$10^{-1}-5\times10^{-2}$ of the value estimated from the Bohm coefficient of $\frac{1}{16}kT/eB$ and is larger than the classical value by 3 orders of magnitude. The magnitude as well as the T_e dependence of the conductivity in the electron temperature range of $T_e > 1$ eV is similar to the particle diffusion coefficient as reported by Chen.[7] This indicates that the same mechanism may be responsible for the anomalous electron thermal diffusion and the particle diffusion.

In the determination of the value $K_\perp$, we simplified the equation as well as the geometrical factors. The electron energy loss due to ionizing neutral gas is neglected in Eq. (2). However, the change in electron temperature due to ionization is less than 30% during the time interval of 0.3 msec used to determine the electron thermal conductivity. The variation of plasma volume in the radial direction, $dV/d\psi$, should also be taken into account. The change of $dV/d\psi$ is less than 20% in the 2.0-cm radial extent over which the measurements were carried out, and was therefore assumed constant.

In conclusion, the electron thermal conductivity was measured by utilizing the localized upper hybrid resonance heating. The observed $K_\perp$ increases with an increase of T_e. This dependence is similar to that of the particle diffusion coefficient. The absolute value $K_\perp$ is $\frac{1}{10}-\frac{1}{20}$ of the Bohm coefficient. The success of the present approach suggests that other types of resonant heating, such as lower hybrid resonance and ion-cyclotron resonance, may be applicable to obtain electron and ion thermal conductivities in tokamak devices.

The authors wish to thank Dr. D. Meade and Dr. J. Sinnis for stimulating discussions of these results. They are also grateful to Dr. D. Jassby for his interest in their experiments.

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*Work supported by U. S. Atomic Energy Commission under Contract No. AT (11-1)-3073.

[1] D. L. Dimock, H. P. Eubank, E. Hinnov, L. C. Johnson, and E. B. Meservey, Nucl. Fusion 13, 271 (1973).

[2] L. A. Artsimovich, A. V. Glukhov, and M. P. Petrov, Pis'ma Zh. Eksp. Teor. Fiz. 11, 449 (1970) [JETP Lett. 11, 304 (1970)].

[3] See, for example, M. Okabayashi, K. Chen, and M. Porkolab, Phys. Rev. Lett. 31, 1113 (1973).

[4] J. Sinnis, M. Okabayashi, J. Schmidt, and S. Yoshikawa, Phys. Rev. Lett. 29, 1214 (1972).

[5] M. Okabayashi and R. Freeman, Phys. Fluids 15, 359 (1972).

[6] M. Okabayashi, B. Ripin, J. Schmidt, and S. Yoshikawa, to be published.

[7] K. Chen *et al.*, in *Proceedings of the Sixth European Conference on Controlled Fusion and Plasma Physics, Moscow, U.S.S.R., 1973* (U.S.S.R. Academy of Sciences, Moscow, 1973), p. 139; M. Okabayashi, Princeton Plasma Physics Laboratory Report No. MATT-1003, 1973 (unpublished).

NMR Studies of the *A* Phase of Liquid ^{3}He†

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(Received 25 February 1974)

We report measurements of the transverse and longitudinal NMR spectra of liquid ^{3}He in low magnetic fields which support the axial-state model for the liquid in the *A* phase. A quite unexpected additional result found in this work is that the width of the shifted transverse resonance line becomes extremely broad at temperatures well below *A*.

Direct evidence that the spins of the ^{3}He atoms in the *A* phase of the liquid are correlated in a most unusual way has been furnished through previous observations of a large shift in the position of the nuclear magnetic resonance line.[1] Leggett[2,3] has given a microscopic theory of the NMR behavior of the liquid in this phase in terms of a BCS-type[4] superfluid in which the atoms form Cooper pairs in a triplet spin state. He has considered several possible p-wave states of the liquid and suggests a number of phenomena that may be observed in NMR experiments under a variety of magnetic field configurations that will identify the particular state of the liquid. In this work we have performed the suggested experiments and find that *all* of Leggett's predictions are verified, in detail, for the state given by Anderson and Brinkman[5] as that which minimizes the spin-fluctuation energy of the pairs. The measurements were performed in low magnetic fields (< 75 Oe) oriented either perpendicular or parallel to the resonance coil.

