Anisotropy in Superfluid ^{3}He and the Attenuation of Zero Sound*

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The attenuation of 20-MHz zero sound in superfluid A-^{3}He has been studied as a function of angle between the sound propagation direction and an applied magnetic field, and found to be anisotropic.

Measurements of transverse and longitudinal NMR absorption[1-4] have provided compelling evidence of an anisotropic energy gap[5] for liquid A-^{3}He. In this Letter we report the direct observation of anisotropy in the bulk coefficient α of zero-sound attenuation. We conclude that an applied magnetic field promotes substantial ordering in the liquid and find that the symmetry of this order is consistent with current theoretical models[6-10] for A-^{3}He.

In the present experiments the zero sound propagated horizontally between two 20-MHz X-cut quartz transducers set 4.14 mm apart in a ^{3}He compressional-cooling cell. An external magnetic field could be applied at any orientation in the horizontal plane. Details of the experimental apparatus and techniques will be published elsewhere[11]; for the purposes of this paper they were essentially the same as in the earlier work of Lawson *et al.*[12,13] Typical transmitted pulses were 0.5 μsec wide and 15 V or less in peak-to-peak amplitude. Each first-received pulse was video detected and integrated. Linearity was checked by comparing attenuation-peak data for different transmitted-power levels. The repetition rate was typically 5 sec^{-1}. Because of improved refrigeration techniques much less solid was formed between the transducers than in the earlier experiments. This resulted not only in reproducible attenuation peaks but also in background attenuations which were only slightly affected by prolonged compressional cooling. (The attenuation just above T_A changed by only 3%, for instance, during 1.5 h of operation at lower temperatures.) Temperatures were derived from the melting-curve pressure with use of the data of Halperin *et al.*[14]

Measurements were made in magnetic fields of 0, 0.75, 1.0, 1.5, 2.0, 4.0, 7.5, and 10.0 kOe. Values chosen for the angle θ between propagation direction and applied field were 0, 54, and 90°. Previous zero-sound work was done in near-zero fields or at a fixed orientation of $\theta = 90°$.[12,13,15]

For fields of 2 kOe and greater the A_1 and A_2 components, into which the A transition splits in a magnetic field,[16] are evident in the attenuation. At the highest fields there are two, well-separated peaks.[17] By far the most striking anisotropic effect in these data is the simplicity and reproducibility of the attenuation peaks at $\theta = 0$, in contrast with the situation at $\theta = 90°$. A comparison of these two orientations at magnetic fields of 4.0 and 7.5 kOe is shown in Fig. 1.

Certain regions of the $\theta = 90°$ curves are markedly unreproducible—the A_1 peaks, for instance, and the low-temperature tails. At $H = 4$ kOe and $\theta = 90°$ [see Figs. 1(a) and 1(c)] we found a strong, repeatable, warming-cooling asymmetry in the A-transition peaks. Another new phenomenon was found at the high-temperature edge of the A_2 attenuation peak for $\theta = 90°$. Observed at all fields ≥ 2 kOe, this new feature is a narrow ($\lesssim 3$ μK), reproducible *oscillation* of attenuation with temperature, about 0.5 cm^{-1} in maximum amplitude (see inset in Fig. 1). In addition there were previously observed phenomena such as fluctuations in α with characteristic periods of order 10 sec and large transient effects accompanying compression-rate changes.[13] The fluctuations persisted at temperatures well below T_{A_2}. *None of these effects—fluctuations, transients, nonreproducible regions, asymmetries, or the A_2 oscillation—were seen for $\theta = 0$.*

At fields of 2 kOe and less both the A and the B transitions could be observed. Supercooling in the A liquid allowed us to compare attenuations in the two superfluid phases over a common temperature interval. We observed small

