For the magnetic field to conduct the flow of ions stably one needs $\beta \equiv 2\mu_0 p_h / B_\theta^2 \lesssim 1$,[5] which sets a limit to the laser-heated electron density. If the electron density far exceeds this limit, the process may suffer from magnetohydrodynamic instabilities, for which our theory is not valid. One then must take turbulent processes into account. Experimentally,[6] the duration of the electric field is much longer than the characteristic time τ_0, so that we can take the electron distribution to be static in the first approximation. However, our analysis is not completely self-consistent because the electric field is indeed modified by the motion of ions. But this does not change the essential physical picture of the process. For a more detailed analysis of this problem, further numerical simulations need to be carried out with additional experimental data.

We wish to thank Professor T. Sato and Professor A. Hasegawa for helpful discussions and all the members of Daisen Summer Seminar. Our original motivation for this problem arose from participation in this seminar organized by Professor C. Yamanaka. We also wish to thank Professor S. S. Yamamoto for helpful discussions and encouragements.

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Mobility of Negative Ions in Superfluid ^{3}He

A. I. Ahonen, J. Kokko, O. V. Lounasmaa, M. A. Paalanen, R. C. Richardson,* W. Schoepe,† and Y. Takano

Low Temperature Laboratory, Helsinki University of Technology, SF-02150 Espoo 15, Finland

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We have found that the mobility of negative ions increases rapidly below T_c in both superfluid ^{3}He phases. The ratio μ/μ_N of superfluid to normal mobility is larger in the B phase than in the A phase. A critical velocity consistent in magnitude with the Landau limit for pair breaking has also been observed. In the normal fluid we find a temperature-independent mobility between 30 mK and T_c for all pressures between 0 and 28 bars.

An issue of current interest is the temperature dependence of the excitation spectrum in superfluid ^{3}He. In this work we have extended previous studies[1,2] of the normal ^{3}He fluid down to T_c and have surveyed the ion behavior at several pressures in the superfluid phases of ^{3}He. Ions injected into liquid helium form tiny probes that are very useful in studies of the microscopic excitations of the fluid. In superfluid ^{4}He, ion experiments revealed a great deal about the density of phonon excitations[3] and about the hydrodynamic structures of the liquid such as the quantization of vortices[4] and even the spatial arrangement of vortex lines.[5]

We have found that the resistance of superfluid ^{3}He to the motion of negative ions decreases approximately exponentially with the inverse of the temperature at low temperatures. Our studies suggest that ion experiments may eventually provide a direct method for measuring the pairing energy gap Δ in superfluid ^{3}He.

There have been recent theories by Soda[6] and by Bowley[7] predicting an increase in the negative-ion mobility below T_c. Neither theory, however, predicts increases that are as large as those we have found. In sufficiently small electric fields the ionic drift velocity $\vec{v}_d$ is proportional to the field intensity and a mobility μ can be defined through the relation $\vec{v}_d \equiv \mu\vec{E}$. If the ion has a cross section σ the retarding force it experiences through collisions with n scattering centers per unit volume is $n\vec{v}_d \sigma p_F$, where p_F is the Fermi momentum of the excitations.[8] This force is balanced by that of the electric field $e\vec{E}$ and thus the mobility is $\mu = e(n\sigma p_F)^{-1}$. The principal information that we obtain from mobility measurements is knowledge about the density of the excitations that scatter from the ion to restrain its motion in the electric field. However, it may also be that σ changes when the liquid becomes a superfluid.[6,7]

