Superfluid ^{3}He in Strong Magnetic Fields: Anomalous Sound Attenuation in the *B* Phase and Evidence for Splitting of the *AB* Transition

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(Received 10 October 1989)

Zero sound attenuation at 8.9 and 26.8 MHz in ^{3}He-*B* shows an extremum at T_{AB} in a field of ~ 2 kG at low pressures, both in the stationary and in the rotating superfluid. This is in accordance with the prediction that a critical magnetic field separates two types of *B* phases at the *AB* transition line, with and without nodes in the energy gap, respectively, and with a change in the nature of the transition. The *AB* phase transition takes place via an intermediate state, possibly a new phase, characterized by excess sound attenuation.

PACS numbers: 67.50.Fi, 64.70.Ja

The transition between the topologically different *A* and *B* phases of superfluid ^{3}He is a matter of considerable interest at present.[1-4] In zero magnetic field, ^{3}He-*A* is stabilized by the strong-coupling effects only at high pressures, and the *AB* transition is of first order. In a nonzero field, the *A* phase exists at all pressures as a consequence of a susceptibility difference between ^{3}He-*A* and ^{3}He-*B*. The *A* phase is known to be in the axial state,[5] with two nodes in the energy gap. The isotropic energy gap of the *B* phase is distorted by the magnetic field; this makes the nature of the *AB* transition more complex.

In this Letter, we present zero sound attenuation measurements in the vicinity of the *AB* transition in magnetic fields up to 3.5 kG and at pressures below 9.3 bars. We have performed experiments in both stationary and rotating ^{3}He. We have found a critical magnetic field of ~ 2 kG in ^{3}He-*B*, characterized by a rapid change in sound attenuation. Our observation is in agreement with calculations of Ashida and Nagai[6] (hereafter AN) about the structure of the order parameter in the *B* phase and on the nature of the transition in strong fields. In addition, we have quite surprisingly found a region with excess sound attenuation at the *AB* phase transition, possibly indicating the existence of a new intermediate phase.

Approximate free-energy calculations by Cross[7] suggest that the *AB* interface consists of the planar phase,[5] while Kaul and Kleinert[8] claim that a linear combination of ^{3}He-*A* and ^{3}He-*B* would be preferable. More recently, Schopohl[3] and Salomaa[4] have found several possibilities for the structure of the *AB* interface, with a continuous deformation of ^{3}He-*A* into ^{3}He-*B* via an axiplanar phase[5] sheet, only a few coherence lengths thick. The possibility of the *AB* transition taking place via an intermediate phase has also been considered in the weak-coupling limit.[9] AN propose the planar phase as an alternative to the axial phase at low pressures. Furthermore, they predict that the nature of the *AB* transition changes from second to first order at a critical magnetic field H_c; below H_c, the energy gap Δ of the *B* phase is continuously deformed: Δ is almost isotropic at $T=0$, but *A*-phase-like with two nodes at T_{AB}. Above H_c, according to AN, the change is discontinuous, and the transition is of first order.

Experimental data about the *AB* transition in high magnetic fields and on the structure of the *AB* interface are very limited. Feder[10] and Hoyt, Scholz, and Edwards[11] have measured the susceptibility jump at the *AB* transition in magnetic fields up to 2.5 kG. The scatter in their data, however, makes it difficult to draw any firm conclusions about the possible change in the order of the transition. Meisel[12] observed, in his acoustic impedance measurements, a double-step structure below 15 bars and oscillations at the *AB* transition under higher pressures up to 23 bars. The field-independent width of these anomalies was a few μK at 38 MHz. Meisel concludes these to be surface effects, because no sign of them was seen in sound transmission experiments.

Our measurements are done in the ROTA-2 cryostat described elsewhere;[13] we use a pulsed sound transmission technique. Our experimental cell has two *X*-cut quartz crystals, 4 mm apart. The diameter of the cylindrical ^{3}He volume is 6 mm and the superfluid in the cell is in liquid contact with the main ^{3}He volume through several 1×1-mm^2 square holes at both ends of the quartz spacer. Sound pulses at $f=8.9$ and 26.8 MHz frequencies are used. A persisted superconducting solenoid outside the sound cell provides a magnetic field H up to 3.5 kG with an inhomogeneity less than 10^{-3}. In addition, an axially oriented linear field gradient, up to 200 G/mm, can be applied. In our geometry, $\mathbf{H}$ is always parallel to the sound propagation direction $\mathbf{q}$ and the rotation axis $\mathbf{\Omega}$. A standard pulsed platinum NMR thermometer is used for temperature measurements.

