Wharton, but is similar to that of ion acoustic waves studied by Sato et al. At an amplitude minimum, a phase transition is observed.

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[1]J. H. Malmberg and C. B. Wharton, Phys. Rev. Lett. 19, 775 (1967); C. B. Wharton, J. H. Malmberg, and T. M. O'Neil, Phys. Fluids 11, 1761 (1968).

[2]T. Armstrong, Phys. Fluids 10, 1269 (1967).

[3]J. M. Dawson and R. Shanny, Phys. Fluids 11, 1506 (1968).

[4]N. Sato, H. Ikeji, N. Takahashi, and Y. Yamashita, Phys. Rev. 183, 278 (1969).

[5]J. H. Malmberg and C. B. Wharton, Phys. Rev. Lett. 17, 175 (1966).

[6]P. J. Barrett and H. G. Jones, Plasma Phys. 10, 911 (1968).

[7]J. L. Hirshfield and J. H. Jacob, Phys. Fluids 11, 411 (1968).

[8]T. O'Neil, Phys. Fluids 8, 2255 (1965).

[9]L. M. Al'tshul' and V. I. Karpman, Zh. Eksp. Teor. Fiz. 49, 515 (1965) [Sov. Phys. JETP 22, 361 (1966)].

Anomalous $P_V(T)$ of Solid ^{3}He in High Magnetic Fields*

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The low-temperature variation of the pressure at constant volume of a 24-cm^3/mole solid-^{3}He sample has been measured at 40.3 and 57.2 kG. No difference was observed from the zero-field curve. This result is thermodynamically inconsistent with previous measurements on solid ^{3}He if the system is in equilibrium. Implications of this anomalous result are discussed.

The magnetic properties of solid ^{3}He are of interest for two reasons. First, because of the large zero-point motion, the nuclear spins experience a large exchange interaction J. This has been confirmed by NMR measurements of spin relaxation and spin diffusion[1], by measurements of pressure as a function of temperature at constant volume, $P_V(T)$[2], and by measurements of the nuclear susceptibility.[3,4] Only by the last method has the sign (antiferromagnetic) of J been determined. Secondly, because of the simple lattice and the apparent absence of magnetic asymmetry, ^{3}He is thought to be an excellent example of a Heisenberg antiferromagnet.[5] A precise comparison of the Heisenberg theory with experiment should be feasible for this substance in the paramagnetic range.[6] In an attempt to accomplish this we have used a capacitance–strain-gauge technique to measure $P_V(T)$ in a large magnetic field.

Our experiment consists of measurements of $P_V(T)$ at three fields, 1, 40.3, and 57.2 kG, of a 24-cm^3/mole, bcc solid-^{3}He sample. This is the first time, to our knowledge, that solid ^{3}He has been examined at such a high field. At 1 kG, as expected, we get very good agreement with the zero-field results of the Florida group.[2] However, contrary to all expectations we have observed no difference, within experimental accuracy, between $P_V(T)$ measured at low field and at high fields.

Adams et al.[2] have shown that at zero field and for temperatures between 15 and 200 mK the effect of the exchange interaction dominates $P_V(T)$. Their data can be described by the relation

$$P_V(T) = 3\frac{R\Gamma}{V}\left(\frac{J}{k}\right)^2\frac{1}{T}, \tag{1}$$

where $\Gamma \equiv \partial \ln|J|/\partial \ln V$ is an "exchange Grüneisen constant." The effect of a magnetic field on $P_V(T)$ can be calculated from the susceptibility data by using the Maxwell relation $(\partial P/\partial H)_{V,T} = (\partial M/\partial V)_{H,T}$. The susceptibility data fit the form $M = CH/T(1+4J/kT)$ (where C is the Curie constant). Integrating the Maxwell relation we obtain

$$P_V(T) = P_0 + \frac{3R\Gamma}{V}\left(\frac{J}{k}\right)^2\frac{1}{T} + 2\frac{\Gamma}{V}\left(\frac{J}{k}\right)\frac{CH^2}{T^2} + \cdots. \tag{2}$$

For bcc ^{3}He at 24 cm^3/mole and 60 kG the magnetic term becomes equal to the zero-field term at approximately 20 mK. The higher-order terms in Eq. (2), which reflect the model details, also become appreciable in this range of fields

