that electron localization is independent of the degree of order in solid or gaseous He, the experimental results conclusively show that the electron state is localized in the solid up to pressures of 4000 atm. Furthermore, since helium does not undergo a large volume change on melting (< 5%) it is most probable that similar sized bubbles exist in the solid near the melting point at 6760 atm. Thus the present observations are consistent with the presence of cavity-localized electrons in the solid at the highest experimental pressure which is approximately 60% larger than the 4000 atm estimated by Cohen and Jortner.[7]

The size of the negative ion in the dense gas can be estimated in the following manner. Stokes's Law gives a classical hydrodynamic expression for the mobility of a charged solid sphere in a viscous fluid[13]:

$$\mu = e/6\pi\eta R ,$$

where e is the electronic charge, η is the viscosity of the fluid, and R is the radius of the sphere. One can determine the viscosity of the dense gas by using the measured value of μ for the positive ions and a theoretical value of the positive ion radius. This radius is calculated using Atkins's model[14] for positive ions in liquid helium which takes into account the effect of electrostriction on the effective mass of the ion. Accordingly, the ion radius is given by

$$R_+ = \left(\frac{N\alpha e^2}{2V_M \epsilon_0^2 (p_s - p)}\right)^{1/4} ,$$

where $N\alpha$ is the molar polarizability, p_s is the solidification pressure, p is the external pressure, V_m is the molar volume, and ϵ_0 is the permittivity of vacuum. The polarizability is $N\alpha/V = 6\times10^{-3}$ C^2 sec^2/g cm^3.[13] This gives

$$R_+ = 3.9\times10^{-8} \text{ cm}.$$

This leads to a calculated viscosity of the dense helium gas near 80 °K of

$$\eta = 4.4\times10^{-4} \text{ P}.$$

From the measurement of μ_- at this pressure and temperature and the above estimate of η one can obtain the electron-bubble radius

$$R_- = 6.2\times10^{-8} \text{ cm}.$$

This estimate of the bubble radius is consistent with the measurements of Triftshäuser *et al.*,[15] who find $R_- \approx 8$ Å at 170 atm in solid helium.

The density of the helium gas has been estimated by scaling the reduced molar volume as a function of the reduced temperature. The molar volume measurements of Bridgman[16] in helium gas at 65 °C and the PVT data of Dugdale[17] were used to obtain the value $V_M = 9.1$ cm^3/mole. The corresponding density is $\rho = 0.44$ g/cm^3 which is similar to that in solid helium at 4000 atm.

To summarize, we have assumed that the effect of trapping is negligible in the solid-helium sample and shown as a result that cavity-localized electrons persist to pressures of 6400 atm and all temperatures below the melting point of the solid. This pressure is well in excess of the minimum collapse pressure of 4000 atm calculated by Cohen and Jortner.

Let us now reexamine their solution to the problem of excess electrons in solid helium to see if a more accurate critical pressure can be calculated using the present results. Following Cohen and Jortner[7] the energy of the cavity-localized electron can be written

$$E_t = XV_0 + \tfrac{4}{3}\pi R_0^3 p + 4\pi R_0^2 F_s .$$

These terms account for the increased electron energy due to confinement in the cavity, work done against pressure to create the cavity, and work done against the surface stress, respectively. V_0 represents the energy of a quasifree electron, estimated by a Wigner-Seitz calculation, and X is a parameter related to the cavity-edge boundary conditions.[18] R_0 is the cavity radius and p is the external pressure. F_s is the surface free energy of the cavity. In their work, Cohen and Jortner used the low-energy electron–helium-atom scattering length $a = 1.13$ a.u. $= 0.60$ Å as the radius of a hard sphere which was their model of the electron-helium potential used in the Wigner-Seitz calculation.[19] However, in the present case the increased pressure leads to a significant decrease in the Wigner-Seitz radius. The resulting Bloch wave function corresponding to $\vec{k} = 0$ will now contain a significant amount of high-energy plane-wave components. The presence of these high-energy components implies that the simple low-energy constant scattering length approximation is no longer quantitatively correct and the complete energy-dependent nonlocal electron-helium pseudopotential[8] must be used to determine V_0 by the Wigner-Seitz method.

