through second order; clearly the result is causal on the τ_0 scale and acausal on the τ_2 scale.

The nonadiabatic approximation implies the use of the fully causal Green's function.[5] The results for the two-body correlation function $G(\vec{x}, \vec{x}_1, \vec{v}, t) = G_1$ can be extended to s bodies. Writing

$$F^s = K_{1,2,\cdots,s-1} + \sum_c K_{i_1,\cdots,i_{s-2}} + \cdots + \sum_{i=1}^{s-1} G_i + F,$$

where the index c in the second term denotes combinations of $s-1$ indices in $s-2$ places, it can be shown by induction that the s-body correlation function satisfies $[\partial/\partial t + \vec{v}\cdot\nabla]K_{1,2,\cdots,s-1}$ = source term involving lower-order correlations, where terms of magnitude ϵ or smaller in the s-body and higher correlation functions have been dropped. From this equation, we see that the exact Green's function for the s-body correlation is causal and of the same form as for two bodies. Our previous remarks on the Bogoliubov and time-scales approximations also extend without difficulty.

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Exotic Negative Carriers in Liquid Helium*

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We have confirmed the existence of a new negative carrier of high mobility in superfluid helium, reported by Doake and Gribbon, and determined its zero-field mobility. We suggest that it may be the negative helium ion in a small cavity in the liquid. A series of carriers with mobilities between that of the "fast" and the "normal" (electron bubble) carrier is also shown to exist.

Doake and Gribbon,[1] in a brief note, have reported the discovery of a negative carrier in superfluid liquid helium having a mobility substantially larger than that of either the negative or positive carrier which have been studied extensively in many laboratories for more than a decade.[2] We report in this Letter confirmation and extension of their results, experiments and some speculative discussion on the nature of the carrier, and evidence indicating the existence of a large family of negative carriers. The usefulness of a weak electrical discharge in the vapor as a source of ions is also shown.

In their experiments Doake and Gribbon produced both normal and fast negative carriers from an α source (presumably immersed in the liquid) and measured velocities by the method of Cunsolo.[3] We have employed a time-of-flight method, applying a short gate pulse between two grids (G_1 and G_2) and detecting the arrival of a group of carriers at the collector C by using a fast electrometer and signal averager. Figure 1(a) shows a diagram of the cell with two types of source. Figure 1(b) is a representative recorder trace showing both the normal and fast negative carriers. Measurement of the velocity of the new carrier versus the applied electric field in the drift region confirms the result of Ref. 1: The fast carrier apparently reaches a limiting velocity governed by roton emission, and does not produce vortex rings in the range of temperatures and fields we have studied. We are able to operate at sufficiently weak electric fields to study the region where the drift velocity is proportional to the drift field and to obtain a mobility in the temperature range from 0.95 to 1.2 K. The temperature dependence of the mobility is shown in Fig. 2, curve 1, and although the range of temperature is limited, the dominance of roton scattering in determining the friction is

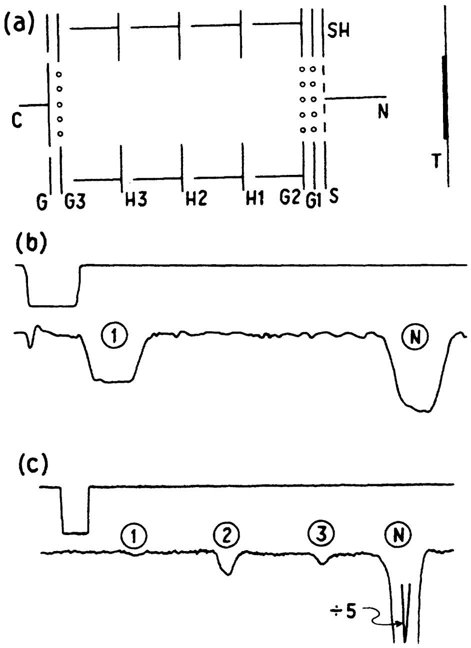

FIG. 1. (a) The experimental cell. S is the source plane containing either a perforated disc (SH) or a tritium β source (T)—the needle (N) is used with the "shower head" source and is grounded (potential of C, the collector); H_1, H_2, and H_3 are field homogenizers; G_3 is a Frisch grid. The drift region (G_2 to G_3) is 2.6 cm long. (b), (c) Typical recorder traces of data with gate reference pulse; the abscissa represents time, and the ordinate is collected current. (b) Fast (1) and normal negative (N) pulses; trace length is 0.010 sec. (c) Two intermediate (2 and 3) and the normal negative (N) pulses—the fast-ion pulse (1) is barely perceptible; trace length is 0.020 sec.

