Physics Letters B 680 (2009) 301–304

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

High-efficiency deflection of high-energy negative particles through axial channeling in a bent crystal

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 23 July 2009
Received in revised form 1 September 2009
Accepted 8 September 2009
Available online 11 September 2009
Editor: L. Rolandi

PACS:
61.85.+p

ABSTRACT

Deflection due to axial channeling in a silicon crystal bent along the ⟨111⟩ axis was observed for 150 GeV/c negative particles, mainly π^- mesons, at one of the secondary beams of the CERN SPS. The whole beam was deflected to one side with the efficiency of about 90% and with the peak position at the bend crystal angle $\alpha = 43$ µrad. The deflection occurs mainly due to doughnut scattering of above-barrier particles by the atomic strings of the crystal. However, due to a high probability of particle recapture into bound states with the atomic strings their contribution to the deflection should be about 15% for our case according to simulation results.

When high-energy charged particles enter a crystal with small angles, $\theta \ll 1$, to the atomic planes or axes their transverse motion is governed by the crystal potential averaged along the planes or axes, respectively [1]. In this condition, there are bound and unbound types of the particle motion. The bound states of particles are realized in the potential wells (channels) of one-dimensional planar lattice or two-dimensional axial lattice of a crystal. For positive particles the potential well is formed by either two neighboring planes or a few atomic strings for a planar and axial case, respectively. For negative particles the potential well is centered at a plane (it can be pair of planes for (111) Si) or an axis position, respectively. The transverse energy of particles in the unbound states is larger than the potential barrier between two channels. These above-barrier particles crossing the planes or scattering by the strings pass from one crystal channel to the other.

The bound channeling states of particles are also possible in a bent crystal if its radius is larger than the critical one R_c [2]. Particles following the bent crystal channels can be deflected by the crystal bend angle. The deflection of positive particles due to planar channeling in bent crystals is well studied (see the review [3]) and such crystal deflectors are used to extract particles from cyclic accelerators [4]. Recently the deflection of negative particles, 150 GeV/c π^- mesons, in bound states with the bent planes in short silicon crystals was observed in our experiment (will be published separately). The deflection possibility for relativistic negative particles in the bound states with atomic strings in a bent crystal had been shown in the numerical experiment [5] using the model of binary collisions of particles with the crystal atoms.

Relativistic charged particles in unbound states at the axial orientation of a bent crystal can be deflected due to the pecu-

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

0370-2693/$ – see front matter
doi:10.1016/j.physletb.2009.09.009

liarities of multiple scattering by atomic strings. When angles of particles with the axis direction are smaller than the critical channeling angle ψ_1 a uniform distribution of the transverse momentum directions of particles is reached due to multiple scattering by the atomic strings after traversing a distance λ (equalization length) [1]. The process, which leads to such a distribution, is called doughnut scattering. The condition for particle deflection in a bent crystal due to doughnut scattering was first formulated in [6]. However, the sufficient condition for the particle deflection due to doughnut scattering was then formulated in [7] where it was underlined that the deflection should occur also for negative particles. According to [7] the average square of the particle scattering angle by the atomic strings at the exit from a bent crystal should be smaller than the square of the critical angle

$$\overline{\psi^2} = \frac{\lambda L}{R^2} \leqslant \psi_1^2,$$

$$\psi_1 = \sqrt{\frac{4Z_1 Z_2 e^2}{pvd}}, \qquad \lambda(\psi_1) = \frac{4}{\pi^2 N d a \psi_1}, \tag{1}$$

where R and L are the bend radius and length of the crystal, Z_1 and Z_2 are the atomic numbers of the incident particle and the crystal atom, p and v are the momentum and velocity of the particle, d is the interatomic spacing in the string, N is the atomic density in the crystal and a is the screening length for the particle–atom potential ($a = 0.194$ Å for Si). The deflection due to doughnut scattering of 400 GeV/c protons in a silicon crystal bent along the $\langle 111 \rangle$ axis when the condition (1) was satisfied was recently observed in the experiment [8]. The deflection efficiency of protons at the crystal bend angle was about 30%. Small deflection effect had been registered in the experiments [9] with 200 GeV/c negative pions at the axial $\langle 110 \rangle$ orientation of a bent silicon crystal. However, the condition (1) was not satisfied and the beam was deflected by the angle much smaller than the crystal bend angle.

This Letter presents the results of the observation of the deflection for ultra relativistic negative particles in a silicon crystal bent along the $\langle 111 \rangle$ axis. The deflection has occurred mainly due to doughnut scattering of particles but according to our simulation there was also the contribution of the bound states of particles with atomic strings. The experiment has been performed with 150 GeV/c negative particles, mainly π^- mesons, at one of the secondary beams of the CERN SPS. The experimental setup was the same as described in [8]. Four microstrip silicon detectors, two upstream and two downstream of the crystal, were used to measure the particle angles with resolution of $\sigma_a = 8$ μrad, which is limited by the multiple scattering of particles in the detectors and the air.

