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Angular asymmetry of the nuclear interaction probability of high energy particles in short bent crystals

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Abstract The rate of inelastic nuclear interactions in a short bent silicon crystal was precisely measured for the first time using a 180 GeV/c positive hadron beam produced in the North Experimental Area of the CERN SPS. An angular asymmetry dependence on the crystal orientation in the vicinity of the planar channeling minimum has been observed. For the inspected crystal, this probability is about $\sim 20\%$ larger than in the amorphous case because of the atomic density increase along the particle trajectories in the angular range of volume reflection, whose dimension is determined by the crystal bending angle. Instead, for the opposite angular orientation with respect to the planar channeling, there is a smaller probability excess of $\sim 4\%$.

1 Introduction

When high-energy charged particles enter a straight crystal at small angles relative to the crystal planes their transverse motion is governed by the crystal potential $U(x)$ averaged along the planes. If the incident angle is smaller than the critical channeling angle $\theta_c = (2U_o/pv)^{1/2}$, where p, v are the particle momentum and velocity and U_o the depth of the planar potential well, the particle can be captured into the planar channeling regime [1]. Channeled particles of positive charge move through the crystal oscillating between two neighbouring planes. Therefore, all the processes requir-

ing close collisions with the crystal atoms are strongly suppressed in a crystal well aligned with the beam. For incident angles slightly larger than the critical one the yield of such processes is larger than for the crystal orientations which are far from the directions of the main crystal planes and axes (amorphous crystal orientations). Channeling is also realised in a bent crystal if its bending radius $R > R_c$, where R_c is the critical bending radius (see in the review [2]). Channeled particles are deflected as they move along the bent crystals and an additional centrifugal term contributes to the effective inter-planar potential, as shown in Fig. 1. This term breaks the symmetry of the motion relative to bent planes. For particles moving in the direction of the inner side of the bent crystal (particle 1 in Figs. 1 and 2), a reflection occurs when the trajectory is nearly tangential to the bent crystal planes. When approaching the reflection point, the atomic density increases because the particle incoming angles with respect to the crystal planes decrease. At the reflection point, the volume reflection process occurs with large probability [3,4], i.e. the transverse momentum changes sign and the incoming particles are reflected to the side opposite to the crystal bending. Because of the multiple scattering on the atomic nuclei and electrons, near the reflection point, a small fraction of the incoming particles is captured into channeling regime, instead of being volume-reflected. Particles moving along the side opposite to the bending direction (particle 2 in Figs. 1 and 2) encounter the crystal planes at increasing angle. Along their trajectories, the atomic density continuously decreases, eventually approaching the amorphous
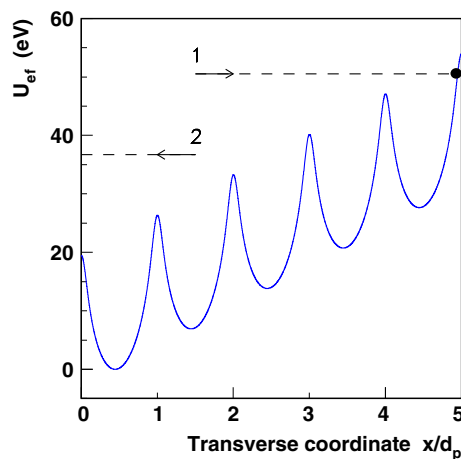
Fig. 1 Transverse crossing of particles 1 and 2 in the effective potential U_{ef} of a silicon crystal bent along the (110) planes, reported as a function of the planar channel width d_p, equal to 1.92 Å. Particle 1 moves to the inner side and reaches the reflection point in the effective potential (shown by a closed circle), where the particle changes its transverse direction, that is volume reflection occurs. Particle 2 moves to the side opposite to the bending and its transverse energy increases

Fig. 2 Scheme of the different coherent processes of a positive charged particles in a bent crystal. Volume reflection occurs when the particle incoming angle is positive and inside the interval between the critical and the bending angle ($\theta_c < \theta_{in} < \theta_b$): the atomic density increases because the crossing angles of the crystal planes decrease (particle 1). For negative particle incident angle it encounters atomic planes at increasing angles and the atomic density continuously decreases to the amorphous density value (particle 2). Planar channeling is possible when the incident angle of the particle is smaller than the channeling critical angle ($\theta_{in} < \theta_c$) and it is deflected by the crystal bending angle (particle 3)

density value. Planar channeling and volume reflection are used for beam collimation, extraction and splitting in particle accelerators [5].

