"elementary calculation," arrive at $4\pi D\langle R\rangle$ as the rate constant for exciton capture by an impurity. In view of the above discussion we believe that their interpretation that previous experimental results demonstrate coherent motion for singlet excitons in naphthalene is incorrect.

Most determinations of the diffusion coefficient reported in this paper were made for diffusion perpendicular to the *ab* plane. For diffusion in the *ab* plane we found a value of D within the range cited in the first paragraph. Theoretical predictions[6] indicate a large anisotropy, $D_{\perp ab}/D_{\parallel ab} \sim 10^{-3}$, which was not observed.

The results reported here are consistent with those reported by Avakian and Merrifield[4] of a diffusion distance of $7\,\mu$ in a $20\,\mu$-thick crystal. Our results predict a $9\,\mu$ diffusion distance from the relation $l=(2D\tau)^{1/2}$, assuming $D=4\times10^{-3}$ cm^2/sec and the effective $\beta=(\tau)^{-1}=\pi^2D/L^2$, where $L=20\,\mu$. Our results are inconsistent with theirs for the thicker crystals.

The assistance of Lowell Jones in collecting the experimental data is gratefully acknowledged.

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*This work was supported by the U. S. Atomic Energy Commission. Reproduction in whole or in part is permitted for any purpose of the U. S. Government.

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ANOMALOUS ENERGY LOSSES OF PROTONS CHANNELED IN SINGLE-CRYSTAL GERMANIUM*

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(Received 1 April 1965; revised manuscript received 4 June 1965)

The process of "channeling," i.e., the crystallographic orientation dependence of the energy loss of particles which are incident on a crystalline solid,[1-3] has been invoked to explain anomalously small energy losses of charged particles incident along crystallographic orientations having "channels" of low electronic density.[4-6] Recently, channeling was used to account for the crystallographic orientation dependence of charged-particle reactions[7,8] and x-ray production.[9] The orientation dependence of the transmission of charged particles has also been observed photographically,[10,11] demonstrating the phenomena of interplaner channeling.

In previous investigations[4,6] when protons were incident on silicon crystals along crystallographic channeling directions, the energy spectrum of the emergent protons showed a high-energy tail indicative of a continuum of lower than normal energy losses in the crystals. The most marked results in silicon were reported to occur when the beam was incident along the $\langle 110\rangle$ direction, which is the most open direction in a diamond-type lattice.

In the present investigation the energy and angular dependence of protons channeled in germanium have been studied, with high angular resolution.[12-14] The results show that under certain conditions a clearly resolved peak is observed at energies well above the normal energy-loss peak, indicating the existence of a channeling process having a specific energy loss. Furthermore, the energy loss of this peak is a function of crystallographic orientation.

The description of the scattering chamber has been given elsewhere.[5] The beam of protons emergent from the crystal was finely collimated before being recorded in a junction detector. The detector, which subtended a solid angle of $\sim 5\times 10^{-3}$ sr, was moved about the center of the pattern of protons emergent from the single crystal. The angular and energy dependences of the intensity of the emergent protons were recorded for a total of approximately 20° about the center of the pattern of emerging protons for an incident energy of 6.75 MeV. With the beam incident along the ⟨110⟩ direction of the germanium crystal, which was about 3.5 mils in thickness, observations were made at the center of the pattern of emergent particles for incident proton energies between 4.25 and 7.75 MeV and for incident deuterons at 7.63 MeV. Observations were also made along ⟨111⟩ and ⟨112⟩ directions with 6.75-MeV protons.

Figure 1 shows three spectra of emergent protons for 6.75-MeV protons incident on the Ge crystal. For curves A and B the beam is along the ⟨110⟩ axis of Ge. Curve A shows the spectrum taken at the center of the pattern of emergent channeled protons. Curve B shows a spectrum taken −0.86° away from the center of the pattern. Curve C shows a spectrum at the center of the pattern of emergent protons, with the crystal oriented away from its ⟨110⟩ direction in an arbitrary direction with respect to the incident beam.

