New Stability Limit of Electrons Trapped on the Surface of Liquid Helium

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We report the discovery of a density, n, and electric field, E_p, dependent critical temperature for electrons trapped on the surface of liquid helium for densities $n > 1.2E_p/2\pi e$. Above this critical temperature a finite fraction of the electrons escape rapidly from the surface into the vacuum. The critical temperature increases with decreasing density, for a given electric field.

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Electrons, at a density n, trapped on the surface of liquid helium constitute an almost ideal 2D system in which the interactions are known and thought to be well understood. Motion of electrons within the plane have been studied extensively through measurements of mobility, the plasma modes, and interactions with surface excitations (ripplons).[1] The strong electron-electron correlation due to the Coulomb interaction is manifested by a crystallization at sufficiently high densities and low temperatures.[2] The motion of electrons normal to the plane is governed by the image potential in the helium (dielectric constant $\epsilon = 1.05723$), the external electric field, E_p, and the electron-electron interactions.[3] E_p is due to the applied potentials and the image charges in the metallic cell walls and it is always directed so as to force the electrons onto the helium surface. Electrons close to the surface are governed by the image charge in the helium and E_p so that the Hamiltonian becomes approximately that of a Stark-shifted one-dimensional hydrogen atom (only S states). The influence of the correlations on thermally activated escape over the top of the barrier is described with reasonable quantitative accuracy by a relatively simple theory.[3,4] However, in Ref. 4 we have measured quantum tunneling rates that are too rapid to be explained by that theory. These measurements indicate the need for a more careful treatment of electron-electron correlations.

In highly correlated systems the electron-electron interactions become important for heights $z \cong n^{-1/2}$ above the surface. For $z \gg n^{-1/2}$ the effect is that of an electric field, $E_C = 2\pi ne$, in a direction such as to force the electrons toward the top plate. In this experiment $|E_C| > |E_p|$ so that the surface layer of electrons is "overcharged." We report here the discovery of an additional and unanticipated manifestation of collective behavior in the system. As the temperature is increased, with fixed electron density n, for $n > 2.5 \times 10^8$ cm^{-2}, a critical temperature, T_c, is reached at which a finite fraction of the charge suddenly escapes from the surface. T_c increases with decreasing n.

The experimental cell (Fig. 1) has two horizontal parallel capacitor plates 2 cm in diameter, separated by 1 cm. The upper plate has a small hole through the center. A pointed electrode located just above this hole is charged to about -300 V to initiate a discharge. The discharge is performed at a temperature of 0.98 K. During the discharge the magnitude of the (negative) potential of the upper plate, V_p, is gradually increased so as to force the electrons onto the surface of the helium. The lower plate is held at dc ground potential.

The liquid-helium surface is located 0.44 cm above the lower plate. A cylinder surrounding the plates, but insulated from them, is held at a negative potential, V_r, so as to provide a radial field to prevent the electrons from reaching the walls of the container. In this geometry the charge forms a circular disk with a diameter that depends on V_p, V_r, and the total charge, Q.[4,5] If the diameter of the charge disk is close to that of the retaining

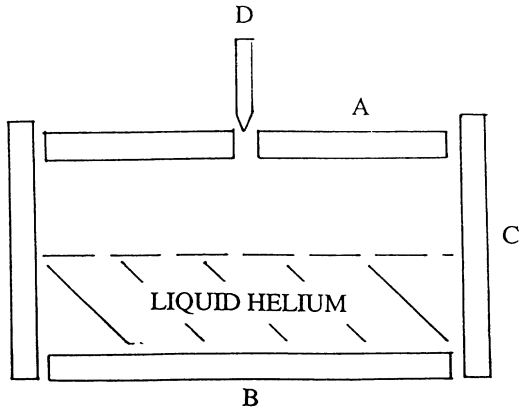

FIG. 1. Cross-section diagram of the cylindrical sample container. A is the upper capacitor plate, B is the lower plate, C is the cylinder providing the radial confining field, and D is the point of discharge for generating the free electrons.

cylinder, the capacitance between the plates is substantially reduced. As the diameter of the disk decreases, its shielding effect decreases so that the capacitance between plates increases. Thus the capacitance can be used as a measure of the disk diameter and consequently of the total charge on the surface. Knowing the capacitance, V_p, V_r, and the geometry, we can compute values of the density n, and the electric field E_p on the electrons, at the center of the charge pool, by numerical methods.[4,5] At the beginning of each experiment the surface is fully charged so that $2\pi ne = E_p$.

The experiments commence by our reducing V_p, and therefore E_p. This means that the electron pool is overcharged ($2\pi ne > E_p$) since the reduction in V_p reduces E_p while also reducing the radius of the pool. In our earlier experiments, for $|V_p|$ sufficiently large, the radius of the charge pool varied reversibly with V_p without any loss of charge. For smaller $|V_p|$ charge began to leave the surface either by thermal activation at high temperatures or by quantum tunneling at low temperatures. Both thermal activation and tunneling occurred slowly for small changes in $|V_p|$ so that detailed measurements of the rate as a function of temperature and V_p were made.

