East European Journal of Physics. 4. 68-75 (2021)
DOI: 10.26565/2312-4334-2021-4-07 ISSN 2312-4334

ON THE IMPACT PARAMETER DEPENDENCE OF THE IONIZATION ENERGY LOSS OF FAST NEGATIVELY CHARGED PARTICLES IN AN ORIENTED CRYSTAL†

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Received July 27, 2021; revised September 29, 2021; accepted November 15, 2021

When a fast charged particle passes through matter, it loses some of its energy to the excitation and ionization of atoms. This energy loss is called ionization energy loss. In rather thin layers of matter, the value of such energy loss is stochastic. It is distributed in accordance with the law, which was first received by L.D. Landau. In amorphous substances, such a distribution (or spectrum), known as the Landau distribution, has a single maximum that corresponds to the most probable value of particle energy loss. When a particle moves in crystal in a planar channeling mode, the probability of close collisions of the particle with atoms decreases (for a positive particle charge) or increases (for a negative charge), which leads to a change in the most probable energy loss compared to an amorphous target. It has recently been shown that during planar channeling of negatively charged particles in a crystal, the distribution of ionization energy loss of the particles is much wider than in the amorphous target. In this case, this distribution can be two-humped, if we neglect the incoherent scattering of charged particles on the thermal oscillations of the crystal atoms and the electronic subsystem of the crystal. This paper explains the reason for this distribution of ionization energy loss of particles. The ionization energy loss distribution of high-energy negatively charged particles which move in the planar channeling mode in a silicon crystal are studied with the use of numerical simulation. The dependence of this distribution on the impact parameter of the particles with respect to atomic planes is considered. The dependence of the most probable ionization energy loss of particles on the impact parameter is found. It is shown that, for a large group of particles, the most probable ionization energy loss during planar channeling in a crystal is lower than in an amorphous target.
Keywords: ionization energy loss, planar channeling, negatively charged particles.
PACS: 61.85.+p; 34.50.Bw; 34.50.Fa

If a high-energy charged particle penetrates through a crystal having a small angle θ between its momentum and one of atomic planes, correlations in scattering by neighboring atoms may occur. This happens when θ is of the order of the critical angle of planar channeling θ_c [1] or smaller. In this case the distance between particle and atomic plane changes weakly upon scattering by neighboring atoms. This means that a large number of sequentially located atoms deflect the particle in the same direction, that is, they act coherently. This coherent interaction leads to existence of the so-called planar channeling, in which the particle moves in a potential well formed by adjacent planes. The particle motion in this case is periodic [1]. The ionization energy loss of particles in this mode of motion differs significantly from the ionization energy loss in an amorphous target. For positively charged particles, this loss has been well studied both theoretically and experimentally [see, e.g., 2–5]. In this case, planar channeling leads to a significant decrease in the most probable ionization energy loss (MPEL) due to the fact that particles less often approach close enough to the crystal atoms than in an amorphous target. The case of negatively charged particles has been much less studied. In the recent work [6] the distribution of ionization energy loss of high-energy negatively charged particles in the planar channeling mode was obtained via computer simulation. This distribution was broader than in the case of an amorphous target and had a peculiar shape (particularly, a two-humped structure in the case when dechanneling can be neglected). In [6] the physical reasons for such peculiarities of the distribution were not deeply investigated since the main attention there was focused on the possibility of applying the ionization loss for determining the dechanneling length of negatively charged particles. In the present paper we investigate the reasons for the above peculiarities of the distribution of ionization energy loss of negatively charged particles at planar channeling in a crystal. We show that the parameters of such distribution are directly correlated with the probability of close collisions between the incident particles and crystal atoms. It is demonstrated that a certain part of negatively charged channeled particles can move in the so-called 'hanging' mode (which is usually typical for over-barrier positive particles) having a decreased probability of close collisions and forming the low-energy peak of the two-humped distribution.

