SHEAR WAVES IN SOLID He^4†

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(Received 10 May 1965)

In this Letter we report on measurements of the velocity of 10-Mc/sec transverse sound waves in both the body-centered cubic and hexagonal close-packed phases of solid He^4. The velocity in the bcc phase is 347 m/sec and appears to be nearly isotropic, while the velocity in the hcp phase varies between 230 and 315 m/sec at about 25.6 atm, indicating a high degree of anisotropy.

A conventional pulse time-of-flight apparatus was used to measure sound velocities, as shown in Fig. 1. Two AC-cut quartz transducers, ground to produce shear waves at 10 Mc/sec were employed. Microsecond pulses from a pulsed oscillator were applied to the transmitting quartz transducer every millisecond, and the times of flight were observed on an oscilloscope after amplification. The criteria for taking a time of flight were that the received pulse have a large amplitude and a sharp leading edge. In many cases several echoes were seen. Timing was accomplished with a time-mark generator and an oscilloscope delayed sweep. Times could be measured to about ± 0.2 μsec. The error in velocity due to all sources (errors in timing, path length, etc.) is estimated to be less than 1%. To measure pressures directly, a strain gauge was mounted on the outside of the $\frac{1}{4}$-in. o.d. by 0.006-in. wall stainless steel tube containing the sample, and was calibrated against an external Bourdon gauge. Temperatures were determined with a carbon resistor and from the vapor pressure of He^4 over the bath. The chamber was mounted vertically and was immersed in the bath. The sample was pressurized at nearly constant temperature into the solid phase through a fill line, vacuum jacketed over most of its length to prevent a block of solid helium from forming before the chamber was full. The crystal structure could then be deduced from measured values of pressure and temperature and the phase diagram of pure He^4.[1]

The shear velocities in the bcc phase were consistently within the range 337 to 351 m/sec for all samples grown, the average value being 347 m/sec where the small range in velocity exceeds errors in timing. The velocity showed no discernible pressure dependence. By comparison, the bcc 10-Mc/sec compressional velocities found by Vignos and Fairbank[2] varied from 540 m/sec at 26.2 atm to 555 m/sec at 30 atm, and also showed a small amount of scatter. The hcp shear velocities were measured over a small range of temperatures (1.2-1.4°K) and pressures (25.4-25.9 atm) along the melting curve and below the lower triple point (1.45°K, 26.0 atm).[1-4] In contrast with our bcc results, each time a new crystal was grown, an entirely different value of the velocity was obtained, the velocity varying from 230 to 315 m/sec. The hcp compressional velocity given in reference 2 for this pressure region was approximately 470 m/sec. A summary of the

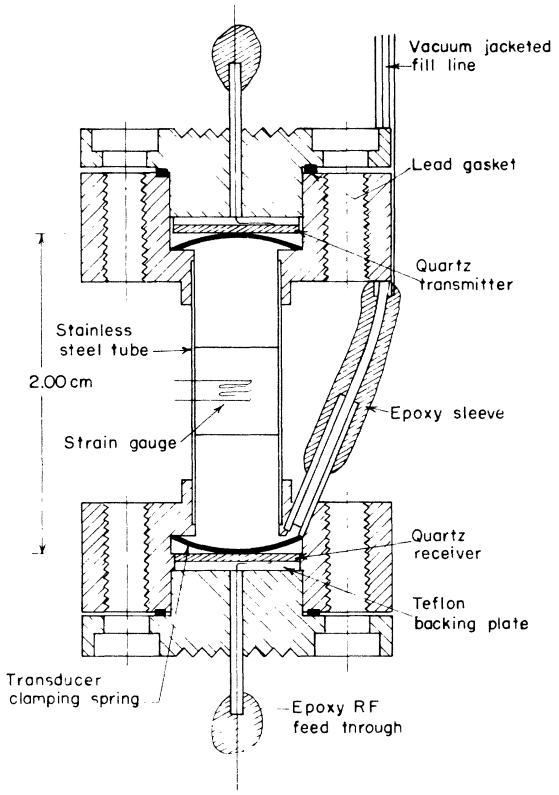

FIG. 1. Apparatus used to determine sound velocity.