Soda has calculated the mobility near T_c and has given numerical coefficients in the B phase and Bowley has given expressions for the ratio of the superfluid mobility to the normal mobility μ/μ_N for a wide temperature interval below T_c in both phases. In the B phase he obtains

$$\mu/\mu_N = \tfrac{1}{2}[\exp(\Delta/kT)+1]. \tag{1}$$

The mobility increases because the superfluid pairing decreases the number of excitations free to scatter from the ion. The A phase has a similar factor in the mobility ratio but the theory includes additional features related to the anisotropy of both Δ and σ. Bowley predicts that the mobility of ions moving parallel to the A-phase anisotropy axis $\vec{l}$ will be essentially the same as that of the B phase, while the mobility ratio for ions moving perpendicular to $\vec{l}$ will be approximately 10% greater than that of the B phase. In our experiment, unfortunately, the magnetic field was perpendicular to the electric field driving the ions. Since $\vec{l}$ may lie anywhere in the plane perpendicular to the magnetic field, its orientation with respect to the direction of the ion motion was not well determined.

The cooling method was the nuclear demagnetization technique we have previously described.[9] Temperature was measured using the nuclear magnetic susceptibility of the platinum powder. In the case of experiments in the A phase we also used measurements of the transverse frequency shift of ^{3}He to determine the temperature. The ^{3}He NMR signal was obtained from liquid in a slab of rectangular cross section 0.6 mm$\times$5.0 mm, located below the ion apparatus.

The apparatus is illustrated in Fig. 1. A narrow packet of electrons from a tungsten field-emission tip was driven across the 5-mm drift space with various electric fields.[10] When operating the tip several volts above the threshold potential for production of field-emission electrons, typically near 300 V, the heating of the ^{3}He by the ion current was negligible, less than 0.1 nJ per 100-msec pulse. However, operation of the tip by as little as 15 V above this threshold produced much larger current discharges which warmed the ^{3}He in the ion apparatus significantly above the temperature of the platinum thermometer. Therefore the ion current was kept small and at a particular temperature many repetitions of the experiment were stored in a signal averager.

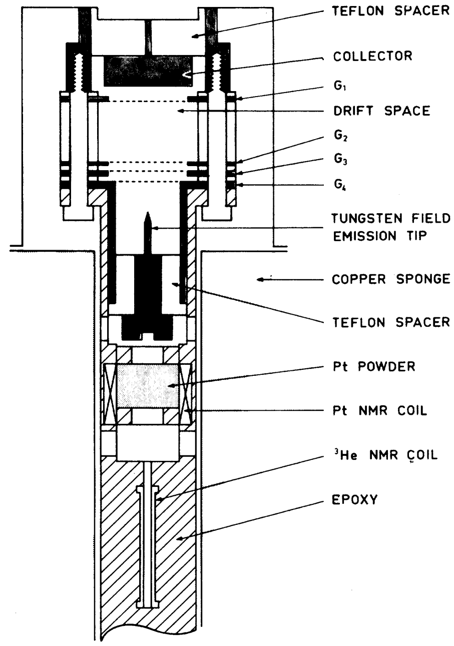

FIG. 1. The ion apparatus. The apparatus in the sketch was inserted within the ^{3}He sample volume of the nuclear demagnetization cryostat discussed in Ref. 9. A cloud of negative ions was produced through the pulsed application of typically −300 V between grid G4 and the tungsten field-emission tip. Typical pulse lengths were 100 msec repeated at 1- or 2-sec intervals. Brief gating of the normally repulsive potential on grid G3 shaped the cloud into a narrow packet and permitted its transit into the 5-mm drift space between grids G2 and G1. The drift velocity was determined through the analysis of the arrival time of the current pulse to an electrometer connected between G1 and the collector.

Further details about the method of the measurement and the analysis will be given elsewhere.

Before presenting our results for the mobility in the superfluid phases we will briefly mention our experiments in the normal fluid. Previous measurements by Anderson, Kuchnir, and Wheatley[1] and by Kuchnir, Roach, and Ketterson[2] showed that at high temperatures the mobility decreased as T^2, but below about 100 mK the mobility became independent of temperature.

