[7]S. Rodriquez, Phys. Rev. **130**, 1778 (1963).

[8]See, for instance, H. N. Spector, Solid State Phys. **19**, 342 (1966); J. Mertsching, Phys. Status Solidi **32**, 465 (1970), and references therein.

[9]Generalization of the work in Ref. 10.

[10]M. H. Cohen, M. J. Harrison, and W. H. Harrison, Phys. Rev. **117**, 937 (1960).

[11]Calculation in Ref. 2 is in error for this reason.

[12]See, for instance, Ref. 4. The derivation in this paper is incorrect for the same reasons as those in Ref. 2. However, in the limit which the authors use ($ql \gg 1$), the additional terms are negligible.

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Scintillation Response of NaI(Tl) and KI(Tl) to Channeled Ions*

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The scintillation pulse-height response of NaI(Tl) and KI(Tl) to ^{4}He and ^{16}O ions in the 2–60-MeV range has been studied with the ion beam aligned along low-index planes and axes and also aligned along a random direction. The scintillation efficiency increases by as much as 50% when the ion beam is channeled along a major symmetry direction. The effect of channeling has been observed by recording the pulse-height spectra for monoenergetic ions oriented along {100}, {110}, and {111} planes, and along ⟨100⟩, ⟨110⟩, and ⟨111⟩ axes. The increase in pulse-height response is in semiquantitative agreement with recent model calculations. Observation of this effect permits study of channeling phenomena in thick crystals that are scintillators. In particular, this paper reports a measurement of the critical angle for channeling of 15-MeV ^{16}O along a {100} plane.

I. INTRODUCTION

It is well known that energetic positive ions experience a reduced stopping power dE/dx when incident along low index axes or planes of a crystalline solid.[1] This effect arises from a correlated scattering of the incident ion by the lattice atoms for incidence along major symmetry directions. This correlated scattering and the associated steering of the incident ion along the open regions of the crystal is known as channeling and has been studied in detail in many solids, especially semiconductors and metals.

Luntz and Bartram[2] (denoted LB hereafter) suggested that channeling should have a pronounced effect on the scintillation response of NaI(Tl) and CsI(Tl) to positive ions. Their calculations predicted that the scintillation pulse height from an energetic positive ion could be enhanced by as much as four times its normal value if the ion experiences a channeled rather than a random trajectory, where "random" refers to an ion incident upon the crystal in a nonaligned direction. The cause of this effect can be seen by an examination of the scintillation efficiency dL/dE as a function of stopping power dE/dx for various positive ions. Scintillation efficiency dL/dE is defined as the slope of a pulse-height–versus–energy curve, where L represents the scintillation pulse height arising from a particle of incident energy E that is completely stopped in the crystal. A survey[3] of dL/dE vs dE/dx for various positive ions in NaI(Tl) and CsI(Tl) shows that the scintillation efficiency decreases with increasing stopping power. The effect of aligning the incident beam along a major symmetry direction is to reduce dE/dx, thus to increase dL/dE along the ion's path and therefore produce a greater pulse height L.

This paper reports the results of a series of experiments on the scintillation response of NaI(Tl) and KI(Tl) to ^{4}He and ^{16}O ions in the range 2–60 MeV for random incidence and for incidence along the {100}, {110}, and {111} planes and along the ⟨100⟩, ⟨110⟩, and ⟨111⟩ axes. The results are in qualitative agreement with the calculations of LB as the channeled ions yield a distinctly greater pulse height. The magnitude of the increase in pulse height is, however, substantially less than that predicted by LB.

Most of the work reported here was on NaI(Tl). Several experiments were performed with KI(Tl), confirming that the effects were substantially the same.

II. EXPERIMENT

Experiments were performed with NaI(Tl) scintillation crystals (nominal 0.1-mole% thallium) obtained from Harshaw Chemical Co. as cylindrical

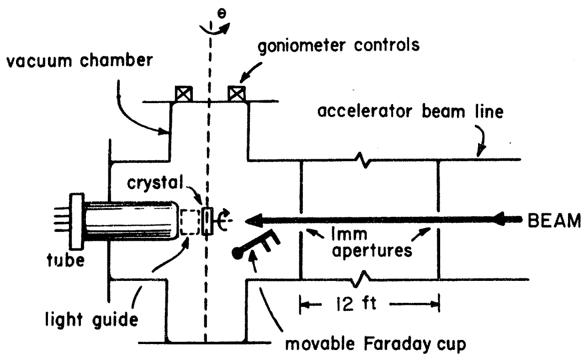

FIG. 1. Schematic diagram of apparatus.

ingots. The crystals were cleaved into circular platelets (approximately 3 $cm^2 \times 2$ mm) in an atmosphere of dry air in a dry box, and mounted in a goniometer while in the dry box. The surface of the crystal to be presented to the beam was protected by a cap and O-ring seal. The crystal and goniometer were then wrapped in plastic bags and transferred to the beam line of the accelerator where the plastic bags and protective cap were removed in a flow of dry argon gas. The system was then promptly evacuated and kept under vacuum for the duration of the experiment. There is, of course, no guarantee that the surface exposed to the beam remained uncontaminated during the process, as NaI is highly hygroscopic. However, each series of experiments was begun by recording the scintillation pulse-height spectrum of 10-MeV ^{16}O ions channeled along $\{100\}$ planes, and the crystal was used only if this initial spectrum was essentially identical to that recorded in previous experiments. On this basis we believe that the surface properties of all crystals used were substantially the same as regards the effect of the surface on channeling.

Since channeling is dependent upon very precise alignment of the incoming beam with low-index axes or planes, it is necessary to orient the crystal (with respect to the collimated beam) accurately and reproducibly. In order to achieve this the samples were mounted in a precision goniometer that permitted rotation of the crystal about a horizontal axis perpendicular to its face (through an angle ϕ) and rotation about a vertical axis that lay in its face (through an angle θ) (see Fig. 1). The crystal could be oriented with a precision better than $\pm 0.02°$ in either angle.