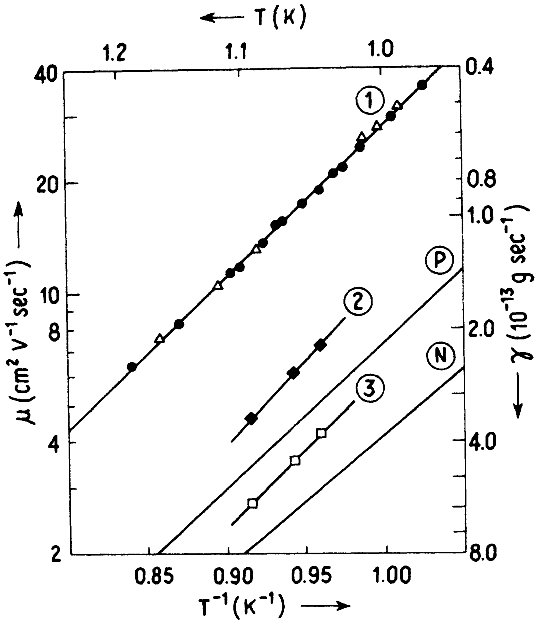

FIG. 2. Mobility μ and friction coefficient (force/velocity) γ versus reciprocal temperature T^{-1} and temperature T for charge carriers in liquid helium. Curve 1 is for the fast ion; the line has a slope of 9.6 K; the two symbols denote data taken three months apart in two different apparatus with 2% errors. Curves 2 and 3 are for intermediate ions. Curves P and N are for the normal positive and negative ions, respectively (mobilities were taken from Ref. 2).

clearly indicated.

In addition to asking what the nature of the new carrier may be, one might also inquire why neither we nor other workers in this field had detected it previously. Our first experiments were carried out in a cell previously used to measure the mobility of potassium impurity ions in liquid helium[4]; it had a tritium β source at the *top* of the cell and the collector at the bottom, and was normally filled to a few millimeters above the source and all exposed electrical leads. Experiment showed that the key variable determining the strength of the signal was in fact *the level of the liquid*; the fast carrier was undetectable unless the liquid level was set less than 3 mm above the β source. When voltages were applied to the cell, visual inspection revealed that the liquid meniscus distorted near the source, and the signal appeared only when the liquid surface came into contact with the source, at which point the surface took on an unstable appearance. Best signals were seen when a visible glow discharge appeared in the vapor. At this stage we had only observed fast carrier pulses for rather high values of source and drift electric fields (as was the case in Ref. 1). But these were needed only to produce the large surface distortion and glow discharge and were not an inherent property of the carriers. Apparently, with high enough fields, an α source can produce a fast ion signal as in Ref. 1.

We incorporated into the cell a bellows, permitting careful and reversible adjustment of the liquid level without adding or removing material, and have operated both with the tritium β source and with an electrode structure designed to produce a controlled discharge [SH and N in Fig. 1(a)], dissipating only a few milliwatts in the region of the liquid surface. With the discharge source, and with the liquid level set at the perforated plate (SH), sizable fast-ion currents (of order 10^{-12} A) are readily produced at temperatures up to 1.2 K. Points taken with the β source and with the discharge source are both shown in Fig. 2. There is no doubt that the same carrier can be produced by either source (as well as by the α source of Ref. 1).

There are several obvious models for the fast carrier. It might be a free ("conduction-band") electron. This possibility seems ruled out because the mobility is too low by two orders of magnitude and, at the modest drift fields employed here, a free electron is expected to form a bubble state in a very short time. It might be an impurity ion. This model seems to be impossible because both theory[2, 5] and experiment[4] indicate that any massive ion, positively or negatively charged, will have a mobility very near that of the normal positive carrier. This new carrier has a mobility significantly higher. It might be a one- or two-electron bubble in some state other than the ground state. We can think of no state which would be stable and have a mobility six times higher than the ground state. It might be related to He^3 impurities; to test this idea we raised the He^3 concentration from the natural abundance to 100 ppm with no measurable effect. Finally, it might be a state related to that of the negative helium ion, known to occur in vacuum. Since we seem able to rule out all other possibilities we have thought of, we have concentrated on experiments to test this last hypothesis.

The free negative atomic ion occurs in a $1s2s2p$ ^4P state and is bound by 0.08 eV relative to a 2^3S metastable atom and a free electron.[6] This bound system would presumably carve out a cavity smaller than the free electron,[7] and yield a higher mobility. The $^4P_{5/2}$ substate decays *in vacuo* by Auger emission of an electron in an f wave with a lifetime of 345 μsec, whereas the fine-structure states of smaller J can decay by emitting a p-wave electron, and have a considerably shorter lifetime[8] (11 μsec). We have observed the new carrier in liquid helium to be stable for flight times up to 10 msec with no evidence of decay into a free electron (which would quickly form a bubble), so that if this carrier is identified with the free negative ion the Auger process must be inhibited in the liquid. Further, the lifetime of the free ion is markedly shortened by application of a magnetic field of a few hundred gauss, which mixes the long- and short-lived states.[8] We have observed the fast carrier in the presence of magnetic fields up to 1.2 kG without detecting any differential reduction of the fast-carrier signal relative to the normal one, or any carriers with intermediate transit times. A final negative result may be mentioned: Energetic *neutral* excitations are known to be quite stable in liquid helium, but they are efficiently quenched by the addition of impurities.[9] We have admitted up to 1000 NTP cm^3 of air to the lead tube connecting the cell with room temperature (we have no way to know how much material reached the liquid) and observed no change in the intensity of the fast-ion signal.

