Mobility of Positive and Negative Ions in Superfluid ^{3}He

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The mobility of positive and negative ions has been studied as a function of temperature, electric drift field, and (in the A phase) magnetic-field direction in superfluid ^{3}He; the A-phase mobility is observed to be anisotropic with $\mu_\perp > \mu_\parallel$ for both positive and negative ions.

Numerous interesting phenomena have been uncovered in studying ion motion in ^{4}He and ^{3}He-^{4}He solutions,[1] and it is reasonable to expect a similar situation in ^{3}He, especially in the superfluid phases. Several studies of normal ^{3}He have been carried out revealing the following general properties: The negative-ion mobility falls with temperature and becomes unexpectedly constant at low temperatures,[2-4] a phenomenon which was best explained by Josephson and Lekner.[1,5] In the vicinity of 150 mK and near the vapor pressure, the positive-ion mobility depends on the measurement conditions and, possibly, the purity[2,6,7]; as the temperature is decreased below this anomalous region, the mobility *rises*,[2,4] and appears to be approaching a constant value when the superfluid transition intervenes. It is perhaps not surprising that the positive and negative ions show distinctly different behavior, since their physical structure is quite different. The positive ion is a small cluster of ^{3}He atoms solidified around a $^3He^+$ ion by the attractive polarization forces and has a mass of approximately thirty ^{3}He atoms. The negative ion, on the other hand, is a large bubble surrounding a bare electron and has an effective mass of approximately 300 ^{3}He atoms.

Negative-ion studies in the superfluid A and B phases have been carried out recently by Ahonen *et al.*[8] They observed that the mobility increased rapidly as the temperature was decreased below T_c. In addition, they observed an electric-drift-field dependence of the mobility that was consistent with pair breaking for ion velocities above a Landau critical velocity, Δ/p_F, where Δ and p_F are the energy gap and Fermi momentum, respectively; above this threshold, the field-velocity plots took up a slope parallel to that for the normal liquid. A magnetic field, $\vec{H}$, was present during these measurements and was oriented perpendicular to the electric drift field, $\vec{E}$. For this geometry, the $\hat{l}$ vector in the A phase may lie anywhere in the plane perpendicular to $\vec{H}$ and thus at any angle with respect to $\vec{E}$. Since the direction of $\vec{H}$ could not be varied in these experiments, no information could be obtained on the anisotropy in the A phase; in addition, positive ions were not studied.

In the present Letter, we present new measurements of the motion of both positive and negative ions in the A and B phases of superfluid ^{3}He. Furthermore, new information on the anisotropic behavior of ions in the A phase was obtained by using an auxiliary magnetic field whose direction could be varied.

The ion mobility was measured in an epoxy cell which was attached via a threaded seal to the bottom of an adiabatic-demagnetization refrigerator employing cerium magnesium nitrate (CMN). The powdered CMN was used both as the refrigerant and as a thermometer, and was in direct contact with the ^{3}He liquid in the experimental cell. Tungsten field-emission tips were used to produce either positive or negative ions. The ions were produced in short current bursts, which were timed during transit through a region of uniform electric field. The details of the ion cell have been described elsewhere.[4]

Anisotropy effects in the superfluid A phase were studied in an auxiliary magnetic field, $\vec{H}$, of approximately 18 G. This magnetic field could be rotated so as to make an angle, θ, with respect to the direction of the electric drift field, $\vec{E}$.

The auxiliary magnetic field caused a shift in the CMN magnetic thermometer readings, relative to the zero-field readings. The magnitude of this shift was small for our geometry because the susceptibility axis was perpendicular to the auxiliary field, giving a minimum Casimir–du Pre effect. This shift has been determined by comparing magnetic-thermometer readings, with and without the auxiliary field, at certain fixed temperatures. The temperatures used were the superfluid transition temperature, T_c, and several temperatures corresponding to specific values of the mobility in the B phase, where the mobility is expected to be independent of the small auxiliary field. Calibration of the temperatures was achieved by measuring T_c* (the transition temperature indicated by the magnetic thermometer) as a function of pressure and using the La Jolla temperature scale[9] to convert to the actual temperature. Future adjustments in this provisional temperature scale would imply a corresponding adjustment in our indicated temperatures.

