THE ROLE OF MULTIPLE SCATTERING IN CAPTURE OF PROTONS BY CRYSTAL LATTICE CHANNELS

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The capture of 100–180 keV protons by axial and planar channels has been studied experimentally in single-crystal films of gold oriented at an arbitrary angle with respect to the primary beam direction. It is shown that with increasing proton energy the role of diffusely scattered particles in producing the channeling effect decreases, whereas their role in producing the shadow effect pattern increases.

1. INTRODUCTION

It is well known[1] that channels in a crystal lattice exert a directing influence on protons whose momentum is oriented at an angle to the channel axis less than some limiting angle. The limiting angle θ_0 is determined from the condition of equality of the kinetic energy associated with transverse motion of the proton and the potential energy U of interaction between the proton and lattice ions:

$$\theta_0^2 E = U(\tfrac{1}{2}b - y_0); \tag{1}$$

E is the proton kinetic energy, and U depends on the maximum displacement y_0 of the proton from the channel axis (b is the channel width). It is easy to show that the following estimate of θ_0 follows from Eq. (1):

$$\theta_0 \approx (Z_1 Z_2 a_0 E_R / Ed)^{1/2}, \tag{2}$$

where Z_1 and Z_2 are the respective charges of the channeled particle and lattice ions, a_0 is the Bohr radius, E_R is the Rydberg energy, and d is the interatomic distance in the direction of the channel axis.

In agreement with this estimate of θ_0, the results of a large number of experiments on channeling of protons of energy $\sim 10^2$ keV indicate that $\theta_0 \approx 1$–$3°$.

The elementary considerations and estimates presented above mean that a parallel beam of protons forming an angle $\theta < \theta_0$ with the channel axis must be practically completely pulled into the channels; protons incident at an angle $\theta \gtrsim \theta_0$ will be pulled into channels only partially, and in the case where $\theta > \theta_0 + \Delta\theta$ the lattice will diffusely scatter the protons and the channeling effect should disappear. According to an estimate by Lindhard,[2] $\Delta\theta \approx \theta_0$, i.e., no channeling should be observed for $\theta > 2\theta_0$.

The estimates presented have been made with neglect of the very real effect of multiple scattering. As the result of multiple scattering a proton (or multiply charged ion) whose momentum initially formed a large angle with the direction of the channel axis, as the result of a sequence of scattering events in the crystal volume, can satisfy the channel conditions and be drawn into the closest channel—axial or planar.

In the present article we report the results of experiments in which we have observed the possibility in principle of channeling under conditions in which the beam incident on the surface of a crystal from the outside is oriented with respect to the symmetry elements of the crystal in such a way that the conditions for direct channeling are clearly not satisfied, i.e., at an angle $\theta > 2\theta_0$.

2. EXPERIMENTAL CONDITIONS

The experiments were carried out in single-crystal films of gold of thickness $\sim(5$–$6) \times 10^{-5}$ cm obtained by epitaxial growth of gold from a molecular beam onto the {100} surface of a single crystal of NaCl which was specially treated beforehand. With the technique used, films were formed whose surface coincided with the {100} plane.[3]

The films were fastened to a holder which was firmly mounted on a goniometer head. By means of the head a definite orientation could be given the film with respect to the direction of the collimated proton beam. The technique used to fasten the film guaranteed its mirror smoothness, a fact of great importance, since misorientation of a film with respect to the beam by crimping would place some portions of it in a position corresponding to channeling. Orientation of the film in our experiments was specified by the angle ψ between the normal to the plane of the film and the primary proton beam direction, and the angle φ of rotation of the film about the normal, measured from the ⟨001⟩ direction lying in the plane of the film (see ref. 3).

The proton source was the proton-electron injector of the Physico-technical Institute of Low Temperatures, Academy of Sciences, Ukrainian SSR.[4] The protons could be accelerated to 180 keV, the diameter of the collimated beam was 1 mm, and the current was 5×10^{-10}–5×10^{-9} A. Since it was necessary to obtain information not only on the integrated intensity of the transmitted proton beam but also on its distribution in space, the transmitted beam was detected by means of nuclear photoemulsions. In order to guarantee absolutely identical processing of the plates used in a given series of measurements, all plates were mounted in a common cassette and subjected to simultaneous processing. The local intensity of the transmitted beam was determined by photometry of the corresponding portions of the plates; quantitative estimates of the intensity were made by means of previously plotted calibration curves, showing the blackening as a function of incident beam intensity, determined by independent direct measurements.

