Two-roton bound state in helium II

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Results of an experiment in the neutron scattering in helium II at $T = 1.2$ K in the energy transfer region $\epsilon \sim 2\Delta$ are discussed. Experimental data indicate the presence in the excitation spectrum of He^4 branch of a two-roton bound state.

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The concept of hybridization of an unperturbed spectrum of quasi-particles with a two-roton spectrum provides a means of explaining the special features of the observed spectrum of elementary excitations, and it leads to the confirmation of the existence in liquid helium of a bound two-roton state over a wide range of momentum q.[1,2]

The lifetime of a roton is substantially affected by the two-roton bound state, and also by the number of atoms in a condensate, since the hybridization of single- and two-roton states occurs with the participation of the condensate atom.[1] The inadequacy of the mechanism of direct roton-roton scattering in explaining the experimentally observed single-roton width $\Gamma(T)$ in terms of the constant q_4, was also pointed out in Ref. 3.

The current experiment in inelastic scattering of neutrons, carried out using of the DIN-1M time-of-flight spectrometer,[4] was designed to investigate special features in the excitation spectrum in the region $\epsilon \sim 2\Delta$. The experimental conditions were chosen to analyze the possibility of neutron scattering by the condensate atoms ($\epsilon = q^2/2M_{\text{He}}$) in the region of momentum transfer 1 Å$^{-1} < q < 2$ Å^{-1}, in addition to obtaining information on the two-roton branch.

The observed neutron spectra ($E_0 = 3.807 \pm 0.002$ MeV; six scattering angles) are shown in Fig. 1. The vertical dashed lines indicate energies Δ and 2Δ. Arrows point to centers of uniquasi-particle peaks. The count at the roton peak maximum (Fig. 1c) is 1.35×10^4. The width of the resolution function for all ϵ is not greater than 0.15 MeV. The clearly expressed characteristic feature in the scattering spectra for $\epsilon \sim 2\Delta$ was approximated in processing by two Lorentz distributions. The shape of the phonon-roton spectral peaks was considered to be symmetrical. The multiphonon scattering peak was considered to be background for the purpose of processing, and was also characterized by a Lorentzian distribution. A wing of this peak is indicated in Fig. 1 by the dashed curves. The result of processing is indicated in Fig. 1 by the solid lines. Similar processing in which the Lorentzian distributions are substituted by Gaussian also reveals the two-component structure of the observed effect.

Each of the two peaks behaves differently when q varied. One of these exhibits the same energy $\epsilon \approx 2\Delta$ at all the scattering angles. This branch, which we identify with the two-roton state, is shown in Fig. 2. The second peak sustains a substantial energy shift (from 2 to 0.65 MeV). Characteristics of the second peak will be discussed in a subsequent article.