The liquid ^{3}He was cooled by the technique of adiabatic compression and the temperature was monitored through measurements of the melting pressure using an apparatus similar to the one previously described.[6] The compression cell had two NMR coils embedded in the epoxy tail section, one with axis parallel and the other with axis perpendicular to the axis of the cylindrical tail. The inside of the tail was 100 mm long with a 4.8-mm diameter. Most of the data taken were with the rf field parallel to the cylindrical axis. The static magnetic field, $\boldsymbol{H}_0$, was provided by a 76-cm-diam Helmholtz coil which could be oriented in any direction. H_0 was sufficiently homogeneous to give an NMR linewidth of less than 30 Hz for the normal Fermi liquid.

Leggett[2,3] proposed that very low-frequency NMR experiments might provide a means of determining the correct state for liquid ^{3}He A. This was the principal motivation for undertaking these experiments. States thought to be appropriate to the anisotropic phase, liquid ^{3}He A, are characterized by the presence of only the spin-up and spin-down substates ($S_z = \pm 1$). A number of these states have been discussed by various authors.[2,3,5,7] Applicable unitary states include the polar, planar, and axial states. Anderson and Brinkman[5] had made the important observation that the axial state was the state that minimizes the spin fluctuation energy.

Previous experiments of Osheroff *et al.*[1] showed that for relatively high applied fields ($\omega_L{}^2 \gg \omega_0{}^2$), the frequency observed in the usual transverse NMR experiment ($\boldsymbol{H}_{\rm rf} \perp \boldsymbol{H}_0$) shifted to higher frequencies as the temperature was reduced below A according to the equation

$$\omega^2 = \omega_L{}^2 + \omega_0{}^2(T), \tag{1}$$

where $\omega_L = \gamma H_0$ corresponds to the Larmor frequency of the normal Fermi liquid. Leggett[2,3] suggested that the transverse NMR shift at lower fields and frequencies would behave differently for the various proposed states and, furthermore, he has predicted the existence of a longitudinal resonance which should be observable when the radiofrequency field is parallel to the applied steady field ($H_{\rm rf} \parallel H_0$). The frequency of the longitudinal resonance does not depend on the strength of the applied field as long as there is a field sufficiently strong to cause some polarization. This longitudinal frequency is highly dependent on the state of the A liquid, however. Among the states considered by Leggett, *only* the axial state has a transverse resonance frequency given by Eq. (1) for *all* values of the applied field *and* a longitudinal frequency given by $\omega_0(T)$.

In this work we have extended the measurements of the position of the transverse resonance line down to spectrometer frequencies as low as 60 kHz and to applied fields less than 10 G ($\omega_L/2\pi < 32$ kHz). We find no measurable deviation (within less than 2%) in the values of $\omega_0{}^2(T) = \omega^2 - \omega_L{}^2$ when we vary the field from $\omega_L/\gamma = 10$ G to $\omega_L/\gamma = 70$ G at any temperature. For the axial state, no deviation is expected. For the planar state we would have expected deviations in $\omega^2 - \omega_L{}^2$ from Eq. (2) as high as 25% at the conditions of our minimum field and frequency.

The magnitude of $\omega_0(\tau)/2\pi$ is plotted as a function of the reduced temperature $\tau \equiv (T_A - T)/T_A$ in Fig. 1. The data for the transverse resonance shown in Fig. 1 were obtained with a fixed spectrometer frequency of 130 kHz. We find the same result, within the reproducibility of our melting-pressure measurements of the temperature, for all frequencies we have studied in the range 60 to 230 kHz. In this work we have found that $\omega_0(\tau)$ is about 5% larger at all temperatures than that reported by Osheroff *et al.*[1] We attribute the difference to the increased precision in the measurements of the position of the resonance line in the current work which was performed in a much

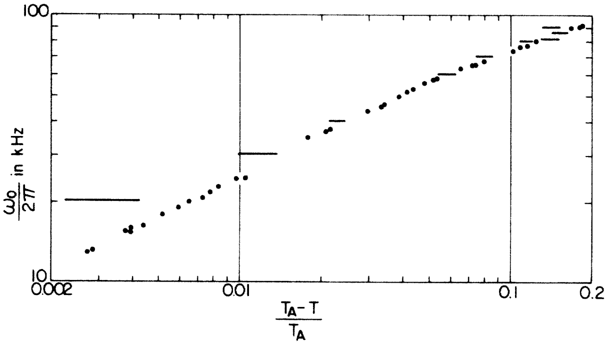

FIG. 1. Comparison of the reduced transverse resolution shift (circles) with the position of the longitudinal resonance (bars). The parameter $\omega_0(\tau)/2\pi = (2\pi)^{-1}[\omega^2 - (\gamma H_0)^2]^{1/2}$ for the transverse measurement is obtained from an experiment at 130 kHz. The width of the symbols for the longitudinal resonance corresponds to the temperature points at which the absorption signal was observed to have half of the maximum depression. The temperature scale was determined from measurements of the melting pressure.

