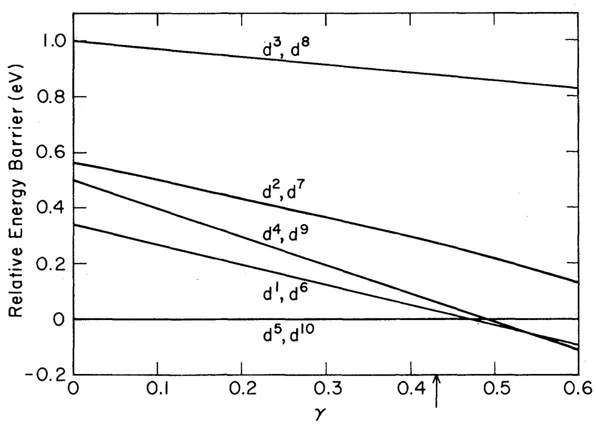

FIG. 1. Energy barrier for impurity migration in AgCl relative to that for Mn^{2+} or Zn^{2+} as a function of a crystal-field parameter γ for the "average calculation," as defined in the text. The arrow indicates the value of γ for the best fit.

As may be noted, the main effect of taking some detailed differences among the ions into account is to cause a splitting between d^n and d^{5+n} ions, thus reproducing the experimental difference of ~ 0.2 eV between V^{2+} and Ni^{2+}, along with the experimental ordering for them.

The agreement between calculation and experiment is excellent and appears to represent a first demonstration of the role of electronic structure in affecting the mobility of ions in an ionic crystal. This strongly suggests the desirability of including crystal-field effects in the theory of diffusion in ionic crystals.

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†Work supported by the Materials Research Center, University of North Carolina, under Grant No. DMR-7203024 from the National Science Foundation, and by the National Science Foundation, Grant No. 72-03212-A01.

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Dynamics of Electron Localization in Dense Helium Gas*

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(Received 9 October 1975)

A new experiment shows that in dense, cold helium gas an excess electron can occupy either a distinct group of highly mobile states or another group of relatively immobile, presumably localized states. The rapid decrease in average mobility with increasing gas density observed in previous experiments arises primarily from an exponential increase in the lifetime of the electron in the localized states.

A helium atom scatters low-energy electrons much like a hard sphere. An excess electron in a gas of helium atoms therefore acts approximately as a particle in a potential consisting of randomly placed billiard balls. Since it is not difficult to achieve gas densities and temperatures such that the interatomic distance is comparable to the thermal wavelength of the electron, this system provides an elegant and experimentally flexible prototype for the study of electronic states in a disordered material.

Interest in this system originated with the early mobility measurements of Levine and Sanders,[1] who showed that as the gas density is increased beyond $n \approx 10^{21}$ cm^{-3}, the average mobility $\bar{\mu}$ of an excess electron decreases precipitously from the high values characteristic of plane-wave electron states to the very low values usually associated with locally bound states. Further experimental work on this interesting localization transition has been limited to extending the mobility measurements over a wider temperature range[2] and to a recent measurement of the effective mass of the localized electron states.[3] On the theoretical side, several authors[4] have studied the static aspects of the problem by calculating the distribution of electronic states, assigning a mobility to each state, and taking a thermal average to obtain $\bar{\mu}$.

A phenomenological description of some dynamical aspects of the transition has been proposed in Ref. 1 and extended by Young,[5] who divides the states available to an electron into one distinct group of fast states with mobility μ_f and another group of very slow states with mobility μ_s. The lifetimes τ_f, τ_s of the electron in the fast and slow group of states, respectively, are assumed to be independent of the applied electric field, and long compared to the thermal averaging times within the groups. Thus, mobility measurements done over times long compared to τ_f, τ_s will yield the average value

$$\bar{\mu} = (\mu_f \tau_f + \mu_s \tau_s)/(\tau_f + \tau_s), \quad (1)$$

while measurements done on a swarm of electrons over shorter time intervals should show the existence of two groups of carriers with differing mobilities μ_f, μ_s. The rapid drop in $\bar{\mu}$ as n is increased is then interpreted as arising primarily from an increase in τ_s/τ_f.