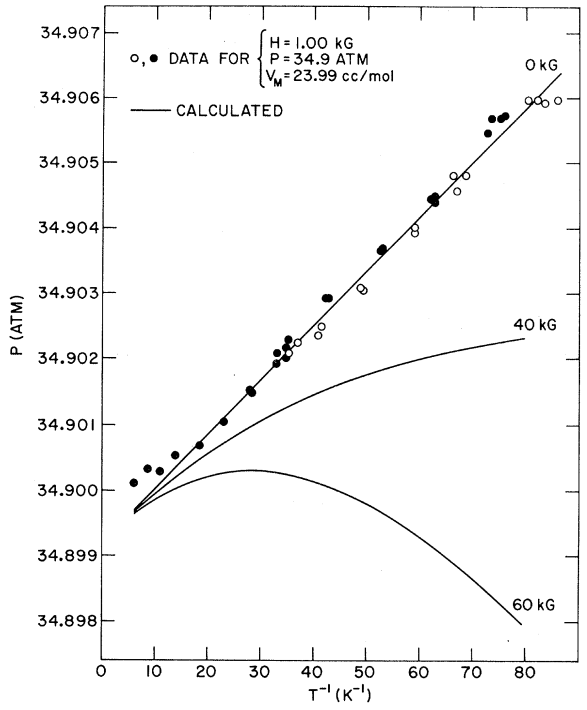

FIG. 1. $P_V(T)$ for ^{3}He at 1 kG. Open and closed circles refer to data taken on different days.

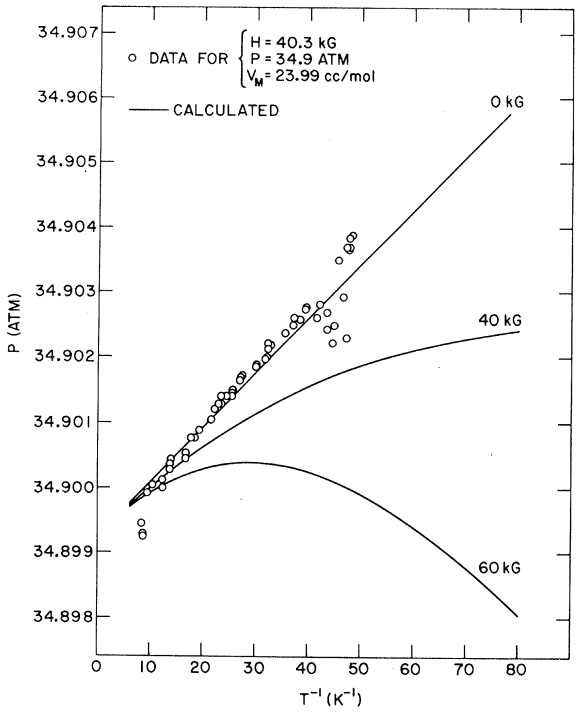

FIG. 2. $P_V(T)$ for ^{3}He at 40.3 kG.

and temperatures. Following Goldstein[6] and using the high-temperature expansion of the Heisenberg model with the nearest-neighbor interaction of Baker et al.,[7] we have calculated $P_V(T, H)$ to terms in T^{-9} for a molar volume of 24 cm^3/mole and fields of 0, 40, and 60 kG. Numerical values of the parameters Γ and $|J|$ were taken from Ref. 2 and J was assumed to be negative. The calculated curves are shown as the lines in Figs. 1-3. The lower dashed line in Fig. 3 is an evaluation of Eq. (2) at 60 kG.

The experiment was carried out in the demagnetization cryostat used previously.[3] A capacitance strain gauge was used which is like that described by Straty and Adams.[8] A sintered copper sponge occupied the upper part of the sample volume to increase thermal contact to the ^{3}He. The ^{3}He used had a ^{4}He content of less than 4 ppm. The overall precision of the pressure measurement was $\pm 0.8 \times 10^{-4}$ atm. Within these limits there was no drift with time, temperature, or field in an empty cell. For thermometry a thin slab from a nominal 10-Ω Speer resistor[9] was calibrated against NMR in copper at 1 kG. By comparison with a resistor outside of the magnet and by comparison with the melting curve above 100 mK we estimate the magnetoresistance to give us errors in the temperature of less than

