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Experimental evidence for a discrete transition to channeling for 1.0-MeV protons in Si⟨100⟩

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The present work reports the experimental evidence of anomalies exhibited by the energy loss and energy straggling of channeled protons in silicon in transmission measurements versus the incident angle. Results are presented for 1.0-MeV protons channeled along the ⟨100⟩ axis for a silicon foil of 3.8 μm thickness. It is shown that the transition from random to a channeling condition is discrete. The energy spectra of transmitted ions show a random peak (lower energy) and a channeled peak (higher energy). The random peak has a fixed energy, while the energy of the channeled peak increases as the target crystal's axis approaches alignment with the direction of the incident ion beam. The results support a model suggesting that the channeled ions lose energy only to valence electrons and are concentrated in a narrow cone about the direction of incidence when they emerge from the crystal. The energy straggling of channeled particles reaches a minimum in the hyperchanneled condition. Both the energy loss and the energy straggling of channeled protons show a dependence on the local electron density. [S1050-2947(98)03304-6]

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Ion channeling occurs when the direction of a well-collimated ion beam is aligned with an axis or plane of low Miller index in a crystal. To fully understand the stopping process for channeled ions, it is necessary to know both the reduction of the total energy loss $(dE/dx)_t$ and the shape of the energy spectrum of the channeled ions.

For MeV energy protons, the nuclear stopping power is very small. The energy loss is basically determined by the electronic stopping power, which is defined as $S_e = (dE/dx)_e/NZ_2$ in an amorphous medium, where N is the atom number density and Z_2 is the target atomic number. Electronic stopping power is greatly reduced in the channeling orientation compared to an unaligned, or random, orientation [1–7]. Using the local electron density (LED), Lindhard developed a formula for the stopping power under channeling conditions as a function of the incident angle based on the equipartition rule and the atom-string model [1]:

$$S_e(\theta)=S_e^{ran}[1-\alpha\ \exp(-2\theta^2/\psi_1^2)]. \tag{1}$$

Here $S_e(\theta)$ is the electronic stopping power in the channeling condition, $\alpha=1-S_e(\theta)/S^{ran}$, θ is the angle measured from the incident ion direction to the channel axis, $\psi_1 = (2Z_1Z_2e^2/E_1d)^{1/2}$ is the characteristic angle, and S^{ran} is the electronic stopping power in an unaligned direction [1]. If the equipartition rule holds, $\alpha=0.5$. Equation (1) indicates that $S_e(\theta)$ is a continuous function of incident angle. Jin and Gibson [2] measured the energy loss as a function of incident angle θ for 2-MeV He$^+$ in ⟨100⟩ silicon in 1986. Their results agree well with Eq. (1) using experimentally determined values for α and ψ_1. Appleton, Erginsoy, and Gibson [3] showed overlapping energy peaks for random and channeled ions, which implies that the channeled particles interact only with valence electrons in silicon. However, the transition from random movement to channeling as the ion direction turns to the crystal axis should not be a smooth function of incidence angle due to the difference in the dissipation of the transverse momentum.

To fully understand the stopping process, it is necessary to know the shape of the energy spectrum of transmitted particles. As a statistical process, the multiple collisions that ions undergo generally broaden the width of the transmitted energy distribution. Energy straggling for amorphous targets is basically determined by the fluctuations in the energy-loss processes and has been studied in the past by many groups (see, for instance, Refs. [1,8–11]). Unlike energy loss, energy straggling under channeling conditions has not been studied very thoroughly. Many published channeling spectra have peaks with either long low-energy tails or widths comparable to that of the random peak [3–6]. However, Eisen *et al.* reported [5] that at a fixed incident energy, the energy difference between the channeled peak's leading edge and the peak maximum is independent of the target thickness. The same phenomenon was observed by Della Mea *et al.* [6]. Therefore, they claim that the hyperchanneled ions suffer only minimal energy straggling. However, it should be noted that the low-energy tail also measured by Eisen *et al.* [5] appears to be inconsistent with their claim. The experimental data in the present paper help resolve this paradox.