Scintillation pulses were detected with an end-window photomultiplier tube (RCA 7326 or 7265) that was mounted horizontally within the beam-line vacuum system, with its axis along the beam axis. In most experiments the photocathode surface was placed as close as possible to the back side of the scintillation crystal and no light guide was used (to permit freedom of rotation through θ). In some experiments a lucite light guide was used to couple the back side of the crystal to the photomultiplier tube; this resulted in better pulse-height resolution and still permitted rotation through ϕ.

Experiments were performed with the tandem Van de Graaff accelerator of the Nuclear Effects Laboratory at Edgewood Arsenal. The charged-particle beam was collimated to a half-angle of 0.016° by 1-mm apertures separated by a distance of 3.65 m.

Scintillation pulse-height spectra were recorded on a Nuclear Data multichannel analyzer. The pulse-height scale was calibrated with an ORTEC model No. 448 precision pulser after recording each spectrum, thus permitting an accurate determination of peak pulse height vs beam energy. In addition, in some experiments a small NaI(Tl) crystal containing an internal α-particle source was mounted directly on the face of the photomultiplier tube. The α-particle spectrum appeared in each run with the collimated beam, and this provided an internal check against photomultiplier-gain shifts as the beam energy or current was varied. Count rates from the ^4He or ^{16}O beam were typically 10^3 counts/sec.

Orientation of the crystals was straightforward, as NaI cleaves along a $\{100\}$ plane. The crystal was mounted in the goniometer with a cleavage plane facing the beam. In order to align a low-index plane with the beam, the angle θ was fixed at a value other than 0° and the angle ϕ was varied. To align a crystal axis with the beam, it was necessary to vary both ϕ and θ. Various planes and axes were then identified with the aid of a stereographic projection for a cubic lattice.

Experiments on KI(Tl) were performed with crystals from Harshaw. The mounting procedure was the same as that for NaI(Tl).

III. RESULTS AND DISCUSSION

A. Pulse-Height Spectra

Figure 2(a) shows the pulse-height spectrum resulting from 10-MeV ^{16}O ions incident on NaI(Tl) at a random angle. In this case and in Figs. 2(b) and 2(c) the crystal was optically coupled to the photomultiplier tube through a lucite light guide; however, there was no reflector covering the front surface of the crystal. Figure 2(b) shows the spectrum observed when the 10-MeV beam is aligned along a $\{100\}$ plane. In addition to a peak at the same pulse height as for random incidence, there is now an additional peak at a pulse height approximately 42% greater. There is also a continuous distribution of pulses between the two peaks. The spectrum for 24-MeV ^{16}O along a $\{100\}$

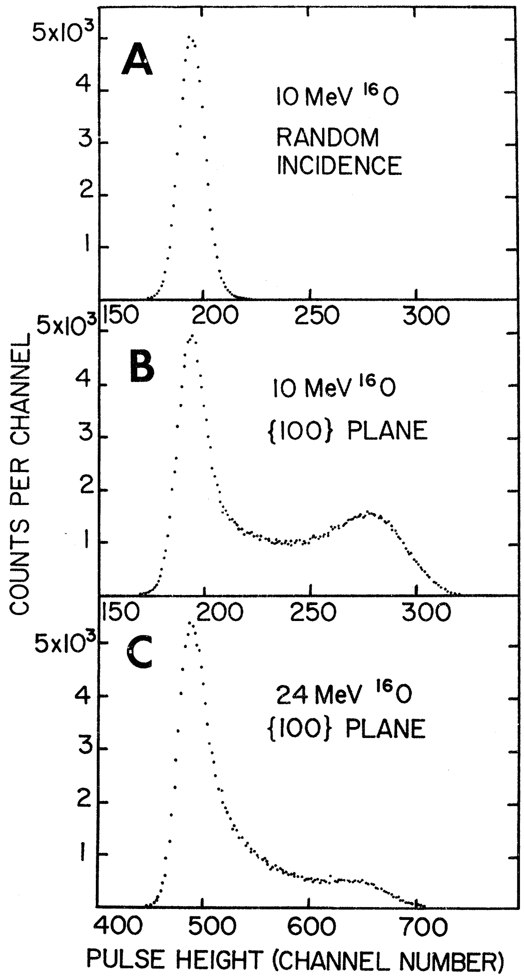

FIG. 2. (a) Pulse-height spectrum from 10-MeV ^{16}O on NaI(Tl) for incidence along a random direction. (b) Pulse-height spectrum from 10-MeV ^{16}O along a {100} plane. (c) Pulse-height spectrum from 24-MeV ^{16}O along a {100} plane. A light guide was used in all cases.

plane is shown in Fig. 2(c). The relative number of pulses in the right-hand peak is clearly reduced from that in the 10-MeV case. We have recorded spectra for alignment along the {100} plane for ^{16}O ions in the range 5–32 MeV, and the general features of the spectra over this entire range are illustrated by Fig. 2. As the energy is decreased below 10 MeV the relative number of counts in the right-hand peak increases. At energies above 24 MeV the right-hand peak becomes a continuous tail.

Figure 2 shows the individual data points as recorded in the pulse-height analyzer. In all subsequent figures the statistics are as good as or better than in Fig. 2, and pulse-height spectra will be shown as smooth curves.

Figure 3 shows pulse-height spectra from 10-MeV ^{16}O on NaI(Tl) for both random incidence and for alignment along a {110} plane. In the latter

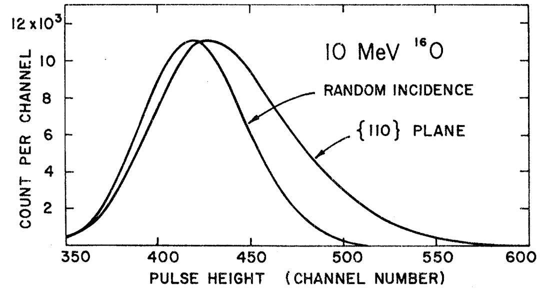

FIG. 3. Pulse-height spectrum from 10-MeV ^{16}O on NaI(Tl) for random incidence and along a {110} plane. Curves are normalized to same peak height. No light guide.

case a second peak is not discernible, but there is clearly a distribution of counts above the random peak. A similar effect is observed for alignment along a {111} plane, as shown in Fig. 4. In both Figs. 3 and 4 the crystal was not coupled to the photomultiplier tube with a light guide, so that the resolution is not as good as in the case of Fig. 2. The channeling effect is, however, clearly observed. (The abscissas of Figs. 3 and 4 are not related.)