In spite of these negative results we are still inclined to picture the new carrier as a He^- ion in a bubble, the principal argument in favor of this picture being that all others seem more rigorously excluded. An additional (weak) argument in its favor is that the source conditions which favor its production would be expected to lead to production of metastables in the vapor and a liquid surface charged with electrons, which might efficiently produce these ions by the reaction $He^* + e^- \rightarrow He^-$ in the presence of other bodies to absorb the energy released. The Auger process $He^- \rightarrow He + e^-$ may be inhibited in the liquid since the He^- wave-function tail will be truncated by the vacuum-liquid interface of the bubble, causing poor overlap with the Auger-electron wave function. Also, the liquid should be a large perturbation on the various J-state energy levels, and, in fact, J may not be a good quantum number. This would make the vacuum magnetic quenching theory inapplicable.

Finally we must note that when the liquid level in the cell is lowered still further, until it is between the source and source grid, qualitatively new phenomena appear. The normal-ion pulse becomes very strong, the fast-ion pulse becomes very weak, and a series of pulses of intermediate transit times appears. A recorder trace taken under these conditions is shown in Fig. 1(c). These appear to be genuine charged-particle signals; their mobilities are plotted versus temperature in Fig. 2, curves 2 and 3. Negative carriers with still different mobilities have also been observed. These might be bubbles containing either electrons alone or combined with excited states of the helium atom (such as other substates of the ^4P complex), or some undreamed-of new species. The catalog of charge carriers in liquid helium may be far richer than we have known (or would wish). As a final observation we note that when polarities in the cell are reversed we observe only the usual positive-ion pulse; no anomalous positive carriers have been detected in these experiments.

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Demonstration of a Body Force Produced on a θ-Pinch Plasma Column by Helical Magnetic Fields*

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We report experiments in which small helical magnetic fields are added to the basic confinement field of a 3-m-long θ pinch. A combination of these fields having $l=1$ and $l=0$ symmetries produces a transverse body force on the plasma column. The strength of the body force has been measured by studying the plasma dynamics and is found to be in agreement with the theoretical value.

When a straight θ pinch is bent into a torus, the plasma is no longer in equilibrium, and the magnetic pressure gradient of the longitudinal field B_0 pushes the plasma towards the outside of the torus. In order to overcome this effect small transverse fields in addition to the basic longitudinal field must be introduced. One approach is to use helical fields[1] whose scalar potentials are of the form

$$\chi_l = (B_0/h)[C_l I_l(hr) + D_l K_l(hr)] \sin(l\theta - hz). \quad (1)$$

The equilibrium and stability of this system for a sharply-bounded, straight, θ-pinch plasma column has been treated extensively in the magnetohydrodynamic approximation.[2-4] Recently Ribe and Rosenbluth[5] and Weitzner[6] showed that a combination of fields characterized by l and $l \pm 1$ might be used to give a uniform transverse body force to counteract the toroidal pressure gradient and also to feedback stabilize the expected $m=1$ instability. In this paper we report an experiment in which $l=1$ and $l=0$ helical fields are applied to a 3-m-long straight θ pinch. We demonstrate that this combination of fields produces a transverse body force and infer its magnitude and direction from the motion of the plasma column.

For this experiment the main helical field has $l=1$ symmetry with a longitudinal period of 30 cm ($h = 2\pi/30$ cm^{-1}). For a high-β (ratio of plasma pressure to external magnetic field pressure) plasma, magnetohydrodynamic theory[2,3] predicts that this configuration should have a lower $m=1$ instability growth rate than for fields with other l values. In order to produce the body force an additional smaller $l=0$ field was applied. The effect of these fields on a straight plasma column of radius a is to produce excursions δ_l of the plasma radius about $r=a$ given by

$$r = a[1 + \delta_l \cos(l\theta - hz)]. \quad (2)$$

The experiments were performed on the Scylla IV-3 θ pinch[7] whose main capacitor bank has an energy storage of 700 kJ at 45 kV and produces a magnetic field B_0 inside the 3-m-long, 13.5-cm-diam main compression coil which rises to 42 kG in 3.7 μsec. At maximum field the bank is crowbarred (shorted), giving a peak-to-peak modulation of the nearly constant magnetic field of 20%.[7]

Figure 1 shows the arrangement of the $l=1$ and $l=0$ coils inside the main compression coil.