New Mode of Growth of ^{3}He-B in Hypercooled ^{3}He-A: Evidence of a Spin Supercurrent

S. T. P. Boyd[(a)] and G. W. Swift
Condensed Matter and Thermal Physics Group, Los Alamos National Laboratory, Los Alamos, New Mexico 87545
(Received 29 August 1989)

We report results of an investigation of the growth of the ^{3}He-B phase into the hypercooled ^{3}He-A phase. The form of the magnetization signal associated with the interface evolved radically with increased hypercooling, suggesting a transition to a new mode of growth. We propose a model based on magnetization transport by a spin supercurrent which accounts for many features of the data.

PACS numbers: 67.50.−b, 64.60.Qb, 64.70.−p

Ordinarily in an equilibrium cooling through a first-order phase transition, the rate at which material can be converted from the higher-temperature phase to the lower-temperature phase is governed by the rate at which the latent heat released can be extracted from the transition region. In the ^{3}He superfluids, though, the higher-temperature A phase can be supercooled far enough below the equilibrium AB transition temperature T_{AB} that a volume of ^{3}He can convert from A to B, contain within itself all the latent heat released in the conversion, and still be at or below T_{AB}. This rare case is identified as a "hypercooled" phase transition. In a hypercooled phase transition the rate of conversion of material to the low-temperature phase is no longer constrained by thermal diffusion, and the growth dynamics of the low-temperature phase provide us with a novel probe of both the material and the phase transition.

Our previous experiment[1] and the theory of Leggett and Yip[2] clarified the basic growth dynamics of the B phase for hypercooling down to $T/T_{AB}=0.75$. They found our velocity measurements of the AB interface $v_{AB}(T/T_{AB})$ well accounted for by an inherently quantum-mechanical retarding force on the AB interface due to momentum transfer to quasiparticles through Andreev reflection.

Here we present similar, but unexpectedly rich observations for hypercooling down to $T/T_{AB}=0.55$. We again use the differing magnetizations of the A and B phases in a magnetic field to mark the passage of the propagating AB interface. The magnetization signal evolves radically for $T/T_{AB}<0.75$, as the experiment now probes dynamic magnetic effects. Many features of the new data can be accounted for by a critical-velocity limited counterflow of the spin-up and spin-down superfluids. Other interesting features remain unexplained. The data suggest that the rapid creation of excessively polarized B phase by the hypercooled AB transition will provide a new, non-NMR probe of spin dynamics in superfluid ^{3}He.

The experimental cell we used is sketched in Fig. 1. ^{3}He at 29.3 bars fills a Cu-Ni tube 17.0 cm long with a 0.37 cm i.d. The bottom of this tube is open to a region of copper-flake sinter which provides thermal contact to the nuclear demagnetization refrigerant. We deduced the temperature T of the ^{3}He from the magnetic susceptibility of powdered lanthanum-diluted cerium magnesium nitrate (LCMN) immersed in the ^{3}He, and calibrated at the A-normal and AB transitions against Greywall's measurements.[3]

We detected the passage of the phase transition by measuring the reduction of the magnetization (due to the change in static magnetic susceptibility $\Delta\chi_{AB}\equiv\chi_A-\chi_B$) as the ^{3}He transformed from A to B. The long primary coil provides a homogeneous magnetic field $H_{\rm prim}$ parallel to the axis of the column. Inside the primary coil we wrapped four superconducting coils around the column. The numbers of turns in the coils, their senses of winding, and their separations are indicated in Fig. 1. The four coils were connected in series, and the circuit was completed through the input flux transformer of a dc SQUID. The output of the SQUID, then, was proportional to a linear combination of the fluxes through the four coils.

