Mechanism of self-collimation and **weakening of dechanneling** during realistic channeling of positive ions in crystals

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The traditional description of channeling processes is based on two main assumptions:

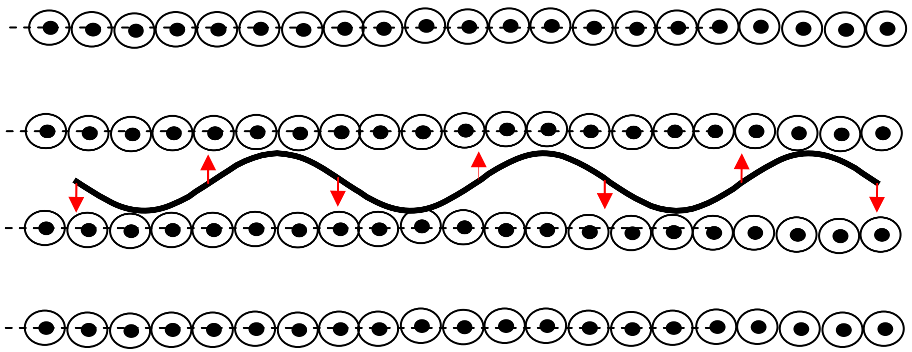
- a significant influence of the averaged channel potential $< V(x) >$ on the ordered periodic motion of ions with mass M_0;
- complete neglect of the **ordered influence** of the moving ions on the atoms of the channel (mass M_a).

Additionally, **it is traditionally believed** that the size of the spatial region of channeling of positively charged ions in crystals L_d is limited by the diffusion process of dechanneling of these ions due to scattering on electrons and nuclei of the crystal and **there are no methods to reduce dechanneling and increase the dechanneling length L_d.**
In fact, such a compensation method exists, but it has not been considered by anyone before due to the idealization of the channeling process.

This report discusses a self-controlled mechanism of possible anti-dechanneling for positive ions.

The physical basis of the channeling mechanism is associated with alternating processes of reflection of a moving ion from the potential of the channel walls and the corresponding transfer of transverse momentum to the atoms that form these walls.

It is traditionally assumed that with such reflection of a channeled ion from a crystalline plane, due to the fulfillment of the law of conservation of momentum, elastic reflection occurs **without transfer of part of the transverse energy to those atoms of the lattice that are within the reflection region $\Lambda/2=v_z/2\omega$**.



This conclusion is usually associated with the **assumption that the momentum of the reflected channeled particle is transferred to the entire crystal lattice with a very large total mass, formally consisting of an unlimited number of atoms with individual masses M_a.**

A more detailed analysis shows that **this traditional assumption is incorrect**, and the process of each **alternating reflection leads to a decrease in the transverse both momentum and energy of the moving particle.**

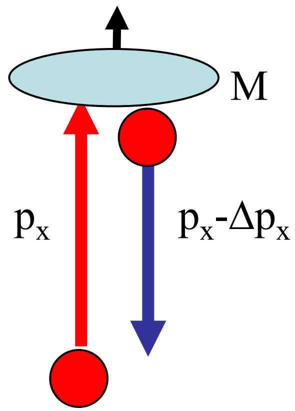
From the laws of conservation of energy and momentum