DISTRIBUTION OF IONIZATION ENERGY LOSS OF NEGATIVELY CHARGED PARTICLES DURING PLANAR CHANNELING IN A CRYSTAL

In [6] the case of 150 GeV/c π^- mesons impinging on a silicon crystal along the (110) plane was considered. The secondary beam of π^- mesons with such a momentum is delivered by SPS accelerator at CERN. The crystal thickness was chosen to equal 1 mm. Fig. 1 shows the distribution (spectrum) of the ionization energy loss for this case (solid

† ***Cite as:*** S.V. Trofymenko, I.V. Kyryllin, and O.P. Shchus, East. Eur. J. Phys. **4**, 68 (2021), https://doi.org/10.26565/2312-4334-2021-4-07

line) as well as the corresponding distribution for the case when the crystal is disoriented and behaves like an amorphous target (dashed line) (hereinafter in the text, by the term ‘amorphous target’ we mean a disoriented silicon crystal). For clarity, the spectrum for the oriented crystal is presented here without the account of incoherent scattering of the impinging particle on the crystal atoms, which leads to the particle dechanneling. It shows the distribution of ionization loss value of 10^6 particles which impinge on the crystal having arbitrary values of impact parameters with respect to the crystal plane, which models the incidence of a real beam on the crystal (neglecting the beam divergence).

We see that the spectrum for the disoriented crystal has a conventional shape of Landau-Vavilov distribution [7–9] with a single maximum corresponding to MPEL. The spectrum for oriented crystal differs significantly from it. It is much broader and has a two-humped structure. Its high-energy maximum at $\mathcal{E} \approx 700\,\text{keV}$ (which is larger than MPEL for the disoriented crystal) is intuitively expected as a result of the effect opposite to the one taking place for positive channeled particles, which have smaller MPEL values than in disoriented crystals. Indeed, positive particles are repelled from the atomic planes and spend a lot of time on relatively large distance from them in the region of low atomic electron density, while the negative ones are attracted to the planes and it is natural to expect the increase of their ionization loss while proceeding from the overbarrier to channeling mode. The existence of low-energy maximum of the two-humped distribution in Fig. 1, therefore, seems to be counterintuitive. Its explanation requires some deeper analysis of the impact parameter dependence of the particle ionization energy loss in crystal, which is the object of the present paper.

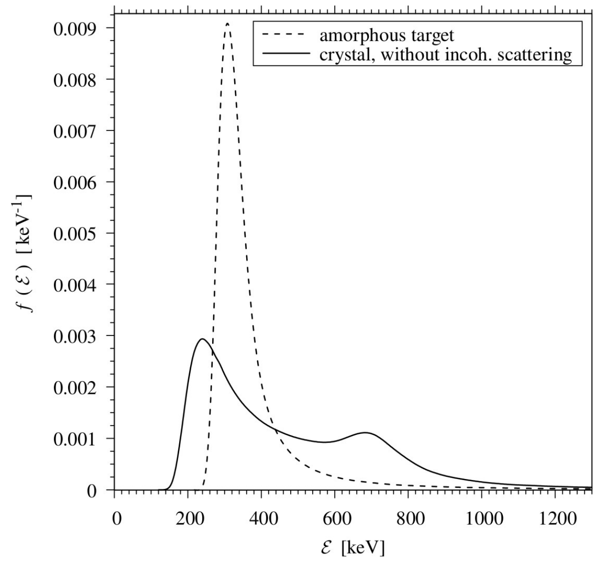

Figure 1. The distribution of ionization energy loss of 150 GeV/c π^- mesons during planar channeling in the field of (110) planes of Si crystal (solid line) and during motion in an amorphous target (dashed line).

The particle trajectory inside the crystal we define via numerical solution of the equation of particle motion (see formula (3) in the next section) in the field of crystalline atomic planes. For the latter field the Doyle-Turner model is applied. The probability for the particle to interact with an atom within the segment dl of its trajectory can be defined as $dP = n_{\text{eff}}\sigma dl$, where σ is the total collision cross section with an arbitrary energy transfer $\mathcal{E}$. The quantity n_{eff} here is some effective atomic electron density. It can be presented as a combination of two other quantities $n(\mathbf{r})$ and n as $n_{\text{eff}} = (1-\alpha)n + \alpha n(\mathbf{r})$ [1,6]. Here $n(\mathbf{r})$ is the real local electron density at the points of the particle trajectory, associated with the contribution of close collisions to the probability of particle interaction with the atom. The quantity n is the electron density averaged over a macroscopic volume inside the crystal, associated with the contribution of distant collisions to the above probability. The quantity α, belonging to the interval $0 < \alpha < 1$, defines the relative contributions of close and distant collisions to the particle ionization energy loss. At high particle energies these contributions can be considered as approximately equal [1,10,11], which corresponds to the choice $\alpha = 1/2$.

