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Observation of nuclear dechanneling length reduction for high energy protons in a short bent crystal

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ABSTRACT

Deflection of 400 GeV/c protons by a short bent silicon crystal was studied at the CERN SPS. It was shown that the dechanneling probability increases while the dechanneling length decreases with an increase of incident angles of particles relative to the crystal planes. The observation of the dechanneling length reduction provides evidence of the particle population increase at the top levels of transverse energies in the potential well of the planar channels.

When high energy charged particles enter a crystal with small angles relative to the crystal planes, $\theta_o << 1$, their motion is governed by a crystal potential, $U(x)$, averaged along the planes [1]. If the angles are smaller than the critical angle $\theta_o < \theta_c = (2U_o/pv)^{1/2}$, where p, v are the particle momentum and velocity, respectively, and U_o is the well depth of the averaged planar potential, the particles can be captured into the channeling regime. Channeled particles move in a crystal oscillating between two neighboring planes. Channeling is also possible in a bent crystal if

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its bend radius is larger than the critical value, $R > R_c = pv/eE_m$ [2], where E_m is the maximum strength of the electric field in the planar channel. In a bent crystal, the particle motion is governed by the effective potential $U_{eff}(x, R) = U(x) + x \cdot pv/R$.

The averaged planar potential provides an approximate description of channeling, in which the transverse energy of particles is the integral of motion. Incoherent (multiple and single) scattering by the crystal electrons and nuclei changes the transverse energy of channeled particles and they leave the channels, that is dechanneling occurs. The density of atomic nuclei reduces quickly with the distance x from the planes according to a Gaussian distribution $P_n(x) \sim \exp(-x^2/u_\perp^2)$, where $u_\perp = \sqrt{2}u_1$ and u_1 is the amplitude of thermal vibrations of the crystal atoms. Therefore, the dechanneling process has two stages for most of channeled particles entering the crystal sufficiently far from the channel walls. In the first slow stage particles increase their transverse energy due to multiple scattering on the crystal electrons. The experimental data [3] have shown that a good approximation for the critical approach distance to the channel walls is $r_c = 2.5u_1$ where the fast dechanneling stage due to multiple scattering by atomic nuclei begins ("nuclear corridor"). The value of the planar potential at the distance r_c determines the critical transverse energy for the stable channeling states $E_{xc} = U_{eff}(x = r_c)$. The dechanneling process has an exponential character in the first approximation, $N_{ch}(z) \sim \exp(-z/S_d)$, where S_d is the dechanneling length. The dechanneling length measured in the experiment [4] is about 10 cm for 200 GeV/c protons in the (110) channels of a 44 mm long straight silicon crystal. It determines the reduction of particles in the stable channeling states due to multiple scattering on the crystal electrons, the electron dechanneling length S_e. The dechanneling length is approximately proportional to the particle energy.

Short crystals with length $L << S_e$ are required to study the fast mechanism of nuclear dechanneling. The crystal bend provides the angular unfolding of the dechanneling process. The first measurement of the nuclear dechanneling length was realized in the experiment [5] using a 2 mm long silicon crystal bent along the (110) planes with a bend radius $R = 40$ m for 400 GeV/c protons. The measured nuclear dechanneling length was about 1.5 mm which is more than 100 times smaller than the electron dechanneling length for this energy of protons.

It should be noted that for the planar channeling of negative particles nuclear multiple scattering is the main mechanism of dechanneling because all the particles oscillate around the crystal planes. The dechanneling length for 150 GeV/c π^- mesons was measured in the experiment [6]. Its value, $S_n \approx 1$ mm, is the same order of magnitude as the nuclear dechanneling length for positive particles with the same energy.

Fig. 1 shows the effective potential $U_{eff}(x, R)$ in the silicon crystal bent along the (110) planes with the radius $R = 10.26$ m for 400 GeV/c protons. The interval of transverse energies (E_{xc}, E_{xm}), where $E_{xm} = U_{eff}(0, R)$ is the potential well depth, determines the particle fraction undergoing dechanneling due to strong multiple scattering by the crystal nuclei. One would expect that dechanneling should be faster for particles when their transverse energy is closer to the well depth E_{xm}. The number of such near-barrier particles should increase with an increase of the beam orientation angle relative to the planes at the crystal entrance.