$$M_0 v_0^2 / 2 = M_0 (v_0^I)^2 / 2 + M v^2 / 2;$$

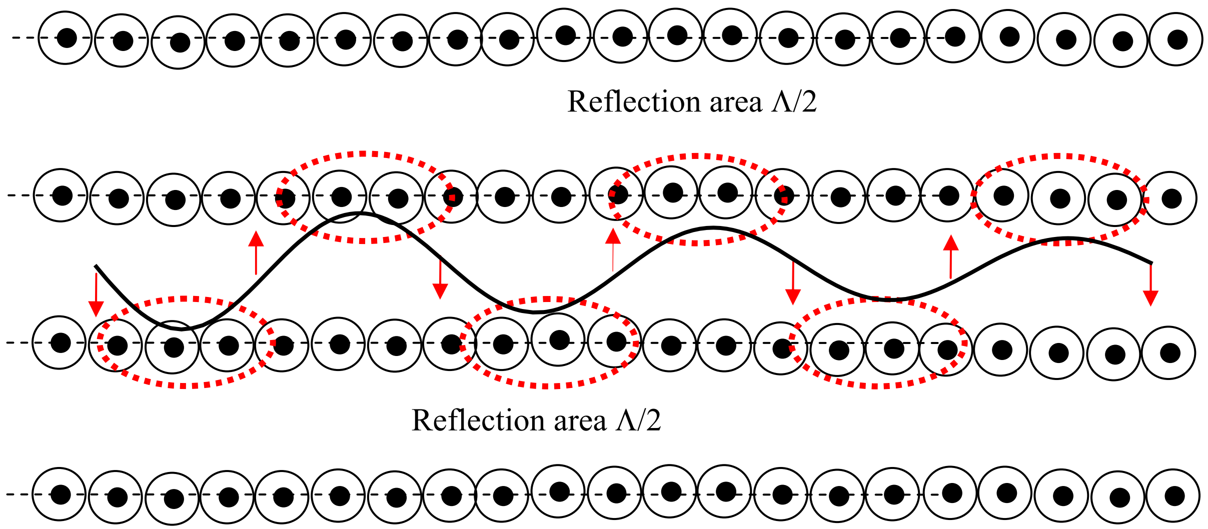
$$M_0 v_0 = M_0 v_0^I + M v$$

in elastic scattering follows an expression for the **decrease in the momentum of a particle with mass $\mathbf{M_0}$** when it is reflected in transverse x-direction by an object with total mass M

$$\Delta p_x = -\left\{ \frac{2M_0}{M_0 + M} \right\} p_x$$



The same reason corresponds to the decrease in the kinetic energy of the reflected particle



For channeling mode during each reflection, the ion loses part Δp_x of its transverse momentum

$$\Delta p_x = -\left\{\frac{2M_0}{M_0 + \sum_n M_{a(n)}}\right\} p_x = -\left\{\frac{2M_0}{M_0 + \sum_n M_{a(n)}}\right\} M_0 \frac{dx}{dt}$$

over the time $\Delta t = \Lambda / 2v_z = 1/2\omega$ it takes to travel half a spatial oscillation in the channel $\Lambda / 2$, and transfers Δp_x to atoms located on the surface of each channel wall within this interval along the trajectory of moving ion. These results are in good agreement with quantum concepts of delocalization of the interaction of a particle with crystal atoms during channeling.

It can be shown that this momentum Δp_x and the corresponding kinetic energy is transferred only to the atoms lying within the space interval $\Lambda / 2$ **of the channel wall.**

The subsequent transfer of both transverse mechanical momentum and kinetic energy $T_x(z)$ to atoms in more distant walls occurs through acoustic waves (AW), which travel at a speed $v_{AW} \approx (3-5)\cdot 10^5 cm/s$ in a solids.

The duration of each interval of reflection $\Delta t = 1/2\omega$ from the channel wall at a typical frequency of particle oscillations

$$\omega \approx \sqrt{8V_{\max} / M_0 d_x^2} \approx (3-5) \bullet 10^{14} s^{-1}$$

is equal to the value

$$\Delta t \approx (3-2) \bullet 10^{-15} s \ \ for \ \ proton \ \ at \ \ V_{\max} \approx 10-40\, eV, d_x \approx 2\mathring{A}.$$

From these data, we can obtain the estimate of the distance of transmission of an acoustic pulse during the time of a one reflection of a particle from a plane

$$\Delta t \cdot v_{AW} = \frac{v_{AW}}{2\omega} = \frac{v_{AW} d_x}{4}\sqrt{\frac{M_0}{V_{\max}}} \approx (0.03-0.015) d_x$$

From these relations it is evident that the size of **the possible region of the transfer of transverse momentum** from the particle to the lattice atoms located outside the channel during the time of particle repulsion from the channel wall **is much smaller than the distance d_x between the planes.** From this result it follows that **this momentum will be perceived only by atoms located on the "wall" of this channel within the band including atoms lying along the projection of the particle's line of motion**.
In this case we have the following repulsive mass

$$M = \sum_n M_{a(n)} \approx M_a(\Lambda / 2 < d_z >)$$

Only for very heavy particles and in the case of a very small channel wall height, the recoil momentum will be transmitted not only by the atom on which the scattering occurs, but also by neighboring atoms due to acoustic waves.
This process is **similar to the Mössbauer effect**, in which the emission of low-energy quanta occurs without the transfer of recoil energy (the recoil momentum in such emission is perceived by a large ensemble of nearby atoms with, accordingly, a large total mass). In this case, a similar process for high-energy quanta is accompanied by a decrease in the energy of these quanta due to the transfer of part of the energy to one nucleus.

