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Neutron Scattering Study of Elementary Excitations in Liquid Helium-3†

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The neutron inelastic scattering function of liquid helium-3 at 0.015 K has been measured for wave vectors in the range 0.8 Å^{-1} ≤ q ≤ 2.2 Å^{-1}. For q < 1.4 Å^{-1}, the scattering function contains two peaks. The peak at lower energy is due to spin-fluctuation scattering in the particle-hole region while the peak at higher energy is identified to be the zero sound mode. By comparing the measured structure factor with the x-ray structure factor, the spin-dependent scattering cross section and the corresponding structure factor are determined.

The importance of neutron inelastic scattering results for liquid ^{3}He has long been recognized,[1,2] but the large neutron absorption cross section of the ^{3}He nucleus has discouraged experimental efforts in the past. However, recent development of high flux reactors and experimental techniques has made such measurements feasible; and a series of experiments at ILL in Grenoble has been reported by Scherm *et al.*,[3] and Stirling and coworkers.[4,5] The lowest temperature of the Grenoble measurement was 0.63 K and, in all cases, the spectra consisted of a broad peak with no discernible structure. In particular, no structure consistent with a well defined zero-sound mode was observed. In the present Letter we report measurements of the neutron inelastic scattering function for liquid ^{3}He at 0.015 ± 0.005 K and for wave vectors in the range 0.8 Å^{-1} ≤ q ≤ 2.2 Å^{-1}.

The measurements were made at the CP-5 reactor at the Argonne National Laboratory.[6] This is a rather modest flux reactor; to overcome the experimental difficulties associated with the large absorption in the sample, the statistical chopper time-of-flight technique was used.[7] In order to utilize fully the advantage of the statistical modulation technique, great care was taken to suppress scattering of the modulated beam other than by ^{3}He. In order to avoid systematic errors, it is also very important that an accurate correction for the extraneous scattering by applied. The sample arrangement which was used in the present study was designed with these criteria in mind and will be described in detail elsewhere. The sample was cooled in a ^{3}He-^{4}He dilution refrigerator[8]; and the sample temperature was monitored by two carbon resistors attached to the sample container.

Time-of-flight spectra were measured in fifteen separate groups of detectors at scattering angles between 30.4° and 106.7°; the incident neutron energy was 4.82 meV. Data were collected for 10 days with liquid ^{3}He in the container and for an equal length of time with the container empty. The scattering observed with the container empty was subtracted from the scattering observed with liquid ^{3}He in the container after normalization to equal incident flux as measured by a beam monitor. Examples of the resulting time-of-flight spectra are shown in Fig. 1. Standard correction procedures were used to transform the time-of-flight spectra to the scattering function at constant angle.[9] Three points are worth mentioning with regard to these procedures: (i) The data were put on an absolute scale by normalization to the elastic scattering from a vanadium foil in a geometry closely reproducing the geometry of the ^{3}He surface; (ii) the correction for absorption in the sample was made along the lines recently discussed by Sears[10]; and (iii) no correction for instrumental resolution has been applied to the data; the energy resolution is ≈0.3 meV and the wave-vector resolution is less than 0.1 Å^{-1} over the range of the measurement.

It is clearly more advantageous to represent the scattering function at a constant value of q rather than at a constant angle of scattering. Standard interpolation procedures[9] were employed to obtain the scattering function values of q in the