results of the present work is shown in Fig. 2. Vignos and Fairbank[2] found the compressional velocity in the less-dense phase (bcc) to be faster than that in the denser phase (hcp); the same situation holds for the shear velocities measured. As expected, the shear velocities are slower than the compressional velocities. By driving the transmitting transducer at a higher harmonic, several measurements in the bcc phase at 30 Mc/sec and one at 50 Mc/sec were made and yielded a velocity of 348 m/sec, indicating negligible dispersion in this frequency region. Photographs of sound signals are shown in Fig. 3. As can be seen, the first received pulse for the bcc phase appears sharper than that for the hcp phase, possibly indicating excitation of two moderately close nondegenerate transverse modes in the hcp phase. The very large spread of velocities in the hexagonal close-packed phase obtained for different samples prepared at approximately the same temperature and pressure is interpreted as evidence that the solid is in the form of one or a few large crystallites, and that the velocity of sound is highly anisotropic in this phase. The tendency of solid helium to form large crystals is well known from previous work.[5-9] A recent measurement of longitudinal sound obtained in this laboratory yielded compressional velocities as high as 539 m/sec at approximately 26 atm, giving a further indication of anisotropic sound propagation in the hcp phase of solid helium.

In the bcc phase, if we again make the assumption of a few large crystallites in the chamber,[5] the small spread in the transverse sound velocity is taken to be an indication that sound propagation is nearly isotropic in this phase. Another possible explanation of the lack of a large spread in the bcc shear velocities is that

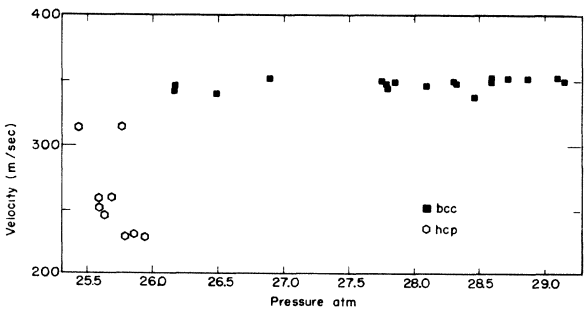

FIG. 2. Shear velocities in the hcp and bcc phases of solid helium.

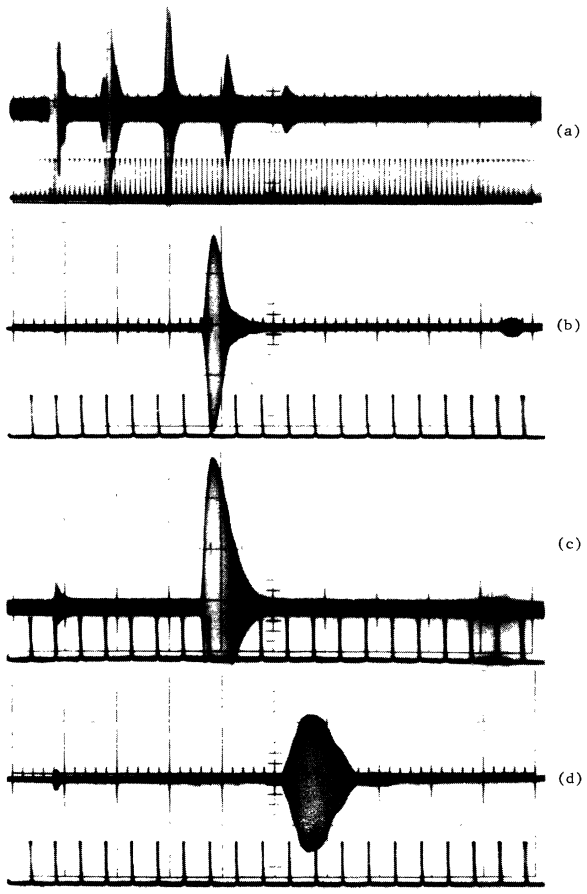

FIG. 3. Photographs of received signals. Lower trace shows 10-μsec timing pulses. Pulse from transmitter is lined up with second pulse. (a) Direct signal and four echoes in the bcc phase at 10 Mc/sec. Measured absorption coefficient 0.2 cm^{-1}. (b) Signal in bcc phase at 10 Mc/sec. (c) Signal in bcc phase at 30 Mc/sec. (d) Signal in hcp phase at 10 Mc/sec.

the crystals always tend to grow in a preferred orientation relative to the chamber. In view of the spread in the hcp velocities indicating no single preferred orientation, such an effect is thought to be unlikely in the bcc phase as well.