In case the collision takes place within dl, the value $\mathcal{E}$ of the particle energy loss in this collision can be further simulated using the probability distribution for this value $\rho(\mathcal{E}) = \sigma^{-1}(d\sigma / d\mathcal{E})$. For the differential cross section of energy transfer $d\sigma / d\mathcal{E}$ we apply the expression derived in [12], which proved its validity in comparisons with the experimental results for high-energy particles ionization loss in disoriented silicon targets, reported in the same paper. For very high particle energies, which we presently consider (namely, $\gamma >> 100$, where γ is the particle Lorenz-factor), it can be presented as follows:

$$\frac{d\sigma(\mathcal{E})}{d\mathcal{E}} = 6.25\times 10^{11}\,\frac{2\pi e^4}{mc^2}\sum_i \frac{f_i}{\mathcal{E}}\left\{ \ln\frac{2mc^2\mathcal{E}}{(\hbar\omega_p)^2}\,\delta(\mathcal{E}-E_i) \;+\; \mathcal{E}^{-1}H(\mathcal{E}-E_i)\right\}, \tag{1}$$

where the numerical factor in front of the formula ensures that all the quantities with the dimension of energy, i.e. $\mathcal{E}$, $\hbar\omega_p$ and mc^2 can be taken in eV, σ in cm^2, while e is the CGS value of the electron charge. Here m is the atomic electron mass, ω_p is the crystal plasma frequency, $\delta(x)$ and $H(x)$ are Dirac delta function and Heaviside step function, E_i are the effective ionization potentials of the atomic shells and f_i are the corresponding dipole oscillator strengths. The sum is performed over the occupied atomic K, L and M shells of silicon and the parameters E_i and f_i should be assigned the following values [12]: $E_K = 4033\,\mathrm{eV}$, $E_L = 241\,\mathrm{eV}$, $E_M = 17\,\mathrm{eV}$, $f_K = 2/14$, $f_L = 8/14$, $f_M = 4/14$.

Having simulated the particle energy loss on each segment of its trajectory we obtain the total particle ionization energy loss $\mathcal{E}$ inside the crystal. This value is stochastic and varies for different particles even if they travel along the same trajectory (which can take place for the particles impinging on the crystal with the same impact parameter only in the idealized case, when incoherent scattering is neglected). Fig. 1 shows the example of distribution of the value of $\mathcal{E}$ in the case when the impinging particles have arbitrary impact parameters.

IMPACT PARAMETER DEPENDENCE OF THE PROBABILITY OF CLOSE COLLISIONS OF NEGATIVELY CHARGED PARTICLES WITH CRYSTAL ATOMS DURING PLANAR CHANNELING

As we saw in the previous section, ionization energy loss of fast particles in a crystal is proportional to the probability of close collisions, associated with $n(\mathbf{r})$. Thus, in order to explain the peculiarities of ionization loss distribution, it is necessary to find the dependence of this probability on the impact parameter of negatively charged particles during planar channeling in a crystal. To do it analytically we will use a parabolic approximation of the planar potential, in which a particle with the charge of electron in the field of atomic planes has the potential energy

$$U(x) = -U_0\left[\left(2\frac{x}{d_p}-1\right)^2 H(x) + \left(2\frac{x}{d_p}+1\right)^2 H(-x)\right], \tag{2}$$

where the x-axis is perpendicular to the atomic plane, $|x| \le d_p/2$, d_p is the distance between neighboring atomic planes. Atomic planes are located in the points $x = nd_p$, $n \in \mathbb{Z}$, and presently we consider the particle channeled motion in the vicinity of the plane located at $x = 0$.

