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Deflection of high-energy negative particles in a bent crystal through axial channeling and multiple volume reflection stimulated by doughnut scattering

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ABSTRACT

Different kinds of deflection 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 in quasi-bound states of doughnut scattering (DSB) by atomic strings with the efficiency $(95.4 \pm 0.2)\%$ and with the peak position close to the bend crystal angle, $\alpha = 185$ μrad. It was observed volume capture of π^- mesons into the DSB states with a probability higher than 7%. A beam deflection opposite to the crystal bend was observed for some orientations of the crystal axis due to doughnut scattering and subsequent multiple volume reflections of π^- mesons by different bent planes crossing the axis.

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When high-energy charged particles enter a crystal with sufficiently small angles to the crystallographic axis their transverse motion is governed by the potential of the lattice of atomic strings averaged along the axis that is the axial channeling regime is realized [1]. The transverse momentum of a particle changes its direction due to scattering by atomic strings. Particles with the orientation angle ψ are distributed along the arc (circle) with the radius ψ around the axis direction as a result of multiple scatterings by atomic strings during the passage through the crystal. This was a reason to call such a process of multiple scattering of particles by atomic strings "doughnut scattering".

The estimate of the crystal length required to obtain a full randomization of the transverse momentums of particles (equalization length) was suggested by Lindhard [1] and for the orientation angle $\psi = \psi_1$ equals

$$\psi_1 = \sqrt{\frac{4Z_1Z_2e^2}{pvd}}, \qquad \lambda_1 = \lambda(\psi_1) = \frac{4}{\pi^2 N d a \psi_1}, \tag{1}$$

where ψ_1 is the critical angle for axial channeling, 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). For 150 GeV/c π^- mesons in a silicon crystal oriented along the ⟨111⟩ axis $\psi_1 = 33.8$ μrad and $\lambda_1 = 26.3$ μm. A full randomization is also possible for $\psi > \psi_1$ but

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it requires larger crystal lengths. Our simulation results show that the real equalization length for our case is about ten times larger than the estimates of λ_n for $\psi = n\psi_1$ given in [2].

The bound states with a single atomic string are also possible for negative particles due to the attractive character of the forces acting between the particles and the atomic strings. The particles in these states move along the precessing elliptical orbits around the strings. 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 [3] using the model of binary collisions of particles with the crystal atoms.

High energy charged particles in unbound states performing doughnut scattering at the axial orientation of a bent crystal can be also deflected. The condition for the particle deflection in the regime of doughnut scattering had been considered in [2,4]. The deflection occurs if particles have time to finish the momentum randomization around the angular position of the axis changing along the crystal and if the crystal length is not very large. The particles deflecting in this case can be considered as quasi-bound with the axis direction in contrary to the real bound states with a single atomic string. Let us call this regime "Doughnut Scattering Bound" (DSB). The motion regime for particles performing multiple scattering by atomic strings but do not following to the crystal bend will be called "Doughnut Scattering Unbound" (DSUB). Let us note some peculiarities, which are important for understanding the DSUB regime. The particle momentum randomization center is determined by the angular position of the axis therefore it shifts with the penetration of a particle into a bent crystal. Besides, the transverse momentum of a particle, which determines the randomization radius at the given crystal depth, is changed due to Coulomb multiple scattering and doughnut scattering (DSUB) in the previous crystal layers.

The sufficient condition for the particle deflection due to doughnut scattering was formulated in [4] from the requirement that the average square of the particle deflection angle due to multiple scattering by the atomic strings at the exit from a bent crystal should be smaller than the square of the critical angle

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

where R and L are the bend radius and length of the crystal. The deflection of high energy charged particles in the DSB regime, when the condition (2) was fulfilled, was observed for 400 GeV/c protons [5] and 150 GeV/c π^- mesons [6]. In the last case the crystal bend angle as well as the crystal length were small, $\alpha = 43$ μrad $= 1.27\psi_1$ and $L = 0.98$ mm. Therefore, the contribution of the bound states of π^- mesons with single atomic strings was sufficiently large, about 15%, according to the simulation results.

