of the damaged surface region, we again find that R_{max} is almost unaffected by the prebombardment.

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Channeling in Diamond-Type and Zinc-Blende Lattices: Comparative Effects in Channeling of Protons and Deuterons in Ge, GaAs, and Si†

ALLAN R. SATTLER
Sandia Laboratory, Albuquerque, New Mexico
AND
G. DEARNALEY*
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico

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The energy losses of ions channeled through GaAs, Ge, and Si were compared. The average number of electrons per atom participating in the stopping of channeled particles is about the same for elemental Ge and partially ionic GaAs. The number of electrons per atom participating in the stopping of channeled hydrogen ions is less for Si than for Ge or GaAs. Axial and planar channeling are discussed. The energy losses of axial channeling appear to be characterized by the energy losses of the plane having the largest interplanar spacing in the axial intersection. A much larger fraction of the incident beam undergoes channeling when the beam is incident along an axial intersection than when the beam is along a plane of the intersection. Comparison of energy losses of H^+ and D^+ shows that the mass dependencies of the minimum energy losses in channeling can be correlated simply with a velocity-dependent function. Velocity is, therefore, the important parameter in the slowing down of channeled ions within a given host lattice. The analyses of the data give evidence that an equation of the same form as the Bethe equation accounts for the minimum energy losses of channeled particles.

INTRODUCTION

THIS paper describes a study of energy losses of protons and deuterons channeled by single-crystal Ge, GaAs, and Si, and shows the importance of directional effects on the interaction of incident charged particles with solids. Until recently, theories of energy loss, while adequate for amorphous solids, did not account for the orientation dependence of charged-particle interactions with crystalline solids. These directional effects of crystal lattices on charged particles are proving to be a useful tool for probing crystalline solids. Applications of these phenomena and techniques are already being extended to semiconductor devices such as solid-state detectors, solar cells, and ion implantation. An earlier paper reported our initial observations of channeling in Ge.[1] A preliminary account of the comparison of the energy losses of channeling for Ge, GaAs, and Si has already been given.[2]

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* On leave from Atomic Energy Research Establishment, Harwell, Berkshire, England, from November 1963 to March 1965.

[1] A. R. Sattler and G. Dearnaley, Phys. Rev. Letters **15**, 59 (1965).

[2] A. R. Sattler, Bull. Am. Phys. Soc. **11**, 230 (1966).

The term channeling has been applied to the anomalous penetration of energetic charged particles along low-order crystal axes and planes. Channeling was predicted in computer calculations of ion ranges by Robinson and Oen[3] just before this anomalous behavior was discovered experimentally by Davies and his group.[4] Although the work was initially confined to low energies, below 100 keV, a similar behavior was discovered when the experiments were first extended to MeV energies by Dearnaley.[5] More recently, comprehensive theories of channeling by Brice,[6] Lindhard,[7] and Erginsoy[8–11] discuss mechanisms of channeling in some detail. A partial list of references for some earlier work on channeling is found in Ref. 1.

[3] M. T. Robinson and C. S. Oen, Phys. Rev. **132**, 2335 (1963).

[4] G. R. Piercy, F. Brown, J. A. Davies, and M. McCargo, Phys. Rev. Letters **10**, 399 (1963).

[5] G. Dearnaley, IEEE Trans. Nucl. Sci. **NS11**, 249 (1964).

[6] D. K. Brice, Phys. Rev. (to be published); D. K. Brice and A. R. Sattler, Bull. Am. Phys. Soc. **11**, 177 (1966).

[7] J. Lindhard, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. **34**, No. 14 (1965).

[8] C. Erginsoy, Phys. Rev. Letters **15**, 360 (1965).

[9] C. Erginsoy, B. R. Appleton, and W. M. Gibson, Bull. Am. Phys. Soc. **11**, 176 (1966).

[10] H. A. Fowler and C. Erginsoy, Phys. Letters **24A**, 390 (1967).

[11] C. Erginsoy, Bull. Am. Phys. Soc. **12**, 80 (1966).

The structure of the channeling peak, found independently by three different groups[1,12,13] in three separate systems, readily lends itself to quantitative analyses of the energy losses in channeling. Scattering studies,[14] blocking effects,[15] and nuclear reaction yields[16,17] are very important in the study of the mechanisms of channeling; however, the energy losses in the channeling peak are among the most definite and quantitatively interpretable phenomena observed in channeling.

This paper makes a comparison of the effects of channeling in Ge and GaAs. A comparison of the effects of channeling in Ge and GaAs is of significance because a comparison can be obtained between a covalent elemental substance Ge and a partially ionic diatomic substance GaAs since they have nearly identical crystal lattice structures. Ge is between Ga and As in the periodic table. Therefore, the average mass and electron density of these two materials are almost the same. The normal stopping powers differ by only ~0.2%. Thus, measurements were made to see if the effect of a different chemical binding on the channeling energy-loss mechanism would be observed.

The channeling directions investigated in GaAs are all asymmetric in some sense with respect to the two types of atoms in the diatomic GaAs lattice. The existence of the channeling peak in any of these directions would then be significant in itself. Moreover, if channeling in GaAs does exist, it would then be important to determine if the magnitude of the minimum energy losses are the same as for Ge under identical conditions (type of direction, energy, etc.). In other words, it would be determined if the minimum energy losses of GaAs are a function of the average of two types of atoms (in the sense of a similarity to Ge) or if the energy losses are strongly affected by the lower symmetry of the GaAs lattice relative to that of Ge.

The related questions of axial and planar channeling are discussed, first for elemental Ge and then for diatomic GaAs. Combining these data with data on Si indicates the A and Z dependence of channeling. The energy losses of protons and deuterons channeled in GaAs and Ge are correlated to demonstrate the importance of velocity as a parameter in the energy loss of channeled particles. The question of whether an equation of the form of the well-known Bethe stopping equation can account for channeling phenomena is also investigated.