In this paper, the results of the experiment at the CERN SPS on the deflection of 400 GeV/c protons by a short bent silicon crystal are considered. The analysis of different beam fractions for the crystal orientation optimal for channeling allows to observe the reduction of the nuclear dechanneling length with an increase of the orientation angle of the considered beam fraction relative to the planes at the crystal entrance.

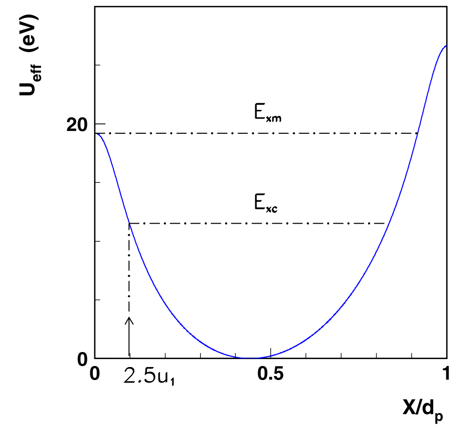

Fig. 1. (Color online.) The effective potential $U_{eff}(x, R)$ in the bent silicon crystal for 400 GeV/c protons as a function of a relative coordinate x/d_p, where $d_p = 1.92$ Å is the distance between two planes. The crystal is bent along the (110) planes with the radius $R = 10.26$ m. Here E_{xm} is the maximal transverse energy for channeled particles, $E_{xm} = U_{eff}(0, R)$ is the potential well depth, E_{xc} is the critical transverse energy for stable channeling, $E_{xc} = U_{eff}(x = 2.5u_1)$. The interval (E_{xc}, E_{xm}) determines the range where dechanneling of particles occurs due to multiple scattering by the atomic nuclei of the crystal.

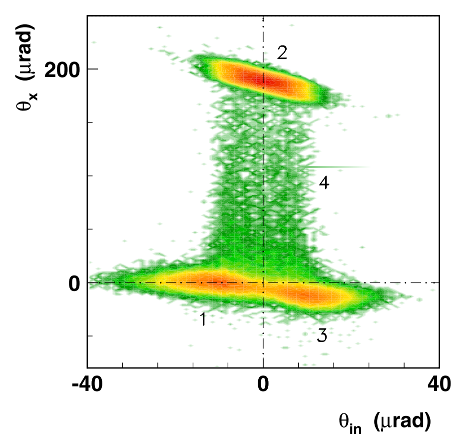

Fig. 2. (Color online.) The intensity distribution of 400 GeV/c protons passed through the bent silicon crystal when its orientation is optimal for channeling in the deflection angles θ_x as a function of incidence angle θ_{in} of particles relative to the (110) planes at the crystal entrance.

The experimental setup was the same described in [7]. Four microstrip silicon detectors, two upstream and two downstream of the crystal, were used to detect the particle trajectories with an angular resolution of 3 μrad, which is limited by the multiple scattering of particles in the detectors and air. A $70 \times 1.94 \times 0.5$ mm^3 silicon strip crystal with the largest faces parallel to the (110) crystallographic planes was fabricated according to the methodology described in [8,9]. The strip-crystal was bent along its length and placed vertically, so that the induced anticlastic bending along the crystal width was used to deflect particles in the horizontal plane (see Fig. 2b in [7]). The beam of 400 GeV/c protons had the RMS value of the horizontal angular divergence of $\sigma_x = (9.34 \pm 0.06)$ μrad. A high precision goniometer, with an accuracy of 2 μrad, was used to orient the (110) crystal planes parallel to the beam direction. An angular scan was performed and the optimal orientation was found, which gives the maximum of the deflected beam fraction.

Fig. 2 shows the intensity distribution of 400 GeV/c protons passed through the bent silicon crystal when its orientation is optimal for channeling in the deflection angles θ_x as a function of incidence angle θ_{in} of particles relative to the (110) plane at