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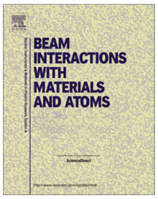

Measurements of multiple scattering of high energy protons in bent silicon crystals

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ABSTRACT

The ordered positions of atoms in crystals give a reason to study multiple Coulomb scattering of high energy charged particles within them. In addition, the accurate representation of multiple scattering of high energy protons in a bent crystal is important for studies of crystal assisted collimation at the SPS and the LHC. Multiple scattering of 400 GeV/c protons in bent silicon crystals was measured for orientations far from the directions of main crystallographic planes and axes in conditions excluding channeling of protons. The observed RMS widths of the angular distributions are a little larger than those obtained from the Moliere theory. Simulation of multiple scattering in a model of binary collisions with the crystal atoms shows about 3.5% decrease of the RMS deflection with respect to the model of a sequence of random collisions. We consider this as a possible indication of a reduction of multiple scattering of protons in a crystal in comparison with its amorphous state.

1. Introduction

High energy charged particles passing through a matter experience multiple deflections in collisions with atoms. The theoretical description of multiple scattering is based on the solution of the transport equation considering the particle balance for a given deflection. The multiple scattering theory of Moliere, whose description may be found in [1], is the most popular one. The angular distribution of particles due to multiple scattering is close to a Gaussian one because the deflections are formed by sequences of a large number of small deflections. Past measurements of multiple scattering of high energy particles performed for different thin targets [2] have shown a good agreement with the theory.

Multiple scattering (MS) of charged particles in crystals is a less studied subject. In this case, the assumption of a uniform distribution of incident particles across the collision area with the target atoms, which is made in theoretical considerations of MS in amorphous targets, can hardly be justified. Indeed, high energy charged particles entering a crystal with angles smaller than the critical channeling angle relative to the crystal planes or axes can be captured into the channeling regime. Successive collisions with atoms

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are correlated for a particle in the channeling conditions. The trajectories of channeled particles are described in a first approximation by the potential averaged along some crystallographic planes or axes [3]. The distribution across the area of collisions with the crystal atoms becomes non-uniform for channeled particles.

Multiple scattering of charged particles in a crystal target with an orientation far from the main crystallographic axes and planes is considered to be the same as in a target with an amorphous state of the same substance (these crystal orientations are called “amorphous” ones). Therefore, it is assumed that the distribution of particles in collisions with the crystal atoms is uniform across the collision area in this case too. Multiple scattering of high energy protons in a silicon crystal has been considered by simulation in [4]. The RMS deflection value of multiple scattering obtained by the simulation was 15% larger than follows from the Moliere theory.

This paper presents the measurement results of multiple scattering for 400 GeV/c protons in bent silicon crystals in amorphous orientation conditions. We consider the Gaussian approximation for the central 98% of the projected angular distributions of multiple scattering as was done in [5] and presented in [6]. The experimental results are compared with calculations based on the Moliere theory and with simulations in a model of binary collisions with the crystal atoms and in a model of a sequence of random collisions. The results obtained with these two simulation methods allow us to draw the conclusion of a possible reduction of multiple scattering in a crystal for its amorphous orientations in comparison with the amorphous state of the same material (in our case, silicon).

2. Experimental layout and results

The experiment has been performed with a primary 400 GeV/c proton beam at the CERN SPS H8 external beam line. The beam spot diameter at the crystal location has been measured to be about 1 mm. The RMS values of the horizontal and vertical angular divergence of the beam were 11.2 μrad and 8.5 μrad, respectively. The beam spill duration of about 10 s was followed by a gap of about 35 s. There were about 3×10^5 protons per spill.

Fig. 1 shows the experimental layout in the horizontal plane. A high precision goniometer was used to align the crystal planes and axes with respect to the beam direction with an accuracy of 2 μrad. The accuracy of preliminary crystal alignment using a laser beam was about 0.1 mrad. Five pairs of silicon microstrip detectors D_1–D_5, two upstream and three downstream of the crystal, were used to measure both incoming and outgoing angles of the particles [7]. The distances of about 10 m and 11 m were between two first and two last detectors, respectively. The detector spatial resolution was measured to be about 7 μm. The scintillation detector D_c upstream of the silicon telescopes was used as a trigger.