In the following order, the paper (1) discusses experimental techniques; (2) presents the energy-loss data in tabular form as a function of incident ion energy, crystallographic direction, type of crystal, and type of ion; (3) discusses the question of axial-versus-planar channeling in Ge and Si; (4) compares energy losses in channeling through Ge, GaAs, and Si single crystals; (5) discusses channeling in directions of GaAs with different asymmetries; (6) discusses energy-angle measurements in GaAs similar to those made in Ge; (7) compares energy losses of protons and deuterons through a simple velocity function; and (8) shows that an equation with the same energy dependence as the Bethe stopping equation will correlate energy losses of channeled particles.

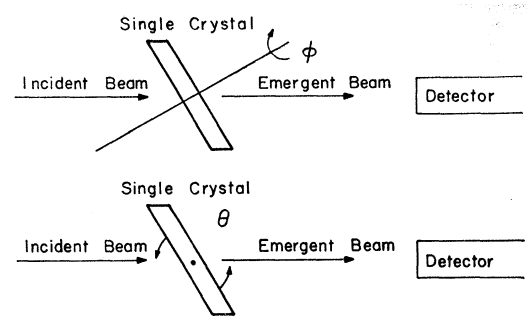

FIG. 1. Schema of apparatus. The beam emergent from the single crystal is detected in a crystal at the rear. The crystal in the form of a cylindrical wafer can be rotated azimuthally (top) and/or along a polar axis (bottom). The incident beam and detector are colinear.

EXPERIMENTAL

The basic experimental arrangement has been given elsewhere[1,5] and is only summarized here. A single crystal cut normal to the [111] axis is mounted so that it can be rotated around an (azimuthal) axis by an angle ϕ, or around the polar axis by an angle θ, with respect to the beam (Fig. 1). The particles emergent from the crystal are recorded in a junction detector.

The angular positioning apparatus was mounted in a scattering chamber. The beam of charged particles from the Los Alamos P-9 vertical Van de Graaff accelerator was incident on a thin foil target of gold, and the scattered flux at a forward angle, collimated to 0.2 deg, was incident on the single crystal. This angular acceptance, while somewhat greater than the acceptance angle for channeling, is still adequate to obtain very useful data. The channel selects a fraction of incident particles. The spectrum is analyzed effectively using the energy (and angle) dispersion to select the well-collimated particles. Apparatus with improved angular resolution is under construction. For energy-loss measurements, the beam, appropriate crystal axes, and detector were colinear. The energy losses of the channeling peak were measured for the beam incident along the ⟨110⟩-, ⟨112⟩-, and ⟨111⟩-type directions.

When the crystal is oriented in a random direction with respect to the incident beam (Fig. 2), the energy

[12] W. M. Gibson, C. Erginsoy, H. E. Wegner, and B. R. Appleton, Phys. Rev. Letters 15, 357 (1965).
[13] S. Datz, R. S. Noggle, and C. D. Moak, Phys. Rev. Letters 15, 254 (1965).
[14] L. C. Feldman, B. R. Appleton, E. J. Ludwig, and W. M. Gibson, Bull. Am. Phys. Soc. 11, 176 (1966).
[15] D. S. Gemmell and R. E. Holland, Phys. Rev. Letters 14, 945 (1965).
[16] E. Bøgh, J. A. Davies, and K. O. Nielsen, Phys. Letters 12, 129 (1964).
[17] M. W. Thompson, Phys. Rev. Letters 13, 756 (1964).

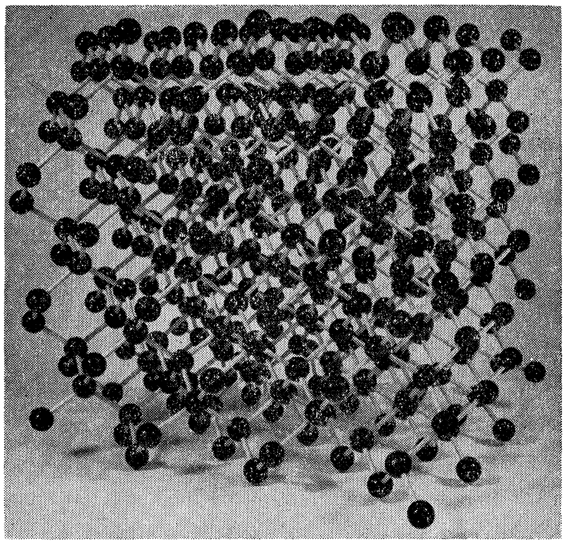

FIG. 2. A model portraying a random orientation of a diamond-type lattice.

spectrum of emergent particles consists of a peak of normal energy loss. Under conditions of channeling (i.e., where the beam is aligned along a preferred direction of the crystal, Fig. 3), it is possible to observe both (1) high- and low-energy tails on the peak of normal energy loss (associated with lower than normal and higher-than-normal energy losses,[18] respectively); and (2) a second discrete peak, denoted as a channeling peak, of lower than normal energy loss indicative of a single energy-loss process. The mechanisms of the energy losses of the channeling peak are different from those of normal energy losses.[6–11] A spectrum of protons emergent from a crystal displaying both a peak of normal energy loss and a channeling peak is shown in Fig. 4. A spectrum taken with the crystal oriented at random to the beam, is also shown. Broadening of the normal peak at the low- as well as the high-energy side is clearly evident in the channeling case showing that larger than normal energy losses are also associated with channeling.[1,18] The crystal was rotated about its axis (top, Fig. 1); hence, the thickness of the crystal was the same for both spectra. The only difference in the experimental configuration, then, in the two cases in Fig. 4 is the relative orientation of the beam with respect to the crystal axes.

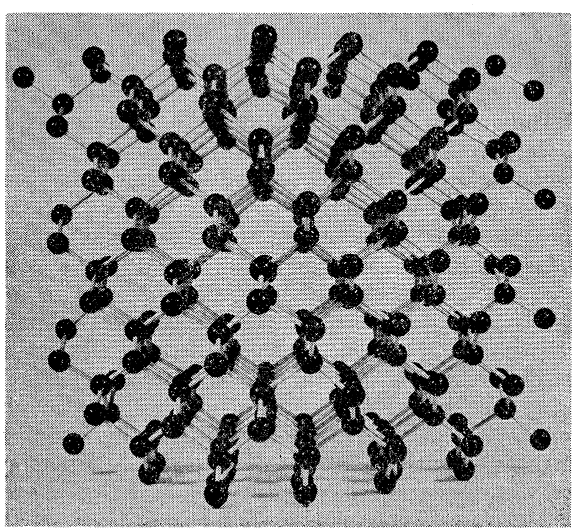

FIG. 3. The same model as in Fig. 2 where the lattice is now viewed along the [110] direction.

