Localized Electrons in Liquid Neon*

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We have measured the mobility of negative carriers in liquid and gaseous neon. The results suggest that an electron injected in the liquid is localized in a bubble.

The behavior of electrons injected in liquid neon, near the melting point, has been studied theoretically by Springett, Jortner, and Cohen[1] (SJC). The same problem has also been investigated by Miyakawa and Dexter[2] (MD) for the whole temperature range between the melting and the critical points. In both calculations the Wigner-Seitz approximation was used. It was assumed that an electron was acted upon by a hard-core potential plus a polarization term. Here we will refer particularly to MD.[2] These authors also performed a cross check of their final results, taking multiple scattering into account, in the optical approximation. They found that the stability of the electron-bubble system depends very critically on the value of the low-energy scattering length l. The experimental values for the scattering length reported by various authors are spread in a rather broad range, from $0.03a_0$ to $0.39a_0$, where a_0 is the Bohr radius. The most widely accepted values[3] are between $0.24a_0$ and $0.39a_0$. MD found that an electron localized in a bubble should be a stable system in liquid neon, at all temperatures between 25 and 44°K, if $l = 0.39a_0$. On the contrary, at no temperature can the electronic bubble be stable if $l = 0.24a_0$. The total energy of the electron-bubble system obtained by MD with $l = 0.39a_0$ is in good agreement with the value previously obtained by SJC. The latter used a theoretical hard-core scattering potential,[4] and treated the polarization effects in a rather different way. However, the various approximations involved in either calculation prevented the authors from reaching any definite conclusion about the stability of the electron-bubble complex in liquid neon.

A test of the electron localization can be performed by measuring the mobility of negative carriers. In fact a quasifree electron in liquid neon can be expected to have a mobility in the range 10^2–10^3 cm^2/V sec, like quasifree electrons in very pure liquid argon.[5] On the other hand an electron localized in a bubble of radius R, moving in a liquid of viscosity η, can be estimated to have a mobility $\mu = e/4\pi R\eta$. Using experimental values for the liquid-neon viscosity at various temperatures,[6] and a value of 10 Å for the radius R, one gets mobilities in the range between 8.5×10^{-4} and 4.5×10^{-3} cm^2/V sec. Therefore the mobilities of quasifree and localized electrons should differ at least by 5 orders of magnitude.

We have measured the mobility of negative carriers in both liquid and gaseous neon at several temperatures between 25 and 44°K. The experimental cell was similar to those currently used in our laboratory.[7] The grid-to-collector gap, and the source[8]-to-grid gap were 0.5 cm each. The cell was enclosed in a pressure-tight brass container, placed inside a cryostat and cooled by a liquid-helium bath. The temperature of the cell and its container were monitored by a carbon resistor. The value of the temperature was obtained from the measurement of the liquid-neon vapor pressure.[9] The neon gas[10] was slowly condensed into the cell after passing it through a charcoal trap at liquid-nitrogen temperature. The liquid level inside the cell was monitored by measuring the interelectrode capacities. The mobility was measured by the square-wave time-of-flight method.[11]

The experimental results for the liquid phase are shown in Fig. 1, where the mobility versus temperature is plotted. Because the aim of the experiment was to get a test on electron localiza-

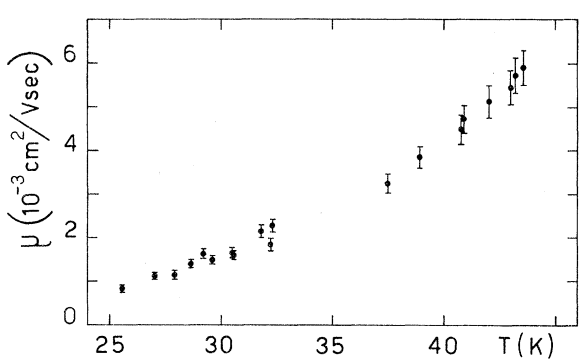

FIG. 1. Mobility of negative carriers in liquid neon at vapor pressure.

tion, the measurements were not performed with great accuracy. The experimental error is of the order of ± 7%, including a small systematic shift due to the space-charge effect. The measurements were made at vapor pressure, with electric fields between 400 and 900 V/cm. No significant dependence on the electric field was observed. Moreover, no components of the negative current with high mobility were observed. Therefore only one species of negative carriers was present in the liquid. The measured mobility has the same order of magnitude as expected for an electron localized in a bubble.

