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## Compressibility of Liquid He<sup>4</sup> as a Function of Pressure\*

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The compressibility,  $\beta = -(1/V)(\partial V/\partial P)_T$ , of liquid He<sup>4</sup> was measured from 1 atm to the melting pressure and between 1.6 and 2.5°K.  $\Delta V$  and  $\Delta P$  were determined from deflections of the cell walls. The normal decrease of  $\beta$  with increasing  $P$  was observed except in an area below the  $\lambda$  line. For an isotherm crossing the  $\lambda$  line,  $\beta$  showed a minimum at  $P < P_\lambda$  and a peak at  $P_\lambda$ . The minimum also occurred between the lowest  $T_\lambda$  (1.76°K) and 1.70°K. The variation of  $\beta$  with  $P$  near  $P_\lambda$ , relative to  $\beta$  at 2.20°K, followed an equation of the form  $\beta_T - \beta_{2.2} = a - b \log |P - P_\lambda|$ , where  $a$  and  $b$  for  $P < P_\lambda$  are greater than  $a$  and  $b$  for  $P > P_\lambda$ . Between the  $T$  limits of the  $\lambda$  line,  $(\partial\beta/\partial T)_P$  was definitely negative for  $P$  just above  $P_\lambda$ , but it approached zero for  $P \gg P_\lambda$ .

### I. INTRODUCTION

IN general, the isothermal compressibility coefficient,  $\beta \equiv -(1/V)(\partial V/\partial P)_T$ , of a liquid decreases with decreasing temperature and with increasing pressure. The anomalous increase of  $\beta$  with increasing pressure in liquid He<sup>4</sup> near the  $\lambda$  transition was first indicated by the density measurements of Keesom and Keesom.<sup>1</sup> Their Fig. 3 seems to show  $(\partial\rho/\partial P)_T$  at 30 atm rising above the values at 25 and 20 atm in a narrow temperature interval 1.80-1.85°K. However, the authors left the point without comment while they noted "as a remarkable fact that the He II parts of the curves seem to approach at decreasing temperatures to a production of the He I parts. It looks as if there is an intermediary region of increased compressibility, which abruptly ends at the  $\lambda$  curve." On the other hand, no pressure anomaly was shown by the adiabatic compressibility derived from sound-velocity data of Atkins and Stasiar.<sup>2</sup> Direct measurements of  $\beta$ , i.e., through small  $\Delta P$  and  $\Delta V$  at constant temperature, were made by Grilly and Mills<sup>3</sup> over a short range of pressure and at several temperatures. The values of  $\beta$  peaked at  $P_\lambda$ , but the continuity of  $\beta$  was indefinite. However, it was clear that  $\beta$  had an anomalous variation with temperature near the  $\lambda$  transition for  $P > P_\lambda$ . Then, Lounasmaa<sup>4</sup> measured  $\beta$  with very high resolution in the immediate vicinity (within  $10^{-3}$  to  $10^{-2}$  atm) of one  $\lambda$  point (2.023°K and 13.04 atm). He obtained a linear variation of  $\beta$  with pressure on each side of  $P_\lambda$  and a discontinuity of 10% in  $\beta$  at  $P_\lambda$ .

All these measurements left unanswered some questions. What is the nature of the expected minimum in the  $\beta$  versus  $P$  curve? Does the abnormal variation of  $\beta$  with temperature near the  $\lambda$  transition revert to normalcy at  $(P, T)$  far above  $(P_\lambda, T_\lambda)$ ? To answer them,

$\beta$  was measured directly as a function of pressure at several constant temperatures.

