Back-scattering Energy Spectra near the Critical Angle for Proton Channeling

By

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Abstract

Back-scattering energy spectra of 1.0 and 1.5 MeV protons from Si single crystals have been studied. At the shoulder of the dip-shoulder pattern of the scattering yield around {110} channeling direction, the energy spectrum shows a conspicuous hump in the high energy part. The simple model is proposed for the origin of this hump.

1. Introduction

Many experiments on channeling have been done by means of back-scattering of energetic ions impinging on single crystals[1~24]. When an incident beam is aligned in the direction of a crystal axis or plane, the yield of back-scattered ions is greatly reduced over the whole range of energy. As the direction of the incident beam departs from the channeling direction, the back-scattering yield increases and the shape of the energy spectrum varies continually. The spectrum near the maximum energy varies markedly, showing a hump at about the critical angle for channeling. This part of spectrum corresponds to the back-scattering from the surface layer of the single crystal target[22,23,25]. For the angle of incidence much larger than the critical angle, the spectrum shape becomes that of random incidence. The back-scattering yield for the incident beam near the critical angle is larger than that of the random incidence. The curve of the back-scattering yield as a function of the angle of incidence shows a shoulder near the critical angle. This pattern is similar to the so-called compensation shoulder in blocking phenomena. Their origins, however, are different[23].

In the present work, the back-scattering spectra of 1.0 and 1.5 MeV protons

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from Si single crystal are investigated experimentally, and the simple model for the shoulder pattern in channeling is considered.

2. Experimental Procedures

Monoenergetic beams of protons from the Van de Graaff accelerator of Kyoto University were collimated by two two-dimension-slits which were two meters apart. The angular spread of the beam at the target is lest than 0.05°. These slits were very useful not only for making the beam alignment easy but also for changing slightly the position of the beam spot on the target keeping a constant direction of incidence. A small piece of silicon single crystal, abot 0.3 mm thick, with specific resistance of 1000 $\Omega\cdot$cm was stuck on a copper plate which was supported by an insulating teflon cylinder. The crystal surface was almost parallel to a {111} plane. In order to change the crystal orientation with respect to the direction of the incident beam, the tilting angle θ and the angle of rotation ϕ of the goniometer were adjusted independently with accuracy of 0.025°. The goniometer was fixed to the upper lid of the scattering chamber, and θ and ϕ could be varied smoothly in the vacuum. The scattering chamber was evacuated to pressure of 8×10^{-7} Torr with a diffusion pump, a liquid nitrogen trap, a getter pump and an ion pump. The beam duct was evacuated to pressure of 2×10^{-6} Torr.

The back-scattering yield was measured by a solid-state detector (SSD) placed about 15 cm apart from the target. The diameter of the window of SSD was 5 mm. The scattering angle was 135°. The energy resolution of the detecting system was approximately 30 keV. The beam current to the crystal target was kept to be about 10 nA. The total incident charge to obtain one spectrum was chosen as $(1.5\sim2.1)\times10^{-5}$C. We used H_2^+ ion beam with energy of 2.0 and 3.0 MeV, because the intensity ratio of H^+ ions to H_2^+ ions were less than 1/3. There is no trouble caused by molecular ions in this experiment[26]. The energy spectra of the scattered protons were analysed with a 256-channel pulse-height-analyzer (PHA). The accurate orientation of the single crystal target with respect to the direction of the incident beam was determined by measuring the variation of the back-scattering yield as a function of the angle of rotation ϕ.

3. Experimental Results

By counting only the high energy parts of the spectra of back-scattered protons, one can obtain clearly the so-called dip-shoulder pattern. Fig. 1 a) and b) show such patterns for 1.0 and 1.5 MeV protons, respectively. These