Comparison of Figs. 2(b), 3, and 4 shows that channeling produces the most distinct effect along a {100} plane, and that the effect is reduced progressively in going to a {110} and a {111} plane.

Figure 5 illustrates the channeling effect for 2-MeV ^{4}He ions along a {100} plane. A separate channeled peak is not resolved, although there is clearly a distribution of counts at higher pulse heights. We have recorded spectra for ^{4}He ions along a {100} plane from 1.5 to 8 MeV. As in the case of ^{16}O ions the effect of alignment becomes less pronounced as the energy of the incident ^{4}He

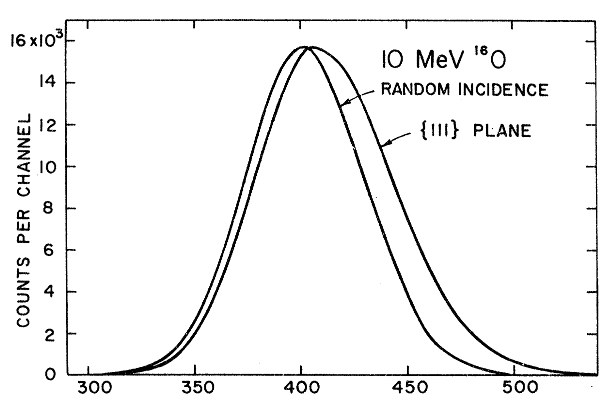

FIG. 4. Pulse-height spectrum from 10-MeV ^{16}O on NaI(Tl) for random incidence and along a {111} plane. Curves were normalized to same peak height. No light guide.

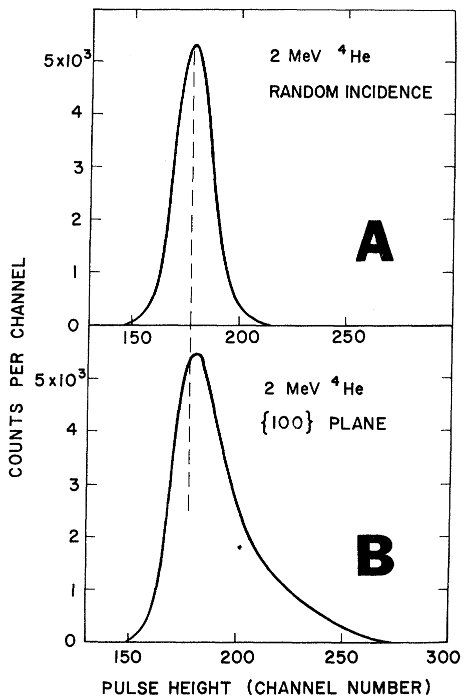

FIG. 5. (a) Pulse-height spectrum from 2-MeV ^{4}He on NaI(Tl) for random incidence. (b) Pulse-height spectrum from 2-MeV ^{4}He along a {100} plane. A light guide was used for both spectra.

ions increases; however, even at 8 MeV a tail due to channeled ions was observed. In these spectra for ^{4}He ions, a light quide was used to improve resolution.

It is interesting to compare pulse-height spectra for {100}-channeled ions of the same initial velocity but different atomic number. Figure 6 shows the spectrum for 8-MeV ^{16}O channeled along a {100} plane and this spectrum can be compared with that of Fig. 5(b), as both cases involve ions of the same initial velocity. Clearly, the ^{16}O case shows a well-defined peak due to channeled ions, in contrast to the tail of the ^{4}He spectrum.

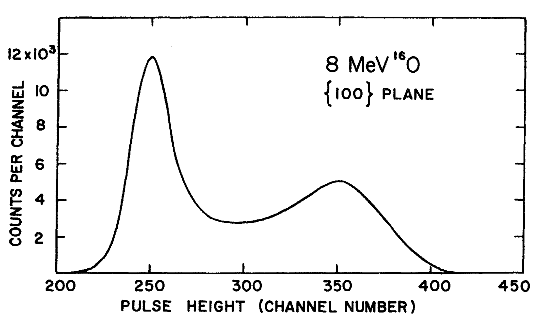

FIG. 6. Pulse-height spectrum from 8-MeV ^{16}O on NaI(Tl) along a {100} plane.

The effect of channeling along low-index axes is more pronounced than the effect along low-index planes. Figure 7 shows pulse-height spectra for ^{16}O ions of three different energies incident along a ⟨100⟩ axis. In Fig. 7(a) for 9-MeV ^{16}O, the dominant feature of the spectrum is the peak at high pulse heights due to channeled ions. The smaller peak on the left-hand side coincides with the spectrum observed for random incidence. Figures 7(b) and 7(c) show spectra for ⟨100⟩ incidence for ^{16}O ions of 18 and 40 MeV, respectively-