more homogeneous field. We obtained the temperature scale from the melting-pressure measurements[8] through the relation $\tau = 1.00\times10^{-2}p + 2.1\times10^{-5}p^2$, where p is the pressure difference, in millibars, between the liquid pressure of the observation and the pressure of the A transition. The A transition was determined by a linear extrapolation of the measured field of the resonance line as a function of pressure to the pressure at which the resonance appears at the usual, unshifted, Fermi-liquid position. We occasionally observed that the resonance line was still shifted from the Fermi-liquid position at temperatures 10 μK warmer than the thermal transition registered by the discontinuity in the rate of change of the liquid pressure. The origin of this effect is not clear, but at any rate the shifts in the apparent pressure of the A transition are not significant in determining the temperature of points in Fig. 1 for $\tau > 0.05$.

Also shown in Fig. 1 are the reduced temperatures τ at which we have observed the longitudinal resonance at various frequencies from 20 to 95 kHz. Prior to our observation of the longitudinal resonance, we were notified of its existence at the frequency $\omega_0(T)$ by Osheroff.[9] The longitudinal resonance observed in our work also appears at $\omega_0(\tau)$. The amplitude of the longitudinal resonance line was comparable to that of the transverse resonance observed at the same frequency with about a 1 Oe linewidth. Considering both the position of the transverse resonance in low fields and the position of the longitudinal resonance, we conclude that the resonance lines we have observed in the A phase of ^{3}He are unambiguously described by the frequency tensor Ω^2 given by Leggett[2] for the axial state.[10]

The longitudinal resonance was detected by varying the temperature of the liquid while observing the level of "rf" at a fixed frequency with magnetic fields of various arbitrary strengths between 3 and 75 Oe applied parallel to the axis of the NMR coil. The longitudinal line observed this way appears to have an approximately Gaussian shape and is quite broad. The width of the longitudinal line at a given frequency, defined as the difference in temperature between the points where the change in the absorption signal reached half of the maximum value, is indicated by the width of the horizontal bars in Fig. 1. This temperature width of the longitudinal line does not appear to vary with the strength of applied field at these low values of field strength, but does increase as the temperature is lowered.

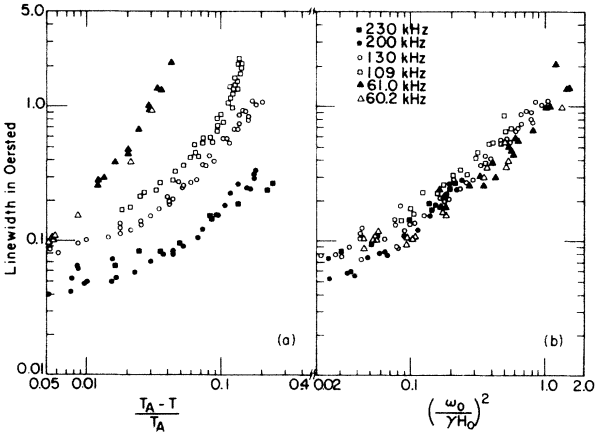

FIG. 2. (a) Width of the transverse resonance lines (at half height) as a function of reduced temperature τ for a number of different spectrometer frequencies. (b) Width plotted as a function of the parameter $[\omega_0(\tau)/\gamma H_0]^2$, where $\omega_0(\tau)$ is the frequency shown in Fig. 1 and H_0 is the applied field.

The transverse resonance width in the A phase was found to have a very large dependence upon both the applied magnetic field strength and the temperature. Values of the measured width are shown in Fig. 2(a) for several frequencies as a function of the reduced temperature τ. The lines were obtained by sweeping the applied magnetic field while holding the cell temperature constant. The linewidth is defined as the full width at half-height. Highly asymmetric lines were frequently observed, particularly at temperatures close to the A transition. The linewidths observed at a large number of different temperatures and in different magnetic fields are plotted as a function of $(\omega_0/\omega_L)^2$ in Fig. 2(b). On the basis of the apparent correlation of linewidths, when plotted this way, we make the empirical observation that the linewidth can be represented by $\Delta H_0 \approx 1.1(\omega_0/\omega_L)^2$ Oe.