Except where noted, all data were taken with $H_{\rm prim}=1.50$ kOe (calculated). T_{AB} decreases with increasing magnetic field, and we measured $T_{AB}(1.5\ {\rm kOe})=1.890$

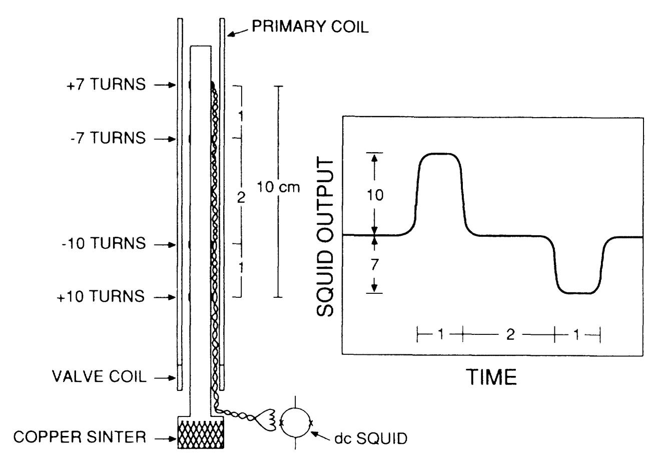

FIG. 1. The experimental cell. The four coils span a total length of 10.1 cm. Inset: The "nominal magnetization signature" generated by the simplest AB interface.

mK.

The valve coil provides a short region of high field at the bottom of the column. The first step in making a measurement was to set a valve-coil field larger than $H_{\rm prim}$. Then, starting from $T > T_c$, we cooled the cell. The B phase always nucleated first in the sinter region (cf. Ref. 1). The suppression of T_{AB} by magnetic field constrained the B phase to grow only to fill the region below the valve field. We continued slow cooling until the AB interface grew through the saddle point of the valve field up into the column, thus introducing the B phase into the hypercooled A phase. The hypercooled AB interface then propagated up the column.

The simplest SQUID output signal results from an AB interface which is planar, perpendicular to the length of the column, and moving upward at constant velocity. When this interface moves through a coil, the SQUID output deflects in proportion to the number of turns and sense of winding of that coil. Thus, the "nominal signature" resulting from the passage of this interface up the column has the proportions indicated in the inset in Fig. 1. The absolute measurements of this signature tell us $\Delta\chi_{AB}$ and v_{AB}.

We obtained signatures over a range of T/T_{AB} [by which we mean $T/T_{AB}(H_{\rm prim})$] extending much lower than in our previous Letter[1] and have uncovered some completely unexpected behavior. The signatures in Fig. 2 are from the cold end of that sequence. The ordinate is SQUID deflection, but each group is offset vertically in proportion to its T/T_{AB}. Within each group are superposed the three or four signatures obtained at that T/T_{AB}. All signatures are adjusted horizontally so their leading edges are at the same time coordinate.

The signatures with $T/T_{AB} \geq 0.747$ (only $T/T_{AB} = 0.747$ is shown here) have the proportions of the nominal signature and $\Delta\chi_{AB}(T)$ and $v_{AB}(T)$ corroborating our previous data[1] and the theory of Yip and Leggett.[2] However, for $T/T_{AB} < 0.747$, the signatures unexpectedly evolved away from the nominal form. The four-coil geometry complicates interpretation, but we can point out some interesting features.

In contrast with the warmer data, for $T/T_{AB} < 0.747$ the magnetization profile of the interface is clearly evolving as it goes up the column.

Note the downward going "precursor" pulse preceding the main body of the signature (e.g., Fig. 2, feature P). The B phase is less magnetized than the A phase, and when the B phase hits the bottom coil the output of the SQUID deflects upwards. When the precursor hits the bottom coil the output of the SQUID deflects downwards. This means that the precursor is more magnetized than equilibrium A phase. Its magnetization increases as T/T_{AB} decreases. Closer examination finds the precursor to be visible on signatures as warm as $T/T_{AB} = 0.767$. Its presence for $T/T_{AB} > 0.767$ would be hidden by the noise and granularity of our measurement.

