The basic role of open systems in attaining Bose condensation in spin-polarized atomic hydrogen gas

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The impossibility of attaining Bose condensation in a closed system because of the Kapitsa jump at the gas (atomic hydrogen)–liquid helium boundary can be overcome in open systems with a single "magnetic wall" which can be cooled by releasing excited molecules and fast atoms.

1. Three-body dipole recombination in the volume and at the surface, an unavoidable process in a spin-polarized atomic hydrogen gas which was predicted theoretically[1] (see also Ref. 2) and observed experimentally,[3–5] imposes a fundamental restriction on the maximum density, $n \lesssim 10^{19}$ cm^{-3}. Kagan *et al.*[6] have shown that the Kapitsa temperature jump at the atomic hydrogen–liquid helium boundary puts the Bose-condensation temperature $T_c(n)$ out of reach (even if the wall temperature $T_0 \rightarrow 0$) in a closed system when a substantial part of the recombination energy is thermalized in the gas. The controlling factor here is the increase in the surface density of absorbed atoms, n_S, to a value approximately equal to the limiting value at the required temperatures $T \lesssim 50$ mK and, accordingly, a sharp increase in the heat liberated due to a dipole recombination at the surface.

2. To reach the temperature region $T < T_c(n)$, we must sharply reduce the fraction of recombination energy required to heat the gas. This can be done by switching to a system with a single open surface which has only a "magnetic wall" because of a nonuniform magnetic field. A gas can easily release through this surface the excited, spin-flipped molecules and atoms, which are produced as a result of recombination, and the polarized particles with a kinetic energy that exceeds a certain threshold value, ϵ_c, determined by the magnetic-wall height.

Let us consider the most favorable situation from the standpoint of removing heat through the surface, when $T_0 \ll T$. According to Kagan *et al.*,[6] the quantity of heat Q that remains in the gas per unit time, and the gas temperature T, are related in this case by

$$\frac{Q}{S} = \frac{15}{8}\frac{nT^2}{\hbar K_*}\begin{cases} 0{,}44(T/T_c)^{3/2}\ ; & T \leqslant T_c\ , \\ 1 & T \gg T_c \end{cases} \tag{1}$$

where $K_* \approx 4\times 10^8$ cm^{-1} (He^4), and S is the surface area. The value of Q is

$$Q = \alpha_V' n^3 V \Delta E_V + \alpha_S n_S^3 S \Delta E_S . \tag{2}$$

Here α_V and α_S are the volume and surface dipole-recombination rate constants, ΔE_V is the energy that remains in the gas after a single recombination event in the volume, and ΔE_S is the energy that remains in the gas after a single recombination event at the surface.

At $T_0 \ll T_c(n)$ the surface density n_S is approximately equal to the limiting value, $n_{S0} \approx 10^{14}$ cm^{-2} (He^4). In the case of gas-layer thickness (d) considered below, the second term in (2) is larger than the first term in the direction perpendicular to the open surface. Comparing (2) with (1) and setting $T = T_c(n)$, we find the maximum value $\Delta E_S = \widetilde{\Delta E}_S(n)$, which puts the Bose-condensation region within reach. At $n \approx 10^{19}$ cm^{-3}, we have $\widetilde{\Delta E}_S(n) \approx 100$ K[1)]; as n is reduced, this value falls off monotonically in proportion to $\widetilde{\Delta E}_S \sim n^{7/3}$.

The most likely time for production of molecules in the highest vibrational state ($v = 14$) with a binding energy $\Delta E_0 \sim 100$ K is during a three-body recombination (see Ref. 1). Further release of energy occurs as a result of vibrational relaxation of these molecules, whose cross section is approximately two orders of magnitude smaller than that of the elastic scattering. This means that at $d/\lambda < 10$ (λ is the mean free path of the particles) most of the produced molecules escape through the open surface. As a result of inelastic processes, these molecules leave in the gas an energy that is clearly lower than the kinetic energy of the particles that scatter during recombination, i.e., ΔE_0. At such values of d/λ (the condition $d/\lambda \approx 10$ corresponds to $d \approx 10^{-3}$ cm), when $n \approx 10^{19}$ cm^{-3}, it is possible, in principle, to advance into the Bose-condensation region.