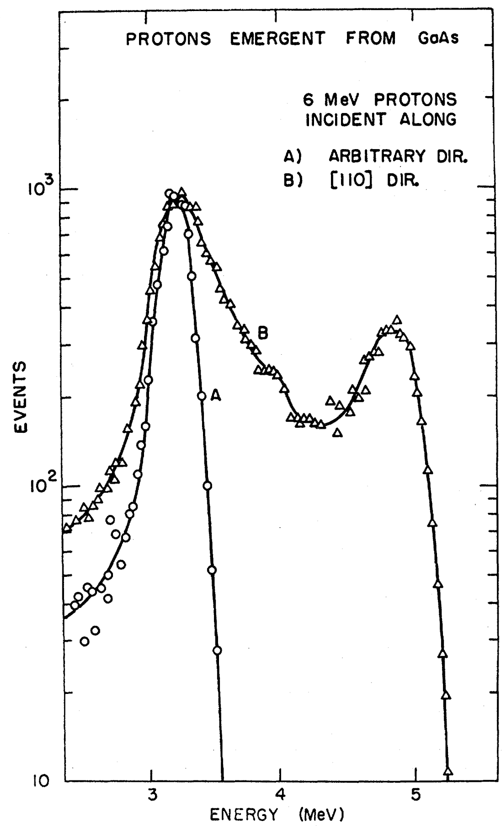

FIG. 4. A spectrum of protons emergent from GaAs (A) along a direction random with respect to the crystal, and (B) with the beam incident along the [110] axis. Incident proton energy is 6 MeV. Note that in addition to the channeling peak, the broadening of the normal peak of normal energy loss is indicative of abnormally high- as well as low-energy losses.

In the energy–angular-distribution study made in this investigation to demonstrate the enhancement of channeling along the axes, the incident beam, and detector are colinear. The crystal is rotated along a polar axis (bottom, Fig. 1), and the spectra of particles emergent from the crystal are recorded in the detector for a fixed amount of charge incident on the crystal. Channeling was observed over a range of ≈60 deg in the {110}-type plane, and this included major axial directions formed by the intersection of this plane with other planes.

[18] C. Erginsoy, H. E. Wegner, and W. M. Gibson, Phys. Rev. Letters 13, 530 (1964).

The energy calibration was accomplished with the aid of the beam from the accelerator itself as well as from natural radioactive sources. The thicknesses of the single crystals were obtained from the peaks of normal energy loss by numerically integrating

$$\int_{E_i}^{E_f} \frac{dE}{dE/dx}$$

with the aid of tabulations of dE/dx.[19]

TABLE I. Channeling in germanium.

Incident ion energy E_i (MeV)	Energy loss, normal peak ΔE_n (MeV)	Energy loss, channeling peak ΔE_{cp} (MeV)	$\frac{\Delta E_{cp}}{\Delta E_n}$	$\bar{B}$ (10^{-3} MeV²/cm)
Ions incident along [110] direction				
7.59 H⁺	2.77	0.97	0.350	0.483
7.07 H⁺	2.93	1.00	0.341	0.461
6.57 H⁺	3.22	1.01	0.314	0.429
6.10 H⁺	3.50	1.08	0.309	0.420
5.54 H⁺	3.80	1.14	0.300	0.396
5.05 H⁺	···	1.25	···	0.387
4.54 H⁺	···	1.44	···	0.385
4.03 H⁺	···	1.71	···	0.380
7.35 D⁺	4.93	1.60	0.325	0.747
Ions along the [112] direction				
7.07 H⁺	2.42	0.82	0.339	0.470
6.57 H⁺	2.62	0.90	0.344	0.447
6.10 H⁺	2.90	1.01	0.348	0.455
5.54 H⁺	3.18	1.04	0.327	0.442
5.05 H⁺	3.68	1.18	0.321	0.427
7.28 D⁺	5.18	1.43	0.276	0.803
6.78 D⁺	5.75	1.56	0.271	0.760
Ions along the [111] direction				
6.57 H⁺	2.36	0.98	0.415	0.544
6.10 H⁺	2.60	1.10	0.423	0.537
5.05 H⁺	3.24	1.31	0.404	0.506
4.50 H⁺	···	1.47	···	0.476
6.78 D⁺	4.20	1.75	0.417	0.909

Because of limits on angular resolution, defects in the crystalline samples, etc., the measured most probable energy of the channeling peak may not be characteristic of the true most probable energy loss. The true energy loss can be somewhat lower. Ideally, the peak of a Gaussian curve fitted to the high-energy edge of the peak should give the true most probable energy loss. This point was estimated within a few percent by the high-energy edge of the channeling peak. In instances where the channeling peak is broad, Gaussian curve fitting is quite difficult. Calculations are proceeding, however, in cases where thinner crystals were used and the energy spread (full width at half-maximum) of the channeling peak is much smaller than that of the peak of normal energy loss. This is to be expected from theoretical considerations.[6,8,9]

[19] C. Williamson and J. P. Boujot, Saclay Report No. C.E.A. 2189, 1962 (unpublished).

TABLE II. Channeling in GaAs.

