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Investigation of a New Kind of Energetic Neutral Excitation in Superfluid Helium*

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We present evidence for the existence of a new kind of neutral excitation generated in superfluid helium in the presence of a Po^{210} α-particle source. The flux of neutral excitations is negligibly small above 0.6°K and increases as the temperature is decreased. The neutral excitations travel in the liquid at low temperatures through distances greater than 1 cm without appreciable scattering or attenuation. They produce He_2^+ ions and electrons at the free surface of the liquid, and positive ions and electrons at a suitably arranged metal plate immersed in the liquid. Experiments indicate that these neutral excitations are not photons. A possible model for the neutral is some kind of exciton. In addition, we also present evidence that, at temperatures below 1°K, electrons within superfluid helium may emerge from the liquid into the vapor above its surface when they arrive at the liquid surface trapped in vortex rings. No such behavior is observed for positive ions.

I. INTRODUCTION

Foreign particles such as neutrons, He^3 impurities, and charged particles have been introduced into liquid helium in order to study its superfluid properties and its elementary excitations (quasiparticles) close to the ground state.[1] At sufficiently low temperatues, the interactions between quasiparticles are small so that the properties of individual excitations become apparent. Thus charged particles have been used to investigate the scattering of ions by phonons, rotons, and He^3 impurities.[2] The detailed structures of the ion complexes formed in liquid helium have also been studied.[3] Furthermore, charged particles have been used to create quantized vortex rings in superfluid helium and to probe the nature of quantized vortex lines and rings.[4,5] Study of the motion of these vortex rings has also yielded information about the scattering between vortex lines and phonons, rotons, and He^3 impurities.[5] In the present paper, we shall be concerned with effects which occur at low temperatures when ions in superfluid helium arrive at the free surface of the liquid. Our predominant interest, however, will be the investigation of a new kind of *neutral* excitation which is free to travel in the liquid and is capable of producing charged particles at its surface.

The basic experimental arrangement used in our experiments is similar to that of Rayfield and Reif;[5] the main difference is that the demountable vacuum-tight seals consists of indium O rings instead of solder joints. A nonrecirculating He^3 refrigerator is used to achieve temperatures as low as 0.3° K. Temperatures are measured with a calibrated germanium resistance thermometer. A typical experimental arrangement in the sample chamber is shown in Fig. 1. The ion source S, immersed in liquid helium, consists of a metal disk plated with Po^{210}. α particles from S produce ions and electrons within a 0.2-mm thick layer of liquid adjacent to S. Electric fields in the apparatus are adjusted by potentials applied to the source S and to metal grids placed between S and the collecting electrode C. Currents arriving at C are measured with a vibrating-reed electrometer. The sample chamber, source, grids, and collector are gold-plated to prevent oxidation which can result in the formation of undesirable insulating layers.

In the typical experimental arrangement shown in Fig. 1, we shall be concerned with charged particles which emerge from the liquid surface into the vapor above the liquid and then impinge on the metal collector C. The temperatures used in most of our experiments were below about 0.6°K; the mean free path of an ion or electron in the vapor is then greater than the size of the apparatus (~1 cm), so that the vapor region is effectively a vacuum. Under these conditions, the current measured at the collector C located in the vapor region is found to vary with the energy of the charge carriers impinging on C, presumably because of the ejection of secondary electrons and positive ions from the collector. It is found that this difficulty can be circumvented by applying to a grid B', located immediately in front of C, a potential difference of about 40 V and of a sign

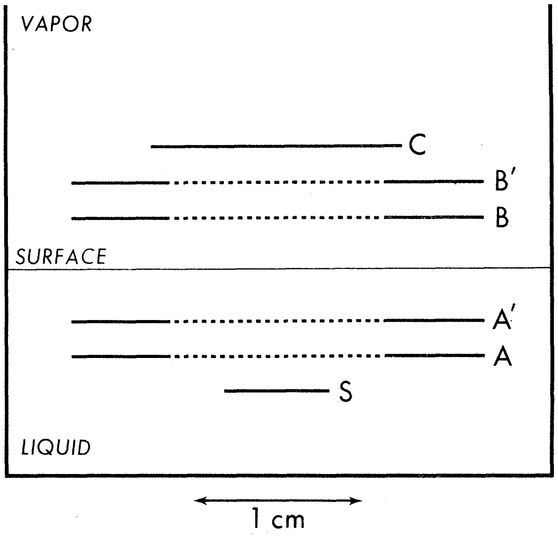

FIG. 1. Typical experimental arrangement showing the ion source S, the collector C, and several grids A, A′, B, and B′. The surface of the liquid lies between A′ and B.

such that incoming charge carriers are accelerated toward C. The current collected by C then becomes approximately independent of the energy (0–40 eV) of the charge carriers traveling in the region between the liquid surface and B′. This charge-collecting arrangement has been used in all experiments where the collector is located in the vapor above the liquid.

In previous work at temperautres above 1°K, it was found that current emerges from liquid helium into the vapor above its surface in the presence of an applied electric field normal to the surface, and that this current decreases as the temperature is decreased.[6] This work showed that negative ions are extracted from the liquid more easily than positive ions, but that both the negative and positive currents become vanishingly small as the temperature is decreased below about 1°K. Recently, however, we have reported[7] finding a distinctly new temperature regime (below about 0.7°K) where the current extracted from the liquid surface *increases* as the temperature is decreased. This current can be shown to consist of two contributions of comparable magnitude. One of these, which we shall call the *anomalous current*, is completely independent of any electric fields existing within the liquid; it is the only current observed if these fields are such as to stop the passage of charged particles from the source S to the liquid surface. The remaining part of the current, operationally defined as the total current minus the anomalous current, will be called the *normal current* since it does respond to electric fields within the liquid.

In the following sections we shall study these two current contributions in detail. In the case of the normal current, we shall be principally concerned with its origin at low temperatures and with the mechanism by which the charge carriers emerge from the liquid. In particular, we shall show that this behavior is related to the formation of charged vortex rings in the liquid. In the case of the anomalous current, which is insensitive to electric fields existing inside the liquid, we present evidence showing that it is due to a new kind of *neutral* excitation in superfluid helium. A detailed investigation of the properties of this neutral excitation will be the primary concern of this paper.

II. NORMAL CURRENT AND VORTEX RINGS

At temperatures between 0.7 and 1.0°K, no observable current is detected at a collector C in the vapor above the liquid, even in the presence of electric fields (up to 100 V/cm) which accelerate charged particles from the region near the source to the collector. Below about 0.7°K, *normal* current (i.e., current which responds to electric fields in the liquid) is observed at C. This normal current is of negative sign.[8] It is vanishingly small above 0.7°K, increases rapidly as the temperature is decreased between 0.7 and 0.6°K, and is relatively constant (within 20%) from 0.6 to 0.3°K (the lowest temperature attainable in our apparatus).

Previous work has shown[5] that ions in superfluid helium can form vortex rings and be trapped by them. At temperatures below about 0.7°K, these vortex rings can grow to large sizes (i.e., can acquire large energies) and can travel through the liquid with negligible loss of energy. On the other hand, at temperatures appreciably above 0.7°K, the energy loss of these vortex rings in the liquid is large so that the rings are quickly reduced to negligible size. Thus, in the temperature region where the normal current due to charges emerging from the liquid is varying rapidly, the number of charged vortex rings arriving at the liquid surface is also varying rapidly. In fact, the temperature dependence of the current of charged vortex rings traveling through the liquid (and then arriving at its surface) is found to agree quite well with the temperature dependence of the normal current of charges emerging from the liquid surface.[9] Furthermore, at low temperatures where these vortex rings lose negligible energy, the current of charged vortex rings detected at a collector immersed in the liquid is equal (within 10%) to the normal current detected at a collector in the vapor. Thus the normal current *emerging from* the liquid surface has essentially the same magnitude and temperature dependence as the vortex ring current *arriving at* the liquid surface. Hence we arrive at the following conclusion: At temperatures below 1°K, negative charges in the liquid can emerge into the vapor above its surface only if they are trapped in vortex rings in the liquid.[10]

