NEUTRON SCATTERING FROM LIQUID HELIUM AT HIGH ENERGIES

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Neutron scattering from liquid helium at large energy and momentum transfers was found to be qualitatively consistent with an independent particle model. No evidence for a sharp peak related to the occupation of the zero momentum state was observed but, from the temperature dependence of the width, a value of $(17\pm10)\%$ for the population of this state was deduced. Possible evidence for vortex creation accompanying the scattering process was obtained.

The neutron scattering from liquid helium at large momentum transfers, 2-9 Å^{-1}, and high energy transfers, $\Delta E/k_B = 0$-$1000°$K, has been measured as a function of temperature. In earlier experiments,[1] the one-phonon excitation was studied up to momentum transfers of 3.8 Å^{-1}. However in these experiments most of the scattering occurred at energy transfers higher than that of the one-phonon excitation, and the present experiments were performed to study the nature of this scattering. The results are qualitatively consistent with an independent particle model and give information about the change of momentum distribution of the helium atoms with temperature, and also about the way in which excited helium atoms lose energy.

At momentum transfers much larger than the inverse of typical interparticle distances, where the static structure factor is close to unity and energies, or frequencies, are much greater than the inverse of interparticle collision times, the scattering arises from bare helium atoms. In these circumstances an independent particle model suggested initially by Miller, Pines, and Nozières[2] but discussed more explicitly by Hohenberg and Platzman[3] is expected to describe the scattering. A free helium atom with momentum $\hbar\vec{p}$ has an energy given by $\hbar^2p^2/2M$, where M is the mass of the helium atom. If neutrons are scattered with a momentum transfer $\hbar\vec{Q}$ the momentum of the scattered helium atom is $\hbar(\vec{p}+\vec{Q})$. The energy transfer $\hbar\omega$ to the helium atom is then $\hbar^2(Q^2+2\vec{p}\cdot\vec{Q})/2M$. The scattering cross section $S(\vec{Q},\omega)$ is then obtained by averaging over the initial momentum distribution $n(\vec{p})$ of helium atoms to obtain

$$S(\vec{Q},\omega)=\sum_{\vec{p}} n(\vec{p})\delta(\hbar\omega-(\hbar^2/2M)(Q^2+2\vec{Q}\cdot\vec{p})). \quad (1)$$

On this model the scattered distribution at fixed momentum transfer is centered around the free-particle energy $\hbar^2Q^2/2M$, and its shape reflects the distribution function $n(\vec{p})$.

Most of the experiments were performed with a rotating-crystal spectrometer,[4,5] using an aluminum monochromator and (220), (331), and (511) planes to reach momentum transfers up to 6.4 Å^{-1}. Figure 1 shows the distributions obtained at 1.1 and 4.2°K with a scattering angle of 82° and (331) monochromator planes which give an incident wavelength λ of 1.47 Å. In this figure a flat, time-independent background has been subtracted, and the results are plotted against the energy transfer.

A triple-axis crystal spectrometer[5] was used to obtain results at the higher momentum transfers and was programmed to give energy distributions while $|\vec{Q}|$ remained constant. Before the

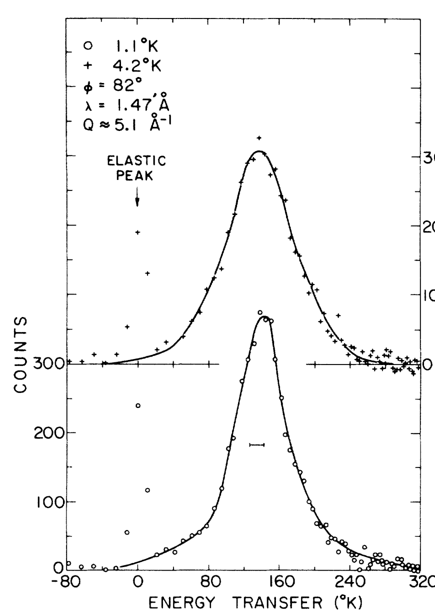

FIG. 1. Scattered neutron distributions obtained from liquid helium at 1.1 and 4.2°K with the rotating crystal spectrometer. The plots are of time-of-flight spectra plotted on an energy-transfer scale and with background subtracted. The elastic peak arises from scattering by the cryostat and by the air. The experimental resolution (about 15°K in energy) is shown.

results from the two different spectrometers could be compared, it was necessary to correct those from the rotating-crystal spectrometer, firstly to obtain an energy distribution instead of a time-of-flight distribution, and secondly to allow for the change in momentum transfer as the energy transfer altered. When these two corrections had been made, the results were in excellent agreement with one another as shown in Fig. 2.

The energy distributions all showed peaks at finite energy transfers that were considerably broader than the experimental resolution (see Fig. 1). The centers of these distributions were close to the free-particle energies, although at the smaller momenta they were of somewhat lower energy. In particular the energies were $(86\pm3)\%$, $(94\pm3)\%$, and $(97\pm3)\%$ of the free particle energies at momentum transfers of 3, 5, and 7 $Å^{-1}$, respectively. These results thus support the use of the independent particle model to describe the scattering in this region.