Incident ion energy E_i (MeV)	Energy loss, normal peak ΔE_n (MeV)	Energy loss, channeling peak ΔE_{cp} (MeV)	$\frac{\Delta E_{cp}}{\Delta E_n}$	$\bar{B}$ (10^{-3} MeV²/cm)
Ions incident along ⟨110⟩-type direction				
7.82 H⁺	1.97	0.73	0.371	0.506
7.33 H⁺	2.03	0.74	0.362	0.486
6.82 H⁺	2.14	0.76	0.352	0.450
6.31 H⁺	2.32	0.78	0.334	0.435
5.79 H⁺	2.50	0.81	0.324	0.420
5.30 H⁺	2.78	0.92	0.330	0.415
4.80 H⁺	3.22	1.03	0.314	0.411
4.28 H⁺	···	1.13	···	0.391
3.79 H⁺	···	1.31	···	0.382
3.28 H⁺	···	1.51	···	0.355
7.79 D⁺	3.43	1.09	0.317	0.735
6.78 D⁺	3.98	1.31	0.329	0.747
5.76 D⁺	···	1.48	···	0.692
4.81 D⁺	···	1.84	···	0.667
4.34 D⁺	···	2.07	···	0.637
Ions along the ⟨112⟩-type direction				
6.976 H⁺	2.096	0.656	0.313	0.411
5.974 H⁺	2.474	0.754	0.304	0.403
4.972 H⁺	3.032	0.912	0.301	0.389
4.470 H⁺	···	0.960	···	0.361
6.715 D⁺	3.835	1.195	0.300	0.690
6.464 D⁺	3.994	1.154	0.299	0.621
5.962 D⁺	···	1.202	···	0.609
Ions along the ⟨111⟩-type direction				
7.477 H⁺	1.829	0.881	0.487	0.622
6.976 H⁺	1.940	0.888	0.459	0.583
6.475 H⁺	2.052	0.949	0.465	0.572
5.473 H⁺	2.508	1.111	0.442	0.549
4.972 H⁺	2.786	1.215	0.436	0.532
4.476 H⁺	3.205	1.362	0.437	0.518
3.968 H⁺	···	1.534	···	0.494
7.477 D⁺	3.170	1.441	0.456	0.977
6.976 D⁺	3.352	1.571	0.469	0.975
5.974 D⁺	4.132	1.812	0.438	0.918
5.473 D⁺	···	1.956	···	0.882
4.972 D⁺	···	2.242	···	0.864

RESULTS AND DISCUSSION

General

The minimum energy losses of the ions channeled in single-crystal Ge, GaAs, and Si were found from analyses of the channeling peak and are shown in Tables I, II, and III. The results are listed as a function of crystal type, incident-ion energy, type of ion, and crystallographic direction. The tables also give the

TABLE III. Channeling in silicon along [110] direction.

Incident ion energy E_i (MeV)	Energy loss, normal peak ΔE_n (MeV)	Energy loss, channeling peak ΔE_{cp} (MeV)	$\frac{\Delta E_{cp}}{\Delta E_n}$	$\bar{B}$ (10^{-3} MeV²/cm)
7.08 D⁺	1.94	0.860	0.442	0.573
5.28 H⁺	1.48	0.650	0.439	0.323

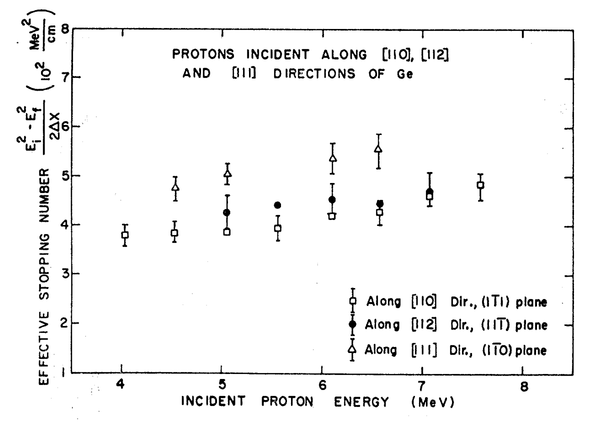

FIG. 5. Effective stopping numbers of protons channeled along the [110], [112], and [111] axes of Ge as a function of incident proton energy.

ratios of the energy losses of the normal peak to the channeling peak which show that the smallest energy losses are encountered along the most open axes and planes. The results of the energy losses will be discussed in detail.

Presentation of the Data—Effective Stopping Number

The data in Tables I, II, and III are presented as a function of an experimental parameter $\bar{B}$ called the effective stopping number. The effective stopping number is defined from Bethe's[20] treatment of energy loss based on the Born approximation applied to the collisions between incident heavy-particle and atomic electrons.

Use of the Born approximation requires that the amplitude of the wave scattered by the field be small compared to the amplitude of the undisturbed incident wave. The criterion is

$$Ze^2/hv \ll 1, \tag{1}$$

where Ze is the charge of the primary particle and v is the velocity. This condition is fairly well satisfied for MeV protons and deuterons. This approximation also implies that the incident hydrogen beam remains ionized throughout its trajectory. Moreover, the velocity of the incident ions is assumed to be large compared to the orbital velocity of the outer (valence) electrons of the atoms of the host lattice.

Under these conditions, the energy loss can be written as

$$dE/dx = -(C/E)\ln bE. \tag{2}$$

Collecting all constants and logarithmic terms so that

[20] H. A. Bethe and J. Ashkin, in *Experimental Nuclear Physics*, edited by E. Segrè (John Wiley & Sons, Inc., New York, 1953), pp. 166–357.

$$B(E) \equiv C \ln bE,$$

$$dE/dx = -B(E)/E, \tag{3}$$

$$-\Delta x = -\int_0^{\Delta x} dx = \int_{E_i}^{E_f} \frac{E dE}{B(E)}, \tag{4}$$

where E_i is the ion energy incident on the crystal, E_f is the ion energy emergent from the crystal (characteristic of minimum energy loss of channeled particles), and Δx is the crystal thickness.

The logarithmic dependence upon E, together with all the constants, is contained in B. Since the denominator in Eq. (4) varies much more slowly than the numerator, B is removed from the integral. The value $\bar{B}$ is defined from Eq. (4) by[21]

$$\bar{B} \equiv \frac{1}{\Delta x} \int_{E_f}^{E_i} E dE = \frac{E_i^2 - E_f^2}{2\Delta x}. \tag{5}$$

This defines the effective stopping number $\bar{B}$ and it will be used to relate experimental results. This quantity can be related to the measurable quantities determined in this experiment, E_i, E_f, and Δx. The quantity $\bar{B}$ is almost independent of crystal thickness. The thickness effects will change $\bar{B}$ less than the order of a percent over the range of incident-ion energies and crystals used in this investigation. It will be shown subsequently that the use of the quantity $\bar{B}$ is a highly profitable way to tabulate the data since the fundamental quantities of interest can easily be extracted.

