HIGH-ENERGY POSITRON IONIZATION LOSS SPECTRA IN A SILICON CRYSTAL AT VARIOUS INCIDENCE ANGLES WITH RESPECT TO A CRYSTALLINE AXIS

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The ionization energy loss distributions (spectra) of high-energy positrons in oriented silicon crystals are considered on the basis of computer simulation. Evolution of the spectra with the change of crystal orientation from the axial $\langle 100\rangle$ to the planar (100) and (110) is investigated. It is shown that both the most probable E_{MP} and average E_{AV} energy losses in these cases change non-monotonically, while E_{MP} may change even discontinuously. Correlation of these variations of E_{MP} and E_{AV} with the change of the particle motion regime is discussed.

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INTRODUCTION

Penetration of a high-energy charged particle through a medium is accompanied by different processes of the particle energy loss. They include several types of electromagnetic radiation (bremsstrahlung, Cherenkov, transition, channeling etc.) and energy loss on excitation and ionization of atoms known as ionization energy loss (or simply, ionization loss). Incident hadrons are likely to trigger nuclear reactions as well. In thin silicon detectors the ionization loss leads to production of electron-hole pairs, which create a measurable current upon application of an external voltage. Thereby, it is possible to measure the ionization loss of each separate particle of the beam and investigate the probability distribution of the value of this loss in the case when the beam current is not very high. In thin amorphous targets, or disoriented crystalline detectors, this probability distribution, which we will further call the ionization loss spectrum (ILS), was derived by Landau [1] and further vastly investigated both theoretically and experimentally.

The ILS of high-energy particles in oriented crystals have been experimentally studied as well (see [2, 3] and refs. therein). The peculiarity of this case is in the fact that when a charged particle enters a crystal at a small angle with respect to a crystalline axis or plane, the channeling mode of motion can take place. In this mode the particle is trapped in a potential well created either by separate atomic planes or strings (in the case of negatively charged particles) or by neighboring planes or strings (for positively charged particles). Particularly, positively charged particles, being repelled from the planes and strings, experience a reduced amount of close collisions with atoms losing less energy. As shown [2, 3], this leads to a shift of the ILS maximum, corresponding to the most probable value E_{MP} of the particle ionization energy loss in the target, to the region of smaller losses. In the cited works, only the case when the mean direction of the incident particle beam is parallel to the crystal axes or planes has been considered. In [4] the ILS evolution with the change of angle θ between the particle velocity and a crystal plane has been investigated. In the present work we investigate evolution of ILS with the change of angle ψ between the incident particle momentum and the axis $\langle 100\rangle$ of a silicon crystal. As an example of the particles we consider 3 GeV positrons, which are available, e. g. at DESY II Test beam facility. The transitions from the axial $\langle 100\rangle$ to planar (100) and (110) orientations are investigated. The simulation in the random string model, corresponding to transition from the axial $\langle 100\rangle$ orientation to a non-oriented crystal, is performed as well.

1. SIMULATION METHOD

For simulation of a particle ionization loss we separate it into contributions of distant and close collisions. Simulation of distant collisions is based on separate treatment of interactions with the atoms on small ($\rho_a < \rho_0$) and large ($\rho_a > \rho_0$) distances ρ_a from the particle trajectory. For the first ones the probability of energy transfer considerably depends on the particle coordinates (x, y) in the plane perpendicular to its direction of motion inside the crystal unit cell (the particle is supposed to move at a small angle with respect to a crystal axis or plane). The interactions at $\rho_a > \rho_0$ are supposed to occur like in an amorphous medium and the corresponding probability of energy transfer is not sensitive to the exact particle position inside the cell. Simulation of the distant collision contribution is based on the expression for the probability of excitation or ionization of the atom by the incident particle as a function of the particle impact parameter ρ [5]. On the basis of this expression it is possible to derive the probability for the particle to undergo a distant collision with an atomic electron at i-th shell (K, L, M etc.) and lose energy ε_i per unit path. The contribution from close collisions is defined from the Rutherford cross section, where one has to apply the local atomic electron density $n(\boldsymbol{r})$ depending on the particle position.

The particle trajectory is defined by numerical solution of the equation of its motion in the averaged potential of atomic stings or planes, depending on the crystal orientation. The particle incoherent scatterings on atomic electrons and thermal vibrations of atoms are taken into account.

2. EVOLUTION OF IONIZATION LOSS SPECTRA WITH THE CHANGE OF ψ

Fig. 1 demonstrates the simulated ILS for various angles ψ between the incident positron momentum and the axis $\langle 100 \rangle$ of a 200 μm silicon crystal.

