

# PROBABILITY OF INELASTIC NUCLEAR INTERACTIONS OF HIGH-ENERGY PROTONS IN ALIGNED CRYSTAL

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## Abstract

A number of tests were performed in the North area of the SPS in view of investigating crystal-particles interactions for future application in hadron colliders. The rate of nuclear reactions was measured with 400 GeV proton beams directed into a silicon bent crystal. In this way the background induced by the crystal itself either in amorphous or in channeling orientation was revealed. The results provide fundamental information to put in perspective the use of silicon crystals to assist halo collimation in hadron colliders, whilst minimizing the induced loss.

## INTRODUCTION

When charged particles enter a crystal with small angles  $\theta$  relative to the crystal planes, their transverse motion is governed by the potential well  $U(x)$  averaged along the planes. For angles smaller than the critical channeling angle  $\theta_c = (2U_0/pv)^{1/2}$ , where  $p$ ,  $v$  are the particle momentum and velocity and  $U_0$  the depth of the planar potential well, particles can be captured into the channeling regime and will move oscillating between two neighboring crystal planes. For moderate bending of the crystal, that is for  $R < L/\theta_c$ , where  $L$  and  $R$  are the length and the radius of curvature the crystal, the potential well is preserved and the channeling remains effective. In channeling regime, close collisions with the crystal atoms should be strongly suppressed.

In a crystal bent by the angle  $\alpha$ , particle with  $\theta \leq \alpha$  that cannot be channeled at the entry face of the crystal proceeds until the tangency point with the bent planes. Here two effects may take place: either the particle partially loses its transverse energy and gets trapped into the channel (volume capture) or its transverse direction is elastically reversed by the interaction with the potential barrier (volume reflection). For most of their path inside the crystal, volume reflected particles cross randomly the crystal planes except that at the tangency point.

Particles with larger incoming angles, which cannot be channeled neither reflected, traverse the entire crystal along a path uncorrelated to the crystalline structure and hence interact with it as if it was an amorphous medium.

In a two-stage collimation system a bent crystal used as primary deflector may deviate coherently the incoming halo at angles larger than what can be obtained with amorphous materials, either by channelling or by reflection process with an increase of the collimation efficiency that is the fraction of the halo collected by the

secondary absorber. Inefficiency is mostly governed by nuclear reaction rate inside the crystal itself. Criteria to minimize it are thus important when selecting the optimal crystal technology and mode of operation.

Hereafter we present results relative to a single strip silicon crystal, 1.94 mm long, bent along the (110) planes by  $\alpha = 189 \mu\text{rad}$ , well suited for UA9 test in the CERN-SPS [1]. The nuclear interaction rate was measured with 400 GeV/c protons in H8 beam line of the North area of the CERN-SPS as a function of the crystal orientation respect to the incoming direction of the particles [2].

## INTERACTION RATE

Particles traversing a crystal along an amorphous orientation experience inelastic nuclear interactions with a probability  $P_{in} \approx \sigma_{in} N_{am} L$  that is the product of the process cross-section by the target nuclear density and length. The Glauber approach provides the estimate  $\sigma_{in} = 0.506 \text{ b}$  for 400 GeV/c protons [2], whilst for Si target the nuclear density is  $N_{am} = 0.05 \times 10^{24} \text{ cm}^{-3}$ . Thus, for a crystal length  $L = 1.94 \text{ mm}$  one finds  $P_{in} = 0.49\%$ .

The nuclear density averaged along the trajectory varies by large factors when the particles travel with small angles relative to the crystal planes. For protons trapped in channeling states, the density drops as a Gaussian function of the distance  $x$  from the crystal planes:

$$D(x) = \frac{d_p}{\sqrt{2\pi}u_1^2} \exp\left(-\frac{x^2}{2u_1^2}\right),$$

where  $u_1$  is the amplitude of thermal vibrations of the crystal atoms,  $u_1 = 0.075 \text{ \AA}$  for a silicon crystal at a room temperature,  $d_p$  is the planar channel width. The width of the “nuclear corridor” across the planes is much smaller than the width of the channel itself: for the (110) Si,  $d_p = 1.92 \text{ \AA}$  and  $6u_1/d_p = 0.23$ . Channeled particles with small transverse energies  $E_x$  travel in the potential well between nuclear corridors and cross a very small average density of nuclear targets. As the transverse energy  $E_x$  increases, the particles start interacting with nuclear corridors and cross a rapidly increasing average density of nuclear target, peaking at a value three times larger than  $N_{am}$ , when  $E_x = U_0$ . Finally, for  $E_x > U_0$ , the nuclear density decreases asymptotically towards  $N_{am}$  as  $E_x$  increases.

