Pressure Dependence of Elementary Excitations in Normal Liquid Helium-3

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The neutron scattering function for liquid ^{3}He at 120 mK and pressures of 0, 0.5, 1, and 2 MPa has been determined for wave vectors in the range 3 nm^{-1} $< Q <$ 20 nm^{-1}. This represents the first experimental information on the density dependence of the zero-sound frequency and damping at finite wave vectors, and should serve as a useful test of theories on excitations in neutral Fermi liquids. The results are in qualitative agreement with extensions of the Landau Fermi-liquid theory to finite wave vectors.

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Neutron inelastic scattering offers a unique method to examine directly the elementary excitations in liquid ^{3}He on a microscopic scale, i.e., for wave vectors of order 10 nm^{-1}. Through their spin-dependent interaction with the ^{3}He nuclei, neutrons probe the nuclear spin fluctuations, in addition to the density fluctuations which are probed by the spin-averaged interaction. In the neutron scattering function, one distinguishes three components: the excitation of single particle-hole (p-h) pairs, a collective density mode (zero sound), and a broad distribution corresponding to multiple p-h excitations. The current theoretical and experimental situation in this area has recently been reviewed by Glyde.[1]

Previous neutron-scattering experiments[2-5] have shown that the single p-h spectrum resembles the one expected for a noninteracting Fermi gas but with an effective mass $m^* \approx 3m_0$ which lowers the energy of the p-h band compared with that of the noninteracting system. For $Q < 10$ nm^{-1}, the single-pair spin fluctuations are enhanced and are well described by the paramagnon model.[6] The zero-sound mode is well resolved for wave vectors less than 10 nm^{-1} and shows anomalous dispersion, i.e., the energies are above those corresponding to linear dispersion $\omega = c_0 Q$, where c_0 is the ultrasonic zero-sound velocity. It broadens considerably with increasing wave vector even before the mode overlaps with the p-h band. All the results published so far at saturated-vapor pressure (SVP) are in good general agreement with the predictions of the polarization-potential theory developed by Pines and co-workers.[7] Here the potential parameters, obtained by a fitting to the neutron-scattering results and to the Landau parameters, have been used to calculate transport properties for both normal and superfluid ^{3}He which are in excellent agreement with measured values.[8] The effective interactions in the polarization-potential theory are expected to be sensitive to the density, as discussed by Aldrich and Pines[7] and as shown by the Landau parameters, which are the low-Q limits of the effective interactions.

While in an earlier experiment[9] the scattering function for pressurized liquid ^{3}He could only be measured for wave vectors larger than 12 nm^{-1}, the present experiment explores the wave-vector range 3 nm^{-1} $< Q <$ 20 nm^{-1}. This therefore represents the first measurement of the zero-sound mode at elevated pressures.

The measurements were made at the time-of-flight spectrometer[10] IN6 at the high-flux reactor at the Institut Max von Laue–Paul Langevin in Grenoble. The incident neutron energy was 3.1 meV, and the energy resolution at zero energy transfer varied with increasing wave vector from 0.08 to 0.13 meV. Scattered neutrons were recorded in 337 individual detectors combined into 89 angular groups. Because of the high absorption cross section of the ^{3}He nuclei, the probability for a neutron to be scattered without being absorbed is only 1×10^{-4}. This imposes very stringent requirements on the sample cell; it should cause minimal scattering while being thick enough to sustain pressures in excess of 2 MPa. The sample was contained in a wedge-shaped cavity milled into the flat surface of a half-cylinder of Al (diameter 10 cm) and lined with Cd, in a geometry similar to the one previously used at Argonne.[3] The sample cavity was sealed by a 0.25-mm-thick window of high-purity aluminum glued around the edges of the sample cavity. The window was supported by a matching half-cylinder of silicon single crystal, and the two half-cylinders were held together by an Al strap, mechanically preloaded around the cylindrical surface. The front surface of the sample cavity was oriented at 7.8° to the incoming beam, which entered through the end of the silicon half-cylinder. The sample cell was mounted in an Oxford Instruments dilution refrigerator. A series of Cd shields before the sample and a radial collimator after the sample in conjunction with the particular shape of the sample cavity assured that the only irradiated material viewed by the detectors were the sample, the sample-cell window, and the silicon crystal.

Time-of-flight (TOF) spectra were recorded for liquid ^{3}He at 120 mK and at $p = 0$, 0.5, 1, and 2 MPa for about 90 h each. Background spectra from the empty cell were measured before and after the series of sample runs, and normalization spectra from a vanadium plate in a geometry identical to that of the sample were measure before, between, and after the individual sample runs. The elastic scattering from the Si crystal integrated over all the detectors was 9 counts/s with an energy-independent background of 4 counts/s. This should be compared with an integrated ^{3}He signal of 0.7 counts/s. The large elastic peak obscures the signal for energies below 0.1 meV.