In this work we have found excellent agreement (within 5%) with the earlier low-temperature values of the negative-ion mobility and find that the mobility remains constant down to T_c for pressures between 0 and 28 bars. At very low temperatures an increase in the mobility of normal ^{3}He had been expected[11,12] because the ion recoil forces the scattered ^{3}He quasiparticle to suffer a small energy loss and thus the quasiparticle must find a new and unoccupied state near the Fermi surface. The number of such empty states decreases with temperature. Evidently, the superfluid transition occurs at temperatures above that at which the recoil mechanism becomes important to the normal-fluid ion mobility.

In superfluid ^{3}He we have found two separate regimes of the ion motion: a low-velocity regime in which the drift velocity v_d varies linearly with the driving fields; and a high-velocity regime in which v_d is nonlinear.

Some of our results obtained in the linear regime, for which a mobility can be defined, are shown in Fig. 2. The data were obtained at two pressures, 18.0 and 28.4 bars, illustrating the B- and A-phase results, respectively. At 28.4 bars we observed a sudden large increase in the ion velocity as the liquid passed from the supercooled A phase into the B phase. A qualitative summary of the results is that (1) below T_c mobility of both superfluid phases increases rapidly; (2) at temperatures well below T_c the mobility varies approximately exponentially with inverse temperature; and (3) the B-phase mobility is greater than the A-phase mobility.

Our measurements in the A phase were much more reproducible than those obtained in the B phase, primarily because the thermometry was more direct and accurate. In the A phase the superfluid ordering produces an easily resolved

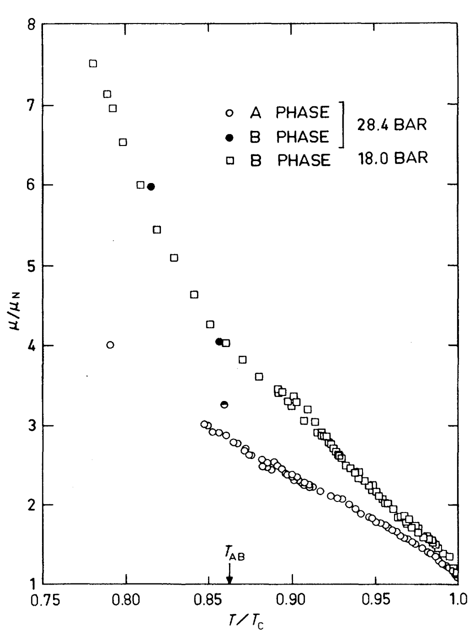

FIG. 2. The ratio of superfluid to normal mobility versus reduced temperature.

shift in the transverse ^{3}He resonance frequency, f, which obeys the relation[13]

$$f^2 = (\gamma H_0/2\pi)^2 + f_L^2(P, T/T_c), \tag{2}$$

where $\gamma H_0/2\pi$ is the frequency of the normal liquid and $f_L(P, T/T_c)$ is the characteristic longitudinal frequency of the A phase. We used our recent measurements[14] of $f_L(P, T/T_c)$ to determine the A-phase temperature scale. Changes in the frequency could be resolved to 10 Hz, corresponding to a temperature resolution of 0.05% in the particular magnetic field we used for the NMR measurements, 28 mT. Our frequency-shift thermometer had the additional advantage that its response time was practically instantaneous.

In the B phase our measurements were less satisfactory because the platinum thermometer provided only 0.5% temperature resolution and because the times required for thermal equilibrium in the platinum were unusually long for such thermometers.

The differences in the A- and B-phase values of μ/μ_N that we measured are opposite to those suggested in the theory of Bowley. In the temperature range of these experiments he predicted that μ/μ_N in the A phase would be either the same as, or at most 10% greater than, that of the B phase.