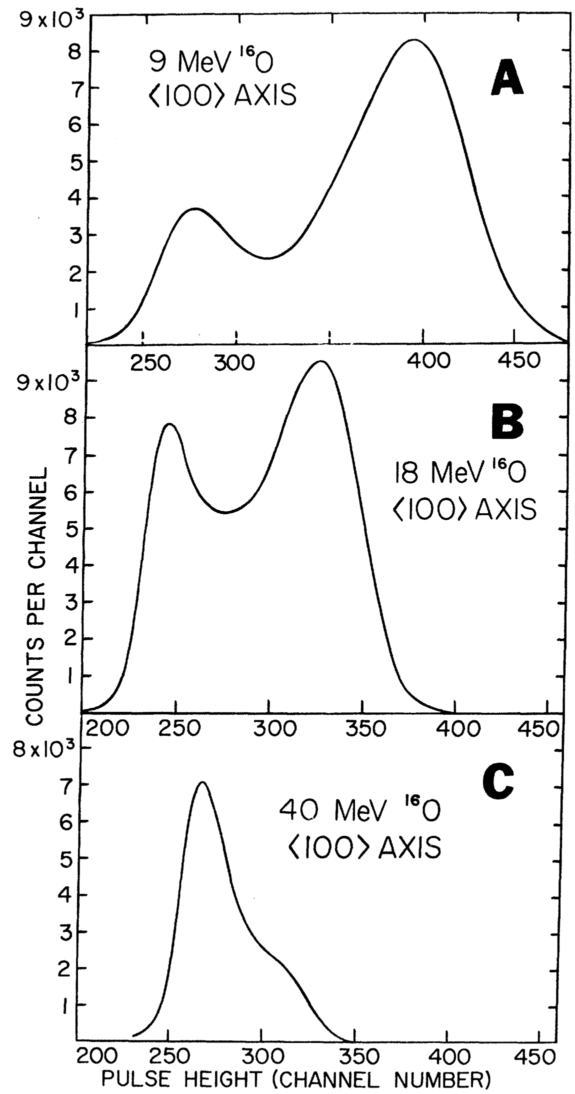

FIG. 7. (a) Pulse-height spectrum from 9-MeV ^{16}O ions on NaI(Tl) along a ⟨100⟩ axis. The smaller peak on the left-hand side coincides with that observed for random incidence. (b) Pulse-height spectrum from 18-MeV ^{16}O along a ⟨100⟩ axis. (c) Pulse-height spectrum from 40-MeV ^{16}O along a ⟨100⟩ axis. No light guide was used. The channel numbers in (a)–(c) are not correlated. lated.

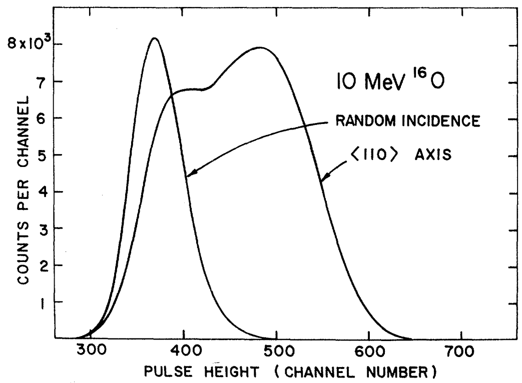

FIG. 8. Pulse-height spectra for 10-MeV ^{16}O on NaI(Tl) for random incidence and for incidence along a ⟨110⟩ axis. Curves are normalized to approximately the same peak height. No light guide.

ly. As in the case of the {100} planes, the relative number of counts in the channeled peak decreases with increasing energy. We have recorded spectra for incidence along a ⟨100⟩ axis for ^{16}O ions in the range 3–60 MeV, and the general features are as illustrated in Fig. 7; i.e., the fraction of counts in the channeled peak decreasing with increasing energy. The ratio of pulse heights of the channeled peak to random peak is energy dependent (as discussed later) and reaches a maximum value of 1.44 at 11 MeV.

Figure 8 presents the pulse-height spectrum from 10-MeV ^{16}O ions for random incidence and incidence along a ⟨110⟩ axis. For the ⟨110⟩ spectrum there is a distinguishable contribution from both a random peak and a channeled peak. For this case the position of the left-hand peak does not coincide with the random-peak position. This is due to a distortion of the random-component peak by the channeled-particle component. The amount of the distortion depends on the resolution and on the enhancement of pulse height for channeled particles. The pulse height (obtained from spectra with better resolution than in Fig. 8) of the channeled peak is approximately 42% greater than that of the random peak. Figure 9 shows similar results for 10-MeV ^{16}O for random incidence and along a ⟨111⟩ axis. The increase in pulse height for the channeled particles cannot be determined accurately in this case because the resolution is not sufficient to reliably extract the position of a channeled peak.

Comparison of Figs. 7(a), 8, and 9 shows that channeling produces the largest effect (separate channeled peak) along the ⟨100⟩ and ⟨110⟩ axes. The ⟨100⟩ and ⟨110⟩ axes and the {100} plane show nearly the same increase in pulse height for 10-MeV channeled ions. This result is reasonable in light of the work of Appleton *et al.*[4] They showed that the least energy loss for protons channeled along axial directions in silicon is the same as that of the most open plane containing the axis. In our case, both the ⟨100⟩ and ⟨110⟩ axes lie in the {100} plane, which in NaI is the most open plane.

It is evident in Fig. 2(b), and in other spectra with ^{16}O ions in the range 5 to about 25 MeV, that a substantial fraction of the incident particles contribute pulses to a well-defined peak at a pulse height greater than that for random incidence. We attribute this peak to particles that remain channeled to the end of their range, and thus experience the lower dE/dx of a channeled trajectory over their entire path. Such a behavior has been clearly demonstrated in other channeling experiments; for example, the work of Eriksson and co-workers[5] on range measurements of various heavy ions in oriented crystals of tungsten. The existence of a peak at low pulse heights, nearly coincident with that recorded for random alignment, is due to those particles that are never channeled. The area under this peak provides a measure of the minimum yield[1] (fraction of incident particles that are never channeled) for alignment along a symmetry direction. The continuous distribution of pulses between the two peaks is attributed to particles that are initially channeled but are subsequently deflected from a channeled trajectory to a random trajectory. The continuous distribution due to dechanneled ions of course overlaps both peaks. The observed spectrum is thus interpreted as arising from ions in three different trajectories: (i) those that are never channeled, (ii) those initially channeled and subsequently dechanneled, and (iii) those that remain channeled throughout the entire range. This analysis is completely analogous to the interpretation of the differential stopping distribution for

