INFLUENCE OF THE ELECTROMAGNETIC SPIN-ORBIT INTERACTION ON THE MOTION OF IONS IN CRYSTALS UNDER PLANAR QUASI-CHANNELING

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The influence of the electromagnetic spin-orbit interaction on the motion of ions in crystals under the condition of instable trajectories in planar channeling is considered. It has been shown that the spin-orbit interaction can cause the polarization of particles that were scattered at angles close to the angle of mirror reflection from crystal planes and abandoned the crystal. The effect's experimental check scheme is offered. The scheme has been tested and its reason and feasibility have been verified.

Introduction

The theoretical analysis of the channeling effect is based on the assumption that only the long-range Coulomb interaction of a particle with the screened charge of a crystal atom is essential [1, 2]. Taking this type of interaction into account, a channeling theory based on classical mechanics was developed. The concept of continuous potential, as a result of averaging the actual periodic potential of the row or plane over a direction parallel to it, is the basic assumption of this theory. The theory well describes the channeling effect for particles with masses equal to or greater than the proton mass. Within the scope of this theory, the criteria for instability of a channeling particle trajectory have been estimated [1].

Still, there are other types of long-range interaction that are relatively weaker and dependent on the velocity. They are caused, in particular, by the existence of spin of incident particles and therefore by the existence of the magnetic moment. We lay emphasis on the electromagnetic spin-orbit coupling, which means the interaction of the particle magnetic moment with the nucleus Coulomb field in which the particle is moving. It is known also as the Mott—Schwinger interaction because it was first investigated by Mott [3] (for electron scattering) and Schwinger [4] (for neutron scattering by nuclei). The investigation of the influence of such an interaction on proton scattering appeared later [5—7]. Because of the much stronger Coulomb interaction, the Mott—Schwinger scattering for protons can hardly be measured separately. However, it influences the scattered proton polarization. In [5], such a study was done for the proton scattering by aluminum and iron, E_p = 130 MeV. In [6, 7], the scattering by nuclei of carbon was studied for proton energies below the Coulomb barrier.

We note that individual attempts to search for new features of the channeling of particles with spin other than zero are known from the literature [8—11]. Major details and results of this search are as follows. (i) Works [8, 10] are theoretical. In [9], qualitative estimations are presented, and a hypothesis is grounded in [11]. There is no evidence for any experimental investigation. (ii) These investigations concern the relativistic energy region (GeV) of the light particles (e^-, e^+) [8—10] and protons (p) [11]. According to [9, 10], the value of additional force conditioned by the interaction of the particle magnetic moment with an inhomogeneous magnetic field of the crystallographic plane for fast particles can considerably affect the motion trajectory of a particle in a channel. (iii) Major attention is paid to planar channeling in bent single crystals [8, 10, 11]. In [8, 10], the influence of inhomogeneities of the plane electric field on the spin precession and the radiation self-polarization of fast channeled particles is considered. Radiative transitions take place between states with different projections of a spin on the direction of the magnetic field. Here, the rest system of a channeling particle is implied. Spontaneous transitions lead to an increase of the amount of particles on the low-lying energy level, i.e. the beam is being polarized. The comparison of such calculated observables as the lengths of dechanneling, spin precession, and self-polarization demonstrates that the indicated effects can be detected for the lightest particles only, (e^+, e^-). (iv) In [11], it is proposed to use bent single crystals for capturing the relativistic protons scattered by a crystallographic plane in a channel. In the area of Coulomb-nuclear interference, such protons will be polarized after a single

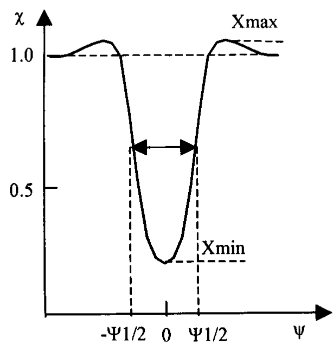

Fig. 1. Orientation dependence of the normalized yield of a close-encounter process

scattering on the planar arrays of atoms. Since scattering angles are small, a bent crystal is used for the spatial separation of a direct beam and scattered particles.

It is more than 40 years now since the discovery of the channeling effect [12, 13]. A lot of theoretical and experimental investigations were done on the subject. One may assert that most phenomena connected with the channeling have been studied [14]. The aim of the present work is to investigate under what conditions and how the electromagnetic spin-orbit interaction of nonrelativistic channeling ions can manifest itself in addition to the directing Coulomb interaction.