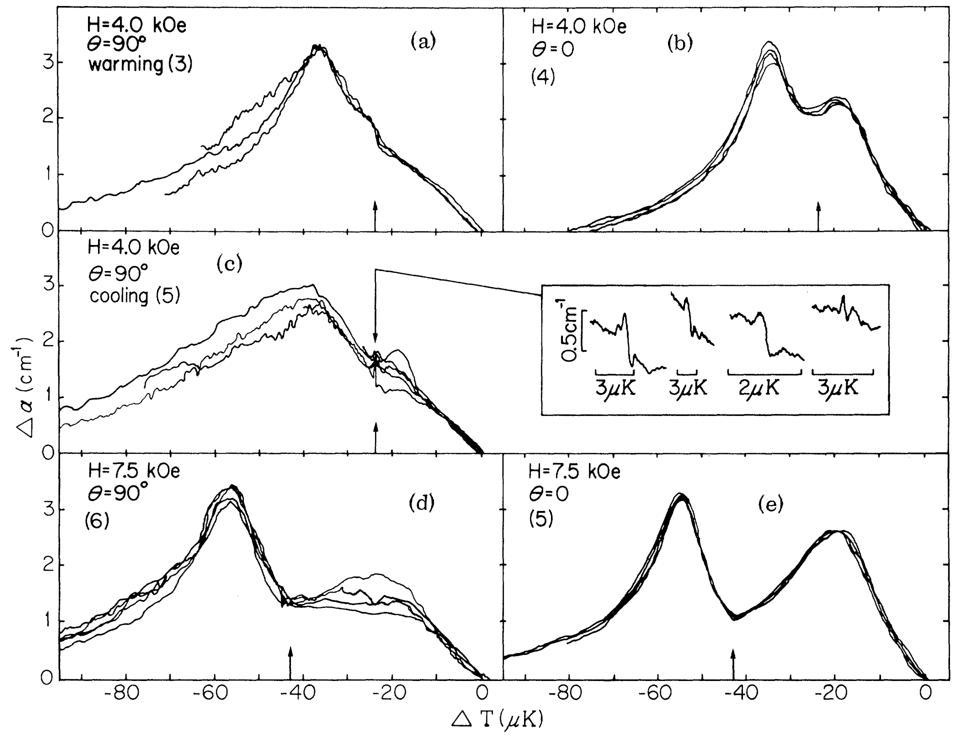

FIG. 1. A-transition attenuation peaks for various magnetic field strengths and orientations. $\Delta\alpha = \alpha - \alpha(T_{A_1})$; $\Delta T = T - T_{A_1}$. The number of experimental curves included is shown in parentheses for each case; the ΔT corresponding to T_{A_2} is indicated by an arrow. Except for (a) and (c), each plot includes data taken both while warming and while cooling. The inset shows in more detail, from the $H=4$ kOe raw data, some examples of the A_2 "oscillation." $T_{A_1} \simeq 2.8$ mK; $\alpha(T_{A_1}) \simeq 2$ cm^{-1}.

steps in zero-sound attenuation at the B transition consistent with the previously observed[13] weaker temperature dependence of the attenuation in the lower-temperature phase. These abrupt changes in attenuation by amounts of order 0.1 cm^{-1} also provide indications of anisotropy in the A phase well below the A transition. At $\theta = 90°$ we find that the magnitude of the attenuation increase on warming through the B transition may differ by more than a factor of 2 from that of the previous transition on cooling at the same temperature. Cooling-transition signatures, however, agree quite well with the immediately preceding transition on warming. Even though the size of the steps may change each time the A phase is formed, the attenuation always drops to the same value upon returning to the B phase. Thus for $\theta = 90°$ the A-phase attenuation is preparation dependent, even at temperatures near the B transition. For the $\theta = 0$ orientation the B-transition attenuation steps are reproducible at constant temperature and show no dependence on preparation. The absence of any attenuation peak at B in the present case—with the A-B liquid interface parallel to the propagation direction—supports the interface-scattering interpretation given to the peaks observed earlier for vertical propagation of zero sound.[12,13]

In Fig. 2 we present some examples from the A-transition attenuation data at low fields. The anisotropy is shown for $H = 750$ Oe. Even in this low field the $\theta = 0$ peaks are substantially more reproducible than those at 54 or 90°. Notice also the difference in the relative heights for the three orientations at the attenuation peak itself and on its low-temperature shoulder. These narrow peaks are typical of data obtained under "good" compressional-cooling conditions (low starting temperatures, smooth compression curves). A quite different "broad" peak shape was seen on some runs, accompanied by evidence of substantial thermodynamic disturbance in the cell. These broad peaks were highly reproducible and showed no evidence of anisotropy (see the $H = 1$ kOe examples in Fig. 2). In rare instances we obtained conditions intermediate to

