About the mechanisms of high-energy charged particle deflection by a bent crystal

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Abstract

Computer simulations of the passage of high-energy charged particle beams through a bent crystal near a crystallographic axis are presented. The influence of the magnitude of the particle charge, of the particle charge sign and of incoherent scattering processes by thermal oscillations of the crystal's atoms and by the atomic electrons of the crystal on the beam deflection efficiency is considered. Conditions for the realization of deflection and splitting effects for a high-energy charged particle beam in a bent crystal are discussed.

Keywords: High-energy particle; Beam deflection; Bent crystal; Channeling; Simulation; Splitting of the beam; Charged particles; Highly charged ions

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1. Introduction

In [1,2], the possibility of deflection of high-energy charged particle beams by multiple scattering by atomic strings of a bent crystal was considered. This beam deflection mechanism differs from the beam deflection mechanism proposed by Tsyganov [3], which is connected with the phenomenon of planar channeling of particles in bent crystal planes. The effect considered in [2] takes place for particles not bound to atomic strings. The given effect is possible both for positively and negatively charged particles.

The present work deals with analysis of the different deflection mechanism of high-energy charged particles in a beam incident upon a bent crystal along a crystalline axis. The deflection conditions for hyperchanneled and over-barrier particles and also splitting conditions of a beam are discussed. The influence of the particle charge, both magnitude and sign, and of incoherent scattering processes by thermal oscillations of crystal's atoms and by the electrons on the beam deflection efficiency is considered. Computer simulations of the passage of high-energy charged particle beams through a bent crystal are represented.

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2. Conditions for beam deflection

The motion of a fast charged particle near a crystallographic axis (z-axis) is determined mainly by the continuous string potential, which is the crystal potential averaged along the z-axis [4,5]. For positively charged particles, the continuous string potential contains small wells in the region between atomic strings. Therefore, for a beam in a crystal, part of the particles can be captured by these potential wells. In a bent crystal, these particles will follow the bend of the crystal's axis if these potential wells are not destroyed by the bend. This mechanism of the beam deflection differs from Tsyganov's mechanism of beam deflection only by the property that the considered potential well is two-dimensional. Such a mechanism of beam deflection will be realized if the radius of curvature is sufficiently large,

$$R > \frac{\varepsilon \cdot \boldsymbol{a}}{U_{\mathrm{H}}} \tag{1}$$

Here ε is the particle energy, $\boldsymbol{a}$ is the typical width of the potential well and U_{H} is its depth (typical values of U_{H} are of the order of serveral eV for proton beam passage through a Si crystal; see for example [5]).

For negatively charged particles, the potential wells are centered at the atomic strings. Their depth U_{c} is significantly larger than the one for positively charged particles ($U_{\mathrm{c}} \sim Ze^2/d \gg U_{\mathrm{H}}$, where $|Ze|$ is a charge of the crystal atoms and d is the distance between the atoms along the motion direction (along the z-axis)). Therefore, the condition (1) in which the beam deflection by a bent crystal is possible may be fulfilled for much larger values of R for negatively charged particles than for positive. Nevertheless, until the present time the beam deflection of negatively charged particles was not observed experimentally even in the case of planar channeling. This is connected with the fact that negatively charged particles are attracted by the atoms of the crystal planes or strings. Such particles will quickly leave the potential wells due to the multiple scattering on the crystal atoms.

A considerable part of the particles in a crystal is not captured by the potential wells and performs non-bound (over-barrier) motion with respect to the atomic strings. But the particles are multiply scattered by the different atomic strings, so-called doughnut scattering. It was shown in [6,7] that the condition for the particles to follow the crystal bend could be fulfilled for such particles. Such a deflection mechanism for the over-barrier particles is possible both for positively and negatively charged particles, if [6]

$$\alpha = \frac{l_\perp}{R\psi_{\mathrm{c}}}\frac{L}{R\psi_{\mathrm{c}}} < 1, \tag{2}$$

where L is the crystal thickness, R is the curvature radius of the bent crystal, $l_\perp$ is the characteristic length of transverse momentum equalization due to multiple scattering by the atomic strings, and ψ_{c} is the critical angle of axial channeling. For $\psi \leqslant \psi_{\mathrm{c}}$ $l_\perp \approx (\psi_{\mathrm{c}} n d a_{\mathrm{TF}})^{-1}$, where n is the atomic density and a_{TF} is the screening radius of the atomic potential [4].

