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DECHANNELING OF RELATIVISTIC PROTONS AND NUCLEI IN STRAIGHT AND BENT CRYSTALS. RECHANNELING ROLE

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Деканалирование релятивистских протонов и ядер в прямом и изогнутом кристаллах. Роль реканалирования

Моделированием исследовано плоскостное деканалирование релятивистских протонов и ядер свинца с одинаковым импульсом на единицу заряда p_z в прямом и изогнутом кристаллах. Показано, что различная вероятность перезахвата в режим каналирования протонов и ядер нарушает инвариантность длин деканалирования относительно p_z в прямом кристалле, тогда как в изогнутом кристалле приближенная инвариантность имеет место.

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Dechanneling of Relativistic Protons and Nuclei in Straight and Bent Crystals. Rechanneling Role

Planar dechanneling of relativistic protons and Pb nuclei with the same momentum per unit charge p_z in straight and bent crystals was investigated by simulation. It was shown that the different probability of the recapture into the channeling regime for protons and Pb nuclei infringes the dechanneling length invariance with respect to p_z in the straight crystals, whereas in the bent crystals the approximate invariance occurs.

The investigation has been performed at the Laboratory of High Energies, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna, 1997

Motion of planar channeled particles in the oriented crystals is governed by the electric field of the crystal atoms averaged along the crystal planes. The channeling parameters determined by the averaged potential such as the spatial period λ of the particle oscillations in the planar channel and the critical channeling angle ϑ_c are invariant relative to the value of $p_z = p/Z$, where p,Z are the particle momentum and charge. The critical radius of the crystal bending is also invariant with respect to p_z

$$R_c(p_z) = \frac{p_z c}{eE_{max}}, \tag{1}$$

where E_{max} is a maximum electric field intensity in the planar channels.

In the bent crystals the channeling parameter invariance is observed at the same relative crystal curvature $r = R/R_c$ [1]

$$\vartheta_c(p_z; r) = \left(\frac{2E^1_{xc}(r)}{p_z v}\right)^{1/2}, \tag{2}$$

$$\lambda(ZE_x, p_z; r) = \sqrt{2p_z v} \int_{x_1(E_x)}^{x_2(E_x)} \frac{dx}{\sqrt{E_x - U^1_{ef}(x, r)}}, \tag{3}$$

where U^1_{ef} is the effective planar potential for protons in the bent crystal, x_1, x_2 are the turn points of particles in the potential, $E^1_{xc} = U^1_{ef}(r_c)$ is the critical transverse energy of particles for existing the stable trajectories in the channels, r_c is the corresponding critical distance of particle approach to the channel wall.

For the given r the probability of particle capture into the channeling regime will be identical at the same relative beam divergence $\xi = \bar{\vartheta}/\vartheta_c$. So, when the angular distribution of the beam is Gaussian then for the capture probability we have

$$P_c(r, \xi) = \frac{1}{d_p} \int_{r_c}^{x_{ch}} Erf\left[\frac{1}{\sqrt{2}\xi}\left(1 - \frac{U^1_{ef}(x_o, r)}{E^1_{xc}(r)}\right)\right] dx_o, \tag{4}$$

where d_p is the channel width, x_o is the coordinate of particle entrance into the channel, x_{ch} is the coordinate which determines the transverse region for channeling, $U_{ef}(x_{ch}) = E_{xc}$.

The particle dechanneling in the defect-free crystal occurs mainly due to multiple scattering by the crystal electrons. For silicon crystals a main contribution is provided by the valence electrons whose density is approximately constant over the channel. The experimental investigations and simulation show that the depth dependence of the channeled particle number is close to the exponential one. The dechanneling length can be estimated as

$$S_{1/e} \sim \frac{\vartheta_c^2}{\overline{\Delta\vartheta_x^2}/\Delta z}\,, \qquad (5)$$

where $\overline{\Delta\vartheta_x^2}/\Delta z$ is the mean square of the particle deflection angle projection per unit path length due to multiple scattering by the electrons

$$\frac{\overline{\Delta\vartheta_x^2}}{\Delta z} = N Z_v \frac{2\pi e^4}{v^2 p_z^2}\, L_e\,, \qquad (6)$$

$$L_e = \ln(b_{max}/b_{min}) = \ln(Z r_a \sqrt{2 p_z v\, E^1_{xc}}/\hbar v)\,. \qquad (7)$$

Here b_{max}, b_{min} are the maximum and minimum impact parameters of collisions [2], r_a is the atomic radius. The dechanneling length depends on the particle parameters through the momentum per unit of charge p_z in the first approximation only. Besides, there is a logarithmic dependence upon the nuclei charge Z.

