Distortion of Superfluid ^{3}He-B as a Function of Magnetic Field and the First-Order Transition to ^{3}He-A at the $T=0$ Limit

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We have observed the distortion of the gap and associated excitation spectrum in superfluid ^{3}He-B with increasing magnetic field up to the first-order transition to the A phase at a temperature of T_c/T of about 7 (≤ 140 μK at $P=0$). The pair-breaking critical velocity of a vibrating-wire resonator is monitored as a function of field. By plotting the critical velocity we can follow changes in the B-phase excitation spectrum with increasing magnetic field, which are in excellent agreement with the calculations of Ashida and Nagai. The sudden transition to the A phase at the critical field is clearly seen.

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Superfluid ^{3}He exists in several forms depending on the structure of the order parameter. The two predominant phases are the A phase with axial nodes in the gap and the B phase with an isotropic gap. In the very-low-temperature region the dissimilar gap configurations of these two phases mean that the thermal and transport properties are likely to be very different, since the nodes in the A-phase gap lead to a high thermal population of quasiparticles whereas the B phase has virtually none. At low pressures and low temperatures the stable phase is the B phase. However, as a consequence of the higher susceptibility of the A phase, the free-energy difference between the phases can be reduced by the application of a magnetic field. At a field of order 0.5 T the A phase is stabilized over the whole superfluid region of the phase diagram.

As a magnetic field is applied to the B phase the isotropy of the gap is lifted. The gap component parallel to the field, $\Delta_\parallel$, falls and the perpendicular component, $\Delta_\perp$, increases. At high temperatures the distortion is followed by a second-order transition to the A phase. However, at low temperatures the transition to the A phase becomes first order. The distortion of the gap is accompanied by a spin splitting of the excitation spectrum according to the k-vector component in the field direction and this will also influence the pair-breaking critical velocity in the field direction. This behavior has been discussed by Schopohl [1] and by Ashida and Nagai [2], and a preliminary mapping of the transition has been made by Kyynäräinen *et al.* [3].

In the present paper we report a very direct observation of the first-order transition and the distortion of the B phase leading up to it as the field is increased on a sample of superfluid at $T_c/T \approx 7$. This is essentially the $T=0$ limit, since at this temperature the gaps have reached their zero-temperature values. The transition is monitored by the response of a vibrating-wire resonator in the liquid. Wire resonators are sensitive to the gap, since the impedance offered by the liquid increases suddenly when the critical velocity for pair breaking is reached. The response of such a resonator can therefore be used to follow the effect of an increasing field on the gap and the associated excitation spectrum.

The experimental cell is shown in Fig. 1. The ^{3}He sample in the inner cell is cooled by slabs of copper, coated with sintered silver, immersed in the liquid. The outer cell, filled with deformed copper flakes and ^{3}He, acts as a thermal guard. The A phase is stabilized in the lower extension, which is surrounded by a small solenoid able to provide a vertical local field of up to 1 T. This configuration can stabilize the A phase in the lower part of the extension and the B phase in the upper part separated by a phase interface which can be moved vertically by adjustment of the field. In a typical experiment, the cell is

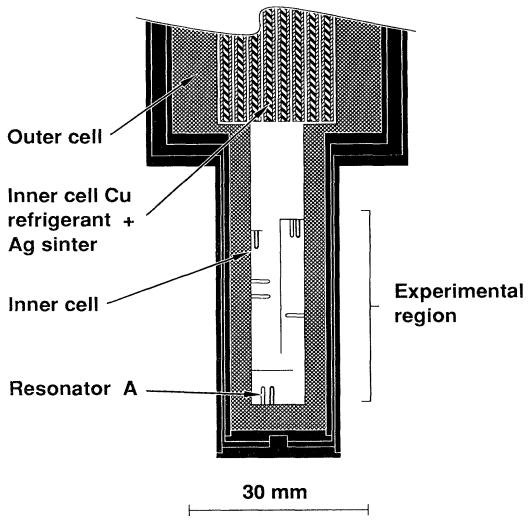

FIG. 1. The experimental cell. The outer cell which acts as a guard and remains at around 700 μK is filled with deformed copper flakes and liquid ^{3}He. The A phase is stabilized in the projection at the bottom of the cell and is exposed to the field of a small solenoid held at still temperature. The vibrating-wire resonator used in the experiment is indicated. The various subdivisions of the experimental region are intended for other measurements.

precooled to 7 or 8 mK in a 6.5-T field supplied by the large external demagnetization solenoid. The cell is then demagnetized to around 50 mT which allows the A phase, at 0 bar, to cool in the local field to around 140 μK or below.

