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### PHASE SEPARATION IN SOLID He<sup>3</sup>-He<sup>4</sup> MIXTURES, AS SHOWN BY SPECIFIC HEAT MEASUREMENTS\*

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In a recent publication<sup>1</sup> we have presented specific heat data, in the range 0.05°K to 1°K, for pure He<sup>4</sup> and for nearly pure He<sup>3</sup> in the solid state. The specific heats of He<sup>3</sup> with small amounts of He<sup>4</sup> impurity were found to show anomalies corresponding to the appearance of the entropy of mixing and it was suggested that, at low temperatures, the solid separated into two phases, one rich in He<sup>4</sup>, and that equilibrium was established via diffusion by quantum mechanical tunnelling.

The specific heat measurements have now been extended using the same calorimeter over a much larger range of concentrations up to 80% He<sup>4</sup>, and the results, reported here, show that the two isotopes are probably completely separated at 0°K.

The new data are shown in Fig. 1 as a graph of  $C/R$  versus  $T$  for a number of values of  $x_0$ , the atomic fraction of He<sup>3</sup>.

Since  $PVT$  data for solid He<sup>3</sup>-He<sup>4</sup> mixtures are not yet available, the freezing pressures, molar volumes, etc. used to calculate the number of moles and the final pressure in the calorimeter have been obtained by linear interpolation between the properties of the pure isotopes. The measurements shown in Fig. 1 are confined to pressures not much greater than the melting pressure; at higher pressures the equilibrium times associated with the "mixing" specific heat are too long for reliable data to be obtained. For the measurements shown, the equilibrium times vary from a few seconds to several min-

utes. On the other hand, the equilibrium heat capacity and transition temperature do not appear to be strongly dependent on pressure, as is shown by the curves for the 50% mixture at 35.8 atmospheres and at 27 atmospheres.

As we remarked previously<sup>1</sup> the specific heats have a common envelope on the low-temperature side of the anomalies for different initial concentrations,  $x_0$ , from almost unity down to 0.2. This envelope agrees very well with the properties of a simple phenomenological model for phase separation put forward by Edwards and Yang<sup>2</sup> (solid lines in Fig. 1).

In this model it is assumed that the internal energy, minus the  $T^4$  term, of a single homogeneous He<sup>3</sup>+He<sup>4</sup> solid phase of composition  $x$  and containing  $N$  atoms is given by<sup>3</sup>

$$U = \frac{1}{2}N[xE_{33} + (1-x)E_{44} + x(1-x)\Delta E], \quad (1)$$

where  $\Delta E = 2E_{34} - E_{33} - E_{44}$ .

In Eq. (1)  $E_{ij}$  is the energy of interaction between an atom of isotope  $i$  and  $s$  nearest neighbors of isotope  $j$ , where  $s$ , the coordination number, is 8 for bcc structure and 12 for close-packed structure. It is assumed that  $\Delta E$  is positive, so that separation into the pure isotopes is favored at 0°K and there is no long-range order. It then follows, again neglecting phonon entropy, that

$$S = -Nk[x \ln x + (1-x) \ln(1-x)]. \quad (2)$$

Assuming that two such phases may be present and that both phases have the same constant

