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Dynamical chaos and stochastic mechanism of high-energy negatively charged particle deflection by bent crystals

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ABSTRACT

Deflection of high-energy negatively charged particles in straight and bent crystals through multiple scattering by crystal atomic strings was considered for the case in which the initial angle between the particle momentum and one of the main crystallographic axes was approximately four critical angles of axial channeling. It was shown that in a bent crystal with a small crystal thickness, when the crystal bend was less than the beam incidence angle, the beam deflected in the direction opposite to the direction of the crystal bend. At larger crystal thicknesses, the large part of the beam starts to deflect in the direction of the crystal bend. In addition, there is a group of particles that follow the crystal axis bend in the angular region of approximately the critical angle of axial channeling with respect to the current direction of the crystal axis. It was shown that in all of these deflection processes, the periodicity of the location of atomic strings in the crystal does not influence the angular distributions of scattered particles. This fact is connected with the effect of dynamical chaos in particle motion in the periodical field of bent crystal atomic strings. It was also shown that observed in a recent CERN experiment effect of beam deflection, when the angle between the initial particle momentum and the crystal axis was approximately four critical angles of axial channeling, is due to peculiarities of the stochastic multiple scattering of particles by bent crystal atomic strings. These peculiarities are connected with the effect of dynamical chaos in particle motion in crystals.

If a high-energy charged particle moves in a crystal with a small angle with respect to one of the main crystallographic axes (z-axis), correlations between consecutive collisions of the particle with lattice atoms appear. As a result of these correlations, the particle motion in the crystal is basically defined by the continuous potential of the atomic strings parallel to the z-axis [1–3]. Due to strong intra-crystalline fields, the direction of high-energy particle motion can be changed within quite small distances. The passage of high-energy charged particles through a bent crystal is of particular interest because, in this case, it is possible to deflect the beam direction with a small-sized crystal. There are several mechanisms of deflection of high-energy charged particles by a bent crystal connected with finite (channeling) and infinite (above barrier) motion in relation to bent atomic strings or bent crystal atomic planes [4–7]. These mechanisms are realized in the planar and axial channeling in a bent crystal, in the stochastic mechanism (connected with multiple scattering by bent atomic strings) and volume reflection from bent crystal atomic planes.

When negatively charged particles move in a crystal, the potential of their interaction with atoms is attractive, so the region of their motion is much closer to crystal atomic strings then in the case of positively charged particles. Thus, the scattering on thermal oscillations is more intensive for negatively than for positively charged particles. Therefore, the dechanneling length for negatively charged particles is much smaller than that for positively charged particles, which is the reason that the channeling mechanism is not efficient for the deflection of negatively charged particles by means of bent crystals. However, negatively charged particles can be efficiently deflected by a bent crystal if they are moving near one of the main crystallographic axes in the regime of stochastic scattering by crystal atomic strings. The stochastic mechanism of beam deflection by a bent crystal was predicted in [6], and it was experimentally demonstrated in CERN experiments [8,9]. This mechanism is based on the multiple scattering of charged particles by bent atomic strings and is effective for both positively and negatively charged particles. Beam deflection occurs when the angle ψ between the particle momentum and the crystallographic axis is less than or approximately equal to the critical angle of axial channeling $\psi_c = \sqrt{4Z|qe|/Ed}$, where e is the electron charge, $Z|e|$ is the atomic charge, q is the particle charge, E is its energy and

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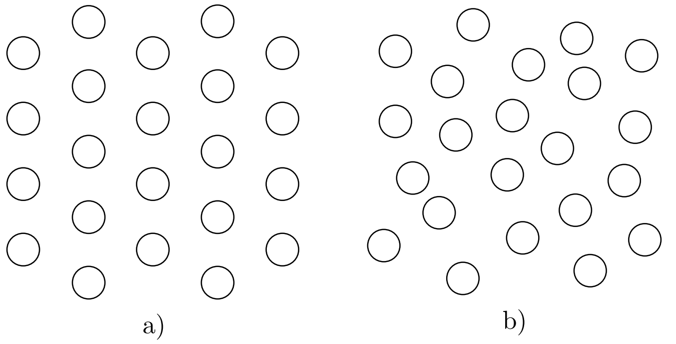

Fig. 1. (a) Periodic location of atomic strings in the plane orthogonal to the ⟨111⟩ axis of Si crystal, (b) random location of atomic strings.

d is the distance between neighboring atoms in the atomic string parallel to the selected axis.

The situation in which the angle ψ between the particle momentum and the crystal axis is greater than one critical angle of axial channeling [10–12] is of particular interest. In this case, the effective deflection of positively and negatively charged particles is possible even by means of a straight crystal. This effect is due to the multiple scattering of particles by crystal atomic strings, which leads to the so-called doughnut particle scattering by crystal atomic strings [13]. It is important that, in this case, for the large interval of angles $\psi > \psi_c$, the periodical location of atomic strings in a crystal is not required for beam deflection. In other words, this effect is possible for both the periodic (Fig. 1(a)) and the chaotic (random strings approximation, Fig. 1(b)) location of atomic strings in the plane orthogonal to the crystal axis, and it is connected with the dynamical chaos phenomenon in particle motion in the periodic field of crystal atomic strings [3,14]. This phenomenon manifests itself especially clearly for negatively charged particles.

