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NUCLEAR COOLING APPLIED TO MEASUREMENTS IN He^3†

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An apparatus for the use of nuclear adiabatic demagnetization has now produced and maintained submillidegree temperatures for as long as seven hours. It has cooled 0.45 cm^3 of He^3 at various pressures to 4 mdeg K in the liquid state and to approximately 7 mdeg K in the solid state. Measurements of the nuclear-spin susceptibility, specific heat, and thermal-boundary impedance have been made to these temperatures in the liquid and some preliminary observations made in the solid.

The first measurements[1] of the properties of He^3 below 8 mdeg K indicated a specific-heat anomaly at 5.5 mdeg K which was interpreted as evidence of a predicted superfluid transition[2] in liquid He^3. A large number of measurements made since that time by the Illinois group[3] have exhibited no anomalies and no radical departure from the predictions of the Landau theory of Fermi fluids. The measurements reported here use a different cooling method, different thermometers, and different measuring techniques from those of the other experiments. The results indicate that the spin susceptibility is independent of temperature to within ±5% between 4 and 30 mdeg K. Thus, there is no transition of the type predicted in which the spins align antiparallel and the susceptibility decreases. The specific-heat measurements are less accurate but if there is an anomaly it must be much smaller than that reported by Peshkov.

The apparatus, similar to one reported earlier,[4] involves three cooling stages below 1°K: a He^3 refrigerator at 0.35°K, a cerium magnesium nitrate salt at 0.013°K, and the nuclear cooling stage. Figure 1 is a schematic diagram of the nuclear stage. There are two important thermal barriers between the cold nuclei in the high-field magnet at the bottom of the sample and the nuclei of the same copper wires in the Helmholtz pair where the temperature is measured. The first is the spin-relaxation process by which energy can be transferred from the conduction electrons to the cold nuclei. The second is the electronic conduction along the copper wires. The relaxation is determined by the Korringa relation which says that the relaxation time, T_1, times the temper-

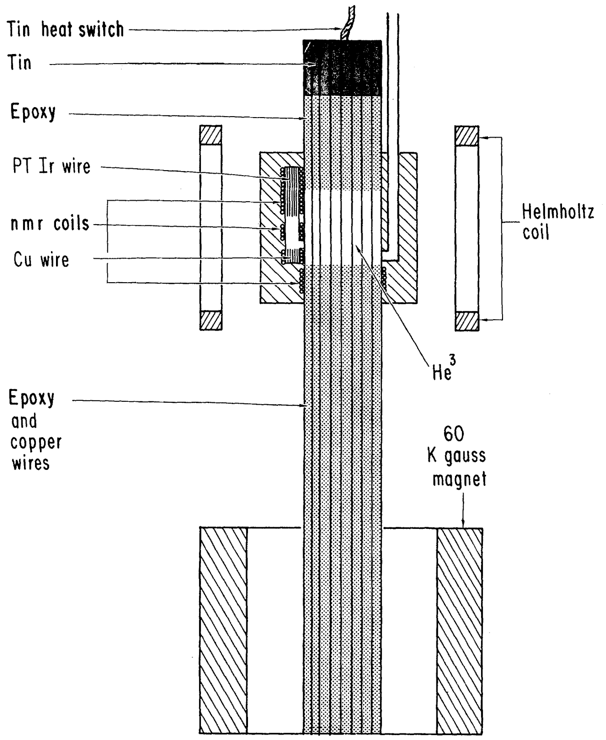

FIG. 1. Schematic diagram of the nuclear cooling stage consisting of 8500 No. 46 copper wires. Diameter of bundle is 0.2 in. and length 20 in. Copper thermometer wire is 0.0005 in. diam and Pt-Ir heater wire 0.001 in. diam.

ature of the electrons is a constant (1.27 deg sec for copper[5]). The conduction is determined by the Wiedemann-Franz law and the residual resistance. During a demagnetization in which the field was decreased to a value such that the nuclei at the bottom should have been at 0.36 mdeg K, the lowest temperature measured in the Helmholtz coil was 0.80 mdeg K. This agrees with the temperature difference expected from the above thermal impedances in the presence of a heat leak between $\frac{1}{2}$ and 1 erg/min and indicates that the demagnetization is adiabatic as far as it has been taken.

The temperatures of the two sets of copper wires are measured in the 600-G field of the Helmholtz coil using a steady-state nuclear magnetic resonance (nmr) technique. The temperature is assumed to be inversely proportional to the amplitude of the nmr signal in accordance with the expected Curie-law dependence of the susceptibility. The signal amplitude is calibrated against the He^3 vapor pressure between 0.35 and 1°K. In order to check that the susceptibility of the copper really did obey Curie's law, the nmr signal of a pure platinum sample was compared to the copper signal. Between 40 mdeg K and the lowest temperature obtained, the Pt signal increased roughly 25% more than the copper but more measurements are necessary to determine if this discrepancy is real. In addition, the spin relaxation time of the copper was measured as low as 3 mdeg K and found to obey the Korringa relation when the temperature was taken to be that indicated by the signal amplitude.