To find the particle trajectory in the field (2) we must solve the motion equation [13]

$$\frac{d^2x}{dt^2} = -\frac{v}{p}\frac{\partial U(x)}{\partial x}, \tag{3}$$

where p and v are respectively the particle momentum and velocity and c is the speed of light in vacuum. To solve the equation (3) it is necessary to divide the planar channel into two parts, $0 \le x \le d_p/2$ and $-d_p/2 \le x \le 0$, and consider the particle motion in each of them. For definiteness, we will assume that when the particle impinges on the crystal, its impact parameter with respect to the atomic plane with coordinate $x = 0$ is $x_0 > 0$. In this case, in the region $0 \le x \le d_p/2$ we need to solve the equation of motion

$$\frac{d^2x}{dt^2} = \frac{v}{p}\frac{4U_0}{d_p}\left(2\frac{x}{d_p}-1\right). \tag{4}$$

The solution to equation (4) can be written in the following form:

$$x(t) = \frac{d_p}{2} + C_1e^{At} + C_2e^{-At},$$

where C_1 and C_2 are constants, that can be found from the initial conditions, and $A = \frac{2}{d_p}\sqrt{\frac{2vU_0}{p}}$.

If x_0 and v_{x0} are the initial coordinate and velocity of the particle along the x-axis, then the constants C_1 and C_2 in the solution of motion equation in the region $0 \le x \le d_p/2$ can be found as

$$\begin{cases} C_1 = \dfrac{1}{2}\left(x_0 - \dfrac{d_p}{2} + \dfrac{v_{x0}}{A}\right) \\ C_2 = \dfrac{1}{2}\left(x_0 - \dfrac{d_p}{2} - \dfrac{v_{x0}}{A}\right) \end{cases}.$$

Here and below, as in [6], we set $v_{x0}=0$, so that $C_1=C_2=\frac{1}{2}\left(x_0-\frac{d_p}{2}\right)$ and

$$x(t)=\frac{d_p}{2}+\left(x_0-\frac{d_p}{2}\right)\mathrm{ch}\left(At\right)\equiv g(t).$$

Now let us find the moment of time t_1 in which the particle will reach the point $x=0$:

$$t_1=\frac{1}{A}\mathrm{arch}\left(\frac{1}{1-2x_0/d_p}\right). \quad (5)$$

In the region $-d_p/2\le x\le 0$ the solution of equation (3) is

$$x(t)=-\frac{d_p}{2}+C_3e^{At}+C_4e^{-At},$$

where C_3 and C_4 are constants. Taking into account that, in view of the symmetry of the potential relative to the point $x=0$, at $t=2t_1$ the value of $x(2t_1)=-x_0$ and $v_x(2t_1)=v_{x0}=0$, we obtain the following solution of motion equation for $t_1\le t\le 3t_1$

$$x(t)=-\frac{d_p}{2}-\left(x_0-\frac{d_p}{2}\right)\mathrm{ch}\left(A\left(t-2t_1\right)\right)=-g(t-2t_1).$$

In general, the particle *x*-coordinate can be written as

$$x(t)=g\left(t-2t_1\,\mathrm{R}\left(\frac{t}{2t_1}\right)\right)\mathrm{sgn}\left(\cos\left(\frac{\pi}{2}\frac{t}{t_1}\right)\right), \quad (6)$$

where R(t) is a function that rounds its argument to the nearest integer.

Thus, in the parabolic potential model, we found the trajectories of negatively charged particles with different impact parameters. These trajectories are periodic non-sinusoidal oscillations with the period $T=4t_1$. It is important that this period substantially depends on the impact parameter x_0 of the particles. To illustrate this fact, Fig. 2 shows several trajectories with different impact parameters.

