PHYSICAL REVIEW LETTERS

VOLUME 1 | AUGUST 15, 1958 | NUMBER 4

ENERGY-MOMENTUM RELATION IN LIQUID HELIUM BY INELASTIC SCATTERING OF NEUTRONS

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(Received July 14, 1958)

Measurements of the momentum changes of neutrons scattered inelastically from condensed systems yield information about the atomic motions of the scatterers. The scattering of neutrons from liquid helium at about 1°K may be interpreted in terms of the theory of Cohen and Feynman[1] to yield the energy-momentum relationship first proposed by Landau[2] and later by Feynman and Cohen[3] and Brueckner and Sawada.[4]

The wavelength change of neutrons scattered inelastically from liquid helium at several temperatures has been measured at four angles of scattering. Two instruments have been used. With one, the wavelength shift of the beryllium "edge" of neutrons scattered from liquid helium has been measured at 45.4° and 90° using the Chalk River filter chopper apparatus.[5] With the other, the actual spectrum of neutrons scattered from liquid helium at several temperatures has been measured at 80° using the rotating-crystal time-of-flight neutron spectrometer[6] while the shift at low liquid temperatures has been measured at 35° and 80°. The upper limit of the broadening of the spectrum at the lowest liquid temperatures has been estimated from the change in the slope of the edge caused by the liquid helium measured with the first apparatus.

For all the measurements, the liquid helium was contained in a scattering chamber $2\frac{7}{8}$ in. diameter and $2\frac{1}{2}$ in. high. For analysis of the wavelength distribution of the incident neutrons, a 1 in. diameter vertical cylinder of vanadium chips was mounted axially in the scattering chamber.

At the lowest liquid temperatures, the broadening due to the liquid helium is <0.5°K. Thus at the lowest liquid temperature there is a well defined change in wavelength of the scattered neutrons. The corresponding changes in energy ΔE and momentum Q of the scattered neutrons have been calculated for each angle of scattering and the results are listed in Table I.

Table I. Momentum and energy change of neutrons scattered from liquid helium.

Liquid temperature	Angle of scattering	Neutron wavelength	Q	ΔE
°K	Degrees	A	A^{-1}	°K
1.27	35	4.14	0.86	13.1
1.27	45.4	3.95	1.16	13.8
1.27	80	4.14	1.87	8.3
1.46	90	3.95	2.14	10.9

Similar measurements[7,8] are in agreement with those reported here.

These momenta and energies give directly[1] the energy-momentum relation of the excitations in liquid helium at low temperatures. The values are shown plotted in Fig. 1, and a smooth curve has been drawn through the points. The parabolic curve represents the excitations for free helium atoms and the broken line which rises linearily from the origin represents the phonon excitation for a velocity of sound[9] of 237 meters sec^{-1}.

The results indicate that for low momenta, the measured excitations approach the theoretical phononexcitation, while at higher momenta, the

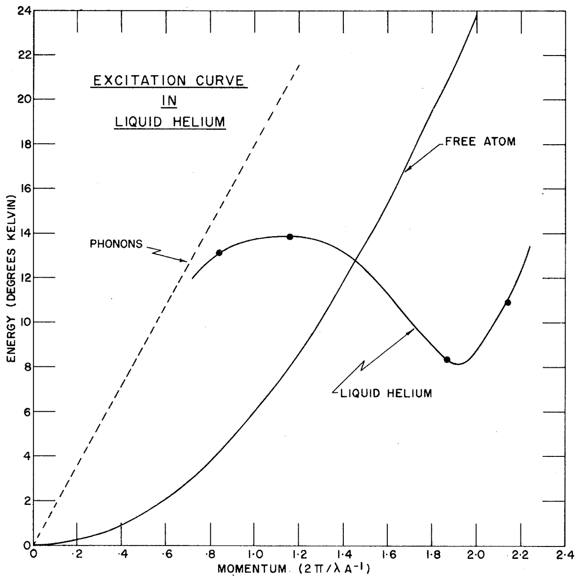

FIG. 1. The excitation curve in liquid helium. The points represent the measured change in energy and momentum of the scattered neutrons. The smooth curve drawn through the points is a guide to the eye and gives the expected form of the excitation curve. The minimum is at $1.93 A^{-1}$ and $8.1°K$ which corresponds to the minimum of the Landau roton curve. The parabolic curve represents the excitation of free helium atoms while the dotted curve gives the calculated phonon excitation curve for a velocity of sound of 237 meters $sec.^{-1}$

measured curve falls below the free-particle excitation curve.[3] The form of the measured curve shows both the minimum and maximum predicted theoretically[2-4] but there is not quantitative agreement between the theoretically calculated and measured curve. The minimum of the excitation curve is about $Q = 1.83\ A^{-1}$ and $\Delta E = 8.1°K$ corresponding to the momentum $p_0/\hbar$, and energy Δ/k, of the minimum of the Landau roton curve. The value of $\Delta/k = 8.1°K$ is consistent with the value of ~8°K deduced from specific heat measurements.[10]

The wavelength distribution of 4.14 A neutrons scattered through 80° by specimens of liquid helijm at 1.27°K, 1.57°K, 2.08°K, and 4.21°K and from a specimen of vanadium chips is shown in Fig. 2. All the curves have been corrected for the wavelength variation of the instrument sensitivity and normalized on the basis of the liquid density. In addition the curves at 4.21°K and 2.08°K have been corrected for instrument resolution using the measured scattering at 1.27°K. With increasing liquid temperature, the spectrum of scattered neutrons broadens and the position of the maximum moves to shorter wavelengths. The change in the form of the spectrum will be more readily seen by comparing it with that expected from a system of free particles having mass of about 2.6 helium masses. This free-particle mass gives the same energy change for neutrons scattered through an angle of 80°. The energy distribution of neutrons scattered from such a system at several temperatures has been calculated using a formula due to Spiers.[11]

The full widths at half maximum of the calculated energy distributions for the system of free particles are compared with the width of the energy distribution of neutrons scattered from liquid helium in Table II.