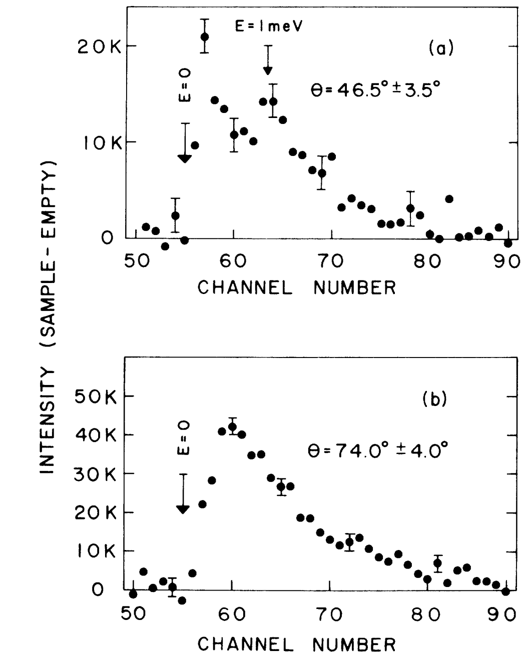

FIG. 1. (a) and (b), examples of time-of-flight spectra at constant angle of scattering after subtraction of scattering with an empty container. Note that the absolute value of the error is the same in all channels. This is a specific feature of the statistical chopper techinique.

range 0.8 $\mathrm{\AA}^{-1} \leq q \leq 2.2\ \mathrm{\AA}^{-1}$. Examples of $S(q, E)$ at selected values of q are shown in Fig. 2. The data are normalized such that the experimental scattering function is

$$S(q, E) = S_c(q, E) + (\sigma_I/\sigma_c)S_I(q, E), \quad (1)$$

where σ_I and σ_c measure the spin-dependent and the coherent scattering, respectively[10]; we take $\sigma_c = 4.9 \pm 0.9$ b.[11]

Before discussing the detailed features of $S(q, E)$, it is useful to assess the reliability of the results by evaluation of the energy moments. In the present case the 0th moment, which is the static structure factor $S(q)$, is of particular interest. $S(q)$ was evaluated by numerical integration of $S(q, E)$ at each value of q and is shown in Fig. 3 together with $S_c(q)$ from x-ray measurements by Hallock[12] and the difference which is then $(\sigma_I/\sigma_c)S_I(q)$. The reason for the downward trend in $(\sigma_I/\sigma_c)S_I(q)$ for $q > 1.5\ \mathrm{\AA}^{-1}$ is probably due to the fact that the integration of $S(q, E)$ is not carried out to large enough energies at these values of q where multipair excitations are becoming of increasing importance.[13,14] We note that $S_I(q)$ is essentially constant for 0.8 $\mathrm{\AA}^{-1} \leq q \leq 1.5\ \mathrm{\AA}^{-1}$ and, if we assume that the function has already reached

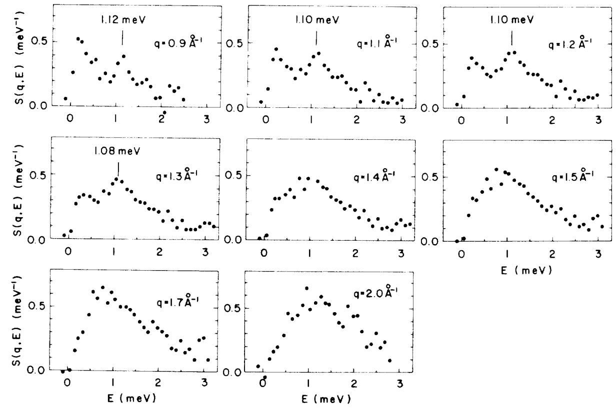

FIG. 2. $S(q,E)$ at selected values of q normalized as in Eq. (1). From the scatter in the data points, it can be seen that the error in $S(q,E)$ increases with E. This is mainly due to the fact that the data are multiplied by a factor t^4 in the conversion from time-of-flight spectrum to scattering function.

the limiting value of 1, we find that $\sigma_I \approx 0.25\sigma_c$.[15] From this and the value for σ_c given above we obtain $\sigma_I = 1.2 \pm 0.5$ b. This is the first experimental determination of σ_I and is in good agreement with the value ($\sigma_I = 1.2 \pm 0.3$ b) estimated by Sears and Khanna.[16]