The experimental volume is furnished with a number of heaters and vibrating-wire resonators. The resonator used in the present work follows our usual pattern [4]. A superconducting filament of NbTi wire with diameter of ≈ 13 μm is bowed into an approximate semicircle with diameter 3 mm. The mechanical "flapping" resonance of the loop is excited by the Lorentz force arising from the action of the steady magnetic field on an ac current at the resonant frequency passed around the loop. The velocity is sensed by a measurement of the ac voltage generated across the loop as a consequence of the transverse motion in the field. The drive current is supplied by a frequency synthesizer and the output voltage monitored by a lock-in amplifier under desktop-computer control. The resonator is mounted vertically and therefore moves in a direction perpendicular to the field.

To make a series of measurements we proceed as follows. The applied magnetic field is set to a low value. The driving current is set at a fixed frequency close to resonance (which unfortunately varies with B). The voltage response is then recorded as the driving current amplitude is incremented from zero by small steps to yield a single force-voltage curve from zero velocity to beyond the onset of pair breaking. The applied magnetic field is then increased and the procedure repeated to generate a family of force-voltage curves as a function of applied magnetic field.

To measure the point at which pair breaking begins we need to know the maximum velocity of the resonator. This quantity is extracted from the output voltage by the procedure used earlier [5]. The rms voltage output of the resonator is converted to velocity by division by the product of field and leg spacing. The result is multiplied by $\sqrt{2}$ to give the temporal maximum, and by a factor of 1.27 which is an estimate of the ratio of the maximum transverse velocity of the resonator (i.e., at the top of the semicircle) to the mean velocity. Since this factor depends on the precise geometry of the resonator it adds an uncertainty of order 5%. From this procedure we obtain a series of force-velocity curves.

The magnetic field at the site of the resonator represents the sum of the demagnetizing solenoid field and the local solenoid field. This is not easy to calculate precisely since the local field is a rapidly changing function of position and the exact relative position of the resonator and solenoid is uncertain to a few millimeters. Fortunately, the *relative* magnitude of the field is known to high precision from the resonator response itself. The force on the resonator, per unit drive current, is proportional to the ambient field B. The output voltage, per unit velocity, is also proportional to B. The product of height times half-width for the resonance is thus proportional to B^2.

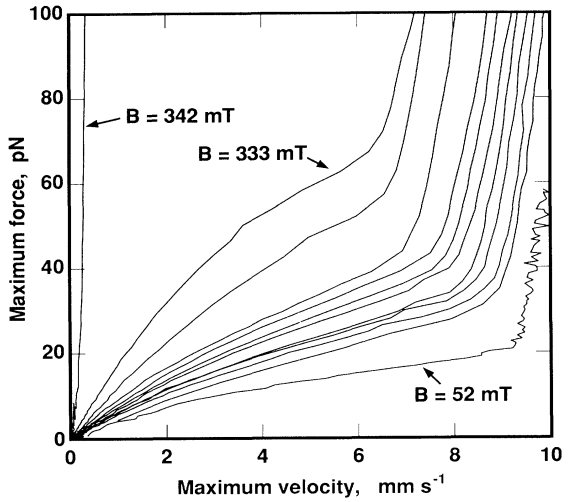

FIG. 2. A family of force-velocity curves at $P=0$ taken as discussed in the text as a function of applied field from 52 to 342 mT. The sudden bend in the curve represents the onset of pair breaking and depends on the minimum excitation energy which is accessible to the quasiparticles produced. The critical velocity for pair breaking is clearly seen to fall with increasing field in the B phase. Between the fields of 333 and 342 mT the discontinuous jump to the A phase is very clear. The noise on the 52-mT trace arises from a poorer sensitivity of the resonator at the lower fields and the fact that the measuring points were more closely spaced in drive level.

This quantity is monitored, and for conversion to absolute field a single calibration constant only is required. The field at the B-to-A transition at $P=0$, $T\approx 0$ provides a well-defined standard. To scale our fields we have assumed a value of 340 mT for this point to agree with the extrapolation of the data of Kyynäräinen *et al.* [3] and Tang *et al.* [6]. This value lies within our own uncertain *a priori* estimate of 305 mT $\pm$ 15%.

A series of force-velocity curves collected in this way at 0 bar for a range of fields is shown in Fig. 2. At low fields, the low-velocity, low-resistance region is very clear. (The curvature of the traces is an inherent effect of the damping by a quasiparticle gas at low temperatures; see Fisher *et al.* [7].) The sudden increase in slope represents the point where pair breaking begins and the resistance increases rapidly. Following the curves, we see that the critical velocity falls with increasing field, until suddenly at around 340 mT the signature changes completely; the sample passes through the first-order transition to the A phase and the finite-critical-velocity behavior disappears discontinuously.

