Electron localization and drift under the surface of condensed krypton

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Electrons localized by an external electric field below the interface between condensed and gaseous phases of krypton remain in a quasifree state with respect to motion along the interface.

An electron near an interface between two dielectrics with different dielectric constants can form surface states by virtue of image forces.[1,2] Previous research on such states has been carried out for interfaces between condensed and gaseous phases of nonpolar dielectrics with a positive energy of the interaction of an electron with the condensed phase, $V_0 > 0$ (hydrogen, helium, and neon). It has been shown for these media that outside the condensed phase an electron localizes in 2D stationary states, while in a liquid phase it is in a self-localized state: a vacuum bubble.[2–4] In the condensed phases of heavy inert gases, we have $V_0 < 0$, and an electron is in a quasifree state. It is therefore interesting to monitor the behavior of such electrons near an interface.

In the experiments we used a two-electrode parallel-plane ionization chamber partially filled with liquid or solid krypton (Fig. 1). The source of electrons was x radiation with a maximum x-ray energy of 35 keV. The absorption length for this radiation in condensed krypton does not exceed 1 mm. An x-ray pulse 2 μs long was produced by a controlled tube, and it entered the condensed krypton through an aluminum window in the cathode. The density of electrons produced per x-ray pulse in the condensed krypton depends on the field which pulls electrons away from the tracks of the x-ray photoelectrons; in fields $\sim 10^3$ V/cm, this density does not exceed 10^6 cm^{-3}. The temperature of the chamber was regulated by means of a liquid-nitrogen jacket and a heat shield around this jacket. The temperature was monitored with copper-constantan thermocouples. The thickness of the layer of condensed phase was

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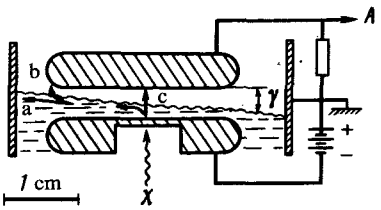

FIG. 1. The measurement arrangement.

determined from the volume of condensed gas. The chamber is described in more detail in Ref. 5.

Using a charge-sensitive amplifier with a time constant of 35 μs, we displayed on an oscilloscope screen the voltage pulse which arises between the electrodes of the ionization chamber as electrons are collected from one x-ray pulse. The repetition frequency of the x-ray pulses (0.1–50 Hz) was chosen such that the temporal shape of the ionization signal was not distorted by the buildup of a space charge of relatively immobile carriers (positive krypton ions and negative ions formed as a result of capture of electrons by electronegative impurities, e.g., oxygen). Before the condensation, the krypton and the chamber itself were purified by repeatedly circulating the gas through calcium shavings heated to 800 K.

We observed basically three types of ionization signals (Fig. 2), depending on the potential difference between the electrodes and thus on the electric field (E) in the condensed phase. At $E \sim 10^2$–10^3 V/cm the signal is trapezoidal (Fig. 2a) with a length of 10–30 μs. With increasing field the amplitude of the signal increases, since there is an increase in the number of electrons drawn by the field from the tracks of the x-ray photoelectrons. The shape of the signal gradually transforms to that shown by curve b in Fig. 2. The amplitude of the second peak on curve b increases until the field E reaches a critical value E_0 (near the triple point for liquid krypton, $E_0^l = 1600 \pm 20$ V/cm; for solid krypton, $E_0^s = 980 \pm 20$ V/cm). At $E \gtrsim E_0$, the amplitude of the first peak begins to grow, and it continues to grow until the pulse acquires the shape shown by curve c. With a further increase in E, the shape of the pulse does not change, but the amplitude increases rapidly until it begins to correspond to the curve of the ioniza-

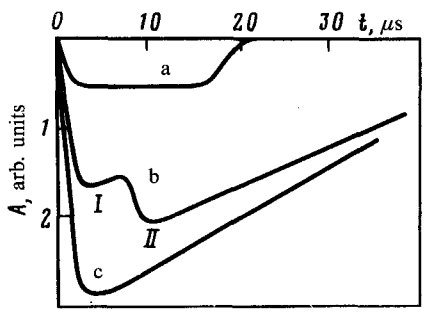

FIG. 2. Some typical oscilloscope traces.

