Lifetime of roton in liquid helium

N. M. Blagoveshchenskiĭ and E. B. Dokukin

Institute of High Pressure Physics, USSR Academy of Sciences
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The temperature dependence of the lifetime and energy of the roton was investigated by the method of inelastic scattering of neutrons. It follows from the results that the elementary theory of the roton lifetime in superfluid He^4 does not explain satisfactorily the Γ (T) dependence, and calls for invoking additional broadening mechanisms. Strong damping of the roton at the λ point was experimentally demonstrated.

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Among the problems connected with the study of superfluidity, an important place is occupied by the investigation of the lifetime of the elementary excitations in He^4. An analysis of the lifetime yields information on the strength and the type of the interquasiparticle interactions that are responsible for important details of the excitation spectrum (termination of the single-phonon branch,[1] two-branch structure,[2] etc.) At $T \ll T_\lambda$, the rotons are stable and can be well observed when neutrons are scattered by the excitations: the energy and momentum conservation law forbids the decay of the rotons into phonons. The main contribution to the lifetime of the roton is made by roton–roton scattering (broadening due to collisions), the cross section of which at $T > 1$K prevails over the cross sections of other processes that lead to broadening. The roton–roton interaction constant g_4, obtained from experiments on light scattering, amounts to -0.12×10^{-38} erg-cm^3 (Ref. 3), smaller by one order of magnitude than the value of g_4 required to reconcile the Landau–Khalatnikov theory[4] with the viscosity data. However, the width of the single-roton state can be directly obtained only from an analysis of the spectrum of the neutron scattering, since light interacts with the spectrum of only second-order interactions, i.e., with roton pairs. The data of Refs. 5 and 6 make it possible to estimate quantitatively $\Gamma(T)$ only near T_λ.

The experiments were performed with the DIN-1M time-of-flight spectrometer.[7] The initial energy E_0 and the scattering angle θ corresponded to the momentum of the produced excitation near the roton minimum: $E_0 = 6.87$ meV, $\theta = 71.0°$, $q = 2.05$ Å^{-1}. The temperature of the He^4 sample was set by pumping off vapor over the liquid. Two typical spectra of scattered neutrons ($T = 1.2$ and 2.04 K) are shown in Fig. 1. The first peak corresponds to elastic scattering of neutrons by the construction details of the cryostat container. The second peak is due to the production of rotons in the helium. One can observe visually both that the peaks come close together with increasing T, and that the inelastic peak broadens. It is typical that despite the broadening and the approach, both peaks can be resolved even at $T \sim T_\lambda$. The asymmetry of the inelastic peak is due to multiphonon scattering.

The observed spectra were approximated by two Gaussian distributions (see Fig. 1). The energy and the momentum of the roton were defined as $\epsilon = E_0 - E(T)$ and

$\mathbf{q} = \mathbf{k}_0 - \mathbf{k}$, where $E(T)$ is the energy of the scattered neutrons and corresponds to the maximum of the inelastic peak; $\mathbf{k}_0$ and $\mathbf{k}$ are the wave vectors of the incident and scattered neutrons.

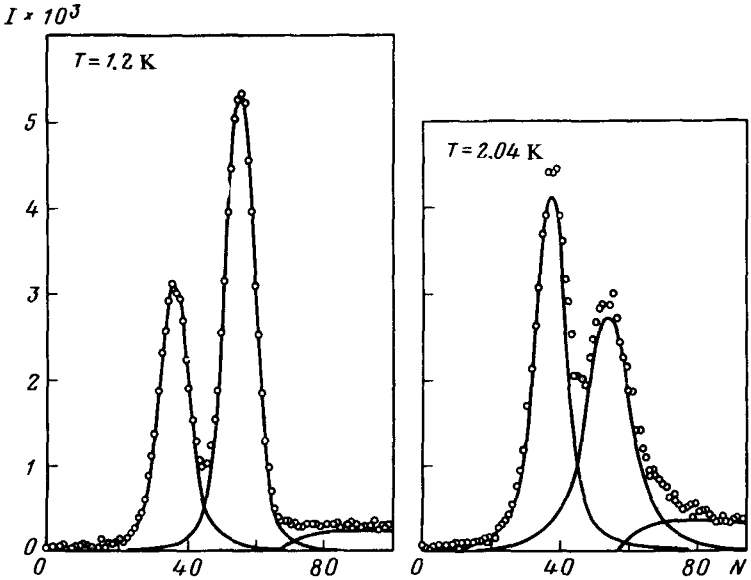

FIG. 1.

In the data reduction, recognizing that the proper width of the roton line is equal in order of magnitude to the width of the resolution function, the convolution of the Gaussian resolution function or with the Lorentz-shaped roton line was replaced, without substantial errors in the determination of the width, by a double-Gaussian convolution. In this case $\Gamma_\theta(T) = 2(2\ln 2)^{1/2}[\langle\sigma\rangle^2(T) - \sigma_R^2]^{1/2}$, where $\langle\sigma\rangle^2(T)$ is the dependence of the dispersion of the observed line on T, and σ_R^2 is the dispersion of the resolution function, obtained by extrapolating $\langle\sigma\rangle^2(T)$ to $T = 0$. $\sigma_R = 0.160 \pm 0.002$ meV. The obtained value of $\Gamma_\theta\ (T)$ is the width at a fixed neutron scattering angle θ. Of physical meaning in the theory, however, is the quantity $\Gamma_q(T)$, i.e., the width at a fixed roton momentum. The conversion from $\Gamma_\theta(T)$ to $\Gamma_q(T)$ is with aid of the formula $\Gamma_q(T) = \Gamma_\theta(T)(\sin\beta + |\cos\beta|\tan\alpha)$, where $\tan\alpha = (d\epsilon/dq)_q$ is the slope of the dispersion curve at the investigated point; $\tan\beta$ is the slope of the neutron energy-conservation curve for $\theta = 71°$. Figure 2 shows, in a single scale, plots of $\epsilon(T)$ and $\Gamma_q(T) \equiv \Gamma(T)$. The filled circles denote the data[6] for $\Gamma(T)$ and $P = 1$ atm. The dashed line shows the theoretical curves constructed by the Landau-Khalatnikov formula:

$$\hbar\Gamma(T) = \frac{\hbar^2 q_0^4}{15\eta_r}\left(\frac{kT}{8\pi^3\mu}\right)^{1/2} e^{-\Delta/T}$$

As seen from Fig. 2, the $\Gamma(T)$ plot obtained in our experiment differs from the results of Ref. 6 and is not described by the Landau–Khalatnikov theory. The formula of the theory of Ref. 8 differs from that of Ref. 4 only by a factor, and therefore is likewise in disagreement with our data on $\Gamma(T)$. This disparity indicates that the roton–roton interaction is more complicated than assumed in the first theories, for example, it is anisotropic. In Refs. 4 and 8, no account was taken also of other broadening mechanisms, such as interaction with nonzero angular momentum or processes with single excitation in the final state (of the two-roton-resonance type). In Ref. 3, the existence of pairs of bound rotons, which strongly influence the lifetime, was verified in He-II. According to Ref. 9, hybridization requires that He^4 contain a Bose-condensate phase. Thus, from a comparison of the data on the $\Gamma(T)$ theory, which is based on a hybridization scheme, it is possible in principle to estimate the value of the condensate density $n_0(T)$ and compare it with the data of Ref. 10, but this is beyond the scope of the present article.

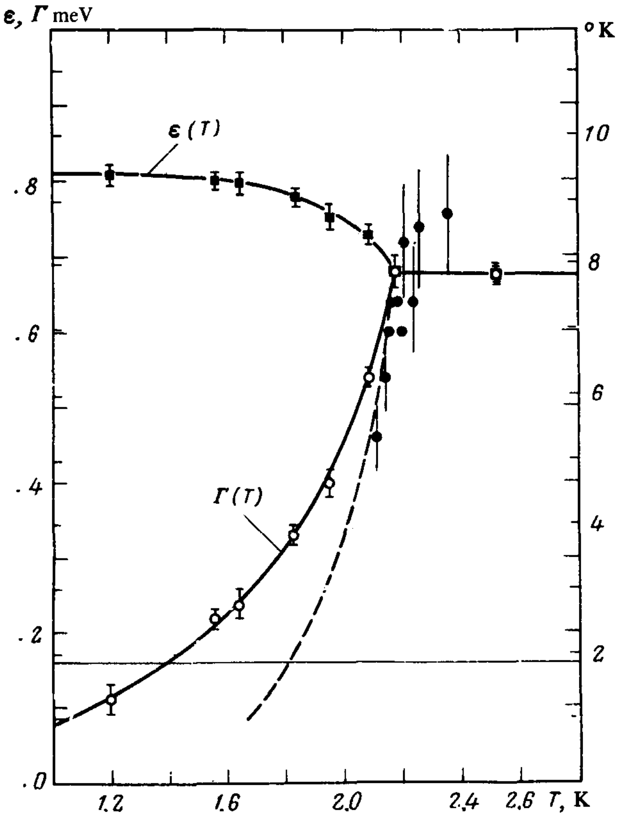

FIG. 2.

At $T = 2.17$ K, the $\epsilon(T)$ and $\Gamma(T)$ curves have kinks due to a phase transition. A characteristic feature of the results is the agreement between the values of the energy and width of the roton length at the λ point: $\epsilon(T_\lambda) = \Gamma(T_\lambda) = 0.68$ meV (7.89 K). This result means physically that the roton at the λ point loses the meaning of a well defined elementary excitation: the Heisenberg uncertainty of the energy becomes equal to the energy itself. At low temperatures, the rotons in liquid He^4 can be regarded as a gas whose concentration $N_r(T)$ is low, and this does not lead to a noticeable broadening $\sigma_{rr} \sim N_r(T)$. The effective background against which this gas exists is the superfluid component of He-II, whose density decreases with increasing T because of the increase of the number of excitations responsible for the normal component. Finally, near the λ point the concentration N_r becomes so high that the effective region of the roton–roton interactions turns out to be equal to the total volume of the liquid, which suppresses fully superfluid component. The estimate of N_r near the point, according to the formula $N_r(T) = 2q_0^2(\mu kT)^{1/2}(2\pi)^{-3/2}\hbar^{-3}\exp(-\Delta/T)$, is 7.6×10^{21} cm^{-3}. At this high concentration, the "roton gas" concept becomes meaningless. The average distance between the rotons near the λ point amounts to $[N_r(T)]^{-1/3} \sim 5.1$ Å, i.e., it is of the same order as the spatial uncertainty of the roton $\hbar[\mu\Gamma/2]^{-1/2} \sim 4.4$ Å and the average interatomic distance $[m_{\rm He}/\rho(T)]^{1/3} \sim 3.6$ Å. Taking into account the strong damping of the roton, we can conclude that near the λ point the roton gas goes over into a real liquid that participates in the normal motion, i.e., He-I.

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