Silicon strip crystals produced using techniques described in [8,9] with their largest faces parallel to the (110) planes and mechanically bent along their height were used for the measurements. The anticlastic bending produced along the crystal width was used for beam deflection in the horizontal plane (see the crystal scheme in Fig. 1 in [10]). The entrance face of the crystals was cut parallel to the (111) planes. Thus, the ⟨1 1 1⟩ axis direction, which is normal to the entrance face, was nearly aligned with the beam direction. The crystal length along the beam was measured with an infrared interferometer with an accuracy of 0.3 μm.

For the present study, orientation of a crystal should exclude the situation when the beam position is by chance near some crystallographic plane or axis. The critical angles of 400 GeV/c protons for channeling along the (110) planes and ⟨1 1 1⟩ axes are 10.6 μrad and 20.7 μrad, respectively. The orientation is simpler to realize with a bent crystal using the beam deflection in channeling regimes. Our simulation results show that a small crystal bend does not change the effect of multiple scattering.

To this end, after installation, a horizontal angular scan of the crystal was done to align the (110) planes parallel to the beam direction. The aligned horizontal position of the crystal was detected through the observation of the maximum beam fraction deflected due to planar channeling. Then a vertical angular scan of the crystal was performed to align the ⟨1 1 1⟩ axis parallel to the beam direction. The vertical position of the crystal aligned with the axis was detected when the maximum beam fraction deflected due to axial channeling was observed. Fig. 2a shows the angular space around the ⟨1 1 1⟩ axis of a silicon crystal. After both horizontal and vertical alignments of the crystal, the beam direction became close to the ⟨1 1 1⟩ axis direction, $(\theta_{xo},\theta_{yo}) = (0,0)$. Then horizontal and vertical angular rotations of the crystal by 3 mrad and 20 mrad, respectively, provided the amorphous crystal orientation when all planes and axes were far from the beam direction. The corresponding beam position is shown in Fig. 2a.

The difference of the outgoing and incoming angles gives the deflection angle for every particle. The deflection angle distributions were measured with the crystals in the selected amorphous orientation. The distribution of horizontal deflection angles for a crystal with 1.94 mm length is shown by the histogram 1 in Fig. 3a. The histogram 2 shows the distribution of deflection angles for background conditions without the crystal. Both histograms were fitted by a Gaussian within their central 98% range giving the RMS deflections σ_{am} and σ_{bg}, respectively. The variance of the deflection distribution for the measurement with the crystal is determined by the sum of the distribution variance for the case without the crystal and by the contribution due to multiple scattering of particles in the crystal. Thus, the variance of the particle deflection distribution due to multiple scattering in the crystal may be found as

$$\sigma^2 = \sigma_{am}^2 - \sigma_{bg}^2. \tag{1}$$

The accuracy of the MS measurements does not depend on the angular resolution of the telescopes (the resolution of deflection angles in our case, σ_{bg} is about 5 μrad) and is determined by statistics as already mentioned in [2].

The measurements were performed for three crystals with lengths S = 0.97, 1.94 and 4.02 mm, their parameters are given in Table 1. The crystal bend radii are considerably larger than the critical one R_c for channeling of 400 GeV/c protons along the (110) planes, R_c = 0.68 m. Fig. 4 shows the MS variance for these crystal

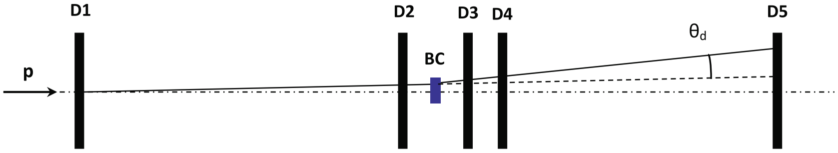

Fig. 1. A schematic view of the layout of the experiment on the measurement of multiple scattering of protons in the crystal deflectors. D_1–D_5 are the silicon microstrip detectors, BC is a bent silicon crystal. The crystal bend is small and is not shown. A particle trajectory is shown before and after the crystal. θ_d is the particle deflection angle.

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