A $70 \times 0.98 \times 0.5$ mm^3 silicon strip (length × width × thickness) with the largest faces parallel to the (110) planes and with the side faces, which are 70×0.5 mm^2, parallel to the (111) planes fabricated according to the technologies [10,11] was used in our experiment. The crystal was placed with its length along a vertical direction. The beam entered the crystal through its side face nearly parallel to the large ones (see Fig. 1 in [8]). Thus, the $\langle 111 \rangle$ axis direction became nearly aligned with the beam. The crystal was mechanically bent along its length. The anticlastic curvature produced along the crystal width was used for the beam deflection in the horizontal plane.

The crystal bend angle α according to the measurement of the deflection angle of particles at the planar orientation of the crystal was about 43 μrad. For 150 GeV/c π^- mesons the critical angle of channeling along the $\langle 111 \rangle$ axis is $\psi_1 = 33.8$ μrad, and the equalization length $\lambda = 26.3$ μm that gives $\overline{\psi^2} = 0.043\psi_1^2$. Thus, the condition (1) for π^- mesons deflection due to doughnut scattering was satisfied in our experiment.

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. All angular parameters in our experiment were sufficiently well determined with the measurements ($\sigma_a \ll \alpha, \sigma_x, \sigma_y$). A high precision goniometer was used to orient the crystal with respect to the beam axis in the horizontal and vertical planes with the accuracy of 2 μrad.

After the installation the scan of the horizontal orientation angles θ_v of the crystal was performed. As a result the (110) planes were aligned with the beam. In this angular position the deflection of particles at the bend angle due to planar channeling was maximally efficient. This angular position of the goniometer in the horizontal plane was fixed and then the vertical angular scan was performed, which allowed to get the alignment of the $\langle 111 \rangle$ axis with the beam in the vertical plane.

Fig. 1 shows the beam intensity distribution in the deflection angles of particles in the horizontal θ_x and vertical θ_y planes for the different orientation angles θ_v of the $\langle 111 \rangle$ crystal axis with the beam direction. The narrow fraction of the incident beam with the angles $(\theta_{x0}^2 + \theta_{y0}^2)^{1/2} \leqslant 10$ μrad was selected. When the crystal is not aligned with the beam that is the crystal axes and plane directions are far from the beam direction, particles undergo ordinary Coulomb multiple scattering as in an amorphous substance and the beam is not deflected. When the crystal axis becomes close to the beam direction particles are governed by the averaged potential of atomic strings. They undergo multiple scattering by the atomic strings. As a result the transverse momentums of particles are partly randomized. We can see an arc shape of the particle distribution for the orientation angle of the $\langle 111 \rangle$ crystal axis $\theta_v = -40$ μrad (a). The arc radii are determined by the particle angles to the axis direction at the crystal entrance $|\theta_v|$ and exit $|\theta_v| + \alpha$. For the orientation angle $\theta_v = -20$ μrad (b), the distribution shape becomes close to a circle, which is shifted to the bend side. However, the maximum of the beam intensity continues to be near the incident beam direction. For the nearly perfect alignment at $\theta_v = 0$ (c), the whole beam is deflected by the bend angle. In the contrary to the case with positive particles [8] there is no any leakage of π^- mesons into skew planar channels intersecting the $\langle 111 \rangle$ axis because the planar motion of negative particles having small angles with atomic strings of the planes cannot be stabilized. Really, the impact parameters of π^- mesons in subsequent collisions with the atomic strings of skew planes fast decrease due to the attractive character of forces. Therefore, they undergo strong scattering in close collisions with the atomic strings by the angle larger than the critical one for planar channeling and leave the planar channel.

Fig. 2 shows the horizontal projection of the two-dimensional distribution for the nearly perfect alignment presented in Fig. 1(c). The distribution maximum position corresponds to the crystal bend angle, $\alpha = 43$ μrad. The distribution width FWHM = (55 ± 2) μrad. The crystal considerably broadens the beam due to multiple potential scattering of particles by the atomic strings, which leads to the randomization of their transverse momentum, and due to strong incoherent multiple scattering on the atomic nuclei. The efficiency of the beam deflection to one side from the initial direction $P(\theta_x > 0) = (90.6 \pm 0.5)$%.