The dechanneled particles can be again captured into the channeling states due to the strong nuclear scattering in the capture region, where the particle momentum direction is nearly parallel to the atomic planes [3]. However, in the bent crystals the dechanneled particles fast leave the capture region due to the bending of the planar channels. Therefore, the particle recapture is practically absent. This fully justifies the application of the boundary conditions which forbids the exchange between the beam fractions for the Fokker — Planck equation describing the evolution of the particle distribution over the transverse energy [2], as well as the application of the equation (5) for the dechanneling length estimation in the bent crystals.

The experimental study of the deflection of an ultra-relativistic Pb^{82+} ion beam at a momentum of 33 TeV/c by a bent silicon crystal has been recently performed at the CERN-SPS [4]. The observed deflection efficiency was close to the one obtained for protons with the same p_z. Our simulation results in the frame of the atomic plane model [3] give the efficiency values close to the experimental ones. So, because of a low particle recapture role the approximate dechanneling length invariance really occurs in the bent crystals.

On the other hand, in the straight crystals the recapture of protons into the channeling regime is considerable because the particles gradually leave the near-barrier region only as a result of multiple scattering.

The dechanneling lengths observed in the experiments with the straight crystals considerably depend on the recapture process, which makes the lengths much bigger than it follows from the estimation (5).

Fig.1a shows our simulation results for the channeled particle number as a function of the beam penetration depth into the silicon straight crystal oriented along the (110) planes. The proton beam with the momentum of 100 GeV/c and the uniform angular distribution in the interval of $(-\vartheta_c, \vartheta_c)$ enters the crystal parallel to the (110) channel walls. The beam fraction being in channeling states all the way from the entrance into the crystal, it can be called a planar gyperchanneled fraction $N^o_{ch}(z)$, and the full number of channeled particles $N_{ch}(z)$ accounting the recapture are shown. The recapture contribution does not change the dependence character for the full number of channeled particles which is also close to the exponential one. The dechanneling lengths are $S^o_{1/e} = 35$ mm, $S_{1/e} = 62$ mm. The second value accounting the recapture is in good agreement with the experiment [5].

On the contrary, for heavy nuclei the above-barrier beam fraction fast decreases crossing the crystal because of a high cross-section for nuclear and electromagnetic inelastic interactions. So, the nuclear inelastic length is about 1 cm for the Pb nuclei in the silicon. This stipulates a considerably smaller recapture probability for the dechanneled Pb nuclei than for protons. In the bent crystals this recapture reduction does not considerably change the observed dechanneling length for heavy nuclei in comparison with protons because the recapture is already "forbidden" due to the channel bending. However, in the straight crystals the situation with nuclei channeling is quite different than for protons due to a different intensity of inelastic interactions for the above-barrier particles.

Fig.1b shows the same as fig.1a for the Pb nuclei with $p_z = 100$ GeV/c. The small difference observed between a full number of channeled particles and the gyperchanneled fraction occurs due to a low recapture probability because of the fast reduce of the above-barrier beam fraction. The dependences of the full number of channeled particles for the protons and Pb nuclei are compared in fig.2. The corresponding dependences for the particle number recaptured into the channeling regime are shown in fig.3. So, a considerable growth of the inelastic interaction cross-section for Pb nuclei in comparison with the protons reduces the recapture probability and, therefore, infringes the dechanneling length invariance with respect to p_z in the straight crystals.