Using the arrangement of Fig. 1, it is readily possible to determine the energy of the charge carriers responsible for the normal current. The current collected at C is measured as a function of a retarding potential applied between grids B and B′. It is found that, in the absence of an applied electric field in the region between A′ and B, the negative carriers arriving at B have energies up to about 0.8 eV. This energy is, however, not equal to the energy of the charges emerging from the liquid surface since a correction must be made for space charge effects arising from the slowly moving vortex rings near the surface of the liquid. These charged rings produce in the region between the surface and B a small electric field which accelerates the charge carriers so that their energy at B is larger than that at the liquid surface. The size of this space-charge effect can be estimated by knowing the magnitude of the normal current, the velocity of the vortex rings, and the geometry; it is large enough to account for about 0.5 eV of the energy of the carriers at B. (When the distance between grids A′ and B is decreased, the energy of charge carriers at *B* decreases roughly by the amount predicted by this estimate.) Thus our measurements (carried out on vortex rings with energies between 5 and 50 eV) lead to the following conclusion: The negative charge carriers emerge from the liquid surface with an energy which is essentially negligible ($\lesssim 0.3$ eV); furthermore, this energy is independent of the energy of the charged vortex rings arriving at the surface.[11]

To determine the nature of the charge carriers escaping from the liquid into the vapor, their charge-to-mass ratio Q/M was measured with the arrangement shown in Fig. 2(a). Charge carriers emerging from the liquid are accelerated by a known electric field $\vec{E}$ in the region between the liquid surface and the plate D. A slit in D collimates the charge carriers as they enter the region between D and D′. If the carriers are not deflected, they strike the plate D′ and are not collected at C. But if a magnetic field B of the proper magnitude is applied in a direction perpendicular to the plane of Fig. 2(a), the charge carriers will be deflected while traversing the region between the liquid surface and D′ and thus will be collected at C after passing through one of the slits in D′.[12,13] The magnitude of this magnetic field determines then the charge-to-mass ratio of the negative normal charge carrier. The result was found to be

$$Q/M = (0.97 \pm 0.15)e/m, \qquad (1)$$

where e/m is the charge-to-mass ratio of a free electron. Hence the charge carriers responsible for the normal current are electrons. This experiment also shows unambiguously that these charge carriers do travel through the vapor and not along possible leakage paths provided by the walls of the container. In summary, we conclude that the negative normal current is produced by negative charge carriers (presumably electrons[3]) which are trapped in vortex rings while they travel from the region near the source to the liquid surface, then emerge from the vortex rings and the liquid, and finally travel as electrons through the vapor to the collector.

Using the arrangement of Fig. 2b, an upper limit can be placed on the time τ_0 necessary for an electron to emerge from a vortex ring into the vapor above the liquid. The vortex ring current is turned on and off by rectangular voltage pulses applied to the grid P_1 located in the liquid. The current of electrons traveling through the vapor to the collector is then turned on and off by voltage pulses applied to the grid P_2. A measurement of the current arriving at the collector C as a function of the time delay between the pulses applied to P_1 and P_2 allows one to estimate the total time τ required for charges to travel from the region near P_1 to that near P_2. The time τ_1 required for a vortex ring to travel from P_1 to the liquid surface can be calculated from the known relation between the velocity and energy of a vortex ring;[14] the time required for electrons with energies of several electron volts to travel through the vapor from the liquid surface to P_2 is negligible. Hence the measurement allows one to deduce the time $\tau_0 = \tau - \tau_1$ required for an electron to emerge from a vortex ring within the liquid into the vapor above. This time τ_0 is found to be negligibly small ($< 10^{-3}$ sec) and, within the experimental error, independent of the energy of the vortex ring arriving at the liquid surface.

The behavior of the normal current below 1°K may thus be summarized in the following way: Electrons emerge from the liquid surface at temperatures below 0.7°K where the electrons form, and are trapped in, vortex rings in the liquid. They emerge with little or no time delay ($<10^{-3}$ sec) and with negligible energy ($\lesssim 0.3$ eV). On the other hand, *positive* ions in the liquid do not emerg from the surface (even in the presence of electric fields up to 100 V/cm) although, at temperatures below 0.7°K, they too are trapped in vortex rings which arrive at the liquid surface.[10]

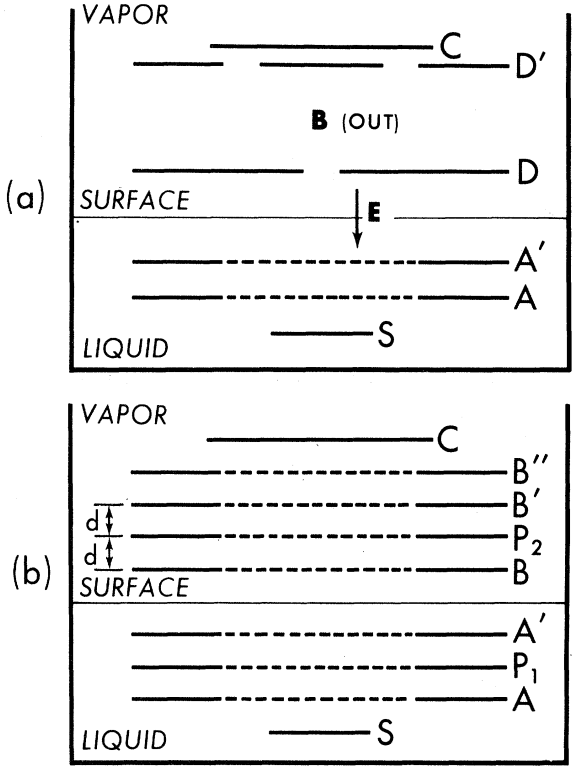

FIG. 2. (a) Arrangement for the magnetic deflection experiment used to determine the charge-to-mass ratio of negative charge carriers in the vapor. (b) Arrangement of grids for time-of-flight experiments.

Note added in proof. In a recent publication [Phys. Rev. Letters 21, 74 (1968)] S. Cunsolo, G. Doll'Oglio, B. Maraviglia, and M. V. Ricci report that, when a negatively charged vortex ring arrives at the surface of liquid helium, the electron trapped in the ring is ejected into the vapor region with a kinetic energy equal to the original energy of the vortex ring. It should be pointed out that our experimental results, discussed in Sec. II, appear to contradict the findings of these authors, since we found that the electrons are ejected with negligible energy (≤ 0.3 eV) irrespective of the energy (between 5 and 50 eV) of the vortex ring arriving at the liquid surface.

III. ANOMALOUS CURRENT AND NEUTRAL EXCITATIONS

A. Evidence for the Existence of Neutral Excitations

The fact that the *anomalous current* does not respond to electric fields inside the liquid indicates that it is due to some kind of *neutral* excitations which travel through the liquid before becoming converted to charged particles at the liquid surface. To substantiate this inference and eliminate the possibility of spurious effects, the following experiments were performed: The anomalous current was shown to be an increasing function of the strength of the source S and to be vanishingly small when this source is absent; thus the anomalous current clearly depends on the presence of the source. The anomalous current was still observed when the source was enclosed in a container made of solid metal except for one wall in the form of a metal grid; thus the anomalous current is not due to stray ion currents traveling from the source to the surface along some unsuspected path. Measurements by magnetic deflection and time-of-flight techniques, described in detail later on, indicate that the charge carriers responsible for the current do travel through the vapor; thus the anomalous current cannot be due to charges which originate at the liquid surface and arrive at the collector by traveling in the superfluid helium film covering the walls of the container. Finally, the anomalous current can be detected not only at a collector in the vapor above the surface of the liquid, but also at a suitably arranged metal plate immersed inside the liquid. All these tests confirm the conclusion that the anomalous current is due to some kind of neutral excitation which is created in the region near the source and then travels through the liquid.

B. Properties of the Neutral Excitations

1. *Generation of the Neutral Excitations*

The preceding discussion shows that the neutral excitations can be generated in liquid helium in the presence of a Po^{210} α-particle source. Using the experimental arrangement of Fig. 1 at 0.4°K with a 25-microcurie source S, a negative anomalous current of about 5×10^{-12} A is collected at C when an electric field of 40 V/cm at the liquid surface is in a direction designed to extract negative charges from the liquid. Under the same circumstances, a positive anomalous current of 2×10^{-12} A is collected at C in the presence of an electric field of the same magnitude and opposite direction. These currents depend somewhat on the magnitude of the applied electric field, and appreciably on the geometry of the apparatus.[15] Attempts to generate the neutral excitations by means of a different type of source will be discussed in Sec. III, B-8.

2. *Detection of the Neutral Excitations*

As already mentioned, neutral excitations may be detected by their conversion to positively and negatively charged particles at the free surface of the liquid. The sign and magnitude of the currents measured at the collector depend on the sign and magnitude of the electric field at the liquid surface. The nature and energy distribution of the charge carriers emerging from the free liquid surface will be discussed in Secs. III, B-5 and B-6.