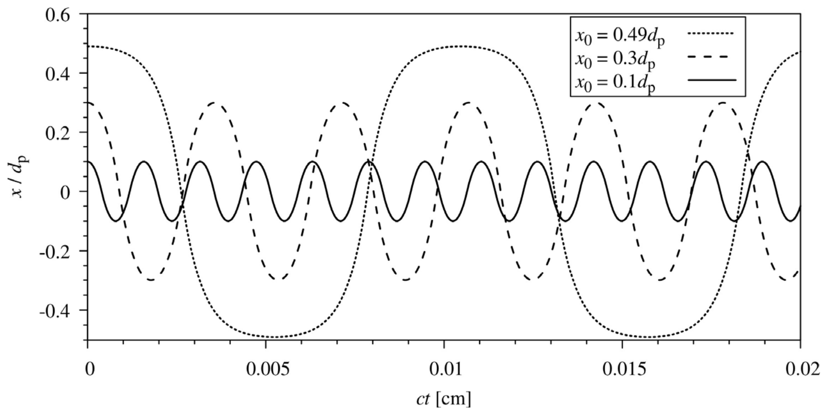

Figure 2. Trajectories of 150 GeV/c π^- mesons during planar channeling in the field of (110) planes of Si crystal.

The probability of close collisions of fast charged particle with atoms in a thin amorphous target can be written as a product of collision cross-section σ_c, atomic density N and thickness of the target L: $P=\sigma_c NL$. In a short oriented crystal this probability of close collisions can be written in a similar way with the help of integration over the particle trajectory inside the crystal: $P=\sigma_c\int N(x,y,z)dl$, where atomic density depends on the particle coordinate. In the case of motion in the field of atomic planes atomic density depends only on one coordinate: $N(x,y,z)=N(x)$. If we assume that atomic density near atomic plane has Gaussian distribution, then the probability of close collisions of fast charged particle with atoms during planar channeling can be found as

$$P(x_0) = B \int_{T_{\text{in}}}^{T_{\text{out}}} \exp\left(-\frac{x^2(t)}{2r_T^2}\right) v(t)dt\,, \tag{7}$$

where r_T is the atomic root mean square thermal vibration amplitude in one direction, B is a constant that includes σ_{c} and takes into account crystal parameters, T_{in} and T_{out} are the moments of time at which the particle enters the crystal and exits from it. If one substitutes expression (6) into equation (7), then one obtains the probability of close collisions of fast negatively charged particle with atoms as a function of the impact parameter x_0. This dependence is shown in Fig. 3 for 150 GeV/c π^- mesons that pass through the silicon crystal of thickness 1 mm in the regime of planar channeling in (110) atomic planes. For convenience, $P(x_0)$ is normalized to the value of $P(0)$.

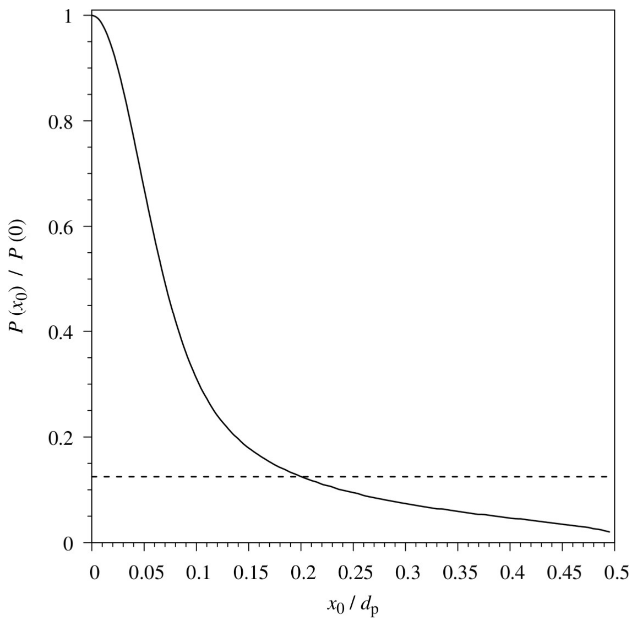

Figure 3. The dependence of probability of close collisions of 150 GeV/c π^- mesons with atoms on the impact parameter (solid line). Dashed line shows the mean probability of close collisions in the amorphous target.

