numbers (1.76) may therefore be interpreted to mean that the 55.6-second activity in thorium relative to the 22.0-second activity is 1.76 times more intense than that in the case of uranium. The 55.6-second and the 22.0-second activities are believed to be due to bromine 87 and iodine 137[3] respectively, and the fission yield curve[7] indicates that 2.5 percent of the fission products are mass 87 and 6.7 percent are mass 137. If it is assumed that the production of mass 137 is the same percent in the case of thorium fission as for uranium fission, then the fission yield of mass 87 would be increased from 2.5 percent for uranium fission to 4.0 percent for thorium fission.

Table I shows a comparison of the relative saturation intensities of the delayed neutrons from uranium and plutonium previously reported. Also shown are the values from thorium reported in this paper.

When uranium and thorium were bombarded with 10-Mev deuterons directly, the delayed neutron activity obtained from both elements was small compared to that obtained when irradiated with Li neutrons. The delayed activity, however, from uranium under deuteron bombardment was approximately 5.3 times that from thorium. For neutrons between 2.4 Mev and about 10 Mev, the cross sections for uranium fission and thorium fission are 0.5 and 0.1 barn, respectively.[8] Since a (d, p) bombardment is essentially a neutron bombardment, the above observed ratio (5.3) is expected. No measurable delayed neutron activity resulted from bombarding uranium and thorium with 20-Mev alpha-particles. The threshold for alpha-particle induced fission in thorium has recently been reported as 23 to 24 Mev.[9]

Attempts were made to obtain delayed neutrons from other elements by lithium neutron irradiation. Negative results were obtained from the following elements: radium, bismuth, tungsten, and tantalum. With fast neutrons the cross section of radium for the production of delayed neutrons, if any, was less than 10^{-2} of that of uranium and less than 10^{-4} for the other elements mentioned. With 10-Mev deuterons no delayed neutrons were observed.

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Second Sound Velocity in Helium II*

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Pulse methods are applied to extend the measurements of second sound velocity in liquid helium II to a temperature of 0.86°K. The rise in velocity below 1.1°K observed by Peshkov is verified and extended to lower temperature. The theoretical implications are discussed.

I. INTRODUCTION

It is rather generally accepted that the peculiar properties of helium II have to be explained by means of a two-fluid model. This viewpoint has two variants in the theories of Tisza[1] and Landau.[2] The theory due to Tisza is based on London's interpretation of the λ-point transition of helium as an Einstein-Bose condensation.[3] The elementary excitations of the liquid were assumed to possess translational momenta (states analogous to Bloch waves in metals) and to obey Bose-Einstein statistics. The "condensation" implied by the statistics led to a division of the liquid into a "normal" and a "superfluid" fraction, the latter having practically no entropy. This incomplete vanishing of the

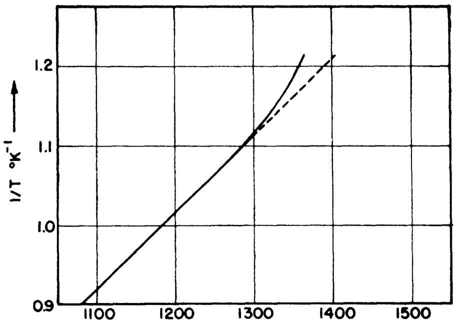

Fig. 1. Comparison of temperature obtained from vapor pressure with temperature obtained from magnetic susceptibility.
——— temperature measured from pressure.
- - - - - - - - actual temperature.