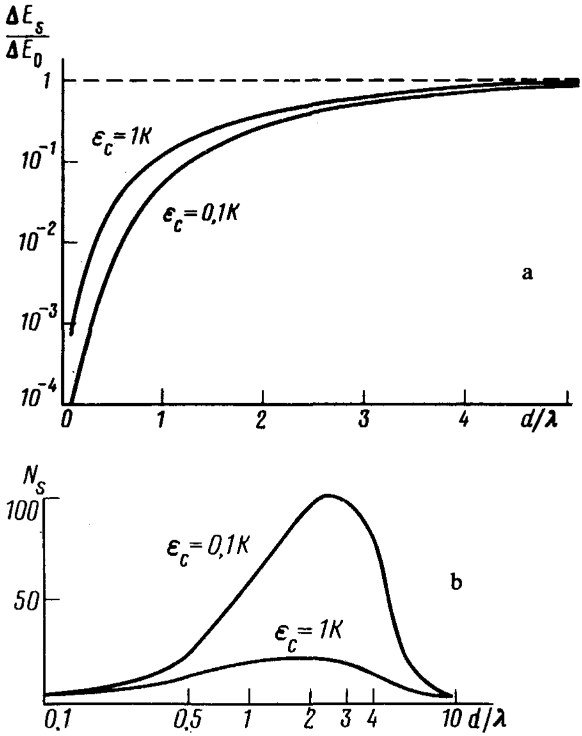

FIG. 1. (a) Dependence of ΔE_S on d/λ; (b) dependence of N_S on d/λ.

At lower gas densities, a part of the energy, ΔE_0, must be removed from the system. Since a fast particle transfers to a gas atom approximately half of its kinetic energy during each elastic collision, $\widetilde{\Delta E}_S(n)$ can be reduced substantially in comparison with ΔE_0 if the condition $d/\lambda \lesssim 1$ holds. To determine the energy left in the system, we must find the spatial and momentum distributions of particles which arise due to a systematic multiplication of fast particles as a result of multiple collisions. The energy is carried off by particles that reach the free surface with $\epsilon > \epsilon_c$. The number of generations that should be taken into account increases with decreasing ϵ_c, and ΔE_S $(\epsilon_c \gg T)$ also decreases.

As a result of some calculations in a planar configuration, we were able to plot ΔE_S as a function of the parameter d/λ for two values of the energy ϵ_c, which is in fact equal to $\mu_B \Delta H$, where ΔH is the variation of the magnetic field in a gas layer of thickness d. This plot is shown in Fig. 1. In the simplifying calculations, we assumed that the elastic scattering cross section does not depend on the collision energy (that it is $\sigma \sim 10^{-15}$ cm^2) and that the fast particles are reflected from the helium surface. It follows from these results and from the condition $\Delta E_S(d/\lambda) = \widetilde{\Delta E}_S(n)$ that the parameter d/λ decreases with decreasing n over a relatively broad density range due primarily to the increase in the mean free path. The thickness of the gas layer remains the same: $d \sim 10^{-3}$ cm.

An open surface thus allows us, in principle, to take advantage of the conditions under which the Bose-condensation region can be reached. The condition $\mu_B \Delta H \gg T_c$ presupposes that the magnetic-field gradient is large if the dimension d is small ($\Delta H / d \sim 10^6$–10^7 Oe/cm).