By contrast, in the present experiments with $n \gtrsim 2.5\times10^8$ cm^{-2}, until T is raised to a sharply defined critical value the escape rate is less than (7×10^{-6} sec^{-1})/electron. Then the rate increases by more than a factor of 10^3 (to a rate too rapid to measure by our technique) over a temperature change less than 1 mK and a finite fraction, approximately 1% of the total charge leaves the surface. Subsequently, the temperature can be increased further without loss of charge until the critical temperature corresponding to the new, lower charge density is reached and another sudden loss of charge occurs. This can be repeated several times to trace out a critical boundary as shown in Fig. 2. The amount of charge that escapes on each burst depends on how far the temperature overshoots the boundary and is difficult to control. Therefore the charge increments shown in the data of Fig. 2 are not uniform.

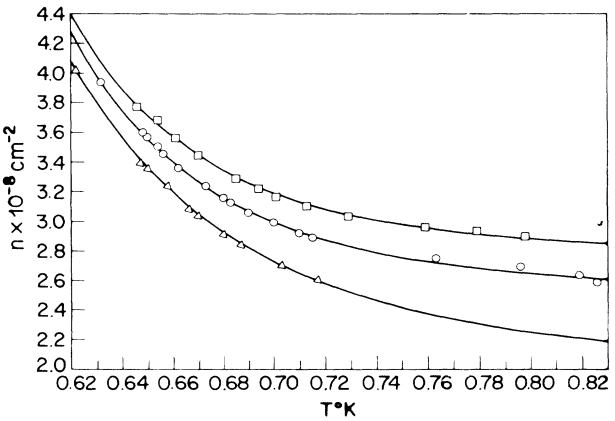

FIG. 2. The critical boundary for three values of the pressing field E_p. E_p is held constant by our resetting V_p for each new value of n. The value of V_p to be set was computed numerically for each measured value of n. The solid curves are fits of Eq. (1) to the data with values quoted in the text: squares, $E_p = 204$; circles, $E_p = 186$; triangles, $E_p = 168$ V/cm.

Since the independent variables for the system are n, E_p, and T, a two-dimensional plot is meaningful only if one of the variables is constant. The data shown in Fig. 2 were obtained by our adjusting V_p for each new value of n so that E_p was constant for each of the three sets of data. We held E_p constant since it enters directly into the potential binding the electrons to the helium surface. The adjustments of V_p are small and represent the correction for the changing image charge in the cell walls as charge escapes from helium surface. The functional form which best fits the data is

$$n = Ae^{+E/T} + n_c, \tag{1}$$

and the corresponding curves are shown as solid lines in Fig. 2. The constants for the three fits are

$$A = 2.77\times10^3,\ E = 6.9,\ n_c = 2.20\times10^8,\ E_p = 167.5;$$

$$A = 1.62\times10^3,\ E = 7.2,\ n_c = 2.51\times10^8,\ E_p = 186;$$

$$A = 1.10\times10^3,\ E = 7.4,\ n_c = 2.75\times10^8,\ E_p = 204.$$

E is given in K, A and n_c in cm^{-2}, and E_p in V/cm. The values of E and n_c are determined by the fit to within about 5% and 10%, respectively. The value of A for a given value of E is determined to within about 5%.

Several potential causes of the instability have been ruled out by the data:

(1) A previously observed stability limit at density $n = 2\times10^9$ cm^{-2} occurs at high pressing fields and is preceded by the formation of "dimples" and then deep troughs on the surface of the liquid.[6] The electrons then leave the surface by passing through the liquid. By measuring the sign of the current pulse to the top plate when T_c is reached, we have determined that the electrons in our experiment escape into the vacuum and strike the upper plate. Consequently, the process that we observe is unrelated to the other instability.

(2) A resonance of the electron layer could have been excited by the ac field of the capacitance bridge. However, the phase boundary occurred at the same values of T_c and n with frequencies 300, 1000, and 3000 Hz.

(3) The escape rate in the thermally activated and quantum tunneling regimes is strongly influenced by electron-electron correlations in the plane of the surface.[3,4] Consequently, we anticipated that we would observe a change in the escape rate at the transition between liquid and solid phases of the electrons. The phase boundary occurs when the ratio of potential to kinetic energy is $\Gamma = \pi^{1/2}e^2n^{1/2}/k_BT = 137\pm15$ (Ref. 2) so that $n_{\text{solid}} = 2.14\times10^9T^2$. This phase boundary would cross the curves fitted to our data at $n = 7\times10^8$ cm^{-2}. Thus

the instability that we observe has the wrong temperature dependence and occurs in the wrong range of T and n to be explained by the crystallization.

(4) Waves on the surface of the liquid helium could change the electric field so as to reduce the barrier for escape temporarily and allow escape by thermal activation. An accelerometer was attached to the apparatus to monitor the ambient vibration level. Although fluctuations in the level were observed, they did not lead to measurable changes in escape rates or to measurable changes of the stability boundary of Fig. 2. Thus we conclude that waves on the surface are *not* the cause of the instability.