Using the known values of the density,[10] the compressional velocity[2] c_L, and the shear velocity c_T in the bcc phase at 1.70°K, we have applied the relationship[11]

$$c_L^2 = 1/\kappa\rho + \tfrac{4}{3}c_T^2,$$

which is valid for an isotropic solid, to compute an adiabatic compressibility of 3.8×10^{-3} atm^{-1}. This is to be compared with an isother-

mal compressibility of $(4.7 \pm 0.3) \times 10^{-3}$ atm^{-1} given by Kidder,[12] a value of 3.3×10^{-3} atm^{-1} given by Grilly and Mills,[10] and values of (1.8 and 3.1) $\times 10^{-3}$ atm^{-1} given by Ahlers.[4] Since the thermal expansion coefficient is on the order of 10^{-3}°K^{-1},[4] the isothermal and adiabatic compressibilities should differ only very slightly.

In this work we have directly observed shear waves in solid He[4] and have obtained preliminary velocity measurements. A detailed study of the propagation of sound in solid helium will probably require a simultaneous determination of crystal orientation, perhaps using x-ray techniques or multiple transducers.

We take this opportunity to thank Dr. J. H. Vignos for suggesting this measurement and for the use of his thesis. We should also like to thank Dr. R. C. Hanson, Dr. E. H. Bogardus, Professor G. V. Chester, Professor J. A. Krumhansl, and Professor H. S. Sack for interesting and informative discussions.

†Research supported by the Advanced Research Projects Agency and the National Science Foundation.

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MEASUREMENT OF THRUST IN A LINEAR HALL ACCELERATOR

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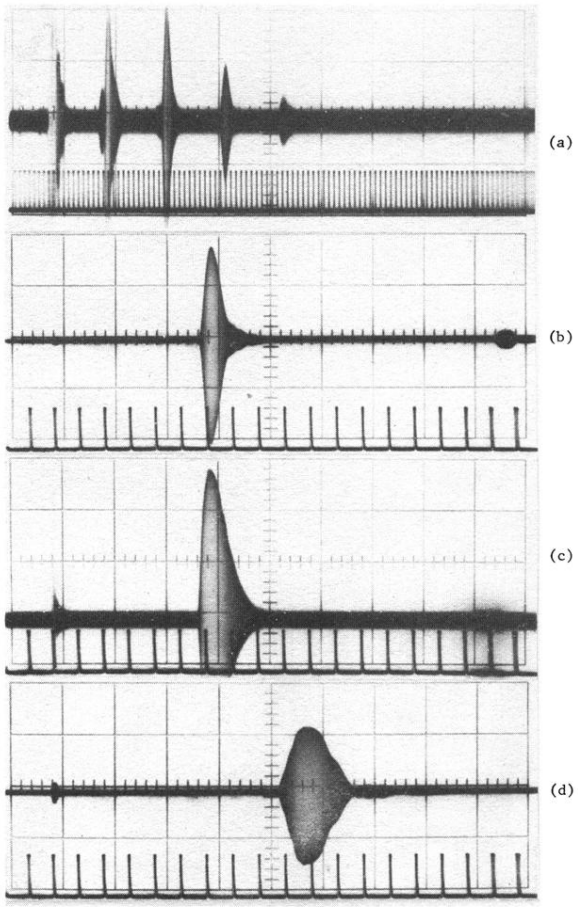
(Received 29 April 1965)

This Letter describes the measurement of the axial mechanical force or thrust acting on the magnetic field coil in a linear plasma Hall accelerator. The magnetic field components around a closed path linking the field coil are found by magnetic probes, and the force on the coil is evaluated by integrating the associated magnetic stress tensor. In the pulsed high-current accelerator used in this experiment, a typical value of this force is 13.9 Kg-wt ±7%.

The principle of the linear Hall accelerator can be described as follows: We consider any cylindrical conductor which possesses a Hall coefficient, and apply an axial electric field to it so as to cause current to flow in this direction. Around the conductor and coaxial with it is placed an independent current-carrying coil which produces radial and axial magnetic field components in the cylindrical conductor. The radial magnetic field interacts with the axial current in the conductor to produce an azimuthal Hall current i_θ. In turn, this current interacts with the radial magnetic field B_r to produce a magnetomotive force, $i_\theta B_r$, in the axial direction. Since the radial magnetic field and, hence, the azimuthal Hall current change sign through the plane of the coil, their product does not. Thus, despite the ap-



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