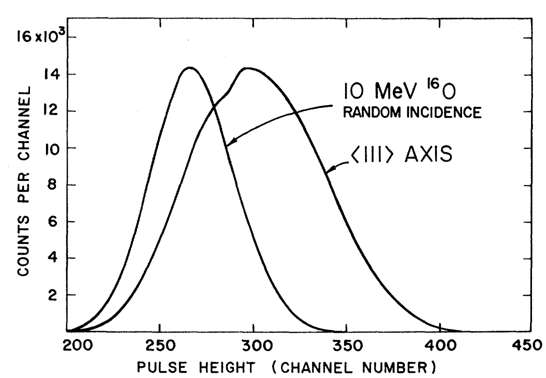

FIG. 9. Pulse-height spectra for 10-MeV ^{16}O on NaI(Tl) for random incidence and for incidence along a ⟨111⟩ axis. Curves are normalized to the same peak height. No light guide.

positive ions in crystals, which is well known (e.g., see Ref. 5). We discuss the pulse-height spectra below according to (i) dechanneling effects and (ii) dependence of spectra on particle energy and mass.

1. Dechanneling Effects

The escape of initially channeled particles to nonchanneled trajectories has been documented in several types of experiments.[1] For planar channeling the number of particles N_c that remain channeled after penetrating a distance x (with $x \ll$ range) can be described by an exponential function

$$N_c(x) = N_c(0)e^{-0.693x/x_{1/2}} , \tag{1}$$

where $x_{1/2}$ is a characteristic length for dechanneling that depends on the energy and identity of the moving particle. For distances x large enough so that there is appreciable energy loss, it is necessary to consider the energy dependence of $x_{1/2}$ and Eq. (1) is not applicable. The fraction of particles that remain channeled to the end of their range is then

$$\frac{N_c(R)}{N_c(0)} = \exp\left(-0.693\int_0^R \frac{dx}{x_{1/2}(E(x))}\right) , \tag{2}$$

where R represents the range for the channeled component. Since the dependence of $x_{1/2}$ on x is not known exactly and since the range R of channeled ions is not known, we cannot determine $N_c(R)/N_c(0)$ by evaluation of the right-hand side of Eq. (2). However, we can determine the ratio $N_c(R)/N_c(0)$ from experiment by analyzing a pulse-height spectrum such as Fig. 2(b) by assuming that all counts in the higher peak arise from particles channeled to the end of their range. If A_{1r} is the area under the pulse-height distribution due to particles that are initially random, A_c is the area under the higher peak, and A the total area, then

$$\frac{N_c(R)}{N_c(0)} = \frac{A_c}{A - A_{1r}} = \frac{A_c/A}{1 - A_{1r}/A} . \tag{3}$$

In analyzing spectra, A_c/A was determined by fitting a Gaussian function to the right-hand side of the higher peak. The fraction of particles initially random A_{1r} cannot be obtained reliably from our pulse-height spectra. However, it is possible to calculate a reliable estimate of this quantity which is called the "minimum yield." Lindhard[6] has formulated the minimum yield for planar channeling as $2r_{min}/d_p$, where d_p is the distance between adjacent planes and r_{min} is the minimum distance of approach to the plane for stable channeling to occur. Recent experiments[7] have indicated that for planar channeling in silicon the appropriate interaction distance (r_{min}) should be taken as u, the thermal-vibration amplitude perpendicular to the plane. This conclusion results from analysis of energy-loss spectra. Taking u as appropriate to a Debye temperature of 192 °K,[8] we find $A_{1r}/A = 2u/d_p = 0.078$. We then obtain for $N_c(R)/N_c(0)$ the value 0.33. This result should be viewed as a lower limit for $N_c(R)/N_c(0)$ since the calculated value of A_{1r}/A for a perfect crystal with a clean surface is surely smaller than that realized in our experiment where surface contaminants and imperfections were present to some extent. Thus at least $\frac{1}{3}$ of those particles initially channeled remain channeled to the end of their range for the case of 10-MeV ^{16}O along $\{100\}$.

It would be of considerable interest to confirm the above conclusion regarding $N_c(R)/N_c(0)$ by direct evaluation of the integral in Eq. (2). This requires knowledge of $x_{1/2}$ as a function of the penetration depth or, alternatively, $x_{1/2}$ as a function of energy. It is possible to determine $x_{1/2}$ as a function of energy by recording the energy distribution of particles backscattered from a crystalline surface; experiments of this type have been initiated.

2. Dependence of Spectra on Particle Energy and Identity

As in Sec. IIIA1, the quantity of interest is the integral

$$I \equiv \int_0^R \frac{dx}{x_{1/2}(E)} = \int_0^{E_0} \frac{dE}{x_{1/2}(E) - dE/dx} . \tag{4}$$

In order to find the dependence of I on incident energy we investigate the derivative

$$\frac{dI}{dE_0} = \frac{1}{x_{1/2}(E) - dE/dx}\bigg|_{E=E_0} > 0 .$$

Since $dI/dE_0 > 0$ for all E_0, we conclude that for a particular incident particle the fraction of particles channeled to the end of their range decreases. as the incident energy increases. This is, in fact, precisely the behavior observed (see Fig. 2).

A very similar behavior is observed experimentally for the case of axial channeling. In Fig. 7, the area under the right-hand peak decreases as the energy changes from 9 to 18 MeV and has become just a slight shoulder by 40 MeV.

The difference in spectral shape for different types of channeled ions at the same incident velocity can be seen in Figs. 5(b) and 6. Here are shown the pulse-height spectra for ^{4}He ions having an initial energy of 2 MeV and ^{16}O ions having an initial energy of 8 MeV. The ^{16}O spectrum contains a much larger fraction of particles that have been channeled to the end of their range as is evidenced by the large peak on the right-hand side of the ^{16}O spectrum as opposed to the tail on the right-hand side of the ^{4}He spectrum. This interpretation depends on the assumption that at a given velocity, the ratio L(channeled)/L(random) is substantially independent of the atomic number of the incident particle. Preliminary measurements at the Nuclear Effects Laboratory at Edgewood Arsenal for particles of $v = 1.38\times 10^9$ cm/sec in the range $Z_1 = 3$ to $Z_1 = 8$ indicate that the ratio of L(channeled)/L(random) lies within the range 1.3–1.4, confirming the above assumption.

