[10]D. J. Kaup and A. C. Newell, Proc. Roy. Soc. London, Ser. A 361, 413 (1978).
[11]T. Ogino and S. Takeda, J. Phys. Soc. Jpn. 41, 257 (1976).
[12]N. Hershkowitz *et al.*, Plasma Phys. 21, 583 (1979); F. Ze *et al.*, Phys. Fluids 22, 1554 (1979).
[13]F. Ze *et al.*, Phys. Rev. Lett. 42, 1747 (1979).
[14]Y. Nakamura and Y. Nomura, Phys. Lett. 65A, 415 (1978).
[15]L. D. Landau and E. M. Lifshitz, *Fluid Mechanics* (Pergamon, Oxford, 1966).
[16]J. W. S. Rayleigh, *The Theory of Sound* (Dover, New York, 1945); A. Sommerfeld, *Lectures on Theoretical Physics* (Academic, New York, 1964), Vol. IV.

Influence of a Magnetic Field on Flowing Superfluid ^{3}He

J. P. Eisenstein,[a] G. W. Swift, and R. E. Packard
University of California, Berkeley, California 94720
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With use of a U-tube device, substantial effects of a magnetic field on flowing superfluid ^{3}He at saturated vapor pressure have been observed. Data are presented that show marked magnetic distortions of the otherwise isotropic B-phase order parameter. Above a critical temperature the magnetic field appears to destroy the B phase in favor of another type of state.

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The superfluid B phase of liquid ^{3}He is believed to be a Balian-Werthamer state.[1] In equilibrium, and in the absence of external fields, the gap is isotropic over the Fermi surface. Unlike the A phase, there are no macroscopic anisotropy axes (neglecting the tiny dipole-dipole interaction) in the B phase. This leads to substantial distortions of the Balian-Werthamer (BW) order parameter when a modest (~1 kG) magnetic field or superflow (~1 cm sec^{-1}) is imposed.[2] The A phase can, in principle, remove these distortions by suitably orienting its internal degrees of freedom.

For the case of zero flow it is well known that a magnetic field destabilizes the B phase in favor of the A phase, resulting in the interposition of A phase between the normal Fermi liquid and the B phase at pressures below the polycritical point.[3] Below the A-B transition temperature, T_{AB}, the B-phase superfluid density, ρ_s, is depressed below its zero-field value, the depression lessening as the temperature is reduced. Fetter[2] has given a Ginzburg-Landau derivation of T_{AB} which, if weak coupling is assumed, is

$$1 - T_{AB}/T_c = [7\zeta(3)/8\pi^2(1+\tfrac{1}{4}Z_0)^2](\gamma\hbar H/k_B T_c)^2, \qquad (1)$$

where $\zeta(3)$ is the Riemann zeta function,[4] γ the ^{3}He gyromagnetic ratio, k_B Boltzmann's constant, T_c the superfluid transition temperature, and Z_0 the first magnetic Landau parameter. Taking $T_c = 1.04$ mK and $Z_0 = -3.08$, both values appropriate to saturated vapor pressure,[5] then $1 - T_{AB}/T_c = 0.045H^2$ for H in units of kilogauss.

The presence of an equilibrium superflow, v_s, further suppresses ρ_s in the B phase.[2] The A phase, believed to be an Anderson-Brinkman-Morel (ABM) state[1] can, in principle, orient itself to reduce the kinetic energy of flow. These combined effects may shift T_{AB} from the zero flow value but the magnitude of the effect will depend on which, if any, stable A-phase texture exists.

We have used a U-tube technique to study the influence of a magnetic field on superfluid flow at saturated vapor pressure. The device consists of two reservoirs connected by a narrow flow channel designed to lock the normal component. The channel is a circular pipe of 177 μm radius and 1.0 cm length. The U-tube reservoirs are the gaps of concentric cylinder capacitors. These are used to electrostatically drive and detect the flow. Our measurement technique consists of recording flow transients induced by applying fixed high-voltage steps to one capacitor reservoir. (This produces a pressure head quadratically dependent on the bias voltage. For our apparatus the typical 400 V bias gives a pressure head of approximately 9 dyn cm^{-2}.) The flow transients are digitized and an on-line computer calculates the initial slope. A solenoid is wound around the flow channel and produces a field of up to 2 kG parallel to it. The solenoid has trimming coils