After normalization to the beam monitor the empty-cell data were subtracted channel by channel from the full-cell data. The TOF data were normalized to vanadium and then corrected for self-absorption in ^{3}He, for scattering and absorption in the Si, and for detector efficiency. Energy distributions at constant Q were generated by regrouping of the constant-scattering-angle TOF data into wave-vector bins of 1 nm^{-1} in the range 3–20 nm^{-1} and into energy bins of 0.02 meV, resulting in eighteen constant-Q representations of the dynamical structure factor $S(Q,\omega)$ on an absolute scale:

$$S(Q,\omega) = S_{\text{coh}}(Q,\omega) + (\sigma_{\text{inc}}/\sigma_{\text{coh}}) S_I(Q,\omega).$$

The absolute normalization was obtained with the coherent cross section of ^{3}He, $\sigma_{\text{coh}} = 4.40$ barns.

The experimentally determined scattering function is shown in Fig. 1 for the four pressures measured and at a few selected wave vectors. At low Q, the low-energy "paramagnon" scattering is largely independent of pressure, while at larger wave vectors, the spectra show pronounced "softening" of the single-pair excitations with increasing density (cf. Ref. 9). This latter effect is a manifestation of the increase in the effective quasiparticle mass.

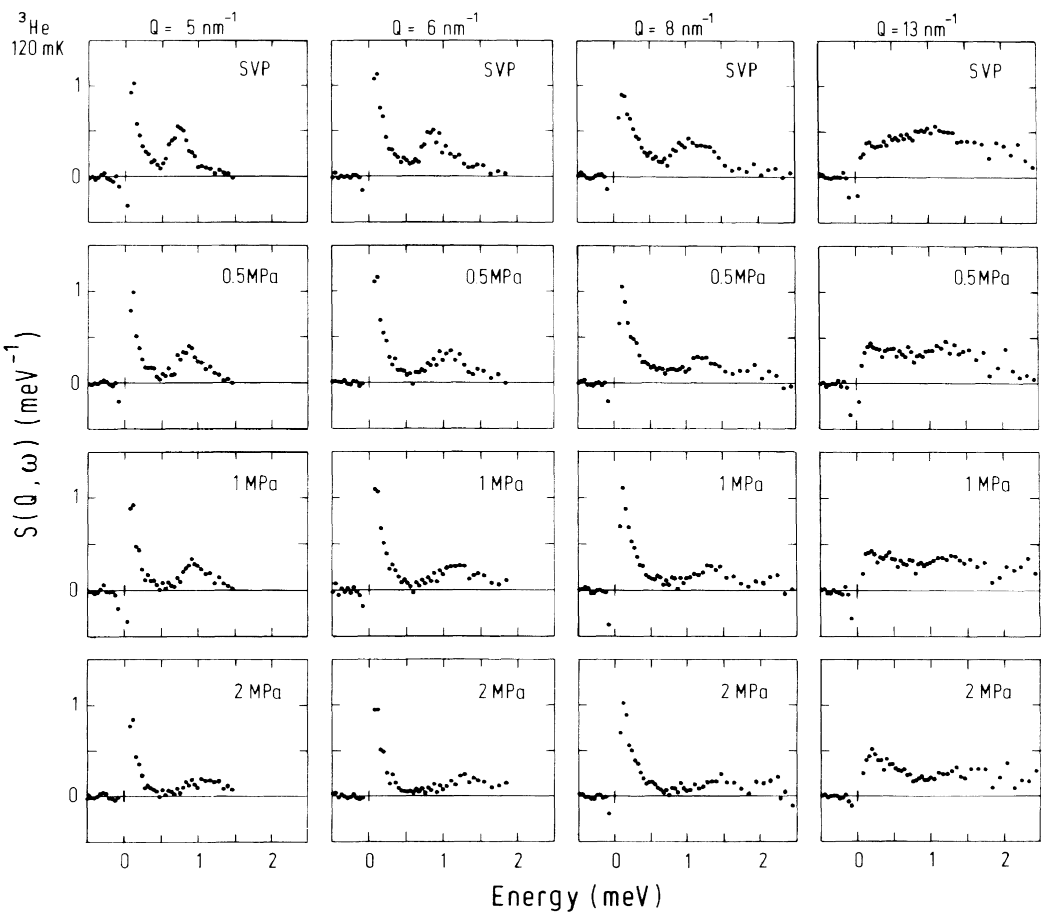

FIG. 1. Dynamical structure factor of liquid ^{3}He at 120 mK for pressures and wave vectors as shown.

The density dependence of the zero-sound mode is even more distinct. The frequency of the mode increases, the width increases, and the spectral weight decreases as the pressure is raised. Figure 2 shows the frequencies and intrinsic widths of the zero-sound mode at the four densities measured. The values are extracted from the experimental data on the assumption that the zero-sound peak is superimposed on a sloping background from single and multipair excitations. The widths have been corrected for both energy and momentum resolution. The linewidths obtained by Hilton *et al.*[5] at saturated vapor pressure (SVP) are also shown in Fig. 2(b) and are seen to be in excellent agreement with the present results. The widths reported by Sköld *et al.*,[3] taken at a much coarser Q resolution, are approximately a factor of 2 larger than those shown.