To find the basis of this behavior one must investigate the dependence of I on the parameters of the incident ion. We first rewrite the integral as

$$I \equiv \int_0^R \frac{dx}{x_{1/2}(E)} = \int_0^{E_0} \frac{1}{x_{1/2}} \left(dE \Big/ \left| \frac{dE}{dx} \right| \right)$$
$$= \int_0^{v_0} \frac{1}{x_{1/2}} \left(M_1 v\, dv \Big/ \left| \frac{dE}{dx} \right| \right) \quad . \tag{5}$$

The result of a diffusion-model calculation[9] for planar dechanneling shows that

$$x_{1/2} = 1.12(\psi_c^2/\langle \theta^2 \rangle) ,$$

where ψ_c is the critical angle for channeling and $\langle\theta^2\rangle$ is the mean-square multiple-scattering angle per unit thickness. The energy and charge dependence of ψ_c is $\psi_c \propto (Z_1/E)^{1/2}$. Lindhard[6] formulates the multiple scattering (electronic) as

$$\langle\theta^2\rangle = (m/2M_1E)S_e\rho ,$$

where S_e is the electronic stopping power, m is the electron mass, and ρ is the local electron density sampled by the channeled particles. Assuming that ρ is independent of E and Z_1, we then have

$$x_{1/2} \propto M_1 Z_1 \Big/ \frac{dE}{dx} ,$$

where dE/dx is the channeled energy-loss rate (as in the integral above). Finally, the result for I is

$$I \propto \int_0^{v_0} \frac{v\,dv}{Z_1} = \frac{1}{Z_1} \left(\tfrac{1}{2} v_0^2\right) .$$

Since v_0 is the same for both the ^{4}He and ^{16}O ions, it can thus be seen that the spectrum for 8-MeV ^{16}O should contain a larger fraction channeled to the end of the ion's range than the spectrum for 2-MeV ^{4}He. As discussed above this is the experimental observation. Quantitative estimates of the fraction channeled would require knowledge of ρ, the local electron density within the channel.

B. Pulse Height as Function of Energy

In one series of experiments a careful measurement was made of the peak pulse height as a function of energy for ^{16}O ions on NaI(Tl) for both random incidence and for incidence along a $\langle 100\rangle$ axis. In these experiments "random incidence" was obtained by a rotation of approximately 1° away from the $\langle 100\rangle$ axis, a rotation that did not affect the optical coupling between crystal and photomultiplier. For these measurements an auxiliary encapsulated crystal of NaI(Tl) ($\frac{1}{4}$-in. diam) containing ^{241}Am was mounted on the photomultiplier window to serve as a pulse-height standard as discussed in Sec. II. All ^{16}O pulse-height spectra thus contained a peak due to the ^{241}Am α counts from the standard crystal. The magnitudes of all peaks in the ^{16}O spectra were measured relative to the ^{241}Am α peak from the standard. This method eliminates possible errors in peak pulse height due to gain shifts in the photomultiplier and electronics.

Results of this experiment are given in Fig. 10, showing the pulse height of the ^{16}O peak for random incidence and the pulse height of the channeled peak for incidence along a $\langle 100\rangle$ axis. The pulse height for the channeled peak was determined by fitting a Gaussian function to the right-hand side of the channeled peak using a digital-computer least-squares program. It was not possible to obtain a reliable pulse height for the channeled peak above 45 MeV as it is small and smeared out. The scintitillation efficiency dL/dE was obtained for both curves of Fig. 10 by a method outlined previously,[10] and is plotted as a function of incident energy in Fig. 11. The curve for random incidence is nearly flat for energies up to 10 MeV and then increases smoothly up to 60 MeV. The curve for $\langle 100\rangle$ axial channeling decreases slowly up to about 16 MeV and then increases up to 40 MeV, the highest energy at which dL/dE could be determined. It should be noted that the two curves

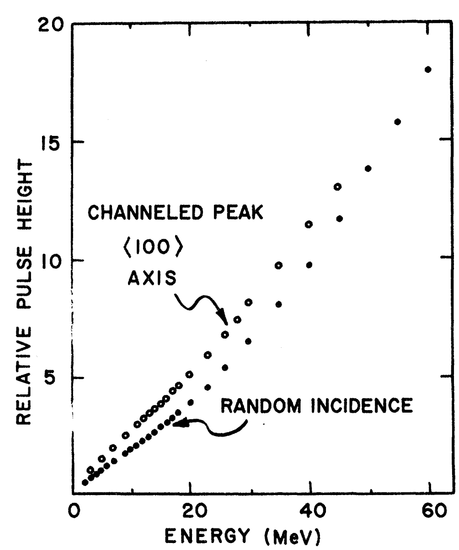

FIG. 10. Pulse height vs energy for the channeled peak for ^{16}O on NaI(Tl) along a $\langle 100\rangle$ axis, and for random incidence.

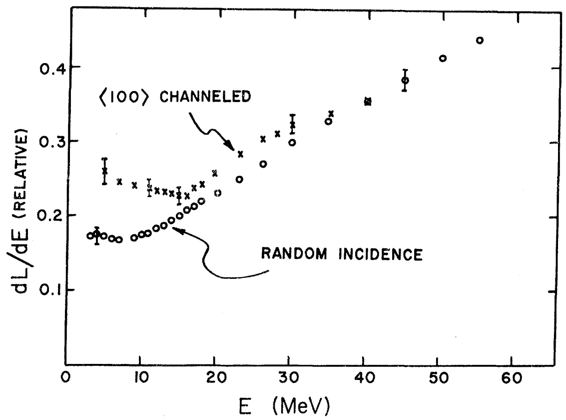

FIG. 11. Scintillation efficiency dL/dE as a function of incident-ion energy for ^{16}O ions on NaI(Tl), for both random incidence and for channeling along a ⟨100⟩ axis.

are substantially different for energies below about 16 MeV and are nearly the same in the region of 35–40 MeV. The ratio of (dL/dE) (channeled) to (dL/dE) (random) is 1.5 at 5 MeV, and decreases to 1.0 at 40 MeV. The ratio of the peak pulse heights L(channeled)/L (random) reaches a maximum value of 1.43 at 11 MeV as shown in Fig. 12.