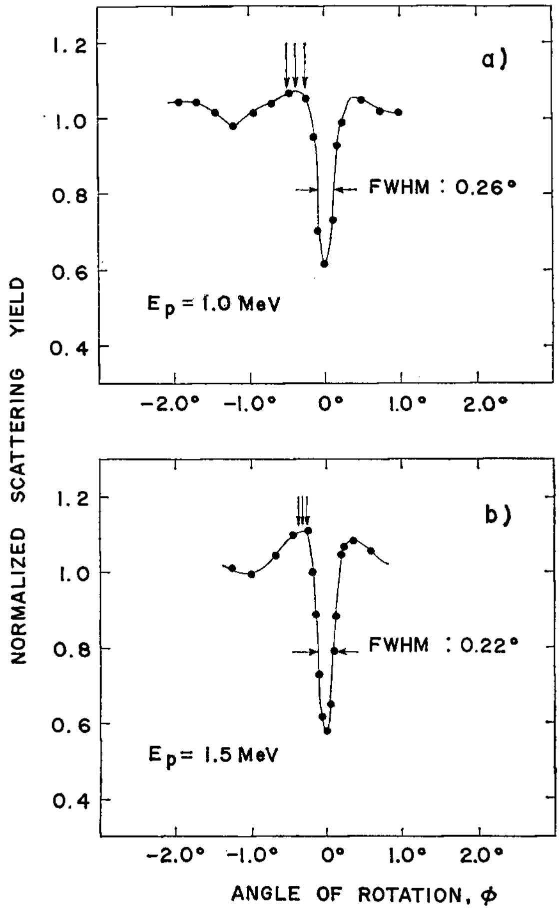

Fig. 1. Dip-shoulder pattern for back-scattering yield.

curves were obtained with the discrimination-levels of energy of 0.6 and 1.0 MeV, respectively.

For the tilting angle θ, the value of the angle of rotation ϕ should be corrected by the following relationship:

$$\phi_{true} = \phi(\theta) \sin \theta.$$

In the present experiment, the tilting angle θ was fixed to be 15°. The FWHM values of the dips are 0.26° and 0.22° for 1.0 and 1.5 MeV protons, respectively. These values are considered to be twice the experimental critical angles for Si {110} planar channeling of protons.

At three angles of rotation shown with arrows in these figures, energy spectra of back-scattered protons were measured and shown in Fig. 2. The energy spectra for random incidence were obtained by making uniform rota-

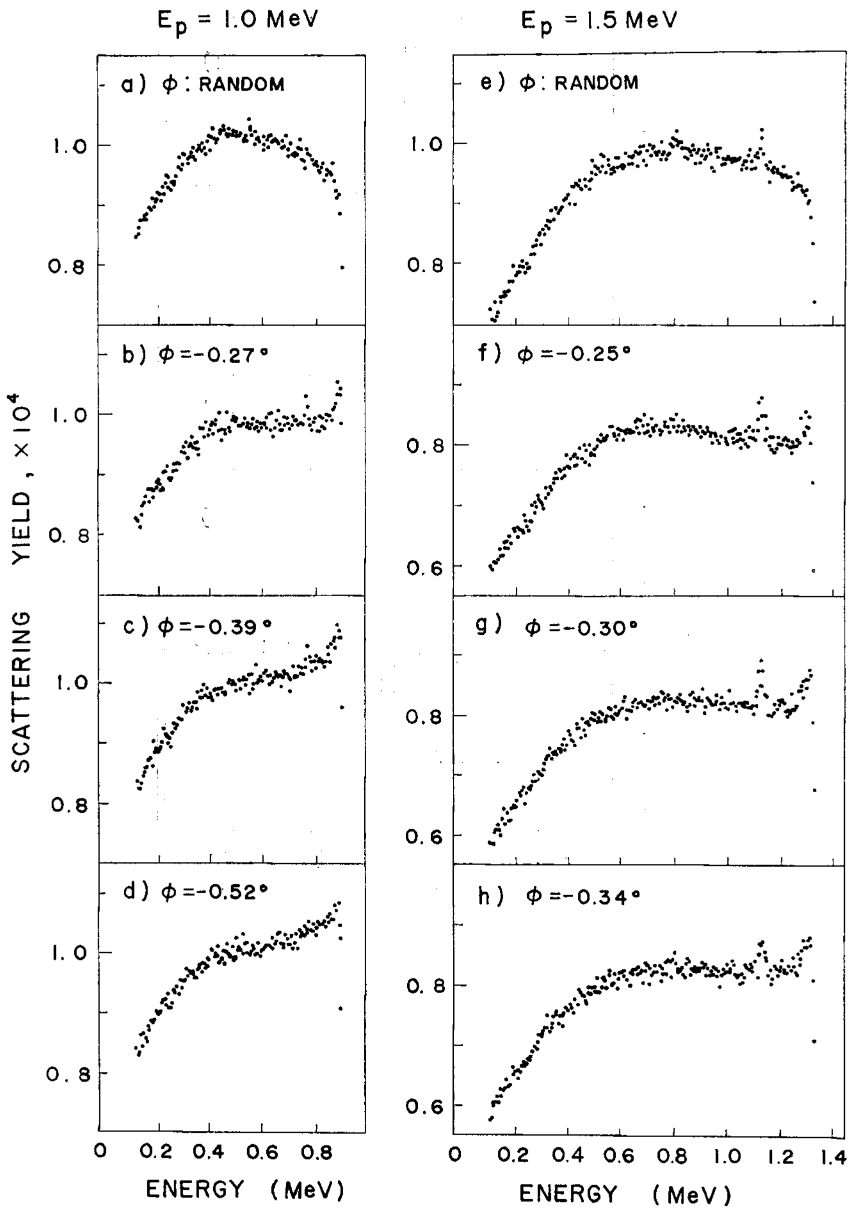

Fig. 2. Back-scattering energy spectra (raw data).