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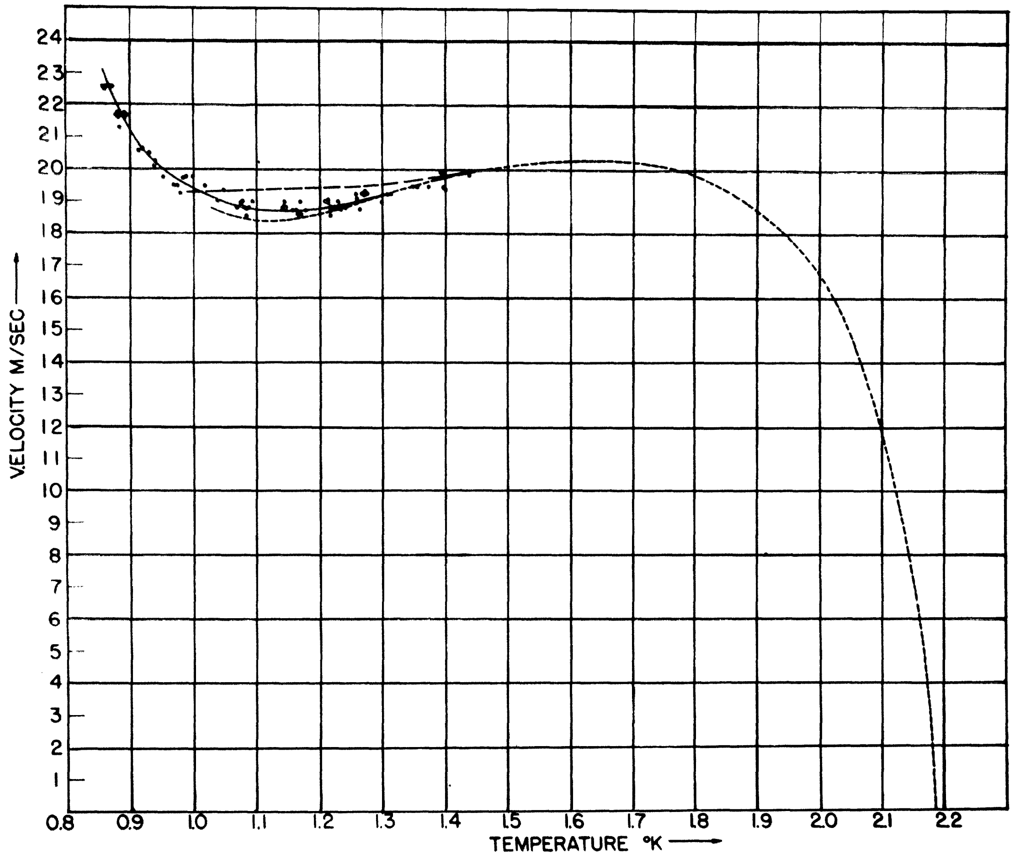

FIG. 2. Second sound velocity as a function of temperature.
— —— curve drawn from Pellam's data.
------ curve from Peshkov.
——— curve fitted to authors' data.

entropy was assumed to stem from elementary excitations of another type (phonons) contributing to the whole liquid and to the superfluid fraction in particular. This contribution could be expected to be important only below 1°K. Landau modified this theory in two respects. Denying the relevance of Einstein-Bose statistics, he concluded that the elementary excitations are phonons and rotons. Second, he assumed that these two types of elementary excitation together compose the "normal" flow of the liquid. Hence, the superfluid liquid was supposed to be entirely devoid of entropy. In spite of considerable differences in the assumed molecular mechanisms, the two theories led to essentially identical conclusions. However, differences in the conclusions do occur at temperatures where the role attributed to the phonons becomes significant.[4] Such a difference occurs in the predicted velocity of second sound below 1°K and led to the experiment reported here.

II. EXPERIMENT

Second sound may be excited by periodic or pulsed transfer of heat into liquid helium II. It was first observed by Peshkov,[5] following its theoretical prediction by Tisza[1] and Landau.[2] Peshkov measured its velocity down to 1.03°K, using a standing wave technique,[5] and other investigators have covered portions of this same region. Pellam,[6] and Osborne,[7] have developed pulse techniques, which were also employed in the present work.

