Physics Letters B 681 (2009) 233–236

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

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

W. Scandale [a], A. Vomiero [b], E. Bagli [c], S. Baricordi [c], P. Dalpiaz [c], M. Fiorini [c], V. Guidi [c], A. Mazzolari [c], D. Vincenzi [c], R. Milan [d], Gianantonio Della Mea [e], E. Vallazza [f], A.G. Afonin [g], Yu.A. Chesnokov [g], V.A. Maisheev [g], I.A. Yazynin [g], V.M. Golovatyuk [h], A.D. Kovalenko [h], A.M. Taratin [h,*], A.S. Denisov [i], Yu.A. Gavrikov [i], Yu.M. Ivanov [i], L.P. Lapina [i], L.G. Malyarenko [i], V.V. Skorobogatov [i], V.M. Suvorov [i], S.A. Vavilov [i], D. Bolognini [j,k], S. Hasan [j,k], A. Mattera [j,k], M. Prest [j,k], S. Shiraishi [l]

[a] CERN, European Organization for Nuclear Research, CH-1211, Geneva 23, Switzerland
[b] INFM-CNR, Via Vallotti 9, 25133 Brescia, Italy
[c] INFN Sezione di Ferrara, Dipartimento di Fisica, Università di Ferrara, Via Saragat 1, 44100 Ferrara, Italy
[d] INFN Laboratori Nazionali di Legnaro, Viale Università 2, 35020 Legnaro (PD), Italy
[e] Dipartimento di Ingegneria dei Materiali e Tecnologie Industriali, Università di Trento, Via Mesiano 77, 38050 Trento, Italy
[f] INFN Sezione di Trieste, Via Valerio 2, 34127 Trieste, Italy
[g] Institute of High Energy Physics, Moscow Region, RU-142284 Protvino, Russia
[h] Joint Institute for Nuclear Research, Joliot-Curie 6, 141980 Dubna, Moscow Region, Russia
[i] Petersburg Nuclear Physics Institute, 188300 Gatchina, Leningrad Region, Russia
[j] Università dell'Insubria, via Valleggio 11, 22100 Como, Italy
[k] INFN Sezione di Milano Bicocca, Piazza della Scienza 3, 20126 Milano, Italy
[l] Fermi National Laboratory, PO Box 500, Batavia, IL 60510-0500, USA

ARTICLE INFO

Article history:
Received 20 August 2009
Received in revised form 8 October 2009
Accepted 8 October 2009
Available online 13 October 2009
Editor: W.-D. Schlatter

PACS:
61.85.+p

ABSTRACT

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_o the particle moves along the trajectory oscillating between two neighboring crystal planes (planar channeling regime). The potential barrier height U_o determines the critical channeling angle $\theta_c = (2U_o/pv)^{1/2}$ 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 [2], $R > R_c = pv/eE_m$, where E_m is the maximum strength of the atomic electric field averaged along the planes (E_m 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 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

* Corresponding author.
E-mail address: alexander.taratin@cern.ch (A.M. Taratin).

0370-2693 © 2009 Elsevier B.V. Open access under CC BY license.
doi:10.1016/j.physletb.2009.10.024

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 π^- 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 $U_o = 25.24$ eV and the critical angle for 150 GeV/c π^- mesons $\theta_c = 18.34$ μrad.

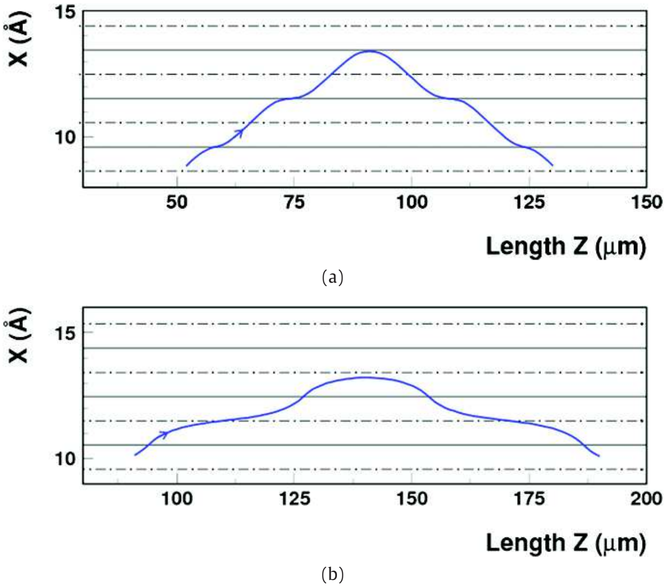

Fig. 1. (Color online.) The calculated trajectories of 150 GeV/c π^+ meson (a) and π^- meson (b) at volume reflection in a silicon crystal bent along the (110) planes near the turning area in the commoving coordinate system, which rotates around the crystal curvature center with the particle velocity. The coordinate X is measured in the direction opposite to the radial one. Solid horizontal lines show the crystal planes.

