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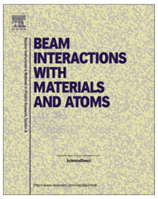

Orientation dependence of the probability of close collisions during passage of high-energy negatively charged particle through a bent crystal

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ABSTRACT

The probability of close collisions of high-energy negatively charged particle with atoms in a bent crystal was considered as a function of the angle between the initial particle momentum and the bending plane. This allowed to compare the probability of close collisions of high-energy negatively charged particle in a bent crystal in two different regimes of deflection: planar channeling and stochastic deflection. The results of simulation of negatively charged particle motion in a bent crystal shown the great efficiency of high-energy negatively charged particle beam deflection by a bent crystal due to stochastic deflection and small efficiency of deflection due to planar channeling.

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1. Introduction

When a high-energy charged particle impinges on a crystal with a small angle ψ^{in} with respect to one of the main crystallographic axes (z-axis) or planes, correlations between successive collisions of the particle with lattice atoms appear. As a result of these correlations the phenomenon of particle channeling in the crystal is possible. This phenomenon consists in particle motion along the channels formed by crystal atomic strings or crystal atomic planes [1–6]. The yield of processes associated with small impact parameters (nuclear reactions, scattering on big angles, etc.), in this case, may differ significantly from the yield of such processes in the motion of particles in an amorphous medium. This is due to the fact that the character of particle motion in the crystal in the channeling regime significantly differs from the nature of particle motion in an amorphous medium. It is essential that with the change of the crystal orientation the regime of particle motion in a crystal changes. This leads to a significant orientation dependence of the processes associated with small impact parameters.

During scattering in the crystal particle can come close to atomic string and participate in processes governed by small impact parameters. In the article [7] it was shown that the probability of such close collisions for high-energy negatively charged particle moving in a straight crystal increases with the decrease of ψ^{in} due to axial channeling if $\psi^{in} < \psi_c$, where ψ_c is a critical angle of axial channeling [5]. In the work [8] the analysis of the probability of close collisions of high-energy positively charged particle in a bent crystal as a function of the angle ψ^{in} was done. This analysis shown that this probability decrease with the decrease of ψ^{in} if $\psi^{in} < \psi_c$ because for positively charged particles the smaller is the angle between particle momentum and the axis of crystal atomic string the less is particle orthogonal energy and therefore the probability to come close to atomic string. It was also shown that the probability of close collisions of high-energy positively charged particle in a bent crystal in the case of $\psi^{in} = 0$ (such initial orientation of the crystal with respect to the impinging particles corresponds to a particular case of stochastic deflection) is about ten times smaller than in the case of initial conditions that correspond to planar channeling ($\psi^{in} \gg \psi_c$). In this article we study the probability of close collisions of high-energy negatively charged particle penetrating through a bent crystal in the regimes of stochastic deflection and planar channeling and in a transition between this regimes of motion.

Many theoretical and experimental investigations were focuses on the problem of high-energy negatively charged particles scattering in crystal (the first ones were published in [11–13], see also [14,15] and references therein). This problem still is subjected to a serious study [16]. The possibility of stochastic deflection of negatively charged high-energy particles (which means deflection

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in the result of chaotic scattering of particles on bent crystal atomic strings) was proposed in [17,18] and experimentally demonstrated in [19].

2. High-energy negatively charged particle deflection by means of a bent crystal

Let us start the consideration with the analysis of angular distribution of negatively charged particles after passing a bend crystal in two cases: when particles impinge on the crystal in the conditions of stochastic deflection and in the conditions of planar channeling. For this analysis we carried out simulation of π^--mesons passage through a bent Si crystal. The simulation was based on the same approach as in [9]. Despite the fact that the consideration was carried out for π^--mesons, the results are valid for most of high-energy negatively charged particles (for electrons the effects associated with the loss of energy of the particles to radiation must be also taken into account).

To observe stochastic deflection of high-energy charged particle several conditions should be fulfilled. First of all initial angle between particle momentum and crystal axis should be less than the critical angle of axial channeling. Then as it was shown in [10] for observation of stochastic deflection of charged particles along the entire length of the crystal the bending angle of the crystal should be less than

$$\alpha_{cr} = \frac{2R\psi_c^2}{l_0}, \tag{1}$$

where R is the radius of curvature of the crystal, $l_0 = 4/(\pi^2 n d R_a \psi_c)$, n is the concentration of atoms in the crystal, R_a is the atomic screening radius and d is the distance between neighboring atoms in the atomic string parallel to z-axis.

To observe planar channeling in a bent crystal in the plane that is orthogonal to the bending plane the angle ψ^{in} must be higher than several ψ_c and the angle between particle momentum and the considered plane must be less than critical angle of planar channeling $\theta_c = \sqrt{2U_0/E}$, where E is the particle kinetic energy, U_0 is the depth of the potential well formed by two neighboring planes which form the planar channel. Also the radius of curvature of the crystal must be greater than the critical radius of curvature $R_c = \frac{E}{|dU(x)/dx|_{max}}$, where x-axis is perpendicular to planes in the field of which particle channeling takes place, $U(x)$ is particle potential energy in the field of atomic planes in straight crystal. If mentioned conditions are fulfilled some part of beam particles will impinge on the crystal in the conditions of planar channeling.

