Experimental observation of volume capture by a curved single crystal in the channeling regime

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It is shown for the first time that a curved single crystal can capture particles in the channeling regime for angles exceeding the Lindhard angle. 1-GeV protons were captured during channeling by (111) and (110) planes and by ⟨110⟩ axis along the entire length of a 1-cm silicon single crystal curved along a radius of 46 cm in the entire angular range up to 20 mrad.

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It was recently shown experimentally[1,2] that deformed single crystals can be used to control the trajectories of channeled high-energy protons.

O.I. Sumbaev hypothesized, in analogy with the so-called effect of elastic quasi-mosaicity for x-ray radiation diffracted in a curved single crystal,[3] that the angle for capturing particles in the channeling regime can be greatly increased in curved crystals. The essence of this effect, called volume capture, lies in the fact that the capture conditions in the channeling regime arise in the bulk of the crystal in a region where the particle trajectory coincides with the tangent to the curved crystallographic plane.

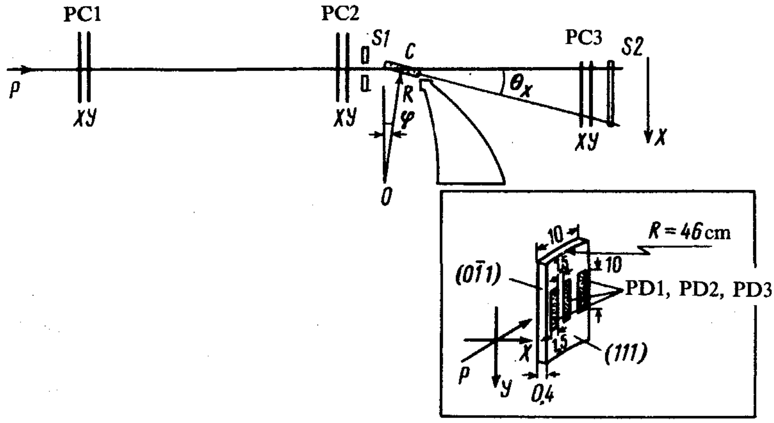

FIG. 1. Schematic diagram of the experimental arrangement. P-Protron beam; S1 and S2-scintillation counters; PC1, PC2, PC3—proportional chambers; *C* silicon single crystal with detectors PD1, PD2, and PD3. Crystal can rotate around the axis 0, which coincides with the axis of the cylinder along which it is bent.

Thus capture is possible for particles in a beam incident within the entire angle between the tangents to the curved planes within the boundaries of the crystal. After capture the particles move along the curved planes and can form a deflected beam with a narrow angular distribution. The possibility of such capture is not obvious, but the apparent violation of the second law (decrease in entropy) is removed by the dissipative nature of the system.

The purpose of the present experiment was to check this hypothesis. The experiment was performed on the synchrocyclotron at the Leningrad Institute of Nuclear Physics. The beam of 1-GeV protons had a specially formed large angular divergence $\sigma_x = 1$ mrad and $\sigma_y = 0.4$ mrad.[1)] The arrangement of the experiment is shown in Fig. 1. The proportional chambers PC1, PC2, and PC3 (the pitch of the filaments is 1 mm along the *X* and *Y* axes) determine the trajectory of the particles before they reach the curved crystal *C* and after exiting the crystal. The scintillation counters *S* 1 and *S* 2 and the chambers PC1 and PC2 separated the protons that entered the crystal. The counter *S* 1, which had a 0.4×10 mm slit, operates in the anticoincidence regime. The distance between the chambers PC1 and PC2 is 5.4 m and the distance between the chambers PC2 and PC3 is 2.4 m.

