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[1]G. F. Pieper, A. J. Zmuda, and C. O. Bostrom, J. Geophys. Res. 67, 4959 (1962).

[2]A. J. Zmuda, G. F. Pieper, and C. O. Bostrom, J. Geophys. Res. 68, 1160 (1963).

[3]R. Takaki, M. Perkins, and A. Tuzzolino, IRE Trans., Nucl. Sci. 8, 64 (1961).

[4]D. A. Bryant, T. L. Cline, V. D. Desai, and F. B. McDonald, Phys. Rev. Letters 11, 144 (1963).

[5]L. J. Cahill (private communication).

[6]E. C. Stone (to be published).

LIQUID HELIUM AS A BARRIER TO ELECTRONS*

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To explain the properties of extraneous electrons in liquid helium, three models have been proposed. These are as follows: (1) The electron is associated with a density maximum produced by electrostrictive forces.[1] (2) The electron is located in a self-formed cavity which serves to reduce its zero-point energy.[2,3] (3) The electron is essentially free, with an effective mass on the order of the electronic mass.[4]

In this Letter an experiment is described which indicates that liquid helium appears as an energy barrier of more than one electron volt to electrons.[5] This appears to represent decisive evidence in favor of model (2), the only one of the three consistent with this result.

The experimental chamber is shown schematically in Fig. 1. The electrons are supplied by a dc discharge ion source. A fraction of the electrons pass through the central hole in electrode 2 into the bottom chamber, where the interaction with the liquid surface is investigated by measurements made at electrodes 3 and 4. Electrode 3, which is shielded by dielectric ring *S*, is positioned half-way between electrodes 2 and 4, both spatially and in potential, so the applied field may be as uniform as possible. Holes in the bottom electrode allow both the liquid level and temperature in the chamber to be in equilibrium with the outer bath. The chamber may be raised and lowered in the Dewar to position the electrodes relative to the liquid surface.

A qualitative demonstration of the surface barrier effect may be made as follows. The chamber is lowered until the helium level is near the top of shield *S*. With several hundred volts between electrodes 2 and 4 and the electron source on, no electron current is detectable[6] at either electrode 3 or 4. The electron source is turned off at this stage and the system left undisturbed while the liquid level drops as the helium evaporates. When the helium level reaches the bottom of the shield (up to 10 minutes after the electron source has been turned off), a large negative current pulse is recorded at electrode 3. The pulses for long

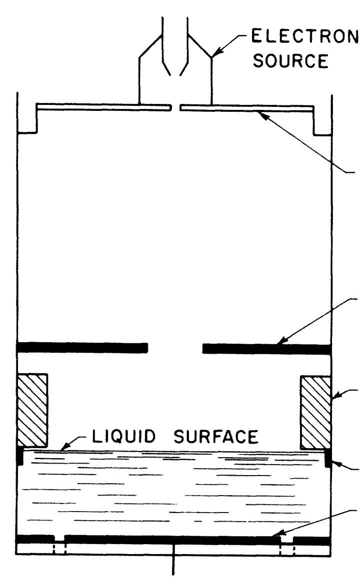

FIG. 1. The experimental chamber.

waiting times, corresponding to high starting liquid levels, are smaller than those for short waiting times by an amount which would roughly be expected to correspond to the difference in capacitance between electrode 3 and the liquid surface in the two cases. If, during the waiting period, the voltage is momentarily dropped to zero and then returned to its original value, no pulse appears.[7]

In order to investigate this barrier effect in more detail, the liquid surface is positioned below the shield, near the top of electrode 3, with the electron source and all voltages on. Since the surface charge is continuously drained away by electrode 3, a field now exists between electrode 2 and the surface, and the impinging electrons can be given energies up to several electron volts. As the field is increased, raising the average electron energy, a threshold is reached after which a fraction of the electrons is able to pass through the surface and be collected at electrode 4. If the total current, I_3+I_4, is made sufficiently small, the ratio of I_4 to the total current for a given applied field becomes constant. It may then be assumed that space charge is negligible[8] and nearly all electrons are striking the surface. By comparing the fraction transmitted, $I_4/(I_3+I_4)$, to the theoretical energy distribution function for electrons drifting through a gas in an electric field, it is possible to arrive at a measure of the energy barrier.