We extract a value for the critical velocity from the force-velocity curve by identifying it as the intersection of straight lines fitted to the regions immediately above and below the pair-breaking edge. A graph of this critical velocity versus magnetic field at $P=0$ is shown in Fig. 3.

Before discussing the data we need to consider what

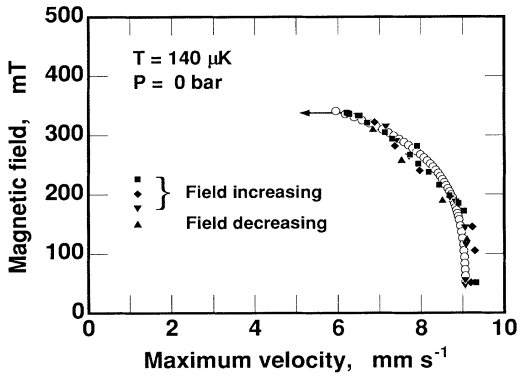

FIG. 3. The maximum resonator velocity at the onset of pair breaking plotted as a function of field for $P=0$. The measurements are represented by solid symbols, different symbols denoting different experimental runs. The arrow indicates the field at which the sudden transition to the A phase occurs. The open circles represent a calculation of the critical velocity expected from the excitation curves of Ashida and Nagai [2,9] for $P=0$ (see text).

happens when a moving cylindrical wire starts pair breaking in the liquid. We begin by repeating the argument of Lambert [8] for an isotropic gap, i.e., such as for the B phase in zero field. Let the wire move with velocity v_w. We assume that the gap has the usual bulk value Δ far from the wire and that the gap goes to zero at the wire surface. In the reference frame of the wire, the bulk liquid approaches at velocity v_w while the liquid flowing round the wire has a maximum relative velocity of $2v_w$ (for pure potential flow around a cylinder). The dispersion curves are thus distorted to give a maximum quasiparticle energy leaving the wire of $2v_w p_F$. The dispersion curve out in the bulk has a minimum energy of $\Delta - v_w p_F$ along the line of relative motion of the wire and bulk liquid. When these two quantities are equal quasiparticles created near the wire can just escape, that is to say, the wire begins pair breaking. Equating the two quantities gives $v_c = \Delta/3p_F$, i.e., one-third of the Landau velocity.

When the gap is distorted by the field, as here, we can use the same argument but we have to take into account the fact that the minimum in energy associated with the excitation curves out in the bulk liquid no longer lie in the direction of relative motion. The gap develops a maximum along the line of motion in the presence of the field. Furthermore, parallel to the field the excitation spectrum develops a Zeeman spin splitting, reducing even further the excitation minimum below the gap value. This means that we have to make an angular search for the direction at which excitations can first escape and which thus defines the critical velocity.

Ashida and Nagai [2] give the excitation energy in the form

$$E_{p\sigma} = [(E_z - \sigma\tilde{\omega}_L/2)^2 + \Delta_1^2(\hat{p}_x^2 + \hat{p}_y^2)]^{1/2},$$

where $\sigma = \pm 1$ is the spin index, $E_z = (\xi^2 + \Delta_2^2 \hat{p}_z^2)^{1/2}$ with ξ the kinetic energy measured from the Fermi energy, and the Larmor frequency taking into account Fermi-liquid effects, $\tilde{\omega}_L$, is given by $\omega_L - 4f_0^a S_z$, where ω_L is the bare Larmor frequency γH. Nagai [9] has provided us with tabulations of these quantities which we have used to calculate the critical velocity. We need one more assumption. In the simple argument above, excitations leave the wire with a maximum energy of $v_w p_F$. Strictly speaking this only occurs in precisely the forward and backward directions. If we assume that a fraction of the excitations, initially created near the wire, have the possibility of being scattered once more by the wire, then this maximum energy is no longer restricted to excitations moving in the direction of motion of the wire. Thus quasiparticles can leave the wire with energy $2v_w p_F$ in *all* possible directions. Now that we have a value for the maximum energy of the emitted quasiparticles we can calculate the minimum energy of the excitation spectrum out in the bulk liquid to give the critical velocity. This is not trivial as the excitation spectrum in the bulk changes as a function of field, k-vector direction, and wire velocity.