In the present work, a similar problem of particles scattering when the beam enters the crystal with $\psi > \psi_c$ is considered for particle motion in a bent crystal. The main focus is the role of the periodicity of the location of bent atomic strings in the formation of the angular distributions of scattered particles and the dependence of these distributions on crystal thickness for negatively charged particles.

We note in this connection the recent CERN experimental data on π^--mesons scattering in a bent silicon crystal [15] when the angle ψ between the initial particle momentum and the ⟨111⟩ crystal axis was approximately four critical angles of axial channeling. The experiment showed that, after passing through the crystal, where bend angle α was slightly larger than ψ, the main portion of scattered particles was concentrated in the angular region $0 < \theta_x < \alpha$, where θ_x is the angle between the scattered particle momentum projection on the plane orthogonal to the initial direction of the ⟨111⟩ crystal axis and the x-axis (the crystal was bent along the x-axis in the direction of positive values of the x). In other words, the experiment showed that, in this case, the beam was effectively deflected in the direction opposite to the direction of the crystal axis bend. The experiment also showed that the angular distribution of particles differed from the angular distribution in the case of doughnut scattering in a straight crystal. These experimental results are analyzed below.

The problem of the motion of a high-energy charged particle in a bent crystal near one of the crystal axes is quite complex because, in this case, the dynamical chaos phenomenon in the particle motion is possible. Thus, methods of computer simulation of the particles passage through the crystal play an important role in the analysis of this process. The analysis in the present work is conducted on the basis of a previously developed method [7] for the numerical simulation of the passage of high-energy particles through straight and bent crystals near one of crystal axes. This simulation allows us to investigate the influence of different factors on particle motion in a crystal, such as the effect of dynamical chaos, the influence of crystal atomic planes on particle motion in a crystal, the role of incoherent effects in scattering and to conduct the simulation of the passage of particles through rather thick crystals. In this simulation model, to find the particle trajectory in a bent crystal, the crystal is divided into a large number of straight parts, each of which is slightly rotated relative to the previous one. The particle trajectory on each part is defined by solving the motion equation in the field of the continuous potential of atomic strings $U_c(\vec{\rho})$ [3]

$$\frac{d^2}{dt^2}\vec{\rho} = -\frac{1}{E}\frac{\partial}{\partial\vec{\rho}}U_c(\vec{\rho}), \tag{1}$$

where $\vec{\rho}(t)$ is the particle trajectory in the plane, orthogonal to the current direction of the crystal axis. At the end of each straight part, both the crystal bend and incoherent effects in scattering are taken into account by the following relations:

$$\begin{cases} \theta'_x \to \theta'_x - l/R + \theta_x^{(i)}, \\ \theta'_y \to \theta'_y + \theta_y^{(i)}, \end{cases} \tag{2}$$

where θ'_x and θ'_y are the angular coordinates of the particle in the plane orthogonal to the current direction of the crystal axis, R is the crystal curvature radius, l is the length of the crystal part, $\theta_x^{(i)}$ and $\theta_y^{(i)}$ are the terms corresponding to the scattering on thermal oscillations of crystal atoms and on the electron subsystem (incoherent scattering) at length l. The particle angular coordinates in the plane orthogonal to the initial direction of crystal axis θ_x and θ_y are connected with θ'_x and θ'_y by the following relations: $\theta_x = \theta'_x + L'/R$, $\theta_y = \theta'_y$, where L' is the length that the particle has already passed through the crystal. On the basis of this method, the problem of particle scattering in both straight and bent crystals, when the angle ψ between the initial beam direction and the crystal axis is larger than the critical angle of axial channeling ψ_c, can be successfully considered, as well as in the case of $\psi < \psi_c$.

The simulation results concerning the same initial conditions as in the experiment [15] are considered below. In this experiment, 150 GeV π^--mesons entered the silicon crystal at the angle $\vec{\theta}$ with coordinates $\theta_x = \psi = 129$ µrad and $\theta_y = 0$ with respect to the ⟨111⟩ axis (for such conditions, $\psi \approx 3.8\psi_c$ and $\psi_c = 33.8$ µrad). The beam divergence was 10 µrad. The crystal thickness in the experiment was $L = 8$ mm.

Consider first the particle scattering in a straight crystal. Fig. 2 shows the simulation results of the angular distributions of 150 GeV π^--mesons after passing through the straight silicon crystal with the initial conditions described above. Fig. 2(a) corresponds to the initial conditions of beam incidence on the crystal: the values $\theta_x = \theta_y = 0$ represent the ⟨111⟩ axis direction, the bold point corresponds to the initial angular coordinates of particles, the size of the bold point corresponds to the beam divergence and the dashed line labels the initial θ_x direction. Figs. 2(b) and 2(c) show the simulation results of the angular distributions of the scattered particles after passing through 4 mm and 8 mm of the straight silicon crystal, respectively. The simulations were performed for motion in the field of crystal atomic strings periodically located in the plane orthogonal to the ⟨111⟩ crystal axis by taking into account the incoherent effects in scattering.

Similar simulations were performed using the random strings approximation model. In this model, atomic strings are not located periodically and are shifted from their real positions in crystal, as shown in Fig. 1(b). In this model, atomic strings do not form