The magnetic-field dependence of the zero sound attenuation α in ^{3}He-*B* is presented in Fig. 1, just below the *AB* transition. Data taken at both 8.9 and 26.8 MHz show a clear anomaly in α at $H_c \approx 2$ kG, almost independently of the pressure *P*. At 8.9 MHz, the cusp is most prominent when $P=0$. A simple qualitative ex-

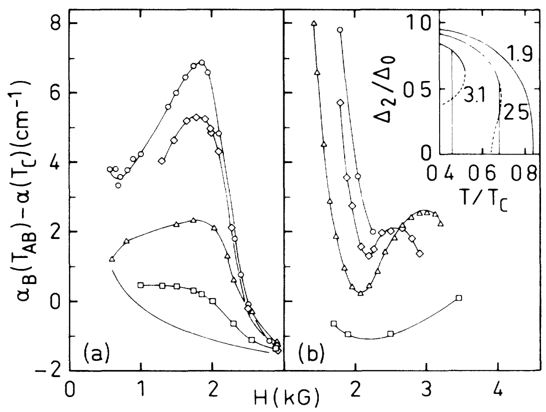

FIG. 1. Sound attenuation α vs the magnetic field H in ^{3}He-B at T_{AB}. Circles correspond to $P=0$, diamonds to $P=0.5$ bars, triangles to $P=2.3$ bars, and squares to $P=6.6$ bars. The lines connecting the data points are just for guiding the eye. (a) $f=8.9$ MHz. The lowest curve shows α measured at $H=0$ as a function of $T_{AB}(H)$. (b) $f=26.8$ MHz. Inset: The minimum energy gap Δ_2, normalized by the $T=0$ gap Δ_0, as a function of the reduced temperature for $H=1.9$, 2.5, and 3.1 kG, according to calculations by AN (Ref. 6). The vertical lines show the positions of the first-order AB transitions.

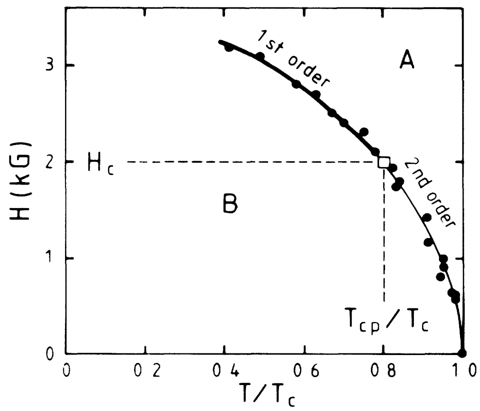

FIG. 2. The measured AB transition line in the H-T plane at $P=0$. The square represents the critical point (T_{cp},H_c). The solid line is a least-squares fit to the data. The proposed order of the transition below and above H_c is also shown.

planation for the drop in α above H_c can be given by using the theory of AN. Below H_c, the energy-gap minimum Δ_2 in the direction of **H** and **q** vanishes at the transition, which leads to high attenuation owing to pair breaking at all temperatures. Above H_c, Δ_2 increases with the field ($\Delta_2 \gg hf$), and α decreases. In other words, increasing the magnetic field in the vicinity of H_c increases Δ_2 rapidly so that it meets the requirement for pair breaking $hf=2\Delta_2$ and the conditions for other possible collective modes ($hf \sim \Delta_2$) at about H_c. The nonvanishing width of this peak is characteristic to all collective modes in ^{3}He and it is mainly due to quasiparticle collisions.[14] Unfortunately, the lack of predictions for sound attenuation in the field-distorted ^{3}He-B prevents us from making quantitative analyses of our data.

At 26.8 MHz, α has a minimum at $H_c \approx 2$ kG [see Fig. 1(b)]. The steep rise of α with decreasing field is caused by the proximity of the squashing mode.[15] The maximum at $H \approx 2.5$–3 kG is probably a manifestation of the pair-breaking edge at $hf=2\Delta_2$; this condition is met at $\Delta_2/\Delta_0 \approx 0.4$, where Δ_0 is the energy gap of the B phase at $T=0$ [see the inset of Fig. 1(b)].

The location of the critical point on the measured AB transition line is shown in Fig. 2, and it is found to be in good agreement with theoretical estimates. Using the values $F_0^a=-0.75$ and $T_c=1.0$ mK, where F_0^a is the Landau parameter, AN obtained $H_c=2.04$ kG and $T_{cp}/T_c=0.80$, where $T_{cp}=T_{AB}(H=H_c)$. Greywall's data[16] at zero pressure, $F_0^a=-0.70$ and $T_c=0.93$ mK, yielded $H_c \approx 2.3$ kG, which is somewhat more than our experimental value. The agreement becomes worse at higher pressures, which may indicate the importance of strong-coupling corrections.