In order to separate the channeled and random peaks in the energy spectrum of transmitted particles, the target foil has to be fairly thick. However, it cannot be so thick that

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dechanneling effects drastically increase the energy width of the channeled peak. This work reports the experimental results of the transmitted energy loss and straggling measurements for 1.0-MeV protons penetrating a (3.8 ± 0.4)-μm silicon foil along its ⟨100⟩ direction. The silicon foil was prepared by growing a boron-doped Si film on a Si substrate using molecular-beam epitaxy and then etching away the Si substrate [12]. The measurements were performed on a beam line of the 3-MV tandem accelerator in the Ion Beam Modification and Analysis Laboratory at the University of North Texas. Two collimators, 6.15 m apart, were located prior to the target on the beam line. The first one had an aperture of $1.0\times1.0\ \mathrm{mm}^2$ and the second 0.5 mm horizontal ×1.0 mm vertical. A final 0.2-mm vertical slit was located 1.04 m after the target to define the transmitted ion beam to be detected. The silicon surface barrier detector (SSBD) used to detect the transmitted ions in this work had an active area of $50\ \mathrm{mm}^2$. The detailed experimental setup has been discussed elsewhere [7].

Figure 1 shows a chronicle series of the transmitted energy spectrum versus the incident angle θ measured between the incident ion direction and the channeling direction for 1.0-MeV protons. The energy distribution of the incident ions detected directly in the SSBD is shown in Fig. 1(a). When the ion-beam direction is away from the channel axis, as in Fig. 1(b), the spectrum of randomly scattered ions (transmitted off channel) shows a Gaussian peak. Starting at angles of about $\theta\cong0.49°$, the spectrum begins to split into two peaks with the higher-energy peak growing larger as the ion beam gets closer to the hyperchanneling condition. Here one should notice that $\psi_1=0.49°$ is the theoretical characteristic angle. At the angle $\theta\cong0.27°$, the channeled peak is clearly evident in Fig. 1(c). The lower-energy peak is the random peak and the higher-energy peak is the channeled peak. At $\theta\cong0.23°$, the random peak and the channeled peak have about the same height [Fig. 1(d)]. The fitted widths of the two peaks in Fig. 1(d) are larger than the corresponding widths in Figs. 1(b) and 1(f), where the random and channeled peaks are dominant, respectively. This is because there are a number of ions switching from random to channeled motion and visa versa, e.g., accidental channeling of random particles and dechanneling of channeled particles. The channeled peak becomes dominant as the beam is aligned with the ⟨100⟩ direction, where the exiting ion energy spectrum exhibits the narrowest width and the highest energy [Fig. 1(f)]. When the sample is rotated away from the channel in the other direction, the random peak becomes larger again. The random peak does not change in energy as much as the channeled peak when the crystal is rotated toward the channel; only the number of random ions decreases. This indicates that the random energy loss is a statistical process involving multiple interactions. The channeled peak, on the other hand, starts at a higher energy relative to the random peak and then gradually grows larger and increases in energy as the crystal is rotated closer to the perfect channeling condition. This clearly suggests the LED dependence of the channeled energy loss process as originally proposed by Lindhard [1], which attributes the energy loss to the electron density "sampled" by the ion along its trajectory. It should also be pointed out that the two-peak phenomenon was observed by Appleton, Erginsoy, and Gibson [3] in their experiment of transmission measurements versus the emergent angle, although the detailed energy information was not given in their paper.