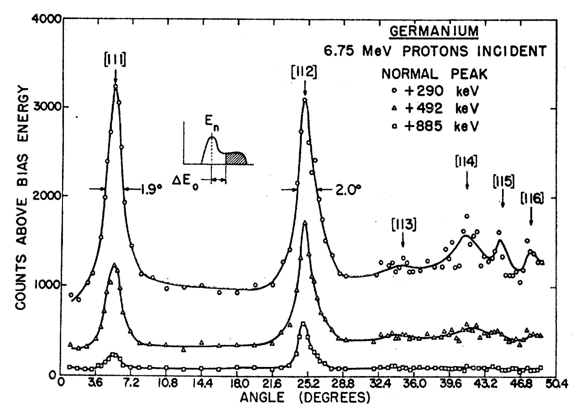

FIG. 6. Energy-angle distribution of protons emergent from Ge. Protons incident along {110}-type plane. Plotted are the counts above an energy fixed relative to the peak of normal energy loss E_n as a function of angle in the plane for a fixed amount of charge on the crystal. This corresponds then to the shaded area of the illustrative spectrum (middle of figure) plotted as a function of both the distance ΔE_0 above the peak of normal energy loss as well as the angle.

[21] From Eq. (2) it is seen that $\bar{B} \propto AZ^2$, where A and Z are mass number and nuclear charge of the incident ion. It will be shown here that this velocity dependence appropriate for normal energy losses is also appropriate for energy losses in channeling. A universal function independent of A (and Z) is simply obtained, $G = \bar{B}/AZ^2$. The charge dependence is to be seen in A. R. Sattler, Bull. Am. Phys. Soc. **12**, 392 (1967).

Axial Versus Planar Channeling

Germanium is an elemental crystal. The energy losses of the channeling peak in this covalent crystal are discussed first because they do not present the additional considerations (or possible complications) of a diatomic lattice. Figure 5 shows the effective stopping number for protons channeled along the [110], [112], and [111] axes of Ge as a function of incident-ion energy. The effective stopping numbers are about the same for protons channeled along the [110] and [112] directions and are larger for the [111] direction.

The experimental work of Datz *et al.*,[13,22–24] and Gibson, Appleton, Feldman *et al.*[12,25–27] and the theoretical works of Brice,[6] and Erginsoy[8,9] suggest that at these incident hydrogen-ion energies, $\gtrsim 2$ MeV, the minimum energy losses of the most open plane (largest interplanar spacing) in an axial intersection determines the minimum energy loss in channeling. Therefore, energy losses of axial channeling would be characterized by those of the most open plane in the axial intersection. For both the [110] and [112] directions, the {111}-type planes are the most open planes of the axial intersection, whereas, the smaller {110}-type planes are the most open planes intersecting at the [111] axis. The effective stopping numbers are indeed nearly the same along the [110] and [112] directions, which indicates that the minimum energy losses in channeling are planar in nature in the energy range investigated. If this is so, then these energy losses would be characterized by those of the {111} planes. The effective stopping numbers are larger along the [111] direction. Energy losses associated with this direction would then be characterized by those of somewhat smaller {110}-type planes.

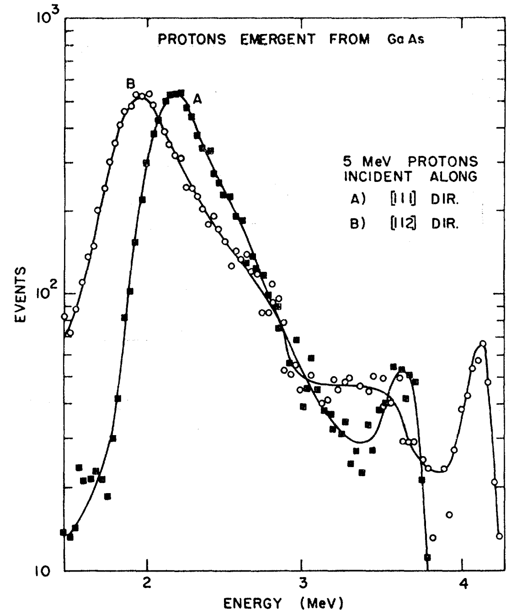

FIG. 8. Spectrum of protons emergent from the same GaAs crystal. Protons incident along (a) the [111] direction, and (b) the [112] direction.

Differences between planar and axial channeling can be observed. For example, an enhancement of the effect of channeling is seen at axial intersections, even along higher-order directions. Figure 6 shows an angular measurement which illustrates this effect for Ge. The beam of incident ions was moved along the {110}-type plane crossing a number of axial intersections. The number of protons above a given energy, fixed relative to the peak of normal energy loss, is shown as a function of angle for a fixed amount of charge incident upon the crystal. A very marked enhancement of channeling occurs along the directions with high-order symmetry, the [111] and the [112] directions. Also, the effect of channeling in the {110}-type plane is enhanced along axial directions which have lower-order symmetry, the [113], [114], [115], and [116] directions.

A similar study is shown in Fig. 7 for a silicon crystal of about the same thickness. The effects of the enhancement of channeling are present, but the effects are less marked along directions of lower symmetry. The relative effects of high- and low-order planes in Si and Ge (Figs. 6 and 7) is then not the same as might have been expected. A quantitative comparison of the effects of channeling in Si versus Ge was obtained in the energy-loss experiments of ions channeled in Si. The effective stopping number for hydrogen ions channeled along the [110] direction is included in the data dis-

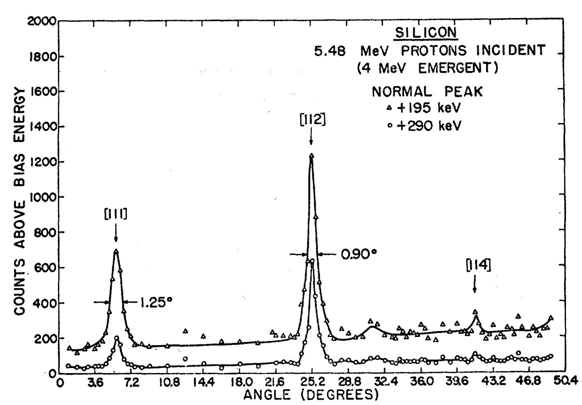

FIG. 7. Energy-angle distributions of protons emergent from Si. Protons incident along {110}-type plane. Plotted are the counts above an energy fixed relative to the peak of normal energy loss E_n as a function of angle in the plane for a fixed amount of charge on the crystal.