The apparatus used by Pellam in this laboratory was selected for this investigation because of its low heat input and consequent possibilities for attaining very low temperatures. A Du Mont type 256D oscillograph was used to trigger a pulse generator which fed into a carbon-sheet resistor in the end of the second-sound tube. This pulse initiated the thermal wave which traveled to the other end of the tube where the change in temperature affected another carbon-sheet resistor acting as a resistance thermometer. The change in voltage across it was amplified, filtered for noise, and fed back into the vertical plates of the range scope. To reduce heat input, photographs of the scope were

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TABLE I. Second sound velocity in helium II (smoothed values taken from the fitted curve of Fig. 2.)

Temperature (°K)	Velocity (m/sec.)
1.45	19.95
1.40	19.78
1.35	19.55
1.30	19.20
1.25	18.95
1.20	18.75
1.15	18.70
1.10	18.75
1.05	19.00
1.00	19.40
0.95	20.05
0.90	21.20
0.86	23.00

taken during the second or so in which the pulse switch was closed. These films could then be analyzed on a microfilm projector in order to count the crystal-controlled time markers. Inasmuch as the pulse began with the sweep, the first marker represented an elapsed time interval of 40 microseconds and each marker thereafter represented an additional interval of 50 microseconds. A fixed path length of 7.97 cm between the carbon resistors was used.

The high capacity pumping system permitted a generally simple design. A Distillation Products type MB-100 diffusion pump, rated at 110 v on the heater and operated at 220 v, was connected with two Cenco Hypervac 25 forepumps. A large-diameter brass pipe followed a semicircular path from the top of the diffusion pump to the top of the liquid helium Dewar vessel. This pipe contained the McLeod gauge entry, for vapor pressure measurement, and also the permanent shield fittings to the signal wires, so that it could be used as the electrical ground.

Two concentric double-walled Dewars were employed. The exterior one contained liquid air. The inner one was specially constructed with walls which joined at a ring seal into a single wall about 10 cm from the top. A liquid air level was maintained above the ring seal so that the conduction of heat down the inner wall to the liquid helium was greatly reduced. The high-speed pumping system made the additional complication of capillaries or diaphragms unprofitable.

A possible source of error in temperature measurement arose from the pressure gradient between the McLeod gauge entry and the liquid helium surface. To correct this, measurements of mutual inductance were made with a coil wrapped around the inner Dewar, which was filled with liquid helium and iron ammonium alum. Since the susceptibility of this salt, and hence the change in mutual inductance of the coil, varies as $1/T$ by Curie's law, comparison could be made with the McLeod gauge readings. Actually, Fig. 1 shows that no such correction was necessary above about 0.92°K.

The data are shown in Fig. 2, and agree with those of Peshkov down to about 1.2°K; but below this temperature they are slightly higher than his most recent evaluations.[5] The deviation of Pellam's results,[6] as he suggested, was due to his failure to correct for the absence of true vapor pressure readings directly over the helium surface. This was serious, since he was pumping through a small capillary. Above 1.45°K, the values given by Peshkov, Pellam, and Lane are essentially in agreement.[5, 6, 8] Table I shows the smoothed values obtained from the fitted curve of Fig. 2.

In these experiments, the strength of the second sound pulses was observed to increase markedly with decreasing temperature. Although the pulse strength depends on many factors, there is qualitative indication that the thermomechanical effect remains strong down to 0.86°K.

III. DISCUSSION

Recent experiments[9] with He^3, showing no superfluidity down to 1°K, seem to bear out the original Bose-Einstein hypothesis[10] rather than the roton hypothesis of Landau. On the other hand, the rise in second sound velocity reported here supports Landau's contention regarding the role of the phonons. As a result, it seems likely that a more refined form of the fluid model should contain elements of both the London-Tisza and the Landau theories—phonons and Bose-Einstein excitations both contributing to the normal flow. It may be added that our experiments bear out Landau's views regarding the role of phonons only in a qualitative way. It would be premature to conclude, as yet, that the superfluid liquid has a rigorously vanishing entropy. However, should this be true, the implications would be considerable; that is, the cooling method based on the thermomechanical effect as advanced by Kapitza[11] should prove a powerful means for reaching low temperatures.

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