Figures 1(a) and 1(b) show the extrapolated zero-drift-field mobilities for positive and negative ions, respectively, at a pressure of 26 bars and a magnetic field of 18 G. Data are shown for several values of θ (the angle between $\vec{E}$ and $\vec{H}$) and a distinct anisotropy is observable in the A phase for both types of carriers. We note the following general characteristics: The negative-ion mobility rises much more rapidly than the positive-ion mobility, when each is compared to its normal-liquid value. When going from the B phase to the A phase, the negative-ion mobility shows a drop for all θ, while the positive-ion mobility shows an increase for small θ and a drop for large θ. In both cases, the mobility in the A phase decreases as θ is increased from 0° to 90°.

We now draw some conclusions regarding the anisotropy of the mobility tensor in the A phase. For lack of a better model, one can assume that the liquid is described by a texture where the $\vec{l}$ vector lies, on the average, uniformly distributed in the plane perpendicular to $\vec{H}$; one might refer to this as a "fan-averaged texture." This model (and we emphasize that it is only a model) leads to a mobility tensor with principal values $\mu_{11} = \mu_{22} = \frac{1}{2}(\mu_\parallel + \mu_\perp)$ and $\mu_{33} = \mu_\perp$; here the magnetic field is parallel to the 3 axis and $\mu_\parallel$ and $\mu_\perp$ refer to the components parallel and perpendicular to the A-phase gap axis, respectively, for a perfectly aligned sample. For an electric field oriented at an angle θ with respect to $\vec{H}$, the measured mobility, $\mu(\theta) = |\overleftrightarrow{\mu} \cdot \hat{E}|$, would be $\mu(\theta) = \mu_\perp \cos^2\theta + \frac{1}{2}(\mu_\parallel + \mu_\perp)\sin^2\theta$; with a similar model, the mobility in the absence of an external magnetic field would be $\langle\mu\rangle = \frac{2}{3}\mu_\perp + \frac{1}{3}\mu_\parallel$. References to