[22] S. Detz and T. S. Noggle, Bull. Am. Phys. Soc. **11**, 230 (1966).
[23] T. S. Noggle, C. D. Moak, H. O. Lutz, and S. Datz, Bull. Am. Phys. Soc. **11**, 177 (1966).
[24] H. O. Lutz, S. Datz, C. D. Moak, and T. S. Noggle, Phys. Rev. Letters **17**, 285 (1966).
[25] W. M. Gibson, Bull. Am. Phys. Soc. **11**, 230 (1966).
[26] B. R. Appleton, C. Erginsoy, H. E. Wegner, and W. M. Gibson, Phys. Rev. Letters **19**, 185 (1965).
[27] B. R. Appleton, M. Altman, L. C. Feldman, E. J. Ludwig, and W. M. Gibson, Bull. Am. Phys. Soc. **11**, 176 (1966).

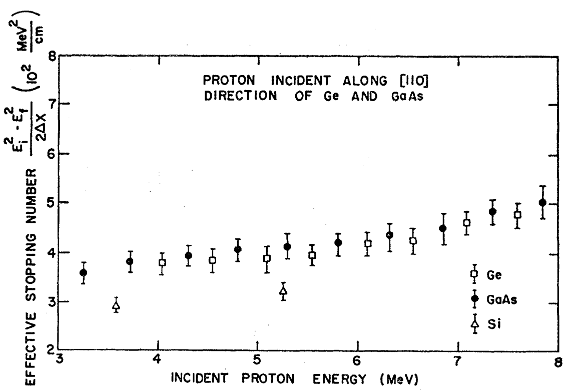

FIG. 9. Effective stopping numbers of protons channeled along the [111] direction of Ge and GaAs as a function of incident-proton energy. Two data points for Si are shown for comparison.

played for Ge and GaAs. (A comprehensive study of channeling in Si is given in Refs. 8–12 and 25–27.) $\bar{B}$ is somewhat less than that for germanium. Even though the lattice constant for Si is smaller than that for Ge, fewer electrons per atom participate in the stopping of ions channeled in Si.

Comparison of Channeling of Ge and GaAs

The first question was whether the channeling peak would exist in a diatomic lattice when there was asymmetry of the two types of atoms with respect to the beam. The ⟨110⟩-, ⟨112⟩-, and ⟨111⟩-type directions all have some type of asymmetry in that sense. Furthermore, the {111}-type planes have predominantly Ga atoms on one side and As atoms on the other. In Ge the energy losses of the [110] and [112] directions appeared to be characterized by that of the {111}-type plane. Investigations of channeling along the [111] and $[\bar{1}\bar{1}\bar{1}]$ direction of GaAs would also be significant because displacement effects in GaAs have been found to be different in these two directions. The channeling peak does exist in the ⟨110⟩-, ⟨112⟩-, and ⟨111⟩-type directions has shown in Figs. 4 and 8.

A strong dependence of the energy loss of channeled particles upon direction (or plane) is also to be seen in Fig. 8. Both emergent-particle spectra were taken using the same crystal. The crystal was grown along the ⟨111⟩ type of direction. It is clearly seen that the energy loss along the more open [112] direction, or {111}-type plane, is less than along the [111] direction or {110}-type plane in spite of a 7% increase in the thickness of the crystal.

A comparison of the effective stopping numbers for protons channeled along ⟨110⟩-type axes of Ge and GaAs is given in Fig. 9. The effective stopping numbers are about the same for Ge and GaAs. The lattice constants, average mass, and charge, are also nearly the same. The almost equal stopping numbers displayed in Fig. 9 show that the number of electrons per atom participating in the stopping of channeled particles must be about the same for both substances. (This conclusion will be amplified by the more detailed discussion of the $\bar{B}$ values in a subsequent section.)

The effective stopping numbers of protons channeled along ⟨110⟩- ⟨111⟩-, and ⟨112⟩-type directions are given in Fig. 10. The effective stopping numbers found for channeling in the ⟨110⟩- and ⟨112⟩-type directions investigated are about the same. Again these families of directions are both characterized by the fact that the {111}-type plane is the most open plane in the axial intersection.

The effective stopping numbers for channeling along the ⟨111⟩-type axis are about equal to those of germanium and the minimum energy losses in channeling (as well as the normal energy losses) are the same along the [111] and $[\bar{1}\bar{1}\bar{1}]$ directions of GaAs. The significant directional dependence of single displacement effects seen in GaAs along the [111] and $[\bar{1}\bar{1}\bar{1}]$ directions[28] then has no analogy in the minimum energy losses of channeled particles. It is tentatively concluded that the minimum energy losses in channeling in GaAs depend on an average effect rather than upon (1) the lower-order symmetry of GaAs with respect to germanium, (2) the particular asymmetries in GaAs itself along the [111] or $[\bar{1}\bar{1}\bar{1}]$ directions, or (3) differences in any other resulting physical properties of Ge and GaAs.

A study was made to see if the larger asymmetry of GaAs affects the energy-angle distribution of GaAs relative to Ge. Preliminary results indicate that at

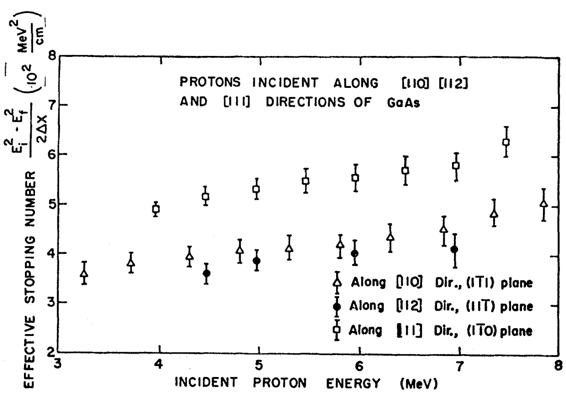

FIG. 10. Effective stopping numbers of protons channeled along [110], [111], and [112] directions of GaAs as a function of incident-proton energy.