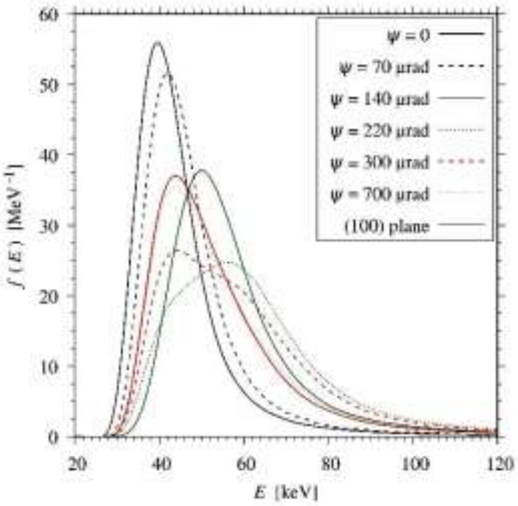

Fig. 1. ILS of 3 GeV positrons in a silicon crystal of 200 μm thickness at various angles between the incident particle momentum and the $\langle 100 \rangle$ crystal axis in the transition $\langle 100 \rangle \rightarrow (100)$

The angle changes in such way that the vector of the incident particle momentum remains parallel to (100) plane.

The figure demonstrates a noticeable variation of the spectrum with the increase of ψ. Presently, the critical angle of axial channeling is $\psi_c \approx 222$ μrad. At small ψ the spectrum is typical for axially channeled particles having the maximum shifted to the left compared to the position typical for a non-oriented crystal (at about 56.5 keV). At $\psi \approx \psi_c$ the spectrum demonstrates a two-humped structure. The right peak (which corresponds to the main maximum in the spectrum for $\psi = 220$ μrad, while for $\psi = 300$ μrad it rather looks like a convexity at $E \approx 60$ keV) in this case is associated with over-barrier particles which can approach rather closely atomic strings and lose almost the same amount of energy as in a non-oriented crystal. The left peak originates from the particles which are already captured into the planar channeling mode.

A non-monotonic nature of ILS evolution in the considered case becomes more evident if consider the change of the most probable energy loss E_{MP} corresponding to the ILS maximum, as well as of the average restricted ionization loss E_{AV} defined as

$$E_{AV} = \int_0^{E_0} f(E) E dE \#(1)$$

where, for definiteness, we choose $E_0 = 250$ keV. Fig. 2 shows the dependence of E_{MP} on ψ for the transition $\langle 100 \rangle \rightarrow (100)$. We see that in this case the value of E_{MP} has a sharp maximum and a discontinuity. The analogous treatment for the transition $\langle 100 \rangle \rightarrow (110)$, when the vector of the incident particle momentum remains parallel to (110) plane as ψ increases, demonstrates a noticeably different behavior of E_{MP}. In this case the discussed quantity remains continuous and has a much smaller amplitude of variation.

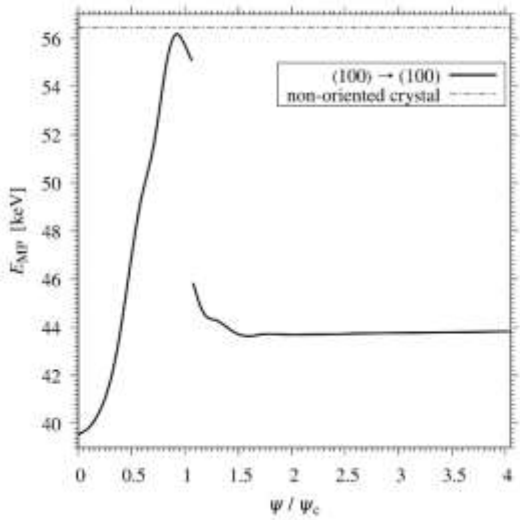

Fig. 2. Dependence of the most probable energy loss of 3 GeV positrons in 200 μm silicon crystal on the angle between the incident particle momentum and the $\langle 100 \rangle$ crystal axis

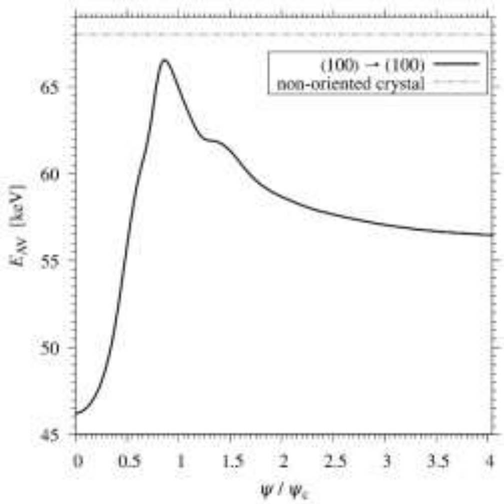

Fig. 3. Dependence of the average restricted energy loss of 3 GeV positrons in a 200 μm silicon crystal on the angle between the incident particle momentum and the $\langle 100 \rangle$ crystal axis

Fig. 3 shows the analogous dependence for E_{AV}. It resembles the dependence of E_{MP}, but does not have a discontinuity. The dependencies presented in Fig. 2 and Fig. 3, as well as the corresponding dependencies in $\langle 100 \rangle \rightarrow (110)$ transition, demonstrate a strong correlation between the values of E_{MP} and E_{AV} and the change of the particle motion regime in the crystal in the considered transitions. Particularly, much smaller variation of these quantities in the transition to (110) plane, than in the transition to (100) plane, is a result of much more efficient particle capture into planar channels formed by (110) planes. It is associated with almost twice as large depth of the potential well in (110) planar channel.

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