As indicated in Sec. I, the basic reason that channeled ions exhibit a greater scintillation efficiency than random ions is the fact that channeled ions experience a lower stopping power. LB[2] calculated the ratio L(channeled)/L(random) for various ions in NaI(Tl) and found that for ^{16}O this ratio was 4 at 20 MeV, decreasing monotonically to about 1.3 at 160 MeV. The experimental results shown in Fig. 12 are in qualitative agreement with LB in the sense that L(channeled)/L(random) is found to be greater than 1 at all energies and is a decreasing function of energy at higher energies. The quantitative discrepancy in the magnitude of L(channeled)/L(random) is attributed to two features of the calculation by LB: (a) the assumption that the dependence of dL/dE on dE/dx is the same for channeled particles as for randomly incident particles, and (b) the calculated ratio of (dE/dx) (channeled) to (dE/dx) (random) that was found to be $\frac{1}{4}$ to $\frac{1}{5}$. The assumption in (a) has been examined recently by Luntz and Heymsfield[11] who conclude that it is not valid. The reason given is that a channeled ion and a random ion of the same dE/dx are moving with different velocities; for energies above 20 MeV (the region calculated by LB) the random ion moves with the greater velocity and produces a secondary-electron spectrum whose peak energy is greater than that for the channeled ion. Consequently, the energy deposited by secondary electrons outside the region of very high ionization density is smaller for the slower moving channeled ion, resulting in a scintillation efficiency smaller than that originally calculated by LB. In addition, the original calculation of $[(dE/dx)$ (channeled)]/ $[(dE/dx)$ (random)] in (b) above gave a ratio that is apparently too small. A recent model calculation[11] shows that the data of Fig. 11 can be reasonably accounted for by a ratio of about $\frac{1}{2}$ as compared to the ratio of $\frac{1}{4}$ to $\frac{1}{5}$ from LB. The original calculation of $[(dE/dx)$ (channeled)]/$[dE/dx)$ random)] was thus apparently too small, and this resulted in an overestimate of L(channeled)/L(random). Thus both of the factors (a) and (b) contributed to an overestimate of L(channeled)/L(random) in LB. These matters are discussed in more detail elsewhere.[11] We conclude that the scintillation efficiency data are understood qualitatively, and there is semiquantitative agreement between Fig. 11 and recent calculations.[11] A more critical comparison of the experimental results with theory must await a measurement of dE/dx for random and channeled ^{16}O in NaI(Tl).

Scintillation efficiency dL/dE is frequently plotted as a function of stopping power, as the general trend for high-velocity ions is that of decreasing dL/dE with increasing dE/dx. The fact that dL/dE does not depend only on dE/dx is well known from experiment[12,13]; this effect has been discussed by Meyer and Murray[14] and Luntz[15] in terms of the energy deposition by secondary electrons. Figure 13 shows a plot of dL/dE vs dE/dx for ^{16}O incident on NaI(Tl) in a random direction, spanning the energy range 3–60 MeV. Figure 13 is taken from the data of Fig. 11, combined with a calculation of dE/dx as a function of energy for ^{16}O in NaI.[16] The calculated dE/dx reaches a maximum at about 20 MeV, so that for a particular value of dE/dx there is both a low-energy and a high-energy point. Figure 13 shows clearly that for a given dE/dx the scintillation efficiency is much

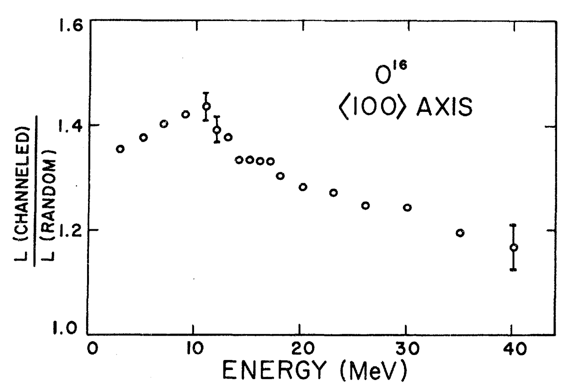

FIG. 12. Ratio of peak pulse heights L(channeled)/ L(random) vs incident-ion energy for channeled ions along ⟨100⟩ axis for ^{16}O on NaI(Tl). Data taken from Fig. 10.

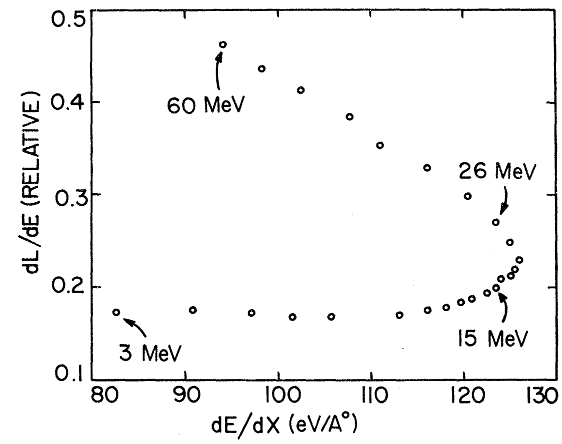

FIG. 13. Scintillation efficiency dL/dE vs stopping power dE/dx for random incidence, ^{16}O in NaI(Tl).

larger for the higher-energy particle. For the lower-energy particle the secondary electrons cannot escape from the immediate vicinity of the particle's track, a region characterized by large damage effects (which may be transient) and hence a low scintillation efficiency. This effect is most pronounced for heavy ions for which dE/dx is large. A plot of dL/dE vs dE/dx for light ions shows that the lower branch almost retraces the upper branch; e.g., for ^4He on CsI(Tl), [10] the lower branch differs from the upper branch by 10% at most.

