Velocity of Propagation of the ^{3}He A-B Interface in Hypercooled ^{3}He-A

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We have measured the velocity of propagation of the ^{3}He A-B interface as a function of temperature and pressure for the ^{3}He-A initially in a hypercooled state. Velocities as high as 67 cm/s have been observed. Nucleation of the B phase occurred at greatly different temperatures in two different regions of the experimental cell.

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Of all the first-order phase transitions that occur in nature those that occur in superfluid ^{3}He, in particular that between ^{3}He-A and ^{3}He-B, are among the most remarkable. The ^{3}He $A \rightarrow B$ transition is remarkable as the interfacial energy, as measured by Osheroff and Cross[1] and interpreted both by them and by Kaul and Kleinert,[2] is a consequence of there being different quantum mechanical order parameters in each of the two phases with an accommodation between the two taking place in the interface. The interface is in a sense the reflection of competing macroscopic quantum effects. The $A \rightarrow B$ transition is also remarkable in that it takes place at all, because of the small bulk free-energy difference between the two phases. This small free-energy difference makes the probability of homogeneous nucleation of the B phase vanishingly small.[3] A possible resolution of the nucleation puzzle, invoking highly nonequilibrium conditions induced by cosmic rays, has been presented recently by Leggett.[3]

The $A \rightarrow B$ transition is also remarkable in that when it does take place after cooling from above the critical temperature T_c, it occurs at a very low reduced temperature T_n/T_{AB}, where T_n is a nucleation temperature, T_{AB} is the thermodynamic transition temperature, and both are functions of pressure. Indeed at commonly observed values of T_n the adiabatic temperature rise for a phase transition which goes to completion irreversibly, L_{AB}/C, where L_{AB} is the latent heat of the transition per unit volume and C is the specific heat per unit volume, is much less than the temperature difference $T_{AB} - T_n$. Indeed at melting pressure L_{AB}/C is about[4] 10 μK while we have observed values of $T_{AB} - T_n$ in excess of 400 μK. Materials are said to have been hypercooled when they have been cooled below the equilibrium transition temperature, T_e, with nucleation at T_n, such that $C(T_e - T_n)/L > 1$. While hypercooling has been observed in other materials,[5] the $A \rightarrow B$ transition in ^{3}He is also remarkable in that far greater degrees of hypercooling can be observed in it than in any other substance. For ordinary supercooling, where $C(T_e - T_n)/L < 1$, the velocity of propagation of the interface between two phases is determined by straightforward thermal considerations.[6] But for a hypercooled transition in our constant-volume cell the propagation of the interface occurs at constant internal energy, as in a Joule expansion. In the present work we have measured the velocity of propagation in hypercooled ^{3}He, with experimental results as large as 67 cm/s. For the case of an $A \rightarrow B$ transition in supercooled ^{3}He a preliminary calculation[7] estimated the thermally limited velocity of propagation to be ca. 0.05 cm/s.

The novel feature of our experimental cell is a heavy-walled epoxy[8] vessel with a central open column for ^{3}He, shown in Fig. 1, which is enclosed in a niobium-shielded tower of 22 mm inside diameter. The velocity of propagation, V_{AB}, of the interface in the column could be measured by magnetic means as the magnetization of the B phase in a given field is less than that of the A phase. The column had three sections of diameters 3.2, 1.6, and 0.8 mm to investigate the dependence of the velocity on macroscopic dimensions. The primary coil of the magnetometer consisted of two layers of closely wound 80-μm-diam Nb-Ti wire producing ca. 30 mT/A. The secondary coils consisted

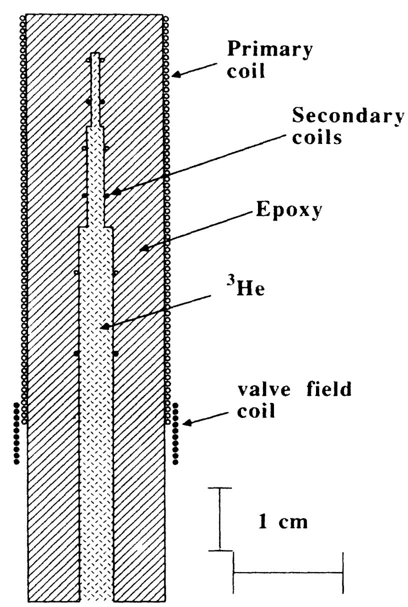

FIG. 1. Interfacial-velocity cell.