The experimental $S(q, E)$ shown in Fig. 2 has several interesting features. First of all we see a well defined peak at $E \approx 1.1$ meV for $q < 1.4\ \mathrm{\AA}^{-1}$ which we identify as the zero sound mode. This is in fact the first experimental observation of zero sound under circumstances where the Landau theory does not apply; the existence of such a mode in liquid ^{3}He was predicted over a decade ago by Pines.[17] The vertical lines in Fig. 2 show the estimated peak positions which are also shown

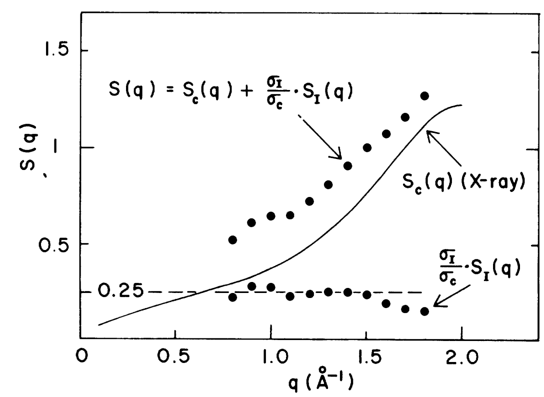

FIG. 3. Experimental structure factor together with the x-ray structure factor by Hallock (Ref. 12) and the difference between the neutron and the x-ray results. The dashed line at $S(q) = 0.25$ shows the average value of $(\sigma_I/\sigma_c)\cdot S_I(q)$ in the region 0.8 $\mathrm{\AA}^{-1} \leq q \leq 1.5\ \mathrm{\AA}^{-1}$.

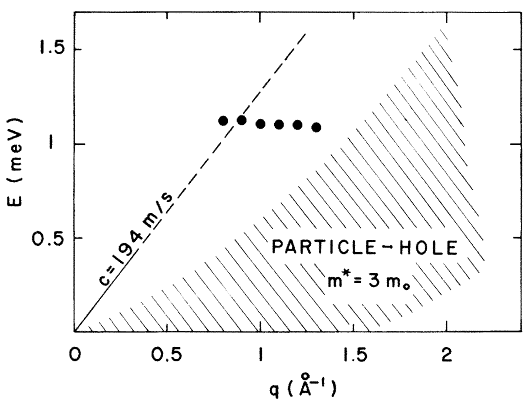

FIG. 4. Peak position versus q for the zero-sound mode together with the linear zero-sound dispersion curve for $c_0 = 194$ m/sec (Ref. 18) and the quasi-particle continuum for $m^* = 3m_0$.

as function of q in Fig. 4 together with the particle-hole continuum for $m^* = 3m_0$ and the linear dispersion curve for $c_0 = 194$ m/sec.[18] The results show that zero sound exists as a well defined excitation in the region where it does not intersect the continuum and that the effective mass is approximately $3m_0$ at $q \approx 4$ Å^{-1}. We also note that the width of the peak is consistent with the experimental resolution width (i.e., the intrinsic width of the mode is small) for $q \lesssim 1.1$ Å^{-1} but that the peak broadens rapidly as the mode approaches the edge of the continuum. The results further show that at $q = 0.8$ Å^{-1} the zero sound mode lies above the linear dispersion curve. This implies the existence of a region with positive dispersion for $q < 0.8$ Å^{-1} in agreement with recent calculations by Aldrich[13] and by Aldrich, Pethick, and Pines.[14]

A comparison of the present results with the results obtained by the Grenoble group[3-5] with regard to the existence of a zero-sound mode shows that the two sets of data are consistent within the experimental uncertainties at $q \approx 1.2$–1.3 Å^{-1}. This is the smallest value of q shown in Ref. 5 and the largest value of q at which the present experiment shows a zero-sound mode. Therefore, although the Grenoble data by themselves do not suffice to deduce the existence of a zero-sound mode, neither are they in any way incompatible with our observation of such a mode.