The linewidth was independent of the amount of solid present in the vicinity of the coil. By controlling the thermal conditions related to the compressional colling process, the fraction of solid ^{3}He detected by the NMR coil could be varied from zero to more than 50%. None of the results reported here depended upon the amount of solid formed. Differentiating Eq. (1) leads to $\gamma^2 H_0 \Delta H_0 \cong \omega_0 \Delta\omega_0$ relating the transverse linewidth to the longitudinal linewidth, which may be influenced by thermal gradients or wall effects. The observed transverse linewidth *cannot* be easily explained in this way.

In these low magnetic fields we also found that the apparent intensity of the transverse resonance signal decreased with temperature below the A transition. The relative intensity of the absorption line was determined by measuring the area under the broadened peak and dividing by the strength of the applied field. The intensity of the absorption signal, measured in this way, decreased in the available temperature range to less than half the intensity of the normal Fermi-liquid signal at the A transition. In previous work,[1] in much larger magnetic fields, the signal intensity was not found to vary with temperature in the A phase, and measurements of the total magnetization of the liquid in the A phase[11] do not show any decrease with temperature. One might conclude that there is a missing component of the absorption spectrum that is either hidden in an extremely broadened form near the line we measure, or found at a frequency we have not investigated.

In view of the discussion by de Gennes[12] of the possible boundary effects upon the macroscopic texture of the liquid, we repeated several of the transverse linewidth measurements using the NMR coil with axis perpendicular to the tail section so that H_0 could be applied parallel to the axis of the cylinder containing the liquid. We again obtained transverse lines that were broadened by approximately the same amount as that found in the previous measurements where H_0 was perpendicular to the cylindrical boundary of the liquid.

In summary, the frequency dependence of the transverse and longitudinal resonances in liquid ^{3}He A is consistent with the expected behavior for the axial state. The observed dependence of the transverse NMR linewidth on applied magnetic field and temperature cannot be explained in terms of a simple diffusion process but may possibly be related to the intrinsic anisotropy of the energy gap in the A phase.

We are grateful to D. D. Osheroff for the communication of the results of his experiments and to W. S. Truscott for valuable discussions in the early stages of this experiment. We have been very much stimulated in this work by conversations with A. J. Leggett, P. G. de Gennes, and the members of the Cornell theory group (V. Ambegaokar, N. D. Mermin, J. Wilkins, J. Serene, H. Ebisawa, D. Rainer, and R. Combescot).

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†Work supported in part by the National Science Foundation under Grants No. GH-35692 and No. GH-38785, and also under Grant No. GH-33637 through the Cornell Materials Science Center, Report No. 2169.

*On leave of absence from DPhG/PSRM, Commissariat à l'Energie Atomique L'Orme des Merisiers, B.P. No. 2, 91190 Gif-sur-Yvette, France.

[1] D. D. Osheroff, W. J. Gully, R. C. Richardson, and D. M. Lee, Phys. Rev. Lett. 29, 920 (1972).

[2] A. J. Leggett, Phys. Rev. Lett. 31, 352 (1973).

[3] A. J. Leggett, to be published.

[4] J. Bardeen, L. N. Cooper, and J. R. Schrieffer, Phys. Rev. 108, 1175 (1957).

[5] P. W. Anderson and W. F. Brinkman, Phys. Rev. Lett. 30, 1180 (1973).

[6] D. D. Osheroff, R. C. Richardson, and D. M. Lee, Phys. Rev. Lett. 28, 885 (1972).

[7] N. D. Mermin and G. Stare, Phys. Rev. Lett. 30, 1135 (1973). See also C. M. Varma and N. R. Werthamer, Phys. Rev. A 9, 1465 (1974).

[8] W. P. Halperin, F. Rasmussen, C. N. Archie, and R. C. Richardson, to be published; the equation given is also consistent with the reduced temperature of the B transition at the melting curve reported by T. J. Greytak, R. T. Johnson, D. N. Paulson, and J. C. Wheatley, Phys. Rev. Lett. 31, 452 (1973).

[9] D. D. Osheroff, private communication; D. D. Osheroff and W. F. Brinkman, to be published

[10] This statement should not be taken as excluding other possible odd angular momentum pair states, e.g., $l \geqslant 3$ or perhaps nonunitary states with $l = 1$.

[11] D. N. Paulson, R. T. Johnson, and J. C. Wheatley, Phys. Rev. Lett. 31, 746 (1973).

[12] P. G. de Gennes, Phys. Lett. 44A, 271 (1973); V. Ambegaokar, P. G. de Gennes, and D. Rainer, to be published.