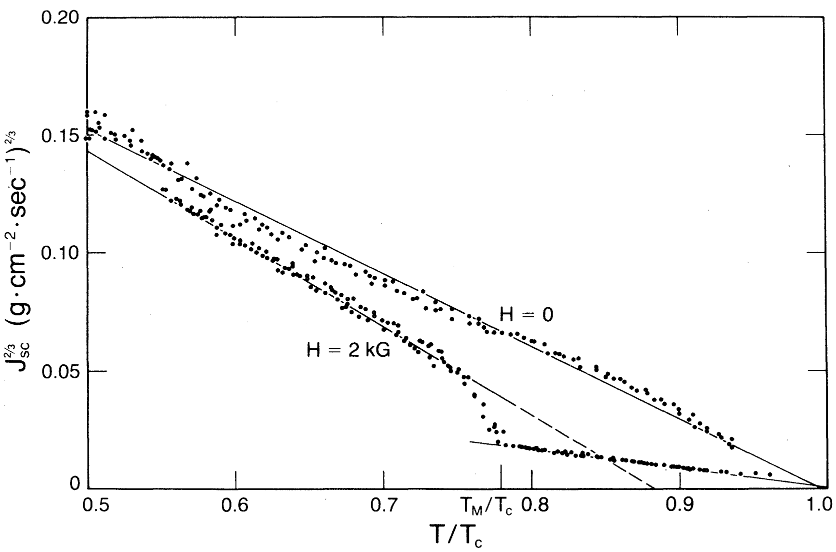

FIG. 1. Mass current (raised to the $\frac{2}{3}$ power) vs temperature both in zero and a 2-kG magnetic field. Solid lines are least-squares fits to straight lines.

on each end to give a field homogeneity over the channel of about 1%. The entire device is refrigerated by conventional nuclear cooling techniques. Thermometry is provided through pulsed NMR on ^{195}Pt, calibrated against T_c where a marked change in the U-tube flow resistance occurs.

We have found that the magnitude of B-phase supercurrents becomes essentially independent of driving force at a value J_{sc}. In zero magnetic field J_{sc} is found to scale[6] with temperature approximately as $(1-T/T_c)^{3/2}$ as Fig. 1 shows. Application of a magnetic field parallel to the flow dramatically alters the temperature dependence of the maximal current. The superfluid transition temperature T_c is, to within our resolution, unshifted by the field. Figure 1 contains data for a 2-kG field. We observe two distinct regimes, separated by a transition region beginning at T_c as shown in the figure.

The first regime lies between T_c and T_M and exhibits flow behavior qualitatively different from the B phase in zero field. The supercurrent is no longer saturated and is considerably smaller than in zero field for the same initial force. This remains true to the largest forces accessible in this experiment. Thus there is no maximal current J_{sc}. Figure 2 presents two typical transients; one taken above T_M is not at all straight. For points in Fig. 1 in this region we have merely plotted the maximum current in the transient. Nevertheless, this current appears to scale as $(1-T/T_c)^{3/2}$. We know of no theoretical reason for this. The magnitude of the current is apparently independent of magnetic field although irreproducibility on the order of 10% prevents a strict statement. We observe such irreproducibilities after warming or cooling out of a particular temperature region and then returning. This explains the apparently larger scatter seen in Fig. 1 for the 2-kG data below T_M than above. This irreproducibility was itself only sometimes observed. Data taken by varying temperature in one direction only results in a constant percent scatter

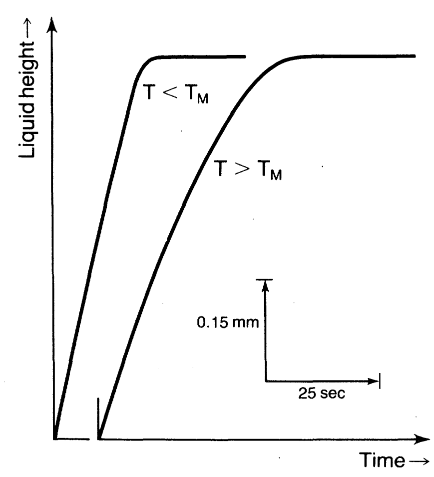

FIG. 2. Two typical transients. These curves show the liquid-level difference after application of a dc bias to one of the capacitors.

over the entire accessible temperature range.

The temperature, marked T_M in Fig. 1, at which the transition region abruptly begins is characterized both by a rise in the current magnitude and also a return to saturation. As Fig. 2 shows, the transients are nearly linear. They appear qualitatively the same as in zero field. Furthermore, T_M is found to scale quadratically with magnetic field as shown in Fig. 3. A least-squares fit to the data gives

$$1 - T_M/T_c = (0.061 \pm 0.002)H^2 - (0.003 \pm 0.007) \qquad (2)$$

with H in kilogauss. The points in Fig. 3, with the exception of the lowest, were taken warming through T_M. The transition is frequently, but not always, warmer on warming through T_M than cooling.

Below the transition region the flow is saturated as in zero field. At fixed temperature below the transition region the current J_{sc} appears to decrease with increasing magnetic field. Irreproducibilities like those mentioned above prevented a quantitative study of this effect. As Fig. 1 reveals, this magnetic suppression of J_{sc} is larger at higher temperature.