Since Δ is proportional to $(1 - T/T_c)^{1/2}$, Eq. (1) may be expanded near T_c in the form $(1 - \mu_N/\mu)^2 = a(1 - T/T_c)$, where $a = 2.3$. The value of a in the expansion by Soda[6] is 4 times smaller, $a = 0.58$. Unfortunately, neither Bowley nor Soda gives numerical expansions for the mobility near T_c in the A phase. We found the quantity $(1 - \mu_N/\mu)^2$ to be linear in the A phase only for $T/T_c \gtrsim 0.97$ and obtained the value $a = 4.1 \pm 0.5$. The rate at which the mobility increases below T_c in the B phase is clearly even greater than that of the A phase but our temperature resolution did not permit an accurate evaluation of the expansion parameter. It is evident that both theories quantitatively underestimate the size of the superfluid mobility.

The nonlinearity of the drift velocity of ions in the superfluid at high velocities is illustrated in Fig. 3, where some of the data obtained at low temperatures at 18 bars are shown. The A-phase data obtained at 28.4 bars is qualitatively similar to that shown. In the normal fluid we found the drift velocity to be linear in the electric field to at least 200 V/cm down to T_c. As the temperature was decreased below the superfluid transition, the range of electric field over which the

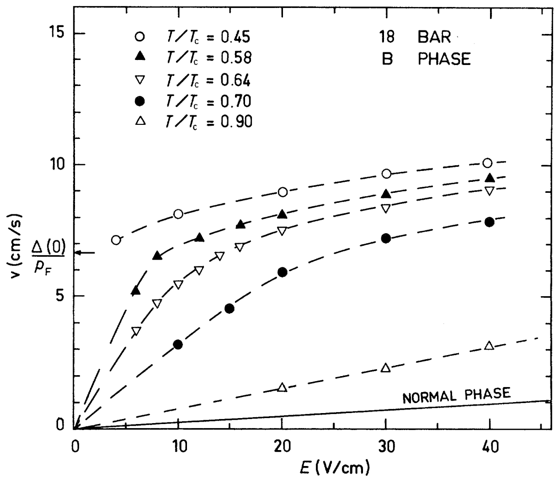

FIG. 3. Nonlinear drift velocities. The quantity $\Delta(0)/p_F$ is the Landau limit corresponding to the velocity for pair breaking at $T=0$.

drift velocity was proportional to the field strength decreased with temperature. At the lowest temperatures, $T/T_c < 0.5$, v_d became nonlinear at even the lowest field for which we could detect the arriving charges, 2 V/cm. Once the electric field required to produce drift velocities in the nonlinear regime had been exceeded, the slope of further velocity changes, dv_d/dE, approached that of the normal fluid.

Without a better theoretical understanding of the processes involved in limiting the ionic motion, it is difficult to know how to use the information shown in Fig. 3 to extract a value of the critical velocity for each temperature. Behavior similar to that shown in the figure is seen in superfluid ^{4}He when the ion velocities exceed the Landau limit and the ions begin to excite rotons.[15] For superfluid ^{3}He the analogous critical velocity is that at which the collision energy $2p_F v_d$ exceeds 2Δ and breaks the superfluid pairs.[7] At the pressure 18 bars, the BCS value of $\Delta(0)$ is $1.764kT_c$ and the corresponding Landau limit at $T=0$ is 6.7 cm/sec. This is the magnitude of the maximum drift velocity that we observed in the linear regime. At the lowest temperatures the mobility becomes so large that very small fields will force the ions to this limiting velocity.

In this work we have made only a brief survey of the possibilities that exist for using the studies of ion motion to obtain fundamental new information about superfluid ^{3}He. Ultimately, we hope that satisfactory theories will exist so that both the mobility and the ionic critical velocity can be used to make a direct mapping of the temperature dependence of the energy gap. The entire question of using the ion mobility as a probe for identifying the anisotropy of the A phase remains to be investigated. Another category of interesting experiments for the future is the use of ions as a tool for locating and/or creating possible hydrodynamic structures in superfluid ^{3}He.

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*Guggenheim Fellow on leave from Cornell University, Ithaca, N. Y. 14853.