It is not the purpose of the present work to perform such a calculation. We can, however, obtain a qualitative understanding of how inclusion of the complete pseudopotential will affect V_0 by simply allowing the scattering length to be a function of energy. Let us estimate the energy values for the highest non-negligible components of the $\vec{k} = 0$ Wigner-Seitz wave function by

$$E = \hbar^2 k^2 / 2m ,$$

where

$$k \approx \pi / r_s ,$$

and r_s is the Wigner-Seitz radius. This gives

$$E \approx 10 - 14 \text{ eV}.$$

The effective s-wave core radius can be estimated from calculations of the electron-helium atom cross section.[20] One obtains

$$0.46 \leq \alpha(E) \leq 0.54\ \text{Å} .$$

Recalling that the total electron energy must be less than V_0 if the electron is to be localized in the cavity, we have calculated the pressure dependence of V_0 for three values of the helium-atom model-potential radius α. This is shown in Fig. 4 and demonstrates the strong dependence of V_0 at any pressure on this parameter. At sufficient pressure, E_t must exceed V_0 regardless of the value of α and the nonlocalized electron state will be favored. The pressure-induced collapse criterion for the cavity-localized electron state can be written[7] as

$$p \gtrsim \frac{3}{4\pi}(1 - X^2)\,\frac{V_0}{R_0^3} .$$

When one adopts a reasonable bubble radius in the range of 4 – 7 Å and appropriate values for X this expression reduces to

$$p \gtrsim 720\ V_0^{5/2} ,$$

where p is expressed in atmospheres and V_0 in electron volts. Using values of V_0 from Fig. 4 for $\alpha = 0.60$ Å, we find that the bubble does not collapse at any pressure. However, application of suitably high pressures for

$$0.46 \leq \alpha \leq 0.54\ \text{Å}$$

will result in collapse of the electron cavity. We estimate critical pressures of

$$p \gtrsim 20\times10^3\ \text{atm} \quad (a = 0.54\ \text{Å}) ,$$

$$p \gtrsim 3\times10^3\ \text{atm} \quad (a = 0.46\ \text{Å}) .$$

The strong dependence of the critical pressure on the core size makes it very difficult to establish reasonable estimates for this quantity. In view of the large uncertainty associated with the estimation

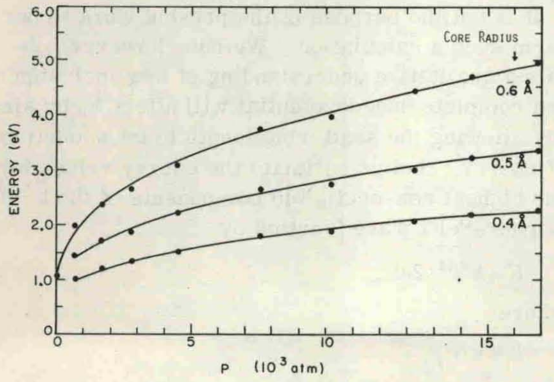

FIG. 4. Pressure dependence of Wigner-Seitz energy calculation of V_0.

of collapse pressure, the results presented here are understandable. Although we have applied pressure 60% in excess of the minimum predicted for collapse of the cavity-localized electron state by Cohen and Jortner,[7] and have failed to see the collapse, it is certainly possible that a 500% excess may be needed.

The likelihood that the cavity-localized electron states in solid helium have not collapsed at the pressures applied is consistent with the observation that there is no high-mobility charge carrier in the solid at these pressures. However, it fails to account for the fact that within the sensitivity of the instrument the charge carriers are not detected at all in the solid. The possible causes for this apparent total immobility are insufficient instrument sensitivity, actual immobility of the localized electrons, and trapping of the electron. The last possibility is consistent with either a localized or delocalized electron, and both must be considered, although we have shown the probable existence of the cavity-localized electron at all experimental pressures of the present work. Neither insufficient sensitivity nor actual bubble immobility alone are complete explanations of these data. The work of Keshishev *et al.*[6] at higher electric fields and at low pressure indicates that both current and mobility sensitivity are satisfactory in the present work, and that, at least in very high electric fields, the localized electrons are mobile enough to have measurable speed under optimum crystal conditions. It is therefore probable that some type of trapping is effective for the excess electrons.

Structural faults such as vacancies and crystal grain boundaries can exist in the solid as well as charged and uncharged impurities. In addition, trapping at the interface between the electrodes and the solid helium is a possible mechanism that would be highly effective for the electrons. A high density of voids in the solid is a possible source of traps in the vicinity of the source electrode where they could be created by radiation damage from the polonium 210. Trapping on the crystal grain boundaries in the solid is also a possible mechanism. The effectiveness of both the void and grain-boundary traps should be strongly temperature dependent, and both should be effective for localized and quasifree electrons. Considering the wide range of temperature employed for the present work, one should have been able to observe some charge release from the traps at temperatures approaching the melting point. This would be especially so for normally quasifree electrons. Impurities as traps may be discounted since they should be nearly as effective in the liquid as in the solid. Finally, we must consider the trapping mechanism operating at the grid–solid-helium interface.

The electrons are created between the source