To observe both stochastic deflection and planar channeling in simulation we chosen Si crystal with thickness of 5 mm and radius of curvature $R = 5$ m. The bending plane was $(0\,0\,1)$ and crystal was aligned close to the $\langle 1\,1\,0\rangle$ crystal axis. So the crystal and its orientation were the same as in [8] (x-axis coincided with the $\langle 1\,\bar{1}\,0\rangle$ crystal axis, y-axis was perpendicular to the $(0\,0\,1)$ plane, z-axis coincided with the $\langle 1\,1\,0\rangle$ crystal axis, the direction of crystal bend coincided with x-axis direction). In the present article we consider 270 GeV/c π^--mesons scattering on a bent crystal. It means that the critical angle of axial channeling in the considered case is 27.9 μrad and the critical angle of planar channeling in the field of $(1\,\bar{1}\,0)$ planes is 14.5 μrad. The critical radius of curvature for channeling in the field of $(1\,\bar{1}\,0)$ planes is 47.5 cm so it is ten times smaller than radius of crystal curvature chosen for simulation. The parameter α_{cr} in the chosen case equals to 200 μrad while for the chosen crystal the bending angle is $\alpha = L/R = 100$ µrad . The fact that $R \gg R_c$ and $\alpha > \alpha_{cr}$ means that in the chosen crystal there is a possibility to observe both planar channeling and stochastic deflection for different crystal orientations. In our simulation the initial beam had no divergence.

Fig. 1 shows angular distributions of π^--mesons after passing the crystal in the conditions of planar channeling and stochastic deflection. Colors in the figure show the beam intensity distribution in logarithmic scale. The left angular distribution corresponds to the planar channeling of π^--mesons in the field of $(1\,\bar{1}\,0)$ atomic planes (the initial angle between particle momentum and $\langle 1\,1\,0\rangle$ crystallographic axis was more than fourteen times higher than ψ_c while the initial angle between particle momentum and $(1\,\bar{1}\,0)$ atomic plane was zero). The right angular distribution corresponds to the stochastic deflection of π^--mesons (the initial direction of particle momentum coincided with the direction of $\langle 1\,1\,0\rangle$ crystallographic axis). Fig. 2 shows the horizontal profiles of these angular distributions. These profiles show how many percent of beam particles were scattered by the bent crystal in the direction of $(\theta_x, \theta_x + \Delta\theta)$, where $\Delta\theta$ is the step of diagram. From Figs. 1 and 2 one can see that only a small part of π^--mesons were deflected after passing the crystal in the conditions of planar channeling despite $R \gg R_c$. This happens because strong dechanneling from the planar channel formed by $(1\,\bar{1}\,0)$ atomic planes. After impinging on the crystal in the condition of planar channeling π^--mesons very intensively participate in incoherent scattering that takes place during close collisions. These processes change the orthogonal energy of scattered particles and particles become above-barrier. It means that they do not participate in the process of deflection by bent atomic planes.

Now let us consider the simulation results for the probability of close collisions of π^--mesons in the bent crystal. For this in simulation we integrated the close collisions probability along particle trajectories considering this probability to be proportional to the probability of atomic nuclei location in each point of the trajectory. We used the model of normal distribution of atomic nucleus location near the lattice site $w_n(\vec{r}) = \frac{1}{\sqrt{2\pi r_T^2}} \exp\left(-\frac{(\vec{r}-\vec{r}_n)^2}{2r_T^2}\right)$, where r_T is the rms atomic thermal vibration amplitude in one direction and vector $\vec{r}_n$ gives the coordinates of the lattice site. Then we summed the obtained from simulation probability of close collisions over all beam particles. If the angle ψ^{in} between particle initial momentum and the z-axis in simulation was equal to zero the obtained results would have corresponded to the stochastic deflection mechanism, while if the angle between particle initial momentum and the plane $(1\,\bar{1}\,0)$ θ_x^{in} was equal to zero and the angle between particle initial momentum and the plane $(0\,0\,1)$ θ_y^{in} was much greater than ψ_c the obtained results corresponded to the planar channeling in the bent crystal. Fig. 3 shows the results of simulation of the probability of close collisions of π^--mesons in the bent crystal for different angles θ_y^{in} while angle θ_x^{in} was equal to zero. In this figure we normalized the probability of close collisions to the probability in the case of planar channeling.

In the case of $\theta_y \gg \psi_c$ that corresponds to the planar channeling the probability of close collisions becomes a constant as well as in the case of protons (see [8]). However for the stochastic deflection conditions we see that the probability is two times higher than for planar channeling. This is due to the axial channeling of π^--mesons which is possible for the initial conditions $\theta_x^2 + \theta_y^2 < \psi_c^2$.

Despite the probability of close collisions for π^--mesons in the case of stochastic deflection is two times higher than in the case of scattering with initial conditions that correspond to planar channeling in Figs. 1 and 2 one can see that most of the particles after passing the crystal in stochastic deflection regime were deflected to the crystal bending angle. This happens because particles that participate in the stochastic deflection can be above-barrier. That is why this deflection regime is not as sensitive to the intensity

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