It is of interest to inquire whether the neutral excitations could not also be observed by a detector immersed *inside* the liquid. In particular, one may ask whether these neutral excitations might produce charged particles when they strike a metal plate immersed in the liquid since metal plates (i.e., "Surface ionization detectors") are frequently used in experiments in gases to convert metastable atoms to charged particles. Indeed, we find experimentally that the neutral excitations incident on such a metal plate immersed in liquid helium do produce charge ejection (i.e., give rise to a measurable anomalous current collected by the plate, provided that a sufficiently large electric field is applied to the liquid adjacent to the plate. (A similar situation occurs when a tunnel cathode is used as a source of electrons. When this device is immersed in liquid helium, a large electric field is required to extract an appreciable current.)[16] The sign of the current depends on the direction of the electric field in the expected way. A current of detectable magnitude requires application of an electric field of the order of 10^5 V/cm. Such a large electric field is produced by applying potentials up to 1 kV to a fine metal grid separated from the metal plate by a parallel array of thin nylon threads.[17] The high fields are presumably necessary to draw charges in the liquid away from the plate in the presence of image forces produced by the proximity of the metal plate and in the presence of energy losses due to scattering in the liquid. (At 0.4°K, with an electric field of 5×10^4 V/cm and a 10-microcurie Po^{210} source, typically 10^{-13} A of positive and 6×10^{-14} A of negative anomalous current are observed.)[18] To verify that the anomalous current measured at the metal plate in the presence of such high electric fields is not due to leakage currents flowing to the metal plate from the closely spaced grid, the following check was performed: A shutter, capable of being rotated into the beam of neutral excitations, was placed between the source and the metal plate detector.[19] When the shutter is rotated into the beam, no neutrals should reach the detector; the observed current, if it is not due to leakage, should then vanish. The results of the experiment showed that the leakage current was negligible. Thus we conclude that the neutral excitations produce an observable current of charged particles at the metal plate immersed in the liquid. However, even at the highest electric fields conveniently available to us, the efficiency of the metal plate as a detector of neutrals is only about 1% that of the free liquid surface. For this reason, the free liquid surface was used as a means of detection in most of our experiments.

3. *Temperature Dependence and Effect of* He^3 *Impurities*

As shown in Fig. 3 (solid lines), the anomalous current emerging from the free liquid surface is strongly temperature dependent and, in particular, becomes negligibly small at temperatures greater than about 0.6°K. This same temperature dependence of the anomalous current is observed at the metal plate detector immersed inside the liquid.[20] These results indicate that the temperature depen-

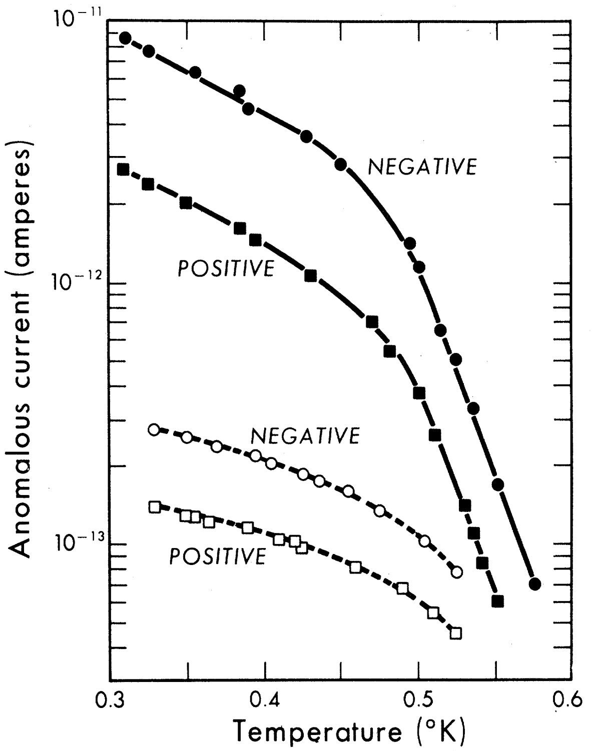

FIG. 3. Temperature dependence of the anomalous current in the case of no added He^3 impurities (solid lines), and in the case of 8×10^{-6} atomic concentration of He^3 (dashed lines).

dence shown in Fig. 3 does not reflect the nature of the particular detection mechanism but is characteristic of the flux of neutral excitations. The temperature dependence of the anomalous current I_{an} is approximately represented by the following expressions:

$$I_{an} \propto e^{A/T} \quad \text{for} \quad T \geqq 0.5\,^{\circ}\mathrm{K}, \tag{2}$$

where $A = (11.0 \pm 0.6)\,^{\circ}\mathrm{K}$ for negative anomalous current and $A = (10.0 \pm 0.6)\,^{\circ}\mathrm{K}$ for positive anomalous current; and

$$I_{an} \propto T^{-\beta} \quad \text{for} \quad T \leqq 0.39\,^{\circ}\mathrm{K}, \tag{3}$$

where $B = 2.5 \pm 0.3$ for both negative and positive anomalous current. These results provide a possible indication that the temperature dependence reflects mean free path effects due to scattering in the liquid by rotons and phonons (see Sec. IV., B).

Since He^3 atoms in superfluid helium act as scattering centers just as phonons and rotons do, the anomalous current was also measured in the presence of a small concentration of He^3. Typical results are shown in Fig. 3 (dashed lines). It is seen that as the He^3 impurity concentration is increased, the anomalous current decreases and becomes less temperature-dependent. It should also be noted that the ratio of negative to positive anomalous current is smaller in the presence of He^3 impurities.

4. *Propagation of the Neutrals in the Bulk Liquid*

It is of interest to ask how the neutral excitations travel in the liquid. To investigate the extent to which the neutrals travel along straight lines, "venetian blind" baffles were placed between the source S and the liquid surface (see Fig. 4a). Two collectors C_1 and C_2 were placed in the vapor above the liquid. If the neutrals travel in the liquid by diffusion with a mean free path less than, or of the order of, the dimensions of the baffles, the currents collected at C_1 and C_2 should be equal. On the other hand, if the neutrals travel in the liquid along straight lines and are annihilated when they impinge on the metal baffles, the current collected at C_2 should be much larger than that collected at C_1. In experiments at temperatures below 0.45°K, it was found that the anomalous current collected at C_2 was much greater than that collected at C_1. This result indicates that the neutral excitations travel in the liquid along straight lines with negligible scattering.[21]

In order to verify further the straight-line propagation of the neutral excitations and the extent to which the neutrals annihilate when they impinge on a metal surface, "chevron baffles" were inserted between the source and the liquid surface [see Fig. 4(b)]. In the presence of these baffles,

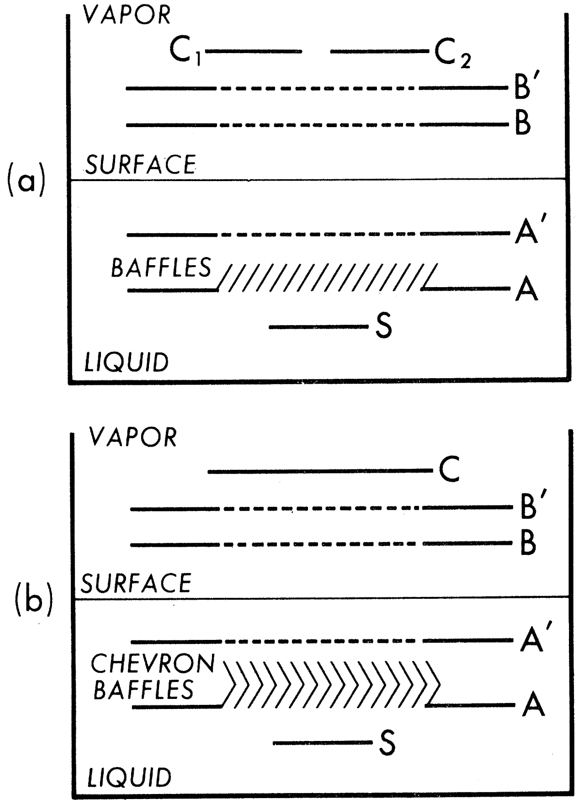

FIG. 4. Experimental arrangement using "venetian blind" baffles to demonstrate straight-line propagation of the neutral excitations in the liquid. (b) "Chevron baffle" arrangement.