1. Theoretical Justification of the Experiment

If the ions with certain velocity fall into an open space (channel) between atomic rows or planes of a monocrystal under small angles to them they undergo a series of elastic, step-by-step, small-angle Coulomb scatterings (or glancing collisions correlated in a direction) [1, 15]. Trajectories of such ions become stable. In contrast to a homogeneous and isotropic material, the distribution of the impact parameters of channeling particles at their collision with atoms of a crystal depends on the relative orientation of the beam and chosen crystallographic directions. Channeling ions do not approach atomic nuclei. Therefore, the physical processes that require a close approach of ions to nuclei, namely nuclear reactions, Rutherford backscattering, and characteristic X-ray emission are suppressed (Fig. 1). An increase of the angle ψ between the axial or planar direction in the crystal and the beam direction makes the trajectories of ions unstable, and the yields χ of the close-encounter processes are increased as well [1, 16]. At still larger incident angles, the yields at last reach the values which are within a small angular interval somewhat greater than that for a random medium (greater than 1). Thus, the compensation of the orientation effect takes place, since the total number of events should not depend on the ordering of a target structure.

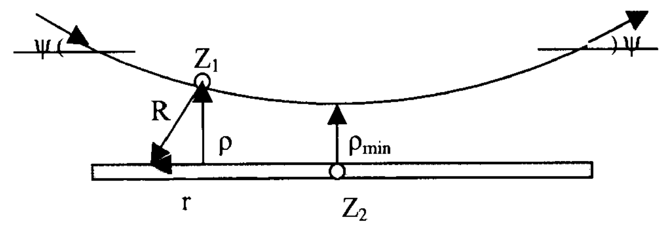

Fig. 2. Schematic illustration of the traveling of channeled particles with charge Z_1e near planar arrays of atoms with charge Z_2e (for the derivation of the plane potential (1))

Concentrating on the planar channeling, it is necessary to note that, in contrast to the axial one, there exists a prevailing direction of the motion of channeling particles in the plane which is perpendicular to their longitudinal velocity. This direction coincides with the normal to the crystallographic planes. In axial channeling, the particle motion between collisions is more complex, unordered, and two-dimensional on the perpendicular plane. Fig. 2 shows the motion of a channeling particle near the crystallographic plane and introduces symbols for the derivation of the formula for the continuous potential of an atomic plane.

The continuous potential for a distance ρ from the atomic plane can be given as

$$V_P = n\int_0^{\infty} 2\pi r V\left(R=\sqrt{\rho^2+r^2}\right)dr, \qquad (1)$$

where $n = Nd_p$, N is the number of atoms in 1 cm^3, and d_p is the interplanar distance. The screened static ion-atom potential $V(R)$ can be given as

$$V(R) = V_{\mathrm{C}}(R)\varphi(R/a), \qquad (2)$$

where

$$V_{\mathrm{C}}(R) = \frac{Z_1Z_2e^2}{R} \qquad (3)$$

is the Coulomb potential of the interaction between an ion (charge Z_1e) and the nucleus of a target atom (charge Z_2e), $\varphi(R/a)$ is a screening function of the Thomas–Fermi type with a as a screening parameter.

The interplanar static continuous potential, which influences a channeled positively charged particle, may be regarded as a first approximation of the harmonic potential. The value of this potential in the channel mid-position is equal to zero [15]. The motion of a particle in a planar channel is just an oscillatory motion in the traverse direction. Estimating the stable trajectory criteria for a channeled particle and, therefore, the admissible range of incident angles ψ of particles into a channel, Lindhard introduced the concept of channeling critical angle ψ_c [1]. The trajectory of a channeled particle remains stable if its transverse energy $E_\perp$ does not exceed $E\psi_c^2$ and, so, the use of the continuum model is confirmed. Particles, whose incidence angles are smaller than the critical angle, do not come to a plane at a distance $\rho_{\min}$ (Fig. 2) closer than the critical distance ρ_c. That is, the condition

$$E_{\perp,c} = E\psi_c^2 \le V_P(\rho_c), \tag{4}$$

where $V_p(\rho_c)$ is a Coulomb barrier height, is satisfied.

It is clear that there exists a certain range of incidence angles ψ,

$$\psi_c \le \psi \le 2\psi_c, \tag{5}$$

when a particle still feels the channel, but its collisions with individual atoms are not small and the transverse energy is not conserved. Ultimately, the particle can be considered as channeled if it has time to cover a distance between neighboring atoms in the longitudinal direction before to come up to a row or a plane in the transverse direction. Trajectories of such particles are not stable and they may leave the channel any moment. Such particles are called quasi-channeled. We are going to focus on them below. Note that, in real experiments, they are not oriented at the angle ψ_c, but at the half-angle $\psi_{1/2}$ slightly different from ψ_c (Fig. 1).