3. EXPERIMENTAL RESULTS

Figure 1 shows a sequence of proton beam photographs which present the experimental results, in which we observed capture into channels of protons from a beam oriented with respect to the film in such a way that the conditions for normal channeling were not satisfied. (In order to make the series of photographs more readily interpretable, we have included in them only those photographs which correspond to film orientations at $\varphi = 45°$.) It is quite apparent from the photographs that under conditions of axial and plane channeling, an appreciable part of the diffusely scattered protons fall into the channels.

A quantitative analysis of these photographs can be made in order to estimate the relative fraction of protons from the primary beam which left the ⟨100⟩ channel on mis-orientation of the film, and the fraction of protons channeled in all possible channels, both axial and planar. As has already been mentioned, the number of protons leaving the film not in arbitrary directions but in certain selected and definable orientations of the channels—axial and planar—was estimated by us from the results of photometry. The corresponding dimensionless ratios $\eta_\Sigma = q_\Sigma/q_0$ and $\eta_{\langle 100\rangle} = q_{\langle 100\rangle}/q_0$ are shown in Fig. 2 as a function of the angle between the primary beam direction and the normal to the plane of the film; here q_0 is the charge of all protons incident on the surface of the film, q_Σ is the charge of protons leaving all axial and planar channels which appear, and $q_{\langle 100\rangle}$ is the charge of protons leaving the ⟨100⟩ channel. From the curves of Fig. 2a it follows that for a clearly unfavorable orientation of the film ~1% of the protons turn out to be captured into channels. We note that in plotting the curves of Fig. 2 we did not take into account the change in the proton path length in the material of the film as the result of the change in its orientation relative to the primary beam. The experiments carried out are inadequate for making the proper corrections.

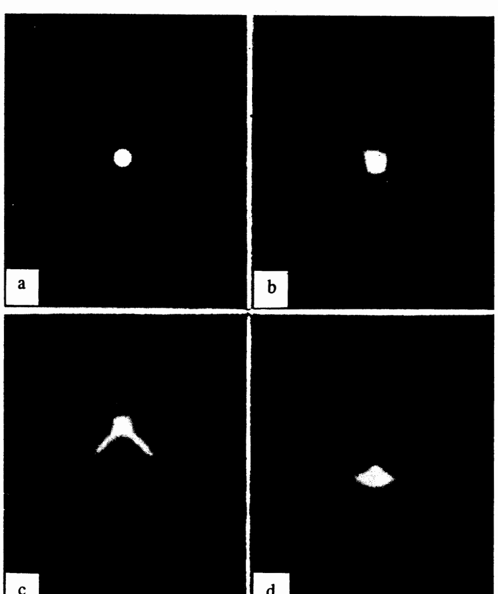

FIG. 1. Series of proton beam photographs (E = 100 keV, $\varphi = 45°$): a–$\psi = 0°$, b–$\psi = 3°$, c–$\psi = 13°$, d–$\psi = 30°$. The track from the primary proton beam is located at the same level.

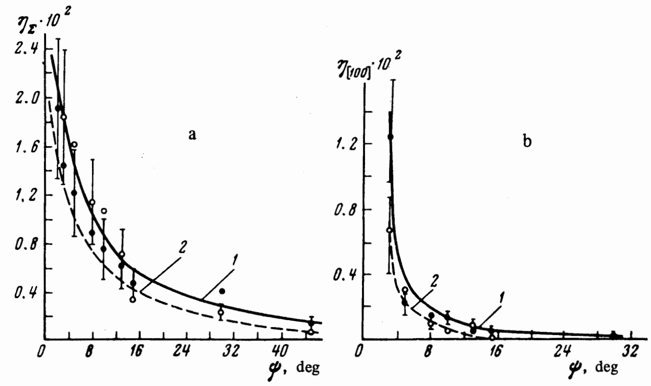

FIG. 2. Curves of η_Σ (a) and $\eta_{\langle 100\rangle}$ (b) as a function of ψ for $\varphi = 45°$: 1–E = 100 keV, 2–E = 140 keV.

