[15]V. P. Myerscough and M. R. C. McDowell, Proc. Phys. Soc. 84, 231 (1964).
[16]H. Kuhn, Chimia (Aarau) 4, 203 (1950).
[17]Felix Gutmann and L. E. Lyons, Organic Semiconductors (John Wiley & Sons, Inc., New York, 1967), Chap. 6.
[18]I. Giaever, Phys. Rev. Letters 5, 147, 464 (1960).
[19]R. T. Payne, Phys. Rev. Letters 21, 284 (1968).

BAND-GAP EFFECTS IN THE STOPPING OF Ge^{72*} ATOMS IN GERMANIUM*

C. Chasman, K. W. Jones, and H. W. Kraner
Brookhaven National Laboratory, Upton, New York

and

Werner Brandt
New York University, New York, New York
(Received 24 September 1968)

Measurements of the ionization losses of 10.0- to 30-keV Ge^{72*} atoms in germanium show no evidence for a cutoff for particle energies less than 23 keV, as might be expected from adiabatic arguments concerning the effect of an energy gap in germanium. The ionization loss is consistent with Lindhard's conjecture that the electronic stopping power of heavy particles is proportional to the particle velocity even at energies far less than this cutoff energy. Any effective energy gap encountered by the germanium atoms moving in a germanium crystal is less than ~0.1-0.2 eV.

We report on a search for the effect of the energy gap on the ionization produced in a semiconductor by slow heavy particles. The results bear on the important practical question as to the inherent lower limits of resolution in solid-state particle detectors. They also resolve, at least for germanium, a basic question of long standing concerning the energy-loss processes of slow particles in insulators and semiconductors, as will be summarized presently.

It is known from the work of Fermi and Teller[1] and of Lindhard and Winther[2] that in a free-electron gas the energy-loss cross section of slow particles approaches zero linearly with the particle velocity. Brandt and Reinheimer[3] studied the theory of the slowing down of a heavy point charge in a uniform electron gas with an energy gap. They found, as did Schweinler[4] who considered the band structure of specific insulators, that the electronic energy loss of a moving point charge has a threshold. It drops to zero as the particle velocity v becomes smaller than a critical value, v_c, which is determined by the energy gap of the material. Bohr[5] and Seitz[6] have argued from adiabatic considerations that heavy ions of mass M moving with an energy $E < E_c$ also encounter a cutoff in the electronic energy loss, with a critical energy $E_c \simeq ME_g/4m$, where m is the band-gap energy. This implies that, for example, Ge atoms moving in a germanium detector cannot be detected if the particle energy has fallen significantly below $E_c = \simeq 23$ keV.

The total energy-loss cross section of heavy atoms in this low-energy range is dominated by the momentum transfer in atomic collisions, and electrons are excited in these processes because of the exclusion principle. Lindhard[7] has argued that these collisions, although slow and practically elastic with regard to momentum transfer, are actually quasielastic in the sense that the electron clouds interpenetrate during the collisions, in effect setting the outer electrons free. If one nevertheless maintains a description of the total energy loss in terms of independent contributions from elastic atomic collisions and from inelastic electronic excitations, the electronic stopping-power component must be nearly the same as that in a free-electron gas, and approach zero linearly with v even for $v \ll v_c$, or $E \ll E_c$.

Our measurements of the ionization yield produced by Ge atoms moving in germanium detectors give no evidence for a cutoff near $E \sim E_c$. They support Lindhard's conjecture of an electronic stopping power proportional to v for particle energies at least down to $(0.1\text{-}0.2)E_c$.

Previous experiments[8-10] determined the ionization yield produced by the stopping of Ge atoms in germanium for energies $\gtrsim E = 23$ keV. There is satisfactory agreement with the theory of Lindhard et al.[11] on the fractions of the initial particle energy lost in electronic excitations and in atomic collisions. In the present experiments the measurements are extended down to 10.0 keV and the accuracy of the data in the 17- to 30-keV range is improved.

