Investigation of single-atom scattering of neutrons and of the branch of the two-roton bound state in He II

N. M. Blagoveshchenskiĭ, E. B. Dokukin, Zh. A. Kozlov, and V. A. Parfenov

(Submitted 2 October 1979)
Pis'ma Zh. Eksp. Teor. Fiz. **31**, No. 1, 7–10 (5 January 1980)

The results of an experimental investigation of a single-atom scattering of neutrons in the region of the phonon-roton spectrum and of the branch of the two-roton bound state in He II at $T = 1.2$ and 1.9 K are discussed.

PACS numbers: 67.40.Db, 61.80.Hg

The purpose of this experiment is to continue the investigation of the properties of spectra for the inelastic scattering of neutrons in He II near $\epsilon = q^2/2M_{\rm He}$ and $\epsilon \sim 2\Delta$ [1] (ϵ and q are the energy and momentum transfer, Δ is the roton gap, and $M_{\rm He}$ is the mass of the helium atom). The experiment was performed using the DIN-1M spectrometer of the IBR-30 pulsed reactor.[2] The initial neutron energy was $E_0 = 3.230 \pm 0.001$ MeV. The scattering angles were 45–122°. The measurements were made for He II at two temperatures, $T = 1.2$ and $T = 1.9$ K.

A typical spectrum of scattered neutrons is shown in Fig. 1. At all scattering angles at the temperature of the sample $T = 1.2$ K, we can clearly see peaks corre-

 0021-3640/80/010004-04$00.60

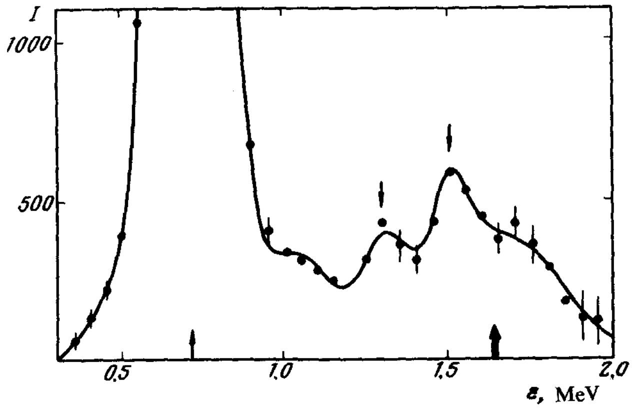

FIG. 1. Spectrum of scattered neutrons. $E_0 = 3.230$ MeV, $T = 1.2$ K, scattering angle $= 109°$.

sponding to single-atom scattering (indicated by a heavy arrow) and the two-roton bound state (indicated by the arrows on top). The complete result of an analysis using Gaussian distributions is shown in the plot of $\epsilon(q)$ in Fig. 2.

Single-Atom Scattering. It can be seen in Fig. 2 that, within the error limits, the experimental data correspond to the function $\epsilon = q^2/2M_{\mathrm{He}}$. The minimum energy of the atomic recoil in this experiment, $\epsilon = 0.47$ MeV, is much lower than Δ. The area under the peak for a single-atom scattering at both temperatures for He II increases monotonically with increasing q. The average ratio of the areas for the two temperatures is $\langle S_0\,(1.2\text{ K})/S_0\,(1.9\text{ K})\rangle = 1.84 \pm 0.55$, whereas the area under the roton peak within the error limits remains unchanged with increasing T: S_r (1.2 K)/S_r (1.9 K) $= 0.97 \pm 0.02$. The density ratio of the superfluid component of these temperatures is ρ_s (1.2)/ρ_s (1.9 K) $= 1.67$.

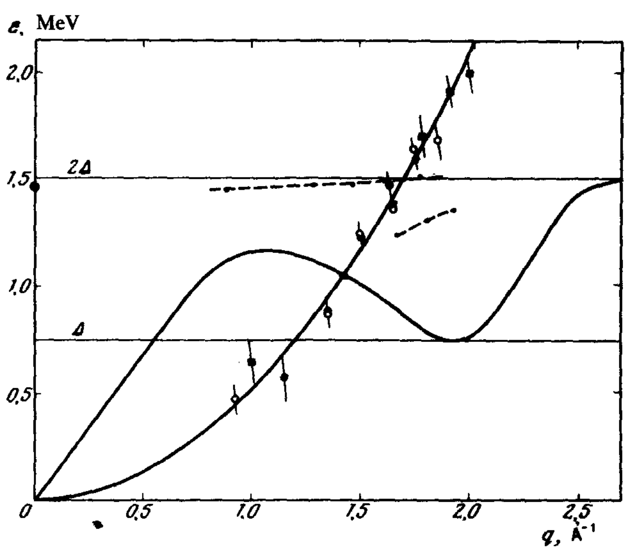

FIG. 2. Diagram of the single-atom scattering of neutrons in He II at $T = 1.2$ K (O) and $T = 1.9$ K (●); ■—data from Ref. 1. The broken line denotes the branch for the two-roton bound state.

The observed width of the peak at half height, which is independent of the scattering angle of neutrons within the error limits, is

$$<\Gamma_0(1.2\text{K})> = 0.21 \pm 0.03 \text{ MeV}; \qquad <\Gamma_0(1.9\text{K})> = 0.15 \pm 0.03 \text{ MeV}.$$

Notice that with increasing temperature a certain decrease in the width of the single-atom scattering peak is observed.