If condition (2) is satisfied, then almost all particles of an initially parallel beam will follow the crystal axis bend within the axial channeling critical angle $\psi \leqslant \psi_{\mathrm{c}}$ with respect to the current axis direction. We note that $\alpha \sim \psi_{\mathrm{c}}^{-3}$ and $\psi_{\mathrm{c}} \sim \sqrt{Q}$, where Q is the particle charge. Therefore, the value of the particle charge is a factor influencing strongly the efficiency of beam deflection by a bent crystal [8]. We also note that the crystal length must be much larger than the length of beam transverse momentum equalization ($L \geqslant l_\perp$) for the deflection process to occur.

3. Simulation of beam passage through a bent crystal

It was assumed for the derivation of inequality (2) that particle collisions with different atomic strings are random. This is true if the conditions of the dynamical chaos phenomenon are satisfied in the particle passage under the influence of the periodical field of the atomic strings [5,7].

In the case of positively charged particles, a small part of the beam can be captured in the planar channeling regime even for $\psi \sim \psi_{\mathrm{c}}$. To study the role of this effect, it is necessary to take into account the real geometry of the atomic string positions in a crystal. This effect is less significant for negatively charged particles.

The incoherent effects in the scattering of particles due to thermal oscillations of crystal atoms and by the atomic electrons can lead to a change of the particle motion in the crystal (dechanneling and rechanneling of particles, transition from regime of axial channeling to planar channeling, etc). This can lead to a redistribution of the beam particles over angle for beam passage through a bent crystal, as compared with the case when these effects are not taken into account. The investigation of these effects can be carried out by the use of numerical simulation of beam passage through a bent crystal.

For this purpose, we have elaborated the computer simulation program of charged particle beam passage through a bent crystal near crystallographic axes [7–9]. The passage of the particles through the crystal is considered as a step-by-step two-dimensional motion in the transverse plane orthogonal to the crystallographic axis direction in the field of the atomic strings. The continuous potential of atomic strings is calculated on the basis of the Moliere approximation for the single atom potential. The particle scattering, both the coherent caused by the averaged continuous strings potential and the incoherent is calculated in each step. The incoherent scattering is connected with the difference of the real string potential from the averaged one. This difference is caused by thermal displacements of crystal atoms from their equilibrium positions and by the crystal's electrons too. The incoherent scattering leads to the change of the particle transverse energy. The basis for the incoherent scattering is the assumption of a Gaussian distribution of calculated values.

Fig. 1 shows simulation results of the passage of different particle beams (π^-, p, U^{+92}) through a bent silicon crystal, taking into account the influence of different factors on the particle–crystal interaction. The simulation was made for identical parameters of beams and crystal. The value of the parameter α for protons and pions is $\alpha_{p,\pi} = 0.9$ and $\alpha_U = 0.09$ for for uranium ions. Thus, condition (2) for the over-barrier particle deflection is satisfied. Condition (1) for the hyper-channeling particle deflection is fulfilled too.

The obtained results show that a considerable part of the beam particles follows the bend of the crystal's axis under the given conditions. The account of the real geometry of the atomic strings leads to capture of part of the beam particles for protons and ions by planar channels and, then, follows the crystal's planar bend. The incoherent scattering by the oscillating crystal atoms exerts a significant influence on the passage of the negatively charged particle through a crystal. The incoherent scattering by the electrons of crystal is essential for highly charged ions.

The dependence of the relative fraction of beam particles within the critical channeling angle relative to the current direction of the crystal axis on the target thickness (the upper curves correspond to all deflected particles and the lower curves do to hyperchanneled particles) is presented by Fig. 2. The represented curves show that the incoherent scattering by thermal oscillation of crystal's atoms leads to fast dechanneling of negatively charged particles. Furthermore, the beam deflection is mainly caused by the mechanism of multiple scattering of over-brarrier particles on atomic strings. For protons, when the condition $\alpha_p < 1$ is satisfied, both hyperchanneled and over-barrier particles follow the crystal's axis bend. For increasing target thickness, when the condition $\alpha_p < 1$ is broken, only the hyperchanneled particles follow the crystal's axis. In the case of the uranium ion beam, fast dechanneling of particles takes place. In addition, the beam deflection mechanism, connected with multiple scattering of particles by atomic strings, is dominating.

Thus, the conditions for a large part of the beam to follow the crystal axis bend can be satisfied for passage of both positively and negatively charged particles through a bent crystal. Furthermore, the beam deflection mechanisms, connected both with the phenomena of hyper-channeling and multiple scattering of particles by atomic strings, can be realized. The real geometry of the atomic strings in the crystal and also the incoherent scattering effects can influence the deflection efficiency significantly.