The change of energy of the protons in the primary beam (for a constant film thickness) shows up distinctly in the nature of the photographs, which were taken by transillumination. It turns out that with increase of the proton energy a change occurs in the location of the streaks of the shadow effect pattern and the streaks corresponding to the channeling effect. Thus, some channels which previously captured protons from the diffuse beam, with increasing energy of the primary beam particles, no longer appear in the proton beam photograph; in their place shadow streaks corresponding to the same orientation arise. This change in the proton beam photographs is accompanied by an accentuation of the pattern of channels located near the primary beam direction.

The features described of the change in the proton beam photographs with increasing energy of the primary beam can be followed distinctly in the photographs of Fig. 3. Qualitatively speaking, the nature of the observed changes in the photographs evidently has the following meaning. With increase of the proton energy, the probability of their capture into channels, other conditions being constant, is reduced for a given film thickness; a substantial fraction of them will pass through the film without falling into channels and consequently will take part in forming the shadow pattern. Obviously, the probability of capture into channels is greater, the smaller the deviation of the channel direction from the primary beam direction. For just this reason the streaks in the photographs corresponding to the channeling effect are transformed into shadow effect streaks sooner if a given channel (or plane) deviates further from the beam direction. This fact, that with increase of the primary proton energy, additional details appear of the pattern of channels located near the beam direction, is due to the fact that the specific energy loss in these channels is high (less open channels appear). With further increase in primary proton beam energy, obviously, the pattern of channels located near the primary beam direction would also be replaced by the shadow effect pattern.[5]

We note that capture of protons into axial and planar channels, for mis-orientation angles between the primary beam direction and the corresponding symmetry ele-

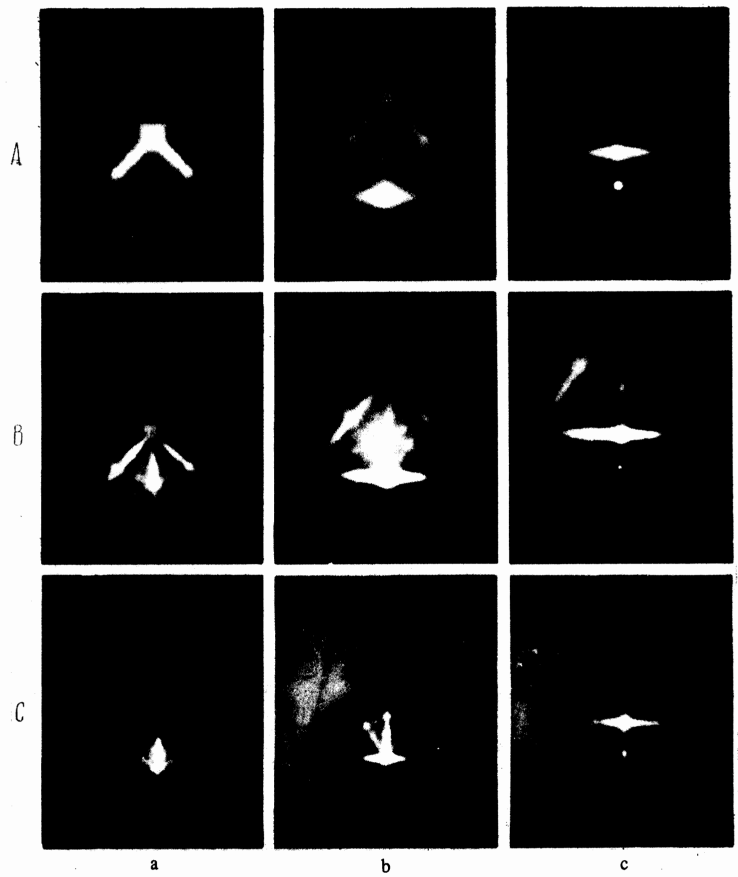

FIG. 3. Sequence of proton beam photographs obtained for $\varphi = 45°$: A–E = 100 keV, B–E = 140 keV, C–E = 180 keV; a–ψ = 15°, b–φ = 30°, c–φ = 45°.

ments of the axial and planar channels $\theta > \theta_0$, has been observed by Appleton et al.[6], who carried out experiments with protons of energy E = 3–10 MeV (germanium and silicon films of thickness 25–50 μ), and therefore incidence of protons under the condition of channeling was observed for θ differing from θ_0 by no more than $\sim 0.5°$.

A correct description of the observed effect can be accomplished only on the basis of the theory of motion of a beam of diffusely scattered protons interacting with the periodic field of the lattice. The set of observations described by us should be taken into account in constructing such a theory.

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