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Inhibition of tunneling from electronic bubble states in liquid helium into the vapor phase at high vapor densities

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It is shown that at temperatures near 4.2 K electron tunneling from liquid helium into the vapor phase will be inhibited due to the increasing vapor density.

The transport of electrons from liquid helium through the free liquid surface into the vapor phase can be described adequately as a tunnel effect from the ground state inside the bubble.[1] A necessary condition for tunneling to occur is that the ground-state energy E_0 inside the bubble is positive with respect to the electronic potential V_0 in the vapor phase. Below 2 K the vapor phase can be considered as vacuum ($V_0 \approx 0$) and the above condition is satisfied. At higher temperatures, however, the vapor becomes so dense that the interaction between the electrons and the He atoms can no longer be neglected. This interaction can be described as an "optical potential" $V_0 = 2\pi\hbar^2 an/m_e$, where a is the low-energy electron-helium scattering length, m_e is the electron mass, and n is the particle density of the vapor.[2] V_0 increases with temperature T proportional to $n(T)$. On the other hand, E_0 decreases with increasing temperature as the surface tension $\gamma(T)$ decreases and hence the bubble radius R increases.

From the simple bubble model one has

$$E_0 \propto R^{-2} \propto \gamma^{1/2} .$$

$V_0(T)$ and $E_0(T)$ are plotted in Fig. 1. $n(T)$ was obtained from Ref. 3, and a was taken to be 0.60 Å. E_0 was fitted at 1.5 K to the value of 0.12 eV,[1] and the surface tension was taken from Ref. 4. As can be seen from Fig. 1, E_0 is smaller than V_0 above 4.2 K.

An immediate interpretation of this result might suggest that the tunneling current would have a steep cutoff near 4.2 K. However, fluctuations of the particle density in the vapor must be taken into account. They give rise to a fluctuating potential $V_0(\vec{x})$, $\vec{x}$ being a space coordinate. $V_0(\vec{x})$ will fluctuate around the average value $\overline{V}_0$ which was actually plotted in Fig. 1. Following the argumentation of Eggarter[5] one can divide the the gas space into cells having an average potential less than E_0 (i.e., "allowed regions") and those having an average potential larger than E_0 ("prohibited regions"). Assuming a Gaussian distribution of V_0 about $\overline{V}_0$ one can calculate the fraction c of the "allowed" space as

$$c = (2\pi)^{-1/2} \int_{-\infty}^{(E_0-\overline{V}_0)/\sigma_{V_0}} dt\, e^{-t^2/2} ,$$

where σ_{V_0} is the standard deviation of V_0, which can be calculated by introducing a characteristic sampling length of the cells[5,6] and taking the equation of state for dense He gas. At 4.2 K we have $E_0 = \overline{V}_0$ and hence $c = 0.5$. Towards higher temperatures c will drop at a rate which is extremely sensitive to σ_{V_0}. We have tried to calculate $c(T)$ but our results remain unreliable because of uncertainties in σ_{V_0} (the choice of the sampling length and the third virial coefficient have a strong influence). We may expect, however,

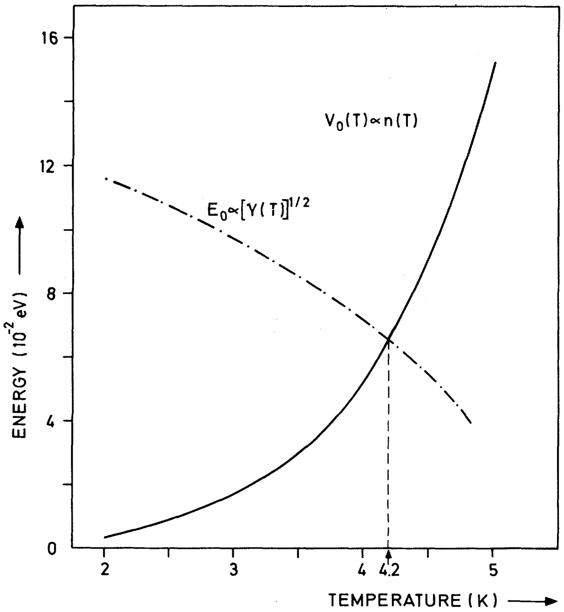

FIG. 1. Ground-state energy E_0 of the electron inside the bubble and the optical potential V_0 of the electron in the vapor phase plotted vs temperature. The curves intersect at 4.2 K.

