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VELOCITY OF SOUND IN LIQUID HELIUM AT LOW TEMPERATURES

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The velocity of ordinary ("first") sound in liquid helium II has been measured at a frequency of 1 Mc/sec between approximately 0.1°K and 1.7°K under the saturated vapor pressure, using a high-resolution technique previously described.[1] A signal from a continuously running, crystal-controlled oscillator, fed through a gated amplifier, provides a transmitter pulse which excites a quartz crystal immersed in the liquid. The resulting ultrasonic pulse is received by a second crystal, amplified, and fed into a 6BN6 phase detector, where its phase is compared with that of the cw reference signal from the oscillator. To make results independent of the detailed characteristics of the phase-detector circuit, a Helidel[2] delay line, continuously variable up to 1 μsec, is used to adjust the phase of the reference signal so that the output of the phase detector is balanced at a null. The total time required for the ultrasonic pulse to traverse the 5.051-cm path used in the experiments was about 210 μsec. Changes in this transit time could be observed with a resolution of ±1 nanosecond, corresponding to changes in velocity of ±5 parts per million. In addition to this random error, there may be systematic error amounting to as much as ±2 % of the observed velocity difference between two given temperatures; below 0.8°K, where the velocity varies so little, this error is negligible compared with the scatter of the data.

Temperatures below 1°K were reached by adiabatic demagnetization, using a cryostat of the type invented by Ashmead.[3] Warmup times from the lowest temperature to 0.9°K were typically half an hour. Temperatures were determined by measureing the susceptibility of the iron-ammonium-alum cooling salt with a conventional ac mutual-inductance bridge, and are estimated to be accurate to about 1 %.

Values of the velocity derived from phase measurements made with different signal amplitudes, and on different days, are shown in Fig. 1. Only changes in velocity could be observed directly; to convert our data to the results plotted, we have adjusted the values of phase obtained in different demagnetizations so that they agree with one another at the lowest temperatures. The absolute value of the velocity has then been chosen so that at 1.6°K it agrees with the results of earlier measurements.[1,4] With the smallest signal the signal-to-noise ratio was poor, and the scatter of the results was larger than for the other runs. The results obtained with the largest signal show a slight systematic deviation from the rest, perhaps as a result of finite-amplitude effects. The observed change in velocity between the lowest temperatures and 1.6°K is 3.66 ± 0.1 m/sec, and the resulting value for the velocity extrapolated to absolute zero is $u_1(0) = 238.27 \pm 0.1$ m/sec. It should be noted that the estimated experimental error in $u_1(0)$ does not include any

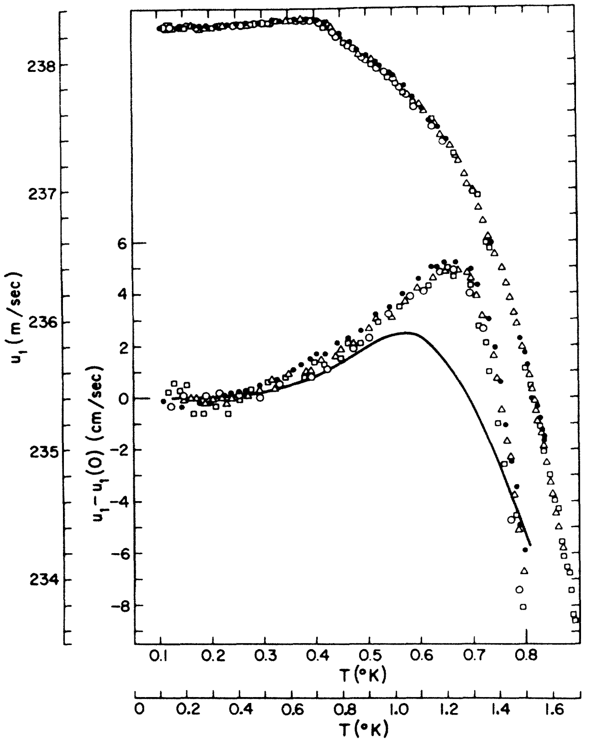

Fig. 1. Velocity of sound in liquid helium II. The lower curve shows the region of the maximum on an expanded scale. □, 30 millivolts rms; o and Δ, 70 millivolts rms, the two symbols designating runs on different days; ●, 140 millivolts rms. Solid curve, theory [Eq. (1)].

errors in the value of the velocity at 1.6°K to which the present data were fitted.

The most significant new result is the discovery of a definite maximum in the velocity at a temperature of 0.66°K. On the low-temperature side of this maximum, $u_1(T)-u_1(0)$ rises approximately as T^3, attaining a maximum value about 0.02% of $u_1(0)$. Between 0.7°K and 1.1°K the velocity falls almost linearly with a slope of -1.6 m/sec-K°, and thereafter decreases more rapidly. The lower curve in the figure shows the region of the maximum on an expanded scale.

