Inelastic neutron scattering of helium II below 1 K

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The temperature dependence of the density of the Bose condensate and of the average kinetic energy per atom in liquid helium has been found through an analysis of neutron inelastic-scattering spectra. The results are discussed.

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Hohenberg and Platzman[1] were the first to show that the relative density of the Bose condensate in liquid helium-4 could be studied experimentally by neutron scattering. For a neutron momentum transfer much greater than the reciprocal of the interatomic distance, the scattering law can be written as a superposition of that for the scattering of a neutron by atoms with a nonzero momentum and that for the scattering of a neutron by atoms in a state of Bose condensate (the impulse approximation).

A mathematical decomposition of the experimental spectrum into two Gaussian curves corresponding to neutron scattering by the atoms of the Bose condensate and scattering by other atoms (the two-Gaussian model[2,3]) can reveal the density of the Bose condensate. Dokukin *et al.*[4] used this method to study the temperature dependence of the density of the Bose condensate, $n_0(T)$, over the temperature interval 1.2–4.2 K. The experimental values of $n_0(T)$ were approximated by the power law

$$n_0(T) = n_0^* [1 - (T/T_0)^m] \tag{1}$$

with the adjustable parameters

$$n_0^* = 0.022 \pm 0.002; \qquad T_0 = 2.24 \pm 0.04; \qquad m = 9.0 \pm 4.0.$$

Sears and Svensson[5] found a similar dependence $n_0(T)$ in the temperature interval from 1 K to T_λ in a recent study of the radial distribution function $g(\mathbf{r})$ and the momentum distribution of the helium-4 atoms. With the parameter $T_0 = T_\lambda$ fixed, they found $n_0^* = 0.139 \pm 0.023$ and $m = 3.6 \pm 1.4$. The difference in the values of n_0^* probably stems from the use of different methods to determine the density of the Bose condensate.

Hyland and Rowlands[6] related the description of superfluid helium in the two-fluid model to the microscopic description of helium based on the method of Ref. 7. They derived an expression for $n_0(T)$ over the temperature interval from 0 to T_λ; this expression predicts a significant increase in n_0 at $T \sim 0.6$ K. Near 0.6 K there are also qualitative changes in the temperature dependence of several macroscopic properties of helium-4 (the viscosity of the normal component, the second sound velocity, etc.). These changes probably result from changes in the relative importance of the rotons and the phonons in the thermodynamics of the liquid helium.

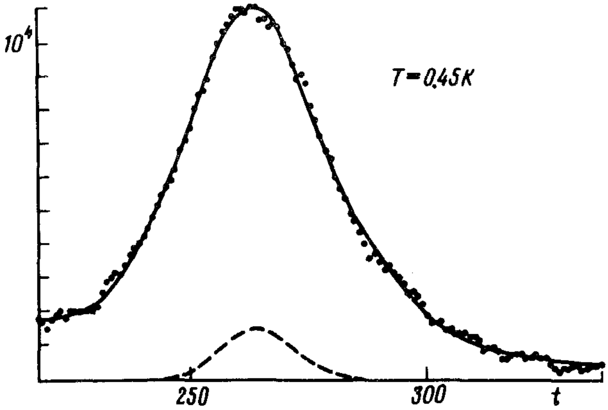

FIG. 1. Measured spectrum of neutrons scattered by liquid helium at $T = 0.45$ K with a momentum transfer of 14.3 Å^{-1}. Dashed curve—The part of the spectrum corresponding to neutron scattering by the Bose condensate; solid curve—description of the spectrum by the two-Gaussian model (t is the channel of the time analyzer).

This letter reports the first study of the density of the Bose condensate below 1 K. The cryostat used in the present experiments allows the helium-4 sample, ~4 liters in volume, to be cooled to ~0.4 K by using an adsorption pump inside the cryostat to pump off the helium-3 vapor. The temperature is regulated within 0.01 K. Measurements were taken at an IBR-30 reactor with a DIN-1M spectrometer at sample temperatures of 0.45, 0.5, and 0.8 K. Figure 1 shows a representative spectrum of the neutrons scattered by liquid helium-4 according to these measurements. Figure 2 shows the values found for the relative density of the Bose condensate over the temperature interval 0.45–4.2 K. The solid curve here is an approximation of the data of

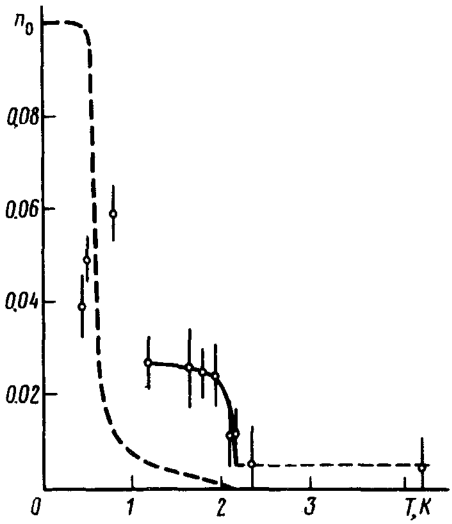

FIG. 2. Temperature dependence of the density of the Bose condensate.

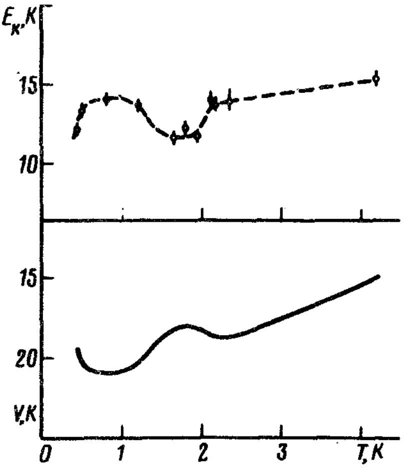

FIG. 3. Temperature dependence of the average kinetic energy and the potential energy per atom of the liquid helium.

Ref. 4 by power law (1). The dashed curve is a theoretical curve from Ref. 6. The density of the Bose condensate is seen to increase near 1 K. This result is in qualitative agreement with the theory of Hyland and Rowlands[6] and consistent with the estimates[8] $n_0 \sim 0.1$ at $T = 0$ K.

As expected, the width of the Gaussian curve corresponding to neutron scattering by the atoms of the Bose condensate corresponds to the spectrometer resolution function, within the experimental error, over the entire temperature interval 0.45–4.2 K.

The average kinetic energy per helium atom in the liquid can be calculated from the measured width of the Gaussian curve corresponding to the atoms "above the condensate"[2]:

$$<E_k> = \frac{3}{8}\left[\frac{\gamma_2 (1-n_0)}{\omega_0} + n_0 \gamma_0^{1/2}\right], \tag{2}$$

where γ_2 and γ_0 are the square widths of the Gaussian curves corresponding to the atoms above the condensate and to the condensate atoms after subtraction of the resolution function (in our case, $\gamma_0 = 0$), and ω_0 is the energy of the recoil nucleus.

The interaction potential energy per liquid helium atom is given by[9]

$$V = \frac{5}{2} kT - E_k - L - P/\rho, \tag{3}$$

where L is the latent heat of vaporization, P is the pressure, and ρ is the density. Figure 3 shows $E_k(T)$ and $V(T)$. The maximum on the $V(T)$ curve at 1.2–2.17 K results from a decrease in the density of helium-4 below T_λ and the appearance of the Bose condensate.

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