tion of the target at the fixed tilting angle θ. It should be noted that such rotation-averaging is significant and useful only for the planar channeling experiment, but not for an axial channeling one. In comparison with the spectra for random incidence, the energy spectra at the shoulder part have

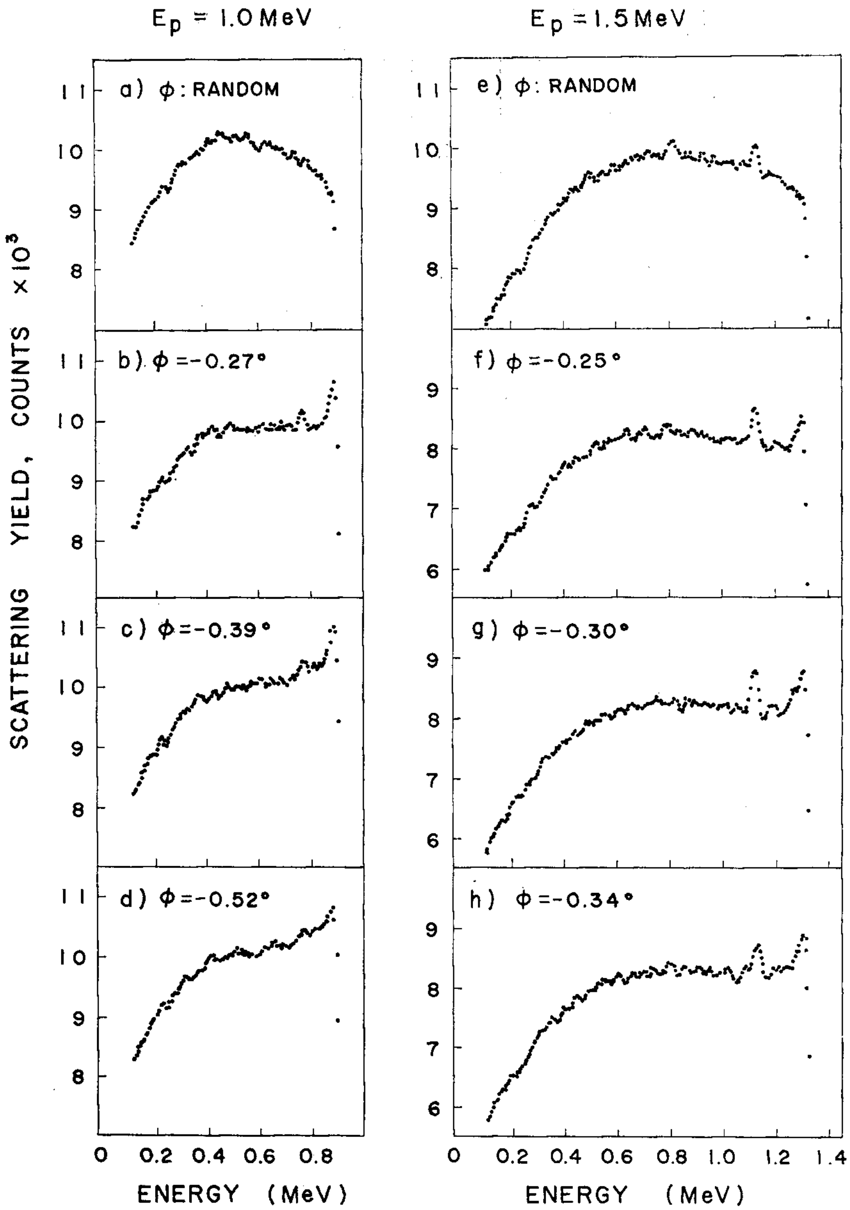

Fig. 3. Back-scattering energy spectra after the smoothing procedure.

conspicuous humps in the high energy part. In addition to the hump, there seem to occur systematic fluctuations in these spectra. To confirm these fluctuations, it is necessary to keep statistical errors as small as possible. For this purpose there are several methods such as "moving average" and

