Two-branch structure of the spectrum of elementary excitations of superfluid helium-4

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The spectrum of elementary excitations of HeII at wave vectors $q \approx 0.1$–1.9 Å^{-1} has been studied by a neutron-scattering method at temperatures $T = 0.42$–1.72 K. At $q \geqslant q_0(T) \approx 0.48$ Å^{-1} and under the condition $\epsilon \geqslant \Delta$, the spectrum has a two-branch structure.

In this letter it is shown, through a two-Gaussian expansion of the sharp peak which is usually called the "phonon-maxon-roton peak," that at wave vectors $q \leqslant q_0(T) \approx 0.48$ Å^{-1} and at energies $\epsilon \geqslant \Delta$ (Δ is the energy of the roton gap) the spectrum of elementary excitations of superfluid HeII consists of two closely spaced branches. It might be suggested that one of these branches corresponds to a scattering of neutrons by an ordinary, "normal" liquid, while the other is due to the excitation of the liquid by a Bose condensate.

The experiments were carried out at the IBR-2 reactor (Joint Institute for Nuclear Research, Dubna) with the help of DIN-2PI spectrometer. The energy of the neutrons incident on the sample, E_0, was 2.05 or 2.45 meV. These energies are lower than the formation energy of most multiphonon-scattering branches. The sensitivity of these experiments was raised by about an order of magnitude, so it became possible to see structural features in the spectrum smaller by a factor of $(3–5) \times 10^2$ than the phonon-roton peak. For the first time, peaks were found. These peaks are associated with a scattering of neutrons in superfluid HeII accompanied by an acquisition of energy, i.e., peaks which are associated with a scattering by excitations in the liquid. The sample temperature was 0.42, 0.45, 1.4, or 1.72 K. The energy resolution was 50–100 μeV, depending on E_0 and ϵ.

Analysis of the experimental spectra revealed that the sharp peak at wave vectors $q > q_0$ and energies $\epsilon \geqslant \Delta$ has a complex structure. Since the elastic peak in some control experiments on neutron scattering by vanadium could be described unambiguously by a Gaussian, the simplest possibility was to decompose the sharp peak into Gaussians. Various library programs were used for the decomposition. The results of a mathematical decomposition showed that a two-Gaussian model gives a better description of the sharp peak (in terms of the χ^2 test, the correlation coefficients of the unknown parameters of the model, the table of deviations of the experimental points from the theoretical curve, etc.). Adding more Gaussians to create a more elaborate model does not improve it. At $q \leqslant q_0$ the experimental data are described better by a single-Gaussian model. All the parameters of the Gaussians were treated as adjustable in the analysis. A model of this sort agrees with the two-fluid picture of HeII.

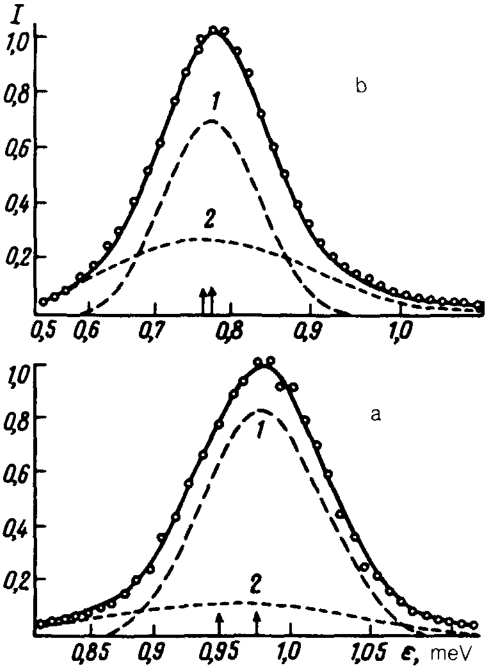

FIG. 1. Experimental spectra of neutrons scattered by HeII. a—$T=1.4$ K, $E_0=2.05$ meV, $q\simeq$ 1.6 Å^{-1}; b—1.72 K, 2.45 meV, $\simeq$1.83 Å^{-1}. The dashed lines show the narrow (1) and broad (2) Gaussians. The arrows show the positions of the Gaussians.

