Steering of charged-particle trajectories by means of a curved single crystal

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It is shown experimentally for the first time that it is possible to steer charged-particle trajectories by using a curved single crystal. 8.4-GeV protons, which were captured during plane channeling by a curved silicon single crystal, were deflected at an angle of 26 mrad. The radius of curvature of the particle trajectory was about 38 cm, which corresponds to the average transverse electric field of about 240 MV/cm acting on the particle. This is equivalent to a magnetic field with the induction of about 0.82 MG.

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It was predicted in Ref. 1 that deformed single crystals can be used to guide the trajectories of charged particles that are trapped during channeling. The critical radius of curvature of the trajectory of particles, at which it is still possible to confine them by

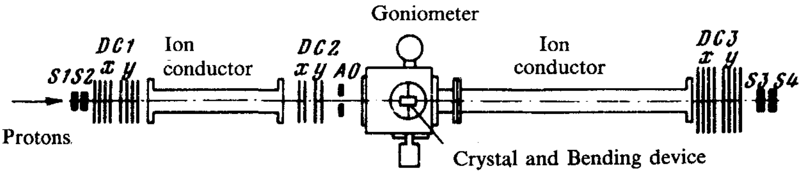

FIG. 1. Experimental setup: $S1$, $S2$, $S3$, $S4$, and A_0 are scintillation counters and $DC1$, $DC2$, and $DC3$ are drift cells.

the curved crystallographic plane, is determined by the expression

$$R = Mv^2/E_c Z_e.$$

Here M is the relativistic mass of the particle, v is the velocity, Z_e is the charge of the particle, and E_c is the average electric field at this distance from the plane of the crystal lattice, where the motion of the particle in the channeling mode is unstable because of the interaction with single atoms. For silicon the value of E_c is approximately 0.5×10^{10} V/cm.

The purpose of our experiment was to verify this hypothesis. The experiment was performed in the High Energy Laboratory of the Joint Institute of Nuclear Research, by using a proton beam extracted from the proton synchrotron. A 8.4-GeV beam had an angular divergence of ± 0.3 mrad, and its transverse dimension at the location of the crystal was about 2 cm. The studies were carried out at a beam intensity of 10^5 particles per accelerator cycle, and the extension time was 0.3–0.4 sec.

The experimental setup is shown in Fig. 1. The trajectories of the particles transmitted through the crystal were determined by using a spectrometer comprised of 20 drift cells. The overall length of the setup was 18 m. The system operated on line with a computer. Up to 500 events per accelerator cycle were recorded on a magnetic tape.

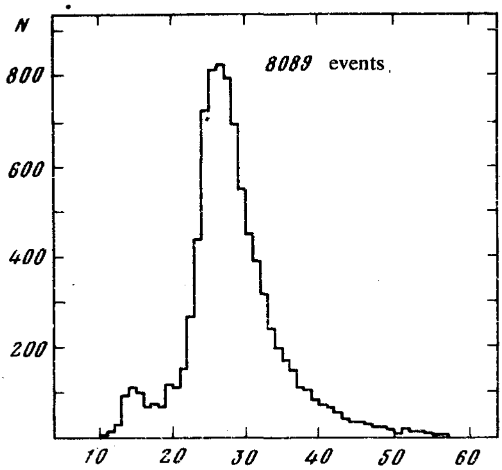

FIG. 2. Amplitude distribution of ionization losses in the semiconductor detector. The (111) plane of the crystal is directed along the beam.