It is also straightforward to estimate the probability of close collisions in a disoriented crystal when channeling is absent and the atoms can be considered as randomly located. Presently, at each moment of time the particle has equal chance to have an arbitrary value of impact parameter x_0 with respect to the atom it moves past. Let us choose the range of possible values of x_0 as $0 < x_0 < d_p / 2$. In this case the average probability of close collisions, normalized to the corresponding probability for $x_0 = 0$ (as in Fig. 3) is

$$\overline{P}_{\text{dis}} = \frac{2}{d_p} \int_0^{d_p/2} \exp\left(-\frac{x_0^{\;2}}{2r_T^2}\right) dx_0 \;=\; \frac{2}{\sqrt{\pi}\xi} \text{erf}(\xi)\,, \tag{8}$$

where $\xi = d_p / \left(2\sqrt{2}r_T\right)$ and $\text{erf}(x)$ is the error function. For the values $d_p \approx 1.92 \times 10^{-8}$ cm and $r_T \approx 7.5 \times 10^{-10}$ cm, typical for (110) planes of silicon crystal, $\xi \approx 9$ and $\text{erf}(\xi) \approx 1$, which gives $\overline{P}_{\text{dis}} \approx 0.125$. From Fig. 3 we see that this value is typical for channeled particles impinging on the crystal with the impact parameter of about $0.2d_p$.

IMPACT PARAMETER DEPENDENCE OF THE IONIZATION ENERGY LOSS DISTRIBUTION FOR NEGATIVELY CHARGED PARTICLES DURING PLANAR CHANNELING

Let us now study how the impact parameter dependence of close collisions, obtained in the previous section, manifests itself in the analogous dependence of the ionization energy loss distribution, resulting in a large width of the distribution for channeled particles in Fig. 1 (which is averaged with respect to impact parameters) and its two-humped structure. This study was carried out using numerical simulation of charged particles motion in oriented crystal, the principle of which is described in [14–17]. The simulation was carried out for 150 GeV/c π^- mesons that pass through the silicon crystal of 1 mm thickness in the regime of planar channeling in (110) atomic planes. For a clearer study of the reasons for appearance of the two-humped distribution, the simulation was carried out without taking into account the incoherent scattering of particles (except for the results shown in the last figure of this section). Some of the obtained distributions are shown in Fig. 4 for the values of the impact parameter $x_0 = 0.05d_p$ (dash-dotted line), $x_0 = 0.25d_p$ (dashed line) and $x_0 = 0.45d_p$ (dashed line with two dots) and for scattering in amorphous target (solid line). The figure shows that each impact parameter corresponds to the Landau distribution with different values of MPEL. The lower is the value of the impact parameter, the higher is the value of MPEL of the particles. From Fig. 3 we see that, this dependence nicely correlates with the impact parameter dependence of probability of close collisions. With the decrease of impact parameter, the probability of close collisions of particles with the crystal atoms increases. This growth leads to the increase in parameter n_{eff}, and, consequently, to the increase in value of MPEL of the particles. The most interesting is the fact that at large values of the impact parameter, the value of MPEL of channeling negatively charged particles turns out to be lower than in an amorphous target. This is both due to the increase in oscillation period of the particles in the planar channel, which occurs with the increase in impact parameter x_0 (see eq. (5)), and to the fact that particles with large impact parameters 'hang' in the regions located close to the center of the gap between the atomic planes. The latter means that such particles have noticeable segments of their trajectory almost parallel to the atomic plane (see, e.g., the trajectory shown in Fig. 2 by the dotted line). The shape of trajectories of such particles is very far from the sinusoid and such particles spend much less time near the plane than far from it. It is such particles with relatively large impact parameters that form the low-energy peak of the two-humped distribution in Fig. 1, while the ones with small impact parameters are responsible for the corresponding high-energy peak. Let us note that such a two-humped structure of the distribution persists after taking into account the particle incoherent scattering on atoms as well, provided the dechanneling length is larger than the crystal thickness [6].