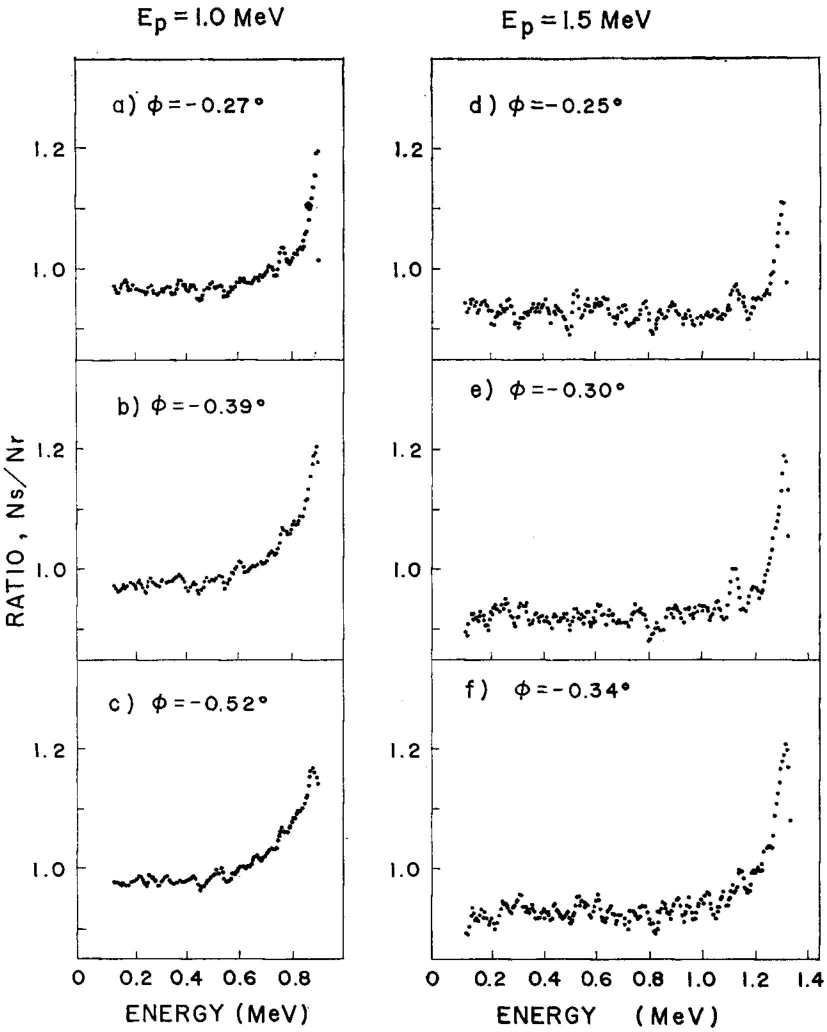

Fig. 4. Back-scattering energy spectra normalized by that of random direction.

"Fourier transformation"[27]. In this paper, we used "Simplified Least Squares Method" by Savitzky *et al.*[28] The convoluting integer N was chosen to be 9 on the channel numbers of 256-channel PHA in accordance with the energy resolution. In Fig. 3 is shown the result after such smoothing procedure. There remain many small peaks in low energy region. From these data only, however, it cannot be answered whether they are due to the target structure or systematic noises of the detecting system. In order to make more clear the high energy hump, the ratios of the yields at the shoulder region to that of random direction are shown in Fig. 4.

4. Discussion

It is well known that, in blocking phenomena, the dip-shoulder pattern results from the conservation of total emission probability. That is, the shoulder in the angular pattern follows as a result of the compensation effect. On the assumption of the reversibility of the particle motion, Lindhard has pointed out that both channeling and blocking show the same angular patterns[29]. The dip-shoulder pattern is expected to occur also in channeling experiments. The reversibility rule of channeling and blocking in back-scattering was verified experimentally by Bøgh and Whitton for the 135° scattering of 1 MeV protons from W single crystals[7]. The meaning of compensation effect, however, is not so clear in the case of channeling as in blocking.

Figs. 2 and 3 together with Fig. 1 give the clue to interpret the shoulder in the angular pattern in channeling experiment. The high-energy humps in the spectra of back-scattered protons arose from those particles which were

