NUCLEAR MAGNETIC SUSCEPTIBILITY OF SOLID He^3 COOLED BY COMPRESSION FROM THE LIQUID PHASE*

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Using the cooling power of the adiabatic solidification of He^3, we have reached temperatures near 2 mK and have measured the temperature dependence of the susceptibility of solid He^3 down to 6 mK. The magnetic ordering is antiferromagnetic, with a Weiss $\theta = 3.0 \pm 0.3$ mK corresponding to a Néel temperature of 2.1 mK for bcc He^3 at 34 atm.

Magnetic ordering of solid He^3 in the millidegree range has been predicted by theory.[1] In this Letter, we present the results of nuclear susceptibility measurements at temperatures down to a few mK, allowing an estimate of the ordering temperature and showing that the transition is antiferromagnetic. We have cooled the He^3 by adiabatic compression of the liquid into the solid phase. This cooling method was proposed by Pomeranchuk,[2] has been discussed in detail by Goldstein,[3] and has been demonstrated experimentally by Anufriyev[4] and Johnson et al.[5] A similar effect has previously been observed in He^3-He^4 mixtures using the present apparatus.[6]

The experimental chamber is shown in Fig. 1. A system of three chambers formed by a pair of concentric bellows is used to solve the problem of solidification of He^3 at temperatures below the melting curve minimum.[7] The He^3 sample is contained in the innermost chamber and He^4 in the outer two chambers. Initially all three chambers are pressurized to approximately the melting curves of their contents, and the sample cell is precooled with a dilution refrigerator to about 25 mK. He^4 is then slowly bled out of the intermediate chamber, giving rise to a downward force on the top plate sufficient to solidify the He^3 sample. The time taken for complete solidification ranges from 1 to 5 h. The He^3 pressure can be determined from the He^4 pressures and the displacement of the bellows.

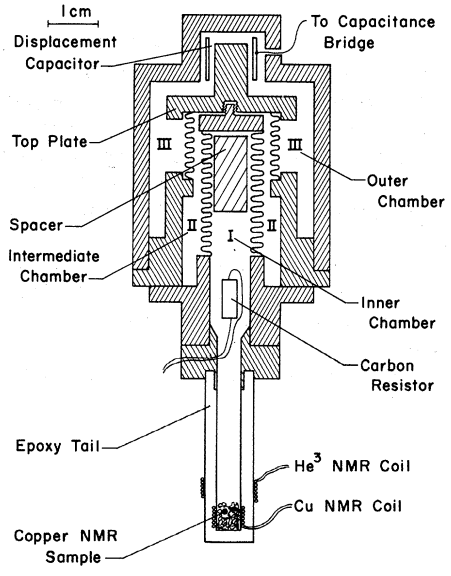

FIG. 1. Compression apparatus.

The He^3 is isolated from the dilution refrigerator by large thermal-boundary resistances between the helium and the metal walls.[8] In order to insure that solid forms in the epoxy tail, this section of the apparatus is heated slightly in the early stages of the compression. The sample purity, as measured by a mass spectrometer,

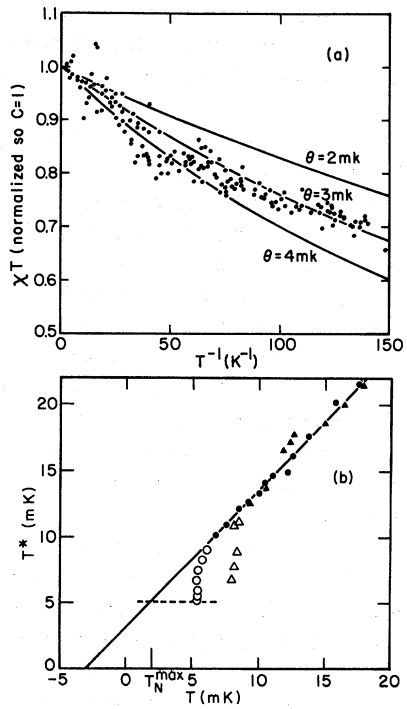

FIG. 2. Susceptibility of solid He^3. (a) χT vs T^{-1} with χ in units of unity Curie constant. Data from five runs are shown. (b) $T^*(=\chi^{-1})$ vs T, showing upper bound on Néel temperature. Circles and triangles represent two different runs. (Every other point is plotted.) Open points are nonequilibrium points, and their abscissas have no significance.

showed a He^4 concentration of less than one part in 10^4 in our He^3 sample.

The temperature of the He^3 is determined by continuous wave NMR susceptibility measurements of Cu^{63} (the sample is 0.25 g of No. 50 AWG insulated copper wire). The copper magnetic temperature is calibrated at high temperatures against the vapor pressure of He^3 and the He^3 melting curve.[9] Between 12 and 35 mK the temperature scale was checked by the Korringa relation for copper: $T_1T = 1.27$ sec K.[10] No deviation from Curie's law was observed, and the temperature scale is believed to be valid to 5% at all temperatures.

The He^3 susceptibility was measured with a pulsed NMR apparatus. The solid He^3 magnetic temperature, $T^* = C/\chi$, is determined by calibrating against the copper scale at high temperatures to obtain the Curie constant C.