Most of the experimental technique has been described earlier.[8,9] Briefly, moving Ge atoms are produced by neutron bombardment of a Ge(Li) gamma-ray detector. The detector output is the sum of the total ionization produced by a moving Ge atom and by the de-excitation radiation of the excited Ge nuclear state in question. The time constants in the electronics are made long enough to minimize the effect of the lifetime of the excited state on the pulse height. For the low-energy measurement the energy of the bombarding neutrons was chosen to be just above the reaction threshold. This makes the emerging Ge atoms essentially monoenergetic with an energy which depends on the threshold for the excited state. Specifically, we observed the 691.4-keV first-excited state of Ge^{72} ($J^{\pi}=0^+$, $T_{1/2}=0.290$ μsec)[12,13] at neutron energies between 703 and 733 keV, i.e., just above the threshold at 701 keV. This state is especially convenient because it decays by the emission of a conversion electron which is detected with nearly 100% efficiency. The resulting maximum Ge recoil energies vary from 9.7 to 10.5 keV, with energy spreads ranging from 2.9 to 8.7 keV. Hauser-Feshbach calculations show that the angular distributions of the scattered neutrons are isotropic, as would be expected so close to the threshold, and therefore the energy distribution of the Ge recoils is nearly rectangular. The ionization produced in the detector is proportional to the level energy of the excited state plus the fraction of the recoil energy that produces ionization. Since at these low energies the fractional energy lost to ionization turns out to be approximately 20%, and since the total spread in the recoil energies is small, the width of the observed line is determined mainly by the ionization statistics of a 691-keV event and by the preamplifier noise. Therefore, the ionization produced by the recoil shifts the line upward in pulse height without changing its shape appreciably. Recognition of these consequences of the kinematics of the inelastic scattering process makes possible the extension of ionization-loss measurements to a hitherto unfeasible low energy. For this experiment counters were used with a resolution of 2 keV or less for the 661.6-keV Ba^{137} gamma ray.[14] The position of the centroid of the line was measured relative to the Ba^{137} line with the aid of an auxiliary pulser calibration. Typical examples of the pulse-height spectrum are shown in Fig. 1. The average amount of recoil energy lost to ionization is found by subtracting the level energy from the energy of the line produced by the inelastic neutron scattering process.

New measurements were performed in the energy range from 17 to 30 keV. Here, the recoil energy lost to ionization becomes a substantially larger fraction of the total recoil energy than at the lowest energies investigated, and it is no longer possible to use the centroid of the line to determine the ionization loss. As described earlier,[8] the sum of the level excitation energy and the maximum recoil energy ionization loss is found to a good approximation from the half-yield point on the high-energy slope of the line. The energy lost to ionization is then equal to the energy so determined minus the level excitation energy of 691.4 keV. The energy resolution of 2 keV in the present experiments is substantially better than the 5 keV resolution in the previous experiments.[8,9]

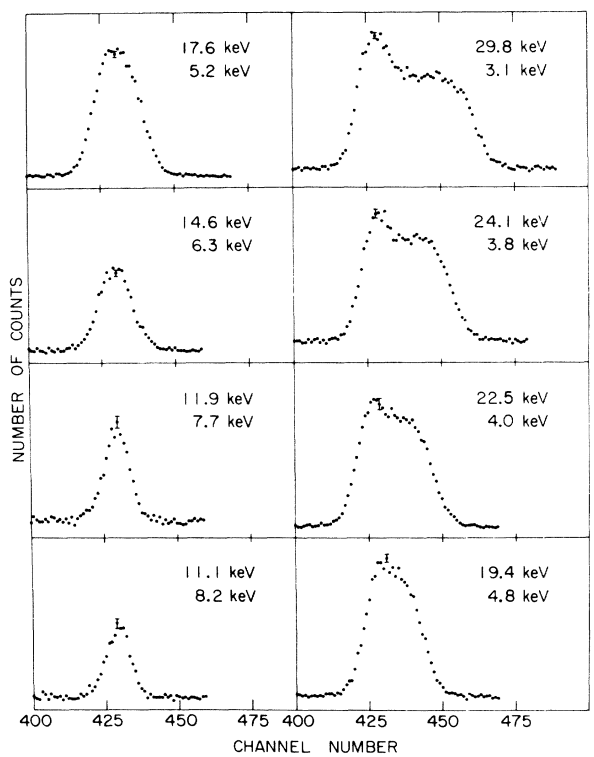

FIG. 1. Pulse-height spectra showing the 691.4-keV conversion-electron line in Ge^{72} produced by inelastic neutron-neutron scattering, for maximum recoil energies of Ge^{72} from 10 to 30 keV. The maximum and minimum recoil energies for various incoming neutron energies are given for each spectrum. The energy dispersion is about 0.2 keV per channel.

Table I. Summary of results.

$\bar{E}_R$ (keV)	Energy lost to ionization (keV)	Fractional energy loss to ionization $\bar{\eta}(E_R)$
10.0 ± 0.2	2.0 ± 0.2[a, b]	0.20 ± 0.02[b]
17.6[c]	4.0[d]	0.23 ± 0.03
19.4	4.7	0.24 ± 0.03
22.5	5.7	0.25 ± 0.02
24.1	6.5	0.27 ± 0.02
29.8	8.2	0.28 ± 0.02

[a]Measured by centroid shift method described in the text. The results given are the averages of seven runs taken under slightly different conditions.