### II. EXPERIMENTAL

#### A. Method

The present measurements of compressibility in liquid He<sup>4</sup> were done in a cell designed for general  $P$ - $V$ - $T$  work in liquid and solid He<sup>4</sup> and He<sup>3</sup>. Essentially, each  $\Delta P$  and  $\Delta V$  was measured by the deflection of diaphragms. The cell, shown in Fig. 1, consisted of three diaphragms joined circumferentially and left separated by two gaps, each of which was connected to a capillary tube leading to room temperature. The upper gap acted as the sample chamber, whose volume  $V_U$  could be changed at will by the pressure of the liquid in the lower gap. The sample under study was confined to  $V_U$  by a valve near the cell. The upper chamber pressure  $P_U$  was determined from the deflection of the top diaphragm, while the lower chamber pressure  $P_L$  was measured at room temperature through the capillary. At any time,  $V_U$  could be determined from  $P_U$  and  $P_L$  through the formula

$$V_U = V_{U_0} + (S_U + S_L)P_U - S_L P_L,$$

where  $V_{U_0}$  is the volume of the upper chamber for no deflection of the diaphragms,  $S_U$  is the sensitivity of the upper diaphragm in terms of volume change per unit pressure difference, and  $S_L$  is the sensitivity of the middle diaphragm. Therefore, the compressibility of

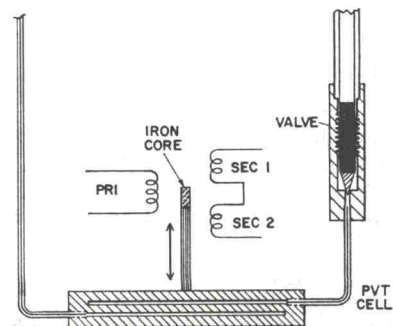


FIG. 1. The  $P$ - $V$ - $T$  cell.

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<sup>1</sup> W. H. Keesom and A. P. Keesom, *Physica* **1**, 128 (1934); *Leiden Comm. Suppl. No. 7b* (1933).

<sup>2</sup> K. R. Atkins and R. A. Stasiar, *Can. J. Phys.* **31**, 1156 (1953).

<sup>3</sup> E. R. Grilly and R. L. Mills, *Ann. Phys. (N. Y.)* **18**, 250 (1962).

<sup>4</sup> O. V. Lounasmaa, *Phys. Rev.* **130**, 847 (1963).

the sample in  $V_U$  is

$$\beta = -\frac{1}{V_U} \frac{dV_U}{dP_U} = \frac{S_L}{V_U} \left( \frac{dP_L}{dP_U} \frac{S_U + S_L}{S_L} \right). \quad (1)$$

Generally, the values of  $\Delta P$  are small enough to represent the differentials directly. With the cell characteristics  $V_{U_0} = 0.3380 \text{ cm}^3$ ,  $S_U = 1.31 \times 10^{-3} \text{ cm}^3 \text{ atm}^{-1}$ , and  $S_L = 1.09 \times 10^{-3} \text{ cm}^3 \text{ atm}^{-1}$ ,

$$\beta \approx 2.5 \times 10^{-3} (\Delta P_L / \Delta P_U - 2.2) \text{ atm}^{-1}. \quad (2)$$

### B. Apparatus

The  $P$ - $V$ - $T$  cell was made from Be-Cu (Berylco-25) disks, welded together by an electron beam, then heat-treated for favorable strength and elasticity. The cell was designed to measure a range of  $\Delta V/V$  values from  $5 \times 10^{-5}$  for thermal expansion to  $10^{-1}$  for melting, a much greater range than needed here for the liquid compressibility. At  $4^\circ\text{K}$ , the diaphragm displacement at the center was  $3 \times 10^{-4} \text{ cm atm}^{-1}$  up to the maximum working pressure of 68 atm. The upper diaphragm deflection was measured with a Sanborn 959 DT 005 differential transformer, whose output was put through a Sanborn 311 amplifier and read on a Weston dc voltmeter. The resolution of 0.01 V corresponded to  $10^{-3}$  atm. The sensitivity was frequently checked between compressibility measurements against a room-temperature gauge. The diaphragm behavior seemed to stay constant, but the over-all sensitivity varied slightly with bath height (an effect of lead resistance) and with axial position of the transformer core.

The volume of the upper (sample) chamber was calibrated against various pressures in the upper and lower chambers by metering withdrawn helium, gas at 296 and  $76^\circ\text{K}$ , liquid at  $4^\circ\text{K}$ . The molar volumes at  $4^\circ\text{K}$  were taken from Edeskuty and Sherman<sup>5</sup> after a  $-0.30\%$  correction. The observed values of the volume sensitivity increased with temperature, 5% for 4 to  $76^\circ\text{K}$  and 14% for 4 to  $296^\circ\text{K}$  but were constant with pressure to 68 atm.