Before reaching any conclusion, we must be sure that the carriers were not electrons strongly bound to electronegative impurities. Such impurities may be present in our sample, and their mobilities happen to be similar to that of an electronic bubble. To settle this point we measured the mobility of negative carriers in the gas at various temperatures and pressures. The measurements in the vapor were made keeping the liquid level below the bottom electrode. We performed these checks before we measured the mobility in the liquid, or at the end of the run, having removed a fraction of liquid neon. The mobility in the gas was found to be several orders of magnitude larger than in the liquid. Moreover, it showed a strong field dependence, even at electric fields of a few volts per centimeter. These facts suggest that the carriers in the gas are quasifree, not thermalized electrons. We can give, as an example, some results obtained at $T = 43.2$°K. At a pressure of 20 atm the gas density is about $\frac{1}{4}$ of the liquid density at the same temperature. The mobility was about 500 cm^2/V sec with $E = 8$ V/cm, and about 250 cm^2/V sec with $E = 20$ V/cm. At the same temperature the density of the saturated vapor is about $\frac{1}{3}$ of the liquid density. The mobility was about 100 cm^2/V sec, to be compared with the value of 5×10^{-3} cm^2/V sec for the carriers in the liquid phase.

If electronegative impurities were present in our samples, the structure of such carriers would be nearly the same in the liquid as in the vapor. Therefore, the carrier mobility should not be different by orders of magnitude, since the phase densities differ only by a factor of 3 at this temperature. We may conclude that our experimental test is not affected by impurities, and that the negative carriers are completely different entities in the vapor and in liquid neon. The measured mobilities agree with the hypotheses that they are quasifree electrons and electrons localized in bubbles, respectively.

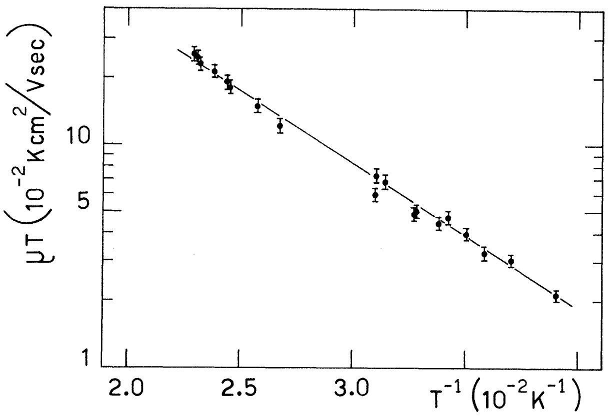

FIG. 2. Same data of Fig. 1 plotted as μT versus the reciprocal temperature $1/T$, as discussed in the text. The constant B_i turns out to be 151 ± 8°K.

We have plotted in Fig. 2 the quantity μT for negative carriers in the liquid, versus the reciprocal temperature $1/T$, on a semilog scale. The dependence is linear within experimental errors, thus suggesting that the electronic bubble is a stable structure at all temperature. In fact, let us assume that the bubble diffusion coefficient D_i has a temperature dependence of the form $D_i = A_i \exp(-B_i/T)$. Then, from the Einstein formula $\mu T = (e/k)D_i$, we obtain the relation $\ln(\mu T) = \ln(eA_i/k) - B_i/T$. If the carrier structure does not significantly depend on the temperature, then the quantities A_i and B_i are almost temperature independent,[12] and we get a linear relation. The stability of the bubble is also indicated by the absence of fast components in the negative current, as mentioned above.