Let us consider now the potential of another long-range interaction (Mott—Schwinger one). If an ion is moving with velocity $\mathbf{v}$, then the Coulomb field $\mathbf{E}$ of a nucleus with charge Z_2 causes the appearance of an inhomogeneous magnetic field with respect to a coordinate system fixed at the incident ion:

$$\mathbf{H} = \left[\frac{\mathbf{v}}{c} \times \mathbf{E}\right] = \frac{Z_2 e}{R^3}\left[\frac{\mathbf{v}}{c} \times \mathbf{R}\right]. \tag{6}$$

The ion magnetic moment $\boldsymbol{\mu}$ interacts with the magnetic field $\mathbf{H}$ and the potential of this interaction is given (for protons, e.g., see [6]) by

$$V_{\mathrm{MS}}(R) = \frac{Z_2}{2}\left(\mu - \frac{1}{2}\right)\left(\frac{eh}{2\pi m^* c}\right)^2 \frac{1}{R}\frac{d}{dR} V_{\mathrm{C}}(R)\,(\mathbf{l}\cdot\boldsymbol{\sigma}) =$$

$$= -\frac{1}{2}\frac{Z_2}{R^3}\left(\frac{eh}{2\pi m^* c}\right)^2 \left(\mu - \frac{1}{2}\right)(\mathbf{l}\cdot\boldsymbol{\sigma}), \tag{7}$$

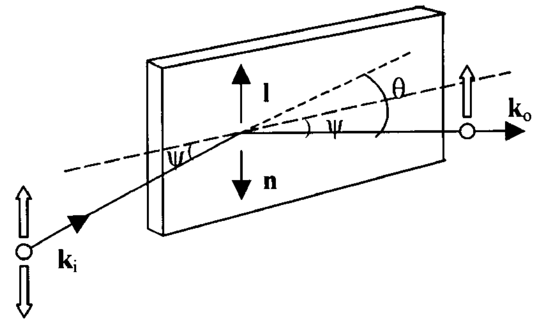

Fig. 3. Schematic illustration of the travelling of quasi-channeled particles with spin near the crystallographic plane of atoms

where m^* is the reduced mass, $\mathbf{l}$ and $\boldsymbol{\sigma}$ are the vectors of orbital and spin momenta. Calculations show that the magnitude of that potential for nonrelarelativistic particles and for the channeled critical distance ρ_c ($\rho_c \approx a \approx 0.1$Å) is approximately by 4 orders less than the potential of the directing Coulomb interaction. Therefore, the influence of the spin-orbit interaction on the channeled motion of particles under the stable trajectory condition can be ignored. Moreover, the orbital moment of a channeled particle changes to the opposite direction, when the particle passes the neighboring walls of a planar channel. But, taking into account different radial dependences of $V_{\mathrm{C}}(R)$ (3) and $V_{\mathrm{MS}}(R)$ (7), the situation changes under the condition of quasi-channeling.

Let us examine what consequence can cause such a change. We note that, for quasi-channeled particles, the condition $R < a$ is valid and the screening of the field of the atom nucleus becomes insignificant. That is, for Eq. (2), it can be assumed that $\varphi(R/a) = 1$, and we have actually the purely Coulomb potential (3) of the interaction with a nucleus. Quasi-channeled particles can be scattered in any direction and may abandon the target. According to (4), only the direction along the channel, i.e. the direction of the stable trajectory, becomes partly restricted. We consider "the fate" of such particles which, having "felt" the channel, are scattered at the mirror angle to the plane and escape the target or go to another channel maintaining the direction of the initial beam (Fig. 3). Thus, these are the particles, whose entrance condition into a channel satisfies (5) and whose close-encounter processes yields are found in the region between $\chi_{1/2}$ and $\chi_{\max}$ (Fig. 1). Fig. 3 defines: $\mathbf{k}_i$ and $\mathbf{k}_o$ are the wave vectors of the incident and scattered particles, ψ is the particle