the anomalous current detected by the collector in the vapor was less than 0.3% of the current collected in the absence of the baffles. This experiment provides a further indication that the neutral excitations do not diffuse through the liquid, but travel along straight lines (with a mean free path much longer than the dimensions of the baffles). Furthermore, if the neutral excitations were scattered elastically when they impinge on the metal surfaces of the baffles, the anomalous current detected in the presence of the baffles should have been at least 20 times larger than that actually observed. Thus we conclude that the neutral excitations are annihilated quite effectively when they impinge on a metal surface.[22]

It is of interest to inquire to what extent the flux of neutral excitations traveling through the liquid is attenuated (e.g., because the neutrals might have a finite lifetime). To answer this question, an experiment was performed in which neutrals were allowed to traverse different thicknesses of liquid while traveling from the source to the liquid surface. The level of liquid above the source was increased from 1 to 2 cm under conditions where the solid angle subtended at the source by the liquid surface is kept constant by inserting a small circular aperture between the source and the surface of the liquid. Thus the number of neutral excitations striking the surface may be kept constant, while the amount of liquid through which the neutrals travel from the source to the liquid surface is increased. It was found that, by raising the liquid level in this way, the anomalous current emerging from the liquid surface is not changed appreciably. This result indicates that the neutrals are *not* attenuated significantly in traveling through the liquid (at least at temperatures $T \lesssim 0.45\,^\circ\mathrm{K}$).[21]

It has already been mentioned that the temperature dependence of the anomalous current is independent of the detection mechanism and thus appears to be characteristic of the flux of neutrals arriving at the detector. This result, combined with the fact that the flux of neutrals is not attenuated by the bulk liquid, implies that the temperature dependence is not due to processes occurring either in the bulk liquid or at the detector. Thus we conclude that, at least for $T \lesssim 0.45\,^\circ\mathrm{K}$, the temperature dependence of the anomalous current (shown by the solid curves in Fig. 3) is characteristic of the flux of neutral excitations emerging from the region near the source.

Finally, the anomalous current was measured as a function of the level of the liquid above the source, when the liquid contained a concentration of He^3 impurities large enough to attenuate the anomalous current by a factor of about 20. The attenuation of the anomalous current by the He^3 impurities was found to be essentially independent of the level of the liquid. Thus we conclude that the He^3 impurities have no large effect on the neutral excitations traveling in the bulk liquid. The influence of these impurities on the magnitude of the anomalous current must thus be due predominantly to processes occurring near the source and/or the liquid surface.

5. *Energy Spectrum of the Anomalous-Current Charge Carriers in the Vapor*

The energy spectrum of the charged particles emerging from the liquid surface was measured by using the arrangement shown in Fig. 1. A potential $V_{A'B}$ was applied between grids A′ and B to draw charges of either sign out of the liquid. The current was measured at C as a function of a retarding potential $V_{BB'}$, applied between grids B and B′.

A typical retarding potential curve for the negative current is shown in Fig. 5(a). The curve for normal current shows that the carriers emerge from the liquid with about zero energy, as previously stated in Sec. II. The anomalous current shows a more complicated behavior: Approximately 60% of the negative charge carriers responsible for this current emerge from the liquid with about zero energy, as indicated by the decrease in current at the potential $V_{BB'} = -V_{\sigma B}$, where $V_{\sigma B}$ is the potential drop between the liquid surface and grid B. It is, however, remarkable that the remaining negative anomalous-current charge carriers emerge from the liquid with energies up to about 10 eV.[23] Furthermore, a magnetic field on the order of 50 G perpendicular to the liquid surface was found to increase the amount of negative anomalous current collected at C. Since such a field tends to make the charge carriers travel in the direction of the field (by making them spiral around the field lines), this result provides evidence that some of the charge carriers responsible for the negative anomalous current do not emerge in a direction normal to the liquid surface.[24]

A typical retarding potential curve for positive current is shown in Fig. 5(b). It indicates that the positive charge carriers emerge from the liquid surface with negligible energy. [After correction for the "space charge effect" (discussed in Sec. II), the data lead to the conclusion that the positive charge carriers emerge from the liquid with energies less than 0.3 eV.] As shown in Fig. 5(b), the difference between the total and anomalous positive currents (i.e., the positive "normal" current) is small but finite. This difference is, moreover, quite unlike the negative normal current in that it exhibits a dependence on *temperature* which is quite similar to that of the positive and negative anomalous currents. We therefore conclude that all the *positive* current observed below 1°K is related to tne anomalous current.

As can be seen from Fig. 5, both the negative and positive anomalous currents have contributions (about 5% of the negative and 30% of the positive, respectively) which do not respond to retarding potentials in the *vapor*. These contributions have the same temperature dependence as the (larger) contributions to the anomalous current which do respond to retarding electric fields in the vapor. From this we conclude that these current contributions are intimately connected with the neutral excitations. It is possible that these currents are due to neutral excitations which remain electrically neutral when emerging from the liquid surface and eject charged particles when they strike the collec-

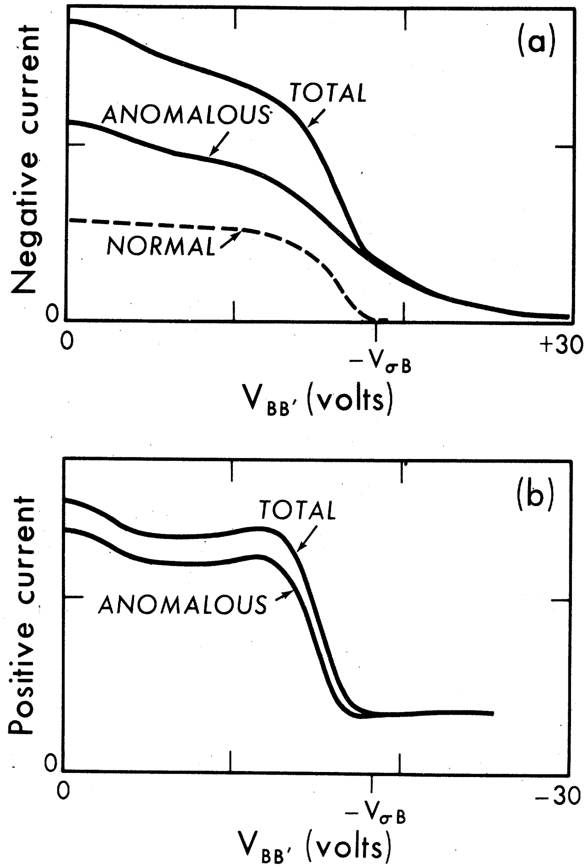

FIG. 5. Energy distribution of (a) negative and (b) positive current contributions in arbitrary units. Here $V_{\sigma B}$ is the potential difference between the liquid surface σ and the grid B in Fig. 1; $V_{BB'}$ is the retarding potential applied between grids B and B'. (The symbol V_{xy} denotes the potential of x minus the potential of y.)

tor in the vapor. (Since we have already shown that the neutrals are annihilated at a metal surface, it seems unlikely that they could travel from the liquid surface to the collector in the helium film covering the metal walls of the container.)

6. *Nature of the Anomalous-Current Charge Carriers in the Vapor*

It is of interest to determine the nature of the anomalous-current charge carriers in the vapor. In the case of the negative anomalous charge carrier, this was done by the magnetic deflection technique described in Sec. II. In the experimental arrangement shown in Fig. 2(a), the current collected at C is measured as a function of the magnetic field $\vec{B}$. The charge carriers were given a specified energy (between 3 and 50 eV). It was not possible to obtain a well-resolved peak in the collector current as a function of magnetic field, presumably because (as pointed out above) the negative charge carriers emerge from the surface with varying amounts of energy (up to 10 eV) and in directions not necessarily perpendicular to the liquid surface. It was, however, found that the negative anomalous current is definitely affected by weak magnetic fields (<50 gauss).[13] This result implies that the charge carriers responsible for this current cannot be ions, even if they are as light as He$^-$. Thus the experimental evidence is sufficient to conclude that the negative anomalous charge carriers are electrons.