Another interesting feature of the scattering function is the intense peak at small energies for small values of q. The shape of the peak is similar to that expected for quasi-particle excitations with $m^* = 3m_0$. However, recent calculations[13,14] indicate that the spectral weight in $S_c(q, E)$ for quasi-particle excitation is neglibible for $q \gtrsim 1.2$ Å^{-1}. In view of the result obtained above for $S_I(q)$ and σ_I, the peak at small energies is believed to represent quasi-particle excitations seen through the spin-fluctuation scattering.[14,19] In particular, for values of q for which the two peaks in $S(q, E)$ can be separated with some confidence ($q \lesssim 1.2$ Å^{-1}) the area of the peak at low energy is consistent with the value for $(\sigma_I/\sigma_c)S_I(q)$ obtained above. A comparison with the Grenoble result with regard to this feature in $S(q, E)$ is unfortunately not meaningful since the Grenoble results[5] are stated by the authors to be unreliable for $E \lesssim 0.5$ meV.

A detailed comparison between the present results and the theoretical results obtained from a generalized polarization potential approach by Aldrich, Pethick, and Pines is presented in the following Letter.[14]

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Zero Sound and Spin Fluctuations in Liquid Helium-3†

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The density fluctuation spectrum of ^{3}He is calculated using a generalized polarization potential approach and shown to yield both zero sound and quasiparticle spectra in good agreement with the recent neutron scattering experiments. Landau Fermi-liquid theory is used to calculate the spin density fluctuation spectrum; and sum-rule arguments are presented which enable us to establish the qualitative nature of this spectrum at larger wave vectors with results in good qualitative agreement with the recent experiment of Sköld *et al.*

In 1952 Pines and Bohm[1] argued, on the basis of random-phase-approximation (RPA) calculations, that a collective mode, analogous to the plasma oscillation, should be present in any strongly interacting neutral system provided its frequency, $\omega_c(q)$, is large compared to characteristic single-particle excitation frequencies. Following the discovery by Woods[2] that well-defined elementary excitations in liquid ^{4}He exist at temperatures above the λ point, Pines[3] introduced a scalar polarization potential, proportional to the density fluctuation, as a way of taking into account, at the outset, the polarization effects responsible for such a mode; he showed by sum-rule arguments that in the strong-coupling limit (which is very nearly the case for ^{4}He) one expects a collective (zero-sound) mode in both the superfluid and normal phases of liquid ^{4}He; and he predicted the existence of a comparable mode in ^{3}He at elevated momenta and temperatures for which the Landau theory[4] does not apply, provided the mode met the basic condition (set forth in Ref. 1) that its frequency be distinct from the characteristic single-particle excitation frequencies. That mode has now been observed by Sköld *et al.*[5] in an elegant application of inelastic neutron scattering techniques to the study of the elementary excitation spectrum of ^{3}He. They find that at a temperature of 15 mdeg a well-defined zero sound mode, at an energy of ~13 K, exists for wave vectors between 0.8 A^{-1} (the lowest momentum transfer at which the experiment was carried out) and 1.4 A^{-1}. Sköld *et al.*[5] observe a low-frequency peak as well (at ~3 K for $q=0.9$ A^{-1}), which they identify with the spin fluctuation quasiparticle excitations.

In this Letter, we describe the results of a generalized polarization potential calculation of the density fluctuation excitation spectrum of ^{3}He which yields good agreement both with the experimental results of Sköld *et al.*[5] and with those carried out previously at larger momentum transfers ($q \gtrsim 1.4$ A^{-1}) and higher temperatures ($T \sim 0.63$–1.2 K) by Scherm *et al.*[6] and Stirling and co-workers.[7,8] We use Landau Fermi-liquid theory and sum-rule arguments to determine the general characteristics of the spin density fluctuation excitation spectrum and show that there is good qualitative agreement between theory and the experiment of Sköld *et al.*[5]

Density fluctuation excitations.—In the polarization potential model, the restoring forces responsible for the collisionless part of the density fluctuation excitation spectrum have their origin in