Summarizing, the results of our experimental test suggest that electrons injected in liquid neon at vapor pressure are localized in bubbles, at all temperatures, and that the electron-bubble complex is a stable entity. Comparing our results with the MD calculations, we can also suggest that the scattering length l of low-energy electrons in neon should be close to the value $l = 0.39a_0$.

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Mechanism for Anomalous Current Penetration*

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A localized collisionless instability that occurs in a nonuniform or skin current flowing along an external magnetic field is shown to produce an anomalous viscosity giving cross-field diffusion of the current. The instability can occur under conditions where the ion-sound wave is stable and is then the dominant process for penetration.

In this Letter we present a collisionless mechanism for the penetration of a skin current into a plasma under conditions where the ion-sound modes are stable. The collisionless penetration is shown to occur through turbulent $\vec{E}\times\vec{B}$ drifts of the electrons produced by fluid instabilities occurring in the nonuniform current profile. Previous studies[1-3] have shown that shear in a beam or current profile can drive fluid instabilities. The growth rates obtained[1,2] are sensitive functions of the angle of wave propagation to the magnetic field, and the angle remains an arbitrary parameter. The theory presented here gives a self-consistent determination of the angle of propagation and yields a growth rate and critical gradient free of the angle parameter.

We show that a nonuniform current $j_z(x)$ flowing along a magnetic field $B_0\hat{e}_z$ can diffuse across the magnetic field by turbulence from a fluid instability with a maximum growth rate of the order $\gamma \sim \frac{1}{2}|du/dx|$, where u is the drift velocity of the electrons in the current $j_z = -en_0u$. The unstable mode has a small parallel electric field which is determined self-consistently in the presence of the sheared magnetic field produced by the current j_z. In the following analysis the plasma density and temperature are assumed sufficiently uniform with respect to the current nonuniformity to neglect their effect. The important electron-temperature gradient modes[3] as well as the ion-sound instability are driven by resonant electrons, in contrast to the present fluid instability driven by $|du/dx|$. As a consequence, the quasilinear change in the parallel electron velocity distribution,[4] which can saturate the resonant temperature gradient and ion-sound instabilities, has little effect on the present instability. Instead, we estimate that saturation of the current gradient mode occurs through the anomalous viscosity and diffusion of the current profile in x space. The anomalous viscosity in the saturated state is estimated in Eq. (17) below.

The equilibrium plasma in slab geometry has a nonuniform current $j_z(x)$ which can be taken as a linear gradient in the neighborhood of the localized mode with $j_z(x) = -en_0(u + x\, du/dx)$. The shear in the magnetic field $\vec{B} = B_y(x)\hat{e}_y + B_0\hat{e}_z$ is given by

$$dB_y/dx = -4\pi e n_0 u/c$$

which yields $B_y(x) = B_y(0) + B_0(x/L_s)$, where the distance L_s given by $L_s^{-1} = \omega_{pe}^2(u/c^2)\omega_{ce}$ is the characteristic distance over which the magnetic field rotates through an appreciable angle.

We take as our basic equations the fluid equations with an electrostatic field $\vec{E} = -\nabla\varphi(\vec{x}, t)$. For the electrons we have

$$\frac{\partial n_e}{\partial t} + \nabla\cdot\left(\frac{cn_e\vec{B}\times\nabla\varphi}{B^2}\right) + \frac{\partial}{\partial x_\parallel}(n_e u) = 0, \tag{1}$$

$$\frac{\partial u}{\partial t} + \frac{c\vec{B}\times\nabla\varphi}{B^2}\cdot\nabla u + u\frac{\partial u}{\partial x_\parallel} = \frac{e}{m_e}\frac{\partial\varphi}{\partial x_\parallel}, \tag{2}$$

$$\epsilon_\perp\nabla_\perp^2\varphi = -4\pi e(n_i - n_e), \tag{3}$$

where $\epsilon_\perp = 1 + \omega_{pe}^2/\omega_{ce}^2$, and it is assumed that $k_\perp v_e < \omega_{ce}$, $\omega_{ce} > \omega > k_\parallel v_e$, where $v_{e,i} = (T_{e,i}/m_{e,i})^{1/2}$.