In the case of volume reflection the average nuclear density is  $N_{am}$  all along the particle trajectory except than in the tangency area, where it becomes significantly larger than  $N_{am}$ . Simulations show that the tangency area is rather short, only a few  $\mu\text{m}$ , and that in our 1.94 mm long crystal the increase of the average nuclear density is only a few percents.

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## THE DETECTOR

The experimental setup shown in Fig. 1 is similar to the one in [2]. Four micro-strip silicon detectors, two upstream and two downstream of the crystal, are used to detect the particle trajectories with an angular resolution of about  $3 \mu\text{rad}$ . Two large scintillation detectors with transverse dimensions  $100 \times 100 \text{ mm}^2$  are placed 60 cm downstream the crystal on both sides from the primary proton beam to register secondary particles generated in inelastic nuclear interactions of protons in the crystal. The distance between the scintillation detectors is 10 mm. The angular clearance of  $\theta_{\text{ed}} = 8.33 \text{ mrad}$  is sufficient to exclude background from primary protons elastically scattered by the crystal, because  $\theta_{\text{el}} \ll \theta_{\text{ed}}$ .

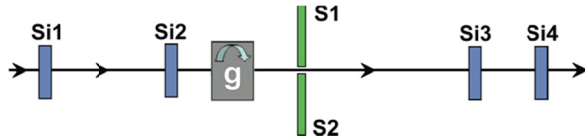


Figure 1: Schematic layout of the detector.

A  $70 \times 1.94 \times 0.5 \text{ mm}^3$  silicon strip crystal with the largest faces parallel to the (110) crystallographic planes is bent along its length and placed vertically, so that the anticlassic bending induced along the crystal width is used to deflect particles in the horizontal plane (see Fig. 2b. in Ref [3]). A high precision goniometer is used to orient the (110) crystal planes parallel to the beam direction. The optimal crystal orientation is the one corresponding to the maximum of the deflected beam fraction.

## THE EXPERIMENT

The measured RMS divergence of the incident beam  $\sigma_x = (13.368 \pm 0.003) \mu\text{rad}$  is larger than the critical channeling angle  $\theta_c \approx 10 \mu\text{rad}$ . By post-processing sets of incident particles in a limited range of incident angles  $|\theta_{\text{xol}}| < \theta_{\text{cut}}$  one can single out less divergent beams.

Figure 2 shows the angular distribution of protons with  $\theta_{\text{cut}} = 1.5 \mu\text{rad}$  resulting from interactions with the crystal.

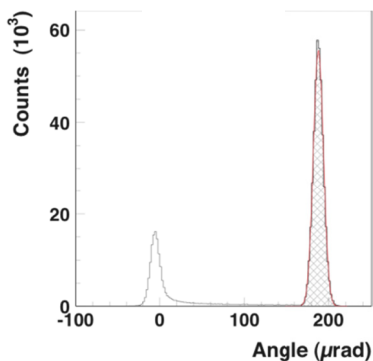


Figure 2: Angular distribution for  $\theta_{\text{cut}} = 1.5 \mu\text{rad}$ .

The two peaks correspond to volume reflection (left) and channeling (right) particles. The residual distribution between the peaks is due to dechanneling or volume capture. The deflection angle is  $\theta_{\text{xm}} = (189 \pm 0.02) \mu\text{rad}$  and the deflected beam fraction is  $P_d = (72.5 \pm 0.117)\%$ .