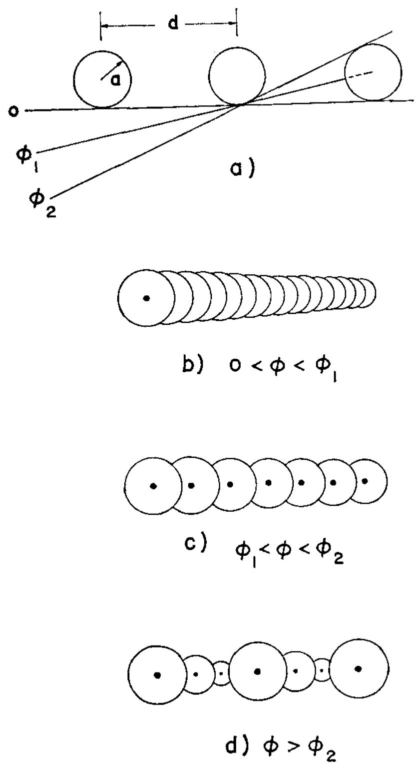

Fig. 5. Model for the high-energy humps in the back-scattering spectrum.

scattered from the very shallow surface layer of the target crystal. Corresponding depth of the surface layer in case of 1.0 MeV protons, for example, is less than 500 Å. This means that these particles have not experienced a full sinusoidal motion in the channel[30]. Therefore, we can consider simply the following mechanism for the production of the high-energy humps. When the direction of incidence is around the critical angle, some protons collide with crystal atoms with the impact parameter p which corresponds to 135° scattering. Fraction of these protons is estimated as follows: taking into consideration the deflections by the neighboring atoms, Si atoms are assumed to be hard spheres whose radii are a. The cross section for 135° scattering is assumed roughly to be the area of the central spot whose radius is p. This approximation is reasonable as far as the de Broglie wavelength of incident proton is the same order of magnitude with the impact parameter p. For 1.0 MeV proton, the former is about 2.5×10^{-4} Å and the latter is about 1×10^{-4} Å. As being seen immediately from Fig. 5 a), the effective cross section of 135° scattering for incident angle ϕ is

$$\sigma(\phi)=0 \quad \text{for} \quad \phi<\phi_1 \qquad (1)$$
$$=\pi p^2 \quad \text{for} \quad \phi>\phi_1,$$

where $\phi_1=\tan^{-1}(a/d)$ and d is the average distance between neighboring atoms in the crystal. The number $N(\phi)$ of the target atoms which are concerned with scattering from the direct channel wall is given by

$$N(\phi)=D\cot\phi/d, \qquad (2)$$

where D is the distance between neighboring rows of crystal atoms. The number $n(\phi)$ of the target atoms which contribute to 135° scattering from other channels is

$$n(\phi)=0 \quad \text{for} \quad \phi<\phi_2 \qquad (3)$$
$$\neq 0 \quad \text{for} \quad \phi>\phi_2,$$

where $\phi_2=\tan^{-1}(2a/d)$. The total yield of 135° scattering $Y(\phi)$ is given by

$$Y(\phi)\propto\{N(\phi)+n(\phi)\}\sigma(\phi). \qquad (4)$$

From eqs. (1)-(4), we obtain

$$Y(\phi)=0 \quad \text{for} \quad \phi<\phi_1 \qquad (5a)$$

$$Y(\phi)\propto\cot\phi \quad \text{for} \quad \phi_1<\phi<\phi_2 \qquad (5b)$$

$$Y(\phi)\propto K(\phi)\cot\phi \quad \text{for} \quad \phi_2<\phi, \qquad (5c)$$

where $K(\phi)(>1)$ is a monotonically increasing function of ϕ. Fig. 5 b), c) and d) show schematically the configurations of targets corresponding to (5a), (5b) and (5c). In Fig. 6, the experimental dip-shoulder pattern are compared

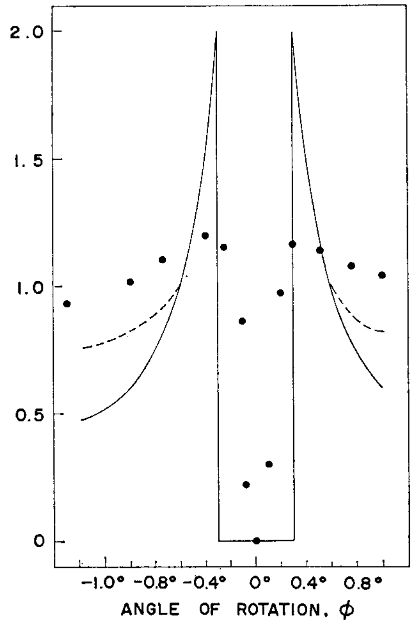

Fig. 6. Simple model for the dip-shoulder pattern.

with $Y(\phi)$ calculated with $a=2.6\times10^{-2}$ Å and $d=5$ Å. It is seen that this simple model reproduces fairly well the general feature of the experimental pattern. Although the above consideration is two-dimensional and rather qualitative, it is expected to become a starting point in analyzing more complicated problems on the back-scattering energy spectra.

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