Fig. 1(d) shows the two-dimensional intensity distribution of the beam crossed the crystal at a perfect alignment, which was obtained by simulation for the experimental conditions. The model of atomic-string lattice [12] with the atomic potential and electron density obtained in the Doyle–Turner approximation for the atomic

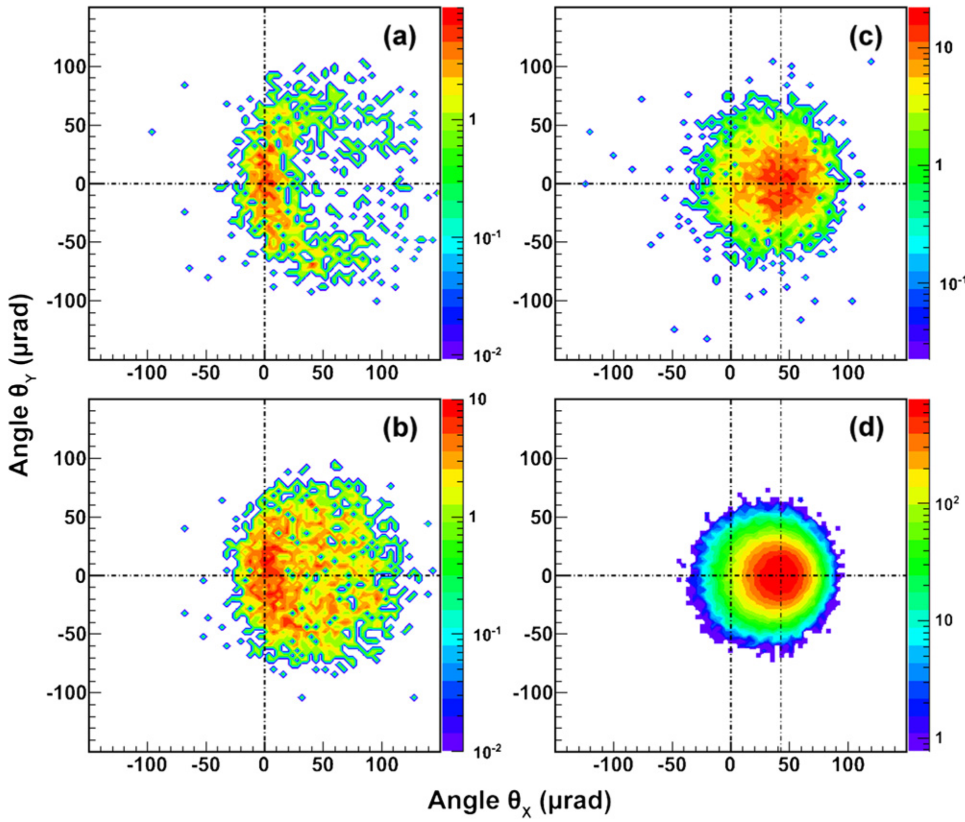

Fig. 1. (Color online.) Beam intensity distribution in the deflection angles of particles in the horizontal θ_x and vertical θ_y planes for the different orientation angles θ_v of the ⟨111⟩ crystal axis with respect to the beam: (a) $\theta_v = -40$ μrad, (b) $\theta_v = -20$ μrad and (c) $\theta_v = 0$. The narrow fraction of the incident beam with the angles $(\theta_{x0}^2 + \theta_{y0}^2)^{1/2} \leqslant 10$ μrad were selected. (d) The distribution obtained by simulation for the perfect alignment with the axis. The bend crystal angle $\alpha = 43$ μrad is shown by the dotted line in (c) and (d).

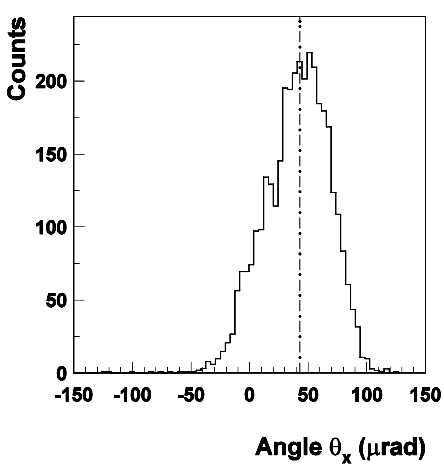

Fig. 2. Horizontal projection of the beam intensity distribution shown in Fig. 1(c). The dotted line shows the crystal bend angle value $\alpha = 43$ μrad.