Figure 3 shows how the non-deflected beam part  $P_{\text{nd}} = 1 - P_d$  depends the angle  $\theta_{\text{cut}}$ .

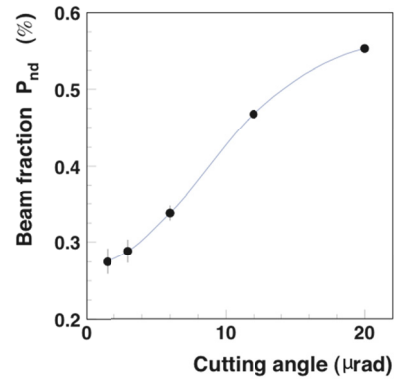


Figure 3: Non-deflected beam fraction.

A discriminating threshold  $A_b$  rejects the intrinsic scintillation detector background, whilst the coincidence rate with the amplitude  $A > A_b$  registered in S1 and S2 when the crystal is removed from the incident beam gives the experimental background induced by inelastic nuclear interactions upstream of the crystal to be subtracted from the nuclear reaction rate. The inelastic nuclear interaction frequency is defined as  $F_{\text{in}} = N_{12}(A > A_b) / N_0$ , where  $N_{12}(A > A_b)$  is the number of coincidence signals in S1 and S2 with amplitudes  $A > A_b$  and  $N_0$  is the number of particles with  $|\theta_{\text{xol}}| < \theta_{\text{cut}}$ , which hit the crystal. A simulation using the FRITIOF model for Si nuclei [4] provides an estimate for the coincidence rate that is  $F_{12} = 0.655 \pm 0.005$ .

Figure 4 shows the measured values of nuclear rate  $F_{\text{in}}$  as a function of the cutting angle  $\theta_{\text{cut}}$  for the amorphous orientation (1), for channeling (2) and without the crystal in the beam that is the experimental background (3). The interaction frequencies without the crystal and with the crystal in its amorphous orientation are constant. The frequency registered in the aligned crystal is smaller than for amorphous orientation and it decreases with decreasing  $\theta_{\text{cut}}$  due to the increase of the fraction of channeled protons not interacting with the crystal nuclei.

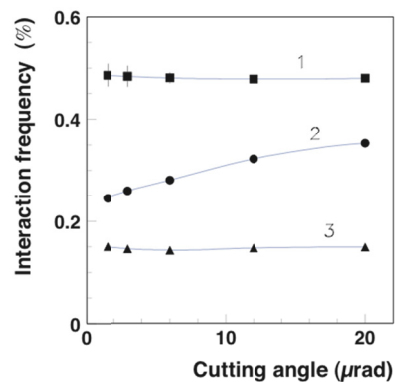


Figure 4: Interaction rate: in amorphous orientation (1), in channelling (2), without crystal (background) (3).

The probability of inelastic nuclear interactions  $P_{\text{in}} = (F_{\text{in}} - F_{\text{in}}(\text{BG})) / F_{12}$  where the experimental background is subtracted and the nuclear event rate  $F_{12}$  estimated by

the simulation above is used as the normalization value. The experimental background is about 0.15%.

Figure 5 shows how the nuclear interaction probability depends on  $\theta_{\text{cut}}$  for amorphous orientation (1), volume reflection (2) and channeling (3). Plot (4) is obtained with the simulation model in [5]. Plot (1) is quasi-constant with  $P_{\text{in}}^{\text{am}}=(0.505\pm 0.005)\%$ , in a good agreement with simulations for amorphous orientation. Plot (2) is also quasi-constant and refers to a situation of symmetric volume reflection when the tangency point is in the middle of the crystal length: practically all particles pass the whole crystal in above-barrier states and the nuclear probability is 3-4% larger than for amorphous orientation. Plot (3) shows a strong dependence on  $\theta_{\text{cut}}$ : for the smallest angular width of the incident beam, the probability is more than 3.5 times smaller in channeling than in amorphous orientation. The discrepancy of plots (3) and (4) for small values of  $\theta_{\text{cut}}$  is due to small imperfections of the goniometer and of the crystal shape, which become less effective for large values of  $\theta_{\text{cut}}$  when the angular size of the incident beam is larger than the angular imperfections. The simulation results show that channeled protons have (0.015-0.02)% probability of producing inelastic nuclear events, that is (3-4)% of the probability for amorphous orientation. Only channeled protons with large oscillation amplitudes, which approach the channel walls at distances  $r < r_c = 2.5u_1$ , can have inelastic interactions with the crystal nuclei. Their transverse energy is  $E_x > E_{xc} = U(r_c)$ . The beam fraction  $P(E_x > E_{xc})$  increases slowly with increasing  $\theta_{\text{cut}}$ , has a maximum at  $\theta_{\text{cut}} = \theta_c$ , then decreases again. The  $P(E_x > E_{xc})$  values for  $\theta_{\text{cut}} \approx 0$  and  $\theta_{\text{cut}} = \theta_c$  differ by about 30%.