3. A three-body dipole recombination leads primarily, as pointed out by Kagan *et al.*,[1] to a spin flip of the third particle. At $n \lesssim 10^{19}$ cm^{-3} and $d \lesssim 10^{-3}$ cm, the atom whose spin is flipped leaves the system, since it cannot manage to participate in the recombination reaction. It is easy to see that three particles leave the system as a result of a single recombination event if $d/\lambda \gg 1$ (in particular, if $d/\lambda \approx 10$) when the energy that was released originally remains in the gas. If $d/\lambda \ll 1$, we will again have three particles, since the fast particles that were produced during the recombination leave the system without encountering any collisions. At intermediate values of d/λ, the number of particles, N, that leave the system increases because of the multiplication of fast particles. This number of particles can be determined directly from the same straightforward calculations that were used to determine the energy ΔE_S. Figure 1 is a plot of N_S (surface recombination) as a function of d/λ for two values of ϵ_c. We see that the maximum value of N_S can be as high as 20 ($\epsilon_c = 1$ K) or even as high as 100 ($\epsilon_c = 0.1$ K) when $d/\lambda \sim 2$.

The reciprocal lifetime of the polarized gas in the range of parameters under consideration is given by

$$\frac{1}{\tau} \simeq N_S\left(\frac{d}{\lambda}\right)\alpha_S \frac{n_{S0}^3}{nd} . \tag{3}$$

If the value of ϵ_c is fixed, the lifetime τ depends on d/λ. We easily see that the maximum lifetime is reached at maximum density, $n \approx 10^{19}$ cm^{-3}. In this case, we have $\tau \sim 0.1$ s at $T \simeq T_c(n)$. The gas temperature T can be further reduced by reducing the dimension (d) of the system, which decreases τ.

In extremely strong magnetic fields $H > 26$ T, the dominant recombination channel, which is accompanied by the formation of H_2 molecules in the $v = 14, j = 3$ state and by a spin flip of the third particle, is suppressed. The dipole-recombination rate constant in such fields is therefore appreciably lower (see Ref. 7) and the lifetime τ increases markedly.

4. Let us now analyze a situation in which the adsorbed atoms cover a surface nonuniformly. This situation, as Kagan and Shlyapnikov[8] have pointed out, arises at extremely low temperatures, $T < T^* \approx 5$ mK, when the adsorption rate of atoms, which decreases with decreasing T, is lower than the rate at which they recombine at the surface when its coverage is maximum.

If the surface density n_S is markedly lower than n_{S0}, the adsorption will be the same as that in a classical two-dimensional gas at the surface. Assuming that $T_0 \to 0$ and disregarding the desorption, we can again use Eq. (1), after adding the factor 2/3 on the right side of this equation, to describe the energy flux from the gas to the surface. The steady-state value of $\tilde{n}_S$ in the expression for Q [Eq. (2)] can be determined by equating the adsorption rate of atoms, Φ, to the rate at which they recombine at the surface:

$$\Phi = 0{,}26 \frac{nT}{\hbar K_*} \left(\frac{T}{T_c}\right)^{3/2} \simeq 3\alpha_S \tilde{n}_S^3 ; \quad T \ll T_c . \qquad (4)$$

If $n \lesssim 10^{18}$ cm^{-1} and $T > 0.1$ mK, we easily see from Eqs. (2) and (4) that the dominant recombination is, as before, the recombination at the surface. In this case, it follows from Eqs. (1), (2), and (4) that

$$\Delta E_S \simeq 6{,}3\ T. \qquad (5)$$

In the temperature interval 0.1 mK $< T <$ 5 mK the values of ΔE_S determined from these equations correspond to the parameter d/λ, which is approximately equal to 0.1 (Fig. 1). The value of N_S is approximately equal to 3 in this case. After taking Eq. (4) into account, we find for the reciprocal lifetime (3)

$$\frac{1}{\tau} \sim 10^3 \left(\frac{T}{T^*}\right)^{5/2} \ \mathrm{s}^{-1}. \qquad (6)$$

It follows that the lifetime τ can be increased markedly in comparison with that examined in the preceding section only at extremely low temperatures, $T \ll T^*$.

Interestingly, it is desirable to reduce the density in the case considered by us, since the absolute value of d increases in this case, thereby reducing the requirements for the magnetic-field gradient.

[1)] We have used the values of α_V and α_S obtained previously[1–5] and took into account that the value of α in a highly degenerate gas is only one-sixth that in a classical gas. We also took into account that approximately half of the fast molecules and atoms produced during surface recombination are drawn into the volume and transfer their energy to the gas atoms.

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