of three astatically wound pairs of the same wire connected in series to the signal coil of a SQUID, one pair per section of the column, each pair having a total of 1 μH of inductance. Measurements were made at 33.6, 29.7, and 24.5 bars. At both 29.7 and 33.6 bars this arrangement allowed very clean detection of the passage of the phase interface with only 10 mT in the primary coil. At 24.5 bars a field of 20 mT was necessary. A typical magnetic signal as a function of time is shown in Fig. 2(a), where the signals from the passage of the interface through each of the six secondary coils can clearly be seen. The velocity was calculated by measuring the time between the half-height points of the magnetization change indicated by succeeding coils and dividing by the previously measured distances between the centers of the coils. These distances were 12.5, 6.9, and 7.3 mm, respectively, for the decreasing-diameter sections. A 1.2% thermal contraction[9] of the epoxy was assumed. At the bottom of the column was another superconducting coil with a central field of 0.15 T/A. This coil provided a "valve" field which allowed precise control of the nucleation process in the column as described below.

The ^{3}He in the column was cooled by a 200-m^2 sintered-copper heat exchanger welded to a copper nuclear demagnetization refrigerator, described elsewhere,[10] to which the column has been sealed. Thermometry consisted of a lanthanum-doped cerium magnesium nitrate (LCMN) susceptibility thermometer located in a tower of 7 mm internal diameter and 37 mm from the sinter. The thermometer was calibrated by observation of T_{AB} and T_c during warming under the residual heat leak (~ 1 nW) with less than 0.02 T on the copper refrigerant. Both the latent heat at T_{AB} and the discontinuity in the heat capacity at T_c could be identified during the warming at both 29.7 and 33.6 bars. Only the discontinuity in the heat capacity at T_c was observed at 24.5 bars. Temperatures for $T_{AB}(P)$ and $T_c(P)$ were taken from the Greywall scale[4] and fitted to the LCMN susceptibility data. Any pressure dependence of the thermometer was checked at higher temperatures by measuring the LCMN magnetization as a function of ^{3}He pressure at a constant temperature determined by a separate CMN thermometer. The LCMN thermometer showed no significant pressure dependence.

The introduction of a valve magnetic field between that part of the cell, including the thermometer, in close thermal contact with the sinter and that part in contact with the magnetometer separated the cell into two regions, that below the valve field, including the sinter and the thermometer, and that above the valve field, i.e., the interior of the epoxy column. As a consequence, with the valve field set so that penetration of the B phase from either direction was impossible, nucleation occurred independently above and below the valve field. To our great surprise, the temperature of nucleation above the valve T_{na} was quite different from the temperature of nucleation below the valve T_{nb}. Nucleation above the valve, i.e., in the column, could be identified by the erratic order in which the A-B interface went through the secondary coils as shown in Fig. 2(b). Nucleation below the valve could be observed in the thermometer as a slight rise in the temperature due to the release of the latent heat as shown by an arrow in Fig. 3. The observed values of T_{na} and T_{nb}, shown in Fig. 4, are related to the method used to measure the velocity of propaga-

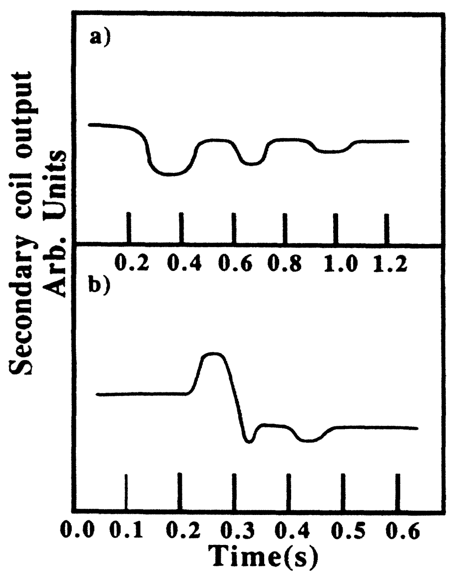

FIG. 2. Output from the secondary coils. (a) Interfacial propagation starting at the valve and propagating up the column (normal) at 29.7 bars and $T/T_{AB}=0.93$. (b) Nucleation in the column at 29.7 bars and $T/T_{AB}=0.85$. The interface propagates both up and down the column, passing through the secondary coils in a different order from when it comes through the valve.