We have also studied the response of ^{3}He-B to rotation in a magnetic field, using the sound frequency of 8.9 MHz. Superflow $\mathbf{v}_s$ tries to turn the anisotropy axis of the energy gap $\hat{\mathbf{h}}=\tilde{R}\mathbf{H}/H$, where $\tilde{R}$ is the rotation matrix of the order parameter, parallel to itself and away from the direction of **H** and **q**. We thus expect α to be reduced with increasing rotation speed, as Δ in the direction of **q** increases.

When rotation is started, a sharp extremum in α first appears, which then relaxes towards an equilibrium shift $\Delta\alpha$, indicating the formation of a vortex lattice. The peak can be identified with a vortex-free state, in which the average velocity of superflow is larger than in the vortex state, resulting in a higher change of attenuation. In Fig. 3, $\Delta\alpha$ in ^{3}He-B at $P=6.6$ bars is shown just below T_{AB}, as a function of the magnetic field. Again, a change is observed at $H_c \approx 2$ kG. Below H_c, α is seen to decrease with increasing Ω. Above ~ 2.4 kG, however, attenuation increases with rotation.

The general form of α for ^{3}He-B in a magnetic field is

$$\alpha(\theta)=\alpha_\parallel \cos^4\theta + 2\alpha_c \cos^2\theta \sin^2\theta + \alpha_\perp \sin^4\theta ,$$

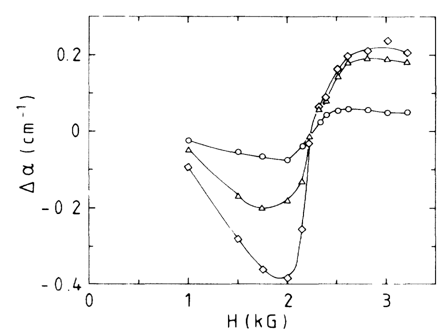

FIG. 3. Field dependence of $\Delta\alpha$, the rotation-induced shift of sound attenuation in ^{3}He-B, just below T_{AB} at $P=6.6$ bars. Circles correspond to $\Omega=1.0$ rad/s, triangles to $\Omega=2.0$ rad/s, and diamonds to $\Omega=3.0$ rad/s.

where θ is the angle between $\hat{\mathbf{h}}$ and $\hat{\mathbf{q}}$. At small θ, the change in α due to rotation is approximately

$$\Delta\alpha \equiv \alpha(\Omega) - \alpha(0) \approx 2(\alpha_c - \alpha_\parallel)\langle \sin^2\theta \rangle_{\text{cell}} ;$$

i.e., a sign difference in the behavior of $\alpha_\parallel$ and $\Delta\alpha$ is to be expected, assuming that $\alpha_\parallel$ is dominant over α_c. This is exactly what we observe [cf. Figs. 1(a) and 3], in support of our simple model.

As the temperature is allowed to drift slowly through T_{AB}, an intermediate regime with α higher than either in ^{3}He-A or in ^{3}He-B appears (see Fig. 4). A linear magnetic-field gradient of ~ 10 G/mm is enough to suppress completely the increased attenuation during the transition.

Under most of our experimental conditions, α changes reproducibly during the $B \rightarrow A$ transition (see Fig. 4). Following a jump, three linear consecutive sections appear, after which a small bump is often observed. Finally, the attenuation level of the bulk A phase is reached. Data have been taken at $P = 0$, 0.6, 1.1, 2.3, 3.1, and 9.3 bars, using frequencies $f = 8.9$ and 26.8 MHz. The $A \rightarrow B$ transition is too abrupt for resolving details (see the high peak in Fig. 4).

We explain our data as evidence for an intermediate phase between ^{3}He-B and ^{3}He-A; we call it the I phase. This interpretation is supported by the presence of sharp corners and linear parts in the attenuation curve (see the $B \rightarrow A$ transition in Fig. 4), which would be difficult to understand if the observed effect were due to textural changes at the phase boundary. Neither would an irregular nucleation of the A phase be likely to result in the observed behavior, because in ^{3}He-A the $\hat{\mathbf{l}}$ vector, which determines α, always orients itself perpendicular to H, independently of the inclination of the phase boundary.[17] If the increased attenuation were due to vanishing Δ_2 in

