Observation of channeling and volume reflection in bent crystals for high-energy negative particles

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A B S T R A C T

Deflection due to planar channeling and volume reflection in short bent silicon crystals was observed for the first time for 150 GeV/c negative particles, π⁻ mesons, at one of the secondary beams of the CERN SPS. The deflection efficiency was about 30% for channeling and higher than 80% for volume reflection. Volume reflection occurs, in spite of the attractive character of the forces acting between the particles and the crystal planes, in a wide angular range of the crystal orientations determined by the crystal bend angle.

When high-energy charged particles enter a crystal with small angles with respect to the atomic planes their transverse motion is governed by the crystal potential averaged along the planes [1]. For positive particles the planar potential is repulsive. When the initial transverse energy of a particle at the crystal entrance is smaller than the planar potential barrier $U_0$ the particle moves along the trajectory oscillating between two neighboring crystal planes (planar channeling regime). The potential barrier height $U_0$ determines the critical channeling angle $\theta_c = \left(\frac{2U_0}{pv}\right)^{1/2}$ between the particle momentum $p$ (velocity $v$) and the crystal planes. The channeling states with small oscillation amplitudes are stable because in this condition particles do not experience close collisions with the crystal atoms. Particle channeling is still possible if the crystal is bent with a radius larger than the critical one $R_c$,

$$R > R_c = \frac{pv}{\sqrt{2Em}}$$

where $Em$ is the maximum strength of the atomic electric field averaged along the planes ($Em$ is close to 6 GV/cm for (110) and (111) channels in silicon crystals). The deflection of positive particles by bent crystals is well studied (see the review [3]) and used to extract particles from cyclic accelerators [4].

For negative particles the planar potential is attractive. When the particle transverse energy is smaller than the depth of the planar potential well it moves along the trajectory oscillating between two neighboring crystal planes (planar channeling regime). The potential barrier height $U_0$ determines the critical channeling angle $\theta_c = \left(\frac{2U_0}{pv}\right)^{1/2}$ between the particle momentum $p$ (velocity $v$) and the crystal planes. The channeling states with small oscillation amplitudes are stable because in this condition particles do not experience close collisions with the crystal atoms. Particle channeling is still possible if the crystal is bent with a radius larger than the critical one $R_c$,

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For negative particles the planar potential is attractive. When the particle transverse energy is smaller than the depth of the planar potential well it moves along the trajectory oscillating around the crystal plane. As a result, the probability of close collisions with the crystal atoms is high for negative particles in the channeling states. Therefore, the dechanneling length for negative particles is much shorter than for positive ones. For this reason up to now channeling along the whole crystal length with the deflection of...
negative particles by the crystal bend angle has not been observed. Only a broadening of the angular distributions towards the crystal bend side has been observed in the previous experiments [5,6].

Positive particles, which enter a bent crystal with the angles \( \theta > \theta_c \) and have the tangency points of their momentum with the bent crystal planes inside the crystal volume, are deflected to the side opposite to the bend by an angle up to \( 1.5 \theta_c \) (volume reflection [7]). Approaching the tangency point the particle crosses the crystal planes with a decreasing angle. Near the tangency point the angle becomes smaller than the critical one and the particle is reflected by the potential barrier of the plane (volume reflection (VR)). See Fig. 1a. After this, removing the tangency point the particle crosses the crystal planes with an increasing angle. Near the tangency point a small fraction of particles can be captured on to the high-energy levels of the planar potential well due to strong multiple scattering on the atomic nuclei of the crystal (volume capture (VC)). This fraction determines the value of the VR inefficiency. The volume reflection of relativistic protons in bent crystals was observed in the experiments [8–10]. The dependence of the deflection angle and of the VR efficiency on the crystal bend radius were studied in [11].