A rigid requirement in the  $\Delta V$  measurements was the tightness of the valve sealing the sample in the cell. The valve tip was a  $55^\circ$  cone of Teflon; its seat was a 0.5-mm hole in the brass body. A leak test after each closing showed the valve to be tight in all cases.

The pressure standards were: (a) a Consolidated Electro-dynamics Corp. 6-201 gas piston gauge to 34 atm; and (b) an Ashcroft 1313A oil piston gauge to 68 atm. The first was calibrated against other standard gauges and the  $\text{CO}_2$  sublimation pressure at the ice point; accuracy was better than 0.01%. Both piston gauges had calibrated weights so that pressure changes

<sup>5</sup> F. J. Edeskuty and R. H. Sherman, in *Low Temperature Physics and Chemistry*, edited by J. R. Dillinger (University of Wisconsin Press, Madison, Wisconsin, 1958), p. 102.

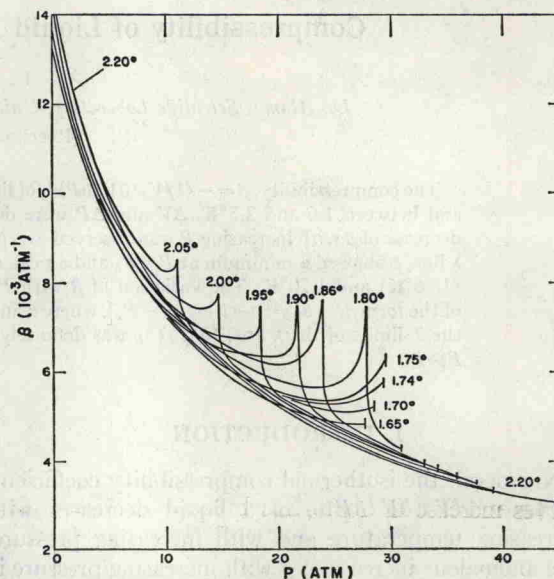


FIG. 2. Isothermal compressibility coefficient versus pressure for liquid  $\text{He}^4$  at several temperatures. The measurements show no deviation from the curves on this scale.

of 0.3 atm were known to 0.01%; this was useful in checking the consistency of the  $P$ - $V$ - $T$  cell diaphragm sensitivity. Routine pressure measurements were made with Heise and Seegers Bourdon-type and Consolidated diaphragm-type gauges.

Temperatures of the liquid  $\text{He}^4$  bath were determined from vapor pressures on the "1958 Scale".<sup>6</sup> The bath pressure was regulated to less than 0.5 mdeg equivalent.

### III. RESULTS

The isothermal compressibility coefficient  $\beta$  was measured directly over a wide pressure range, usually from about 1 atm to the melting pressure, for temperatures between 1.60 and  $2.50^\circ\text{K}$ . Typical results are shown in Fig. 2. The  $2.20^\circ\text{K}$  curve illustrates the monotonic decrease of  $\beta$  with increasing pressure for

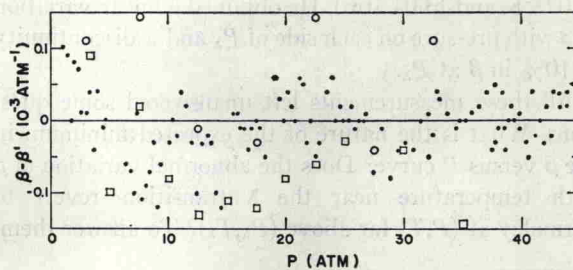


FIG. 3. Deviations of liquid  $\text{He}^4$  compressibility at  $2.200^\circ\text{K}$  from  $0.30 \times 10^{-3} + (72.0 \times 6.66P)^{-1}$ . ● present measurements; ○ derived from density data of Keesom and Keesom (Ref. 1); □ derived from density of Edeskuty and Sherman (Ref. 5).

<sup>6</sup> F. G. Brickwedde, H. van Dijk, M. Durieux, J. R. Clement, and J. K. Logan, *J. Res. Natl. Bur. Std. (U. S.)* 64A, No. 1 (1960).