Three detecting structures (PD1, PD2, and PD3) are placed on the curved single crystal made of semiconducting silicon. This permits following the motion of particles in the crystal at all stages: capture, channeling, and dechanneling. The technique and technology for making such detectors is described in Ref. 4. The energy resolution of each detection zone is no worse than 30–35 keV at 300 K. The investigations were performed with an intensity of $\approx 10^3$ particles per second. The thickness of the plate was 0.4 mm, the length along the beam was 10 mm, the height of the sensitive zones was 10 mm, the width along the beam was 1.5 mm, and the distance between them was 1.5 mm. The crystal rotated relative to the straight beam along the angle φ (see Fig. 1) with an accuracy up to 0.01 mrad and moved across the beam with an accuracy of 10

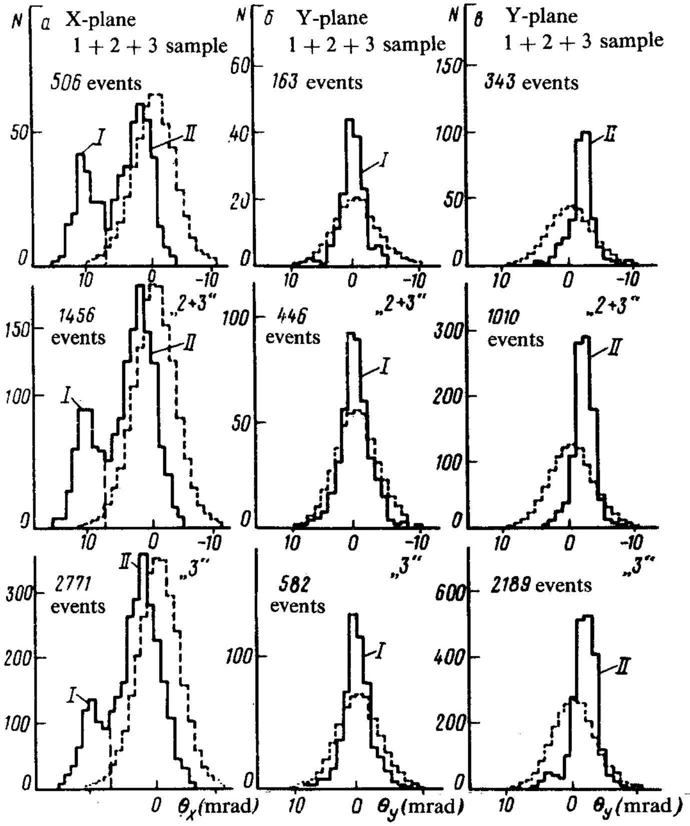

FIG. 2. Angular distribution of particles which pass through the crystal and which are selected according to the criterion of small amplitude: 1 + 2 + 3 in all three detectors, 2 + 3 in the second and third detectors, and 3 in the third detector PD3. The crystal is rotated at an angle $\varphi = 8$ mrad. The dashed line shows the straight beam normalized to one-half the number of channeled particle events.

μm. The setup operated on line with a PDP 11/40 and ES-1030 computers.

Particles which had anomalously small specific ionization losses in detectors were considered as being channeled. An additional criterion for channeling of particles with small specific losses was the rotation of the beam after it exited the crystal and narrowing of its angular width due to the decrease in multiple scattering.

Figure 2 shows the angular distributions of particles that leave the crystal after including in the sample the particles that have amplitudes of less than 0.74 of the most probable amplitude for the straight beam in all three detectors 1 + 2 + 3, in two detectors 2 + 3, and in the last detector 3. The displaced beams are clearly evident (Fig. 2a): I) The beam attributable to channeling on the plane (111) and on the ⟨110⟩ axis, II (the beam attributable to skewed planes [mainly $(1\bar{1}\bar{1})$, (110), and (001)]. The skewed planes are curved and can move the beam both along the horizontal (X) and the vertical (Y) planes (Fig. 2c). A decrease in the angular divergence of the channeled I and II beams is considerable (by a factor of 2–3) compared to the "straight beam,"