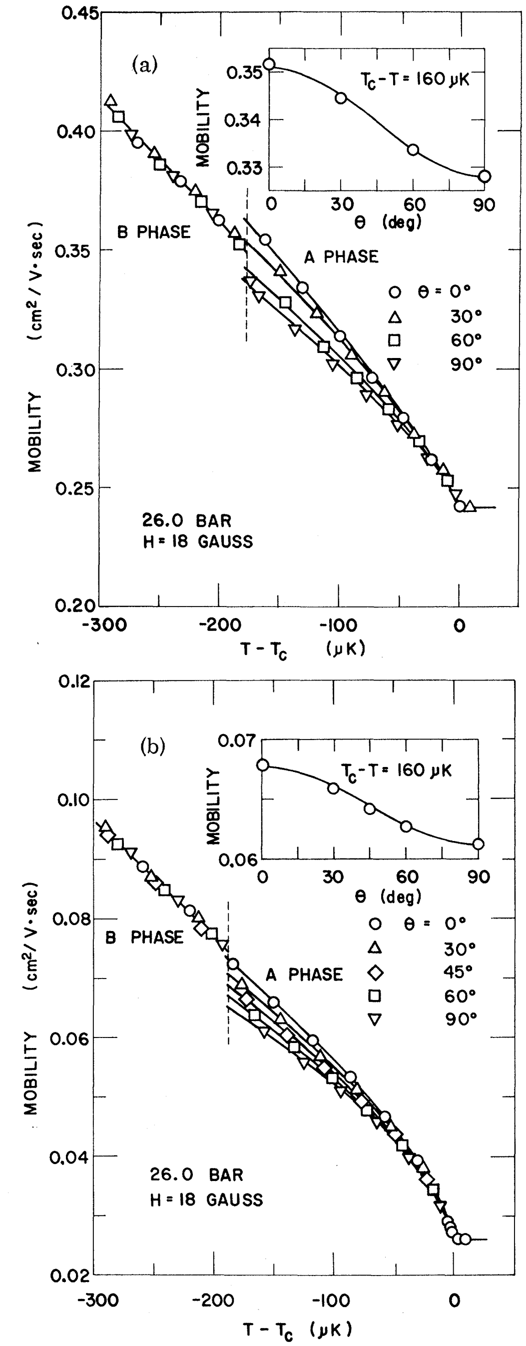

FIG. 1. The temperature dependence of the zero-field mobility of (a) positive ions and (b) negative ions in superfluid ^3He for various directions of the external magnetic field relative to the electric drift field; the inset shows the mobility anisotropy together with the "fan-averaged texture model" (see text).

Fig. 1 shows that $\mu(90°) < \mu(0°)$ and thus $\mu_\perp > \mu_\parallel$ for both types of carriers; this is the behavior one might naively expect since the gap vanishes along the gap axis, thus increasing the number of ther-

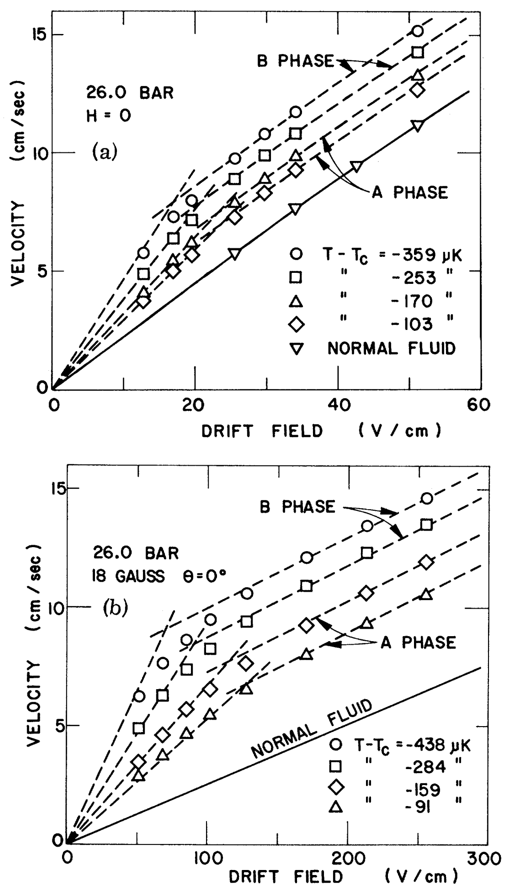

FIG. 2. The dependence of the velocity of (a) positive ions and (b) negative ions on the drift field in the normal and superfluid phases of ^{3}He; the dashed straight lines connect the points in the low- and high-field regions.

mally excited quasiparticles moving in the direction of the ion's motion (where maximum momentum transfer can take place). The insets in Figs. 1(a) and 1(b) show the angular dependence of the mobility for $T_c - T = 160$ μK; the line shows the fitted behavior expected from the above model.

We have also studied the drift-field dependence of the ion velocity, and this is shown in Figs. 2(a) and 2(b). For drift fields low enough to give an ion drift velocity below approximately 6 cm/sec, the velocity is linear with drift field. For higher drift fields, the velocity is no longer proportional to drift field but the nonlinear behavior is such that the curves all become nearly parallel to the normal-fluid curve; this is the same behavior observed by Ahonen *et al.*[8] The curves in Figs. 2(a) and 2(b) include data taken in both the A and B phases at a pressure of 26.0 bars. The general shape of the curves is the same in both phases and was not observed to depend on the auxiliary magnetic field.