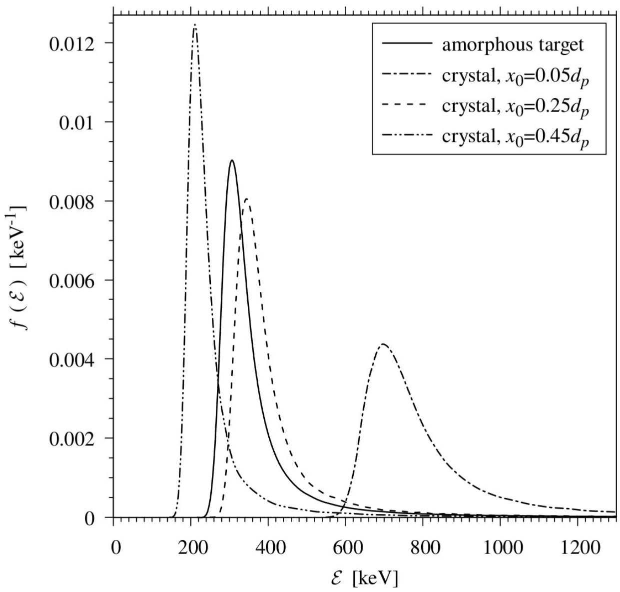

Figure 4. The distribution of ionization energy loss of 150 GeV/c π^- mesons during planar channeling in the field of (110) planes of Si crystal for different values of the impact parameter (dashed and dash-dotted lines) and during motion in an amorphous target (solid line).

The dependence of MPEL of 150 GeV/c π^- mesons on the impact parameter is shown in Fig. 5. The solid line corresponds to the motion of particles in the silicon crystal of 1 mm thickness in the regime of planar channeling in (110) atomic planes without taking into account incoherent scattering, while the dash-dotted line corresponds to the motion of particles in the same crystal, but taking such a scattering into account. Incoherent scattering was taken into account in the same way as in [18]. The behavior of these dependences is very similar to that of the dependence of probability of close collisions with atoms on the impact parameter, shown in Fig. 3. The dashed line in Fig. 5 shows the value of MPEL when particles pass through an amorphous target. It can be noted that taking incoherent scattering into account leads to the fact that the dependence of MPEL on the impact parameter becomes more similar to this dependence in an amorphous target. This is because incoherent scattering leads to dechanneling of some of the particles. The motion regime of these particles changes. They become overbarrier with respect to the potential of atomic planes. In this case, their motion becomes more similar to scattering in an amorphous target. At the same time, from Fig. 5 we see that even after taking into account the incoherent scattering of particles by thermal vibrations of atoms and electronic subsystem of the crystal, there remains a large group of particles, which MPEL in an oriented crystal is smaller than in an amorphous target. This group consists of particles with large impact parameters.

Fig. 5 indicates a rather wide spread of MPEL values in the allowed range of impact parameters, which explains the large width of the distribution in an oriented crystal in Fig. 1 compared to the one in the disoriented crystal. The significant dependence of MPEL of negatively charged particles on the impact parameter is quite unusual, since it is much less pronounced in the case of positively charged channeled particles, which have ionization loss distribution with the width close to the one typical for the disoriented crystal [4]. In this regard, it would be highly desirable to carry out thorough experimental study of the ionization energy loss distribution of negatively charged channeled particles. For such a study it is best of all to use crystal targets of thickness smaller than the dechanneling length in order to minimize the effect of incoherent scattering.

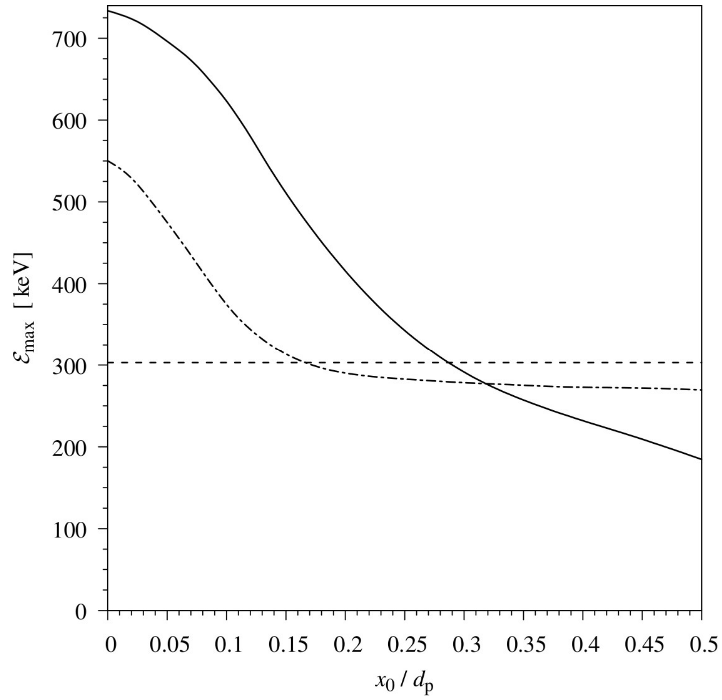

Figure 5. The impact parameter dependence of the most probable ionization energy loss of 150 GeV/c π^- mesons during planar channeling in the field of (110) planes of Si crystal with (dot-dashed line) and without (solid line) taking into account incoherent scattering and during motion in an amorphous target (dashed line).