tion charge yield from the tracks of the photoelectrons in a chamber with a completely filled gap between electrodes.[5]

These observations can be interpreted easily by considering a deviation of the chamber electrode from an arrangement parallel to the surface of the condensed phase. If the interface makes a small angle γ with the electrodes (Fig. 1), a weak field $\sim\gamma E$ will arise along the interface. As has been shown elsewhere, the emission of electrons from condensed krypton sets in after a threshold is reached.[6] Consequently, if the field E in the condensed phase is below the threshold field E_0, the electrons are confined below the interface and can drift along it in the field γE. As they move below the surface, the electrons reach the regions of elevated field near the edges of the electrodes. If the field in these regions is still too low for emission, the electrons move off to the chamber wall (arrow a in Fig. 1), inducing a voltage pulse of positive polarity at the anode. When this pulse is added to the negative-polarity ionization signal induced at the anode in the drift of electrons from the volume of the condensed phase toward the surface, it forms a trapezoidal pulse at the anode. The length of this trapezoidal pulse is on the order of the drift time below the surface (Fig. 2a). If the field near the edges of the electrodes exceeds E_0, the electrons will be emitted into the gas phase here and will collect at the anode (trajectory b in Fig. 1). In this case the pulse has two peaks, the first corresponding to the arrival of electrons at the surface, and the second due to emission near the edges of the electrodes. If the field in the condensate at the center of the chamber exceeds E_0, electrons are emitted as soon as they reach the interface (Fig. 1c), and the pulse has its conventional shape (Fig. 2c).

By tilting a chamber half-filled with liquid krypton we confirmed that the pulse shapes of types a and b in Fig. 2 do in fact depend on the angle between the surface of the liquid and the electrodes. With increasing angle, the length of the pulses of type a decreases, while for the pulses of type b the time interval between peaks decreases.

It follows that the average electron drift time along the interface can be determined from the shape of the voltage pulse. For the pulses of type a, this time can be

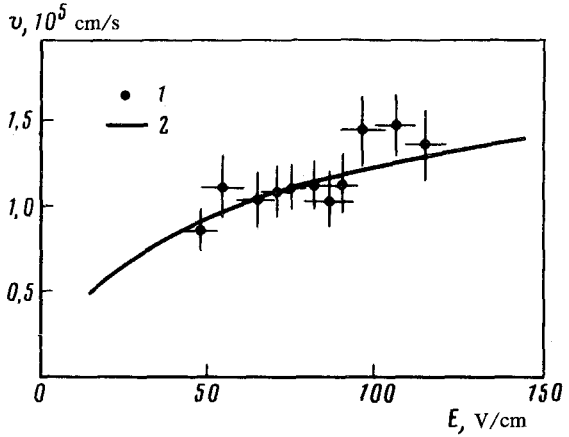

FIG. 3. Electron drift velocity in liquid krypton at $T = 125$ K below the interface (1) and in the volume[5] (2).

determined from the projection of the smaller base of the trapezoid onto the time axis, and for the pulses of type b it can be determined from the distance along the time scale between the peaks. Knowing the average drift time along the surface, we can determine the drift velocity in the plane tangent to the surface under the assumption that the average drift path under the surface is equal to the radius of the cathode for an axisymmetric chamber (Fig. 1). Figure 3 shows drift velocities along the surface found in this manner (1) versus the tangential component of the electric field in liquid krypton at $T = 125$ K for $\gamma = 3°$. The curve (2) is drawn through the experimental data found in Ref. 5 for quasifree electrons drifting in the volume of liquid krypton.

Similar measurements in solid krypton were complicated by intense polarization effects, probably caused by the capture of electrons by defects or structural traps at the surface. We can nevertheless assert that the drift velocity along the surface of solid krypton is comparable in magnitude to that below the surface of the liquid.

Adding 1.5 mole % CH_4 to the liquid krypton doubled the drift velocity under the surface in fields $E \sim 100$–150 V/cm and increased the threshold field E_0 by a factor of 2.8.

The agreement within the experimental errors in Fig. 3 shows that at $E < E_0$ the electrons localize under the surface of condensed krypton along the direction normal to the surface but remain in a quasifree state with respect to motion in the tangential plane.

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