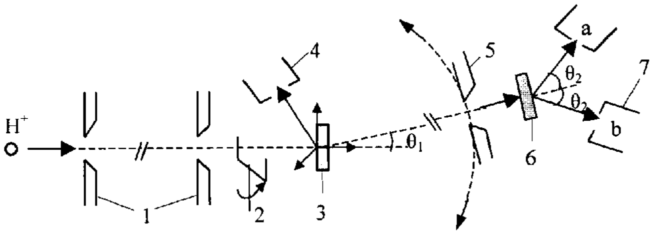

Fig. 4. Schematic diagram of the experiment: *1* — collimator of the particle beam, *2* — monitor-chopper, *3* — three-axis goniometer with crystal under study, *4* — detector of backscattering, *5* — collimator of the scattered beam, *6* — additional target-analyzer of polarization, *7* — detectors

incidence angle into a planar channel and the reflection angle from a plane, $\theta = 2\psi$ is the scattering angle. The selected direction of the normal $\mathbf{n}$ to the scattering plane is defined as

$$\mathbf{n} = \frac{\mathbf{k}_i \times \mathbf{k}_o}{|\mathbf{k}_i \times \mathbf{k}_o|}. \quad (8)$$

In the case of a repulsive force, which is the Coulomb interaction force, the orbital angular momentum vector $\mathbf{l}$ is antiparallel to the vector $\mathbf{n}$.

It is obvious from (7) that the Mott—Schwinger scattering amplitude is dependent on the relative orientation of the vectors of the orbital ($\mathbf{l}$) and spin ($\mathbf{s}$) angular momenta: $A_{\rm MS}(\theta) = A(\theta)(\mathbf{l}\cdot\mathbf{s})$. Consider the Mott—Schwinger scattering together with the Coulomb one, the amplitude of which does not depend on the spin. The amplitudes $A_{\rm MS}$ and $A_{\rm C}$ are coherent for an individual scattering center and interfere. The scattering differential cross-section is expressed by

$$\frac{d\sigma}{d\Omega} = (A_{\rm C} + A_{\rm MS})^2 = A_{\rm C}^2 + A_{\rm MS}^2 + 2A_{\rm C}A_{\rm MS}(\mathbf{l}\cdot\mathbf{s}). \quad (9)$$

The sign of the interference term in this expression depends on the mutual orientation of the orbital and spin angular momenta. Thus, the scattering cross-sections are different for protons with two possible projections of the spin on a selected direction. This is the reason to expect that, in a certain angular interval close to the direction of mirror reflection from a channel plane, the scattered proton beam will show to be enriched by one of the spin components, i.e. it will be polarized. On the contrary, for protons with the inverse spin orientation, the probability to experience the close encounter with the nucleus and to cause a nuclear reaction or to be scattered at a great angle is increased.

It is necessary to point out another circumstance. The general potential of the interaction between a quasi-channeled particle and a target nucleus may have the term of the nuclear spin-orbit coupling. Coherent amplitudes of this type of interaction and the Coulomb one interfere as well. But, for the attraction force, i.e. nuclear interaction, the orbital momentum vector $\mathbf{l}$ is parallel to the vector $\mathbf{n}$ (8). Thus, the polarization sign may give an advantage to a certain type of interaction.

2. One of the Feasible Schemes of the Experiment

For the experimental verification of the statements formulated in Section 1, the experiment scheme similar to that [17] proposed and realized for the measurements of the angular distributions of protons that traversed through a thin single crystal can be used. We present this scheme and indicate the differences (Fig. 4).

Three principal components of the scheme can be selected. They serve the following purposes: Forming of a beam with operating limits that are necessary for channeling experimens (it is maintained by collimator *1*); orientation and movement of a target under study (it is maintained by the manipulator-goniometer for a principle target — *3*); the study of channeling transmission, small-angle scattering and polarization of ions (it is maintained by the manipulator of an additional target — *5, 6*). In contrast to [17], the second target has to be chosen so that it could also serve as a polarization analyzer of particles interacted with a monocrystalline (first) target. In this part, the scheme is similar to the standard double scattering scheme under the nuclear physics experiments for the investigation of the polarization of particles.

The asymmetry to be measured is

$$A(\psi,\theta_1) = \frac{N(+\theta_2) - N(-\theta_2)}{N(+\theta_2) + N(-\theta_2)} = P(\psi,\theta_1)\,P(\theta_2), \quad (10)$$

where ψ is the angle between the accelerator beam direction and the selected crystallographic plane (its variation is defined by (5); see Fig. 3), θ_1 is the scattering angle on the monocrystal target (it changes in the vicinity of an angle of 2ψ), θ_2 is the scattering angle by a target-analyzer of polarization, $N(+\theta_2)$ and $N(-\theta_2)$ are the numbers of counts recorded by detectors 7 (Fig. 4), and $P(\theta_2)$ is the polarization of particles scattered on the target-analyzer.

