

TABLE I. Compressibility minima in liquid He<sup>4</sup>.

$T$ (°K)	$\beta_{\min}$ ( $10^{-3} \text{ atm}^{-1}$ )	$P(\beta_{\min})$ (atm)
2.050	8.20	$10.3 \pm 0.3$
2.000	7.42	$13.7 \pm 0.5$
1.949	6.75	$17.0 \pm 0.7$
1.899	6.35	$19.0 \pm 1.0$
1.880	6.27	$20.0 \pm 1.0$
1.865	6.15	$20.5 \pm 0.5$
1.799	5.65	$23.0 \pm 0.5$
1.750	5.35	$24.5 \pm 0.5$
1.739	5.27	$25.0 \pm 0.5$
1.700	5.07	$26.0 \pm 0.5$

through pressure variations. Generally,  $(\partial\beta/\partial P)_T$  is negative because of the increase in intermolecular repulsive force. In this sense, the present results show liquid He<sup>4</sup> is normal for all pressures at  $T > 2.17^\circ\text{K}$ . In particular, the liquid at  $2.200^\circ\text{K}$  seems to have a high degree of normalcy, as here  $\beta$  versus  $P$  closely follows Tait's relation

$$V\beta = J(L+P)^{-1}, \quad (4)$$

where  $V$  is the corrected molar volume of Edeskuty and Sherman<sup>5</sup> and  $J=3.390$  and  $L=8.47$  are empirical constants. This relation fits a wide variety of liquids and was given a fundamental basis for liquids in general by Ginell.<sup>7</sup>

At  $T < 2.17^\circ\text{K}$ , the sign of  $(\partial\beta/\partial P)_T$  changes as  $P \rightarrow P_\lambda$  from below. The minimum shown in  $\beta$  versus  $P$  is lacking in the curves of specific heat and thermal expansion versus temperature, which simply continue the trends set by the low-temperature portions of their curves, albeit at accelerated rates. The minima in the  $\beta$ -versus- $P$  curves follow a regular pattern for both

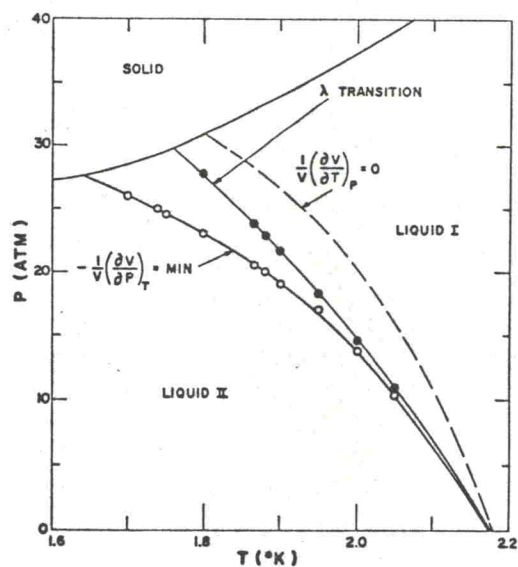


FIG. 7. Phase diagram of He<sup>4</sup> showing the melting curve, the  $\lambda$  line, the locus of zero expansion coefficient, and the locus of minimum in compressibility.

<sup>7</sup> R. Ginell, J. Chem. Phys. 34, 1249 (1961).

$\beta_{\min}$  and  $P(\beta_{\min})$ . The values given in Table I show that  $\beta_{\min}$  decreases linearly with increasing  $P(\beta_{\min})$ . In the phase diagram of Fig. 7 are shown the locus of  $\beta_{\min}$  and the locus of zero thermal expansion, determined by Grilly and Mills.<sup>8</sup> These two loci indicate a sizable area of anomalous behavior in the  $P$ - $V$ - $T$  relations. Goldstein<sup>9</sup> gave a possible explanation for the value of  $(\partial\beta/\partial P)_T > 0$  as  $P$  increases toward  $P_\lambda$ : The exchange-energy density, decreasing rapidly as the number of normal atoms increases with pressure, provides a net decrease in energy density, which is measured by  $1/\beta$ . The same mechanism could account for the minima shown at  $T < 1.76^\circ\text{K}$ , where a  $\lambda$  transition is cut short by the formation of solid.

Near  $P_\lambda$ , the variation of  $\beta$  with  $P$  is best expressed by a logarithmic fit

$$\begin{aligned} 10^3(\beta_T - \beta_{2.2}) &= a_- - b_- \log_{10}|P - P_\lambda| \quad \text{for } P < P_\lambda \\ &= a_+ - b_+ \log_{10}|P - P_\lambda| \quad \text{for } P > P_\lambda. \end{aligned} \quad (5)$$

Here,  $\beta_T$  and  $\beta_{2.2}$  are the measured compressibilities

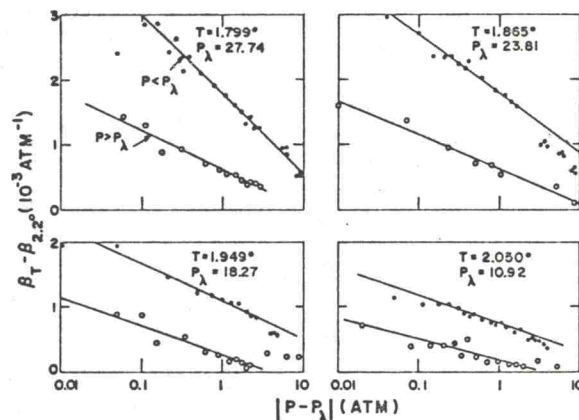


FIG. 8.  $\beta_T - \beta_{2.2}$  versus  $\log|P - P_\lambda|$  for liquid He<sup>4</sup> at several temperatures. The upper curve is for  $P < P_\lambda$  and the lower curve is for  $P > P_\lambda$  at each  $T$ .

at  $(T, P)$  and at  $(2.200^\circ\text{K}, P)$ , respectively, and  $P$  is in atmospheres. The constants  $a$ ,  $b$ , and  $P_\lambda$  were determined from plots of  $\beta_T - \beta_{2.2}$  versus  $\log|P - P_\lambda|$ . Some graphical examples are given in Fig. 8, while the constants are given in Table II. We see that the linear plots become more definite as the temperature is decreased, or as the  $\lambda$  transition of  $\beta$  is accentuated. At the lowest observed  $T_\lambda$  values, 1.86 and  $1.80^\circ\text{K}$ , Eq. (5) appears to hold for  $5 \times 10^{-2} < |P - P_\lambda| < 10$  atm. This resembles the linear functions of  $\log|T - T_\lambda|$  fitted to the thermal expansion,  $\alpha_P = (1/V)(\partial V/\partial T)_P$ ,<sup>9-12</sup> and

<sup>8</sup> L. Goldstein, Phys. Rev. 140, A1547 (1965).

<sup>9</sup> K. R. Atkins and M. H. Edwards, Phys. Rev. 97, 1429 (1955).

<sup>10</sup> M. H. Edwards, Can. J. Phys. 36, 884 (1958).

<sup>11</sup> C. E. Chase, E. Maxwell, and W. E. Millett, Physica 27, 1129 (1961).

<sup>12</sup> E. C. Kerr and R. D. Taylor, Ann. Phys. (N. Y.) 26, 292 (1964).