The energy distributions show no markedly sharp structure (see Fig. 1) and thus may be described by the full width at half-maximum. The widths at 1.1°K are shown in Fig. 2 as a function of momentum transfer. The solid line is the average of 75 independent measurements with the

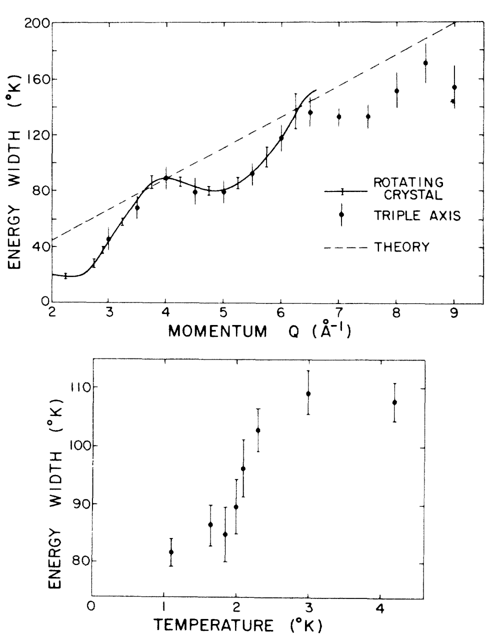

FIG. 2. The width of the neutron groups as a function of momentum transfer at 1.1°K and of temperature with $Q=5.1$ $Å^{-1}$. The theory line is taken from a calculated distribution (Ref. 6) with $n(0)=0$.

rotating-crystal spectrometer and the error bars represent the maximum spread of the individual results, while the results shown for the measurements with the triple-axis crystal spectrometer are each the average of results obtained under several different experimental conditions. The error bars are again the maximum spread of the individual results.

Similar measurements were made at 4.2°K and the results are similar to those at 1.1°K. However at all momentum transfers the width is about 10-30% larger at the higher temperature as illustrated in Fig. 1. Detailed measurements of the change of width with temperature were made at 5.1 $Å^{-1}$ and are shown in Fig. 2. There is a marked increase in the width in the vicinity of the λ transition.

On the independent particle model, Eq. (1), the width of the distributions is a reflection of the distribution of particles $n(\vec{p})$. If there were no scattering of the helium atoms by one another, the distributions would show a sharp peak at 1.1°K corresponding to the macroscopic occupation $n(0)$ of the zero momentum,[2,3] superimposed on a broad distribution associated with the other helium atoms. The distribution at 1.1°K shown in Fig. 1 shows no evidence of such a sharp peak. However the change in width between 1.1 and 4.2°K, and, in particular, the way in which the change occurs close to the superfluid phase transition do suggest that a large part of the change is associated with the occurrence of the superfluid phase and possibly with the $n(0)$ peak. Presumably the latter is broadened by the experimental resolution and by the scattering of the helium atoms by one another to such an extent that it is not directly observable. There is also a change in the peak height with temperature, as shown in Fig. 1, such that the product of the width and the peak height is approximately independent of temperature. The total scattering cross section is thus approximately independent of temperature.

It is of interest to compare our distributions with those calculated from Eq. (1) with the momentum distribution $n(\vec{p})$ of McMillan.[6] If we ignore the $n(0)$ peak, the width of the scattered distribution resulting from his $n(\vec{p})$ function is shown in Fig. 2. It is significantly larger than the width at 1.1°K but very similar to the measurements above the λ point. If we assume that the whole of the narrowing at 1.1°K comes about because some of the particles in the broad 4.2°K distribution form the relatively sharp $n(0)$ peak and therefore deplete the broad distribution, which furthermore does not change in shape with temperature, we may estimate the value of $n(0)$. Unfortunately the result is very dependent on the detailed shape and width assumed for the $n(0)$ peak, but it seems as if values in the region of (17 ± 1)% are consistent with our measurements. Clearly a more precise number can only be obtained when a more satisfactory theory of the shape and width of the $n(0)$ peak is developed. Such a theory should also include the effect of the long-wavelength correlations in $n(\vec{p})$ as described by Reatto and Chester.[7]

Figure 2 shows that the widths of the distributions do not increase linearly with $\vec{Q}$ as expected on the independent particle model. Rapid increases in width occur at approximately 3.2 and 6 $Å^{-1}$, corresponding to the energies of the scattered helium atoms of about 62 and 220°K, respectively. One possible explanation of these rises is that they occur when the scattered helium atoms have just sufficient energy to produce small vortex rings of 1 and 2 quanta of circulation, respectively. The characteristic energies are much larger than any other known excitations and seem appropriate for vortex rings of about 3 Å radius.[8]

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TURBULENT PLASMA HEATING IN A TORUS

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Turbulent heating has been applied to plasmas of density 10^{11} to 5×10^{13} cm^{-3} in a bumpy torus for the purpose of observing afterglow confinement. An rf electric field of up to 250 V/cm ringing at 1 Mc/sec was induced parallel to the axis for 1 μsec. The plasma was observed to remain in confinement for several microseconds after current cutoff, the initial nT being as high as $(5\text{-}7)\times10^{15}$ eV cm^{-3}.

The general principle of turbulent plasma heating might be defined as the conversion of ordered particle motion to random particle motion by means of turbulent pulsations, excited in the plasma by the ordered motion itself. Turbulent heating was first achieved by Zavoisky[1] in 1961. The ordered particle motion in this particular case was provided by strong magnetohydrodynamic waves.

Another kind of ordered particle motion, well-suited for turbulent heating purposes, is the current-produced charged-particle drift in strong electric fields. If the electron-drift velocity exceeds a certain threshold, the current-carrying electron stream should excite in the plasma Buneman and/or ionic sound instabilities. In 1963 we found an anomalously large energy dissipation of the electric current passing along the magnetic field in a high-electric-field electrodeless toroidal discharge. During the electric current passage the $n=10^{12}$ cm^{-3} density plasma had a temperature $T_e\approx10^2\text{-}10^3$ eV and a high level of plasma pulsations in the Langmuir and ionic-sound ranges was observed, the anomalous plas-