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# Excitations in superfluid $^4$He beyond the roton

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**Abstract.** – High-energy resolution inelastic neutron scattering data on excitations in superfluid and normal $^4$He at SVP at wave vectors $Q$ beyond the roton, $2.0 \le Q \le 4.0$ Å$^{-1}$, are presented. The narrow energy resolution of these measurements reveals that the energy of the elementary excitation comes up to twice the roton energy, $2\Delta$, at $Q = 2.8$ Å$^{-1}$ and the energy remains constant at $2\Delta$ between $Q \simeq 3.0$ Å$^{-1}$ and the end point of the dispersion curve at $Q = 3.6$ Å$^{-1}$. The width of the peak is also unobservably small from $Q = 2.8$ Å$^{-1}$ out to the end point, $W = 2\Gamma < 20$ $\mu$eV.

The energy and lifetime of the elementary phonon-roton excitations (EE) in superfluid $^4$He are accurately known at low wave vector up to the roton wave vector, $Q \sim 1.92$ Å$^{-1}$ at SVP [1-5]. However, the energy and lifetime of the EE for wave vectors beyond the roton, $2.5 < Q < 3.6$ Å$^{-1}$, are much less well determined. This is chiefly because the intensity in the single EE component of the observed dynamic structure factor, $S(Q,\omega)$, decreases rapidly with increasing $Q$ beyond the roton and this peak "sits" on a sloping broad component of $S(Q,\omega)$ so that high instrument resolution is required to determine the peak position accurately.

The excitations at $Q$ values beyond the roton (BTR) are also much less well understood [6-10] and microscopic calculations of the EE energy [11-13] reproduce the observed EE energies less well for $Q > 2.5$ Å$^{-1}$. In 1959, Pitaevskii proposed that the energy of the single EE, $\omega_Q$, had an upper limit. When the energy reached the energy of a pair of lower energy EE's, the single EE would decay into this pair. The single EE energy could not exceed this pair energy without decaying. The pair having the lowest energy which meets the conservation conditions for decay is two rotons. The $\omega_Q$ should not exceed $2\Delta$. In this picture, at the $Q$ value where $\omega_Q$ reaches $2\Delta$, the single EE should also broaden.

Earlier measurements [14-17] suggest that $\omega_Q$ exceeds $2\Delta$ for $Q > 2.8$ Å$^{-1}$, particularly at higher pressure. The energies of Cowley and Woods for $Q > 2.8$ $\AA^{-1}$ have been adopted as

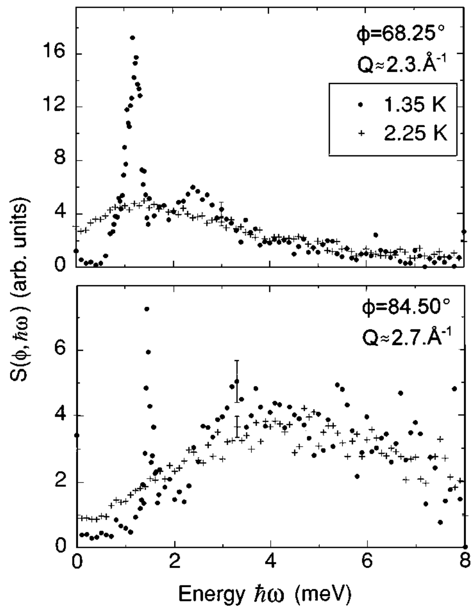


Fig. 1. – Scattered intensity for constant scattering angle $\phi = 68.25°$ and $84.5°$.

a standard [1]. More recently, Fåk and Andersen [18] and Fåk *et al.* [19] have made more precise measurements up to 2.8 $\text{Å}^{-1}$. Several studies are devoted to understanding these measurements in terms of excitation-excitation interactions [6-9].

In this letter we present high-energy resolution ($\Delta\omega = 50$ $\mu$eV FWHM elastic resolution) measurements of excitations in superfluid $^4$He at $T = 1.35$ K focussed on the wave vector range $2.8 < Q < 3.6$ $\text{Å}^{-1}$. Data at $T = 2.25$ K are also presented as a reference. The present data reveals that the single EE energy $\omega_Q$ reaches $2\Delta$ at $Q \sim 2.8$ $\text{Å}^{-1}$ and is constant at $\omega_Q = 2\Delta$ between 2.8 $\text{Å}^{-1}$ and the end point. The EE energy does not exceed $2\Delta$.

The data were taken on the IRIS spectrometer at the ISIS Facility, Rutherford Appleton Laboratory [20]. This is a "time of flight" instrument in which data is collected at constant scattering angles while keeping the final, scattered neutron energy constant, in this case at 7.39 meV. The liquid $^4$He was contained in a cylindrical, aluminum cell 50 mm diameter and 50 mm high separated into cells 10 mm high by Cd discs. Figure 1 shows data collected at two scattering angles $\phi = 68.25°$ and $84.5°$ as a function of energy transfer from the neutron to the liquid.