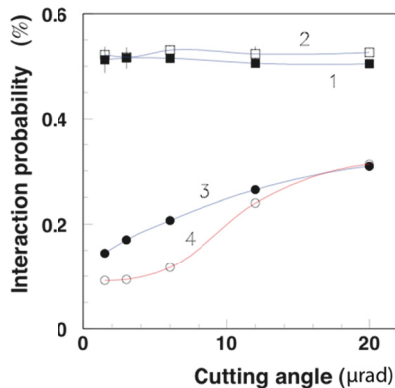


Figure 5: Probability of nuclear interaction: in amorphous orientation (1), in volume reflection (2), in channelling (3) and simulation for channelling (4).

Figure 6 shows the inelastic interaction probability of protons measured in the aligned crystal as a function of the beam fraction that passed the crystal in above-barrier states,  $P_{\text{neh}} = N_{\text{neh}}/N_0$  (solid circles). The probability is shown as a ratio to its value for the amorphous orientation  $P_{\text{in}}/P_{\text{in}}^{\text{am}}$ . The dependence shown by a dashed line,  $P_{\text{in}}/P_{\text{in}}^{\text{am}} = P_{\text{neh}}$ , is a hypothetical one when the probability is the same as in the amorphous case for all above-barrier protons and the contribution from channeled protons is

absent. The probability values measured in the experiment are larger than the hypothetical ones. The difference is about 8% for the large angular sizes  $\theta_{\text{cut}}$  of the incident beam. A half of this difference, about 4%, is due to the fact that the interaction probability for above-barrier protons is larger than for the amorphous orientation (see 2 in Fig. 5). The remaining difference, about 4% for the large values of  $\theta_{\text{cut}}$ , is due to the contribution of channeled protons, which is in a good agreement with the value predicted by the simulation.

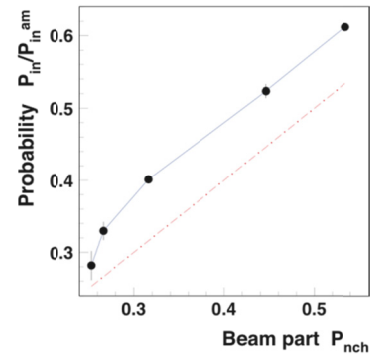


Figure 6: The dependence of the inelastic nuclear interaction probability in the aligned crystal on the non-channeled part of the beam.

The measurements have shown that the probability of inelastic nuclear interactions of high-energy protons in the aligned crystal is significantly smaller than for its amorphous orientation. The probability decreases with decreasing the angular width of the incident beam that is with increasing the number of particles captured into the channeling states. This occurs because channeled protons move through the crystal far from the crystallographic planes where the atomic nuclei are concentrated. The experimental data show that the contribution of inelastic interactions from channeled protons is about 3-4% of the probability for the amorphous orientation.

In the limiting case with a quasi-parallel beam, which should be realized in a collider beam halo, the deflection efficiency can approach 85%. Therefore, the probability of inelastic nuclear interactions of the beam halo protons in a perfectly aligned crystal should decrease more than five times (see 4 in Fig. 5). This is an additional advantage of the crystal primary collimator in comparison with the ordinary amorphous one.

## REFERENCES

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