[b]The random uncertainty is ±5 %. An estimated systematic uncertainty of ±5 % is also included to give a total estimated uncertainty of ±10 %.

[c]Uncertainties, where not given, are ±0.07 keV.

[d]Uncertainties, where not given, are ±0.5 keV. The technique used to obtain this value, and the values below, is described in the text and in Ref. 8.

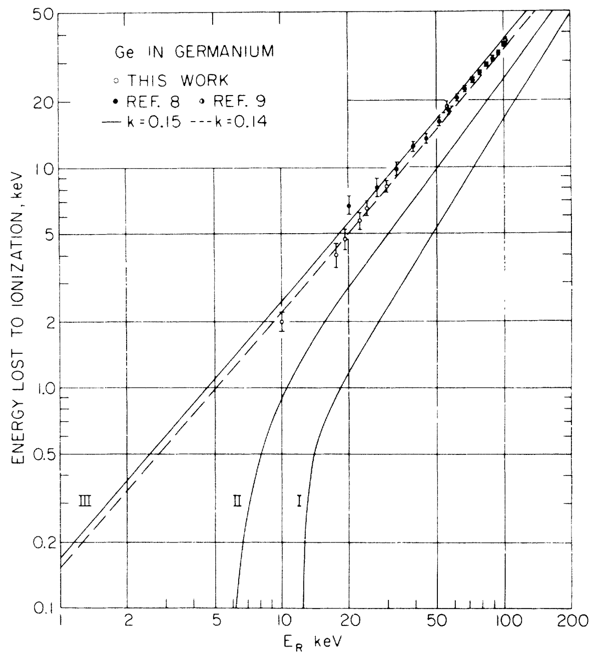

FIG. 2. Comparison of experimental results and theory. The open points 10-30 keV are taken from Table I. The other points stem from Refs. 8 and 9. The three solid curves are calculated with $k = 0.15$, for (I) a sharp cutoff in the electronic stopping power, (II) an intermediate cutoff, and (III) no cutoff, respectively, as specified in the text. The best overall fit is obtained for (III) with a k value between 0.14 and 0.15.

The total recoil energy imparted to the target is calculated from the kinematics of the inelastic neutron scattering event. The ratio of the measured energy lost to ionization and the maximum calculated recoil energy, E_R, gives the fractional energy loss to ionization, $\bar{\eta}(E_R)$. The present results are summarized in Table I.

In Fig. 2, the data are compared with theoretical curves demonstrating the consequences of a cutoff in the electronic stopping power. Approximation I represents the solution of the integral equations given by Lindhard et al.[11] for a sharp cutoff: The electronic stopping cross section $S_e(E)$ is $S_e(E) = C(k)E^{1/2}$ for $E > E_c$, drops linearly to zero for $\frac{1}{2}E_c \leq E \leq E_c$, and is equal to zero for $E \leq \frac{1}{2}E_c$. The constant $C(k)$ is related to Lindhard's reduced constant k which has numerical values between 0.1 and 0.2. The curves are calculated for $k = 0.15$. If the atomic collisions are not completely elastic below $\frac{1}{2}E_c$, but give rise to free electrons, they in effect lower E_c or increase $S_e(E)$ for $E < E_c$. Approximation II is calculated for an intermediate cutoff: $S_e(E) = CE^{1/2}$ for $E \geq E_c$, and $S_e(E) = (C/2)E^{1/2}$ for $E \leq \frac{1}{2}E_c$, with a smooth transition between the two energy ranges. Approximation III has no cutoff: $S_e(E) = CE^{1/2}$ for all E. The constant k perhaps could be as large as 0.2, which would move the curves I and II up, but not enough to fit the data. In fact, for $k = 0.2$, the data exclude a sharp cutoff (I) at energies above 3 keV, and an intermediate cutoff (II) above 6 keV. For $k = 0.15$, a cutoff, if it exists, would have to occur below 2 or 4 keV, respectively. In terms of electronic energies, the measurements are consistent with the inference that the effective energy gap encountered by Ge atoms moving in a germanium crystal is at most $(0.1\text{-}0.2)E_g$. Without assuming a cutoff the data are fitted well with a k value between 0.14 and 0.15.

In conclusion, the present measurements of the energy loss of slow Ge atoms in germanium, if compared with current theories, give no indication of a cutoff for electronic energy losses which is related to the lowest internal ionization level of the target material. They agree within experimental error with the assumption that electrons are excited within the range of interaction with the moving atoms during collisions with the target atoms, and that they behave as if free with regard to the electronic loss cross sections of the moving particles. This implies that for heavy particles the intrinsic low-energy resolution of particle ionization detectors is generally not limited by their energy gap.