In order to obtain additional information about the localization transition, we have performed an experiment using the configuration shown in Fig. 1. Alpha activity plated at the ×'s on the source grid S ionizes the gas in the source region, and a negative bias applied to the repeller R injects a constant current I_0 of electrons into the drift region. This current propagates across the drift space under the influence of a uniform, constant field E_D and is measured as it arrives at the collector C. The novel feature of the experiment is the chopper grid CH placed across the middle of the drift space. As shown in the figure, the grid is constructed so that a rapidly switched field $E_{CH} \approx V_{CH}/d$ can be applied between adjacent wires of the grid, in addition to the field E_D tending to carry the electrons though the grid. To study the nature of the electron states at a given temperature and density, we measured the fraction I/I_0 of the current transmitted by the chopper grid as a function of the period T and amplitude E_{CH} of the chopper field. Some of the transmission data obtained at a density of 1.4 $\times 10^{21}$ atoms cm^{-3} and a temperature of 4.2°K are shown in Fig. 2, these curves being representative of our observations over the entire density range. The shape of the curves did not depend strongly on E_D, provided $E_{CH}/E_D \geq 3$. This condition was always met in our measurements.[6]

The curve in the upper left-hand corner of Fig. 2 has a characteristic shape always seen at sufficiently low values of E_{CH}. At low fields the

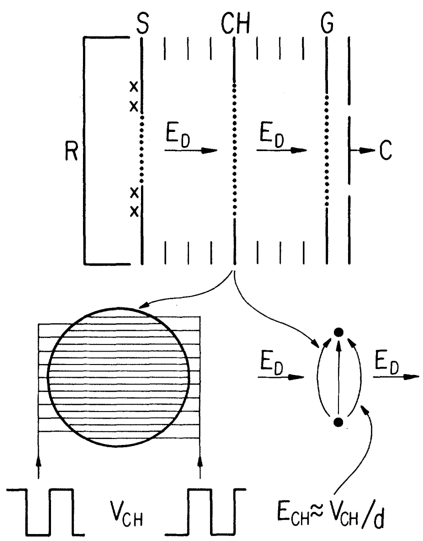

FIG. 1. Geometry of the experiment (not to scale). The spacing between adjacent wires of the chopper grid is 0.032 cm.

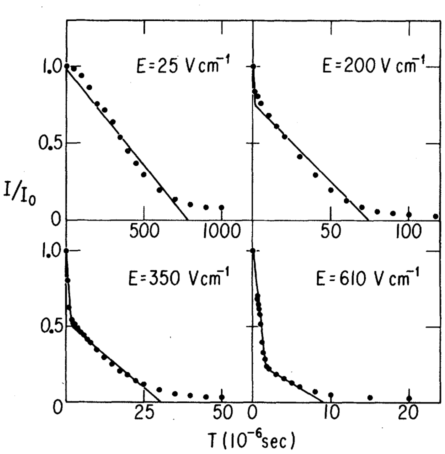

FIG. 2. Transmission curves taken at $n = 1.4 \times 10^{21}$ cm^{-3}, temperature = 4.2°K. E refers to the nominal chopper field E_{CH}. The lines through the data are derived as discussed in the text.

electrons move slowly, each one having plenty of time to average between fast and slow states, and they therefore exhibit a single, well-defined drift velocity $\bar{v}=\bar{\mu}E$. As the electrons drift through the grid, they are moved back and forth laterally through a distance $\approx\bar{v}T/2$. Thus the fraction of the electrons collected by the grid wires is approximately $\bar{\mu}E_{CH}T/2d$, where d is the distance between grid wires. This argument predicts that I/I_0 should decrease linearly with increasing T, with a slope $\approx-\bar{\mu}E_{CH}/2d$. We do indeed find that the shapes of the low-field curves are in reasonably good agreement with this prediction, that the measured slope is closely proportional to E_{CH}, and that the value of $\bar{\mu}$ determined from the proportionality constant is in agreement with previous mobility measurements,[1,2] over the entire density range studied by us.

The analysis of the low-field curves demonstrates that simple arguments suffice to give at least a semiquantitative interpretation of our experiment, but, since $\bar{\mu}$ has been measured before, it can give no new physical information. The real interest lies with the high-field curves, which provide the first convincing evidence that some of the electrons in the gas respond much more quickly to an applied field than do others. Moreover, these data can be consistently interpreted in terms of Young's phenomenological model to yield values of the parameters τ_f, τ_s, and μ_f as functions of gas density. We first consider the effect of E_{CH} at very short T, that is $T\leqslant 2\tau_f$. During one half cycle those electrons which are in the fast state will be moved laterally a distance $\approx v_f T/2$, leaving a region depleted of fast electrons around, say, wires 1, 3, 5, ... The slow electrons are essentially motionless on this time scale, and some of those left behind in the depleted regions will decay into the fast state. During the second half of the cycle, these will be collected, while a depleted region is formed around wires 2, 4, 6. . . . As the electrons slowly drift through the grid under the influence of E_D, they will undergo many such cycles, during each of which all of the fast and some of the slow charge within a distance $\approx v_f T/2$ of the grid wires is collected. Thus two regions of *total* charge depletion will develop around the grid wires, and the fraction of current intercepted by the grid should be $v_f\tau/d$. This prediction is based on the assumption that electrons in the fast states move with $v_f=\mu_f E_{CH}$ for a time $T/2$. However, the typical fast electron will have decayed into the slow state after a time τ_f. As $T/2$ is increased beyond τ_f the initial rapid decrease of I/I_0 with T will therefore change over into one with the slope characteristic of the average electron velocity $\bar{v}$. In summary, I/I_0 should drop with slope $\approx -v_f/d$ until the fraction of current lost equals $2v_f\tau_f/d$ and $T\approx 2\tau_f$. For $T\gtrsim 2\tau_f$, I/I_0 should drop with a slope $\approx-\bar{v}/2d$.