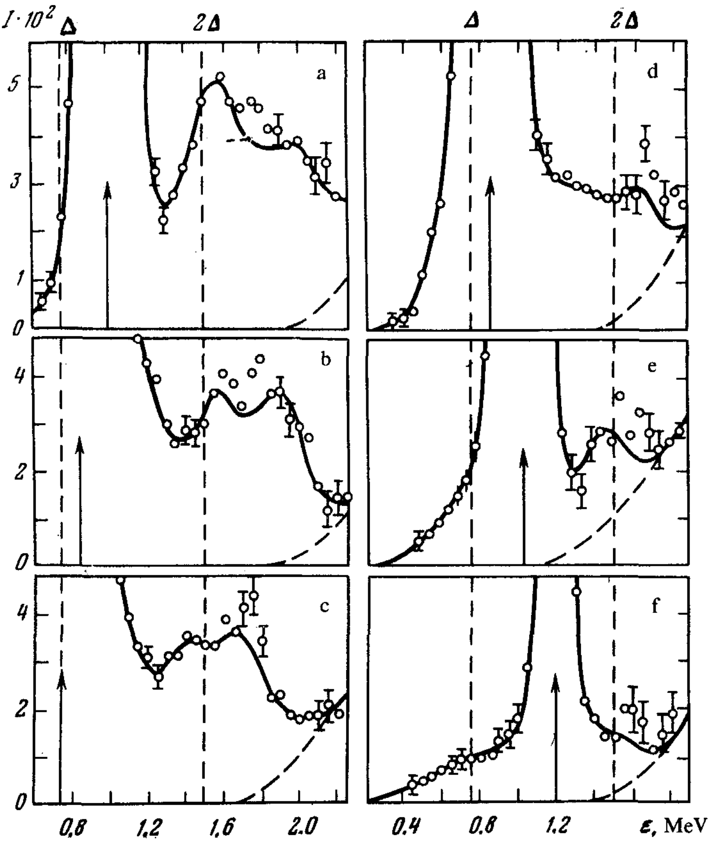

FIG. 1. Experimental spectra of neutrons scattered by helium II. $\theta = 122.62°$ (a); 109.48° (b); 96.54° (c); 83.80° (d); 71.00° (e); and 45.16° (f).

The area under the two-roton state peak increases continuously with increasing q and on the average, equals 10^3. The observed width at half maximum is independent of q and equals 0.23 MeV. An exception to this is the peak at $q = 2.1$ Å^{-1} with a width of $\sim$0.32 MeV. This may possibly be due to the fine structure of the two-roton spectrum in this region of momenta.[2]

With respect to the question of the sign of the roton-roton interaction, let us consider Fig. 1. The model used in the processing is characteristically insufficient to describe the experimental data points in the region $1.6 < \epsilon < 1.8$ MeV. This indicates the presence in this region of a certain additional source of neutron scattering. We associate the nature of this source with multiple scattering (MS) of neutrons in the He^4 specimen. When considering the contribution MS makes to the energy and angular distribution of scattered neutrons, the fraction of neutrons that are scattered with the generation of phonons may be neglected. The MS effect is limited from below by the energy 2Δ. Moreover, the maximum in the neutron scattering cross section is displaced with respect to the roton minimum and is $\epsilon \sim 0.8$ MeV. Therefore, the FIL effect exhibits a maximum at energy $\epsilon \gtrsim 1.6$ MeV which is shifted in the direction of

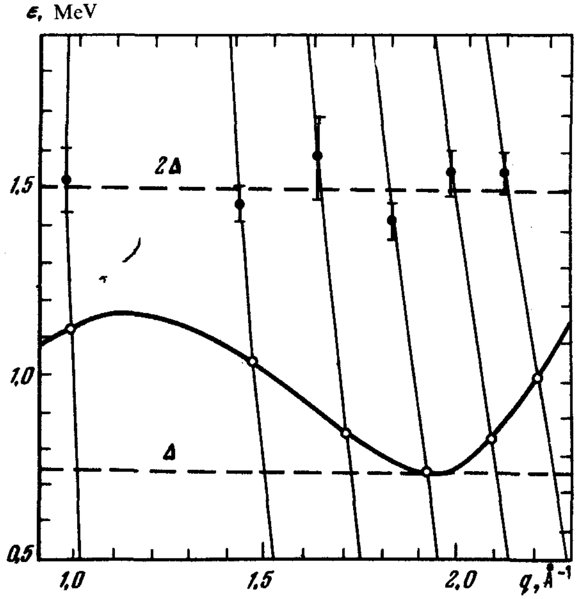

FIG. 2. Two-roton bound state branch. Thin lines correspond to $q = 0.694 [2E_0 - \epsilon - 2\cos\theta\,(E_0(E_0 - \epsilon))^{1/2}]^{1/2}$. The thick line denotes spectrum of elementary excitatons.

higher energies. Due to the presence of a strong dependence of neutron scattering cross section on q, the angular distribution of initially scattered neutrons is highly anisotropic. Calculations show that the maximum FIL effect occurs in our experiment at $\theta \sim 70°$ (Fig. 1e), and the minimum effect is shown in Fig. 1a. The foregoing reasoning shows that a systematic error is evident in the value of ϵ for the two-roton state branch, which is associated with the FIL effect and leads to an effective elevation of two-roton resonance energy. To determine a value of the binding energy E_b and inter-roton coupling force g_4, on the basis of data for the two-roton bound state branch, an experiment is conducted in which the FIL effect is small ($E_0 \sim 3.2$ MeV).

We should also note that based on the experiments in light scattering[5] for $q = 0$, a two-roton bound state is characterized by an angular momentum $l = 2$ (d-type). Since the degeneracy with respect to projection m of momentum l in a direction q is removed for finite value of q,[6] bound roton pairs observed in the neutron experiment show $m = 0$.

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