This Letter presents the results of the experiment on the deflection of negative particles, 150 GeV/c π^- mesons, by a bent silicon crystal oriented along the $\langle 111 \rangle$ axis with the considerably larger bend angle $\alpha = 185$ μrad $= 5.5\psi_1$. This allowed us to observe the dependence of the particle fraction deflected in the quasi-bound states with the bent axis direction, in the DSB regime, on the crystal orientation. The efficiency of the one side deflection was larger than 95%. It was observed volume capture of π^- mesons into the DSB regime with a probability larger than 7%. Besides, the beam deflection to the side opposite to the crystal bend was observed for some orientations of the crystal axis due to doughnut scattering and subsequent multiple volume reflections of π^- mesons by the bent planes crossing the axis. The last effect of multiple volume reflections in one crystal (MVR OC) predicted in [7] was observed recently for 400 GeV/c protons [8] and 150 GeV/c π^- mesons (will be published).

The experiment has been performed at one of the secondary beams of the CERN SPS. The experimental setup was the same as described in [9]. 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 $70 \times 8 \times 0.3$ mm^3 silicon strip (length × width × thickness) with the largest faces parallel to the (110) planes and with the side faces, which are 70×0.3 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 [9]). 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. Because of a small planar dechanneling length for negative particles the crystal has been preliminary tested using 400 GeV/c proton beam. The crystal bend angle measured through the deflection of protons by the (110) bent planar channels was $\alpha = (185 \pm 0.4)$ μrad.

The condition (2) for the particle deflection due to doughnut scattering is fulfilled for our case, $\overline{\psi^2} = 0.098\psi_1^2$. As it was mentioned above the real equalization length for our case is about ten times larger than the theoretical one used in (2). However, the condition (2) with the real equalization length is still satisfied in our experiment for a narrow beam fraction in the aligned crystal.

The measured divergence of the incident beam of π^- mesons was characterized by the RMS deviations $\sigma_x = \sigma_y = (26.5 \pm 0.2)$ μrad. 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. At the beginning the scan of the horizontal orientation angles of the crystal θ_h was made to align the (110) planes with the beam by the fixation of the goniometer position corresponding to the deflection efficiency maximum of particles due to planar channeling. Then the alignment of the $\langle 111 \rangle$ axis with the beam was performed by the scan of the vertical orientation angles of the crystal θ_v.

Fig. 1(a) shows the beam intensity distribution in the deflection angles of particles in the horizontal θ_x and vertical θ_y planes for the perfect alignment of the crystal with the axis, $\theta_h = \theta_v = 0$, when the fraction of particles deflected with the horizontal angles around α (shown by the dashed line) is maximum. The narrow fraction of the incident beam with the angles $(\theta_{xo}^2 + \theta_{yo}^2)^{1/2} \leqslant 10$ μrad was used. Fig. 1(b) shows the horizontal projection of this distribution by the hatched histogram. The distribution maximum is at the angle $\theta_x < \alpha$. The deflection efficiency to the bent side is $P_d(\theta_x > 0) = (95.4 \pm 0.2)\%$. The histogram 2 shows the distribution obtained by simulation for the experimental condition. The model of atomic-string lattice [12] with the atomic potential and electron density obtained in the Doyle–Turner approximation for the atomic scattering factors was used for simulation. The one side deflection efficiency obtained in the simulation $P_d(\theta_x > 0) = (98.5 \pm 0.1)\%$. The maximum position of the calculated distribution is about the crystal bend angle. The reduction of the deflection angles in the experimental distribution maximum is explained by the crystal torsion, which leads to different orientations of the crystal axes along the vertical direction. For comparison the histogram 3 shows the deflection angle distribution of π^- mesons calculated for the straight crystal with the same length. The distribution has a Gaussian shape centered at $\theta_x = 0$ with the RMS deviation value $\sigma = (28.65 \pm 0.24)$ μrad, which is larger than the Coulomb multiple scattering angle $\theta_o = 24$ μrad for the amorphous orientation due

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