Crystallization curves for weak ^3He–^4He solutions at low temperatures

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Crystallization curves of weak ^3He–^4He solutions at temperatures 0.03–1.2 K are measured. In addition to the usual minima, maxima are observed at $T \approx 0.28$ K. The possibility of restoring the melting curves at the given temperatures is discussed.

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There are many papers concerning phase diagrams of ^3He–^4He mixtures (see, for example, the review in Ref. 1), but the temperature range ($T < 0.6$ K) and small ^3He concentrations remain inadequately studied. In connection with the considerable increase in interest in the properties of dilute solutions at ultralow temperatures, we measured the crystallization curves of 1, 2, and 4% solutions of ^3He in ^4He. Here the work is complicated by the presence of minima on the crystallization and melting curves, so that the measurements were performed in a Pomeranchuk chamber (Fig. 1). The volume of the mixture was ~ 12 cm^3. The chamber walls with thickness 0.5 mm served as one of the plates of the capacitive pressure sensor. The temperature was measured with a carbon resistance thermometer, calibrated according to the TsMN susceptibility. During the measurements, the liquid mixture ^3He–^4He confined in the measuring volume was compressed and the change in pressure was recorded with high accuracy (10^{-3} atm). The onset of crystallization was noted by the sudden termination of the increase in pressure.

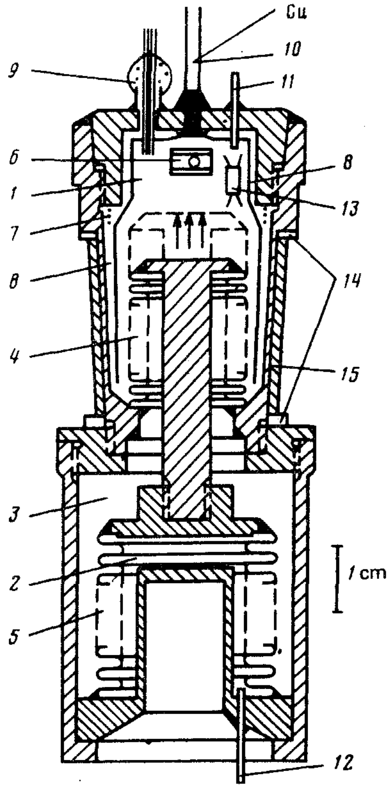

FIG. 1. Pomeranchuk scheme. 1—$^3He/^4He$ mixture; 2—pure ^4He; 3—vacuum; 4—sylphon bellows for mixing chamber; 5—sylphon bellows for pure ^4He chamber; 6—coil with TsMN; 7—heater; 8—heat exchanger; 9—input leads; 10—refrigerant duct; 11—capillary for mixing chamber; 12—capillary for ^4He chamber; 13—thermometer; 14—textolite liners; 15—external capacitor plate.

The crystallization curves are shown in Fig. 2. As a control and for calibration,[3] the crystallization pressure of pure ^4He was measured and the corresponding curve is shown in Fig. 2. In addition to the minimum, the crystallization curves have a distinct maximum and a parabolic trend ($\Delta P \sim T^2$) for $T \to 0$. This temperature behavior can be qualitatively explained as follows. At very low temperatures, because of the vanishingly small solubility of ^3He in the solid phase, the slope of the crystallization curve is determined by the entropy of the liquid phase, $dP/dT \sim T$, $\Delta P \sim T^2$. With increasing temperature the amount of impurity in the solid phase increases, the entropy of the solid phase becomes greater than that of the liquid phase, and the slope of the curve becomes negative; at the same time, the curve passes through a maximum. With further increase in temperature, after passing through a minimum the crystallization curve assumes the usual positive slope. It is interesting that the melting curves, whose direct measurement is greatly complicated by the difficulty of preparing uniform solid mixtures, can be reproduced from the crystallization curve. For this it is enough to use

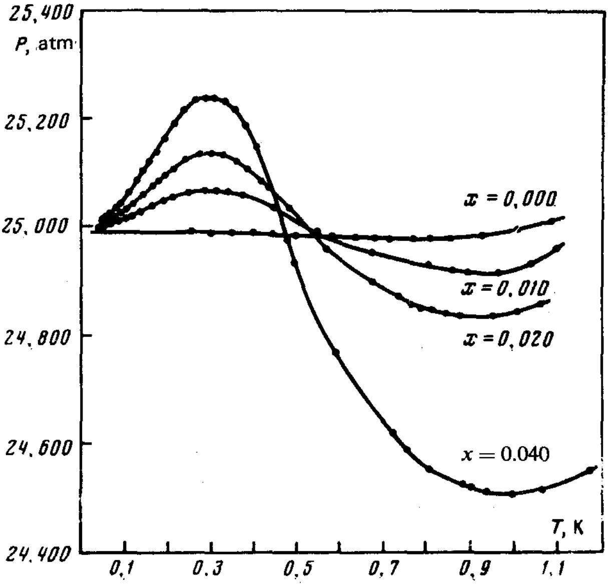

FIG. 2. Curves showing the onset of solidification of ^{3}He/^{4}He solutions.

the Clasius-Clapeyron equation for the melting curve

$$\frac{dP_{\text{melt}}}{dT}=\frac{c_l\,(s_3^l - s_3^s) + (1-c_l)\,(s_4^l - s_4^s)}{c_l\,(v_3^l - v_3^s) + (1-c_l)\,(v_4^l - v_4^s)}\,.$$

This is done especially simply for temperatures at which it is possible to ignore the interaction of impurity atoms with each other, i.e., at $T > T_F$ for liquid solutions. In solid solutions, this interaction can be ignored over the entire temperature range studied. In this case the displacement of the crystallization curve relative to the curve for pure ^{4}He (Ref. 2) is

$$\Delta P=\frac{T(c_l - c_s)}{v_4^l - v_4^s}\,.$$

From this relation it is easy to determine the concentration c_s of the solid phase, which is in equilibrium with the liquid phase with fixed concentration. Research is currently being conducted on the properties of melting of mixtures to concentrations corresponding to attainment of the triple curve.

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