For the analysis, the experimental $d^2\sigma/d\Omega d\tau$ spectra, measured by a time-of-flight method, were converted into a "scattering law" $S(q, \epsilon)$ and analyzed on the energy scale:

$$S(q,\epsilon)\sim E^{-2}d^2\sigma/d\Omega d\tau, \quad \bar{q}=\bar{k}_0-\bar{k}, \quad \epsilon=E_0-E,$$

where $\bar{k}_0$ and $\bar{k}$ are the wave vectors of the incident and scattered neutrons, E is the final energy of the neutrons, and τ is the width of a time channel.

Figure 1, a and b, shows for comparison some experimental spectra of scattered electrons at 1.4 and 1.72 K, along with the components of their two-Gaussian decomposition (we will speak in terms of the "narrow" and "broad" Gaussians). Figure 2 shows the results of an analysis of the positions $\epsilon(q)$, the areas $S(q)$, and the widths $W(q)$ of the narrow and broad Gaussians. Also shown here are the ratios of the area of the narrow Gaussian, S_n, to the total area, $\eta(q) = S_n/(S_n + S_b)$, for $E_0 = 2.05$ meV and $T=1.4$ K. Figures 3 and 4 show η and W as a function of T; the resolution function has been subtracted from W. Where the statistical errors are larger than the symbol itself, they are shown.

Note that the broad Gaussian at $q \gg q_{\rm maxon}$ lies at a lower energy ϵ than the narrow Gaussian (Fig. 2a). The area under the broad Gaussian decreases with decreasing q, vanishing at $q<0.48$ Å^{-1} (Fig. 2b). At $q < q_0$, we can thus talk about only a single Gaussian. As q decreases, the plot of the area of this Gaussian approaches the straight line derived by Feynman for a structure factor $S(q) = \hbar q/2Mc$ in the limit $q \to 0$, where c is the sound velocity, and M is the mass of the He atom. The width of the peak

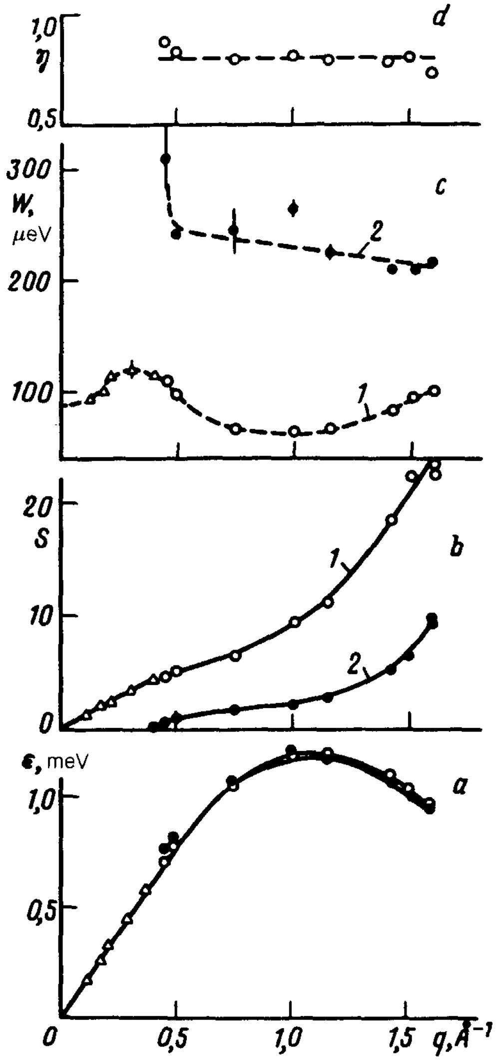

FIG. 2. Results of an analysis of the experimental spectra for $E_0=2.05$ meV and $T=1.4$ K. Open circles and curves *1*—The narrow Gaussian; filled circles and curves *2*—the broad Gaussian; triangles—the single-Gaussian model.