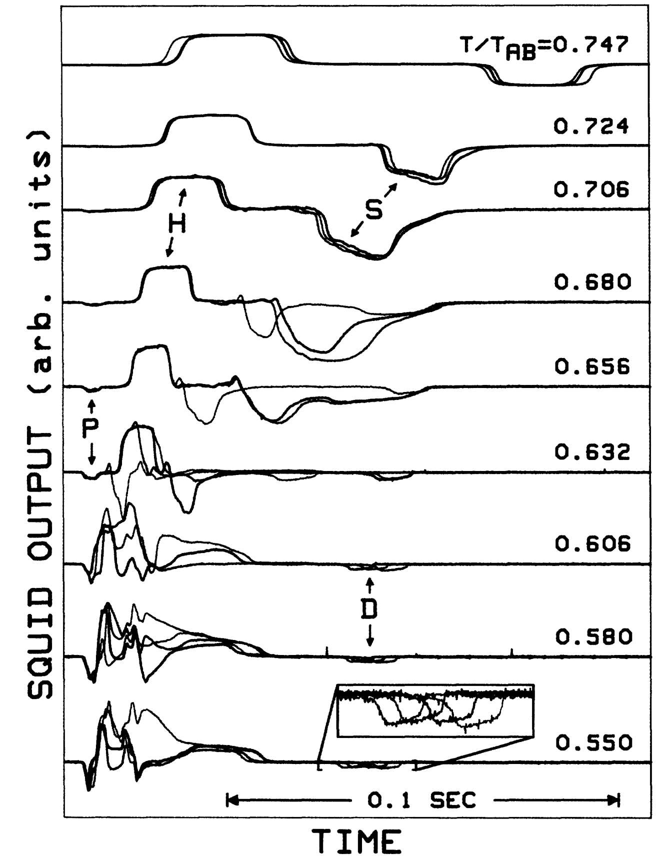

FIG. 2. Groups of magnetization signatures at various T/T_{AB}. Colors aid in distinguishing individual signatures. See text for features S, H, P, and D.

In the signatures at $T/T_{AB} = 0.724$ and 0.706 there is a constant slope while the interface is between the top two coils (Fig. 2, feature S). For $T/T_{AB} \leq 0.747$ the height of the signal while the interface is between the bottom two coils (e.g., Fig. 2, feature H) is anomalously larger than we would expect from the smooth curve of $\Delta\chi_{AB}(T)$ we deduced for $T/T_{AB} > 0.747$.

In the coldest four or five signatures the downward going last pulse (e.g., Fig. 2, feature D) is the first temperature-independent feature associated with the hypercooled AB interface.

The reproducibility of these signatures decreases below $T/T_{AB} = 0.747$ to a minimum near $T/T_{AB} = 0.606$. Below $T/T_{AB} = 0.606$ reproducibility increases as the signatures approach a new consensus form. This behavior suggests a transition to a new mode of growth of the B phase.

Figure 3 shows one of the signatures obtained at $T/T_{AB} = 0.550$. The signature has visibly split into two parts, a leading "fast signal" and a trailing "slow signal." Comparison to a simulated signature (inset) shows that the fast signal is a short supermagnetization pulse, perhaps the descendent of the precursor, which races through the four coils at about 800 cm/s. Since this ve-

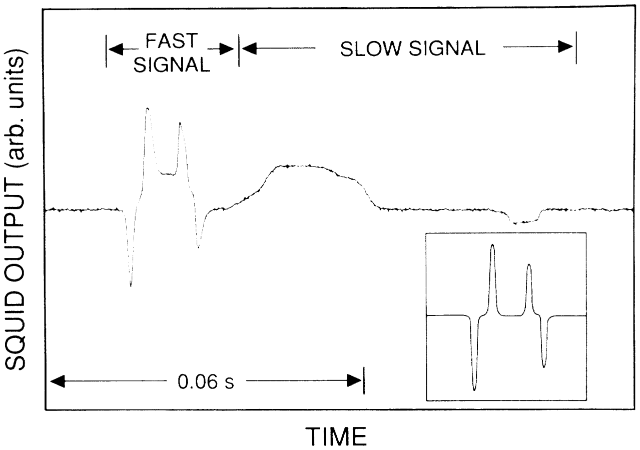

FIG. 3. A signature from the $T/T_{AB}=0.550$ group, showing the division into "fast signal" and "slow signal." Inset: The signature expected from a short uniformly magnetized region (square pulse) traveling up the tube at constant velocity.

locity is a reasonable continuation of $v_{AB}(T)$ we deduced for $T/T_{AB}>0.632$, we tentatively identify the fast signal with the AB interface.