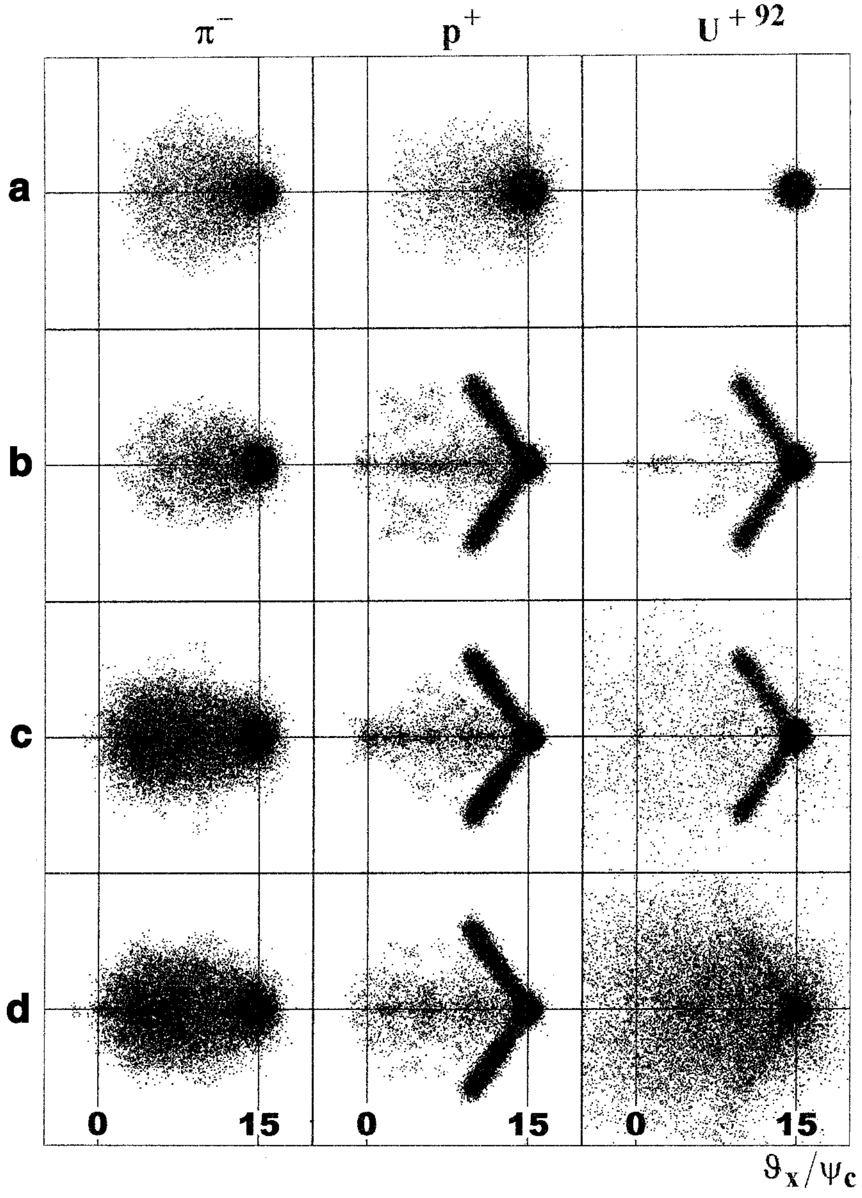

Fig. 1. The particle angle distributions at the exit of the crystal for passage of particles with energy $E = 450$ GeV through the silicon bent crystal of the thickness $L = 33$ mm near $\langle 1\,1\,0 \rangle$ axis. The deflection angle is $\vartheta_R = L/R = 15 \cdot \psi_c$ ($\vartheta_R^{p,\pi} \approx 3.3 \times 10^{-4}$; $\vartheta_R^{U} \approx 3.2 \times 10^{-3}$): (a) the random-string approximation without incoherent scattering; (b)–(d) the real geometry of strings; (b) without incoherent scattering; (c) including incoherent scattering by thermally oscillating crystal atoms; (d) including incoherent scattering by lattice's electrons and crystal's atoms. The coordinates of the initial beam center are $(\vartheta_X, \vartheta_Y) = (0, 0)$; the initial beam divergence is $0.1 \cdot \Psi_c$; the coordinates of the bent axis final direction are $(\vartheta_X, \vartheta_Y) = (15, 0)\Psi_c$. The simulation statistic corresponds to 1000 particles.

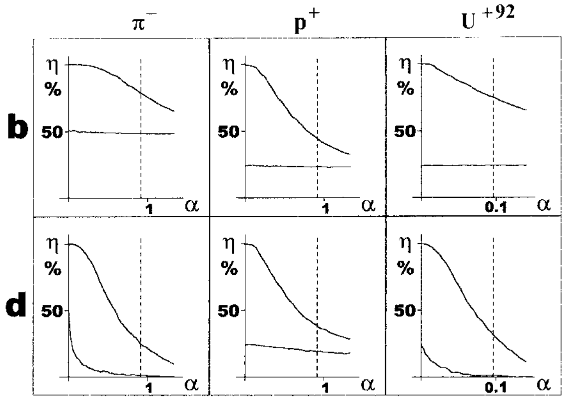

Fig. 2. The dependence of the fraction of deflected (upper curve) and hyperchanneled (lower curve) particles on the α parameter. The dotted lines correspond to the α parameter value for the angular distributions of Fig. 1. The parameters of the beam and crystal are the same as in Fig. 1.