The existence of a maximum in the velocity is implied by the linearized first-order hydrodynamical equations for liquid helium, as given, for instance, by Atkins.[5] It follows from these equations that the velocity is

$$u_1 = (\gamma\beta_T/\rho)^{1/2}[1+\tfrac{1}{2}(\gamma-1)u_{20}^2/(u_{10}^2-u_{20}^2)], \quad (1)$$

where ρ is the density, γ the specific heat ratio, and β_T the isothermal bulk modulus $\rho(\partial p/\partial\rho)_T$. The bracketed expression represents a modification in the velocity resulting from the coupling between first and second sound; u_{10} and u_{20} are the respective velocities in the absence of such coupling. In writing Eq. (1) it has been assumed that $\gamma-1 \ll 1$; the quantity γ can be determined with sufficient accuracy from the thermodynamic relation

$$\gamma-1 \approx T u_1^2 \alpha_p^2/C_p, \quad (2)$$

where α_p and C_p are, respectively, the expansion coefficient and specific heat at constant pressure. (For this calculation u_1 need be known only approximately.)

To evaluate Eq. (1) we treat the liquid as a gas of thermal excitations (phonons and rotons), and assume that β_T can be expressed as the sum of a temperature-independent zero-point term and temperature-dependent terms resulting from the presence of the excitations. The latter terms can be conveniently evaluated from the Helmholtz functions for phonons and rotons. Below 1°K only the phonon contribution turns out to be important, and we have ignored the rotons altogether in calculating the numerical results shown by the solid curve in the figure.

Near 0°K, the predicted isothermal bulk modulus falls as the temperature increases with $\beta_T(0)-\beta_T(T) \propto T^4$. However, $\gamma-1$ increases as T^4 with a larger coefficient, and the velocity thus initially rises with $u_1(T)-u_1(0) \propto T^4$. The velocity maximum is chiefly the result of a maximum in γ, which is in turn dependent upon the behavior of the expansion coefficient[6] through Eq. (2). Eventually, at temperatures near 1°K, the effect of γ becomes negligible, and the velocity falls rapidly as a result of the decrease in β_T.

It is clear from the figure that, although the calculated curve has roughly the same characteristics as the experimental one, it does not account for the results quantitatively. Not only is the calculated maximum smaller than the experimental one and located at a lower temperature, but the temperature dependence of the theoretical curve at low temperatures is T^4, as compared with the experimentally observed approximately T^3 dependence. A reason for the discrepancy may be that the calculations apply strictly only to sound of vanishingly small frequency. Measurements at 4 and 12 Mc/sec, now in progress, show that there is considerable dispersion in the neighborhood of the maximum; consequently, the results at 1 Mc/sec are probably not characteristic of zero frequency. It seems unlikely, however, that this explanation can fully account for the difference in temperature dependence between the experimental results and the theory. It is perhaps significant that the observed temperature dependence of $u_1(T)-u_1(0)$ is the same as that of the attenuation.[7,8] These questions will be discussed more fully in a later paper.

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PLATINUM AND IRIDIUM ABUNDANCES IN METEORITES*

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At the suggestion of Dr. E. M. Burbidge, Dr. G. R. Burbidge, Professor W. A. Fowler, and Professor F. Hoyle, we have carried out a determination of the abundances of platinum and iridium in meteorites. The purpose of the work was to obtain data for a more precise estimation of the abundance peak near mass 195 in the atomic abundance curve, since both the observed[1] and calculated[2] abundances for this interesting r-process abundance region were only approximate.

Platinum and iridium are concentrated primarily in the metal phase of meteoritic matter. Hence, platinum and iridium have been determined spectrographically on twenty-four iron meteorites and the metal phase of five chondritic stony meteorites. The procedures and the detailed results will be reported elsewhere.

The platinum and iridium averages of the iron meteorites and of the metal phases of chondrites are given in Table I. Also given in Table I are the maximum and minimum values, the early results of Goldschmidt,[3] and the ratios of platinum to iridium.

The chondritic metal-phase iridium average agrees quite well with the average metal-phase iridium abundance of 2.85 ppm which was obtained indirectly by Ehmann, Amiruddin, Rushbrook, and Hurst[4] from their neutron activation analyses of samples of five chondrites of known metal-phase content.

The averages for the iron meteorites are statistically weighted averages which take into account a "quantized" distribution of these elements (to be discussed in detail elsewhere) which we have observed within the broad concentration ranges as shown in Table I.

The ratios of platinum to iridium are the same, within the limits of error, for both the iron meteorites and the chondrites. This suggests that

Table I. Platinum and iridium in meteorites, in parts per million.

Description	Ir ppm	Pt ppm	Pt/Ir
	Iron meteorites		
Present work:			
Weighted average	3.7 ± 0.6	11.0 ± 1.3	3.0
Spread	0.3 - 15.3	0.5 - 29.3	
Goldschmidt[a]	4	20	
	Chondrites, metal phase		
Present work:			
Average	2.8 ± 0.4	8.5 ± 1.2	3.0
Spread	2.1 - 3.2	7.9 - 9.1	

[a] See reference 3.