It was shown in [7] that VR in a bent crystal should occur also for negative particles. However, the simplified picture of volume reflection described above for positive particles should be slightly modified. Namely it should be considered how the bend of each crystal plane changes the particle passage through it. Approaching the tangency point after the intersection of each bent crystal plane the particle momentum angle relative to the plane reduces because the plane concavity approaches the plane tangent direction to the particle momentum one. As a consequence, the angle becomes smaller than the critical one after the particle intersection of the plane nearest to the tangency point. Therefore, the particle goes back to the plane due to its attractive force and crosses it again (see Fig. 1b). During this half wave of the oscillation the particle momentum direction changes by the angle about \( 2 \theta_c \) (VR). Its radial velocity changes sign. Then after the second intersection the particle momentum angle relative to the plane increases because the plane convexity removes the plane tangent direction from the particle momentum one. As a result, the angle becomes again greater than the critical one. The particle moves away from the tangency point.

The main contribution to the deflection angle of a particle due to VR occurs in the area of the half wave of the oscillation where a particle changes the sign of its radial velocity (turning area). The final value of the VR deflection angle depends on the particle behavior outside the turning area. A particle follows to the crystal bend if its transverse velocity is small. A negative particle has a small transverse velocity between the crystal planes (see Fig. 1b) where the electric field of the planes has a wide minimum. Therefore, the trajectory parts with small transverse velocities are longer for negative particles. So, the deflection to the crystal bend side acquired outside the turning area, which reduces the VR deflection angle, is larger for negative particles.

This Letter presents the results of the observation of channeling and VR in bent silicon crystals for 150 GeV/c negative particles, mainly \( \pi^- \) mesons, at one of the secondary beams of the CERN SPS (H4, North Area). The experimental setup was the same as described in [11]. Four microstrip silicon detectors were used to measure the particle angles with resolution of 8 μrad, which is limited by the multiple scattering of particles in the detectors and the air.

Silicon crystals produced according to the technologies described in [12–14] with small lengths along the beam have been used in the experiment. The results presented have been obtained with the quasi-mosaic crystal (QM2), which was already used in our experiments [10]. It is bent along the (111) planes and has a length of 0.84 mm. The crystal bend angle is about 65 μrad. The (111) planes in silicon crystals are not equidistant; they are placed in pairs. The ratio of the interplanar distances is 1:3. The potential well depth \( U_0 = 25.24 \text{ eV} \) and the critical angle for 150 GeV/c \( \pi^- \) mesons \( \theta_c = 18.34 \text{ μrad} \).

The divergence of the beam incident on to the crystal measured with the detector telescope was characterized by the RMS deviations \( \sigma_x = (34.4 \pm 0.06) \text{ μrad} \) and \( \sigma_y = (28.2 \pm 0.04) \text{ μrad} \) in the horizontal and vertical planes, respectively. A high-precision goniometer was used to orient the crystal planes with respect to the beam axis with an accuracy of 2 μrad. Fig. 2 shows the intensity distribution of the beam crossed the crystal in the deflection angles of particles (Y-axis) at the different angular positions of the goniometer (X-axis). Only particles hitting the crystal with a horizontal angle \( |\theta_{\text{gon}}| < 10 \text{ μrad} \) were selected.

The picture is very similar to the one obtained in the experiment with 400 GeV/c protons (see Fig. 3 in [10]). Therefore, the
The deflection angle distribution of $\pi^-$ mesons crossed the (111) bent silicon crystal (QM2) for the crystal orientations optimal for channeling (a) and volume reflection (b). The curves show the Gaussian fits of the peaks. The hatched areas show the deflected fractions of the beam due to channeling (a) and VR (b).

Fig. 3. (Color online.) The deflection angle distribution of $\pi^-$ mesons crossed the (111) bent silicon crystal (QM2) for the crystal orientations optimal for channeling (a) and volume reflection (b). The curves show the Gaussian fits of the peaks. The hatched areas show the deflected fractions of the beam due to channeling (a) and VR (b).

The crystal bend radius, which corresponds to this deflection angle, is $\theta = (0.86 \pm 0.11) \mu$rad. The VR deflection angle is about 0.8$\mu$rad. It is smaller than for positive particles as predicted in [7]. So, the VR deflection angle in a bent silicon crystal measured for 400 GeV/c protons achieves $1.4\theta_c$ [11]. A considerable distribution tail with $\theta > 0$ is caused by particles, which were volume captured and then partly dechanneled.

