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High-resolution measurements of the temperature dependence of the roton energy of superfluid ^{4}He

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Abstract

Recent neutron inelastic scattering measurements at the ILL (energy resolution < 1 μeV) of the dependence of the ^{4}He roton energy on temperature have shown significant deviations from the expected behaviour; the temperature variation was found to be slower than predicted by the established roton–roton interaction theory due to Bedell, Pines and Zawadowski (BPZ). New measurements of the roton excitations in superfluid ^{4}He have been made using the IRIS spectrometer (energy resolution ~ 20 μeV) at the ISIS spallation neutron source. The roton energy was determined over a temperature range of 0.5–1.6 K. We find that our results can be described well by the BPZ theory over this temperature range. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Helium; Liquids; Quantum effects; Superfluidity

1. Main text

The elementary excitations of superfluid liquid ^{4}He play an important role in a detailed understanding of the microscopic and macroscopic properties of this fascinating liquid. The phonon–roton dispersion curve describes the elementary excitations of liquid ^{4}He and has been extensively measured using neutron scattering techniques. The energy and (inverse) lifetime of the phonons and rotons are defined as the position and width of the single peak in the observed dynamic structure factor, $S(Q, \omega)$. A sound theoretical understanding of the energy and lifetime of the phonons and rotons was put forward by Landau and Khalatnikov [1] and Bedell, Pines and Zawadowski (BPZ) [2] who showed that a four-phonon decay process predominantly governs the temperature dependence of the excitations [3].

Recent measurements at the ILL, using the IN10 backscattering spectrometer [4] (energy resolution < 1 μeV) have pointed to some disagreement with the predictions of BPZ. There appears to be a discontinuity at about 1.3 K in the temperature dependence of the roton energy Δ, when account is taken of the previous systematic IN6 data (energy resolution approx. 100 μeV) [5]. Here we report on an attempt to investigate this anomalous temperature dependence using the IRIS time-of-flight spectrometer at the ISIS-pulsed neutron source, Rutherford Appleton Laboratory.

Measurements of the line shape were performed for seven temperatures between 0.5 and 1.6 K. The 0.5 K measurement was used solely as an estimate of the instrumental energy resolution. This is possible because the intrinsic roton width at this temperature is negligible compared with the observed width [6].

$S(Q, \omega)$ was sampled around the roton minimum; the single phonon-roton excitation peak can be described by the single-damped harmonic oscillator (DHO) expression [7]. The dispersion in the roton region

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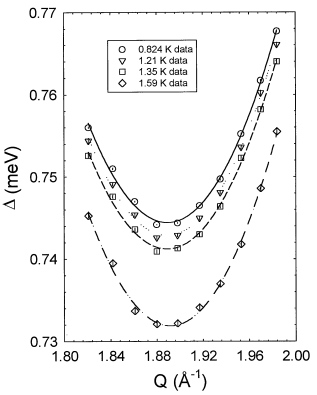

Fig. 1. Dispersion relation close to the roton minimum at representative tempratures (current data).

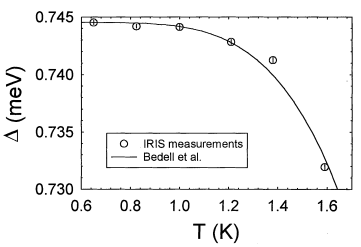

Fig. 2. Roton energy as a function of temperature. The solid line is a fit to the current data points according to the BPZ theory.

$1.8\,\text{Å}^{-1} < Q < 2.0\,\text{Å}^{-1}$ is shown in Fig. 1 along with typical fits to the parabolic expression given by Landau:

$$\hbar\omega(Q) = \Delta + \frac{\hbar^2(Q - Q_R)^2}{2\mu_R}, \tag{1}$$

where Q_R is the roton wave vector and μ_R is the roton effective mass.

The expression for the roton energy $\Delta(T)$ given by BPZ [2] is

$$\Delta(T) = \Delta_0 - P_\Delta(1 + R\sqrt{T})\sqrt{T}e^{-\Delta(T)/T}, \tag{2}$$

where R and P_Δ are dimensionless parameters and all energies and temperatures are measured in units of K. The zero-temperature roton energy Δ_0 was allowed to vary around the lowest temperature value, and it was found that a value of $\Delta_0 = 0.744(5)$ meV was required to produce the best agreement with the theoretical behaviour of Eq. (2) (see Fig. 2). The present value differs from that obtained on IN6/IN10 by approximately 4 μeV which may be a consequence of slight offsets in the energy-scale calibration of IN6, IN10 and IRIS. For comparison, the established low-temperature value of Δ is 0.742 meV [8]. The value of R was kept fixed at the value obtained by Andersen et al. [4] ($R = 0.0603$). The best-fit value of P_Δ for our data is $P_\Delta = 21.00$, in good agreement with tabulated values [3]. This is close to the best-fit value of Andersen et al. of $P_\Delta = 21.95$ for $T > 1.4$ K, but widely differs from their low-temperature best-fit value of $P_\Delta = 3.98$. Thus we can describe the variation with temperature of Δ using a single value of P_Δ. Andersen et al. required two values of $P\Delta$ to describe the two observed regimes, "high" ($T > 1.4$ K) and "low" ($T < 1.3$ K) temperature.

To summarise, we find good agreement between the measured roton parameters and the BPZ theory over the entire temperature range measured. We do not observe the discontinuous temperature dependence found by Andersen et al. [4]. The results presented here are consistent with the large body of existing data regarding the temperature dependence of the roton parameters, in support of the previously undisputed agreement between experimental results and BPZ theory. However, the effects observed by Andersen et al. [4] were very small (< 1 μeV), while the current instrumental resolution, although "high", is many times larger than this.

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