[28] Directional effects have been seen in interactions of charged particles with GaAs since single displacement effects in these materials differ along the (111) and $(\bar{1}\bar{1}\bar{1})$ faces [G. W. Gobeli and G. W. Arnold, Bull. Am. Phys. Soc. **19**, 321 (1965)]. However, permanent damage accounts for only a very small fraction of the normal energy losses and, of course, this fraction should be much smaller for channeled particles. Moreover, no appreciable directional effects in normal energy losses, which could correspond with the observed directional effects involving close Coulomb collisions, have been observed for MeV protons along the ⟨111⟩-type directions in GaSb or InAs. No appreciable difference has been seen in energy-loss experiments of channeled particles for protons incident along the $[\bar{1}\bar{1}\bar{1}]$ or [111] directions of GaSb.

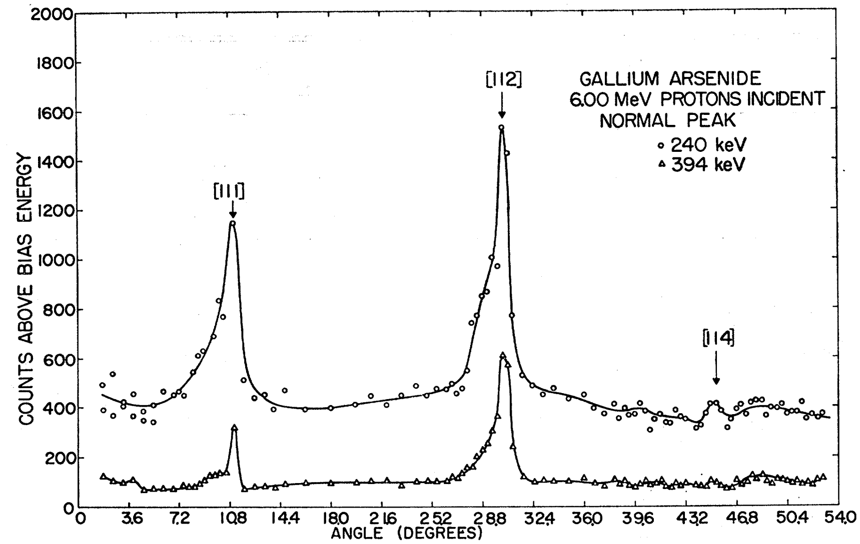

FIG. 11. Energy-angle distribution of protons emergent from GaAs. Protons incident along the {110}-type plane. Plotted are the counts above an energy fixed relative to the peak of normal energy loss E_0 as a function of angle in the plane for a fixed amount of charge on the crystal.

least the gross structure for the type of energy-angle distribution, as studied for Ge and GaAs, is about the same (Figs. 6 and 11). Furthermore, angular studies taken similar to Fig. 11 comparing both sides of the GaAs crystal with the beam incident along the (111) and $(\bar{1}\bar{1}\bar{1})$ faces again show the same gross structure.

The Velocity (Mass) Dependence on the Minimum Energy Losses in Channeling

The velocity (or mass) dependence of the minimum energy losses in channeling was investigated by studying the minimum energy losses of deuterons as well as protons. Since $\bar{B} \propto A$,[20] the results are plotted in terms of $G(v^2)=\bar{B}/A$ against a velocity function discussed below, $\ln \bar{E}/A$ (in MeV). The quantity $\bar{E}\equiv\frac{1}{2}(E_i+E_f)$ and A is the mass number of the incident ion. The

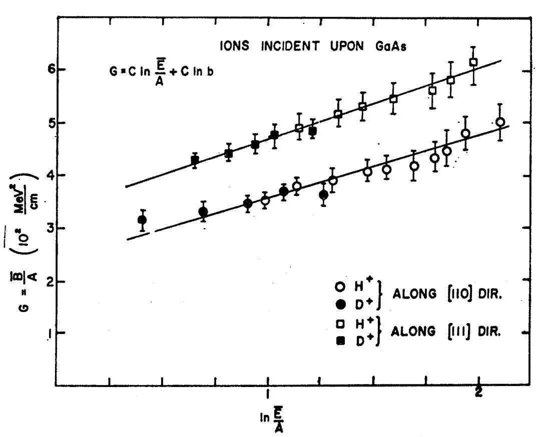

FIG. 12. A universal stopping number, $G(v^2)=\bar{B}/A$, plotted against a simple velocity function ln E/A. The plot shows that energy losses of different ions of the same charge can be correlated by a velocity function in this energy range. Moreover, the display of $\bar{B}$ versus $\bar{E}/A$ is linear as implied by the Bethe equation.

quantity G is then independent of mass. Figure 12, discussed below, shows results for ions incident along the [110] and [111] directions of GaAs. The figure indicates that mass dependencies of the minimum energy losses in channeling can be correlated simply with a velocity-dependent function. Velocity, therefore, is the important parameter in the slowing down of channeled ions. A similar conclusion can be drawn from the Ge data.

Discussion of the Bethe Stopping Formula in Channeling

We will determine whether an equation of the form written in Eq. (2) accounts for the energy losses of channeled particles. In order to do this we will find constants b and C in $B\equiv C\ln bE$. We will use the experimental values of $\bar{B}$ to determine these constants.

The constants can be found by using an approximation for $\bar{B}$ obtained by rewriting Eq. (4), letting $E=\bar{E}+\epsilon$, where $\epsilon_c=E_i-\bar{E}$ and $-\epsilon_c=E_f-\bar{E}$:

$$\Delta x=\frac{1}{C}\int_{-\epsilon_c}^{+\epsilon_c}\frac{(\bar{E}+\epsilon)\,d\epsilon}{\ln b\bar{E}+\ln(1+\epsilon/\bar{E})}=\frac{1}{B}\int_{E_f}^{E_i}E\,dE. \qquad (6)$$

If $\ln(1+\epsilon/E)$ in the denominator of Eq. (6) is small compared with $\ln b\bar{E}$ then the resulting approximation obtained is

$$\bar{B}\approx C\ln b\bar{E}. \qquad (7)$$

The plot of the experimental values of $\bar{B}$ (Fig. 12) does indeed appear to be a straight line as implied in Eq. (7). The constants b and C determined from a least-squares fit to the data show that $\ln(1+\epsilon/\bar{E})$ is indeed small and about an order-of-magnitude smaller than $\ln b\bar{E}$. Furthermore, integration from $-\epsilon_c$ to $+\epsilon_c$ will further reduce the contribution of this already small term.

