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Volume reflection observations in bent crystals with 13 GeV/c particles

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ABSTRACT

The article presents the results on the investigation of the channeling and volume reflection effects in a bent silicon crystal with 13 GeV/c positive and negative hadrons (mainly π+, p and $\pi-$) at the CERN PS T9 line. In particular, this is the first study carried out on volume reflection at this energy providing a deflection angle of 69.4 ± 4.7 μrad and an efficiency of 92.7 ± 3.3%, with positive particles.

The measurements have been carried out on a bent silicon strip crystal, using a high precision tracking system based on microstrip silicon detectors; this setup is allowed to trigger on the desired beam portion and to select the incoming particle angular range. The article presents a brief introduction on the bent crystal phenomena, the experimental setup and the results of the measurements.

1. Introduction

A bent crystal is able to deflect high energy charged particles exploiting the high intensity electric fields which are present on the atomic scale.

The use of bent crystals to steer charged particles was initially suggested by Tsyganov in 1976 [1] who achieved this result using the so-called "channeling" effect, which is the particle trajectory confinement between two crystalline atomic planes. Since this first experiment, the bent crystal study has witnessed great developments both in the theoretical comprehension of the phenomena and in the crystal preparation allowing to reach a deflection efficiency of about 85% [2] (to be compared with the few percent of the first trial).

In 1987 a new effect called "Volume Reflection" (VR) has been predicted in computer simulation [3] and experimentally confirmed in 2006 with 1 [4], 70 [5] and 400 GeV/c [6] protons. As it will be explained in Section 2, VR has a few interesting features that put it in competition with channeling. For this reason from 2006 on, an intense experimental work has been devoted to its study; the measurements have been performed at the energy of 180 [7] and 400 GeV [8] with positive particles and 150 GeV [9] with negative ones using the bent crystal last generation (strip and quasimosaic short bent crystals) and a high resolution tracking system to identify the effects.

These previous experiments that provided quantitative results have been performed at energies of hundreds of GeV for two main reasons: their final goal that is the application of bent crystals in very high energy beam collimation and the limited multiple scattering effect which strongly simplifies the measurements. Nonetheless low energy measurements are needed to extend the theoretical knowledge about bent crystals in view of other applications in the field of beam extraction and photon production, exploitable in a wide range of beam energy.

This article presents the results of the first quantitative measurements carried out at lower energy (13 GeV) with positive and negative particles at the CERN PS T9 line. At this energy the beam features (dimension and divergence) and the multiple scattering effect become very critical issues which have been overcome using a setup based on a silicon microstrip tracking system that minimizes the multiple scattering and allows to select almost parallel beam portions.

Section 3 describes the detector system, the crystal and the high precision goniometer used to align the crystal with respect to the beam. The experimental procedure from the crystal pre-alignment with a laser to the observation of the preliminary results is shown in Section 4, while Section 5 will describe the data analysis for the extraction of the deflection angles and the deflection efficiency values from the raw data.

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2. The channeling and volume reflection phenomena in bent crystals

A crystal is an ordered atomic structure in which the atoms appear organized in planes or strings.

When a charged particle crosses this atomic structure aligned with respect to the planes, it interacts with an average potential generated by the planes themselves [10].

This potential is formed by a series of wells, where the maxima correspond to the atomic planes position (nuclei location) while the minima are in the middle between two neighboring planes.

If a particle, crossing the crystal aligned with respect to its planes, is not able to overcome the potential well, it will be confined between two planes in the so-called channeling condition. This occurs if the misalignment between the particle trajectory and the planes is smaller than a critical value $\theta_c = \sqrt{\frac{2U}{pv}}$, where U is the depth of the potential well and p and v are the particle momentum and velocity. U depends on the material and the orientation of the crystal and for the (1 1 0) planes in silicon it is about 16 eV, which gives $\theta_c \simeq 55$ µrad at 13 GeV/c.

A channeled particle can increase its transversal energy during the crystal crossing, due to scattering, eventually overcoming the interplanar potential barrier being expelled from the channel; this phenomenon called dechanneling is characterized by a typical length [11] that is $\simeq 7$ mm for positive particles and $\simeq 0.7$ mm for negative ones at the energy of 13 GeV.

The channeling effect can be exploited to deflect particles bending the crystal. Fig. 1a presents a schematic view of a bent crystal represented as a series of bent planes. The trajectory of a channeled particle is marked with *C*: once the particle is trapped in the channel, it oscillates in the potential well following the bending, being deflected of an average angle $\phi_c = l/R$, where l is the crystal length and R the curvature radius.