Although the above argument is somewhat crude, there is ample evidence that it is essentially correct. Firstly, we find experimentally that the slowly decreasing parts of the high-field curves (Fig. 2) always have the approximate slope $-\bar{\mu}E_{CH}/2d$, where $\bar{\mu}$ is determined from the low-field curves in agreement with previous measurements. Secondly, $v_f\tau_f$ as determined from the breaks in the curves is generally closely proportional to E_{CH}, in accordance with the expected $v_f=\mu_f E$, $\tau_f=$const. Thirdly, τ_f as independently determined from the period at which the break occurs is observed to be a constant. That is, one can fit *all* of the transmission curves taken at a given gas density and temperature with only three parameters to which we have assigned the approximate meanings $\bar{\mu}$, $\mu_f\tau_f$, and τ_f, and of which one ($\bar{\mu}$) has been measured previously by independent means. The typical quality of the fit is shown by the lines in Fig. 2.

We have taken sets of transmission curves at various gas densities at 4.2°K in order to determine how the parameters of the Young model vary across the localization transition. Equation (1) may be inverted to give $(\tau_f+\tau_s)\geqslant\mu_f\tau_f/\bar{\mu}$, where the inequality becomes an equality if μ_s is very small, as expected. Our results, expressed in terms of τ_f, $(\tau_f+\tau_s)_{\min}$, $\bar{\mu}$, and μ_f, are given in Figs. 3 and 4. The rapid drop in $\bar{\mu}$ observed pre-

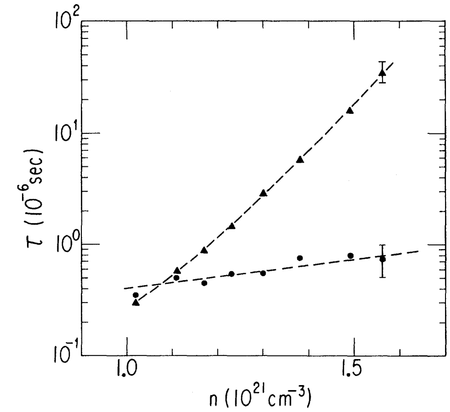

FIG. 3. Lifetimes as a function of gas density. Circles denote τ_f, and triangles denote $(\tau_f+\tau_s)_{\min}$.

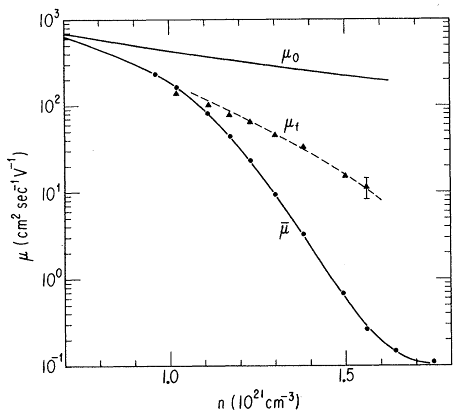

FIG. 4. Mobilities as a function of gas density. Circles denote $\bar{\mu}$ as determined from our data, triangles denote μ_f. The curve μ_0 is that assumed by Young (Ref. 5.)

viously is now seen to arise primarily from a rapid exponential increase in the lifetime of the localized states with increasing gas density. In addition, the mobility characterizing the fast electron states drops more rapidly than has previously been supposed.[5,7] The lifetime of the electrons in the fast states does not vary significantly. It is to be noted that a comparison of Figs. 3 and 4 provides additional support for the manner in which we have interpreted our data. According to Fig. 3, the onset of the localization transition should occur at $n \approx 1.0 \times 10^{21}$: Below this density, $\bar{\mu}$ should equal μ_f. Figure 4 shows that the μ_f curve, derived by taking the ratio of the two independently determined parameters $\mu_f \tau_f$ and τ_f, does indeed join smoothly to $\bar{\mu}$ at this value of the density.

In summary, our experiment indicates the simultaneous existence of distinct delocalized and localized electron states over the entire density range characterizing the transition, and provides quantitative estimates of Young's phenomenological parameters τ_f, τ_s, and μ_f. It therefore yields a great deal of new information, which hopefully should lead to further theoretical insights into the behavior of this interesting system.

*Work supported by a grant from the National Science Foundation. We have also benefited from support of the Materials Research Laboratory by the National Science Foundation.

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