At $T = 2.25$ K in normal $^4$He we observe featureless, broad scattering covering a wide energy range, $0 < \omega < 8$ meV as seen in fig. 1. At $\phi = 68.25°$ and $T = 1.35$ K in the superfluid we observe a sharp peak at $\omega \sim 1.25$ meV and a broader peak at higher $\omega$ ($\omega \sim 2.4$ meV) in addition to the broad scattering. The sharp peak is the extension to higher $Q$ of the phonon-roton excitation. The broader peak centered at $\omega \simeq 2.4$ meV is interpreted as arising predominantly from particle-hole pairs of EE's appearing in the single excitation scattering function. The broad scattering component observed at both $T = 1.35$ K and 2.25 K is independent of temperature for $\omega \gtrsim 4$ meV.

The observed intensity displayed in fig. 1 finds a natural explanation involving the condensate [21, 22]. The sharp peak is identified with excitation of single quasiparticles (qps) out of

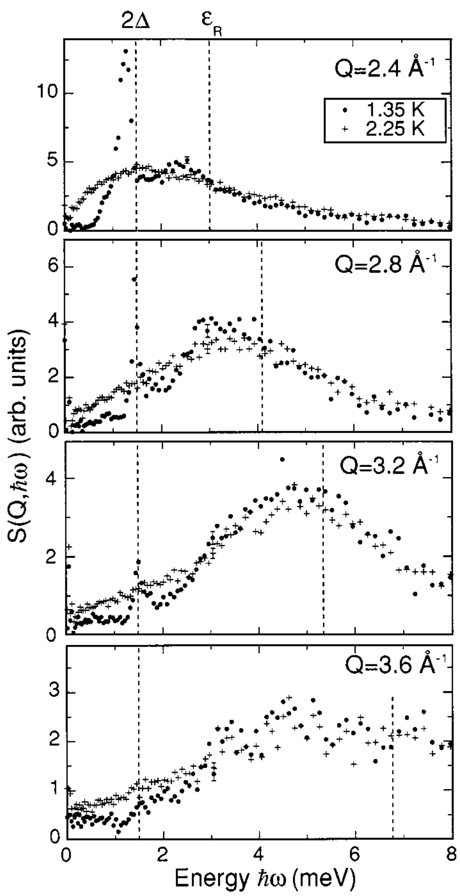


Fig. 2

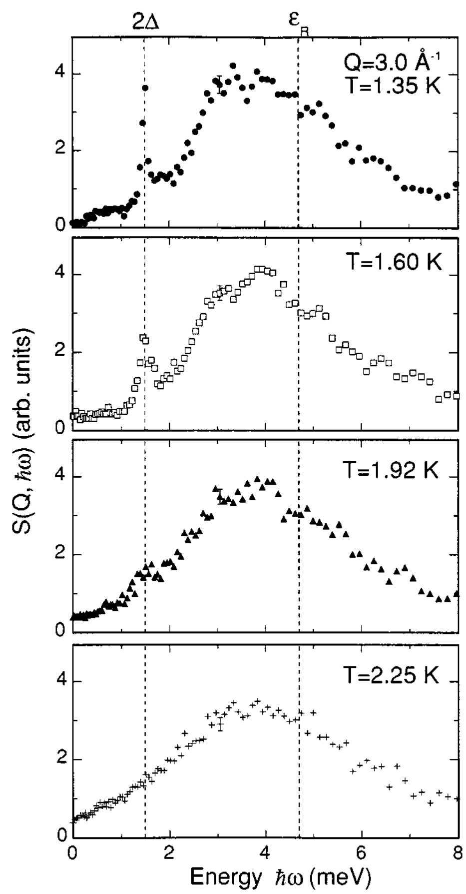


Fig. 3

Fig. 2. – Dynamic structure factor $S(Q,\omega)$ at four constant $Q$ values *vs.* energy transfer, $\hbar\omega$.

Fig. 3. – Temperature dependence of $S(Q,\omega)$ at $Q = 3.0$ Å$^{-1}$.

the condensate, plus some regular density response coupled to it. The broader peak arises from pairs and particle-hole pairs of qps appearing in the single-particle response via interactions involving the condensate. Both these contributions appear superimposed on a featureless, broad component characteristic of scattering from a normal fluid at high $Q$. In this $Q$ range, the fraction of the scattered intensity in the single and pair excitation peaks is expected to be approximately the condensate fraction, $n_0$ [23]. The detailed description of this scattering intensity remains an outstanding problem [21, 22, 10, 24].