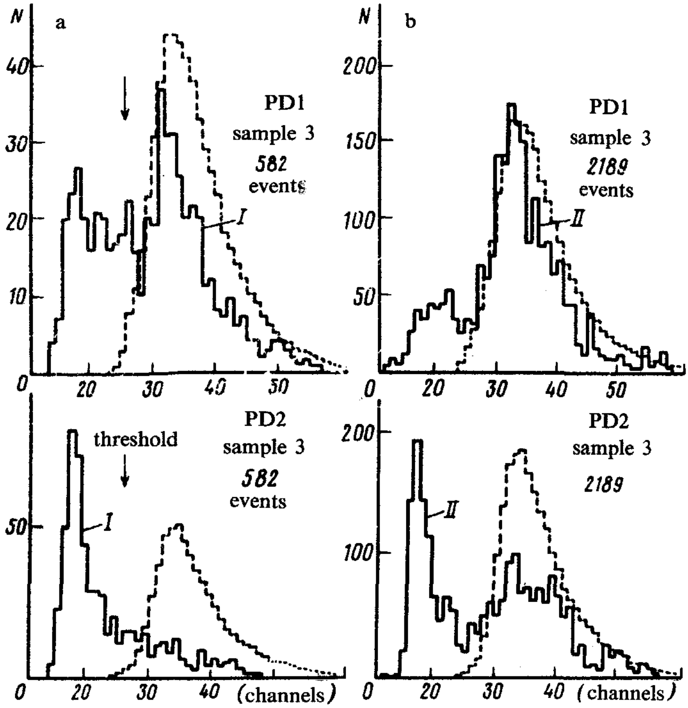

FIG. 3. Amplitude spectra of particles in PD1 and PD2 with $\varphi = 8$ mrad: (a) for beam I, (b) for beam II (Fig. 2a, sample 3). The dashed curve represents the amplitude spectrum of the straight beam.

which corresponds to the normal ionization losses and angle φ outside the channeling region. Figure 3 shows the spectra of ionization losses of particles that form the deflected beams I and II (selected by 3) in PD1 and PD2, i.e., at different sections of their trajectories in the crystal, respectively. A characteristic indication of channeling is the appearance of a peak in the region ≈ 0.5 of the most probable amplitude from normal (unchanneled) particles. We note that the width of this peak, which is three to four

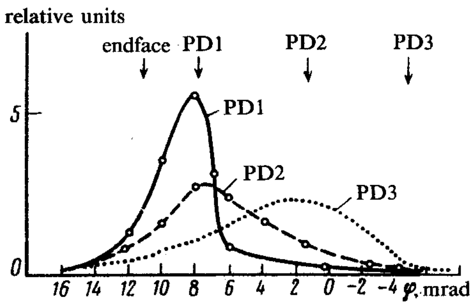

FIG. 4. Dependence of the number of particles with small amplitude in PD1, PD2, or PD3 on the angle φ of rotation of the crystal relative to the incident beam. The threshold for selection according to amplitude is shown in Fig. 3. The positions of the inlet end-faces of the crystal and detectors PD1–3 are also indicated.

times smaller than that for the distribution from unchanneled particles, is determined by the resolution of the detctor.

On the basis of the facts presented above, we conclude uniquely that the separated particles are channeled. From these figures it also follows that volume capture exists in the channeling regime. An increase in intensity of deflected beams depending on the type of selection, $1+2+3$, $2+3$, or 3, indicates that particles are added to these beams due to capture in the sections between the first and second detectors as well as between the second and third detectors. A graphic confirmation of volume capture is also given in Fig. 3, from which it is evident that many particles deflected in maxima I or II were not channeled in PD1 (they had higher ionization losses) and were placed "on track" only at large depths in the crystal.

Figure 4 shows the dependence of the number of particles with small amplitude in PD1, PD2, and PD3 on the angle φ of rotation of the crystal. This figure demonstrates that the region in which the particles are captured in the channeling regime by a curved crystal is concentrated not only near the inlet end-face of the crystal, but is also displaced in the bulk of the crystal. The shape of these curves is determined by dechanneling.

The new phenomenon permits greatly increasing the intensity of channeled particles beams and permits using beams with high angular divergence.

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[1)]The magnitude of the Lindhard angle for 1-GeV protons and the (111) plane is ≈ 0.12 mrad.

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