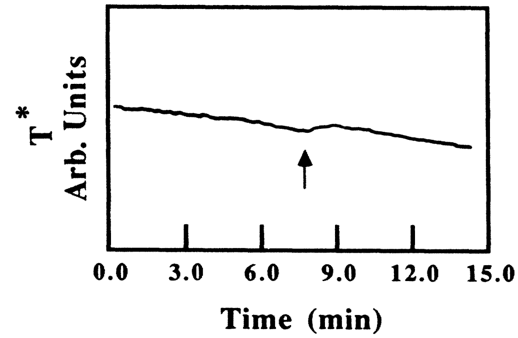

FIG. 3. Thermal signature at the LCMN thermometer of the nucleation at 29.7 bars of the B phase below the valve. The thermal signature starts at ca. 7.5 min. The temperature increase at the thermometer for this phase transition corresponds to ca. 3 μK.

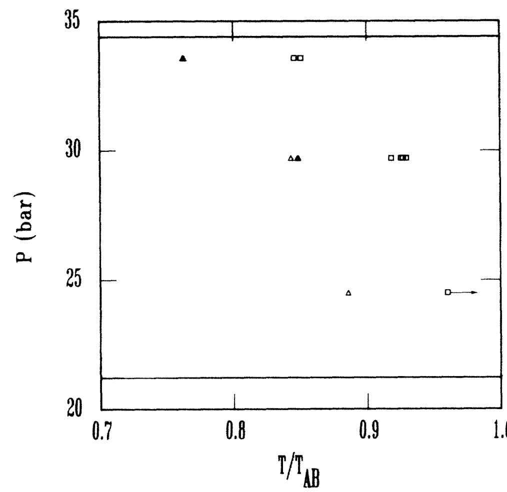

FIG. 4. Reduced temperature of nucleation below the valve (squares) and above the valve (triangles). The top and bottom solid lines are the melting and polycritical point pressures, respectively. The arrow on the highest-temperature square indicates that it is a lower bound (see text).

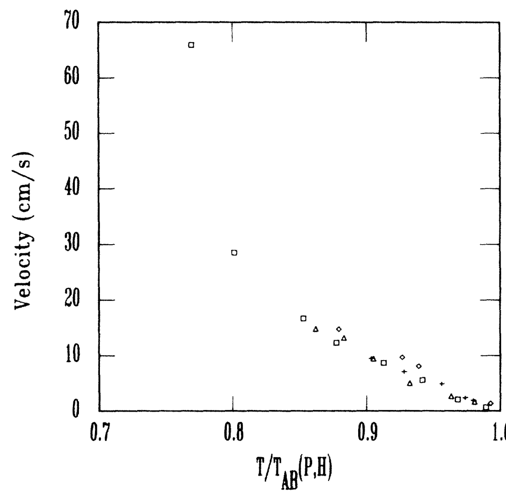

FIG. 5. A-B phase-front velocity: squares, 33.6 bars, 10 mT; triangles, 29.7 bars, 10 mT; crosses, 24.5 bars, 20 mT; and lozenges, 29.7 bars, 40 mT. The measurements shown were obtained for the bottom (large diameter) section of the column.

tion V_{AB} in several regions of temperature as described below. The values of T_n/T_{AB} are strikingly different for the regions above and below the valve, with the largest degree of hypercooling being achieved above the valve in the magnetometer column. For nucleation below the valve only the points shown were measured at a slow enough cooling rate for the thermometer reading to be representative of the temperature below the valve; it was observed that for a given cooling rate the transition took place at the same thermometer reading during each run. For the 24.5-bar data the thermal signature was too small to be observed but the nucleation temperature T_{nb} is inferred to be higher than $T/T_{AB}=0.96$ because only the first technique for measuring V_{AB}, described below, needed to be used. This large difference in the spontaneous nucleation temperature for two different regions of the same experimental cell indicates that some difference in the geometry, or surface area, quality or material, etc., between the two regions is affecting the nucleation process.