The inelastic nuclear interaction (INI) rate in short bent crystals has been experimentally investigated in [6–8]. For high-energy channeled protons, INI event rate considerably smaller than for the amorphous case was reported, while an increase of the rate was preliminarily observed for volume reflection orientations. Nuclear interactions at volume reflection have been considered in the theoretical paper [9]. Probability asymmetry of INI near the perfect alignment has been shown by simulations for single passage of high energy protons in [10].

In this paper, the INI rate of 180 GeV/c positive hadrons in a short bent crystal, recorded with the highest accuracy ever achieved in similar measurements, is discussed. Its asymmetric dependence on the beam-crystal incident angle is observed for the first time using high-energy particles. In particular, the INI rate behavior in the full angular range around planar channeling orientation of a LHC collimation crystal has been measured, giving a reference for machine losses at the crystal position during tests of crystal-assisted collimation. Moreover, in LHC and in future high-energy accelerators as FCC, the only way by now to orient a bent crystal is to perform angular scans around the best channeling orientation and measure the local losses produced by INI in the crystal itself [11]. Precise measurements of INI for different crystal orientation, confirmed by detailed simulations, have a fundamental role for correct interpretation of these scans, hence the importance of the new experimental results presented here.
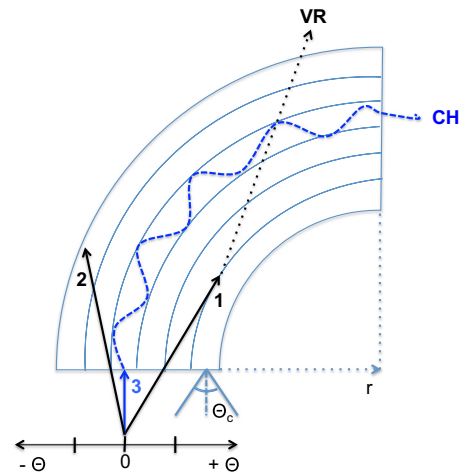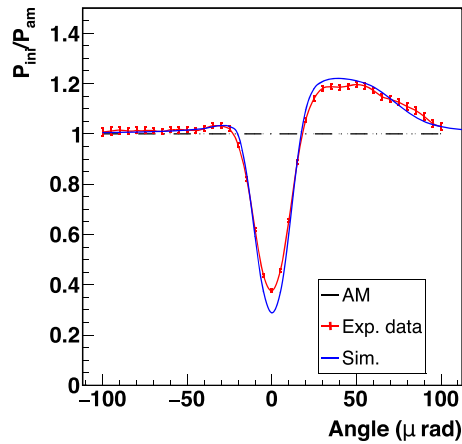
2 Experimental measurements

The main novelty of these measurements is the possibility to study INI of particle in the crystal track by track, precisely measuring their rate for each angular orientation. The detector, built in the framework of the UA9 Collaboration to investigate crystal-particle interactions in the North Experimental Area of the CERN-SPS, is based on a two-arm telescope able to reconstruct single tracks before and after the crystal traversal. The experimental procedure is described in details in [8]. It involves two additional fast plastic scintillators [12] symmetrically located downstream of the crystal position, on both sides of the beam line, the acquisition of whose data is integrated in the telescope DAQ. An high precision angular actuator ($\sim 1~\mu$rad of repeatability), also integrated in the DAQ, is used to orient the crystal. INI events occurring in the crystal have a large probability of producing a burst of hadrons inducing simultaneous signals in the two scintillation detectors downstream. Using the two scintillation counter signals in sharp coincidence with the trigger, it is easy to select the INI events, to reconstruct their tracks in the telescope and to evaluate their rate as a function of the crystal orientation.

