Compressibility of Liquid He⁴ as a Function of Pressure*

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The compressibility, $\beta = -(1/V)(\partial V/\partial P)_T$, of liquid He⁴ was measured from 1 atm to the melting pressure and between 1.6 and 2.5°K. ΔV and ΔP were determined from deflections of the cell walls. The normal decrease of β with increasing P was observed except in an area below the λ line. For an isotherm crossing the λ line, β showed a minimum at $P < P_\lambda$ and a peak at P_λ. The minimum also occurred between the lowest T_λ (1.76°K) and 1.70°K. The variation of β with P near P_λ, relative to β 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 λ line, $(\partial \beta/\partial T)_P$ was definitely negative for P just above P_λ, 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 β with increasing pressure in liquid He⁴ near the λ transition was first indicated by the density measurements of Keesom and Keesom.[1] 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 λ curve." On the other hand, no pressure anomaly was shown by the adiabatic compressibility derived from sound-velocity data of Atkins and Stasior.[2] Direct measurements of β, i.e., through small ΔP and ΔV at constant temperature, were made by Grilly and Mills[3] over a short range of pressure and at several temperatures. The values of β peaked at P_λ, but the continuity of β was indefinite. However, it was clear that β had an anomalous variation with temperature near the λ transition for $P > P_\lambda$. Then, Lounasmaa[4] measured β with very high resolution in the immediate vicinity (within 10^{-3} to 10^{-2} atm) of one λ point (2.023°K and 13.04 atm). He obtained a linear variation of β with pressure on each side of P_λ and a discontinuity of 10% in β at P_λ.

All these measurements left unanswered some questions. What is the nature of the expected minimum in the β versus P curve? Does the abnormal variation of β with temperature near the λ transition revert to normalcy at (P,T) far above (P_λ, T_λ)? To answer them, β was measured directly as a function of pressure at several constant temperatures.

II. EXPERIMENTAL

A. Method

The present measurements of compressibility in liquid He⁴ were done in a cell designed for general P-V-T work in liquid and solid He⁴ and He³. Essentially, each ΔP and ΔV 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
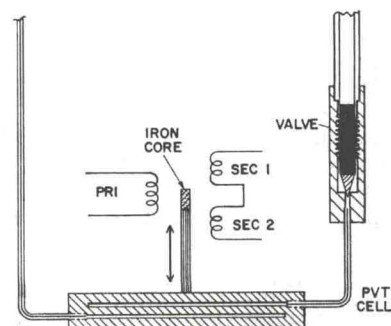
* Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] W. H. Keesom and A. P. Keesom, Physica 1, 128 (1934); Leiden Comm. Suppl. No. 7b (1933).

[2] K. R. Atkins and R. A. Stasior, Can. J. Phys. 31, 1156 (1953).

[3] E. R. Grilly and R. L. Mills, Ann. Phys. (N. Y.) 18, 250 (1962).

[4] O. V. Lounasmaa, Phys. Rev. 130, 847 (1963).

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

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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 ΔP are small enough to represent the differentials directly. With the cell characteristics $V_{U_0} = 0.3380$ cm³, $S_U = 1.31 \times 10^{-3}$ cm³ atm⁻¹, and $S_L = 1.09 \times 10^{-3}$ cm³ 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 5×10^{-5} for thermal expansion to 10^{-1} for melting, a much greater range than needed here for the liquid compressibility. At 4°K, the diaphragm displacement at the center was 3×10^{-4} 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°K, liquid at 4°K. The molar volumes at 4°K were taken from Edeskuty and Sherman[5] after a −0.30% correction. The observed values of the volume sensitivity increased with temperature, 5% for 4 to 76°K and 14% for 4 to 296°K but were constant with pressure to 68 atm.

A rigid requirement in the ΔV measurements was the tightness of the valve sealing the sample in the cell. The valve tip was a 55° 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 Electrodynamics 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 CO_2 sublimation pressure at the ice point; accuracy was better than 0.01%. Both piston gauges had calibrated weights so that pressure changes

[5] 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.
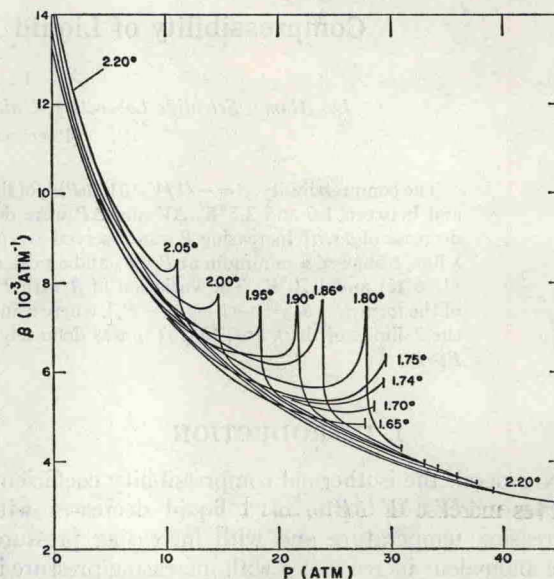

FIG. 2. Isothermal compressibility coefficient versus pressure for liquid He⁴ at several temperatures. The measurements show no deviation from the curves on this scale.

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 He⁴ bath were determined from vapor pressures on the "1958 Scale".[6] The bath pressure was regulated to less than 0.5 mdeg equivalent.

III. RESULTS

The isothermal compressibility coefficient β 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°K. Typical results are shown in Fig. 2. The 2.20°K curve illustrates the monotonic decrease of β with increasing pressure for
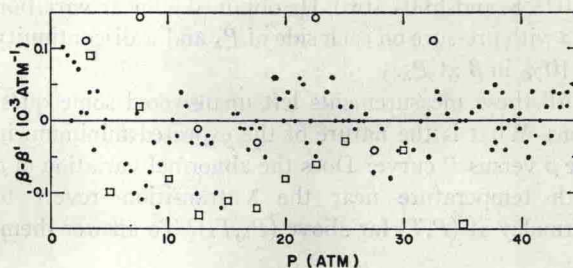

FIG. 3. Deviations of liquid He⁴ compressibility at 2.200°K from $0.30 \times 10^{-3} + (72.0 \times 6.66P)^{-1}$. ● present measurements; ○ derived from density data of Keesom and Keesom (Ref. 1); □ derived from density of Edeskuty and Sherman (Ref. 5).

[6] 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).