The escape rates that we used when measuring the thermal activation and tunneling processes ranged between 10^2 and 10^4 electrons per second. The rate at the critical temperature in this work was too rapid to measure by our technique ($>10^6$/ sec) for $n>3\times10^8$ cm^{-2} and $T<0.7$ K. On the other hand, at the high temperature and low density end of the measurements, the escape rate at the instability boundary becomes slow enough to be observable, eventually obscuring the described critical phenomenon. However, the rates in the region shown in Fig. 2 are still too rapid for quantitative measurement by the present technique and much too rapid to result from the thermal activation process observed in our previous experiment.

The functional form of the curves fitted to the data suggests that the phenomenon is dependent on the small density ($\cong10^4$ cm^{-2}) of electrons in the thermally excited hydrogenic states.[7] The energy difference between the first excited state and the ground state for an electron in the hydrogen potential is

$$E_{10}=\frac{3}{4}\frac{\Lambda^2e^4m^2}{2\hbar^2}\cong5.7\text{ K} \tag{2}$$

when $\Lambda=(\epsilon-1)/4(\epsilon+1)=0.00695$. ϵ is the dielectric constant of liquid helium. The Stark shift will increase this energy separation. Measurements of the shift, for fields comparable to ours but at densities 30 times smaller, indicate that $E_{10}\cong10.5$ K.[8] Higher densities reduce the Stark shift but the amount of the reduction depends sensitively on the effect of the correlations for which no theory has yet been worked out. It is possible that E_{10} is reduced to $\simeq7$ K for $n\cong3\times10^8$ cm^{-2}. The value of n_c, for all three values of E_p, are 1.20 ± 0.04 times the fully charged density. This means that the instability will *not* occur for $n<n_c=1.2E_p/2\pi e$. Rewriting Eq. (1) in the form

$$A=n\exp(-E/T)-n_c\exp(-E/T) \tag{3}$$

implies that the instability occurs when the density of electrons in the first excited state, $n\exp(-E/T)$, exceeds 1.2 times the density in that state for the fully charged system, $n_c\exp(-E/T)$, by a critical density, A. The factor of 1.2 is the excess density required for the repulsive field of the charge pool to reduce the barrier height, as computed in Ref. 3, to the point where it is equal to $\langle V\rangle=e^2(\pi n)^{1/2}$. The parameters E and A, depend only on E_p.

The process by which excited-state electrons play a role could be as follows. The expectation value for the position normal to the surface of an electron in this state for $E_p=0$ is

$$\langle z\rangle_{11}=4\langle z\rangle_{00}\approx4(\tfrac{3}{2})\hbar^2/\Lambda me^2\cong456\text{ Å}.$$

The compression of the wave function by E_p is estimated in Ref. 8 for lower fields and will be less than a factor of 2 for our fields.

At all values of T and E_p there is a small "background" rate at which electrons disappear from the surface. (The rate is consistent with cosmic-ray creation of ion-electron pairs in the liquid. However, the process being described would be independent of the mechanism for initiating the escape of the first electron.) As soon as an electron disappears from the surface, surrounding electrons rush into the hole left in the 2D gas. In the process the potential energy $\langle V\rangle$ at near-neighbor distance ($47\text{ K}<\langle V\rangle<59$ K for our densities) is converted to kinetic energy. This implies that collisions between a pair of electrons which are able to convert the energy of in-plane motion to energy in the z direction will result in the ejection of an additional electron from the surface, with the assumption that the barrier height is less than $\langle V\rangle$. If one of the electrons is in the ground state and the other in the first excited state, the cross section for such a collision is relatively large. It is given approximately by

$$\sigma_e\cong\pi(\langle z\rangle_{11}-\langle z\rangle_{00}). \tag{4}$$

If both electrons are in the ground state, then the corresponding cross section is much smaller. The scattering time is approximately

$$\tau^{-1}\cong n\sigma(2m^{-1}\langle V\rangle^{1/2}\cong10^{10}\text{ to }10^{11}\text{ sec}^{-1}. \tag{5}$$

This is very rapid compared to typical measuring times, plasma frequencies, and other characteristic times in the experiment. When there is more than one hole generated in each collision their number will increase until the new density stabilizes the system. Thus we argue that the instability could be due to a chain reaction which results from collisions between ground-state and excited-state electrons. The specific manner in which the process occurs and the reason for the sharply defined boundary is not yet clear.[9]

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[9]Recent theoretical work (M. Azbel and P. Platzman, to be published) shows how it is possible to include strong Coulombic effects into the description of tunneling and activation in these 2D systems. The theory, among other things, describes "instability" boundaries which are intact, the result of a chain reaction. When applied to current experiments its predictions are in good agreement with available data. In addition, the theory suggests a rather rich spectrum of new phenomenon related to these instability boundaries. These predictions should be subject to experimental verification, particularly at lower temperatures. These exciting results were *not* reported in this paper since they came much after the submission of the first experimental discoveries and because other scientists are involved.