Fig. 1b shows the interplanar potential inside the crystal, presented in a reference system which rotates along the curvature, so that the horizontal axis (r) represents the distance from the center of the curvature. The increasing trend of the potential with respect to r is due to the centrifugal force which adds a linear contribution in r.

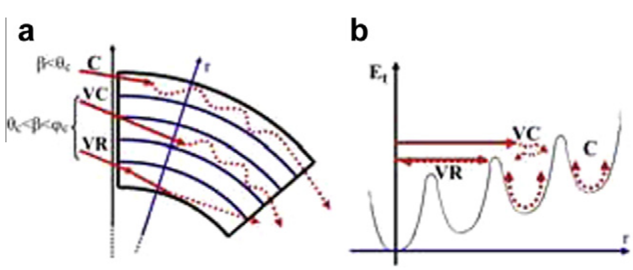

Fig. 1. (a) A schematic view of the planes inside a bent crystal. (b) The effective crystal potential as a function of the radius r; it is the sum of the centrifugal force and the interplanar potential. The arrows indicate the particle trajectories corresponding to: channeling (C), volume capture (*VC*), and volume reflection (*VR*).

In Fig. 1 two other phenomena are represented (marked with *VC* and *VR*); they take place if the misalignment between the particle trajectory and the planes (at the crystal entry face) is larger than θ_c (not allowing channeling) and smaller than ϕ_c. In this angular range the particle trajectory becomes tangent to the planes inside the crystal, where it can be either captured in the channel (Volume Capture, *VC*) or reflected by the interplanar potential (Volume Reflection, VR).

The capture occurs when the particle loses part of its transversal energy, due to the scattering with nuclei and electrons (as shown in Fig. 1b). The particles which are not captured are reflected by the potential barrier of an angle that depends on the single particle trajectory and in average is about $1.5 \cdot \theta_c$ [12]. The capture probability (VC_{eff}) is proportional to θ_c and to the scattering yield, thus it is proportional to $E^{-3/2}$, where E is the particle energy. Since volume reflection is the alternative process to volume capture, its efficiency is $VR_{eff} = 1 - VC_{eff}$ (corresponding to about 97% at 400 GeV [2], for a reasonable bending radius value [7]).

3. The experimental setup

The investigation of the bent crystal effects needs high precision angular measurements. These effects, in fact, are identified by relative small deflections and occur for small angular acceptances, being their order of magnitude defined by the critical angle which is $\simeq$55 µrad at 13 GeV/c.

Two experimental methods can be applied:

- the first one needs an almost parallel and narrow beam, which means a divergence smaller than the critical angle and a dimension smaller than the crystal size (in this case 770 µm in the horizontal direction). With such a beam the setup can be the one described in Fig. 2a: the beam impinges on the crystal which rotates till it reaches the correct alignment; at this point the beam is split in different angular components which separate in space going farther from the crystal. If a position sensitive detector acquires the beam profile at the distance where the effects are separated, the crystal behaviour can be reconstructed.
- the second method can be applied even if the beam conditions are far from the ideal ones, that is a beam divergence larger than the critical angle and a beam dimension larger than the crystal one. The method is based on the capability to measure the single particle track before and after the crystal. This is described in Fig. 2b: several position sensitive detectors determine the single particle position before and after the crystal so that it is possible to select the particles which impinge on the crystal with a certain angle and to compute the deflection produced by the crystal.

Fig. 3 shows the positive 13 GeV/c T9 beam characteristics measured with the silicon microstrip detectors (Section 3.1.2). The beam divergence in the horizontal plane is about 0.5 mrad (Fig. 3c) while the beam dimension in the same plane is 3 mm

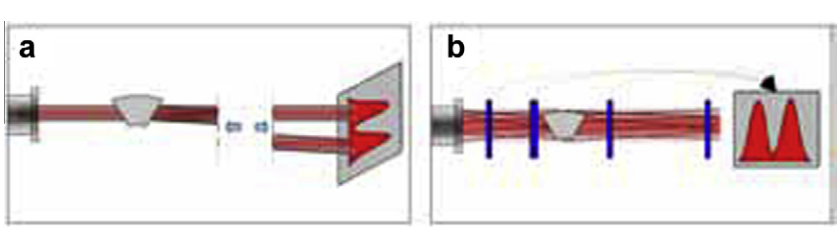

Fig. 2. Schematic description of the ideal experimental setup for the crystal channeling measurements: (a) exploiting a narrow and parallel beam; and (b) if the beam conditions are far from the ideal ones thus requiring a tracking system.