The VR efficiency can be determined as the beam fraction under the Gaussian fit with angles $\theta < \theta_{vr} + 3 \sigma_{vr}$. This gives $P_{vr} = (82.74 \pm 0.28)\%$. The large distribution tail on the bend side indicates that the VC probability is considerably higher for negative particles. They undergo strong multiple scattering on the atomic nuclei passing the potential well center where they have large transverse velocities. Therefore, the same multiple scattering angle gives a larger increase of the transverse energy than for the case with positive particles increasing the VC probability. Our simulation shows that about 50% of particles are volume captured in the considered case. However, most of them are very quickly dechanneled because of the same strong multiple scattering. Then they continue their motion along the volume reflection trajectories outgoing from the tangency points. So, these particles are also deflected due to VR. Nevertheless, the VR inefficiency due to VC approaches 20% for 150 GeV/c $\pi^-$ mesons, which is about one order of magnitude higher than for 400 GeV/c protons.

Fig. 3b shows the distribution of the deflection angles of particles for the crystal orientation in the middle of the VR area. The Gaussian fit gives the peak position, the VR deflection angle, $\theta_{vr} = (-1.64 \pm 0.12) \mu$rad and its RMS deviation $\sigma_{vr} = (10.06 \pm 0.11) \mu$rad. The VR deflection angle is about $0.8\mu$rad. It is smaller than for positive particles as predicted in [7]. So, the VR deflection angle in a bent silicon crystal measured for 400 GeV/c protons achieves $1.4\theta_c$ [11]. A considerable distribution tail with $\theta > 0$ is caused by particles, which were volume captured and then partly dechanneled.

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Table 1
Channeling and VR parameters for 150 GeV/c π− in (111) and (110) Si.

| Crystal          | θc (μrad) | R (m)   | θvr (μrad) | Pvr (%) | Pd (%) |
|------------------|-----------|---------|------------|---------|--------|
| (111) Si, QM2 experiment | 18.34     | 12.92 ± 0.09 | 14.64 ± 0.12 | 82.74 ± 0.28 | 30.24 ± 0.38 |
| Simulation       | 16.6 ± 0.07 | 78 ± 0.13   |            |         |        |
| Theory           | 14.28     |          |            |         |        |
| (110) Si, ST10 experiment | 17.39     | 22.79 ± 0.22 | 11.53 ± 0.23 | 76.75 ± 0.32 | 28.81 ± 0.47 |
| Simulation       | 12.84 ± 0.11 | 74.77 ± 0.14 |            |         |        |
| Theory           | 11.81     |          |            |         |        |

was determined to be θvr = (11.53 ± 0.23) μrad. For negative particles, in contrast to the positive ones, the VR deflection angle is smaller for the (110) planes than for the (111) ones, θvr = 0.66θc.

The same definition as used above gives for the VR efficiency Pvr = (76.75 ± 0.32)%.

The parameter values for channeling and volume reflection of π− mesons obtained for the (111) and (110) crystals in the experiment and in our simulation are listed in Table 1. The agreement between the experimental and simulation results is rather good. However, the values of the VR deflection angles obtained in the simulation using the Moliere approximation of the atomic potential are 10–15% larger than the measured ones, which is similar to what we observed with 400 GeV/c protons. The angle values calculated using the explicit expression [15] and the atomic potential obtained through the experimental X-ray scattering factors are closer to the measured values (see Table 1).

Our experimental results have shown that the sufficiently stable bound states of high-energy negative particles with the bent crystal planes exist and lead to the deflection of particles. Besides, they have shown that volume reflection in bent crystals occurs also for negative particles in spite of the attractive character of the forces acting between the particles and the crystal planes. Thus, there is possibility to deflect high-energy negative particles via either channeling or volume reflection in bent crystals, which can be used for the beam steering in accelerators.

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