In order to determine the charge-to-mass ratio Q/M for the positive anomalous charge carrier, without requiring large magnetic fields, a time-of-flight technique was used.[25] The experimental arrangement is shown in Fig. 2(b). Positive ions are drawn out of the liquid by applying an electric field of the proper sign between grids A′ and B. A retarding voltage is applied between B′ and B″ so that no current is collected at C unless the ions gain some net energy in the region between B and B′. A square-wave voltage of frequency ν is applied to grid P_2 and the current collected at C is plotted as a function of ν. The ions will gain net energy in the region between B and B′ when the frequency ν is such that the time d/v for ions of velocity v to travel the distance d between B and P_2 (or between P_2 and B′) is equal to the time $(2\nu)^{-1}$ between reversals of the electric fields in these regions. Thus the current collected at C will exhibit a maximum when $\nu = v/2d$ (or any odd harmonic thereof). From the position of these maxima and the energy of the ion in the space between B and B′, the charge-to-mass ratio Q/M of the positive anomalous charge carrier was found to be

$$Q/M = (0.59 \pm 0.09)e/m_{\mathrm{He}} , \tag{4}$$

where m_{He} is the mass of a helium atom and e is the charge of an electron. We conclude that $M \approx 2m_{\mathrm{He}}$ and that the charge carrier responsible for the positive anomalous current is $\mathrm{He}_2{}^+$. (This ion is commonly encountered in electrical discharges in dense helium gas.)[26]

7. *Evidence that the Neutral Excitations are not Photons*

The preceding results provide evidence for the existence of an energetic neutral excitation which travels along straight lines. One such neutral is a photon. If it were a photon, it should have an energy of about 25 eV (the ionization potential of a helium atom) in order to produce, at the surface of the liquid, positive ions and electrons with small energies. To determine whether or not the neutral excitations are photons of this kind, we interposed between the source S and the liquid surface a 900-Å-thick aluminum film which acts as a filter transmitting photons with energies between 16 and 55 eV.[27] The interposition of this filter reduced to a negligible value the anomalous current measured at a collector C in the vapor. (Similarly, the anomalous current measured at C was negligible when a LiF crystal was inserted between the source and liquid surface, although such a crystal transmits photons with energies between 0.1 and 12 eV.)[28] Considering the results of the aluminum film experiment, we thus conclude that the neutral excitations are not photons.

8. *Other Experiments*

It is of interest to investigate the possibility that sources of charged particles, other than radioactive Po^{210}, might be used to generate the neutral excitations. In particular, it would be of interest to find a source of the neutral excitations which could be turned on and off rapidly. One convenient source of charged particles is a tunnel cathode, which produces electrons with energies of the order of 1 eV.[16] When this source was used immersed in liquid helium, it was found to generate a normal current but no anomalous current.[29] This is not surprising since, while the electrons from the source have energies of the order of 1 eV, the neutral excitations are expected to have energies of the order of 25 eV. We also used the tunnel cathode above the liquid surface so that emitted electrons could be accelerated to energies of 100 eV before striking the surface. No anomalous current was observed at a metal plate detector immersed in the liquid,[30] but the efficiency of this detector and that of the tunnel cathode itself were quite low. Experiments are in progress to determine whether improvements in this arrangement could yet lead to the generation of a detectable number of neutral excitations.

One may also inquire to what extent the flux of neutrals might be changed by the application of a large electric field in the bulk liquid. An effect would be expected if the large field would induce radiative decay of the neutral or if it would "tear apart" a neutral complex consisting of a weakly bound positive and negative charge. The neutral excitations were subjected to electric fields up to 10^5 V/cm in a 10^{-2}-cm-long region between the source and liquid surface. The large electric field was produced by applying a voltage of 1 kV between two fine metal grids separated by parallel nylon monofilament threads.[31] It was, however, found that the flux of neutral excitations remains unaffected by the application of such large electric fields.

If we assume that the neutral excitation is basically an electronic excitation of the superfluid He^4 then either $s = 0$ or $s \geqslant 1$, where s is the spin of the excitation. If $s \geqslant 1$, it is likely that the magnetic moment μ associated with the excitation will be of the order of, or greater than, $2\mu_B$ (where μ_B is the Bohr magneton). If a neutral with such a magnetic moment has thermal kinetic energy, it should be possible to deflect it appreciably with a magnetic field gradient of the order of 10 kG/cm.[32] The experiment was attempted, using the arrangement shown in Fig. 6. Here the magnetic field is produced by an Alnico 5 permanent magnet with iron pole tips; the shaped pole pieces produce a field of the order of 3 kG and a field gradient of approximately 8 kG/cm oriented perpendicular to the direction of travel of the neutrals from the source to the liquid surface. "Venetian blind" baffles (about 8 mm long and spaced 1 mm apart) are placed between the region of the high-gradient magnetic field and the liquid surface. By rotating the magnet,[33] the direction of the field gradient may be oriented either parallel or perpendicular to the baffles. When the gradient is perpendicular to the baffles, the neutrals, if they are appreciably deflected by the magnetic field gradient, should impinge on the baffles and fail to arrive at the liquid surface. However, when the field gradient is parallel to the baffles, the neutrals should pass through to the liquid surface, even if deflected. Experimentally, at 0.35°K, no change in the anomalous current is observed for the two different orientations of the magnetic field gradient. Since the magnetic deflection of the neutral depends on its kinetic energy,[32] our experimental result leads to the following conclusion: If the neutral excitation is thermalized so that its kinetic energy is less than 0.5°K, then its magnetic moment must be less than $0.2\mu_B$.

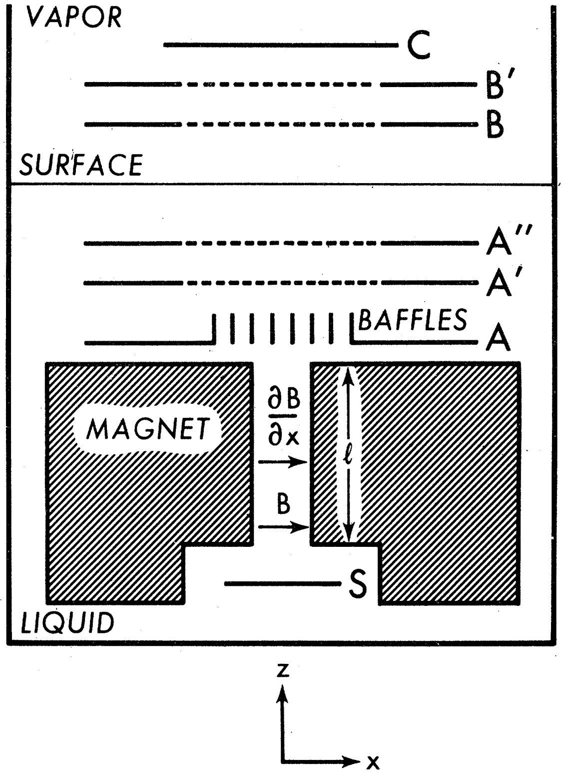

FIG. 6. Experiment designed to use a magnetic field gradient $\partial B/\partial x$ to deflect neutral excitations having a magnetic moment. The direction of the field gradient may be rotated, either normal to the baffles (as shown), or parallel to the baffles (i.e., normal to the paper). In the position shown, deflected neutral excitations will impinge on the baffles and will thus cause a decrease in the current collected at C.

C. Summary

We have presented evidence for the existence of neutral excitations which are generated in superfluid helium in the presence of a Po^{210} α-particle source and travel in the liquid without appreciable scattering or attenuation (at least at temperatures $T \lesssim 0.45°K$). The flux of these neutral excitations emerging from the region near the source is highly temperature dependent; in particular, no neutrals are observed at temperatures greater than 0.6°K. The neutral excitations are sufficiently energetic to produce He_2^+ ions and electrons at a free surface of the liquid, and positive and negative ions at a suitable metal plate immersed in the liquid. The He_2^+ ions and the majority of the electrons emerge from the liquid with negligible energy, however, about 40% of the electrons emerge with energies up to 10 eV. The neutral excitations are not photons.