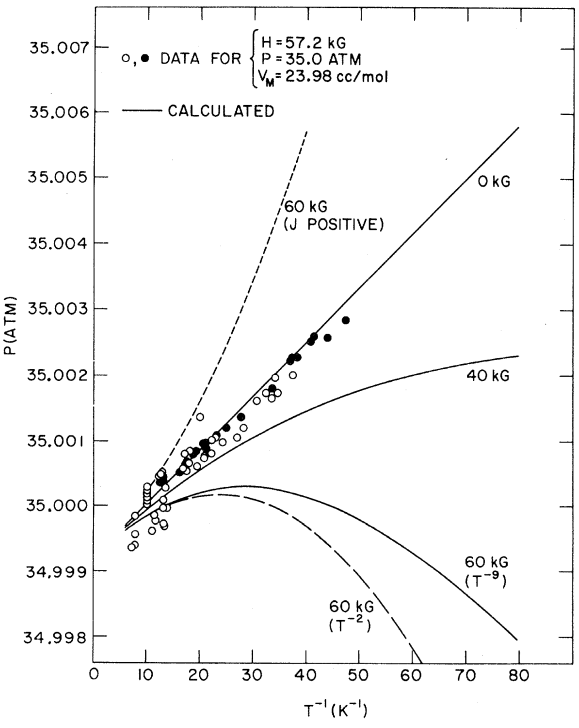

FIG. 3. $P_V(T)$ for ^{3}He at 57.2 kG. Short-dashed line, $P_V(T)$ at 60 kG calculated for positive J; long-dashed line, $P_V(T)$ at 60 kG calculated for negative J and only to order T^{-2}.

5% in 57 kG. The data as presented are not corrected for this effect.

The sample was formed by the blocked capillary method followed by annealing. We experienced some difficulty with annealing the sample which we attribute to effects resulting from the presence of the sintered sponge. We annealed for a period of several hours within 5 mK of the melting curve. In the first several minutes there was a large pressure change. This was followed by a very slow drift in pressure. Several days after annealing, abrupt changes in pressure as large as 10^{-2} atm occurred if the temperature rose above 100 mK. Pressure change did not occur at lower temperatures. Evidence of pressure disequilibrium after long annealing has been seen by the Florida group in a similar cell with many copper wires in it.[10]

Data were taken at constant field. The temperature was changed by changing the field on the cooling salt. At the lowest temperatures and highest fields about three hours were required for equilibrium between points.

If the system is in equilibrium, the data at high fields are thermodynamically inconsistent with the $P_V(T)$ and susceptibility measurements on ^{3}He at low fields. One could make our data consistent with the low-field $P_V(T)$ data by assuming that J is positive for solid ^{3}He and that in a large field the thermometer indicated temperatures lower than the sample temperature by amounts well outside our estimated error.

If one accepts the result of the susceptibility measurements that J is negative, then errors in thermometry cannot account for the discrepancy. This is because pressure changes are observed at 60 kG which are larger than the pressure change at the maximum of the calculated curve. We do not think the pressure measurements are in error because of the good agreement we obtained with the results of the Florida group in low fields, the insensitivity of the empty cell to field and temperature changes, and the reproducibility of our results upon warming and cooling over a period of several days. If J is negative the only conclusion is that the system is not in equilibrium.

Spin relaxation times as measured by NMR have been described in terms of a three-bath model.[1] In this model ^{3}He is assumed to be described by the Hamiltonian $H = H_X + H_Z + H_L + H_I$, the sum of an exchange, a Zeeman, a lattice, and an interaction Hamiltonian. H_X, H_Z, and H_L mutually commute. These three systems have independent specific heats and temperatures. The observed behavior of $P_V(T)$ in low fields depends upon equilibrium between the exchange bath and the lattice. Within this model our data at high fields can be explained only if the coupling between the Zeeman bath and the exchange bath is much weaker than the coupling from the exchange bath to the lattice.

The theory of the Zeeman-exchange relaxation time of Richardson et al.[11] is based on a dipole-dipole coupling between the exchange and Zeeman baths. If J is a scaling parameter of the exchange Hamiltonian that determines the magnitude but not the form of H_X,[12] then the Zeeman-exchange relaxation time can be written in the form $T_1/T_{10} = f(\omega/J)$, where ω is the Larmor frequency (determined by the magnetic field) and T_{10} is the zero-field relaxation time. As long as $\mu H/kT \ll 1$ and $J/kT \ll 1$, T_1/T_{10} is independent of temperature and depends only on the ratio ω/J. (For this work $J/kT < 0.03$ and $\mu H/kT < 0.2$ at the highest field and lowest temperatures.)[13] T_{10} has been determined experimentally for a 24-cm^3/mole sample and measurements of T_1/T_{10} have been made at lower molar volumes and magnetic fields where ω/J is comparable to that used in this work.[14] On the basis of this we calculate that the relaxation times should be about 20 sec at 60 kG and 10 sec at 40 kG. We observed that over a period of 13 h there was no appreciable change in the pressure from the zero-field value. From this we would place a lower limit on the relaxation time, at 40 and 57 kG, of greater than 100 h.

If this interpretation is correct and the relaxation times are long in a high field, this has important consequences for the use of solid ^{3}He as a polarized target, and for thermodynamic measurements of ^{3}He in a high field. In particular, adiabatic demagnetization of the solid in order to study the magnetic ordering would be impossible.