In addition to this new behavior, there remains a heretofore unresolved mystery associated with the acquisition of the nominal signatures for $T/T_{AB}\gtrsim 0.747$. For the AB interface to generate a nominal signature, the magnetization profile accompanying the interface must look like a step function. Thus the AB magnetization difference must disappear over a length short compared to the length resolution of our four coils (≈ 0.4 cm). Unless the interface provides new paths for relaxation of magnetization, it will convert equilibrium A phase to B phase which has some excess magnetization $M_{B,\text{excess}} \equiv M_B-\chi_B H_{\text{prim}}$, where M_B is the local B-phase magnetization. At $T/T_{AB}=0.747$, $M_{B,\text{excess}}$ would have to relax in less than 4 ms. This time is shorter by more than an order of magnitude than relaxation times measured for the B phase in comparable field gradients (<1 Oe/cm).[4]

Our data lead us to propose that this rapid "relaxation" is the manifestation of *transport* of $M_{B,\text{excess}}$ by counterflow of the spin-up and spin-down components of superfluid ^{3}He. Such a spin supercurrent[5] is driven by $\nabla M_{B,\text{excess}}$, and transports magnetization to reduce this gradient.[6] A critical spin supercurrent results from the superfluid's critical velocity. [Since the true "critical spin velocity" in the B phase may be very small or zero,[6] we generalize the term here to mean the boundary between two dissipation regimes (cf. Ref. 7).] We specify the spin supercurrent $(\hbar/2m)J_{\text{spin}}$ by its equivalent mass flux: $J_{\text{spin}}\equiv m(n_\uparrow v_\uparrow - n_\downarrow v_\downarrow)$, where m is the mass of a ^{3}He atom, and n and v are number density and velocity of the $\uparrow$- and $\downarrow$-spin superfluids. Evidence for such a spin supercurrent has been observed in the A phase,[4] and a related, more complex spin supercurrent has recently been observed and understood in the magnetic "homogeneous precession domains" of the B phase.[8]

We believe that a J_{spin} exists in the column of B phase below the AB interface, and conducts $M_{B,\text{excess}}$ to the equilibrated B phase below. This gives the appearance of anomalously fast "relaxation" when the rate of creation of excess spin in the B phase

$$R=v_{AB}(T)\Delta\chi_{AB}(T)H_{\text{prim}}/\gamma$$

(where γ is the gyromagnetic ratio) is less than the critical spin supercurrent $(\hbar/2m)J_{\text{spin},c}$. We expect a dramatic evolution in the signatures as T decreases when R exceeds $(\hbar/2m)J_{\text{spin},c}$. The AB interface then leaves the J_{spin} relaxation region behind.

Measurements of the fastest nominal signature ($T/T_{AB}=0.747$) then give $J_{\text{spin},c}=4.3$ mg/cm^{2}s. This implies a critical velocity $v_{s,c}=0.018(\rho/\rho^{\text{spin}})$ cm/s, where ρ is the ^{3}He density, and ρ^{spin} is the effective spin superfluid density. In the Balian-Werthamer state ρ^{spin} is $\rho(n/5)[1-Y(T)]m/m^*$, where n is between 2 and 4 and Y is the Yosida function.[9] Using $Y(T)$ determined from an experiment at melting pressure[4] gives $0.17<v_{s,c}<0.35$ cm/s, in good agreement with accepted values.[10]

The delocalization of the magnetization relaxation from the AB interface is most clearly resolved in the coldest signatures. In Fig. 3, the slow signal shows the relaxation of $M_{B,\text{excess}}$. This occurs by two paths: First, J_{spin} consumes $M_{B,\text{excess}}$ from the bottom of the cell up, bringing the magnetization to equilibrium in each of the four coils sequentially, and thereby causing the four steps in SQUID output reminiscent of the nominal signature; second, conventional relaxation mechanisms (i.e., that of Leggett and Takagi[11] and relaxation at the cell walls) lead $M_{B,\text{excess}}$ simultaneously to relax uniformly along the length of the tube, causing the continuous decrease over time of the amplitude of the slow signal. The velocity of the leading edge of J_{spin} increases in rough proportion during this relaxation, so that J_{spin} is 3 to 4 mg/cm^{2}s throughout. This supports the idea that J_{spin} at a given T is constant at its critical value. It also agrees with $J_{\text{spin},c}$ obtained above from the nominal signature at $T/T_{AB}=0.747$. The T independence of the slow signal results from the weak dependence of ρ^{spin} and $v_{s,c}$ on T at these low temperatures.