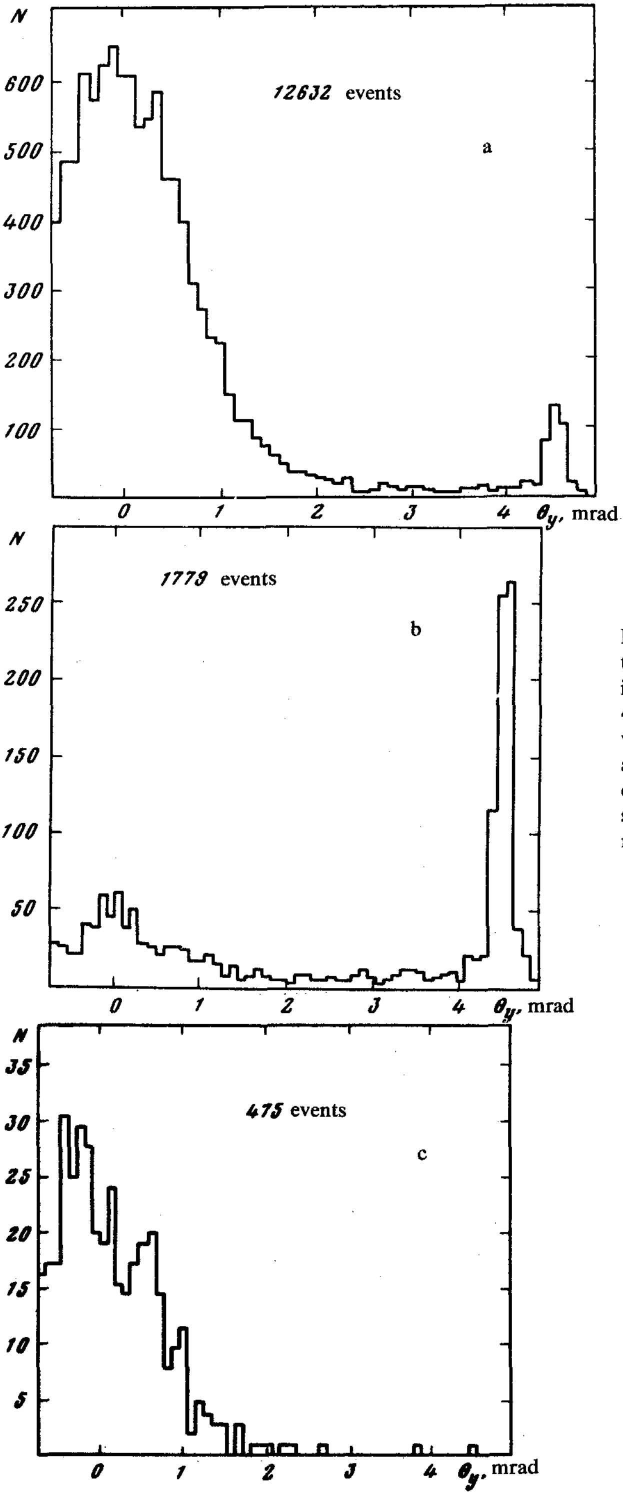

FIG. 3. Distribution of particles emitted from the crystal along the angles in the vertical plane:a—bending angle 4.5 mrad; b—the same as in Fig. 3a, with an additional selection of events according to the channeling criteria; c—the same as in Fig. 3a, but with a selection of events only for nonchanneling particles.