IV. CONCLUDING REMARKS

A. Normal Current

We have presented evidence that electrons in liquid helium below 1°K emerge from the liquid surface only when they are trapped in vortex rings in the liquid. The electrons emerge with little or no time delay ($< 10^{-3}$ sec) and negligible energy ($\lesssim 0.3$ eV), independent of the energy of the vortex ring arriving at the liquid surface. At these temperatures, positive ions in the liquid do not emerge from the surface even in the presence of electric fields up to 100 V/cm perpendicular to the surface.[10]

At temperatures *above* 1°K, the current I of electrons emerging from the liquid into the vapor above has the temperature dependence $I \propto \exp(-\gamma/T)$, where $\gamma = 25 \pm 1$°K[34] $T^{1/2}$. An electron in liquid helium forms a cavity or "bubble" (approximately 15 Å in radius) in the liquid and is trapped in this bubble.[3] The temperature dependence of I was interpreted to imply the existence of a surface barrier which must be overcome by the electron (in a bubble in the liquid) so that it can emerge from the liquid surface.[34] A qualitative explanation for this "surface barrier" was advanced in terms of the short-range repulsive force[35] between the electron and the surrounding liquid and the long-range attractive force due to polarization of the medium. Our experimental results indicate, however, that the situation at temperatures below 1°K is quite different. When an electron in a bubble trapped in a vortex ring[36] approaches the liquid surface, no surface barrier impedes its emergence from the liquid. We shall now discuss the motion of a vortex ring as it approaches the liquid surface and then proceed to suggest mechanisms by which an electron trapped in a vortex near the surface might emerge from the liquid.

Consider a single vortex ring traveling in the liquid and approaching its surface in a direction normal to this surface. We shall assume that the liquid surface remains essentially undistorted, so that it may be approximated by a rigid plane. (A discussion of the validity of this assumption is given in Appendix I.) In the presence of a rigid surface located at $z = 0$, the motion of a vortex ring having a radius R and located at $z = d$ may be treated by the "method of images": The fluid flow in the region $z > 0$ in the presence of the surface will be the same as that produced in the absence of the surface if an additional vortex ring of opposite circulation is located at $z = -d$. (With such an arrangement of vortex rings, the fluid flow along the z direction is zero at $z = 0$. This is precisely the boundary condition applicable when a rigid wall is located at $z = 0$.) The image method provides a qualitative insight into the nature of the motion: As the vortex ring approaches the plane surface, it increases in radius and moves more slowly. This problem can also be treated quantitatively, although some previously published discussions appear to be in error.[37,38] In Appendix I we give a solution applicable when $R \gg a$ and $d \gg a$ (where a is the radius of the vortex core). This calculation verifies the preceding qualitative description and gives the radius R and velocity v of the ring as a function of d, the distance of the vortex ring from the surface. Table I shows, for a vortex ring of 20-eV energy, typical values of R and v as a function of d [obtained from Eq. (A2) and (A4) of Appendix I]. As discussed in Appendix I, this solution is expected to be valid as long as d is not less than about 10 Å. At such close distances one must also consider the perturbed hydrodynamic flow due to the presence on the ring of the electron bubble (of radius $R_B = 15$ Å). Thus our solution, although not rigorously valid very close to the surface, should yet be adequate to describe approximately the approach of a changed vortex ring to within a distance R_B from the surface.

There also exists, however, the possibility that the vortex ring approaching the surface may become sufficiently distorted to break up and become attached to the liquid surface. For example, as a single vortex comes very close to the liquid surface, the flow around the electron bubble might perturb the motion of the segment of vortex line near the bubble to such an extent that the vortex will attach itself to the liquid surface. Furthermore, it is possible that vorticity from vortex rings previously incident on the surface may accumulate near the surface. In this case, a vortex ring approaching the liquid surface would interact strongly with this residual vorticity and would probably break up, attaching itself to other vortex lines or to the liquid surface.

Let us now discuss specific mechanisms by which an electron, trapped on a vortex line near the liquid surface, might emerge from the liquid. Consider first the situation where a single vortex ring, with an electron bubble trapped in it, approaches the surface of the liquid. When the vortex ring approaches very close to the surface, it might force the electron bubble to come in contact with the surface and thus allow the electron to escape. It should be possible for the vortex to

TABLE I. Velocity and energy of a 20-eV vortex ring approaching a plane surface.

d (Å)	R(10^3 Å)	v (cm/sec)
∞	5	16
10 000	5	16
1000	5	13
100	7.5	5.6
10	17	1.5

carry the bubble to the surface despite the surface barrier of 25°K, since the binding energy of the bubble to the vortex is appreciably larger (i.e., 45°K).[36] Another possibility for the emergence of the electron might become important if the vortex becomes attached to the surface of the liquid (e.g., by one of the mechanisms suggested previously). The electron might then escape from the bubble to the liquid surface along the low-density path provided by the vortex core.

It was pointed out that positive ions do not emerge from the liquid into the vapor at temperatures below 1°K.[10] One possible explanation is that, while the electron has a short-range repulsive interaction with respect to the liquid,[35] the positive ion has no such interaction; it would, therefore, be expected to be bound more tightly to the liquid.

It should be pointed out that the preceding discussion has been speculative. Further experiments are required to determine the extent to which the suggested mechanisms of charge escape are actually important.

B. Neutral Excitations

We have presented evidence for the existence of a new kind of neutral excitation generated in liquid helium in the presence of a Po^{210} α-particle source. The neutral excitations travel in the liquid without appreciable scattering and are sufficiently energetic to produce ions and electrons at a free surface of the liquid. After commenting briefly on the creation, propagation, and conversion of the neutral excitations to charged particles, we shall propose a possible model for the neutral excitation.

Consider the generation of the neutral excitations in the presence of the Po^{210} source. This source dissipates enough energy in the liquid to produce about 10^5 ion pairs for every ion extracted from the region near the source. It is, therefore, not unreasonable that energetic neutral excitations are also produced near the source by the α particles, either by direct excitation or during the extensive recombination of the ions and electrons. Our experiments establish that the flux F of neutral excitations emerging from the region near the source is temperature dependent. At temperatures less than 0.4°K, $F \propto T^{-2.5}$, while at temperatures greater than 0.5°K, $F \propto \exp(\delta/T)$, where $\delta \sim 10°\text{K}$. These temperature dependences appear to reflect the decreasing number of phonons and rotons with which the neutrals can interact at low temperatures. Indeed, the temperature dependences are roughly proportional to n_p^{-1} and n_r^{-1} where n_p and n_r denote, respectively, the number density of phonons and rotons [i.e., $n_p \propto T^3$ and $n_r \propto \exp(-8.6/T)$][1]. Such an interaction with scattering centers would also account for the decrease in the magnitude and the reduced temperature dependence of the anomalous current when He^3 impurities are added to the superfluid He^4.

Let us now consider the propagation of the neutral excitations in the bulk liquid. Our experimental results are sufficient to place limits on some parameters associated with the neutral excitations. In particular, we have shown that the neutrals travel in the liquid along straight lines over distances of the order of 1 cm, and that the flux of neutrals in the bulk liquid is not appreciably attenuated by the addition of a small concentration of He^3 impurities. These results are sufficient to estimate that the diffusion cross sections for scattering of the neutrals by phonons, rotons, and He^3 impurities are, respectively, less than 2×10^{-21}, 10^{-14}, and 5×10^{-17} cm². These upper bounds on the cross sections are not unreasonable for an excitation of atomic dimensions. In addition, we have shown that there is no attenuation of the flux of neutral excitations traveling through the bulk liquid for distances of the order of 1 cm. If the neutral excitations have a lifetime τ and travel with velocity v, this result implies that $v\tau > 1$ cm. For example, this inequality implies that an excitation, having thermal energy (corresponding to $T = 0.5°\text{K}$) and the mass of a He^4 atom, would have a lifetime greater than 10^{-4} sec.

Finally, we discuss the conversion of the neutral excitations to charged particles at the liquid surface. It is not surprising that the positive ion emerging from the surface of the liquid is He_2^+, since this ion is the predominant positive ion found in electrical discharges in dense helium gas.[26] Furthermore, the He_2^+ ion has a binding energy (in vacuum) of 2 to 3 eV.[39] Thus, a conversion process of the type

$$(\text{neutral excitation}) \rightarrow He_2^+ + e^- \qquad (5)$$

would presumably require 2 to 3 eV less than would the formation of $He^+ + e^-$. (The ionization potential of a He atom in vacuum is 24.6 eV, hence the formation of He_2^+ and e^- would require about 22 eV in vacuum.)

Although several possible models for the neutral excitation come to mind, most of them seem to be inconsistent with our experimental observations. For example, the neutral excitation might consist of a positive ion and an electron trapped on the same vortex ring, or it might be a positive ion and electron bubble in close proximity and held apart by the locally solidified[3] helium surrounding the positive ion. However, both of these models appear to have a recombination time (for the positive ion and electron) which is much too short to account for our data.