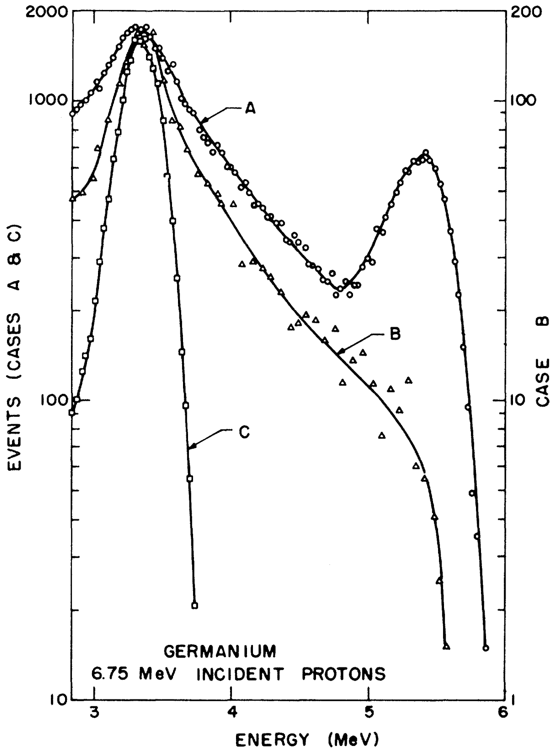

FIG. 1. Spectra of protons emergent from germanium crystal: (A) proton beam along ⟨110⟩ axis of Ge crystal, spectrum taken along center of pattern of emergent channeled particles; (B) proton beam along ⟨110⟩ axis of crystal, spectrum taken ~0.86° off the center of emergent channeled particles; (C) proton beam at arbitrary direction with respect to crystal, spectrum taken at center of pattern of emergent particles.

As curve A shows, instead of only a high-energy shoulder in the spectrum of emergent protons at the particular crystallographic orientation, there also appears a second distinct peak at an energy well above the "normal" energy-loss peak characteristic of a random orientation of the crystal. This "channeling peak" has an energy loss less than one-half that of the lower random-orientation energy-loss peak, and the energy losses of the channeling peak and normal peak are given in Table I as a function of energy. Moreover, the energy loss of the channeling peak relative to that of the normal peak is orientation dependent, as is shown in Table II.

These anomalous energy losses are not observed when the incident beam is in an arbitrary direction with respect to the germanium crystal, as seen in curve C. Furthermore, when the beam is along the ⟨110⟩ direction but the spectrum of emergent channeled protons is taken successively further away from the center of the pattern (curve B), the structure of the channeling peak evolves into a shouldered peak within ~0.6° from the center of the pattern of emergent protons. The general broadening of the normal peak in curves A and B indicates higher than average energy losses as well as lower than average energy losses. This structure has previously been observed in silicon.[6]

This secondary channeling peak apparent in curve A is a special case of low-energy-loss channeling. Its appearance is suggestive of a single energy-loss process. Charged particles lose essentially all their energy to ionization and excitation by two processes: energy loss due to close electronic collisions, and energy loss to distant electronic resonant momentum transfers. The highly collimated particles in the channeling peak suffer very small angle scattering in their trajectories through the crystal. At small correlated scattering angles there exists a limiting angle such that for smaller angles the energy loss to close electronic collisions is negligible compared to the constant energy loss to distant electronic resonant momentum transfers. All particles having these small correlated scattering angles will have essentially the same energy loss and give rise to the channeling peak. The energy of the channeling peak then provides an experimental determination of the energy loss to distant resonant momentum transfers.

Bohr[15] stated that on the average the two components of energy loss are equal at the high-energy limit. This statistical equipartition rule has been proven rigorously for the case of an electron gas by Lindhard and Winther,[16] who further suggest its validity for an atomic system. According to the equipartition rule, the energy loss of a proton in germanium should, on the average, be divided equally between these two components. For a germanium crystal of finite size, however, the energy loss (to distant resonant momentum transfers) of the particles in the channeling peak is less than the energy loss to distant resonant momentum transfers of the particles in the normal peak. This is simply a result of the fact that dE/dx is approximately inversely proportionally to E and the particles in the channeling peak have higher energies (therefore lower energy losses to the distant processes) than those in the normal peak. Therefore, according to the equipartition rule one would expect that for finite crystals the energy loss of the channeling peak should be slightly less than one-half the energy loss of the normal peak. Table I also includes the energy loss of the channeling peak calculated on the basis of the equipartition rule.