The straight lines in Fig. 2(a) represent the ultrasonic zero-sound velocities[11] at the respective densities. For wave vectors less than 9.5 nm^{-1}, the present results clearly show anomalous dispersion at SVP, in full accordance with previous neutron-scattering experiments.[2,3,5] The phase velocity exceeds the ultrasonic zero-sound velocity by as much as 13%. At higher densities the anomalous character gradually disappears while the width of the zero-sound (phonon) mode increases. This observation seems to rule out the one- to two-phonon decay as the dominant damping mechanism, since these three-phonon processes are kinematically allowed only in the region of anomalous dispersion. It is interesting to note that in ^{4}He at SVP, where the anomalous dispersion is only 4% and extends out to 5.5 nm^{-1}, the phonon width of 2 μeV at low temperature may readily be explained by three-phonon processes,[12] while the width in ^{3}He is about 100 times larger.

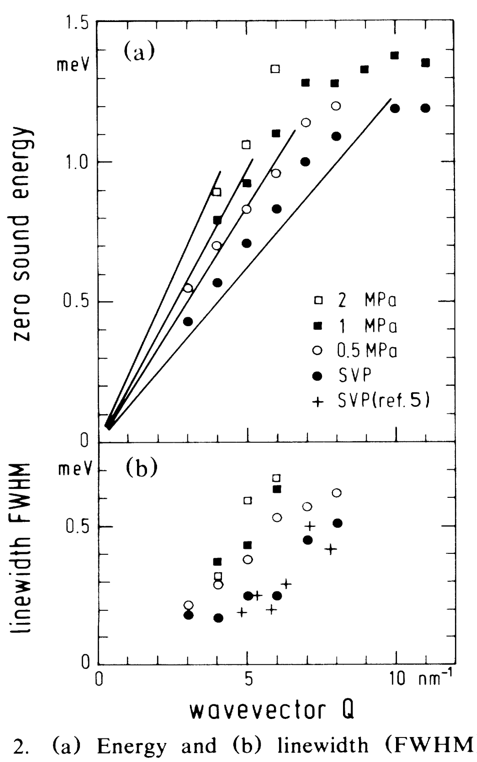

FIG. 2. (a) Energy and (b) linewidth (FWHM) of the zero-sound mode for different pressures. Solid lines in (a) are ultrasonic zero-sound velocities (Ref. 11).

In contrast to ^{4}He, interactions of the collective phonon mode with the p-h excitations open an additional decay channel. The decay of a phonon into a single p-h pair (Landau damping) is possible only beyond 15 nm^{-1}, where these modes directly overlap. The decay into multipairs, however, offers an explanation of our results.

This has, in fact, been calculated by Glyde and Khanna.[13] Their theory is based on the random-phase approximation and the Landau theory, extended to include multipair excitations. The width of the zero-sound mode, obtained from a second-order perturbation expression, increases with increasing pressure in accordance with the present results. At SVP, their predicted FWHM of 0.22 meV at 5 nm^{-1} is identical to our measured value. However, at $q = 10$ nm^{-1}, the calculated width of 0.35 meV is clearly too narrow. At higher pressures their calculation tends to overestimate the widths by as much as a factor of 2. The pressure dependence of the excitations follows directly from the pressure dependence of the Landau parameters: The nearly density-independent paramagnon mode and the predicted pressure dependence of the zero-sound velocity both agree well with our results. The theory does not, however, reproduce the anomalous dispersion, nor does it predict the leveling off of the phonon frequencies around 1.3 meV as experimentally seen at 1 MPa.

In the work of Aldrich and Pines,[7] the density dependence of the zero-sound dispersion relation is analyzed in terms of the range of the repulsive part of the effective interaction. Their theory includes a Q-dependent restoring force and correctly describes the anomalous dispersion at SVP and the flattening of the dispersion curve in the "maxon" region around 10 nm^{-1}. Their approach does not, however, include a damping mechanism for zero sound.

Very recently Pines and Hess[14] calculated the pressure dependence of the zero-sound frequencies. They found that the anomalous dispersion disappears with increasing pressure in analogy to ^{4}He.[15] By adjustment of the range of the effective interaction with pressure, the calculated zero-sound frequencies are brought into excellent agreement with our present results at all pressures.

Finally, we want to emphasize the dominant role of the multiple p-h excitations. Because multipairs and the collective zero-sound mode partly overlap, it is difficult to disentangle these two modes in the experiment. In addition, it is essentially the interaction between these two modes which determines the detailed frequency and the damping of the zero sound.

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