Two techniques, based on the results of Fig. 4, were used for controlling the nucleation of the B phase in the column. For measurements at the lowest temperatures the field in the primary coil was set to the desired value and the valve field was set to a field between 0 to 0.26 T. This suppressed T_{AB} in the region of the valve field to $T_{AB}(H_v)$, where H_v is the maximum field in the valve and $T_{nb} > T_{AB}(H_v) > T_{na}$. Once the fields were set the ^{3}He was cooled with the final cooling rate being approximately 25 nK/s. This cooling rate allowed the thermometer, column, and sinter to stay in close thermal equilibrium. As the cooling proceeded the B phase nucleated below the valve field, which restricted the B phase to the sinter region until $T \simeq T_{AB}(H_v)$. Then the interface could cross the field maximum and propagate up the column, now in equilibrium at $T_{AB}(H_v)$; so that V_{AB} was measured at $T \simeq T_{AB}(H_v)$. This method worked as long as $T_{AB}(H_v) < T_{nb}$.

For any $T_{AB}(H_v) > T_{nb}$, when $T_{AB}(H_v)$ was reached there would be no B phase below the valve to propagate up the column so that no signal could be seen until T_{nb} was reached. Hence to measure V_{AB} for $T_{AB} > T > T_{nb}$ it was necessary to modify the above procedure. The valve field was set initially as above so that $T_{AB}(H_v) < T_{nb}$ and the ^{3}He cooled until the transition was observed thermally below the valve. The valve field prevented propagation up the column. The temperature was then raised almost to T_{AB} and the valve field lowered to a value such that $T_{AB}(H_v) > T_{nb}$. The ^{3}He was then cooled again at 25 nK/s until the new $T_{AB}(H_v)$ was reached, whence the phase transition propagated up the column.

We have measured V_{AB} for T/T_{AB} between 0.99 and 0.77. The data for the lowest, largest-diameter section of the column are plotted versus $T/T_{AB}(P)$ in Fig. 5 for all three pressures. The 33.6- and 29.7-bar data were taken in a 10-mT field while the 24.5-bar data were taken in a 20-mT field. Also plotted are data for 29.7 bars and 40 mT. All of the data fall on a common curve within experimental uncertainties. Velocities for the upper two sections of the column, not shown, were consistently slower, by up to a factor of 2 for the lowest temperatures, than for the bottom section. Because of the design of the cell and the large temperature dependence of V_{AB} we cannot conclude that V_{AB} depends on section diameter. A calculation shows that a heat leak as small as 5 pW down the column would also account for the velocity differences observed.

As discussed above, all of these measurements fall into the hypercooled regime, and so the classical thermal processes of diffusion of the latent heat away from the interface cannot determine the propagation velocity. In the following Letter,[11] Yip and Leggett propose that under the conditions of these measurements the velocity is limited by Andreev reflection of quasiparticles, caused by the change in the order parameter across the interface. Their calculations are in reasonable agreement with our data, which are the first measurements on the dynamics of the *A*-*B* interface; further, they predict that at lower temperatures the inertial mass, of order 10^{-12} g/cm^2, of the interface becomes important in its dynamics, suggesting the possibility of interfacial waves and other interesting phenomena.

We believe that, in addition to the start that we have made in studying the dynamics of the *A*-*B* interface, our observation of two different nucleation temperatures suggests an important direction to proceed in the investigation of the nucleation process, both theoretically and experimentally. These observations do not rule out Leggett's cosmic-ray–induced nucleation hypothesis, but they make the question much more intriguing. One wonders if both cosmic rays and a surface effect simultaneously are necessary for nucleation, or if low-temperature nucleation above the valve is induced by cosmic rays while high-temperature nucleation below the valve is induced by some competing boundary or geometry effect.

We would like to thank Doug Osheroff for the suggestion of the valve field, Tony Leggett, Sugkit Yip, and Gordon Baym for many enlightening discussions about the *A*-*B* interface, and David Turnbull for teaching us about first-order phase-transition interfacial velocities in other systems. We would also like to thank Al Migliori for all his help.

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