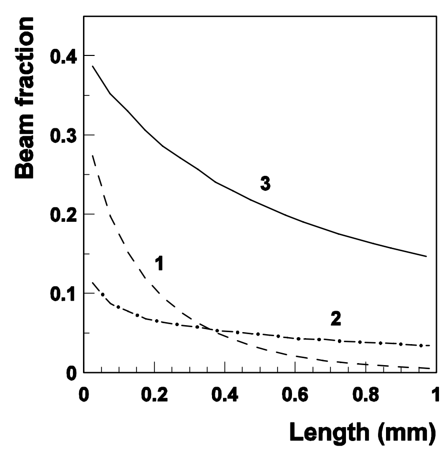

Fig. 3. Fraction of particles in the bound states with the ⟨111⟩ atomic strings as a function of the penetration depth into the crystal (curve 3). Curve 1 is for the hyperchanneled fraction. Curve 2 is for the fraction recaptured into the bound states. The dependencies were obtained by simulation for the perfect alignment of the ⟨111⟩ axis with the beam.

scattering factors was used for simulation. There is a good agreement with the experiment.

The simulation allows knowing the state of every particle during the passage through the crystal. Fig. 3 shows the dependence of the particle fraction in the bound states with the atomic strings, with the transverse energies $E_x < U(R_s)$, where $U(R_s) = 99.4$ eV is the potential value at the distance equal to the string radius R_s (half the distance between the strings), on the penetration depth into the crystal. The capture efficiency of particles into the bound states for the experimental conditions is about 42%. However, the particles fast leave the bound states due to strong multiple scattering on the atomic nuclei. The contribution of hyperchanneled particles, which have crossed the whole crystal length in the bound states, is about 5.5% (the curve 1). However, incoherent multiple scattering causes also the reverse process of the intense recapture of particles into the bound states. The fraction of particles recaptured in the considered crystal layer is shown by the curve 2. The recapture process occurs along the whole crystal length. The total number of particles in the bound states with the atomic strings

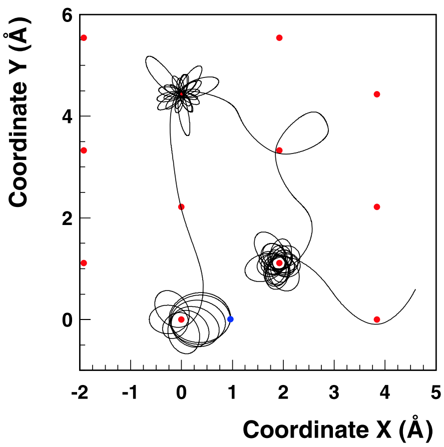

Fig. 4. (Color online.) The trajectory in the transverse space calculated for the particle, which was captured into the bound state with the atomic string located at $(X, Y) = (0, 0)$ at the crystal entrance and then two times was recaptured by the neighboring atomic strings. The bound states are seen by the precessing elliptical orbits. Red dots indicate the ⟨111⟩ axes positions and the blue one — the position of the entrance point of the particle.

increases due to the recapture (the curve 3). The beam fraction deflected at the bend angle in the bound states is about 15%.

Fig. 4 shows the trajectory of one of the particles, which underwent a few recaptures crossing the crystal. The particle was captured into the bound state at the crystal entrance. It fast left this state and was recaptured by the atomic string next to the neighboring one. The precessing elliptical orbit indicates the bound state of the particle. The recapture occurred the second time by the atomic string closest to the first one before the particle left the crystal.

Our experimental results have shown a high-efficient deflection of ultrarelativistic negative particles at the axial orientation of a bent silicon crystal. The deflection mainly occurs due to doughnut scattering of particles by the atomic strings. Besides, it was shown by simulation that strong incoherent multiple scattering of particles on the atomic nuclei causes not only fast dechanneling but also a high probability of the reverse capture of particles into the bound states with the atomic strings. So, the bound states of particles should also give a contribution of about 15% in the observed beam deflection.

References

[1] J. Lindhard, K. Dan. Vidensk. Selsk. Mat. Fys. Medd. 34 (1965) 14.
[2] E.N. Tsyganov, Preprint TM-682, TM-684, Fermilab, Batavia (1976).
[3] A.M. Taratin, Phys. Part. Nucl. 29 (1998) 437.
[4] A.G. Afonin, et al., Nucl. Instrum. Methods B 234 (2005) 14.
[5] A.M. Taratin, S.A. Vorobiev, Phys. Lett. A 72 (1979) 145.
[6] J.F. Bak, et al., Nucl. Phys. B 242 (1984) 1.
[7] N.F. Shul'ga, A.A. Greenenko, Phys. Lett. B 353 (1995) 373.
[8] W. Scandale, et al., Phys. Rev. Lett. 101 (2008) 164801.
[9] A. Baurichter, et al., Nucl. Instrum. Methods Phys. Res., Sect. B 119 (1996) 172.
[10] S. Baricordi, et al., Appl. Phys. Lett. 91 (2007) 061908.
[11] S. Baricordi, et al., J. Phys. D: Appl. Phys. 41 (2008) 245501.
[12] A.M. Taratin, S.A. Vorobiev, Phys. Lett. A 115 (1986) 401.