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TEMPERATURES OF THE VOLUME MINIMA AND STRATIFICATION REGIONS FOR ^3He-^4He MIXTURES*

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From the time that ^3He first became available in research quantities, one of the most active subjects for both experimental and theoretical investigation has been the study of the effect of ^3He on the lowering of the λ temperature of ^4He. The λ points of mixtures of various concentrations have been determined by observations[1] of anomalies in the heat transport phenomena, viscosity, velocity, and attenuation of first and second sound, vapor pressures, specific heats, liquid densities, bubble formation from heaters, etc. Generally, except for certain earlier less quantitative experiments, the results of the various approaches have been in good agreement within the range of small experimental errors inherent in the different methods.

The "λ temperatures" determined by measurements of the liquid density maxima by Kerr[2] and by Ptukha[3] were, however, consistently higher than those obtained by the more reliable of the other measurements. These higher temperatures have generally been assumed to be the result of uncertainties in locating the exact centers of the relatively broad density maxima. The "λ temperatures" resulting from the observation of the disappearance of bubble formation from a heater by Zinov'eva and Peshkov[4] are still higher and more erratic than those from the density measurements. The purpose of the present series of experiments was to investigate the source of these apparent discrepancies.

The observation by Kerr and Taylor[5] and by Chase, Maxwell, and Millett[6] that the density maximum for pure ^4He occurs at about 0.006°K above the λ point as well as the discovery by Lee and Fairbank[7] and by Kerr and Taylor[8] that pure ^3He has a density maximum at about 0.5°K imply that the locus of the density maxima for their mixtures may well be different from the λ line.

The apparatus used by Kerr and Taylor[5,8] for measurements on the molar volumes and expansion coefficients of the pure components has been used to measure corresponding data on mixtures containing approximately 27, 53, 74, and 89% ^3He. This equipment makes possible better temperature and density resolution than was possible in the earlier density measurements. Typical experimental results for two of these mixtures in the regions involving the volume minima and the stratification temperatures are shown in Fig. 1. (The molar volumes as a function of temperature over a more extended range will be the subject of a subsequent paper.) It can be observed here that the temperatures of the volume minima, and particularly those of the stratification region, can be quite well resolved. The λ temperatures cannot be directly observed in these experiments, but reasonable values for them can be obtained from several of the references quoted in the first paragraph.

The molar volumes and temperatures at the volume minima and at the stratification region are summarized in Table I along with data on the pure components and similar data from our ear-

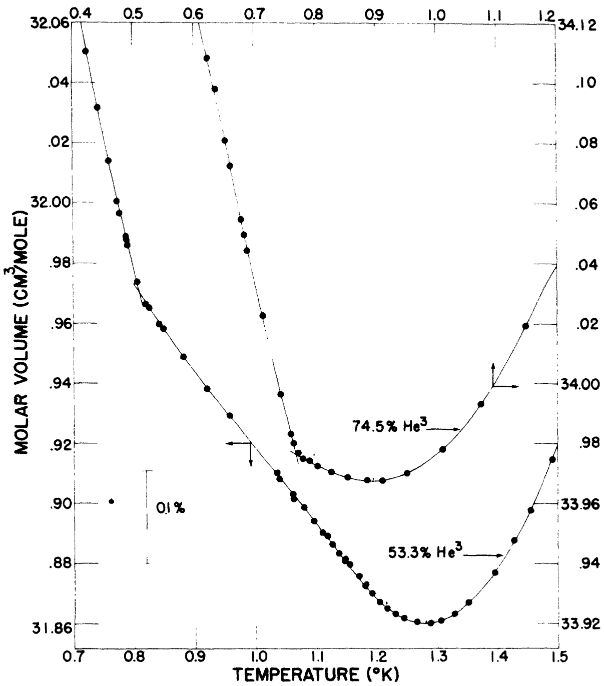

FIG. 1. Experimental molar volume data for 53.3% and 74.5% solutions of ^{3}He in ^{4}He.

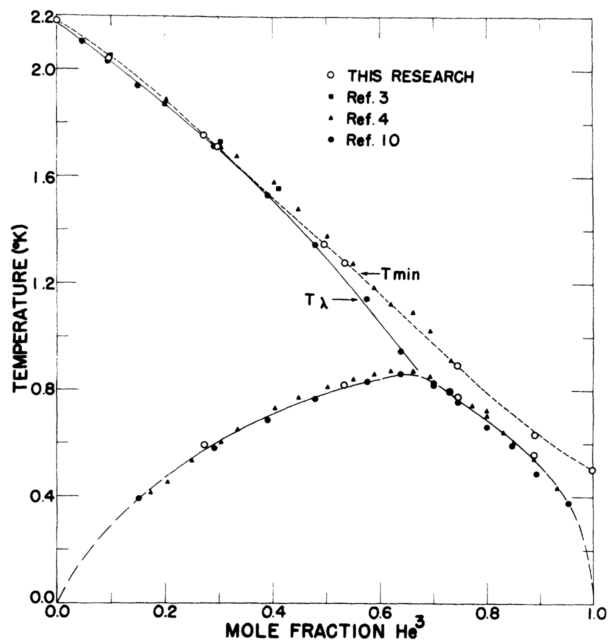

FIG. 2. Phase diagram for ^{3}He-^{4}He mixtures. Solid curves are from Sydoriak and Roberts.[1] The dashed line shows the locus of the volume minima.