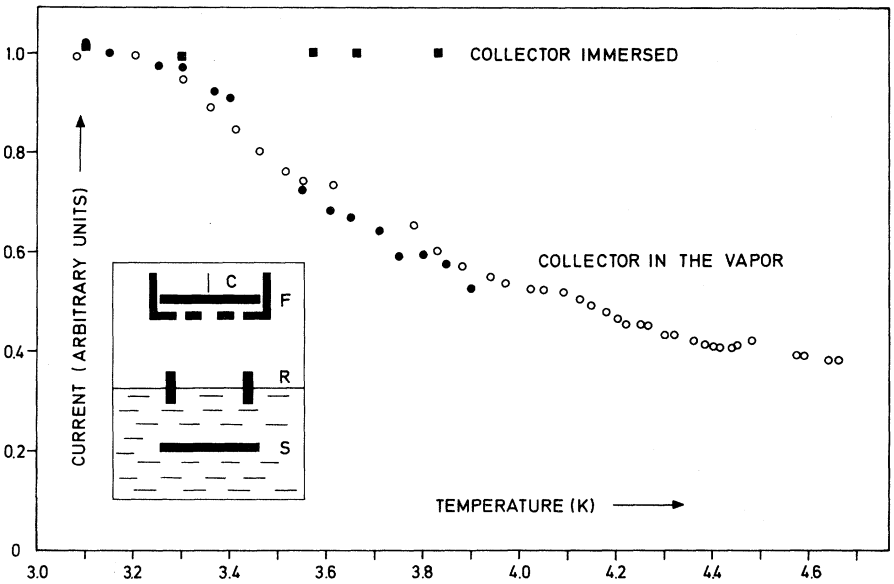

FIG. 2. Temperature dependence of the electron current through the liquid-vapor interface (○, ●) and with the collector being immersed (■). The curves are normalized at 3.1 K. The measuring cell is shown in the inset.

that a rapidly decreasing c will drastically reduce the tunneling probability and the tunneling current.[7]

We have made an experimental effort to observe this behavior by measuring the temperature dependence of a dc electron current through the liquid-vapor interface between 2.2 and 4.7 K. A schematic of the measuring cell is shown in the inset of Fig. 2. The current was produced in the liquid by means of a radioactive source $S(^{241}\mathrm{Am})$ and controlled by a metal ring R. The liquid level was usually located in the middle of the ring to prevent any charge accumulation at the interface. The collector C was shielded by a Frisch grid F. We first made test runs with the measuring chamber completely filled with liquid helium (i.e., collector immersed). In this case no temperature dependence of the current was seen (see Fig. 2). We then lowered the liquid level to the ring and measured the current emerging from the liquid surface as a function of temperature. As can be seen From Fig. 2, the current shows a continuous decrease above 3.2 K.

Though our data might indicate the effect of an inhibition of tunneling, we are unable to prove that in a quantitative manner. In particular, it is not clear why the current starts dropping at 3.2 K where we do not expect any measurable inhibition. On the other hand, mobility changes in the vapor phase can be ruled out as a possible cause since they would produce a change in the current of only a few percent of the actually observed drop. We feel that further experimental work is necessary to demonstrate convincingly the described effect of an inhibition of tunneling into dense He gas. This effort seems worthwhile because the low-energy electron source provided by the liquid-vapor interface might be a useful tool for studying electron tunneling into disordered material, for which He gas seems to be the simplest example.

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[2] See, e.g., J. L. Levine and T. M. Sanders, Jr., Phys. Rev. 154, 138 (1967).

[3] Z. E. H. A. El Hadi and M. Durieux, Physica (Utr.) 41, 305 (1969).

[4] J. F. Allen and A. D. Misener, Proc. Camb. Philos. Soc. 34, 299 (1938).

[5] T. P. Eggarter, Phys. Rev. A 5, 2496 (1972).

[6] J. P. Hernandez, Phys. Rev. A 7, 1755 (1973).

[7] The tunneling probability P into vacuum as discussed in Ref. 1 must be replaced now by Pc.