The constancy of J_{spin} at its critical value also causes the magnetic field dependence of Fig. 4, which shows the group of signatures taken at $T/T_{AB}=0.606$, $H_{\text{prim}}=1.5$ kOe, and another group taken at approximately the same T/T_{AB}, but with $H_{\text{prim}}=2.25$ kOe. The increased H_{prim} had no discernible effect on the fast signals, but the slow signals were dramatically slowed, by about a factor of 2. The magnetization to be removed from the newly created B phase is proportional to H_{prim}, so our critical-velocity model implies that the time interval for the slow signal will be proportional to H_{prim}. In Fig. 4 the slow signal from the top two coils is the most reproducible part, and

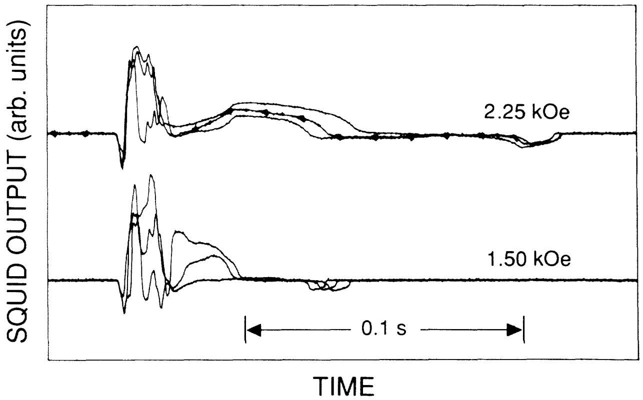

FIG. 4. Effect of magnetic field on signatures at $T/T_{AB} \approx 0.6$. Upper group: $T/T_{AB}=0.595$. Lower group: $T/T_{AB}=0.606$. To compare susceptibility changes, the top group has been scaled by 0.15/0.225.

yields $J_{\text{spin},c}=4.2$ mg/cm^{2}s at 1.5 kOe and $J_{\text{spin},c}=3.5$ mg/cm^{2}s at 2.25 kOe, in agreement with the value deduced above.

So far we have described many features of these data as consistent with a delocalization of the AB interface from the magnetization relaxation provided by $J_{\text{spin},c}$. If this were the whole story, there would be no fast signal. It is also not obvious that the Fig. 2 features S, H, and especially P will be accounted for by action of J_{spin}. At present, these features are not quantitatively understood. We recall that early measurements[12] of a large difference between static and dynamic susceptibilities of the B phase also remain unexplained.

Interestingly, features S and H of Fig. 2 would result from a volumetric compression of the magnetization in front of the interface. The signal heights would then be anomalously large, increasingly so as the interface went up the column, and there would be a larger slope while the interface was between the top two coils than while it was between the bottom two coils. Schopohl and Waxman[13] recently suggested such an effect, due to the spin dependence of the Andreev reflection of quasiparticles by the moving interface. The initial deviation from the nominal signature at $T/T_{AB}=0.724$ may also reflect this interaction, rather than $J_{\text{spin},c}$. This would cause us to underestimate $J_{\text{spin},c}$, but not significantly since the second pulse of the slow signal is already emerging at $T/T_{AB}=0.680$.

We must also remember that each AB interface initially accelerates through the strong valve field gradient. A magnetization disturbance generated in this acceleration might propagate to our four coils. We note that the precursor grows as the valve field increases.

We would like to thank Chris Hammel, Vince Kotsubo, Tony Leggett, John Palmeri, and Dierk Rainer for some very helpful discussions. This work was supported by DOE Office of Basic Energy Sciences.

