever. The particles interact with each other through s-wave elastic collisions, characterized by an energy independent cross section σ. Collisions produce particles on wall-intersecting trajectories, which stick on the wall and are removed from the gas. As the particles which are removed have energies larger than the average energy, the remaining gas is cooled. This process is called evaporative cooling. Elastic collisions between the trapped particles are essential to keep the evaporation going.

We assume that the rate at which particles are scattered into wall-intersecting orbits is much smaller than the collisional internal equilibration rate, so that the trapped gas may be described during the evaporation as evolving in quasi-equilibrium.

In thermal equilibrium the phase space distribution function f of particles in a potential $U_p(\vec{r})$ in the absence of adsorptive walls is given by

$$f(\vec{r},\vec{p}) = n_0(2\pi m k_B T)^{-3/2} \times \exp[-(U_p(\vec{r}) + p^2/2m)/k_B T]. \quad (1)$$

The density n_0 is chosen in such a way that the total particle number $N = \int f(\vec{r},\vec{p})\, d^3r\, d^3p$, where the integration is over the available phase space. We define the effective volume of the system by $V_e \equiv N/n_0$. V_e depends on the temperature T and the specific shape of the potential U_p. Knowing the T-dependence of V_e the total energy E of the gas can be derived:

$$E = (\gamma + 3/2) N k_B T, \quad (2)$$

where $\gamma \equiv (T/V_e)\partial V_e/\partial T$. For a harmonic potential $\gamma = 3/2$.

To enable an analytical treatment of the evaporation process we make the second assumption that any particle coming out of a collision with a total energy $U_p + p^2/2m \geq \epsilon_t$ will actually collide with the wall and be removed from the sample.

As a result of the two assumptions the particle distribution during the evaporation can be described by $f(\vec{r},\vec{p})$ (Eq. (1)), truncated in phase space at the $U_p(\vec{r}) + p^2/2m = \epsilon_t$ surface. Using this distribution we calculate the particle loss rate $\dot{N}_{ev}$ due to evaporation:

$$\dot{N}_{ev} = -\frac{4}{3\sqrt{\pi}} n_0^2 \sigma \bar{v} V_{3/2}. \quad (3)$$

Here $\bar{v} = \sqrt{8k_BT/\pi m}$ and the volume V_ν is de-

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$$V_\nu \equiv \int_{U_p \le \epsilon_t} d^3r \exp[-U_p(\vec{r})/k_BT] \times \int_0^{y_m} dy\,(y_m - y)y^\nu \exp(-y), \quad (4)$$

with $y_m = [\epsilon_t - U_p(\vec{r})]/k_BT$. A similar calculation yields an expression for the energy loss rate of the trapped sample due to evaporation:

$$\dot{E}_{ev} = \dot{N}_{ev}\left\{\epsilon_t + \frac{2V_{5/2}}{5V_{3/2}}k_BT\right\}. \quad (5)$$

For the postulated phase space distribution Eqs. (3), (4), and (5) give an exact description of the evaporation process (no adjustable parameters), in contrast to the phenomenological approach of ref. [2]. If we equate the rate of change of the energy E (Eq. (2)) to $\dot{E}_{ev}$, we arrive at the following equation describing the temperature evolution:

$$\frac{\dot{T}}{T} = \frac{\dot{E}_{ev} - \dot{N}_{ev}(\gamma + 3/2)k_BT}{(\gamma + T(\partial\gamma/\partial T) + 3/2)Nk_BT}. \quad (6)$$

The particle loss is given by

$$\frac{\dot{N}}{N} = \frac{\dot{N}_{ev}}{N} - \tau_1^{-1}, \quad (7)$$

where we introduced a phenomenological decay time τ_1 to account for particle loss due to background gas, not affecting the temperature.

We have used the above model to describe evaporative cooling of magnetically trapped atomic hydrogen. The magnetic field in our Ioffe trap can be approximated quite accurately by

$$B(r,z) = \sqrt{\alpha^2r^2 + (B_0 + \beta z^2)}. \quad (8)$$

The potential energy of the H atoms is given by $U_p(r,z) = \mu_B[B(r,z) - B_0]$. The elastic scattering cross section $\sigma = 8\pi a^2$, where $a = 0.72\,\text{Å}$ is the s-wave scattering length.

For a potential of the form (8) we have obtained closed expressions for V_e, γ, $\dot{N}_{ev}$, and $\dot{E}_{ev}$ in terms of ϵ_t and the trap parameters α, β, and B_0. In our experiment $\alpha = 2.2\,\text{T/cm}$, $\beta = 0.023\,\text{T/cm}^2$, and $B_0 = 0.1\,\text{T}$. The well depth is 1.2 T corresponding to $\epsilon_t/k_B = 0.8\,\text{K}$.

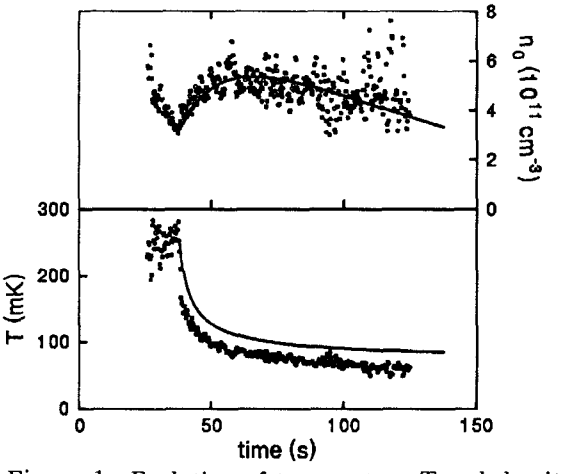

Figure 1: Evolution of temperature T and density n_0 during evaporative cooling.

In Fig. 1 the evolution of T and n_0 are shown for trapped H during evaporative cooling, measured by Lyman-α spectroscopy [2]. At $t = 38\,\text{s}$ the evaporation is initiated, marked by a sudden decrease in temperature. The resulting decrease in V_e leads to an increase in the density, even though the particle number N is strongly reduced. Also shown are the results of the model, using the potential (8). The calculated curves are completely determined by the starting conditions and the choice of τ_1 (90 s). The model gives a good description of the evaporation process, in view of the absence of adjustable parameters. The remaining discrepancy may be partly due to a systematic experimental error and partly due to the sensitivity of the calculated heat capacity $(\gamma + T(\partial\gamma/\partial T) + 3/2)Nk_B$ to the precise shape of the potential well.

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