The temperature of the He^3 is measured by the small bundle of 0.0005-in. diam copper wire.[6] In order to ascertain that the wire is not heated above the temperature of the He^3, a known current can be passed through the wire and the temperature measured as a function of power. The data agree with a T^5 dependence of the boundary impedance such that the eddy-current heating from the nmr measurement would raise the temperature at most 0.01 mdeg K above the temperature of the He^3 at 4 mdeg K. The saturation factor at this temperature was somewhat less than 1%.

The He^3 susceptibility is also measured with nmr. Measurements are made at three different rf power levels to make certain that there is no saturation of the signal. Data taken at 25 atm and at the saturated vapor pressure are shown in Fig. 2.

Specific-heat measurements are made by use of the long time constant for transfer of heat from the He^3 to the cooling wires and the short time constant for internal equilibrium that results from the extremely high thermal conductivity of He^3 at low temperatures. A heat pulse is applied to the Pt-Ir wire (see Fig. 1) and then the temperature of the He^3 is measured as a function of time. The time dependence in the low-pressure data confirms that the "external" thermal relaxation time is indeed long (~15 min at 4 mdeg K) compared with the "internal" relaxation time (less than 1 min). Thus, the temperature immediately before and immediately after the heat pulse provides a direct measurement of the He^3 heat capacity. The scatter in the data on a given demagnetization results from the fact that the scatter in the nmr measurements at the low temperature is about ±1%. Roughly, 10% steps in the temperature were used so that an error as large as 20% in that step is possible. The scatter from one demagnetization to the next results from

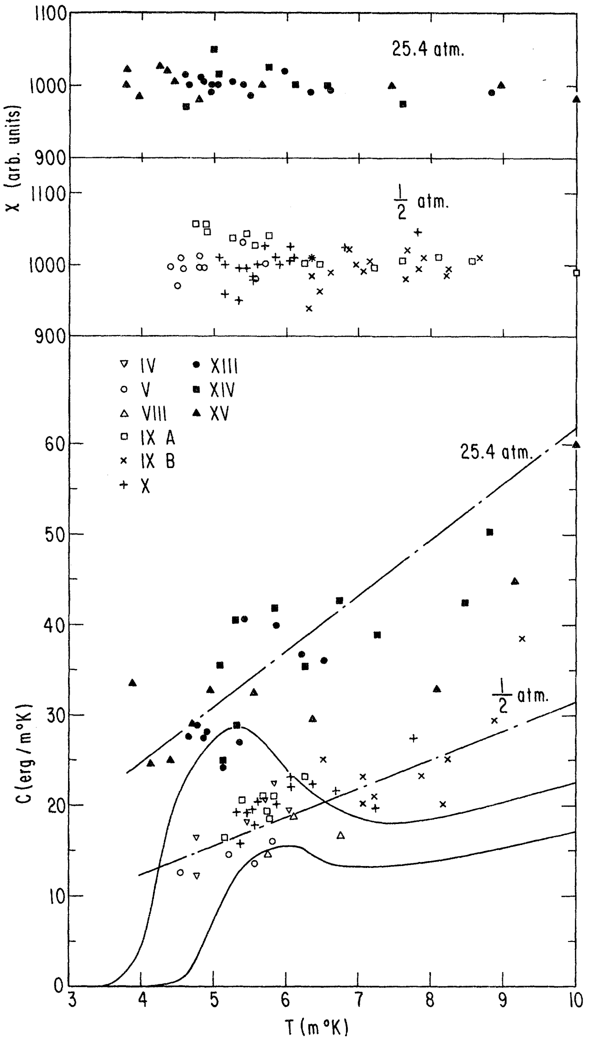

FIG. 2. Nuclear susceptibility and specific heat of liquid He^3 at 25 atm pressure and at $\frac{1}{2}$ atm. Susceptibility data were taken at three different power levels to determine that no saturation of the signals was occurring. The specific-heat data are from several demagnetizations. Solid curves represent the results of Peshkov; the dotted lines are those of Abel, Anderson, Black, and Wheatley.

the fact that the calibration of the absolute temperature on each demagnetization was only accurate to ±10 or 15%. Within a given demagnetization, as can be seen in Fig. 2, the data indicate a small excess heat capacity between 6 and 7 mdeg K. However, the data are not sufficiently accurate to determine if this effect is real. It is accurate enough to rule out an anomaly as large as that reported by Peshkov. The data taken at high pressures are much less satisfactory since the ratio of internal to external time constants is less favorable. However, the most reasonable interpretation of the data leads to the specific heat as plotted. More precise results depend on the development of a faster and more accurate thermometer.

Preliminary observations in solid He^3 at 36 atm indicate that the susceptibility is inversely proportional to the temperature to 7.5 mdeg K and that the spin-relaxation time (in this sample container) is less than ten minutes at that temperature. Although accurate measurements have not yet been made, these preliminary results are adequate to indicate that cooling schemes employing solid He^3 will not be inhibited by a long relaxation time or a nuclear spin ordering at temperatures reported here.

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