[(a)]Permanent address: Department of Physics, University of California at Los Angeles, Los Angeles, CA 90024.

[1]D. S. Buchanan, G. W. Swift, and J. C. Wheatley, Phys. Rev. Lett. **57**, 341 (1986).

[2]S. Yip and A. J. Leggett, Phys. Rev. Lett. **57**, 345 (1986); John Palmeri, Phys. Rev. Lett. **62**, 1872 (1989).

[3]D. S. Greywall, Phys. Rev. B **33**, 7520 (1986).

[4]L. R. Corruccini and D. D. Osheroff, Phys. Rev. B **17**, 126 (1978); Phys. Rev. Lett. **34**, 564 (1975).

[5]M. Vuorio, J. Phys. C **7**, L5 (1974).

[6]M. Vuorio, J. Phys. C **9**, L267 (1976).

[7]Ren-zhi Ling, D. S. Betts, and D. F. Brewer, Phys. Rev. Lett. **53**, 930 (1984).

[8]I. A. Fomin, Zh. Eksp. Teor. Fiz. **93**, 2002 (1987) [Sov. Phys. JETP **66**, 1142 (1987)]; A. S. Borovik-Romanov, Yu. M. Bunkov, V. V. Dmitriev, Yu. M. Mukharskiy, and D. A. Sergatskov, Phys. Rev. Lett. **62**, 1631 (1989).

[9]A. J. Leggett, Rev. Mod. Phys. **47**, 331 (1975).

[10]J. P. Pekola and J. T. Simola, J. Low Temp. Phys. **58**, 555 (1985), and references therein.

[11]A. J. Leggett and S. Takagi, Ann. Phys. (N.Y.) **106**, 79 (1977).

[12]R. A. Webb, Phys. Rev. Lett. **38**, 1151 (1977); R. E. Sager, R. L. Kleinberg, P. A. Warkentin, and J. C. Wheatley, J. Low Temp. Phys. **31**, 409 (1978).

[13]N. Schopohl and D. Waxman, Phys. Rev. Lett. **63**, 1696 (1989).

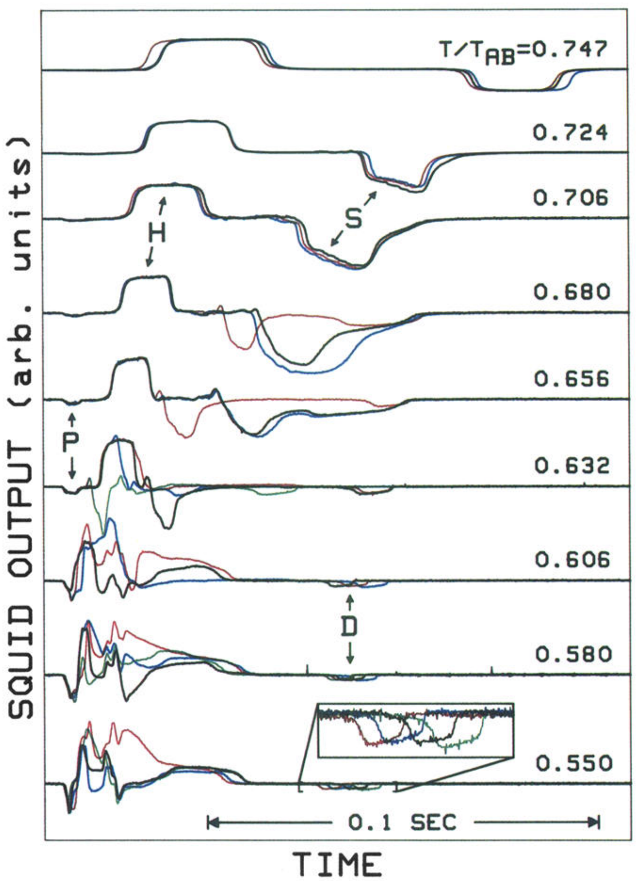

FIG. 2. Groups of magnetization signatures at various T/T_{AB}. Colors aid in distinguishing individual signatures. See text for features S, H, P, and D.