Qualitatively, these observations are in consonance with the expected magnetic distortion of the B-phase order parameter. Since we measure mass current, $\rho_s v_s$, magnetic suppression of the superfluid density ρ_s should be observable. Fetter[2] points out that in an unbounded region, of the four possible superfluid states[7]: polar, planar, ABM, and BW, only the last is magnetically distorted. The others possess orientational degrees of freedom allowing them to relieve the magnetic stress. Well below T_M our data is consistent with the magnetically distorted Balian-Werthamer state.

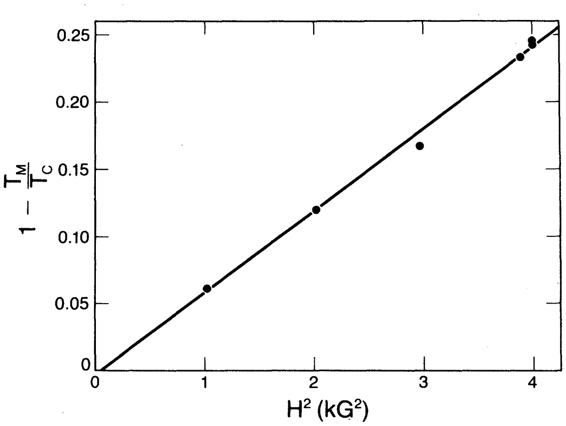

FIG. 3. Magnetic transition temperature, T_M, vs magnetic field. Straight line is a least-squares fit.

On the other hand, above T_M we cannot identify the state. The apparent field independence of the observed (unsaturated) current argues for one of the first three states mentioned above. The polar state is probably ruled out since in weak coupling it has higher free energy than both the planar and ABM states which are degenerate in weak coupling. The weak-coupling assumption is probably a good one at saturated vapor pressure since the observed heat capacity anomaly is very near the BCS value.[8] It is known[2] though, that the BW state deforms continuously into the planar one as the magnetic field is increased. For no flow the (weak-coupling) crossover temperature is the same as T_{AB} in Eq. (1).

As mentioned above, T_M scales quadratically with H as does T_{AB} in Eq. (1). The slope, however, is larger than the weak-coupling T_{AB} value. We note that the theoretical T_{AB} depends sensitively on the Fermi-liquid parameter Z_0 since it is nearly -4. Our slope of 0.06 kG^{-2} is very nearly the same as Feder[9] finds for the AB transition at saturated vapor pressure with no superflow. We have made a naive estimate[10] of the possible hydrodynamic shift of T_M assuming the state above T_M is of the ABM variety with its $\hat{l}$ vector everywhere parallel to the flow. As an input to the calculation we take the current above T_M to be the experimentally observed value. The estimate of this shift comes out less than our temperature resolution.

In conclusion, we have observed marked effects of a magnetic field on flowing superfluid ^{3}He. The field distorts the ordinarily isotropic B-phase order parameter and above a certain temperature, T_M, appears to destroy it in favor of a different, field-independent state.

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[(a)]Permanent address: Department of Physics and Astronomy, Williams College, Williamstown, Mass. 01267.

[1]See, for example, A. J. Leggett, Rev. Mod. Phys. 47, 331 (1975).

[2]A. L. Fetter, in *Quantum Statistics and the Many Body Problem*, edited by S. B. Trickey, W. Kirk, and

J. Dufty (Plenum, New York, 1975).

[3]D. N. Paulson, H. Kojima, and J. C. Wheatley, Phys. Rev. Lett. 32, 1098 (1974).

[4]See, for example, M. Abramowitz and I. Stegun, *Handbook of Mathematical Functions* (Dover, New York, 1965). Approximately, $\zeta(3) = 2021$.

[5]This value of T_c comes from T. A. Alvesalo, T. Haavasoja, M. T. Manninen, and A. T. Soinne, Phys. Rev. Lett. 44, 1076 (1980). The value of Z_0 depends on the value of the effective mass m^* as detailed in J. C. Wheatley, Rev. Mod. Phys. 47, 415 (1975). We have used the m^* value given in T. A. Alvesalo *et al.*

[6]J. P. Eisenstein, G. W. Swift, and R. E. Packard, Phys. Rev. Lett. 43, 1676 (1979).

[7]These are the possible *unitary* states. See Ref. 1.

[8]T. A. Alvesalo, T. Haavasoja, P. C. Main, M. T. Manninen, J. Ray, and L. M. M. Rehn, Phys. Rev. Lett. 43, 1509 (1979).

[9]J. Feder, thesis, Ohio State University, 1979 (unpublished).

[10]J. Eisenstein, thesis, University of California at Berkeley, 1980 (unpublished).