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[1]H. Meyer, J. Appl. Phys. 39, 390 (1968), and references therein.

[2]M. F. Panczyk, R. A. Scribner, G. C. Straty, and E. D. Adams, Phys. Rev. Lett. 19, 1102 (1967); R. A. Scribner, M. F. Panczyk, and E. D. Adams, J. Low-

Temp. Phys. 1, 313 (1969); M. F. Panczyk and E. D. Adams, Phys. Rev. 187, 321 (1969).
[3]W. P. Kirk, E. B. Osgood, and M. Garber, Phys. Rev. Lett. 23, 833 (1969); W. P. Kirk, thesis (unpublished), and BNL Report No. 14363.
[4]J. R. Sites, D. D. Osheroff, R. C. Richardson, and D. M. Lee, Phys. Rev. Lett. 23, 835 (1969); P. B. Pipes and W. M. Fairbank, Phys. Rev. Lett. 23, 520 (1969); R. T. Johnson and J. C. Wheatley, Phys. Rev. A 1, 1836 (1970); H. D. Cohen, private communication.
[5]R. A. Guyer and L. I. Zane, Phys. Rev. 188, 445 (1969), and references therein.
[6]L. Goldstein, Phys. Rev. 171, 194 (1968).
[7]G. A. Baker, H. E. Gilbert, J. Eve, and G. S. Rushbrooke, Phys. Rev. 164, 800 (1967); see also G. A. Baker, J. Eve, and G. S. Rushbrooke, Phys. Rev. B 2, 706 (1970).
[8]G. C. Straty and E. D. Adams, Rev. Sci. Instrum. 40, 1393 (1969).
[9]J. E. Robichaux, Jr., and A. C. Anderson, Rev. Sci. Instrum. 40, 1512 (1969).
[10]E. D. Adams, M. F. Panczyk, and R. A. Scribner, private communication.
[11]R. C. Richardson, A. Landesman, E. Hunt, and H. Meyer, Phys. Rev. 146, 244 (1966).
[12]This assumption of scaling could be violated if there were a next-nearest–neighbor interaction that had a different volume dependence than the nearest-neighbor exchange.
[13]This is assuming thermal equilibrium. If indeed the Zeeman bath is much warmer than the lattice and exchange baths, then $\mu H/kT$ is much smaller than this.
[14]R. C. Richardson, E. Hunt, and H. Meyer, Phys. Rev. 138, A1326 (1965).

Confinement Properties of the Levitated Spherator*

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To eliminate the anomalous loss due to convective cells produced by the existence of the supports in the plasma volume, a levitated superconducting ring was installed in the Princeton spherator. The plasma decay time is increased from 10-15 msec in the supported version to a maximum of 150-220 msec for a helium discharge plasma. At $n_e = 2 \times 10^{11}$ cm^{-3} and $T_e = 1$-2 eV, this decay time is $\frac{1}{2}$ to $\frac{1}{4}$ of the calculated density decay time due to the classical diffusion process.

Anomalous plasma loss across the magnetic fields still persists in many azimuthally symmetric multipole plasma confinement systems,[1-4] even though the magnetohydrodynamic instabilities have been successfully stabilized by the large values of shear and/or the deep magnetic wells. Previous confinement studies in a supported version of the spherator led to the hypothesis that the supports for the internal ring were causing density inhomogeneities within a magnetic surface and, consequently, producing an anomalous particle loss across the magnetic field. A theoretical description of this anomalous particle loss in terms of support-induced nonuniformities of the plasma density successfully describes the observed dependence of the confinement time on the ion mass and neutral density.[2,5] Azimuthal nonuniformities of the plasma density and of the particle loss across the magnetic field were observed experimentally.[6,7] Even when the anomalous loss due to these support-induced density nonuniformities was minimized by lowering the neutral density, the confinement times were limited by the direct loss to the supports due to the flow along the magnetic field lines.[2] Thus, the conversion of the spherator to a levitated version has been of prime interest in the effort to eliminate the convective loss as well as the direct loss to the supports.

A schematic diagram of the levitated version of the spherator is shown in Fig. 1. The magnetic field configuration is similar to that in the previous version with a supported internal ring. In addition to the steady magnetic fields of the previous version, a steady magnetic field is used to levitate the superconducting ring, and time-varying magnetic fields are used to maintain the equilibrium position of the ring. The stabilizing magnetic fields are excited asymmetrically with a magnitude depending upon the displacement of the ring, as measured by the optical sensors. At present, the stabilizing magnetic fields are excited by 3-phase, 60-cycle ac power, causing magnetic perturbations as high as 100 G (10% of the main confining field). To avoid these excessive perturbations during the experiment, a gating (blanking) period, to cut