lier work[2] revised to the temperature scale T_{62}.[9] These data are shown in Fig. 2 in relation to the phase diagram of ^{3}He-^{4}He mixtures. In order to avoid confusion, only a small portion of the data on which the phase diagram is based is included here. Roberts and Sydoriak[1] have summarized the earlier data on this subject, and their smoothed data are represented on the diagram by the solid curves for the λ line and for the stratification region. It is clear from Fig. 2 that the locus of the volume minima is a line different from the λ line, although at concentrations below about 40% ^{3}He, the differences are generally within the experimental errors of the various measurements.

The depression of the volume minima of the mixtures with respect to the temperature of the volume minimum for pure ^{4}He is approximately

Table I. ^{3}He-^{4}He mixtures: Molar volumes and temperatures in the volume minima and stratification regions.

x_3 Mole fraction	Reference	T_{min} (°K)	T_S (°K)	V_{min} (cm^3/mole)	V_S (cm^3/mole)
0.0	a	2.178	⋯	27.386	⋯
0.0975	b	2.045	⋯	28.128	⋯
0.272_6	TR[c]	1.754	0.590	29.500	29.735
0.298_4	b	1.706	⋯	29.760	⋯
0.495_1	b	1.350	⋯	31.475	⋯
0.533_3	TR	1.280	0.810	31.860	31.970
0.745_0	TR	0.894	0.766	33.967	33.976
0.890_4	TR	0.637	0.558	35.601	35.608
1.000	d	0.502	⋯	36.711	⋯

[a]See reference 5.
[b]See reference 2.
[c]This research. All data refer to saturated vapor pressure conditions.
[d]See reference 8.

proportional to the ^{3}He mole fraction, although it is somewhat less at low concentrations and somewhat greater at high concentrations. If possible concentration errors of up to ±0.5% are considered along with the estimated uncertainties in the determination of the temperatures at the minima, then the following formula may be used (for interpolation purposes only) to express the temperatures (T_{mixt}) of the volume minima as functions of the ^{3}He mole fraction and the temperatures of the volume minima of pure ^{4}He (T_4^0) and pure ^{3}He (T_3^0):

$$(T_4^0 - T_{mixt})/(T_4^0 - T_3^0) = x_3 - 0.027 \sin 2\pi x_3.$$

The only other direct measurements of the densities of mixtures, those of Ptukha,[3] are in good agreement with the present results at lower concentrations but give temperatures as much as 0.060°K higher for the density maxima. However, our own analysis of Ptukha's density-temperature data indicates that the density maximum for the 40% ^{3}He solution occurs within 0.005°K of the smooth curve through our data for the temperatures of the volume minima.

Thus it appears that, since the volume minimum follows an independent locus, the experimental determinations of the λ line are in reasonable agreement with each other. An exception is the visual experiment of Zinov'eva and Peshkov[4] which gave unusually high results for the λ temperatures, although their results for the stratification temperatures are in good agreement with the data of other investigations. Roberts and Sydoriak[1] have discussed several reasons why this type of experiment might give erroneous results as a consequence of large temperature and concentration gradients associated with the nature of the method. Such gradients might reasonably be enhanced by the existence of the density maximum just above the true λ temperature. As shown in Fig. 2, all but two of their data points fall within 0.030°K of the curve for the volume minima—an observation which suggests that their experiment may have been more sensitive to the density gradients than to the λ phenomenon.

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[1]References to most of the pre-1961 data on the λ line and the stratification region have been given by T. R. Roberts and S. G. Sydoriak, Proceedings of the Seventh International Conference on Low-Temperature Physics (University of Toronto Press, Toronto, Canada, 1961), p. 633; S. G. Sydoriak and T. R. Roberts, Phys. Rev. 118, 901 (1960).

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PERSISTENT CURRENTS IN SUPERFLUID HELIUM*

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The superconducting ring experiment, first performed by Kamerlingh Onnes, is one of the classic demonstrations in low-temperature physics. In this experiment an electric current is created in a ring of superconducting material. The lifetime of such a current is effectively infinite, provided that the ring remains in the superconducting state.

The superfluidity of liquid helium is, in many ways, analogous to the superconductivity of metals; therefore, it is reasonable to expect persistent currents in liquid helium. The detection of such currents in liquid helium presents certain difficulties. There is no external magnetic field such as exists in the superconducting case, so that any measurement must involve a direct mechanical