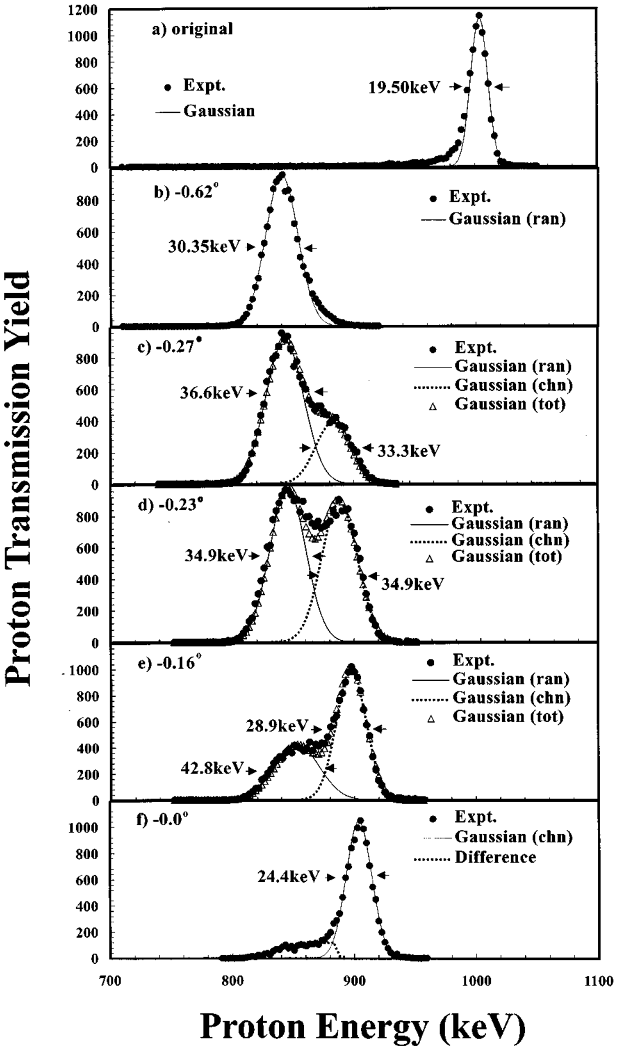

FIG. 1. A chronicle series of the transmitted energy spectrum of 1.0-MeV protons near the ⟨100⟩ axis of a crystalline silicon foil versus the incident angle θ for a few representative angles. The foil had a thickness of 3.8 μm [7]. The curve fitting was done using the program SKEWGAUSS [13] with the fitting uncertainty of the dominant peaks below 3%. (a) shows the energy distribution of incident particles detected directly in the SSBD. (b)–(f) show the gradual change of the random and the channeled peaks with incident angle. The widths of the random and the channeled peaks were determined by treating them as Gaussian peaks.

Figure 2 shows the experimentally determined $(dE/dx)_e$ of random and channeled components of the transmitted proton beam as a function of incident angle and the predictions of the Lindhard-Scharff-Schiott (LSS) theory [1]. One may see in Fig. 2 that the random energy loss decreases ~21% due to the accidental channeling of the initially random protons, while the channeled energy loss decreases ~43%. This observation also supports the notion of Appleton, Erginsoy, and Gibson [3] that the channeled ions interact primarily with the valence electrons of the target atoms. It is clear from the present observations that the channeled ions have a distinct stopping power as a function of incident angle θ that is

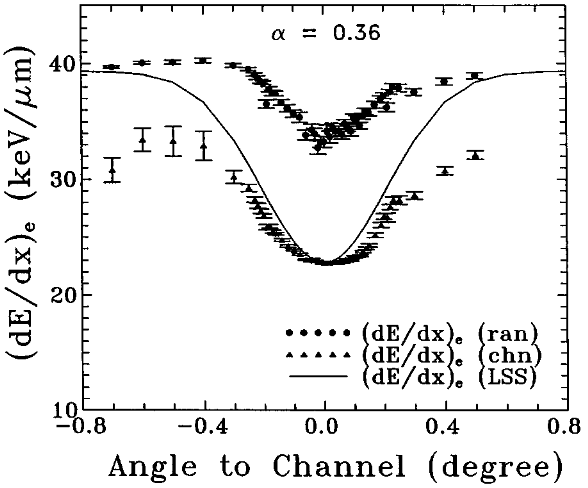

FIG. 2. The $(dE/dx)_e(\theta)$ obtained from the 53 points of experimental data for 1.0-MeV protons in and near ⟨100⟩ axial channel in silicon from $\theta = -0.7°$ to $+0.5°$. For comparison, $(dE/dx)_e$ of LSS [1] theory is also given. Error bars represent uncertainty in the centroid difference given by the SKEWGAUSS program [13]. $(dE/dx)_e$ of the random peak near the ⟨100⟩ channel and $(dE/dx)_e$ of the channeled peak far away from the channel are shown with large error estimates because the respective peaks are small at these angles.

much less than for the random ions.

Based on a theory developed by Bohr [8], Lindhard proposed that the energy straggling in the channeling condition can be written as [1]