The single-atom scattering can be interpreted as the local breakdown of the superfluid, which is related to the artificial population of the spectrum of the single-atom motion as a result of the scattering of neutrons by ^{4}He atoms in the condensed state. For a precise quantitative estimate of the correlation between the densities of the Bose condensate (BC) and the superfluid component, we must determine the temperature dependence of the area under the peak for the single-atom scattering in the region of the spectrum for the elementary excitation of He II. However, the agreement between the ratio of the areas S_0, within the statistical error limits, and the ratio of the densities ρ_s for the two temperatures also indicates that there is a connection between the superfluidity and the Bose-Einstein condensation in ^{4}He, along with the results of the experiment[4] on the study of neutron scattering by BC atoms at $\epsilon \gg \Delta$.

Two-Roton Bound State. The data on neutron scattering[1] indicate the existence in helium II of a two-roton bound state with a nonvanishing total momentum. However, the effect of multiple scattering of neutrons in the region $\epsilon \sim 2\Delta$ failed to give an estimate of the binding energy E_B and of the roton-roton coupling constant g_4. In our experiment the contribution of multiple scattering to the energy transfer of the order of 2Δ can be neglected because of the strong anisotropy of the initially scattered neutrons. As seen in Fig. 2, the branch of the two-roton bound state attains 2Δ at $q = 1.65$ Å^{-1}; the rotons are repelled for large momenta. It can be assumed that the two-roton branch observed at $T = 1.2$ K is a continuation of the branch whose origin was investigated in the light-scattering experiment.[5] This is also indicated by a similar value for the binding energy:

$$|E_B(q)|_{max} = 0.038 \pm 0.006 \text{ MeV } (0.44 \pm 0.07\text{K});$$

$$|E_B(0)| = 0.032 \pm 0.009 \text{ MeV } (0.37 \pm 0.1\text{K}).$$

The roton-roton coupling constant can be estimated from Eq. (3.30) in Ref. 6,

$$g_4 = \left[2\rho_0(q) \ln \frac{E_B}{2D} \right]^{-1}, \tag{1}$$

where $\rho_0(q)$ is the unperturbed density of the two-roton states, $\rho_0(q) = \mu q_r^2/4\pi q$, where $\mu = 0.16\, M_{He}$ is the effective roton mass at $T = 1.2$ K, $q_r = 1.93$ Å^{-1} is the roton momentum, and $D = \Delta_1 - \Delta = 0.4$ MeV is the difference between the energies of the first maximum and the roton minimum in the spectrum of elementary excitations. Substituting the experimental values for the binding energy E_B and for the momentum q in Eq. (1), we obtain for the part of the branch corresponding to attraction between the rotons

$$g_4(q = 0.885 \text{ Å}^{-1}) = -0.51\times10^{-38} \text{ erg·cm}^3$$

$$g_4(q = 1.287 \text{ Å}^{-1}) = -0.52\times10^{-38} \text{ erg·cm}^3$$

$$g_4(q = 1.467 \text{ Å}^{-1}) = -0.70\times10^{-38} \text{ erg·cm}^3.$$

The relative error in determining g_4 is of the order of 0.08. For the total zero momentum of the pair $g_4 = -0.12\times10^{-38}$ erg·cm^3.[5] We note that the peaks in our experiment were observed at $T = 1.2$ K in the region $1.65 \text{ Å}^{-1} < q < 1.95 \text{ Å}^{-1}$, which correspond to the the two-roton bound state and have the energies $\epsilon = 1.228$ MeV, $\epsilon = 1.313$ MeV, and $\epsilon = 1.352$ MeV, which are lower than 2Δ (see Ref. 3).

At $T = 1.9$ K the peaks for the two-roton bound state are strongly broadened, and the statistics of the given measurements are inadequate to obtain the data from the spectra.

Finally, we note the following. The spectrum of elementary excitations observed experimentally reaches a threshold value at $q \sim 3 \text{ Å}^{-1}$, which has an energy slightly larger than 2Δ. Because the extension of the branch of the two-roton bound state to larger momenta has the energy $\epsilon > 2\Delta$, it can be assumed that for $q \sim 3 \text{ Å}^{-1}$ this branch is next to a single quasi-particle branch that is damped at this momentum; the latter, which has an energy $\epsilon = 2\Delta$, becomes "mixed" with the former, which results in an overestimation of the observed energy transfer. A more detailed investigation of the two-roton branch in the region $2 < q < 3 \text{ Å}^{-1}$ will enable us to verify the validity of this assumption.

The authors thank L.P. Pitaevskiĭ for participating in the discussion of the results and S.N. Smol'nikov for his technical assistance with the experiment.

[1]N.M. Blagoveshchenskiĭ, E.B. Dokukin, Zh.A. Kozlov, and V.A. Parfenov, Pis'ma Zh. Eksp. Teor. Fiz. **30**, 14 (1979) [JETP Lett. **30**, 12 (1979)].

[2]V.G. Liforov *et al.*, Res. Appl. Nucl. Pulsed Syst., Vienna (1966), p. 196.

[3]L.P. Pitaevskiĭ, Pis'ma Zh. Eksp. Teor. Fiz. **12**, 118 (1970) [JETP Lett. **12**, 82 (1970)]; L.P. Pitaevskiĭ and I.A. Fomin, Zh. Eksp. Teor. Fiz. **65**, 2516 (1973) [Sov. Phys. JETP **38**, 1257 (1974)].

[4]E.B. Dokukin, Zh.A. Kozlov, V.A. Parfenov, and A.V. Puchkov, Pis'ma Zh. Eksp. Teor. Fiz. **23**, 497 (1976) [JETP Lett. **23**, 453 (1976)]; Zh. Eksp. Teor. Fiz. **75**, 2273 (1978) [Sov. Phys. JETP **48**, 1146 (1978)].

[5]T.I. Greytak *et al.*, Phys. Rev. Lett. **25**, 1547 (1970).

[6]A. Zawadowski, J. Ruvalds, and J. Solana, Phys. Rev. **A5**, 399 (1972).