Using (10), the polarization $P(\psi,\theta_1)$ as a function of angles under study can be found. To exclude the instrument asymmetry attributed to different efficiencies of detectors *7a* and *7b*, the numbers of counts $N(+\theta_2)$ and $N(-\theta_2)$ must add to the counts from both detectors (after the rotation through 180° of the detecting system around the axis of the beam scattered at an angle of θ_1). Monitored values of the $[N(+\theta_2) + +N(-\theta_2)$ sum for selected angles of ψ and θ_1 contain information about the angular distributions of scattered particles. Monitoring is carried on a part of the charge which is transferred by the beam from the accelerator and accumulated by monitor-chopper *2*.

The proposed scheme has been tested in the polarization measurement. We note the key conditions of the experiment. The first target was a 2 mg/cm^2 Si monocrystal with (110) orientation in the beam direction. The second target (an analyzer of polarization) was silicon as well. Its thickness was 1 mg/cm^2, and it was in a random (nonoriented) state. Proceeding from the available means, the energy (E_p = 3.175 MeV) of protons from the accelerator and the angle ($\theta_2 = 60°$) of scattering by the second target were calculated in a way to achieve the maximum analyzing power of silicon concerning protons. The previously made measurement of the analyzing power showed the magnitude $\sim$ 50% under the marked condition [18]. The collimator-formed beam had angular spread $\leq$ 1 min. The angular spread on the second target was the same.

The angular dependence of the proton polarization scattered by the first target is shown in Fig. 5. Measurements were made only for one inclination angle ψ of (110) plane of the Si-monocrystal in respect to the beam direction from the accelerator. This angle was determined experimentally. It is equal to the half-angle of the backscattering yield curve for protons under the (110) planar channeling (Fig. 1). Its value approximates 6 min ($\psi = \psi_{1/2} \approx \psi_c$).

It can be seen from Fig. 5 that the polarization behavior in the vicinity of the $\theta_1 \approx 12$ min angle, that equals the angle of mirror reflection from (110) plane, is not inconsistent with the theoretical substantiation presented above. We note that, taking the beam angular spread into account, condition (5) can be fulfilled only for a part of the proton beam that hits the crystal. Unfortunately, we had no opportunity to carry the experiment to its logical completion on the available accelerator for technical limitations.

Conclusion

The above analysis is an attempt to estimate qualitatively the influence of the electromagnetic spin-orbit interaction on the motion of ions under the condition of instable trajectories in the planar channeling. It has been shown that the spin-orbit interaction can cause the polarization of particles that were scattered at angles close to the angle of mirror reflection from crystal planes and abandoned the crystal. Obtaining the precise expressions for amplitudes of the Coulomb and Mott—Schwinger interactions and thus the expression for the polarization of scattered particles, including the quasi-channeling and thermal displacement of scattering centers relative to equilibrium positions, seems to be rather a complex problem. The experimental results derived, for instance, by using the suggested scheme could facilitate the choice of a simplified model for calculations.

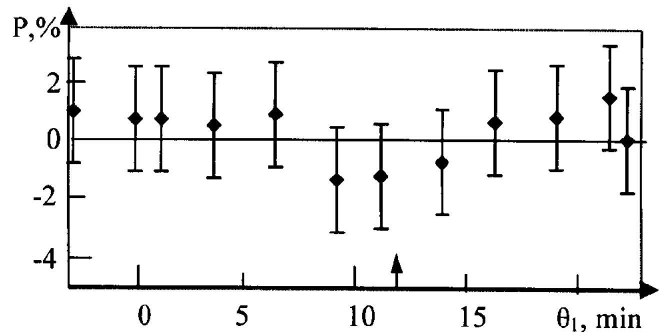

Fig. 5. Angular dependence of the polarization of protons with an energy of 3.175 MeV, being incident on a thin Si-monocrystal at the critical angle of the planar (110) channeling, scattered at small angles, and left the crystal. An approximate position of the angle of mirror reflection ($\theta_1 \approx 2\psi_c = 12$ min) is shown by the arrow at the bottom

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ВПЛИВ ЕЛЕКТРОМАГНІТНОЇ СПІН-ОРБІТАЛЬНОЇ ВЗАЄМОДІЇ НА РУХ ІОНІВ У КРИСТАЛАХ ЗА УМОВИ ПЛОЩИННОГО КВАЗІКАНАЛУВАННЯ

В.І. Сорока

Р е з ю м е

Розглядається питання впливу електромагнітної спін-орбітальної взаємодії на рух іонів у кристалах за умови нестабільної траєкторії при площинному квазіканалуванні. Показано, що спін-орбітальна взаємодія може спричинити поляризацію частинок, які розсіялися під кутами, близькими до кута дзеркального відбиття від кристалографічних площин, і залишили кристал. Запропоновано схему експериментальної перевірки ефекту. Схему випробувано, та підтверджено доцільність і можливості її використання.