We are indebted to M. L. Perlam for his aid and advice during the beta spectrometer measurements and for the loan of his equipment. The Hauser-Feshbach calculations were run by E. Auerbach. We are grateful to T. Karcher for numerical calculations and helpful discussions. One one of us (W.B.) acknowledges the hospitality of Brookhaven National Laboratory during the summer of 1967.

---

*Work performed under the auspices of the U. S. Atomic Energy Commission.

[1]E. Fermi and E. Teller, Phys. Rev. 72, 399 (1947).

[2]J. Lindhard and A. Winther, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 34, No. 4 (1964.

[3]W. Brandt and J. Reinheimer, Can. J. Phys. 46, 607 (1968).

[4]H. C. Schweinler in Semiconductor Nuclear Particle Detectors, edited by J. W. T. Dabbs and F. J. Walter (National Academy of Sciences—National Research Council, Washington, D. C., 1960), p. 91.

[5]N. Bohr, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 18, No. 8 (1948).

[6]F. Seitz, Discussions Faraday Soc. 5, 271 (1949).

[7]J. Lindhard, in Studies in Penetration of Charged Particles in Matter (National Academy of Sciences—National Research Council, Washington, D. C., 1964), p. 1; J. Lindhard, M. Scharff and H. E. Schiøtt, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 33, No. 14 (1963).

[8]C. Chasman, K. W. Jones, and R. A. Ristinen, Phys. Rev. Letters 15, 245, 684(E) (1965).

[9]C. Chasman, K. W. Jones, R. A. Ristinen, and J. T. Sample, Phys. Rev. 154, 239 (1967).

[10]A. R. Sattler, F. L. Vook, and J. M. Palms, Phys. Rev. 143, 588 (1966).

[11]J. Lindhard, V. Nielsen, M. Scharff, and P. V. Thomsen, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 33, No. 10 (1963).

[12]Nucl. Data B1, No. 6, 40 (1966).

[13]The determination of the line shift due to the recoil ionization depends critically on an accurate knowledge of the level excitation energy of this state. Existing data of this energy were not precise enough for our purposes, and an auxiliary experiment was performed to derive it accurately. A Ga^{72} source was prepared in the Brookhaven National Laboratory high-flux beam reactor by neutron capture on Ga^{71}. The energy of the conversion electrons from the Ge^{72} 691-keV level populated in the beta decay of Ga^{72} was measured relative to the energy of the 661.6-keV transition of Ba^{137} in a beta-ray spectrometer. A level energy of 691.4 ± 0.1 keV was found from this work, in good agreement with existing values [Nucl. Data B1, No. 6, 34 (1966)].

[14]R. L. Graham, G. T. Ewan, and J. S. Geiger, Nucl. Instr. Methods 9, 245 (1960).

SELF-FOCUSING EFFECTS ASSOCIATED WITH LASER-INDUCED AIR BREAKDOWN

V. V. Korobkin* and A. J. Alcock
National Research Council of Canada, Ottawa, Ontario, Canada
(Received 4 October 1968)

Sparks produced by focusing the beam from a single-mode ruby laser have been investigated, and photographs of radiation scattered at 90° to the incident beam show that breakdown occurs in filaments or points having a diameter of 5 μ or less. Intense pulses of coherent radiation scattered in the forward direction have also been observed, and the measured divergence of this light indicates the presence of self-focused regions having a diameter of ~1.7 μ. These observations support the hypothesis that self-focusing of the beam may initiate laser-induced breakdown.

Although the production of a spark by focused laser radiation has been investigated in many laboratories, the physical processes involved in this phenomenon are by no means completely understood. In particular, the rapid development of the ionized region has received widespread attention,[1-4] and a number of theoretical models[1,5,6] have been proposed to account for it. Nevertheless, there are certain experimental observations which cannot be explained satisfactorily. For example, it was shown recently[4] that the motion of the spark cannot be explained in terms of only one mechanism, and it was concluded that breakdown occurs in many points with subsequent expansion from these isolated centers. As a possible explanation for this effect, it was suggested that self-focusing of the laser beam may be responsible for the initiation of breakdown. In this paper, experimental results lending support to this prediction are presented.

Sparks were produced in air, at atmospheric pressure, by means of a passively Q-switched ruby laser operating in a single axial and transverse mode. Axial-mode selection was achieved by means of a resonant reflector, consisting of a pair of parallel quartz flats, while for trans-