MEASUREMENT OF NUCLEAR INTERACTION RATES IN CRYSTALS USING THE CERN-SPS NORTH AREA TEST BEAMS

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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 interactions was measured with 400 GeV proton beams directed into a silicon bent crystal. In this way the background induced by the crystal 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 θ relative to the crystal planes, their transverse motion is governed by the potential U(x) averaged along the planes. For angles 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, 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 $R>R_c$, where R_c is the critical bend radius, the potential well is preserved and channeling remains possible. In channeling regime, close collisions with the crystal atoms should be strongly suppressed.

In a crystal bent by the angle α, a particle with $\theta\leq\alpha$, which 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 loses part of its transverse energy and gets trapped into the channel (volume capture) or its transverse direction is elastically reversed in interacting with the potential well (volume reflection). Volume reflected particles pass through a crystal crossing the crystallographic planes.

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 deflect coherently the incoming halo by the 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 determined by nuclear interaction rate inside the crystal. 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 α=189 μrad, 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 for the different crystal orientations with respect to the incoming direction of the particles.

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. For a crystal length L=1.94 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. Channeled particles with small transverse energies E_x travel in the potential well far from its walls and avoid nuclear interactions. As the transverse energy E_x increases, particles cross a rapidly increasing average density of nuclear target, peaking at a value three times larger than density N_{am} of amorphous Si, when $E_x=U_o$. Finally, for $E_x>U_o$, 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}. However, simulations show that in our 1.94 mm long crystal the increase of the averaged nuclear density for the case of volume reflection is only a few percents.

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 μrad. Two large scintillation detectors with transverse dimensions 100×100 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 θ_{ed}=8.33 mrad is sufficient to exclude background from primary protons elastically scattered by the crystal, because $\theta_{el}\ll\theta_{ed}$.

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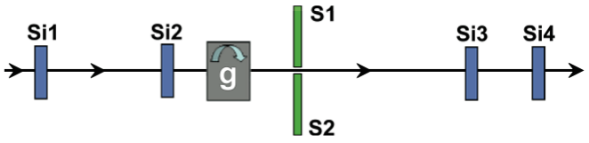

Figure 1: Schematic layout of the experiment.

A 70×1.94×0.5 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 anticlastic bending induced along the crystal width is used to deflect particles in the horizontal plane (see Fig. 2b. in Ref [2]) 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 σ_x=(13.368±0.003) μrad is larger than the critical channeling angle $\theta_c \approx 10$ μrad. However, the off-line analysis with less divergent beams has been performed by selecting the incident particles in a limited range of incident angles $|\theta_{xo}|<\theta_{cut}$.

The probability of inelastic nuclear interactions $P_{in}=(F_{in}-F_{in}(BG))/F_{12}$ where the experimental background is subtracted and the coincidence rate F_{12} estimated by simulations is taken into account. The experimental background is about 0.15%.

Fig.2 shows how the nuclear interaction probability depends on θ_{cut} for amorphous orientation (1), volume reflection (2) and channeling (3). Curve (4) is obtained for the same conditions as (3) by simulation using the model [3]. The probability (2) for a situation of symmetric volume reflection when the tangency point is in the middle of the crystal length is 3-4% larger than for amorphous orientation (1). The probability for the aligned crystal (3) shows a strong dependence on θ_{cut}. For the smallest angular width of the incident beam, the probability is more than 3.5 times smaller than in amorphous orientation. The discrepancy of the dependences (3) and (4) for small values of θ_{cut} is due to small angular imperfections of the goniometer and of the crystal shape, which become less effective for large values of θ_{cut} when the angular size of the incident beam is larger than the angular imperfections.

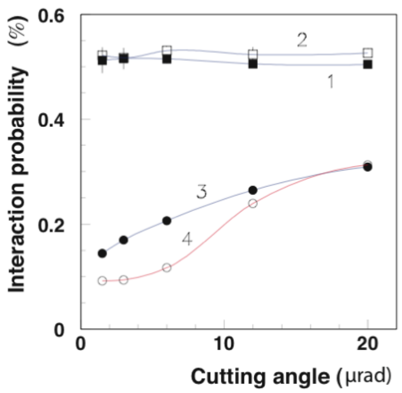

Figure 2: Probability of nuclear interaction: in amorphous orientation (1), in volume reflection (2), in channelling (3) and simulation for channelling (4).

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.

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. This is an additional advantage of the crystal primary collimator in comparison with the ordinary amorphous one.

REFERENCES

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