Data obtained from five compressions are shown in Fig. 2(a) with χT plotted against $1/T$. The data were taken during the warmup after the completion of the compression, when the pressure was constant and very nearly 34 atm. The curved lines correspond to calculations of χT for various values of the Weiss θ, or equivalently $-4J/k$, using the susceptibility expansion of Rushbrooke and Wood for a bcc lattice[11]:

$$\chi T = C\left[1 + 4\frac{J}{kT} + 12\frac{J^2}{(kT)^2} + 34\frac{2}{3}\frac{J^2}{(kT)^3} + 95.8\frac{J^4}{(kT)^4} + 263\frac{J^5}{(kT)^5} + \cdots\right].$$

From Fig. 2(a), we believe the most probable value for $4J/k$, or $-\theta$, to be -3.0 with an uncertainty of ± 0.3 mK. The negative sign of J implies antiferromagnetic ordering in agreement with theory.[1,12] The downward bulge in the data of Fig. 2(a) near 25 mK, or 40 K^{-1}, is thought to be an experimental error resulting from poor thermal equilibrium during some of the runs, since points in the neighborhood of this temperature were often obtained during a period of relatively rapid warmup.

We have used the analysis of Fig. 2(a) because, as pointed out by Fisher and Sykes,[13] the conventional plot of $1/\chi$ vs T is apt to lead to an overestimate of θ. According to results obtained by Rushbrooke and Wood,[11] our value of θ leads to a Néel temperature of 2.1 mK. Earlier susceptibility measurements[14] lead to $T_N = 2.4$, while measurements of $(\partial P/\partial T)_V$ [15] and nuclear magnetic relaxation rates[16] give 2.0 and 1.8 mK, respectively. The latter two measurements were not able to distinguish between ferromagnetic and antiferromagnetic ordering, but higher terms of $(\partial P/\partial T)_V$ can in principle make the distinction.[17]

Figure 2(b) is the conventional C/χ vs T plot (here represented as a He^3 T^* vs T plot), showing only low-temperature data. The open circles and triangles shown in Fig. 2(b) were taken during the compression when thermal equilibrium between the sample and the copper thermometer was not complete. The source of this poor equilibrium at the lowest temperatures has not yet been determined. The solid line drawn on this figure is a fit to the Curie-Weiss law for the equilibrium points shown. The lowest magnetic temperatures reached were 5.2 mK for copper and 5.2 mK for He^3. The minimum He^3 magnetic temperatures provide an upper bound on the antiferromagnetic transition. By extrapolating the Curie-Weiss relation, we find that the lowest He^3 magnetic temperature reached (shown by the broken line) corresponds to an actual temperature near 2 mK. This Curie-Weiss temperature provides an independent upper bound, $T_N^{\max}$, to the Néel temperature which is very close to the value obtained from the analysis of Fig. 2(a).

Our value of T_N should be slightly lower than the zero-field value, since our measurements were performed in an applied magnetic field of 2 kG. If we assume the usual parabolic dependence of the temperature $T_N(H)$ on the applied field, $T_N(H) = T_N(0)(1-H^2/J^2)$, however, our Néel temperature should be lowered by only 5%.

We wish to thank Professor John D. Reppy for suggesting the bellows configuration used in this experiment and for many other useful suggestions throughout the course of the experiment. We are also grateful to Allan Greenberg for constructing and making available to us the pulsed NMR electronics and to James Eckardt for aid in constructing the cryogenic apparatus. One of us (D.M.L.) wishes to thank the John Simon Guggenheim Memorial Foundation for fellowship support covering a sabbatic year at Brookhaven National Laboratory, and to thank the Brookhaven cryogenics group for their hospitality during this period when the experiment was started. Finally, we wish to gratefully acknowledge valuable discussions with Professor Michael E. Fisher and Professor Robert A. Guyer.

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TRAPPED-PARTICLE INSTABILITY*

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A simple model for a new instability resulting from particles trapped in a large-amplitude electrostatic wave is invoked to explain the generation of satellite frequencies in a recently reported experiment by Wharton, Malmberg, and O'Neil. The model predicts satellites on the large-amplitude wave at a frequency separation proportional to $\sqrt{E}$, where E is the amplitude of the large wave. The predicted growth rates reasonably account for the observed growth of these satellites.

In a recent paper, Wharton, Malmberg, and O'Neil[1] describe the excitation of large-amplitude plasma waves by means of a probe immersed in a plasma having an electron temperature of 9.4 eV, an electron density of 5×10^8 cm^{-3}, and relatively cold ions. Apart from observing the reduction in the damping rate for large-amplitude waves predicted by O'Neil[2] and Al'tshul and Karpman,[3] the experiment also showed the growth of sidebands to the frequency of the large-amplitude wave. The frequency separation of these satellite bands was found to be proportional to the square root of the wave amplitude. This indicates that trapped particles bouncing in the potential trough of the wave at a frequency $\omega_B = (eEk/m)^{1/2}$ (E is the wave field, k the wave number) must play an important role in the generation of these sidebands. In addition, a broadening of the frequency of the large-amplitude wave was observed.

We propose the following explanation for these observations. A significant number of particles are trapped in the trough of the wave due to its large amplitude. Because the electrostatic fields are largest in the vicinity of the probe, most of the trapping takes place there. These particles then move with the wave, with a mean velocity equal to its phase velocity. The trapped particles oscillate in the wave trough. The frequency of this oscillation is roughly constant for a large number of the trapped particles, varying only a few percent for all those particles trapped within $\frac{1}{6}$ of a wavelength (±30°) from the bottom of the