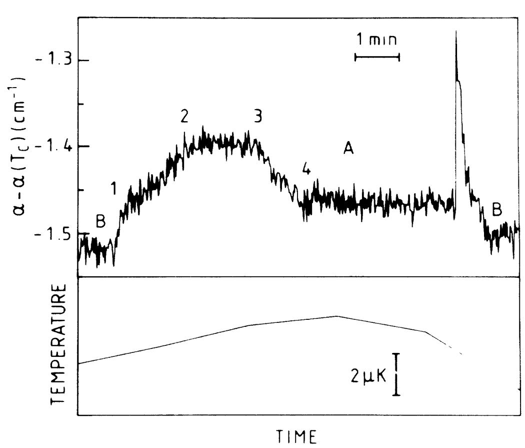

FIG. 4. Anomalous zero sound propagation at the AB transition. α at the $B \rightarrow A$ and $A \rightarrow B$ transitions is shown when $P = 2.3$ bars, $T/T_c = 0.56$, and $H = 3.4$ kG. Approximate temperature, measured by the Pt-NMR thermometer, is also shown. For further explanations, see text.

^{3}He-B, the attenuation would increase smoothly, like in Fig. 1, without any kinks.

The attenuation data can now be understood as follows (see Fig. 4): At the outset, α increases abruptly. This can be understood as the sudden appearance of the B-I phase front in the cell, after a slight superheating caused by surface tension resisting the formation of the interface. In region 1-2, the B-I boundary propagates over some length; the attenuation increases linearly as the phase proportions change. At 2, the interface between the I and A phases appears in the cell, and in region 2-3, the I phase moves through the experimental volume, until at 3 the B-I boundary reaches the far end of the cell. In region 3-4, the I-phase portion decreases, and finally at 4 only the A phase exists.

The increased attenuation in the I state can be due to the anisotropic energy gap, discussed already in context with the B-phase attenuation. The usual axial state has nodes in the gap perpendicular to $\mathbf{q}$, and the B-phase gap is relatively isotropic (see the inset of Fig. 1) in this temperature region thus showing low attenuation. However, any axiplanar state with nodes at inclined angles with respect to $\mathbf{q}$ would probably show higher attenuation.

The transition region widens with increasing magnetic field, covering about 2 μK at $H = 3$ kG, independent of pressure if a constant warm-up rate is assumed. The time for crossing the I-phase region was found to scale linearly with the warm-up rate from 7 to 100 nK/s, confirming that we are not dealing with a transient state. We can calculate the velocity of the phase boundary by taking into account the inhomogeneity of H in the cell, the H^2 dependence of T_{AB}, and the warm-up rate of the sample. We then obtain $v_{AB} \approx 1$ mm/min, which is in good agreement with our measurements. On the other hand, if we neglect the effect of the field gradient and estimate the velocity solely from the approximate temperature gradient across the cell, we find a value which is almost 4 orders of magnitude too high.

The bump often seen at the end of the $B \rightarrow A$ transition sequence (in Fig. 4 after point 4) may originate from an orbital relaxation process in the newly formed A phase. The fact that the warm-up rate through the transition does not seem to correlate with the duration of the bump supports our suggestion that it really is a relaxation effect. Unfortunately, the orbital relaxation rate has been measured only at high pressures.[18] Additionally, at $P = 0$ and at the lowest temperatures, $T/T_c \lesssim 0.4$, where the reentrant normal-flapping mode[15] in the A phase is near, the $B \rightarrow A$ transition is masked by an irreproducible relaxation.

Our results on the splitting of the $B \rightarrow A$ transition, if interpreted by the existence of an intermediate superfluid phase, apparently contradict the newest theories[3,4] about the structure of the phase boundary. An interface less than 10 coherence lengths (< 0.5 μm) thick seems unable to give rise to the observed attenuation increase of

$\sim 0.1\ \mathrm{cm}^{-1}$ in the intermediate state. However, these estimates have been made in zero magnetic field, and the length scales may change in the high-field regime.[4] So far, no definite calculations exist.

To conclude, anomalies of sound attenuation in strong magnetic fields indicate a change in the topology of the B-phase energy gap in the vicinity of the AB transition. Data in rotating ^{3}He support this interpretation as well. An unexpected additional attenuation at the $B \rightarrow A$ transition has been observed, suggesting the presence of an intermediate superfluid state.

We wish to thank A. Balatsky, I. Fomin, O. V. Lounasmaa, V. Mineev, R. Salmelin, M. Salomaa, E. Thuneberg, and G. Volovik for their contributions. We are grateful to A. Babkin, M. Laitinen, and J-P. Kneib for assisting in the experiments. This work was supported by the Academy of Finland, by the U.S.S.R. Academy of Sciences through project ROTA, and by the Körber-Stiftung and Hamburg. Scholarships from the Magnus Ehrnrooth Foundation (J.M.K.) and from the Emil Aaltonen Foundation (A.J.M.) are gratefully acknowledged.

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