It seems more likely that the neutral excitation is some kind of "exciton" in the liquid (analogous to an excited atomic state). Such excitons are undoubtedly formed in the region near the source, either by direct excitation of helium atoms or by recombination of positive ions and electrons. It is difficult to estimate the precise energy of such an excitation in the liquid[40]; this energy is, however, likely to be of the order of 20 eV, since the lowest excited state of the helium atom in vacuum is 19.8 eV above the ground state.[41] Taking into account the considerable uncertainty of the energy of an exciton in the liquid, it is not impossible that such an excitation could produce at the liquid surface $He_2^+ + e^-$ (whose formation energy is about 22 eV in vacuum).[42]

If the proposed exciton were localized, it might correspond to He*, a helium atom in an excited state, or to He_2^*, a helium molecule in an excited state. Since the lowest energy state of He_2^* is about 2 eV less than that of the separated atoms $He^* + He$,[43] it is probable that He_2^* will be formed even if He^* were present initially; indeed, the process $He^* + He \rightarrow He_2^*$ has been observed in helium gas.[44] In order for the excitation to be long-lived, radiative transitions to the ground state must be strongly forbidden. One possibility is that the exciton corresponds to a triplet state. (In the case of He^*, the analogous state in vacuum would be the 2^3S state lying 19.8 eV above the ground state[41]; in the case of He_2^*, the analogous state would be the $a^3\Sigma_u^+$ state lying about 17.6 eV above the ground state.[43]) Transitions from such a triplet state to the singlet ground state involve a spin flip and are, therefore, strongly forbidden. An additional reason can be advanced for a long lifetime of the He_2^* exciton[45]: The metastable level of the helium molecule must decay into a photon plus two helium atoms in their ground states. In the molecular state, the atomic cores are separated by about 1 Å,[43] whereas two ground-state helium atoms will tend to be separated by distances greater than 2 Å because of the strong repulsion of the core electrons. The process $He_2^* \rightarrow 2$ He is, therefore, unlikely to occur as a result of a radiative transition where nuclear separations are not allowed to change by virtue of the Franck-Condon principle. In fact, in helium gas at 300°K, the lifetime of the $a^3\Sigma_u^+$ state has been observed to be longer than 0.05 sec (independent of gas pressure, at least up to 100 mm Hg).[44]

Finally it should be noted that a localized exciton, such as He_2^*, would have a long mean free path in superfluid helium at low temperatures since the number of scattering centers (i.e., rotons and phonons) is very small. The excitation would then be analogous to an ordinary impurity (such as a He^3 atom) which also has a long mean free path in superfluid helium at low temperatures.

In summary, it seems likely that the neutral excitation observed in our experiments is some kind of exciton which has a long lifetime and sufficient energy to produce $He_2^+ + e^-$ at the liquid surface. Our data are, however, insufficient to substantiate this model unambiguously. Further experiments are required to establish more definitely the nature of the neutral excitation.

V. ACKNOWLEDGMENTS

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APPENDIX I: MOTION OF A VORTEX RING INCIDENT ON A RIGID PLANE SURFACE

Consider a vortex ring 1 located at $z = d$ and traveling toward a rigid plane which is located at $z = 0$. As pointed out in Sec. IV.A, the "method of images" can be used to assert that the fluid flow for $z \geqslant 0$ is equivalent to the flow in the absence of the wall if a second vortex ring 2 of radius R and of opposite circulation is located at $z = -d$. The hydrodynamic energy E of the system consisting of both rings is constant.[46] Using Eq. 162.1 of Lamb[47] for the energy of a system of circular vortices having a common axis (taken as the z axis), and denoting the radial coordinate by r, we can write

$$E = -\frac{2\rho\kappa}{a^2}\int_{\text{core }1} dr\,dz[\Psi_1(r,z) + \Psi_2(r,z)] \;, \quad \text{(A1)}$$

where the integration extends over the cross-sectional area of the core of vortex 1. Here ρ is the density of the liquid, κ is the circulation of the vortex, a is the radius of its core (assumed to have uniformly distributed vorticity), and $\Psi_1(r, z)$ and $\Psi_2(r, z)$ are the stream functions due to the vortex rings 1 and 2, respectively. The first term on the right-hand side of (A1) is the energy of two isolated vortex rings of radius R; the second term is the interaction energy of the two rings. The constant energy E may be evaluated in the limit where $d \rightarrow \infty$, in which case $E = \rho\kappa^2 R_\infty[\ln(8R_\infty/a) - \frac{7}{4}]$. Thus, using Eqs. 161.9 and 163.6 of Lamb,[47] we have in the limit where $R, d \gg a$,[48]

$$R_\infty[\ln(8R_\infty/a) - \tfrac{7}{4}] = R[\ln(8R/a) - \tfrac{7}{4}] - (2R/k)[(1 - k^2/2)K(k) - E(k)] \;, \quad \text{(A2)}$$

where $k \equiv (1 + (d/R)^2)^{-1/2}$ and where K and E are complete elliptic integrals of the first and second kind, respectively. Thus (A2) provides an explicit relation for R as a function of d.

The velocity v with which the ring approaches the surface will be, using Eq. 161.1 of Lamb,[47]

$$v = v_0 - r^{-1}\left[\partial\Psi_2(r,z)/\partial r\right]_{r=R,\,z=d} \;, \quad \text{(A3)}$$

where v_0 is the velocity with which the ring would propagate in the absence of the wall. The second term in (A3) is the velocity contribution along the z axis at the core of the ring due to the fluid flow of the image ring. Using Eqs. 161.9 and 163.7 of Lamb,[47] we find

$$v = (\kappa/4\pi R)\{\ln(8R/a) - \tfrac{1}{4} - k[K(k) - E(k)]\} \,. \quad \text{(A4)}$$

Thus knowing R as a function of d from Eq. (A2), we may compute v as a function of d from Eq. (A4). Numerical values for R and v as a function of d, for a 20-eV vortex ring, are given in Table I (Sec. IV, A).

We now examine under what conditons the relations (A2) and (A4) can be expected to remain approximately valid if the surface of the liquid is free to be deformed rather than constrained to be rigidly flat. A necessary condition is that the surface be deformed so little that it remains effectively flat, i.e., that the radius of curvature s of the surface remains always large enough so that $s \gg d$. The approaching vortex ring produces near the surface of the liquid a fluid-flow velocity of the order of $\kappa/2\pi d$, and thus produces a pressure of the order of $\rho(\kappa/2\pi d)^2$. This pressure is balanced by the pressure σ/s resulting from the surface tension σ of the liquid. Thus

$$\sigma/s \approx \rho(\kappa/2\pi d)^2 \ . \qquad \text{(A5)}$$

Using for superfluid helium the values $\rho = 0.15$ g cm^{-3}, $\sigma = 0.35$ dyn cm^{-1}, and $\kappa = 10^{-3}$ cm^2 sec^{-1} (the circulation of a single quantum h/m), the relation (A5) shows that the curvature of the surface produced by a vortex ring a distance d away is given by $s \approx 10^8 d^2$. The condition $s \gg d$ for the applicability of our solution [Eqs. (A2) and (A4)] remains then fulfilled as long as $d >> 10^{-8}$ cm (i.e., as long as $d \gtrsim 10$ Å).

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*Work supported in part by the U. S. Office of Naval Research.

[1] A recent survey of such studies in liquid helium may be found in J. Wilks, The Properties of Liquid and Solid Helium (Oxford University Press, London, 1967).

[2] See Ref. 1, pp. 259-265.

[3] R. J. Donnelly, Experimental Superfluidity (University of Chicago Press, Chicago, 1967), pp. 172–177; see also A. J. Dahm and T. M. Sanders, Phys. Rev. Letters 17, 126 (1966).

[4] See Ref. 3, pp. 196–207.

[5] G. W. Rayfield and F. Reif, Phys. Rev. 136, A1194 (1964).

[6] G. Careri, U. Fasoli, and F. S. Gaeta, Nuovo Cimento 15, 774 (1960); L. Bruschi, B. Maraviglia, and F. E. Moss, Phys. Rev. Letters 17, 682 (1966).

[7] C. M. Surko and F. Reif, Phys. Rev. Letters 20, 582 (1968).

[8] A small amount of positive current is observed which responds to electric fields in the liquid; it is, however, about a factor of 10 smaller than the negative normal current and appears to be directly related to the anomalous current (as will be discussed in Sec. III, B-5).

[9] A detailed comparison of these temperature-dependent currents can be found in Appendix II, C. M. Surko, Ph. D. thesis, University of California, 1968 (unpublished).