The final expression for the loss of transverse momentum of the channeled particle during one reflection from the channel wall has the form

$$\Delta p_x = -\left\{ \frac{2M_0}{M_0 + M_a(\Lambda / 2 < d_z >)} \right\} M_0 \frac{dx}{dt}$$

This process is repeated at each subsequent reflection from the channel walls and it **corresponds to the action of the an averaged braking force** F_x on the transverse oscillations of the moving ion in a channel

$$F_x = \frac{\Delta p_x}{\Delta t} = -\frac{1}{(\Lambda / 2v_z)} \left\{ \frac{2M_0}{M_0 + M_a(\Lambda / 2 < d_z >)} \right\} M_0 \frac{dx}{dt} \approx$$

$$\approx -\frac{1}{(\Lambda / 2v_z)} \frac{2M_0}{M_a(\Lambda / 2 < d_z >)} M_0 \frac{dx}{dt} = -\frac{2M_0}{T} \frac{dx}{dt},$$

$$Here\ T = \frac{M_a \Lambda^2}{4M_0 < d_z > v_z} = \frac{M_a v_z}{4M_0 < d_z > \omega^2}$$

The transverse motion of a particle in the channeling mode in a planar channel <*V(x)*> is described by the balance of forces acting on the particle

$$M_0 \frac{d^2x}{dt^2} = \sum F = -\frac{d <V(x)>_z}{dx} - M_0 \frac{2}{T}\frac{dx}{dt}$$

From this relation follows the equation of particle motion

$$\frac{d^2x}{dt^2} + \frac{1}{M_0}\frac{d <V(x)>_z}{dx} + \frac{2}{T}\frac{dx}{dt} = 0$$

In a parabolic planar channel

$$<V(x)>_z = M_0\omega^2 x^2/2 \equiv V_{max}(2x/d_x)^2$$

the solution of the equation of transverse motion

$$\frac{d^2x}{dt^2} + \omega^2 x + \frac{2}{T}\frac{dx}{dt} = 0$$

corresponds to a damped harmonic oscillator with damping time T

$$x(t) = x(0)\exp\{\pm i\omega t - t/T\}$$

The similar solution is to describe the process of damping of transverse oscillations depending on the longitudinal coordinate $z=v\backslash t_z$

$$x(z=v_z t)=x(0)\exp\left\{\pm i(\omega/v_z)z - z/L_{self-coll}\right\}$$

Here

$$L_{self-coll}\equiv Tv_z=\frac{M_a\Lambda^2}{4M_0<d_z>}=\frac{M_a E_z d_x^2}{16M_0 V_{\max}<d_z>}$$

;

is the ***length of angular self-collimation (angular self-compression)*** of ***moving ion*** (e.g. proton) with mass $M_0=M_p$ in a crystal channel without dechanneling.
As follows from the structure of the general equation of motion

$$\frac{d^2x}{dt^2}+\frac{1}{M_0}\frac{d<V(x)>_z}{dx}+\frac{2}{T}\frac{dx}{dt}=0,$$

the solution with damping of oscillations will be for any type of channeling potential (naturally with a significantly different self-collimation coefficient).

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For typical parameters of channeling phenomena in parabolic channel

$$V_{\max} = 10 - 40eV, d_x \approx < d_z > \approx 2\AA,\ E_z = 1Mev, M_0 = M_p$$

we find

$$L_{self-coll} \approx (0.4 - 0.1)(M_a / M_p)\mu m$$

This value $L_{self\text{-}coll}$ can be compared with the dechanneling length L_d in *Si* crystal with ratio $M_a / M_p = 27$ and similar particle beam parameters

E(kev)	1400	1600	1800	2000	2200	Average
L_d (µm)	1.72±0.05	1.64±0.06	2.28±0.04	2.26±0.13	2.32±0.07	2.03

[Sepideh Shafiei, Mohammad Lamehi-Rachti. Dechanneling and the energy loss of protons along planar directions of Si. Radiation Phys. and Eng., V. 4 (1), 2023, p. 23-28]

It follows from these date that in a crystal lattice consisting of light isotopes with the minimum ratio M_a/M_0V_{max}, the length of self-collimation is comparable to the dechanneling length L_d.

Summary

The discussed angular self-collimation process can partially suppress the dechanneling process, which leads to increase in L_d to significantly larger value

$$L_d^* \approx L_d / (1 - L_d / L_{sc})$$

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It also follows from this analysis that the experimentally observed dechanneling length L_d^* **differs from the idealized calculation L_d of this value due to the presence of such self-collimation**.

In crystals consisting of light isotopes with a minimum ratio M_a/M_0V_{max}. the angular self-collimation effect can very effectively compenaate for the standard dechanneling process.

The same effect is possible when minimizing the ratio $d_x^2 / < d_z >$ of the crystal parameters.

This result is especially important in the analysis and creation of systems for deflecting beams of fast particles using the channeling effect in curved crystals.

Similar dechanneling processes are also possible during the movement of positive ions in planar nonparabolic channels, during channeling of relativistic particles and during axial channeling of positive ions.

Thank you for the attention