Tables I and II and curve A show that the energy loss of the channeling peak is not only orientation dependent[17] but can be significantly smaller than that predicted on the basis of the equipartition rule. This difference becomes more marked as the incident proton energy is lowered.[18] If there is appreciable residual electronic density along the channels, then the deviations from the energy losses predicted by the equipartition rule would be even larger. It then must be concluded that while on the average the equipartition rule may hold in a solid atomic system, the energy losses of the channeling peak along directions of crystalline symmetry are not predicted by the equipartition rule.

This work is being performed on the P-9 ver-

Table I. Incident beam in the ⟨110⟩ direction.

Incident ion energy	Energy loss (ΔE) Normal peak (in MeV)	Energy loss (ΔE) Channeling peak (in MeV) (expt.)	Energy loss (ΔE) Channeling peak (in MeV) (predicted[a])	$\frac{\Delta E \text{ channeling peak}}{\Delta E \text{ normal peak}}$ (expt.)	$\frac{\Delta E \text{ channeling peak}}{\Delta E \text{ normal peak}}$ (predicted[a])	$\frac{\Delta E(\text{channeling peak})\ (\text{expt.})}{\Delta E(\text{normal peak})\ (\text{predicted}^a)}$
7.75-MeV H^+	2.93	1.23	1.32	0.418 ±0.015	0.450	0.932 ±0.020
7.25-MeV H^+	3.15	1.30	1.42	0.412 ±0.015	0.448	0.918 ±0.020
6.75-MeV H^+	3.35	1.35	1.48	0.398 ±0.015	0.442	0.908 ±0.020
6.25-MeV H^+	3.65	1.42	1.59	0.390 ±0.015	0.438	0.891 ±0.020
5.75-MeV H^+	4.01	1.51	1.70	0.375 ±0.015	0.424	0.889 ±0.020
5.25-MeV H^+	···	1.65	1.87	···	···	0.875 ±0.025
4.75-MeV H^+	···	1.73	2.09	···	···	0.835 ±0.030
4.25-MeV H^+	···	2.13	2.62	···	···	0.812 ±0.035
7.63-MeV D^+	5.21	2.25	2.25	0.432 ±0.023	0.432	1.00 ±0.030

[a] Predicted on the basis of the equipartition rule.

Table II. Incident beam in the ⟨110⟩ direction.

Direction of incident beam	Incident proton energy (in MeV)	Energy loss (ΔE) Normal peak (in MeV)	Energy loss (ΔE) Channeling peak (in MeV)	$\frac{\Delta E\text{ (channeling peak)}}{\Delta E\text{ (normal peak)}}$	$\frac{\Delta E\text{ (channeling peak)}^{a}}{\Delta E\text{ (normal peak)}^{a}}$
⟨111⟩	6.75	2.54	1.23	0.484 ± 0.020	0.461
⟨112⟩	6.75	2.70	1.13	0.411 ± 0.015	0.456
⟨110⟩	6.75	3.40	1.32	0.398 ± 0.015	0.445

[a] Predicted from equipartition rule.

ticle Van de Graaff accelerator at Los Alamos. We wish to acknowledge the assistance of the P-9 staff at Los Alamos under J. L. McKibben and R. L. Henkel. We want to thank R. W. Healy for assistance in the experiment and for maintenance of the equipment. We are grateful to F. L. Vook and D. K. Brice, Sandia Laboratory, for aid in interpretation of the data.

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*This work was supported by the U. S. Atomic Energy Commission. Reproduction in whole or in part is permitted for any purpose of the U. S. Government.

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FARADAY EFFECT IN MAGNETIZED SOLIDS*

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(Received 24 May 1965)

In a recent Letter,[1] Mitchell, Palik, and Wallis have reported measurements of the Faraday rotation in PbS. They find that the wavelength variation of the Faraday rotation below interband frequencies has a constant added to the usual λ^2 dependence. This constant term varies approximately inversely proportional to the temperature. Mitchell, Palik, and Wallis explain this constant term as caused by the difference in some interband matrix elements between electrons of different spins. In this Letter a more physical description of the cause of the effect is given. It is shown that the constant term comes from a polarization current produced by the variation in time of the spatial polarization of the electron wave functions,[2] and this constant term is expected to be proportional to the magnetization of the sample. The effect of collisions with the lattice is also estimated.