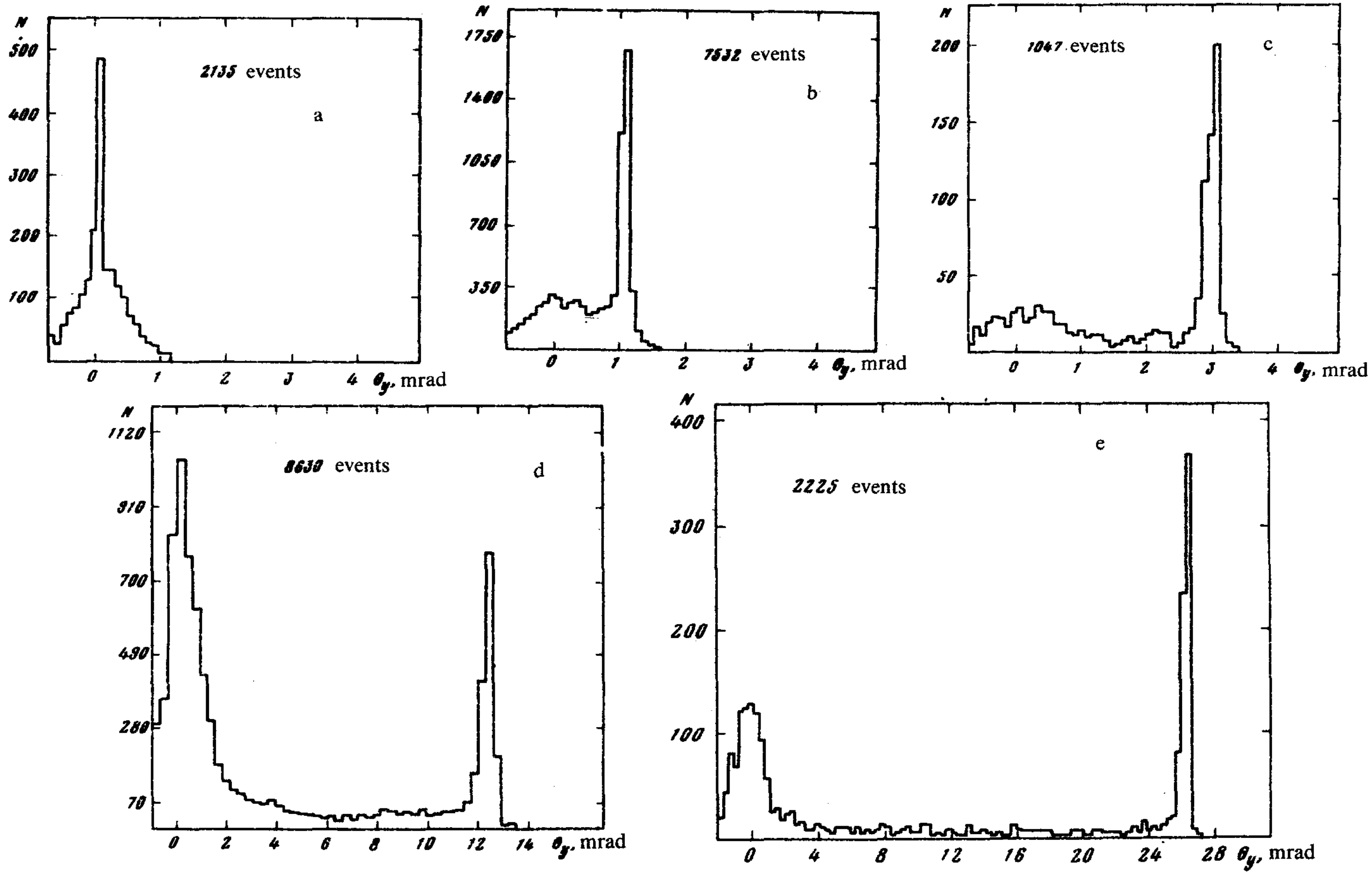

FIG. 4. Distribution of particles according to the exit angles in the vertical plane for different angles of curvature of the crystal; a—0.0 mrad; b—1.0 mrad; c—3.0 mrad; d—12.5 mrad (the criterion for the scattering angle in the horizontal plane was not used); e—26.0 mrad. The events were selected according to the channeling criteria.

The spectrometer was actuated by a system of scintillation counters which separated out the particles striking the working region of the single crystal. A precision goniometer with a scale division of 0.001 ° was used to orient the crystal. The proton beam was transmitted through a 20-mm-long silicon single crystal, part of which was subjected to a controlled bending. The critical radius for 8.4-GeV protons for silicon is about 2 cm. The (111) plane of the single crystal was bent, and the length of the bent section was 10 mm.

The input part of the single crystal was a semiconductor detector. Figure 2 shows the amplitude spectrum of the signals from the particles transmitted through the detecting part of the crystal whose (111) plane is in the direction of the particle beam. The particles captured during channeling can be identified from the ionization losses.

The measurements were performed at bending angles of the crystal of 0.0, 0.5, 1.0, 2.0, 3.0, 4.5, 12.5, and 26.0 mrad in the vertical plane. The channeling part of the beam follows the curvature of the crystallographic plane (111). There was no noticeable increase at all the angles of the number of dechanneling particles due to bending of the crystal. Figure 3a shows the angular distribution of the particles leaving the crystal at a bending angle of 4.5 mrad. A narrow peak due to the effect in question can be observed on the right-hand side of the broad peak produced by the particles as a result of multiple scattering in the sample. Figure 3b shows the angular distribution of the events selected according to the criteria for identifying the channeling particles. For this distribution we selected the events for which the amplitude of the signal corresponded to the amplitude range 0.2–0.7 in the maximum of the spectrum. In addition, it was required that the particles in the horizontal plane should not experience scattering at an angle greater than ± 0.1 mrad. Figure 3b confirms that the peak on the right-hand side corresponds to channeling particles. Figure 3c shows the angular distribution with a selection of the events on the basis of the "hard" criteria that exclude the channeling particles. It can be seen in Fig. 3c that the peak on the right-hand side is due to deviation of the channeling particles by the curved single crystal. Figure 4 shows the events obtained at exit angle in the vertical plane for different angles of curvature of the crystal. The same criteria were used here as in Fig. 3b. It can be seen that the angular position of the peak of the channeling particles corresponds to the angle of curvature of the crystal. For a 26-mrad angle of curvature of the crystal the effective transverse electric field averaged along the particles trajectory is 240 MV/cm.

Thus, it was shown for the first time that it is possible to steer the charged-particle trajectories by using a bent single crystal. This new effect can be used in high energy physics.

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