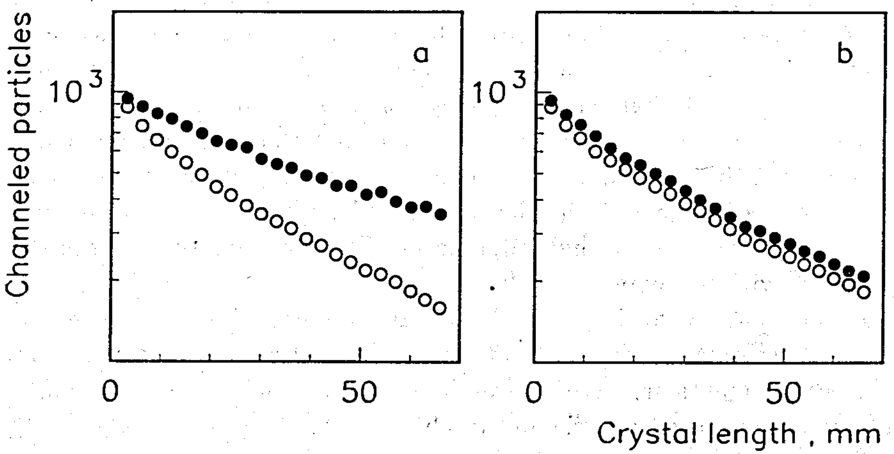

Fig.1. The dependence of the channeled particle number on the beam penetration depth into the Si straight crystal oriented along the (110) planes: **(a)** for the proton beam with the momentum of 100 GeV/c, **(b)** for the Pb nuclei with the same momentum per unit of charge. The black circles show the full number of channeled particles accounting their recapture, the empty ones the gyperchanneled fraction.

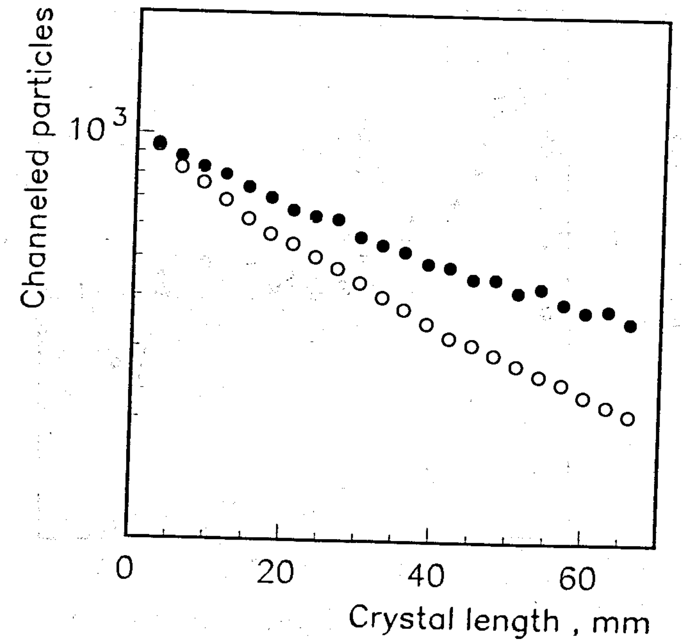

Fig.2. The full number of channeled particles as a function of the crystal length for the protons (black) and Pb nuclei (empty) with the same momentum of 100 GeV/c per unit of charge.

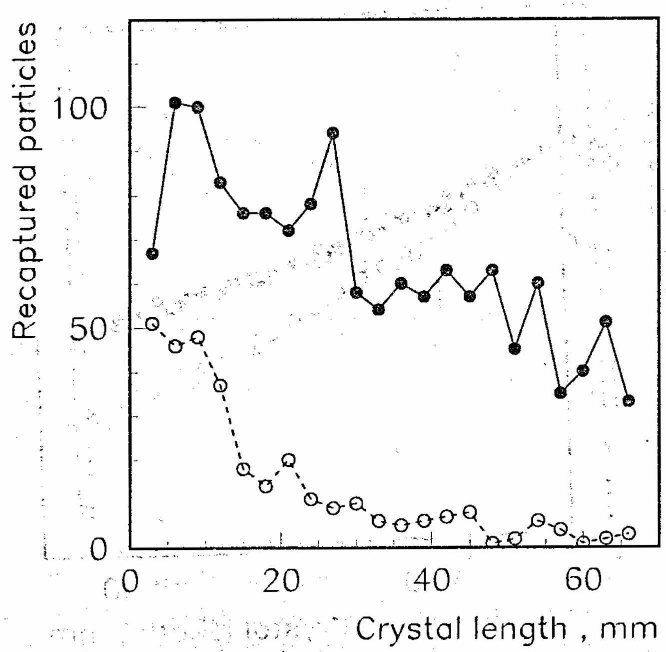

Fig.3. The particle number recaptured into the channeling regime as a function of the crystal length for the protons (black) and Pb nuclei (empty).

Acknowledgements

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