4. Splitting of the beam

The simulation results presented above show that bent planar channels can capture positively charged particles, which leave the axial following regime. This leads to the formation of branches in the particle angle distribution. For increasing target thickness (parameter α), the number of particles following the bent crystal's axis decreases. This leads to an increase in the number of particles captured by the planar channels. At $\alpha \geqslant 1$ the number of particles following the bent crystal's axis decreases to zero. This leads to a stabilization in the number of particles captured by the planar channels and to localization of the beam planar fractions. The simulation results showing this process are presented in Fig. 3. The small fraction of beam particles following the axis bend in Fig. 3(c) is caused by hyperchanneled particles.

Thus, the formation of planar branches takes place at lengths of beam penetration into the crystal l ($l > l_\perp$), such that

$$\alpha_l = \frac{l_\perp}{R\psi_c}\,\frac{l}{R\psi_c} < 1. \tag{3}$$

For larger lengths, the localization of planar branches takes place and beam splits when the following condition is fulfilled:

$$\alpha_L = \frac{l_\perp}{R\psi_c}\,\frac{L}{R\psi_c} \gg 1. \tag{4}$$

Note that it is required for the formation of planar branches (and thus for the beam splitting), that the planar channeling condition should be satisfied too. For negatively charged particles such effect is absent as the particles dechannel quickly from the bent planar channels. For ions having a large charge, the effect of beam splitting is suppressed by fast dechanneling, caused by strong scattering of the ions on the electrons. The simulation results (see Fig. 3) show that such an effect is possible for proton beams.

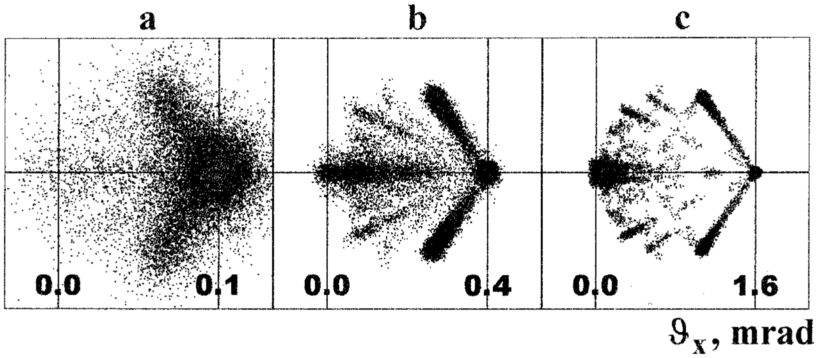

Fig. 3. The particle angle distributions at the exit of the crystal for proton beam passage through the bent silicon crystal with the curvature radius $R = 30$ m near $\langle 1\,1\,0\rangle$ axis: (a) $L = 3$ mm, $\alpha_p = 0.9$; (b) $L = 12$ mm, $\alpha_p = 3.6$; (c) $L = 48$ mm, $\alpha_p = 14.4$. The beam parameters are the same as in Fig. 1.

Recently, there has been carried out an experiment at CERN [10], in which, together with the mechanism of the particle planar deflection, the beam deflection mechanism, connected with multiple scattering of particles by bent atomic strings, was investigated. The experiment has been performed with a proton beam of energy $\varepsilon = 450$ GeV passing through silicon crystals near $\langle 1\,1\,0 \rangle$ axis. The crystal thickness was $L \approx 3.1$ cm and the crystal bend radius was equal to $R \approx 10$ m. In this case, the α parameter has a value of $\alpha_{\mathrm{p}} = 83$. Thus, in this experiment, condition (2) of the beam deflection was not satisfied, but conditions (3) and (4) of the beam splitting were satisfied. According to this, splitting of the proton beam to a few beams was observed in [10]. The effect of the axial deflection of over-barrier protons was not discovered in this experiment. At the same time, the deflection of a small group of hyperchanneled particles was observed in [10]. The simulation results of the proton beam passage through the bent crystal under the experimental condition [10], obtained by the above program, agree with the experimental data rather well (such a comparison is worked out in [9]). To discover experimentally the effect of beam deflection, connected with multiple scattering of particles by bent atomic strings, it is required to change the experimental conditions so that condition (2) is fulfilled.

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