of the broad Gaussian, W_b, increases sharply as q_0 is approached from above (Fig. 2c). The width of the narrow Gaussian has a minimum at $q \approx q_{\rm maxon}$, because of the best energy resolution, itself a result of the minimum final neutron energy E. The plot of the width of the narrow peak versus the wave vector at $q < q_0$ has a structural feature associated with sound dispersion ($W \sim q^2$). Similar results were found for other values of T and E_0. Although the behavior of S_n and S_b as a function of q is complex, the area ratio η depends only weakly on the wave vector at $q > q_0$, while it depends strongly on the temperature T (Fig. 2d). At $T=0.42$ K and $E_0 = 2.05$ meV we have $\eta = 0.88 \pm 0.02$; at 0.45 and 2.45 we have $\eta = 0.86 \pm 0.02$; at 1.4 and 2.05 we have $\eta = 0.78 \pm 0.02$; and at 1.72 K and 2.45 meV we have $\eta = 0.59 \pm 0.02$.

Discussion of results. Glyde and Griffin[1] worked from the experimental results of

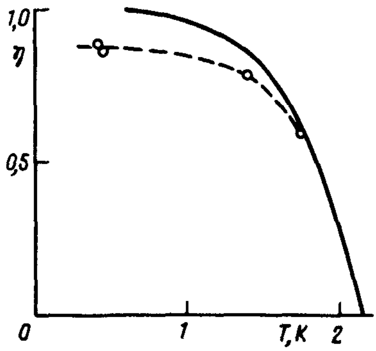

FIG. 3. Temperature dependence of η. The solid line is the temperature dependence of the density of the superfluid component.

Refs. 2–4 and interpreted the long-wave phonon excitation and the maxon-roton excitation as two distinct branches, which are paired by the presence of a Bose condensate (a hybridization induced by a Bose condensate). These branches are seen as a single dispersion curve; the maxon-roton resonance was linked with the Bose condensate. As Andersen *et al.*[5] have pointed out, however, the question of whether there is a correlation between the sharp peak in $S(q, \epsilon)$ and a Bose condensate below T_λ remains unanswered.

Analysis of our own experimental data reveals that the two-Gaussian decomposition of the peak apparently works only at $q > q_0(T)$ and $\epsilon > \Delta(T)$. As T is raised, the region in which a two-Gaussian description is required shifts toward smaller values of q. At $q < q_0$ and $\epsilon < \Delta$, the HeII excitation peak can be described by a single Gaussian. More precisely, it is difficult to link the transition region with the values of Δ and q_0 at this point because of the limited experimental material available. Nevertheless, the significant difference between the behavior of W_b and that of S_b as we

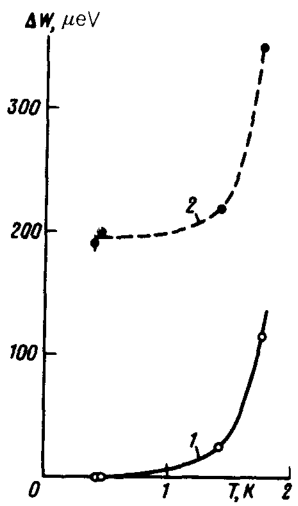

FIG. 4. Temperature dependence of the intrinsic width of the narrow Gaussian (*1*) and that of the broad one (*2*) at $q \approx q_{\text{maxon}}$.

approach q_0 and $\epsilon \approx \Delta$ at various values of T suggests that the threshold for the appearance of the two branches has a temperature dependence.

We believe that the broad Gaussian describes a scattering of neutrons by a "normal" liquid, while the narrow one corresponds to a scattering of neutrons by the superfluid component of HeII. The decomposition into two Gaussians is evidence that the coherent scattering of neutrons by density fluctuations of the superfluid component is different from the corresponding scattering by the normal component. The reason is that the density fluctuations at the superfluid component should be regarded as small, because of the long-range binary correlations of atoms. The peak would thus be narrowed. The comparison of η and the density of the superfluid component in Fig. 3 shows that the temperature dependence of η has the same shape as that of the density of the superfluid component. We should point out that the lifetime of the excitations (Fig. 4) depends on T and also reproduces the temperature dependence of the density of the superfluid component.

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