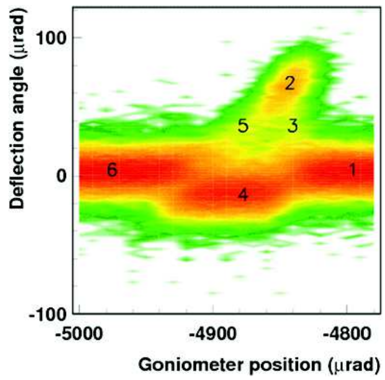

Fig. 2. (Color online.) The intensity distribution of the π^- meson beam crossed the (111) bent silicon crystal (QM2) in the deflection angles of particles (Y-axis) at the different angular positions of the goniometer (X-axis). The following areas are indicated: (1) and (6) amorphous scattering, (2) deflection due to channeling, (3) dechanneling, (4) volume reflection, (5) deflection of volume captured particles.

The divergence of the beam incident on to the crystal measured with the detector telescope was characterized by the RMS deviations $\sigma_x = (34.4 \pm 0.06)$ μrad and $\sigma_y = (28.2 \pm 0.04)$ 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 $|\theta_{xo}| < 10$ 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

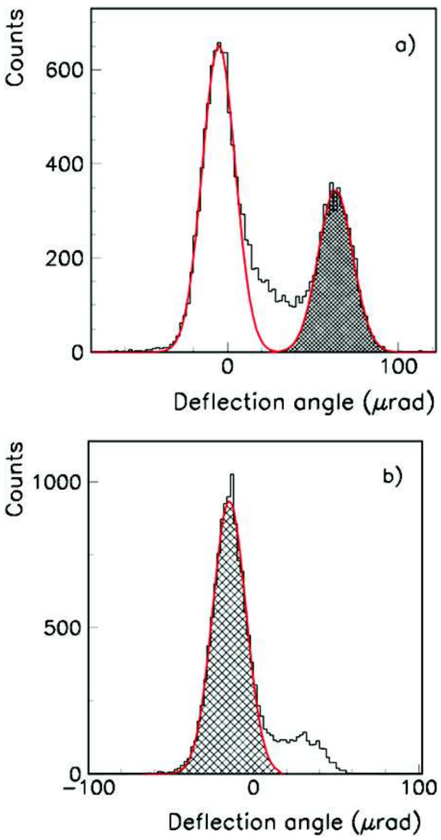

Fig. 3. (Color online.) The deflection angle distribution of π^- mesons crossed the (111) bent silicon crystal (QM2) for the crystal orientations optimal for channeling (a) and volume reflection (b). The curves show the Gaussian fits of the peaks. The hatched areas show the deflected fractions of the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

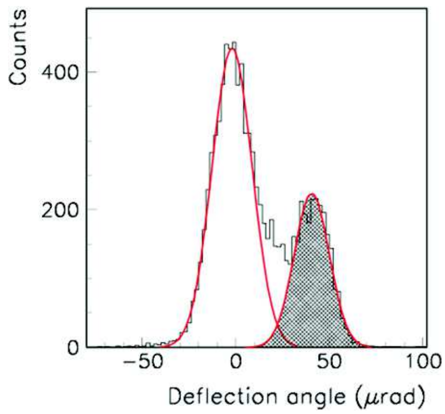

Fig. 4. (Color online.) The deflection angle distribution of π^- mesons crossed the (110) bent silicon crystal (ST10) for the crystal orientations optimal for channeling.

different areas in the figure are marked in the same way. Areas (1) and (6) are the ones where the crystal scatters particles as an amorphous material. Moving from the right to the left of the figure we pass first the crystal orientations where a considerable fraction of the incident beam is captured into the bound states with the (111) planes and deflected by the crystal bend angle (channeled particles) (2). Area (3) shows the fraction of particles dechanneled during the passage through the crystal. The wider area (4), whose width is determined by the crystal bend angle, is the volume reflection area. Area (5) shows the particle fraction captured into the bound states with the bent planes in a tangency area due to multiple scattering on the atomic nuclei (VC) and therefore undergoing a smaller angular deflection.

Fig. 3a shows the distribution of particle deflection angles for the crystal orientation optimal for channeling. The right peak was generated by particles deflected by the crystal in channeling states. Particles, which were not captured into the channeling states and were deflected to the side opposite to the crystal bend due to volume reflection, generate the left peak. The beam fraction between the two peaks outside the fits determines the dechanneled fraction of the beam (about 14%). The Gaussian fit of the channeled fraction gives the mean deflection angle $\theta_d = (63.24 \pm 0.24)$ μrad and the RMS deviation $\sigma_d = (10.16 \pm 0.19)$ μrad. In the assumption of a uniform bend, the crystal bend radius, which corresponds to this deflection angle, is $R = 12.92$ m. The deflection efficiency determined by the beam fraction under the fit (hatched area) is $P_d = (30.24 \pm 0.38)$%.