A series of points calculated in this way from the excitation curves of Ashida and Nagai [2,9] are also shown in Fig. 3. The agreement with the data is extremely good, especially as, once the excitation spectrum is given, there are *no* free parameters. At zero field, excitations are first created by pair breaking along the line of motion of the wire. As the field (perpendicular to the motion) increases, the gap along the direction of motion increases whereas the gap along the field direction decreases accompanied by a further reduction in the excitation minimum by spin splitting. The direction at which pair breaking first occurs thus swings away from the direction of motion with increasing field, until immediately below the B-A transition pair breaking first occurs for excitations leaving the wire at an angle of 82° to the direction of motion. The good agreement between calculation and data suggests that our picture of what is happening is essentially correct. It is interesting to note that in this experiment the quasiparticles emitted at the higher fields must be highly polarized. This presents various possibilities for experiments to investigate spin-dependent scattering processes.

To whet the appetite of those who expect an intermediate phase between A and B, we do occasionally see, between the clearly B-like and clearly A-like curves, a very few anomalous traces which have a completely different signature. A typical case is shown in Fig. 4, where the two curves at 335 mT are quite different from either the B-phase curves or the A-phase curves. These anomalous traces show B-like behavior at low velocities until pair breaking is initiated, at which point the trace becomes quite distinct from those of either A or B phase. A further small increase in the field then yields a curve which is entirely A-like at all velocities. This may indicate that

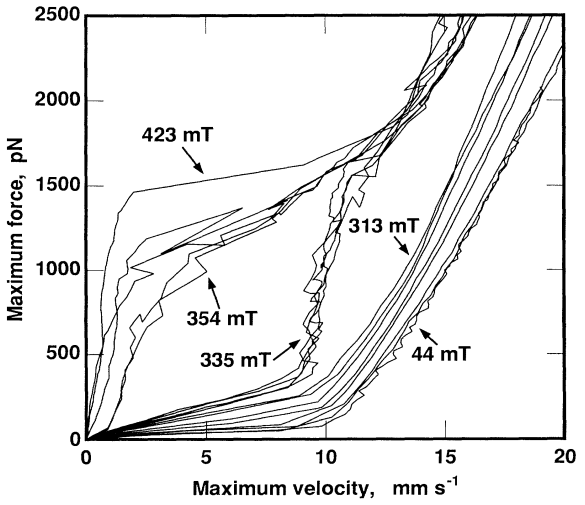

FIG. 4. A family of curves similar to those of Fig. 2, except that the plot extends to higher velocity. In this particular series we see intermediate behavior at 335 mT. These "intermediate phase" curves look B-like until the critical velocity is reached and then behave differently from either the A or B phase; see text.

the unusual state or phase, if that is what it is, is induced over a very narrow range of fields by the pair-breaking process which will itself try to impress a further anisotropy on the liquid near the wire.

We have speculated earlier that the influence of the flux of quasiparticles created by pair breaking might distort the superfluid order parameter sufficiently to induce other phases. Lambert has suggested [10] to us that an aligned stream of quasiparticles might well induce a transition to the A phase, since the directional nodes in the gap would accommodate the quasiparticles with lower free energy. The effect we see here might be interpreted in that way since the traces have more A-like character above v_c. It has to be remembered that our measurements near the transition are made with an A-B phase interface in the cell which gradually rises as the field is increased. Consequently, at fields just below the transition, there is A phase only a very short distance from the active part of the wire and any factors even slightly favoring the A phase may lift the interface enough to be seen by the resonator. Nevertheless, the possibility does remain that these traces may indicate a stable intermediate phase or structure sitting at the A-B phase interface.

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[1] N. Schopohl, J. Low Temp. Phys. **49**, 347 (1982).
[2] M. Ashida and K. Nagai, Prog. Theor. Phys. **74**, 949 (1985).
[3] J. M. Kyynäräinen, J. P. Pekola, A. J. Manninen, and K. Torizuka, Phys. Rev. Lett. **64**, 1027 (1990).
[4] A. M. Guénault, V. Keith, C. J. Kennedy, S. G. Mussett, and G. R. Pickett, J. Low Temp. Phys. **62**, 511 (1986).
[5] C. A. M. Castelijns, K. F. Coates, A. M. Guénault, S. G. Mussett, and G. R. Pickett, Phys. Rev. Lett. **56**, 69 (1986).
[6] Y. H. Tang, Inseob Hahn, H. M. Bozler, and C. M. Gould (to be published).
[7] S. N. Fisher, A. M. Guénault, C. J. Kennedy, and G. R. Pickett, Phys. Rev. Lett. **63**, 2566 (1989).
[8] C. J. Lambert, in *Proceedings of LT19* [Physica (Amsterdam) **165&166B** (1990)], p. 653.
[9] K. Nagai (private communication).
[10] C. J. Lambert (private communication).