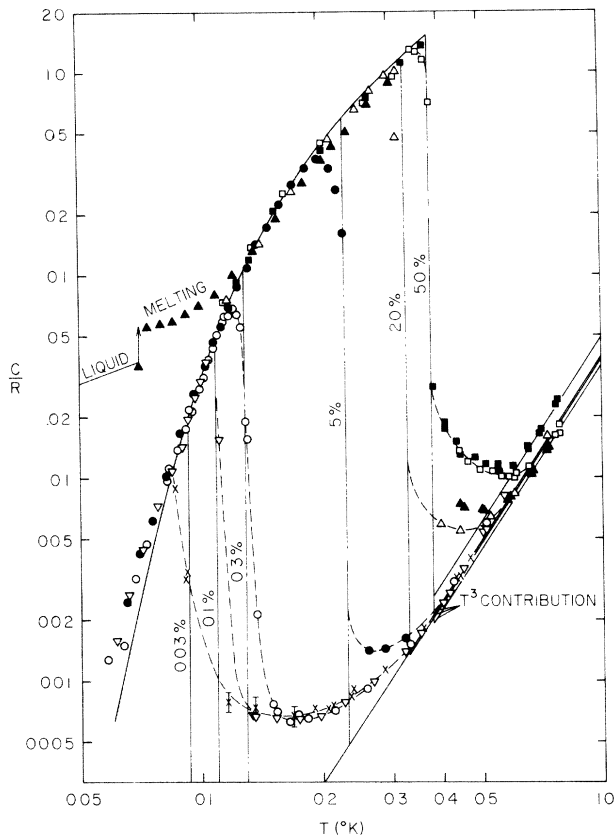


FIG. 1. The specific heat of He<sup>3</sup> - He<sup>4</sup> solid mixtures as a function of temperature. The various symbols denote various atomic percentages of He<sup>4</sup> and various pressures, as follows: X, 0.03% and 35.8 atm; ∇, 0.11% and 35.8 atm; ○, 0.28% and 35.8 atm; ●, 4.7% and 35.8 atm; Δ, 21% and 35.8 atm; □, 50% and 35.8 atm; ■, 50% and ~27 atm; and ▲, 82.4% and 30.0 atm. The solid lines represent the theoretical specific heat added to the observed Debye contributions. The percentages written on the vertical lines give the theoretical values of x<sub>0</sub> or (1-x<sub>0</sub>) for each transition. The dashed lines follow the experimental points. For explanation of points labeled "melting" and the line labeled "liquid," see text.

values of E<sub>ij</sub>, irrespective of temperature or composition, minimizing the free energy gives

$$\frac{\frac{1}{2} - x}{\ln(1/x - 1)} = \frac{kT}{\Delta E} = \tau, \quad (3)$$

where x is the concentration in the He<sup>4</sup>-rich phase and (1-x) the concentration in the He<sup>3</sup>-rich phase, i.e., the phase-separation line is symmetrical (see Fig. 2). In Eq. (3), x = 1/2. For x = 1/2, t = t<sub>max</sub> = 0.25.

The total specific heat of the two phases in

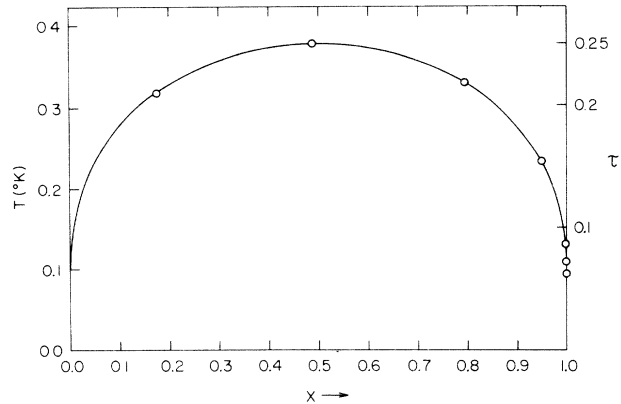


FIG. 2. Phase separation line according to the theory, using  $\Delta E/k = 1.51^\circ\text{K}$  obtained from the specific heat data. The circles indicate the values of x<sub>0</sub>, the atomic fraction of He<sup>3</sup>, for which the transition has been directly observed.

equilibrium according to this model is given by

$$\frac{C}{R} = \frac{(\frac{1}{2} - x)^2}{\tau \{ [\tau/x(1-x)] - 1 \}}; \quad (4)$$

for x = 1/2, C/R = C<sub>max</sub>/R = 1.5.

In Figs. 1 and 2 the single adjustable parameter  $\Delta E/k$  has been determined to be +1.51°K by fitting the specific-heat data to the theory. The theory predicts that, as the temperature is raised, one phase disappears and the specific heat drops discontinuously to zero, when either x or (1-x), given by Eq. (3), is equal to the concentration, x<sub>0</sub>, in the whole sample.