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, $\theta_{vr} = (-14.64 \pm 0.12)$ μrad and its RMS deviation $\sigma_{vr} = (10.06 \pm 0.11)$ μrad. The VR deflection angle is about $0.8\theta_c$. 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 π^- mesons, which is about one order of magnitude higher than for 400 GeV/c protons.

Fig. 4 shows the distribution of the deflection angles of 150 GeV/c π^- for the strip silicon crystal (ST10) when the optimal orientation for channeling occurs. The strip crystal $70 \times 0.98 \times 0.5$ mm^3 (length × width × thickness) with the largest faces parallel to the (110) planes was mechanically bent along its length. The anticlastic curvature produced along the crystal width with the bend angle about 43 μrad was used for the beam deflection in the horizontal plane. The (110) planes are equidistant. The potential well depth $U_o = 22.7$ eV and the critical angle $\theta_c = 17.39$ μrad. Only particles hitting the crystal with $|\theta_{xo}| < 5$ μrad were selected. The Gaussian fits for channeled and reflected fractions are overlapped here because of a smaller bend angle of the crystal. The fit of the channeled fraction gives the mean deflection angle $\theta_d = (40.54 \pm 0.36)$ μrad and the RMS deviation $\sigma_d = (9.41 \pm 0.29)$ μrad. The crystal bend radius, which corresponds to this deflection angle, is $R = 22.79$ m. The deflection efficiency defined as the beam fraction under the fit (hatched area) is $P_d = (28.81 \pm 0.47)$%.

From the distribution of the particle deflection angles for the VR crystal orientation the VR deflection angle for the strip crystal

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

Crystal	θ_c (μrad)	R (m)	θ_{vr} (μrad)	P_{vr} (%)	P_d (%)
(111) Si, QM2 experiment		12.92 ± 0.09	14.64 ± 0.12	82.74 ± 0.28	30.24 ± 0.38
Simulation	18.34		16.6 ± 0.07	78 ± 0.13	30.11 ± 0.15
Theory			14.28		
(110) Si, ST10 experiment		22.79 ± 0.22	11.53 ± 0.23	76.75 ± 0.32	28.81 ± 0.47
Simulation	17.39		12.84 ± 0.11	74.77 ± 0.14	28.67 ± 0.14
Theory			11.81		

was determined to be $\theta_{vr} = (11.53 \pm 0.23)$ 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, $\theta_{vr} = 0.66\theta_c$. The same definition as used above gives for the VR efficiency $P_{vr} = (76.75 \pm 0.32)\%$. The VR efficiency is smaller than for the QM2 crystal because the VC probability of particles is higher due to the larger bend radius.

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.

Acknowledgements

We are grateful to Professor L. Lanceri (INFN & University of Trieste) who provided the tracking detectors, to V. Carassiti and M. Melchiorri for the design and fabrication of the crystal holders. We acknowledge the partial support by the INFN NTA-HCCC and MIUR 2006028442 projects, the INTAS program, the Russian Foundation for Basic Research Grants 05-02-17622 and 06-02-16912, the RF President Foundation Grant SS-3057-2006-2, the "Fundamental Physics Program of Russian Academy of Sciences" and the grant RFBR-CERN 08-02-91020.

References

[1] J. Lindhard, K. Dan, Vidensk. Selsk. Mat. Fys. Medd. 34 (14) (1965).
[2] E.N. Tsyganov, Preprint TM-682, TM-684, Fermilab, Batavia, 1976.
[3] A.M. Taratin, Phys. Particles Nuclei 29 (1998) 437.
[4] A.G. Afonin, et al., Nucl. Instrum. Methods B 234 (14) (2005).
[5] J.F. Bak, et al., Nucl. Phys. A 389 (1982) 533.
[6] A. Baurichter, et al., Nucl. Instrum. Methods B 119 (1996) 172.
[7] A.M. Taratin, S.A. Vorobiev, Nucl. Instrum. Methods B 26 (1987) 512.
[8] Yu.M. Ivanov, et al., Phys. Rev. Lett. 97 (2006) 144801.
[9] Yu.M. Ivanov, et al., JETP Lett. 84 (2006) 372.
[10] W. Scandale, et al., Phys. Rev. Lett. 98 (2007) 154801.
[11] W. Scandale, et al., Phys. Rev. Lett. 101 (2008) 234801.
[12] Yu.M. Ivanov, A.A. Petrunin, V.V. Skorobogatov, JETP Lett. 81 (2005) 99.
[13] S. Baricordi, et al., Appl. Phys. Lett. 91 (2007) 061908.
[14] S. Baricordi, et al., J. Phys. D Appl. Phys. 41 (2008) 245501.
[15] V.A. Maisheev, Phys. Rev. ST Accel. Beams 10 (2007) 084701.