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Symmetry of Orientational Order Fluctuations about the Nematic-Isotropic Phase Transition: An ESR Study*

K. V. S. Rao, J. S. Hwang, and J. H. Freed
Department of Chemistry, Cornell University, Ithaca, New York 14853
(Received 3 May 1976)

The ESR relaxation of a weakly aligned spin probe dissolved in N-[*p*-methoxybenzylidine]-*p*-butylaniline has been studied near T_c, the isotropic-nematic transition. Spin relaxation due to critical orientational fluctuations is observed on either side of T_c and is characterized by a symmetry about T_c that is rather well explained by simple Landau–de Gennes mean-field theory for the weak first-order transition.

Orientational order fluctuations have been studied above the nematic-isotropic phase transition (T_c) by light scattering[1,2] and NMR techniques[3,4] in particular and have been successfully interpreted in terms of the Landau–de Gennes theory,[5,6] which treats the transition as almost second order. Such mean-field theories predict that critical fluctuations should also be observed as T_c is approached from below. However, light-scattering and NMR observations in the nematic phase are usually found to be dominated by fluctuations in the nematic director, and no serious attempts appear to have been made to study order fluctuations below T_c. In this Letter, we report an ESR study of spin relaxation of a weakly ordered spin probe (PD-tempone) dissolved in N-[*p*-methoxybenzylidine]-*p*-butylaniline (MBBA) both above and below T_c. It appears to confirm the essential symmetry of order fluctuations about T_c as predicted by simple mean-field theory, modified for the weak first-order nature of the nematic-isotropic transition.

The experiments were performed with $5\times10^{-4}M$ solutions of the nitroxide spin probe PD-tempone[7,8] dissolved in singly distilled MBBA. The sample reported here had $T_c = 41.4°C$ compared to 42–43°C for pure solvent. ESR spectra were obtained at 9.2 GHz with a Varian E-12 spectrometer using a thermostated Be-Cu vessel containing a slow-wave helix.[7a] The temperature of the system can be controlled to within ± 0.01°C. The temperature of the fluid surrounding the vessel containing the sample could be measured to within ± 0.05°C with a Cu-Constantan thermocouple or to within ± 0.01°C with a Pt resistance thermometer.[7b] The degassed sample is either sealed in a capillary tube of the same length as the helix, or is in a sealed Teflon container.[7a]

We show in Fig. 1 typical ESR spectra in the coexistence region of the isotropic and nematic phases. Such a coexistence region is due to small amounts of impurity and has been reported in a few light-scattering studies.[2] (The small quantity of spin probe is expected to be only a minor impurity affecting the coexistence.) We observe two sets of overlapping spectra in the range $T_c \pm 0.2°C$ as a result of the spin probe dissolved in

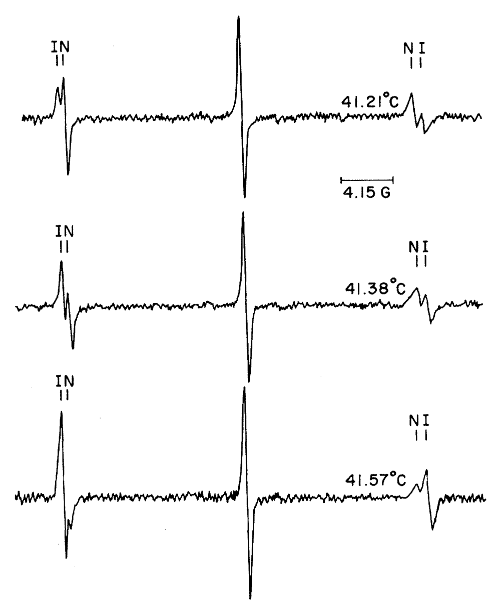

FIG. 1. ESR spectra of PD-tempone in MBBA near $T_c = 41.4°C$. The three main lines are due to the hyperfine splitting from a single ^{14}N nucleus. The peaks marked I and N correspond to isotropic and nematic phases, respectively.