Table 1 Crystal parameters: name, physical dimensions (L_X, L_Y, L_Z), bending angle (α), planar channeling efficiency within $\theta_c/2$ and type of the crystal
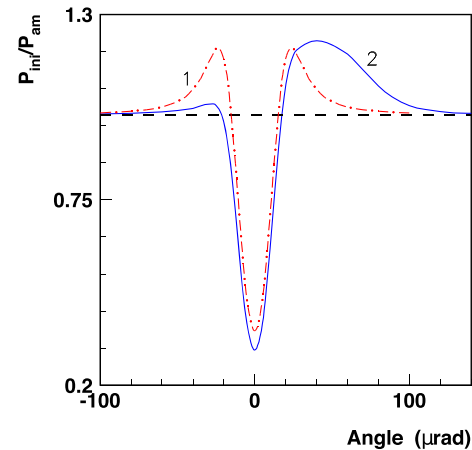
Crystal	L_X (mm)	L_Y (mm)	L_Z (mm)	α (μrad)	Eff. (%)	R (m)
ACP80	3.00 ± 0.02	50.0 ± 0.1	4.00 ± 0.02	61 ± 1	67 ± 2	66 ± 1

Fig. 3 In red the observed dependence of INI rate for 180 GeV/c positive hadrons on the orientation angle of the crystal. The blue curve shows the analytical simulation results. Both are normalized to the amorphous level (black dashed line)

Fig. 4 The simulated dependence of INI rate for 180 GeV/c positive hadrons on the orientation angle of the crystal. Curve 1 is calculated for a straight 4 mm thick, while curve 2 is for a 61 μrad bent crystal of the same thickness (the same as Fig. 3)

For the experiment, a silicon crystal with transversal thickness of 2 mm across the beam was chosen to increase the data acquisition rate. The used sample (ACP80) belongs to new series of LHC-type bent crystals developed by PNPI for crystal assisted collimation. Crystals of this series have (110) channeling planes, which are bent due to anticlastic effect with a titanium holder specially designed to provide given bending angle and high mechanical and thermal stability. The parameters of the ACP80 crystal are presented in Table 1.

The 180 GeV/c positive hadron beam ($\sim$ 70 % of protons and $\sim$ 30% of pions) at the H8 SPS extraction line had the following parameters: $\sigma_x \simeq 2$ mm, $\sigma_y \simeq 2$ mm, $\sigma_{\theta_x} \simeq 31$ μrad, $\sigma_{\theta_y} \simeq 44$ μrad. In these condition, the telescope has an excellent angular resolution of 12.3 μrad on a single track, mainly caused by multiple scattering in the sensor layers [13,14].

The experimental data taken with the ACP80 crystal were used to evaluate the INI probability as a function of the horizontal angular orientation of the crystal with respect to the beam axis direction. Horizontal angular scans have been performed, taking several high statistics acquisitions in different fixed orientations, and measuring the INI rate in each of them. In Fig. 3, the measured INI rate as a function of the orientation angle (red curve), normalised to the amorphous value (black dashed line), is shown. The measured INI absolute probability for the AM orientations is $\sim$ 1%.

The result is a clear profile of what happens in planar channeling, volume reflection and amorphous orientations, and in transition regions. An INI excess (on the right side of the planar channeling well) with respect to the amorphous level is clearly visible in the volume reflection region for positive angles. For negative angles, this excess appears smaller, showing the angular asymmetry of the INI rate. The experimental data are well reproduced by simulations performed according to the model described in [15] (blue curve in Fig. 3). The Thomas–Fermi potential with the Moliere analytical approximation for its screening function is used in our simulations. The potential was obtained using a statistical atomic model [2].