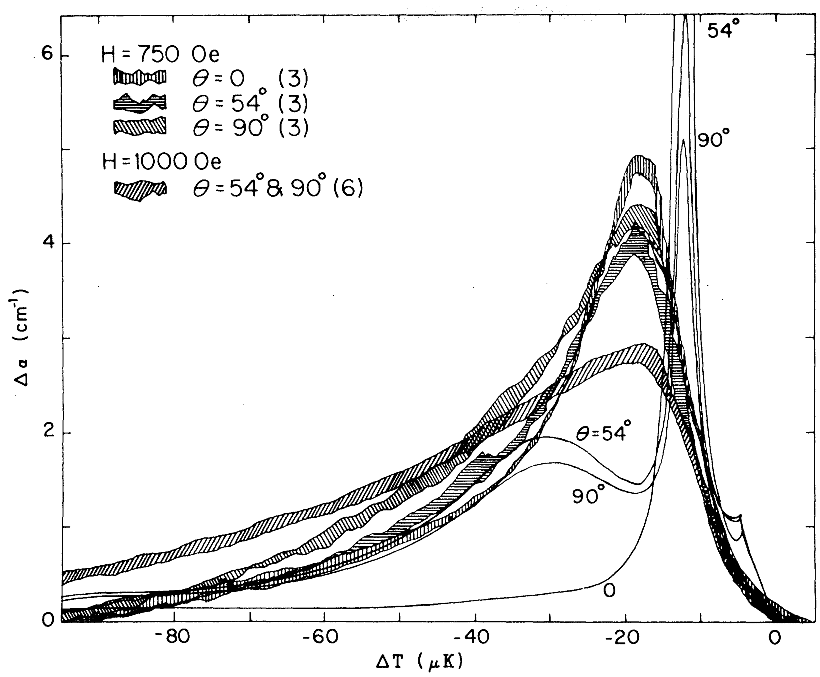

FIG. 2. A-transition attenuation peaks at low field, normalized as in Fig. 1. Each of the shaded bands indicates the range of values for a particular orientation. The number of experimental curves represented by each band is noted in parentheses. The 750-Oe peaks are typical of the "narrow" data discussed in the text; a collection of 1-kOe "broad" peaks is included for comparison. The solid lines are results of theoretical calculations described in the text; the peak of the truncated $\theta = 0$ curve lies at $\alpha = 11.5\ \mathrm{cm}^{-1}$.

the typical cases of broad and narrow peaks and in one of these runs we observed a marked, repeatable, warming-cooling asymmetry. These observations are probably related to the large difference in the earlier, $\theta = 90°$ experiments[13] between the limited data at zero field and those for $H \geqslant 1$ kOe.

The most obvious symmetry suggested by the simplification we have seen in the data for $\theta = 0$ is that the liquid is characterized by a direction in space, $\hat{l}$, which may vary from point to point within the liquid and which tends to be oriented perpendicular to any applied magnetic field. The attenuation is a function of the angle φ between $\hat{l}$ and the direction of zero-sound propagation. Thus, while an experiment in general sees some distribution of angles φ, for the special case $\theta = 0$ all $\hat{l}$ tend to be at $\varphi = 90°$. In view of this symmetry the fluctuations in the attenuation could be described as fluctuations in the distribution of φ, perhaps due to orbital-wave excitations as suggested by Anderson.[18] Other phenomena seen in these experiments, such as preparation effects and the nonreproducible regions of the A attenuation peaks, are suggestive of the liquid-crystal-like textures discussed by de Gennes.[19]

Figure 2 includes theoretical curves calculated for our three values of θ and our frequency, with use of the attenuation obtained by Serene[10] for the $L = 1$ axial state. The attenuation is a function of the angle between the propagation direction and the symmetry axis of the energy gap. The theory includes no dependence on the magnitude of H and we have not included the A_1-A_2 splitting (5.7 μK/kOe). We have assumed that the pair $\vec{l}$ vectors (directed along the gap axis) are *equally* distributed among all orientations in the plane perpendicular to the applied field. While this rather unlikely distribution does not yield an accurate description of our data, the three qualitative features of the calculated attenuations—the cusp within 5 μK of the high-temperature edge, the narrow peak, and the highly anisotropic contribution at still lower temperatures—are at least consistent with our observations. The experimental peak and its low-temperature shoulder in the vicinity of the expected maximum anisotropic contribution change quite differently as functions of θ. At low fields the region of the expected cusp also contains the A_1-A_2 splitting, but such a feature has been resolved on some of our separated peaks at high fields.

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Excitation of Lower-Hybrid Waves by a Slow-Wave Structure*

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We report the excitation of lower-hybrid waves by a multiple-ring slow-wave structure (four waves, $\lambda = 23$ cm) in a magnetized plasma. Wavelengths measured parallel and perpendicular to the magnetic field were in agreement with the theoretical dispersion relation. The waves propagated in a packet defined by the axial length of the slow-wave structure.

The feasibility of heating magnetically confined plasmas to thermonuclear temperatures by high-power radiofrequency sources with frequencies ω, near the lower-hybrid frequency ω_{LH}, has been investigated actively in recent years. In particular, it has been shown theoretically that an appropriately polarized electromagnetic wave launched near the surface of the plasma would propagate toward the lower-hybrid resonance layer as a quasielectrostatic cold-plasma wave.[1] This wave would convert near the layer into a short-wavelength ion plasma wave which would then propagate radially outward and would be readily absorbed, heating the plasma. Alternatively, the incoming wave could parametrically decay into short-wavelength hot-plasma waves and be absorbed.[2] To achieve these goals, two criteria must be met: (a) For wave penetration through the plasma surface without significant reflection (accessibility) we require a slow wave, $\omega/k_z < c$ (here $k_z = \vec{k}\cdot\vec{B}/B$ is the wave vector component parallel to the confining field $\vec{B} = B\hat{z}$ and c is the velocity of light).[3,4] (b) For heating large volumes of plasma, the incoming wave front in the z direction must be large.[2,5] These two criteria can be satisfied using either a finite-length slow-wave structure or a wave-guide array. In addition, because the cold-plasma-wave