$$[d(\Delta E)^2/dR]_e = 4\pi Z_1^2 e^4 \rho(\mathbf{R}), \qquad (2)$$

where Z_1 is the atomic number of the projectile and $\rho(\mathbf{R})$ is the LED. The equation holds for ion velocities $v > v_0 Z_2^{1/2}$, corresponding to protons with energies above 0.5 MeV in silicon ($Z_2 = 14$); $v_0 = e^2/(h/2\pi)$ is the Bohr velocity. If Eq. (2) is accurate, one would expect the energy width of the channeled peak to be smaller than that of the random peak since $\rho(\mathbf{R})$ in the channel is smaller than the average electron density that random ions encounter. It is observed that the energy straggling in the channeling condition is indeed smaller than that for the random case. In the hyperchanneled condition, ions that are injected in the center of the channel will remain in the center and feel only the minimal $\rho(\mathbf{R})$. Those ions that enter the crystal off the channel center will travel in periodic trajectories, where they encounter much stronger $\rho(\mathbf{R})$ at the apexes. As given in Ref. [3], one may define the measured standard deviation as $\Omega = [(\mathrm{FWHM})_T^2 - (\mathrm{FWHM})_O^2]^{1/2}$, where T and O represent transmitted and original, respectively. For the channeled peak, $\Omega_c = 6.2$ keV and for the random peak $\Omega_r = 9.9$ keV. The hyper-channeled spectrum in Fig. 1(f) is fitted very well with a Gaussian function. The fitting uncertainty is 2.8%, or 0.5 keV, for the full width at half maximum (FWHM) of the channeled peak. Figure 3 shows the FWHM of the two peaks versus incident angle θ. As predicted by Eq. (2), the FWHM of the channeled peak shows the dependence on the angular settings of the foil and thus on $\rho(\mathbf{R})$. The FWHM of the random peak increases as the crystal approaches the perfect channeling direction due to the dechanneling of the channeled ions and feed-in of random ions. These observations confirm the claim of Eisen *et al.* [5] and Della Mea *et al.* [6] that the hyperchanneled ions suffer minimal energy straggling.

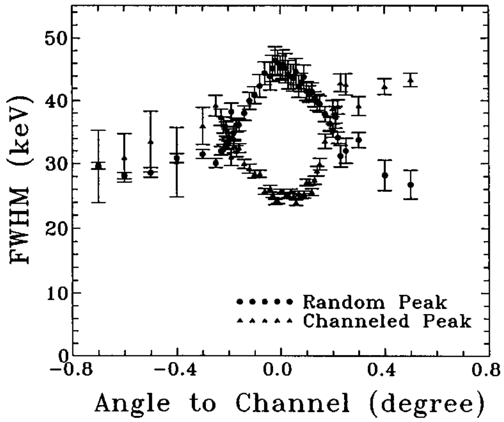

FIG. 3. The FWHM of the channeled and random peaks for 1.0-MeV protons in Si⟨100⟩. The energy peaks were fitted as Gaussian peaks using the SKEWGAUSS program [13]. The fitting uncertainty was kept below 3%, except at $\theta \sim \psi_{1/2}$, where it went up to 15% due to the diminishing channeled peak. The measured crystal half angle in the Si⟨100⟩ crystal was $\psi_{1/2} = 0.35°$.

To obtain the present results, it was extremely important to have a low counting rate in the SSBD. The counting rate was maintained below 100 Hz. If the proton current was not reduced sufficiently, the energy dispersion in the particle detection system would cause the transmitted spectrum to have a long low-energy tail and the peak width would be larger. The detailed information would be obscured and the two peaks would appear as one, leading to a continuous dependence on incident angle. The SSBD used in this work had an energy resolution of 10.0 keV for 1-MeV protons with a leakage current of 0.03 μA.

In addition to the low count rate, there are two more essential experimental details. One is the direct measurement of the transmitted ion-beam energy, which is believed to better reveal information from the channeled and random peaks than the measurement of the scattered ions from a foil after the target. Second, the channeled ions are concentrated in a narrow cone of emergent angle, while the random ions are more widely spread in the emergent angle due to the multiple scattering. In the hyperchanneling direction, a 0.2-mm vertical slit located 1.04 m after the target crystal allowed the well channeled ions to be detected and suppressed the counting rate of the random ions. For larger angles, this experimental arrangement allowed both the channeled and random protons to be detected, thus making it possible to reveal the spectra of two separate peaks. The small channel radius of the ⟨100⟩ axis of silicon, i.e., the small critical angle, also contributes favorably in these experiments. At $\theta = 0.19°$, decreasing the defining slit width from 8 mm to 0.2 mm changes the ratio of channeled to random peaks of 1.5-MeV protons from 0.6 to 1.1. The ratio becomes 1.4 when the slit is changed to a $0.6 \times 0.6\ \mathrm{mm}^2$ aperture. The two-peak phenomenon has also been observed using this aperture.

In summary, the present work has shown that the channeled ions have a distinct stopping power that depends mainly on the LED. As a consequence, a discrete transition from the random direction to channeling is observed as a function of incident angle. It is also observed that the hyperchanneled ions suffer minimal energy straggling due to this LED dependence.

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