The same simulations for a straight (curve 1) and a bent (curve 2) crystal with the parameters of the ACP80 sample are reported in Fig. 4. Curve 2 shows the expected INI probability normalised to the amorphous orientation as a function of the particle incident angle. As previously explained, the deep minimum is due to the planar channeling regime. The shape of curve 2 is different for the left and right sides around the minimum. The INI probability is larger than in the amorphous case for positive orientation angles in the entire volume reflection angular range, where the particles trajectories are tangential to the crystal planes and, for larger positive angles, the INI probability decreases asymptotically to the amorphous value. On the contrary, for negative angles,
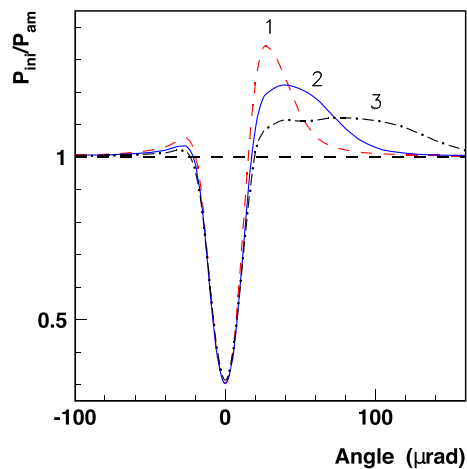
Fig. 5 The simulated INI rate for 180 GeV/c positive hadrons as a function of the orientation angle of two silicon crystals with the same bending radius but a different thickness along the beam direction. Curve 1 refers to a 2 mm thick crystal with a bending of 30 μrad, curve 2 refers to a crystal 4 mm thick with a bending of 61 μrad and curve 3 refers to a 8 mm thick crystal with a bending of 120 μrad

the transverse energy increases fast with the particle penetration into the crystal due to its bending. Therefore, just around the channeling minimum, the INI probability is only a few percent larger than in the amorphous case. This is exactly the same behaviour found in the experiment. Curve 1 in Fig. 4 shows that for a straight crystal of the same length the INI probability is symmetric relative to the plane direction and increases around the channeling minimum, over a shorter range than for a bent crystal. This symmetric behaviour for straight and strained crystal is already well measured using backscattered MeV ions, as reported in [16–18].

The experiment instead clearly showed that an INI probability asymmetry arises in crystals when they are bent. The angular range of the crystal orientation area where the INI probability excess is observed is determined by the crystal bending angle α. The crystal area size S_{vr} where volume reflection occurs is determined by the critical angle and the crystal bending crystal radius, $S_{vr} \approx 2\theta_c R$. The nuclear density averaged along the particle trajectories in this area is higher than the amorphous one. The INI probability excess k_{vr} increases with the ratio of S_{vr} to the crystal length L, $k_{vr} = S_{vr}/L = 2\theta_c/\alpha$. Curve 2 in Fig. 5 shows the INI rate dependence on the orientation angle obtained by simulations of the experimental conditions presented here in which $k_{vr} \approx 0.5$. Curves 1 and 3 are for the same bending angle but for crystal length of 2 mm and 8 mm, respectively, when $k_{vr} \approx 1$ and 0.26. The INI excess is about maximal for 2 mm long crystal because $L \approx S_{vr}$. Otherwise, for 8 mm long crystal the volume reflection area occupies even smaller part of the crystal length than for the experimental case. The averaged nuclear density decreases

and the INI excess becomes twice smaller. At the same value k_{vr}, the INI excess maximum increases a little (few percents) when the bending radius decreases twice. It has been already mentioned that a small beam part is captured into channeling regime in the volume reflection area. Volume captured particles have large oscillation amplitudes in the crystal channels and averaged nuclear density for them is higher than the amorphous one. Therefore, they also contribute to the INI excess in the volume reflection angular region but this contribution is always smaller than 10%.

3 Conclusions

Concluding, for an LHC collimation crystal the INI probability in planar channeling orientation is reduced by $\sim 64\%$ with respect to the amorphous orientation, as expected. An excess of $\sim 20\%$ in the volume reflection region and a small bump with an increment of only $\sim 4\%$ in the angular direction opposite to volume reflection have been precisely measured, showing for the first time the INI asymmetry due to the crystal bending. The crystal deflection properties and INI probability become asymmetric though the crystal bending angle is only 61 μrad, not even visible macroscopically. This is confirmed by theory and analytical simulations. These results, obtained in single pass mode, are very helpful per se for better understanding of bent-crystal physics, providing very precise benchmarks for simulations routines to be applied also to circular accelerator dynamics. This represent an important step forward for their application in future high-energy particle accelerators, not only for collimation purposes [11], but also for other kinds of beam manipulation, such as extraction [19], splitting, focusing, and defocusing [20]. Moreover, a very simple and effective experimental procedure to measure INI in bent crystals has been provided, allowing their complete and detailed characterisation.

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