STEERING OF CHARGED PARTICLE TRAJECTORIES BY A BENT CRYSTAL


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The first experimental evidence has been obtained for steering of charged particle trajectories by a bent silicon crystal. The investigation has been performed at the Laboratory of High Energies, JINR. In the process of planar channeling, an 8.4 GeV proton beam has been deflected up to 26 mrad relative to the incident beam direction. This corresponds to a bending radius of 38 cm. The effective transverse component of the electric field acting on the proton beam is equal to 240 MV/cm. This is equivalent to a magnetic field of 81 T.

In discussing the behavior of a particle traveling near the direction of a plane in a bent crystal, it has been suggested that such a bent single crystal may be used for steering charged particles [1]. It was argued that the effect of the bend is to displace the equilibrium orbit away from the minimum in the crystal potential. This is equivalent to introducing a centrifugal term which makes the potential asymmetric. The magnitude of the asymmetry is related to the magnitude of the bend. Particles entering the crystal and captured into channeled trajectories may follow the curvature of the crystal planes up to the point at which the bending radius of the crystal is greater than some critical radius. The calculated value of the critical radius for a charged particle in this model is given by

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2 Supported by the United States Department of Energy.
\[ R = \frac{Mv^2}{ZeE_c}, \]

where \( M \) and \( v \) are, respectively, the relativistic mass and velocity of the particle, and \( Ze \) is the charge. \( E_c \) is the average interatomic electrical field intensity (in the case of planar channeling for positively charged particles) at the distance from the plane of the crystal lattice where the trajectory of the particle no longer remains stable due to its interaction with individual atoms. The value of \( E_c \) is equal to \( 0.5 \times 10^{10} \, \text{V/cm} \) for a silicon crystal. The planar critical angle for silicon at 8.4 GeV is about 40 \( \mu \text{rad} \), the critical radius is equal to 2 cm.

The purpose of the present studies was to check the hypothesis stated in ref. [1]. The experiment was performed with the 8.4 GeV external beam of the JINR High Energy Laboratory accelerator. The beam pulses, with a spill time of 0.3–0.4 s, contained, on the average, \( 10^5 \) protons and had an angular divergence of 0.3 mrad. The beam size at the position of the crystal was about 20 mm. The experimental setup is shown in fig. 1. The trajectories of the particles passing through the target crystal were read out by a spectrometer system consisting of twenty drift planes. The angular resolution was approximately 15 \( \mu \text{rad} \) for outgoing angles and 80 \( \mu \text{rad} \) for incident angles. A system of coincidence and anticoincidence counters triggered the spectrometer to select the particles that passed through the crystal. A precision goniometer with polar and azimuthal degrees of freedom was used to rotate the crystal with an accuracy of 0.001°. The apparatus was connected on-line with a computer which could store up to 500 events per beam pulse on magnetic tape.

The upstream end of a 2.0 cm long silicon crystal was prepared as a totally depleted semiconductor detector. A simple technique was employed to bend the downstream end of the crystal in the vertical plane over a length of 1 cm. A typical crystal was 1 cm wide in the plane of the bend and 2 mm thick. Thinner crystals (down to 0.5 mm) were used for the larger bends. The bend plane of the crystal coincided with the crystallographic plane (111). The bend angle was measured using a mirror attached to the crystal and a laser beam. The accuracy of measurement of the bending angle was about 5%. A side view of the bending device is shown in fig. 1a. With this apparatus it was difficult to bend the crystals more than 30 mrad without breaking them.

Fig. 2 presents typical energy loss spectra with the crystal oriented randomly with respect to the primary beam direction (a) and with the crystallographic plane (111) aligned with the beam direction (b). As is seen in fig. 2b, the channeled particles may be identified through their anomalously low energy losses. This fea-

![Fig. 1. Schematic drawing of the experimental setup: S1, S2, S3, S4, A0: scintillation counters. DC1, DC2, DC3: drift chamber modules. (a) Side view of a typical single crystal with bending device. The upstream end of the crystal is a totally depleted semiconductor detector.](image-url)
Fig. 2. Energy loss distribution as measured by the silicon semiconductor detector: (a) crystal oriented randomly with respect to the primary beam direction; (b) crystallographic plane (111) oriented along the beam direction (planar channeling).

Fig. 3. (a) Angular distribution in the vertical plane for outgoing protons from a crystal bent at 4.5 mrad. (b) The same as in (a) except that only channeled particles were selected. (c) The same as in (a) except that only nonchanneled particles were selected.

ture makes it possible to orient the crystal and select particles that have been involved in the channeling processes.

With the crystal aligned along the beam direction measurements were performed for crystal bending angles of 0, 0.5, 1.0, 2.0, 3.0, 4.5, 12.5 and 26.0 mrad. It was found that the channeled fraction of the beam followed the bent crystallographic plane for all crystal bending angles. It was observed that the number of de-channeled particles did not change significantly with increasing crystal bend angle.

The angular distribution in the vertical plane for outgoing particles is presented in fig. 3a for a crystal bent at 4.5 mrad. The broad main peak is due to pro-
Fig. 4. Outgoing angular distributions in the vertical plane for protons using various crystal bending angles and selecting channeled particles. (a) 0 mrad, (b) 1.0 mrad, (c) 3.0 mrad, (d) 26.0 mrad.

tons multiply scattered by the silicon crystal. The measured projected multiple scattering angle was 890 μrad half width at half maximum. The narrow right peak corresponds to the deflected part of the beam. As noted above, the angular resolution for outgoing particles in the spectrometer was approximately 15 μrad except for the final measurement at 26 mrad, where it was approximately 50 μrad. The measured width of the outgoing distribution should therefore be consistent with the critical angle for the channeled particles, approximately 40 μrad. However, the distribution is broader and the shape of this distribution varies from one bending angle to another. This variation is due to distortions of the end of the crystal and to twisting in the bending plane.

In order to select only channeled particles for the analysis, we chose events with energy losses in the range of (0.2–0.7)ΔE, where ΔE is the most probable energy loss deposited by the particles in a randomly oriented crystal. Furthermore, to reduce the number
of multiply scattered events, the scattering angle in the horizontal plane was restricted to ±0.1 mrad. Fig. 3b presents the angular distribution of the selected events. This figure confirms that the right peak corresponds to true channeled particles. Fig. 3c presents the angular distribution of the outgoing particles in the vertical plane; this result was obtained for a selection of the nonchanneled events. This figure also confirms that the right peak in fig. 3a is due to the deflection of the channeled particles by the bent crystal.

Fig. 4 shows the angular distribution of the outgoing particles for a variety of crystal bending angles. The events were selected using the same criteria as in fig. 3b. It is clear that the angular peak position is consistent with the crystal bending angle. It should be noted that for an angle of 26.0 mrad the value of the effective transverse field intensity is estimated to be the equivalent of 240 MV/cm, while the effective radius of curvature is 38 cm.

To summarize, in the present investigation the first experimental evidence has been obtained for the steering of charged particle trajectories by a bent single crystal. This new phenomenon may find useful applications in high-energy physics. It is interesting to note that this process should be increasingly interesting at higher energies since the critical angle, which sets the channel admittance, decreases as the square root of the momentum while the divergence of the secondary beams decreases as the momentum. Moreover, the dechanneling length rises with energy. Finally, the critical radius increases with \( E \) so the crystal can be readily bent to the critical radius of curvature.

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