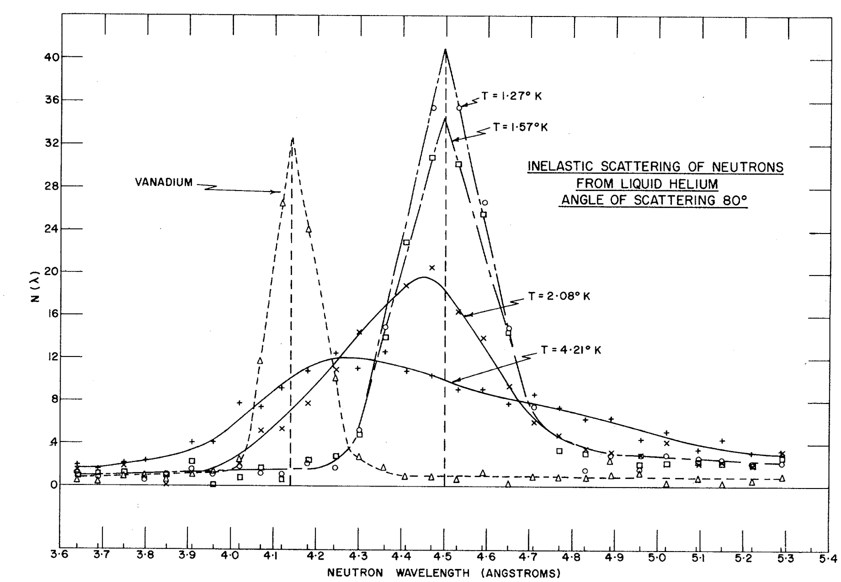

FIG. 2. The spectrum of neutrons scattered from liquid helium at several temperatures using the rotating-crystal spectrometer. The vanadium curve gives the wavelength distribution of incident neutrons uncorrected for the resolution of the instrument. The liquid helium curves have been corrected for the wavelength sensitivity of the instrument and normalized on the basis of liquid density. The curves at 2.08°K and 4.21° K have been corrected for instrument resolution.

Table II. Width of energy distribution of neutrons scattered through 80°.

Experimental liquid helium		Calculated for free particles; m=2.6 helium masses	
Liquid Temperature °K	Full width at half maximum °K	Particle temperature °K	Full width at half maximum °K
1.27	< 0.5	0.5	6.4
1.57	~1	...	...
2.08	8.5	2	12
4.21	22.5	4	17.3

The measured and calculated widths for temperatures at and above the λ point are similar, while for temperatures below the λ point the measured widths are very small compared to the calculated widths. The major portion of the change occurs between the λ point and 1.6°K, the region of the maximum in the specific heat anomaly. This suggests that the λ transition is associated with a marked change in the atomic motions.

Preliminary measurements of the distribution of neutrons scattered through 80° by liquid helium at 1.4°K have been made at pressures of 3.7 and 21.4 atmospheres using the rotating-crystal spectrometer. These results indicate that the spectrum at 21.4 atmospheres is broader and the maximum is at a shorter wavelength than at 3.7 atmospheres. The difference between the two curves indicates that the energy change of the scattered neutrons is lower by about 1°K at the higher pressure. This change is consistent within experimental error with the expected decrease in Δ/k of about 0.8°K predicted by the theory of Landau [12] for a change in liquid pressure from 0 to 25 atmospheres.

Further measurements are being made and the analysis of these measurements is continuing.

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LOW-LEVEL ABSORPTION IN GERMANIUM†

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Values of the absorption coefficient of Ge near the band edge have been extended to much lower levels by measurements of photoconductivity of suitable specimens. These specimens were thin bars of cross section 5×0.5 mm² and length ~4 cm. The radiation from a monochromator was focussed onto one end face. Reflections from the other end face were eliminated by coating the surface with a layer of PbS which has the same refractive index as Ge and an absorption coefficient ~10^4 cm^{-1} in the 2μ region.

Electrodes were soldered to the sides of the bars a few mm from either end. The Ge between the front surface and the first electrode acts as a filter which reduces the sensitivity of the device at short wavelengths, thus minimizing the effects of any scattered radiation when measuring the low signals obtained at the longest wavelengths.

The sides of the bar were etched with superoxol to give low surface recombination. Under these conditions the photoconductive signal is proportional to the total absorption in the sample, i.e.,

$$S \propto \int_{t_2}^{t_1} K\exp(-Kx)\,dx \quad \text{or} \quad S = A\exp(-Kt_1) - A\exp(-Kt_2),$$

where A is a constant and t_1, t_2, are the distances of the electrodes from the illuminated end.

For the first specimen, where $t_1 = 2$ mm and $t_2 = 34$ mm, it is readily shown by differentiation