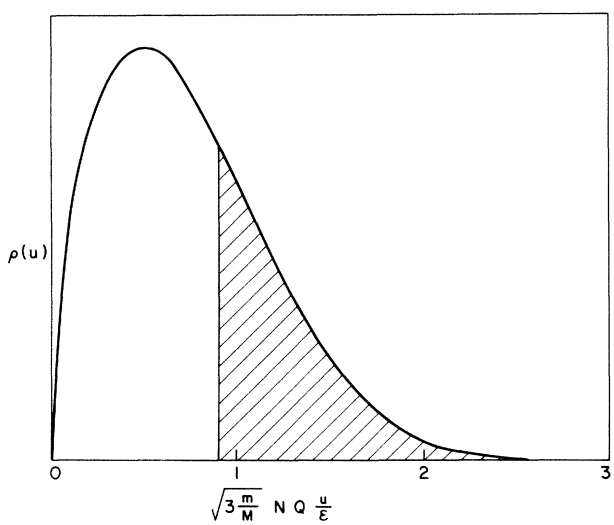

FIG. 2. The energy distribution for electrons drifting through a gas in an electric field. The energy u is in electron volts. The shaded area represents those electrons having energy greater than an assumed barrier height u_0.

The energy distribution function is[9]

$$\rho(u)du = Au^{1/2}\exp\{-[(3m/M)N^2Q^2]u^2/\mathcal{E}^2\}du, \qquad (1)$$

where u is electron energy in electron volts, $\mathcal{E}$ is the electric field, N is the number of atoms per unit volume in the vapor, m the electron mass, M the helium mass, and Q the momentum transfer cross section. In helium at the values of $\mathcal{E}/N$ which are used in this experiment, Q has been experimentally determined[10] to have a nearly constant value of 6.2×10^{-16} cm^2.

This distribution function is plotted in Fig. 2, where the shaded area represents those electrons which can penetrate the surface for some assumed barrier height u_0. By numerical computation, the fraction having energy greater than u_0 is calculated and plotted as a function of $\mathcal{E}/u_0$ in Fig. 3. Using the values of N corresponding to the temperatures and pressures at which measurements are made, it is possible to compare the experimental data to the theoretical curve. A good fit may be achieved by assigning a value of 1.3 electron

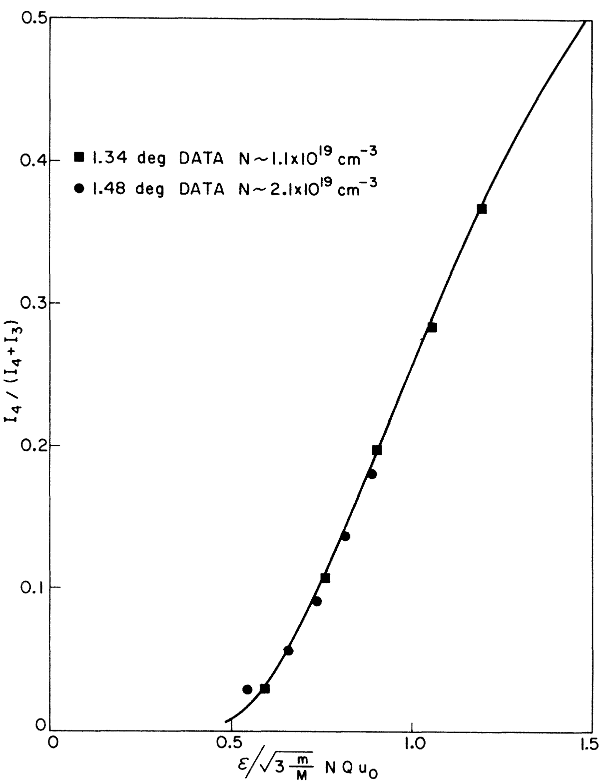

FIG. 3. The fraction of the electrons passing through the surface of the liquid. The solid curve is obtained numerically from the distribution function shown in Fig. 2. It is fitted to the experimental points by assigning a value to the barrier u_0 of 1.3 electron volts.

volts to the barrier.