The experimental data show some rounding off before dropping down abruptly at the transition temperature; this may be due to some technical defect such as large scale inhomogeneity in the concentration of the solid sample. On the other hand, the "tail" on the high-temperature side of the transition for 50% cannot be due to such effects and probably represents the effect of short-range ordering, which is not considered in the theory.

The good agreement between the model and experiment is to some extent surprising, since it is known that at low pressures pure He<sup>4</sup> and He<sup>3</sup> have different crystal structures, hcp and bcc. No latent heat corresponding to the intersection of a crystallographic transition line with the phase-separation line has been observed. The effect of the change in structure may be too small to be observed, or the crystal structure may be metastable at low temperatures so that the present data represent separation between

two bcc phases.

Independent confirmation that solid helium splits into two nearly pure phases near 0°K is given by the data for the mixture with 17.6% He<sup>3</sup>, 82.4% He<sup>4</sup> given in Fig. 1. The pressure for this sample is below the melting pressure for pure He<sup>3</sup>, so that as the temperature is lowered and the He<sup>3</sup>-rich phase becomes purer, this phase begins to melt, as is shown by the deviation of the specific heat from the theoretical line. At 0.07°K the He<sup>3</sup>-rich phase has completely melted and there is a discontinuous drop in the specific heat, as is shown by the data and also by the rate of change of temperature due to the natural heat influx. According to our assumptions the sample is now 17.6% nearly pure liquid He<sup>3</sup> and 82.4% nearly pure He<sup>4</sup>. The contribution of the He<sup>4</sup> to the specific heat should be quite negligible and the value of  $C/R$  is very nearly 17.6% of  $C/R$  for pure liquid He<sup>3</sup> near the melting curve,

shown by the curve labeled "liquid" which is taken from the data of Brewer and Keyston.<sup>4</sup> Moreover, the discontinuity in  $C/R$  at 0.07°K is in good agreement with the appropriate thermodynamic formula using melting curve data<sup>5</sup> for pure He<sup>3</sup>, shown by the arrow.

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## POLARIZATION OF 20-cm WAVELENGTH RADIATION FROM RADIO SOURCES

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Linear polarization has been detected at a wavelength of 20 cm in the radiation from a number of extragalactic and galactic radio sources. In one case, the observed percentage polarization is as high as 38%. The observations were carried out with a parametric receiver on the 210-ft steerable reflector of the Australian National Radio Astronomy Observatory at Parkes, New South Wales.

Those sources found to be polarized are listed in Table I. The data given include the percentage polarization [defined as  $(I_{\max} - I_{\min}) / (I_{\max} + I_{\min})$ ], the position angle of the  $E$  vector, measured east of north, the distance in megaparsecs (Bolton<sup>1</sup>), optical identification, and the physical data where known. Most of the particulars of the double sources are from Maltby and Moffet.<sup>2</sup>

In the preliminary observations reported in this Letter, a total of 15 sources, in three categories, were studied. No polarization above the experimental limit of about 1% was found for three HII regions, the Orion Nebula, the Eta Carina Nebula, and the 30 Doradus Nebula of the Large Magellanic Cloud. A null result was

also obtained for Sagittarius A (the nucleus of our galaxy), from which the radiation is partly thermal in origin. Polarization was not detected in two supernova remnants, Puppis-A and Kepler's Nova, but was observed in a third, Vela-X. Of the nine extragalactic sources investigated, polarization was detected in all but two, Hydra-A and 3C-273. The existence of linear polarization considerably strengthens the hypothesis that the synchrotron mechanism is responsible for the radiation from the nonthermal sources.

All the sources, with the exception of Fornax-A and Pictor-A, were also observed at a wavelength of 75 cm. All results were negative (less than 2%).

The parametric receiver used (Gardner and Milne<sup>3</sup>) has an input bandwidth of 14 Mc/sec. The overall system noise is about 100°K. With a time constant of two seconds, the value used throughout, the output peak-to-peak fluctuation level is about 0.15°K. The aerial temperature of the weakest source investigated was 7°K.

The observations were carried out by using a linearly polarized feed system which could be rotated. The feed antenna consisted either of a