Kinetic evolution of magnetically trapped atomic hydrogen in evaporative cooling

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The recent development of atom-manipulation techniques has realized Bose-Einstein condensation (BEC) in magnetically trapped alkali-metal atoms [1] and atomic hydrogen [2]. In all these experiments, evaporative cooling was adopted at the final stage of the cooling procedures and was essential in obtaining the extremely low temperatures needed for the quantum degeneracy. In the hydrogen system, however, such powerful evaporative cooling is retarded by the heating originated from dipolar spin relaxation, since the anomalously small s-wave scattering length of hydrogen atom strongly reduces the evaporation of trapped atoms. The producible number of condensates is therefore limited by the heating-cooling balance in the cooling process.

We study the evaporative cooling of magnetically trapped atomic hydrogen on the basis of quantum kinetic theory [3]. The dynamics of trapped atoms is described by the coupled differential equations, considering both the evaporation and dipolar spin relaxation processes. The numerical time-evolution calculations quantitatively explain the characteristic features observed in the recent BEC experiment with atomic hydrogen [2].

For our quantitative calculations, we employed the experimental appropriate parameters [2] described in the figure caption. The Ioffe-Pritchard trapping potential was treated exactly to obtain the quantitative description of the system, since many noncondensed atoms still distribute in the high-energy region where usual harmonic approximation to the potential fails even after the BEC transition. The time-evolution of evaporative cooling was calculated for 25 s with the use of the sweeping function of rf-field frequency adopted in the experiment [2, 4].

The time-evolution of the temperature T is plotted in Fig. 1(a). We can see that the cooling speed strongly slows down after the BEC transition at 15.4 s indicated by the arrow in the figure. The considerable heating is caused by the drastic increase of dipolar relaxation loss after the BEC transition, which is known as "relaxation explosion" in the hydrogen system [5]. The calculated results at the BEC transition point are quite consistent with the experiment [2], which confirms the validity of our numerical calculations. The condensate formation process shows the characteristic feature depicted in Fig. 1(b). Condensates first grow very rapidly after the transition. We can explain this by the fact that bosonic stimulation in evaporative cooling process [3] strongly accelerates the growing speed, since the density of condensates becomes

very high in atomic hydrogen. The number of condensates N_0 reaches the maximum value at 17.2 s, and then decreases gradually due to dipolar decay. The calculated parameters at this maximum point are: temperature $T = 49$ μK, peak density of condensates $n_p = 4.3 \times 10^{15}$ cm^{-3}, peak density of noncondensed atoms $n_n = 1.7 \times 10^{14}$ cm^3, total number of condensates $N_0 = 9.0 \times 10^8$, and total number of noncondensed atoms $N_n = 2.0 \times 10^{10}$. The corresponding condensate fraction at the maximum point of N_0 is calculated as $f = N_0/(N_0 + N_n)$ to be a small value of 4.3%. These results quantitatively agree with the recent observation of BEC with atomic hydrogen [2].

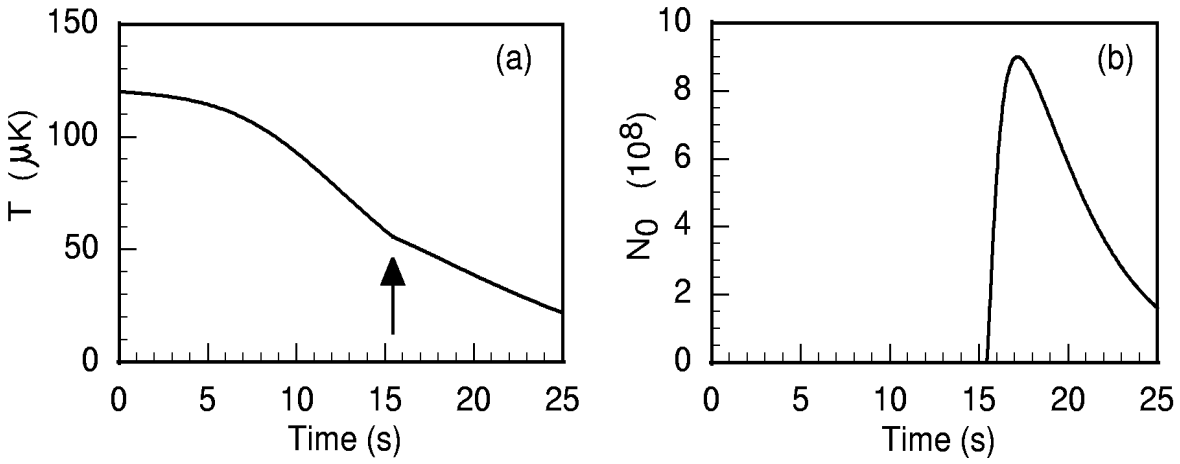

Figure 1: Time evolution of (a) temperature T, and (b) number of condensates N_0. The arrow indicates the point at which the BEC transition occurs. The following numerical parameters corresponding to the experiment with atomic hydrogen [2] are employed in the calculations: s-wave scattering length $a = 6.48 \times 10^{-2}$ nm, the dipolar decay rate constant $G_2 = 1.1 \times 10^{-15}$ cm^3/s [6], initial temperature $T = 120$ μK, initial peak density $n = 5.0 \times 10^{13}$ cm^{-3}, and the initial number of trapped atoms in a truncated potential $N = 1.16 \times 10^{11}$.

To summarize, we have investigated the evaporative cooling of magnetically trapped atomic hydrogen on the basis of the quantum kinetic theory. The calculated results show quantitative agreement with the BEC experiment with atomic hydrogen. This proves our calculations very useful, and the important future work would be to optimize the cooling trajectory for a larger production of condensates.

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