C. Critical Angle

Incident particles are steered in channeling trajectories only if their path is oriented along a symmetry direction within a certain critical angle (or "acceptance" angle). We have measured the critical angle for ^{16}O incident along {100} planes at an incident ion energy of 15 MeV.

To measure the critical angle ψ_c, pulse-height spectra were recorded as the angle between the beam and the {100} plane was varied. Each spectrum was then analyzed by fitting to its left-hand side a Gaussian distribution with the width and peak position of the measured spectrum for a random orientation. The fitting was accomplished by varying the height of the Gaussian distribution until it just matched up with the left edge of the pulse-height distribution. Then the fitted Gaussian distribution was subtracted from the spectrum to which it had been fit. The sum of the remaining distribution gives the number of particles initially channeled for the angle at which the spectrum was measured. Finally, dividing this sum by the sum for the intact spectrum gives the fraction of particles channeled at that particular angle. Figure 14 shows the angular distribution which results from plotting the fraction channeled versus angle to the {100} plane. The half-width at half-maximum is taken as a measure of the critical angle for channeling. For 15-MeV ^{16}O ions channeled along the {100} planes in NaI(Tl) ψ_c is found to be $0.10° \pm 0.02°$. We note in Fig. 14 that the fraction channeled remains above zero even in the wings of the distribution. This feature is frequently observed in measurements of the fraction channeled versus angle by various experimental techniques, and is attributed to particles that are initially random and are then deflected into a channeling trajectory by multiple Coulomb scattering.

The critical angle ψ_c for {100} planar channeling in alkali-halide crystals has been considered by Shipatov[17] based on an interaction potential-energy function of the form

$$V(r) = (Z_1 Z_2 e^2/r)\, e^{-r/a_B} , \qquad (6)$$

where Z_1e is the charge of the incident nucleus, Z_2e is the charge of the lattice nucleus, and a_B is the well-known Bohr screening parameter. Using this interaction he finds for the average potential energy of interaction with a {100} plane in an alkali halide of the NaCl structure

$$\overline{V}(\rho) = (\pi Z_1 e^2/a^2)\,(Z_2' a_B' e^{-\rho/a_B'} + Z_2'' a_B'' e^{-\rho/a_B''}) , \qquad (7)$$

where a is the cation-anion distance, Z_2' and Z_2'' are the atomic numbers of the cation and anion, respectively, and ρ is the distance from the atomic plane. Shipatov takes the limiting channeling angle ψ_c from Erginsoy[18] to be

$$\psi_c = [\overline{V}(\rho_{\min})/E]^{1/2} , \qquad (8)$$

where E is the energy of the incident particle and $\overline{V}(\rho_{\min})$ is the average potential energy at the particle's distance of closest approach to the plane for stable channeling.

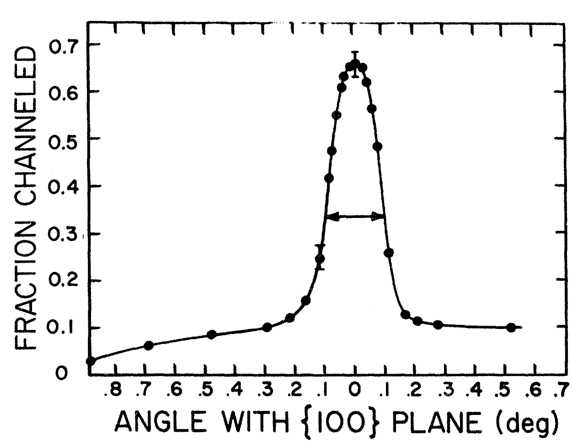

FIG. 14. Fraction of particles initially channeled as a function of angle from a {100} plane, ^{16}O on NaI(Tl) at 15 MeV.

A calculation of $\bar{V}(\rho_{min})$, taking $\rho_{min} = a'_B$, gives $\bar{V}(\rho_{min}) = 81$ eV, and Eq. (8) predicts that ψ_c for a 15-MeV ^{16}O ion is 0.13°. This calculation is based on the assumption of a rigid lattice. Shipatov derives a correction for the temperature dependence which reduces the above critical angle to a value of 0.11° at room temperature. This may be compared with the experimental value of 0.10° ± 0.02°. There is thus a reasonable quantitative agreement between experiment and Shipatov's analysis for the {100} plane.

D. Experiments on KI(Tl)

Several experiments were performed with KI(Tl) in order to confirm the various channeling effects in another alkali-halide crystal. Channeling of ^{16}O ions along {100} planes of KI(Tl) was observed in the range 4–18 MeV. Results were very similar to those shown in Fig. 2 although the resolution was not as good due to the lower scintillation efficiency of KI(Tl) compared to NaI(Tl). The ratio L(channeled)/L(random) was found to be 1.45 at 10 MeV, decreasing at both higher and lower energies in a manner very similar to that shown in Fig. 12 for NaI(Tl). We also observed channeling of 5-MeV ^4He along the {100} planes of KI(Tl) with results very similar to those in NaI(Tl). More detailed studies in KI(Tl) were not undertaken.

IV. SUMMARY

The experiments reported in this paper show that there is a distinct increase in the scintillation efficiency of NaI(Tl) and KI(Tl) to positive ions when the incident beam is aligned along a low-index plane or axis. This effect is associated with the lower stopping power experienced by channeled ions. The magnitude and energy dependence of the effect are in semiquantitative agreement with recent model calculations. Observation of scintillation pulse-height spectra provides a new tool for the study of channeling phenomena in alkali-halide crystals which may be arbitrarily thick. Application of this technique to a measurement of the critical angle along a {100} plane gives a result in good accord with theory. These experiments also provide some new insights into the energy-transfer process betwen the incident ion and the luminescent activator centers: Energy deposition by secondary electrons in a region far from the primary track is of major importance.

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