[10] This behavior is to be distinguished from the behavior of the anomalous current, which appears to be generated at the liquid surface (see Sec. III).

[11] The energy of the carriers in the vapor is affected to a negligible extent by the dependence of the "space-charge effect" on the velocity of vortex rings in the liquid.

[12] The charge carriers inside the liquid move so slowly that they remain essentially unaffected by such weak magnetic fields.

[13] A typical curve of the current collected at C as a function of magnetic field can be found in Fig. 8 of Ref. 9.

[14] The relationship between the velocity and energy of a vortex ring is given in Ref. 5. The decrease in velocity of a vortex ring very close to the liquid surface results in a negligible time delay (see Sec. IV, A).

[15] The geometry enters as follows: The neutral excitations are found to travel in straight lines (Sec. III, B-4). Thus the anomalous current collected at C depends on the solid angle subtended at the source by the liquid surface from which charge is collected.

[16] M. Silver, D. G. Onn, P. Smejtek, and K. Masuda, Phys. Rev. Letters 19, 626 (1967).

[17] The metal grid, with 60% transmission, is 500 line-per-inch copper mesh purchased from the Buckbee Mears Co., St. Paul, Minnesota. The nylon monofilament threads are 0.0017 inch in diameter and are placed about 0.012 inch apart. The average spacing between the grid and the metal plate is about 0.004 inch.

[18] These values are the anomalous currents, detected at the immersed metal plate, which have the same temperature dependence as anomalous current emerging from the liquid surface (see Sec. III, B-3). A temperature-independent current contribution is also detected and may indicate the presence of another energetic neutral excitation.

[19] The shutter is in the form of a piece of magnetized steel mounted on a bearing. It can be rotated in and out of the beam of neutral excitations by applying a 50-G magnetic field from outside the Dewar. Electrical resistance measurements can be made to monitor the "open" and "closed" positions of the shutter.

[20] In this comparison, we neglect the temperature-independent contribution to the current collected at the immersed metal plate (see Ref. 18).

[21] No significant data could be obtained in this experiment at temperatures greater than 0.45°K, since the magnitude of the anomalous current then becomes too small.

[22] In the presence of a large electric field, the neutral excitations impinging on a metal surface give rise to ejected charges which make possible the use of metal plate detectors of the type discussed in Sec. III, B-2.

[23] The magnitude of this energetic contribution decreases in relation to the total negative anomalous current when He^3 impurities are added to the liquid.

[24] If this is the case, it is not surprising that the retarding potential curve for the negative anomalous current (shown in Fig. 5a) is not flat for values of V_{BB}' much less than $-V_{\sigma B}$.

[25] The mass spectrometer which we used is similar in principle to the one developed by W. H. Bennett, J. Appl. Phys. 21, 143 (1950). See also Ref. 5.

[26] J. A. Hornbeck and J. P. Molnar, Phys. Rev. 84, 621 (1951); see also F. L. Arnot and M. B. M'Ewen, Proc. Royal Soc. (London) A171, 106 (1939).

[27] The method of fabrication and the far-ultraviolet transmission characteristics of such films may be found in Om P. Rustgi, J. Opt. Soc. Am. 55, 630 (1965). The thickness of the film was measured with a Fizeau-plate interferometer.

[28] The LiF crystal was purchased from the Harshaw Chemical Co., Cleveland, Ohio. The transmission characteristics may be found in D. F. Heath and P. Sacher, Appl. Opt. 5, 937 (1966); and H. W. Hohls, Ann. Physik 29, 433 (1937).

[29] The fabrication and operating characteristics of this tunnel cathode source are described in Appendix III in Ref. 9.

[30] A normal current was observed at the immersed detector. This current was shown to consist of charged singly-quantized vortex rings by a measurement of the velocity of the charge carriers as a function of their energy.

[31] The average spacing between the grids was 0.0035 inch. For the dimensions of the nylon threads and metal grids, see Ref. 20. The nylon threads were separated by

about 0.012 inch.

[32] The angular deflection is equal to $\tan^{-1}[\mu(\partial B/\partial x)l/2E]$, where l is the linear dimension over which the magnetic field gradient $\partial B/\partial x$ exists, and where E is the energy of the particle. For a particle of energy 0.5°K and a magnetic moment of $2\mu_B$, a magnetic field gradient of 8 kG/cm acting over a region 1 cm in length will produce an angular deflection of about 45°.

[33] The magnet was rotated by a 50-G magnetic field applied from outside the Dewar.

[34] L. Bruschi, B. Maraviglia, and F. E. Moss, Phys. Rev. Letters 17, 682 (1966).

[35] The repulsive interaction is basically due to the Pauli principle which effectively prevents the electron from penetrating a helium atom.

[36] Pressure gradients produced by the liquid moving around the vortex line provide an attractive force between the bubble and line. For details, see P. E. Parks and R. J. Donnelly, Phys. Rev. Letters 16, 45 (1966).

[37] L. Meyer and T. Soda, Phys. Rev. 137, A428 (1965). In the left-hand side of Eq. (16), η should read η_∞. Equation (17) appears to be in error; it is derived from a theorem due to Lamb, which applies to the total system instead of just one vortex ring.

[38] W. M. Hicks, Proc. Roy. Soc. (London) 102A, 111 (1922). See Sec. 13.

[39] P. N. Reagan, J. C. Browne, and F. A. Matsen, Phys. Rev. 132, 304 (1963).

[40] Excitons in rare-gas solids have been studied by G. Baldini, Phys. Rev. 128, 1562 (1962).

[41] C. E. Moore, Atomic Energy Levels (National Bureau of Standards, Washington, D. C., 1948), Vol. I, p. 4.

[42] We have no immediate explanation for the electrons which emerge from the liquid with energies up to 10 eV.

[43] M. L. Ginter, J. Chem. Phys. 42, 561 (1965).

[44] A. V. Phelps, Phys. Rev. 99, 1307 (1955).

[45] We are indebted to Professor Morrel H. Cohen for this suggestion.

[46] The energy E is twice the energy of the "real" system which occupies the half-space $z > 0$.

[47] H. Lamb, Hydrodynamics (Dover Publications, Inc., New York, 1945), 6th ed.

[48] This result may be derived from electromagnetic theory using the analogy between magnetic energy and hydrodynamic energy. In our problem, the analogous case is the magnetic energy in a system of two circular loops of radius R carrying equal currents in opposite directions and separated by a distance $2d$. Equation (A2) may be written down immediately from W. R. Smythe, Static and Dynamic Electricity (McGraw-Hill Book Co., Inc., New York, 1939); Eqs. 8.08 (1), 8.10 (2), 8.03 (6), and 8.06 (1).

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Transport Theory in Strong Magnetic Fields

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A unified treatment of transport phenomena in crossed electric and magnetic fields is presented. This theory is limited to strong magnetic fields, $\omega_c\bar{\tau} \gg 1$, where ω_c and $1/\bar{\tau}$ are the cyclotron and mean collision frequencies, respectively. It is not, however, limited to linear response in the electric field nor is a relaxation time approximation introduced. The semiclassical and quantum theories are developed along parallel lines.

An irreversible transport equation is derived for the asymptotic state of the system, $\omega_c\tau \to \infty$, and it is shown that the asymptotic electron distribution is independent of the absolute values of the coupling constants to the scattering system, but dependent on the form of the scattering interaction. A perturbation theory in $1/\omega_c\bar{\tau}$ is performed and a generalized orbit-jump formula for the dissipative current is derived. Explicit expressions are derived for the ohmic case and are applied as an example to polar optical-phonon scattering.

INTRODUCTION

In this paper we present a theory of transport phenomena in crossed electric and magnetic fields. This work is restricted to strong magnetic fields and is essentially a perturbation theory in $1/\omega_c\bar{\tau}$, where ω_c is the cyclotron frequency and $1/\bar{\tau}$ is an appropriate average collision frequency. Our theory is motivated by the observation that the asymptotic state of the system for $\omega_c\bar{\tau} \to \infty$ is one in which the conduction electrons acquire a drift velocity $\vec{V}_d = \vec{E} \times \vec{B}/B^2$ normal to the electric field, and consequently the average power input to the system vanishes. This is true both classically and quantum mechanically as long as the particle orbits in $\vec{K}$ space are closed, which is the only case we treat in this paper. The simplicity and generality of this result suggests that the strong magnetic field problem is best approached by carrying out a perturbation theory in $1/\omega_c\bar{\tau}$ about