For the negative ions, most of the data were taken in the linear region (below 100 V/cm). This was not convenient for the positive ions since the signal-to-noise ratio was rather poor for the required drift fields in the linear region (below 20 V/cm). A feature that emerges from these curves is that, for any particular drift field, a measured velocity is uniquely associated with a particular low-field slope, which is the desired mobility. In constructing Figs. 1(a) and 1(b), these velocity versus drift-field plots have been used to correct all data taken in the nonlinear-drift-field region to give the corresponding linear-region mobility; interpolation between the curves was used as needed.

Theoretical treatments of the ion mobility in superfluid ^{3}He have been given by Soda,[10] by Bowley,[11] by Baym, Pethick, and Salomaa,[12] and by Fetter and Kurkijärvi.[13] For the negative ions in the B phase, the calculation of Baym, Pethick, and Salomaa are in rather good agreement with the measurements of Ahonen *et al.*, which agree with ours in the temperature range of overlap. Recent calculations by Pethick[14] based on Bowley's work give the anisotropy of the mobility in the A phase, for temperatures near T_c, in the form

$$\mu_N/\mu = 1 - \alpha\Delta_{\max}/k_B T,$$

where $\Delta_{\max} \propto (1 - T/T_c)^{1/2}$, and α takes the values 0.42 for $\mu_\parallel$ and 0.47 for $\mu_\perp$. Our negative-ion mobility data in the A phase are about 30% higher than those given by these calculations and also have greater anisotropy. The temperature dependence agrees with this model only for $T/T_c > 0.98$.

An extension of the calculation of Baym, Pethick, and Salomaa to the A phase may improve the agreement between calculations and experiment for the negative ions. For the positive ions, no theory even predicts the normal-fluid temperature dependence adequately. The data presented here and in the earlier paper [4] should form a useful guide for theoretical studies of the positive-ion mobility in the normal fluid and in both superfluid phases.

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Fluctuation-Induced First-Order Phase Transitions Studied by the Monte Carlo Technique

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The critical behavior of a three-dimensional antiferromagnet described by a six-dimensional order parameter has been investigated by the Monte Carlo technique. A *first-order phase transition* is observed. This result is in agreement with the prediction of renormalization-group calculations in $4-\epsilon$ dimensions and with neutron scattering experiments on UO_2, but in contrast to the mean-field theory, which leads to a second-order phase transition.

Recently it was shown by Bak and co-workers[1] and simultaneously by Brazovsky and co-workers[2] that fluctuations may change a possible second-order phase transition into a first-order phase transition. The calculations were carried out within the framework of Wilson's renormalization-group theory in $4-\epsilon$ dimensions.[3] The theoretical derivation is based on symmetry arguments only and does not depend on the actual physical mechanisms involved. The first-order phase transitions are associated with a lack of stable fixed points of the Ginzburg-Landau-Wilson Hamiltonians corresponding to the actual systems. The nonexistence of stable fixed points is restricted to systems described by order parameters with $n \geq 4$ components. The first-order phase transition takes place when the correlation length exceeds a certain limit, where fluctuations in the order parameter make a discontinuous phase transition energetically favorable. These so called fluctuation-induced first-order phase transitions should take place even in cases where the mean-field theory predicts second-order phase transitions. The theoretical analysis was used to explain the observed first-order phase transitions in the antiferromagnets MnO, UO_2, Eu, and Cr.[1]

The validity of the hypothesis that absence of stable fixed points within the ϵ expansion leads to a first-order phase transition in *three dimensions* may be investigated by calculations on precisely defined three-dimensional models. In this Letter, we shall report a Monte Carlo calculation on a model defined in terms of a microscopic spin Hamiltonian which at low temperatures yields a magnetic structure similar to the magnetic structures of UO_2[4] and $NdSn_3$.[5] For a real spin system like UO_2, we very seldom know the details of the microscopic Hamiltonian governing the physical behavior. It is therefore virtually impossible to prove rigorously that an appropriate mean-field theory taking into account the actual physi-