Figure 2 shows the data rebinned to constant wave vector $Q$ for $Q = 2.4$, 2.8, 3.2 and 3.6 Å$^{-1}$. The width of the bin strip is $\pm 0.1$ Å$^{-1}$ which combines several detectors into a single bin. This improves the statistics but effectively coarsens the instrument resolution. We also made an independent measurement of the roton energy at $T = 1.35$ K. In the analysis we used $\Delta = 0.742 \pm 0.001$ meV $= 8.61 \pm 0.01$ K which is consistent with previous precision measurements [25, 26, 3].

While the energy resolution of IRIS is high, the wave vector resolution is rather coarse;

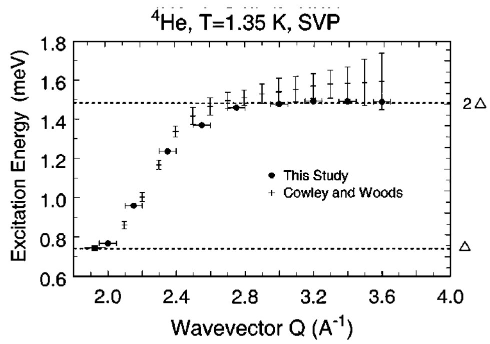


Fig. 4. – The phonon-roton energy dispersion curve in superfluid $^4$He at SVP.

$\Delta Q \simeq 0.10$ Å$^{-1}$ [27]. This effect produces broad EE peaks at $Q$ values where the EE energy, $\omega_Q$, is varying rapidly with $Q$, such as seen in the top frame of figs. 1 and 2. In a careful analysis of IRIS, Crevecoeur *et al.* [27] show that the total observed width is $W^2 = (\Delta\omega)^2 + (\frac{\mathrm{d}\omega_Q}{\mathrm{d}Q})^2 \Delta Q^2$. In addition, if the intensity, $Z_Q$, in the peak is changing rapidly with $Q$, the peak position can be shifted. This is the case for $2.2 < Q < 2.6$ Å$^{-1}$ where both $(\mathrm{d}\omega_Q/\mathrm{d}Q)$ and $\mathrm{d}Z_Q/\mathrm{d}Q$ is large. We have corrected for this effect and indicated $\Delta Q$ with an error bar in fig. 4 and table I. For $Q \geq 2.8$ Å$^{-1}$, where $\mathrm{d}\omega_Q/\mathrm{d}Q$ is small, the peak is sharp, dominated by $\Delta\omega$, and there can be no shift in the peak position. From fig. 2 we see that the peak position remains constant at $2\Delta$ for $Q \geq 2.8$ Å$^{-1}$. The peak does not show broadening for $Q \geq 2.8$ Å$^{-1}$, $W \leq 0.020$ meV. At $Q = 3.8$ Å$^{-1}$ we observed no EE peak.

Figure 3 shows the temperature dependence of $S(Q,\omega)$ at $Q = 3.0$ Å$^{-1}$. There we see that the intensity in the single excitation peak, and in the second, broader peak, centered at $\omega \sim 3.2$ meV, decreases with increasing $T$. The two peaks are very small at $T = 1.92$ K and have disappeared from $S(Q,\omega)$ at $T = 2.25$ K. The single excitation peak also broadens

TABLE I. – *The energy of the sharp peak in $S(Q,\omega)$ at $Q$ values beyond the roton at $T = 1.35$ K,* SVP ($2\Delta = 1.484 \pm 0.002$ meV).

| Wave vector $Q$ (Å) $^{-1}$ | Energy (meV) | Error (meV) |
|---|---|---|
| $2.00 \pm 0.05$ | 0.768 | 0.006 |
| $2.15 \pm 0.05$ | 0.959 | 0.006 |
| $2.35 \pm 0.05$ | 1.237 | 0.006 |
| $2.55 \pm 0.05$ | 1.371 | 0.011 |
| $2.75 \pm 0.05$ | 1.461 | 0.007 |
| $3.00 \pm 0.05$ | 1.479 | 0.008 |
| $3.20 \pm 0.05$ | 1.493 | 0.015 |
| $3.40 \pm 0.05$ | 1.492 | 0.012 |
| $3.60 \pm 0.05$ | 1.490 | 0.012 |

with increasing $T$. In fig. 3, we have maintained the $2\Delta$ line at the low $T$ roton energy value although the roton energy decreases with $T$, by approximately $\delta\Delta = -0.035$ meV between $T = 1.35$ K and $T = 1.90$ K [3]. The position and width of the single excitation peak is difficult to establish at $T = 1.92$ K.

Finally, in fig. 4 we show a revised phonon-roton energy dispersion curve which incorporates the new values of the EE excitation energy for $Q > 2.8$ Å$^{-1}$. The values used and their errors are listed in table I.

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