CONCLUSION

The investigation of ionization energy loss distribution of high-energy negatively charged particles which move in the planar channeling mode in a silicon crystal showed a significant dependence of the value of the most probable energy loss on the impact parameter. It is quite unusual, since such a dependence is much less pronounced in the case of positively charged particles. It is shown that, for a large group of particles with large impact parameters, the most probable ionization energy loss during planar channeling in a crystal is lower than in an amorphous target, while for particles with small impact parameters the most probable ionization energy loss in a crystal is significantly higher than in an amorphous target. It is demonstrated that negatively charged channeled particles with large impact parameters can move in the 'hanging' mode (which resembles the case of positive over-barrier particles) having considerably suppressed probability of close collisions with the crystal atoms. The presented investigation explains the two-humped structure and considerable broadening of the ionization energy loss distribution for negatively charged channeled particles, revealed in our previous study. More detailed investigation of this problem requires taking into account the non-zero angle between the initial momentum of the particles and atomic planes, and is planned to be performed in the future.

ACKNOWLEDGEMENTS

This work was partially supported by the National Academy of Sciences of Ukraine (program "Support for the Development of Priority Areas of Scientific Research" 6541230, projects C-2/56-2021, F30-2021, 60-08/10-2021).

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ПРО ЗАЛЕЖНІСТЬ ІОНІЗАЦІЙНИХ ВТРАТ ЕНЕРГІЇ ШВИДКИХ НЕГАТИВНО ЗАРЯДЖЕНИХ ЧАСТИНОК В ОРІЄНТОВАНОМУ КРИСТАЛІ ВІД ПРИЦІЛЬНОГО ПАРАМЕТРА

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Коли швидка заряджена частинка рухається в речовині, вона втрачає частину своєї енергії на збудження та іонізацію атомів. Ці втрати енергії називаються іонізаційними втратами енергії. У досить тонких шарах речовини значення таких втрат енергії є стохастичним. Воно розподіляється відповідно до закону, що його вперше отримав Л.Д. Ландау. В аморфних речовинах такий розподіл (або спектр), відомий як розподіл Ландау, має єдиний максимум, який відповідає найбільш ймовірному значенню втрат енергії частинок. При русі частинки в режимі площинного каналювання у кристалі відбувається зменшення (при позитивному заряді частинки) або збільшення (при негативному заряді) ймовірності близьких зіткнень частинки з атомами, що призводить до зміни величини найбільш ймовірної втрати енергії порівняно з аморфною мішенню. Нещодавно було показано, що при каналюванні негативно заряджених частинок у кристалі розподіл іонізаційних втрат енергії частинок є значно більш широким, ніж у аморфній мішені. При цьому цей розподіл може бути двогорбим, якщо знехтувати некогерентним розсіянням заряджених частинок на теплових коливаннях атомів кристала та електронній підсистемі кристала. В даній роботі пояснюється причина виникнення такого розподілу іонізаційних втрат енергії частинок. За допомогою чисельного моделювання досліджено розподіл іонізаційних втрат енергії негативно заряджених частинок високої енергії, які рухаються в режимі площинного каналювання в кристалі кремнію. Розглянуто залежність цього розподілу від прицільного параметра частинок відносно атомних площин. Знайдено залежність найбільш ймовірних іонізаційних втрат енергії частинок від прицільного параметра. Показано, що для великої групи частинок найбільш ймовірні іонізаційні втрати енергії при площинному каналюванні у кристалі є нижчими, ніж у аморфній мішені.
Ключові слова: іонізаційні втрати енергії, площинне каналювання, негативно заряджені частинки.