Implied by the fit of the experimental data to a curve of this form is an over-all transmission coefficient of close to unity for electrons of energy greater than the barrier height. This is not unreasonable since an energetic electron initially reflected from the surface, because of oblique incidence, for example, would undergo a random walk back to the surface with small expected energy loss, and so have several tries at the barrier.

If this interpretation of the data is correct, the primary error in determining the barrier height is the uncertainty in the knowledge of the field at the surface, which, due to the fringing field and to the effect of the dielectric shield, may be as large as 30%.

To determine the implication of this measurement to the question of the electronic structure in the liquid, we wish to consider the electron energy in the three models mentioned above. The barrier as measured in this experiment corresponds to the energy necessary for the electron to enter the normally distributed liquid, for the electron velocity is too high to allow significant displacement of the atoms during the moment of impact. If, upon reaching equilibrium, electrostriction took place, the field energy of the electron could be slightly reduced; but the increased density would result in a countering increase in the electron kinetic energy, which the presence of the barrier shows to be the dominant factor in the total electron energy. Disregarding the effect on the kinetic energy, it may easily be shown that for an unattached electron the reduction of the field energy through electrostriction would not be greater than $\alpha^2 n^2 \kappa e^4/l^5$, where α is the atomic polarizability, n is the number of atoms per unit volume, κ is the compressibility, and l is the interatomic spacing. This maximum reduction would amount to 0.2 electron volt and would still leave a total energy on the order of one electron volt.

A substantially lower energy is accessible to the electron if it creates a cavity within the liquid sufficiently large to reduce its zero-point energy.[3] With slight modification of the equations of reference 3, to take account of the different mass and charge of the enclosed particle, the energy would in this case be roughly

$$E = \pi^2\hbar^2/2mr^2 + 4\pi\sigma r^2 + \tfrac{1}{2}(\epsilon^{-1} - 1)e^2/r, \qquad (2)$$

where r is the cavity radius, σ is the coefficient of surface tension, and ϵ is the dielectric constant. At equilibrium radius[11] this energy would be about 0.2 electron volt. The cavity structure would, therefore, be energetically favored over the existence of the electron in the normally distributed or electrostricted liquid.

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[1]K. R. Atkins, Phys. Rev. 116, 1339 (1959).

[2]G. Careri, U. Fasoli, and F. S. Gaeta, Nuovo Cimento 15, 774 (1960).

[3]The cavity structure was first proposed by Ferrell to account for the long lifetime of positronium in liquid helium. R. A. Ferrell, Phys. Rev. 108, 167 (1957).

[4]H. T. Davis, Stuart A. Rice, and Lothar Meyer, J. Chem. Phys. 37, 1521 (1962); see Note added in proof.

[5]The barrier effect exists both above and below the λ point. Because of erratic behavior of the electron source at high vapor pressures, barrier height measurements were made only below 1.5°K.

[6]It is possible, by applying high fields, to produce a hydrodynamic instability which causes all the surface charge to be dumped to the submerged electrodes in one pulse.

[7]This was still true when an extra electrode was added to keep the electrons from going up the walls.

[8]Preliminary observations indicate the mobility of the thermalized surface electrons is nearly as high as that of a free electron in the vapor, so a radial field of a small fraction of a volt per cm would be sufficient to drain off the surface charges.

[9]L. B. Loeb, Fundamental Processes of Electric Discharge in Gases (John Wiley & Sons, Inc., New York, 1939), pp. 211, 212.

[10]A. V. Phelps, J. L. Pack, and L. S. Frost, Phys. Rev. 117, 470 (1960).

[11]Using bulk values for the surface tension, the equilibrium radius would vary from about 18 Å below the λ point to 25 Å at 4.2° due to the temperature dependence of the surface tension.