TABLE IV. Constants obtained from stopping equations.

Type of plane	Axial direction	Ge C(MeV²/cm)	Ge ln b	GaAs C(MeV²/cm)	GaAs ln b
{110}	⟨111⟩	132±9	2.36±0.30	136±7	2.46±0.10
{111}	⟨110⟩	108±12	2.26±0.16	112±9	2.24±0.10
{111}	⟨112⟩	101±12	2.73±0.63	119±12	1.61±0.29

To determine the accuracy of the b and C values obtained using this approximation, an exact expression of $\bar{B}$ is written from the definition

$$\bar{B}\equiv\frac{E_i^2-E_f^2}{2\Delta x}=(E_i^2-E_f^2)\left(\frac{2}{C}\int\frac{EdE}{\ln bE}\right)^{-1}$$

$$=\frac{Cb^2\{E_i^2-E_f^2\}}{2[I\gamma\{\ln(bE_i)^2\}-I\gamma\{\ln(bE_f)^2\}]}, \qquad (8)$$

where

$$I\gamma(\alpha)\equiv\int_{-\infty}^{\alpha}\frac{e^y dy}{y}.$$

It is difficult to use all the experimental values of $\bar{B}$ to get b and C directly from Eq. (8). However, when the constants b and C determined from Eq. (7) are inserted into this exact expression, values of $\bar{B}$ are obtained which agree to within ~0.1% with those obtained from the approximation. Since Eq. (7) is accurate and becomes better for thinner crystals, B itself has been shown to have the logarithmic energy dependence for channeling given by $C\ln bE$ [$\bar{B}\approx B(\bar{E})$, from Eqs. (4) and (6)].

The values of the constants C and ln$b$ are listed in Table IV. The results are almost equal for Ge and GaAs. In fact, agreement of C values in Ge and GaAs is very good for channeling along the {110}-type planes and fairly good for channeling along the {111}-type planes. In the original Bethe equation, C is proportional to the charge of the host lattice. The only other nonconstant factor contained in C in the Bethe equation is the atomic density which should be nearly equal for Ge and GaAs. These results further support the conclusions that within the ranges of energies investigated, the energy losses in channeling in Ge and GaAs are about the same and that the minimum energy losses in channeling appear to be characterized by the most open plane in the intersection.

CONCLUSIONS

The effective stopping numbers for channeled protons in Ge are about the same along the [110] and [112] directions. Since the {111}-type plane is the most open type plane of the intersection, further evidence is obtained that the most open plane of the intersection characterizes the energy loss of channeled particles in this energy region. The minimum energy losses along the [111] direction are larger. The less open {110}-type plane is the largest plane of that intersection implying that more open planes have smaller energy losses.

The channeling peak exists in GaAs. The minimum energy losses that have been observed in the ⟨110⟩- and ⟨112⟩-type directions are about equal to Ge for corresponding type directions. Channeling in the [111] direction of Ge and the [111] and [$\bar{1}\bar{1}\bar{1}$] directions of GaAs again give about the same minimum energy losses. Therefore, the minimum energy losses in channeling in GaAs seem to depend more on average values rather than upon the fact that GaAs has lower order symmetry than Ge.

Silicon has a smaller lattice constant than Ge or GaAs. In spite of this, smaller stopping numbers are obtained for Si than for Ge or GaAs along corresponding directions indicating that fewer electrons per atom are participating in the stopping of channeled particles in Si.

The solution of a stopping equation with the same energy dependence as the Bethe equation adequately describes the minimum channeling energy losses of Ge and GaAs. The energy losses of protons and deuterons can be correlated with a simple velocity function.

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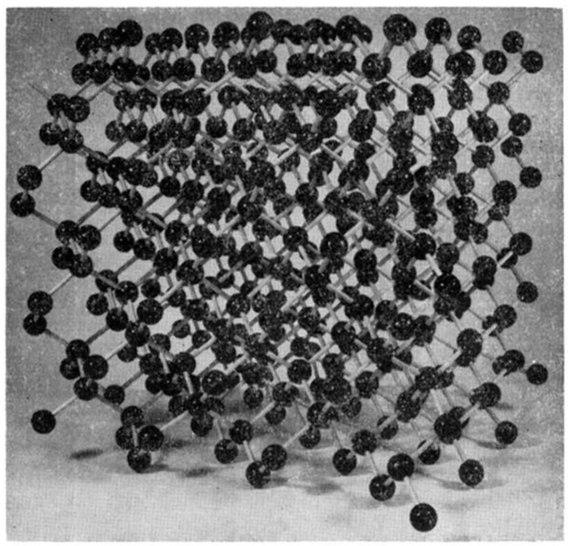

FIG. 2. A model portraying a random orientation of a diamond-type lattice.

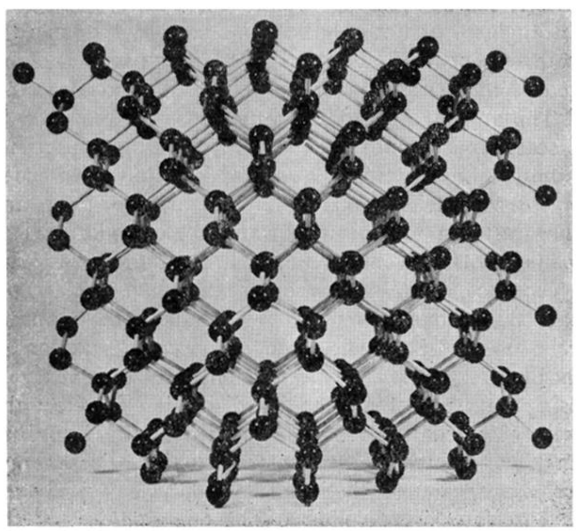

FIG. 3. The same model as in Fig. 2 where the lattice is now viewed along the [110] direction.