Spin rotation and oscillations for high energy particles in a crystal and possibility to measure the quadrupole moments and tensor polarizabilities of elementary particles and nuclei

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Abstract

It is shown that particle motion in a bent (straight) crystal is accompanied by particle spin rotation and oscillations that allows to measure the tensor electric and magnetic polarizabilities of nuclei and elementary particles. It is shown that channelling of particles in either straight or bent crystal with the polarized nuclei could be used both to analyze polarization of high energy particles and polarize them.

Key words: bent crystal, polarizability, polarization of high energy particle beam, polarized target, channelling in crystals
PACS: 61.85.+p, 32.10.DK, 13.88.+e

1 INTRODUCTION

A new method for high energy charged particle beams guiding by bent crystals has been developing for more than 20 years in several prominent laboratories in the world. The idea to use bent crystals for particle beam extraction from a storage ring was proposed in 1976 [1]. Now this idea is experimentally tested and becomes a basis for the method for particle beam extraction from a storage ring with sufficiently high efficiency ($\sim 85\%$).

The next step in application of crystals for high energy particle beams guiding was done in 1979 in [2], where it was first shown that the spin of a high energy particle moving in a bent crystal rotates with respect to its momentum due to the particle anomalous moment (see also [3]). Nowadays this effect has been experimentally discovered [4,5,6]. It has been also shown that the similar experiments are beneficial for measuring the magnetic moments of short-lived particles [7] and, particularly, Λ_c particle [8]. Bent crystals can be used to steer particle spin orientation, too. Moreover, according to [9,10] channelling of high energy particles in a crystal can be used for measuring the quadrupole moments of elementary particles, Ω^- hyperon in particular.

The present paper shows that study of relativistic particle (nucleus) spin behavior in crystals (either bent or straight) allows to find the tensor electric and magnetic polarizabilities of the particle (nucleus). It is shown that phenomenon of channelling in either straight or bent crystal with the polarized nuclei can be used either for making high energy particle beams polarized or for polarization analysis.

2 The effective periodic potential of a crystal

A fast particle passing through a monocrystal is elastically and inelastically scattered due to interaction with electrons and nuclei. The secondary waves appear in the crystal due to particle scattering. It is important that the secondary waves describing elastic scattering (i.e. scattering without crystal excitation) interfere with each other and with the incident wave producing the sum coherent wave in the crystal. The effective periodic potential $U(\vec{r})$ can be introduced to describe passing of the coherent wave in the crystal:

$$U(\vec{r}) = \sum_{\vec{\tau}} U(\vec{\tau}) e^{i\vec{\tau}\vec{r}}, \tag{1}$$

where $\vec{\tau}$ is the reciprocal lattice vector of the crystal,

$$U(\vec{\tau}) = \frac{1}{V} \sum_j U_{j0}(\vec{\tau}) e^{-W_j(\vec{\tau})} e^{i\vec{\tau}\vec{r}_j} \tag{2}$$

here V is the volume of the crystal elementary cell, $\vec{r}_j$ is the coordinate of an atom (nucleus) of type j in the crystal elementary cell and the squared $e^{-W_j(\vec{\tau})}$ is equal to the thermal-factor (i.e. Debye-Waller factor) well-known for X-ray scattering [11],

$$U_{j0}(\vec{\tau}) = -\frac{2\pi\hbar^2}{M\gamma}F_j(\vec{\tau}) \tag{3}$$

M is the mass of the incident particle, γ is its Lorentz-factor, $F_j(\vec{\tau}) = F_j(\vec{k}' - \vec{k} = \vec{\tau})$ is the amplitude of elastic coherent scattering of the particle by the atom, $\vec{k}$ is the wave-vector of the incident wave and $\vec{k}'$ is the wave vector of the scattered wave.

Elastic coherent scattering of a particle by an atom is caused by both Coulomb interaction of the particle with the atom electrons and nucleus and its nuclear interaction with the nucleus. Therefore, the scattering amplitude can be presented as a sum of two amplitudes:

$$F_j(\vec{\tau}) = F_j^{coul}(\vec{\tau}) + F_j^{nucl}(\vec{\tau}) \tag{4}$$

where $F_j^{coul}(\vec{\tau})$ is the amplitude of particle scattering caused by Coulomb interaction with the atom (nucleus) (it contains contributions from the Coulomb interaction of the particle with the atom along with the spin-orbit interaction with the Coulomb field of the atom (nucleus)); $F_j^{nucl}(\vec{\tau})$ is the amplitude of elastic coherent scattering of the particle caused by nuclear interaction (this amplitude contains terms independent on the incident particle spin along with terms depending on spin of both the incident particle and nucleus, in particular, spin-orbit interaction). Therefore, $U(\vec{r})$ and $U(\vec{\tau})$ also can be expressed:

$$\begin{aligned} U(\vec{r}) &= U^{coul}(\vec{r}) + U^{nucl}(\vec{r}), \\ U(\vec{\tau}) &= U^{coul}(\vec{\tau}) + U^{nucl}(\vec{\tau}) \end{aligned} \tag{5}$$

Suppose a high energy particle moves in a crystal at a small angle to the crystallographic planes (axes) close to the Lindhard angle $\vartheta_L \sim \sqrt{\frac{U}{E}}$ (in relativistic case $\vartheta_L \sim \sqrt{\frac{2U}{E}}$), where E is the energy of the particle, U is the height of the potential barrier created by the crystallographic plane (axis). This motion is determined by the plane (axis) potential $\hat{U}(\vec{\rho})$, which could be derived from $U(\vec{r})$ by averaging over the distribution of atoms (nuclei) in the crystal plane (axis).

As a consequence, the potential $\hat{U}(\vec{\rho})$ for a particle channelled in a plane (or axis) channel or moving over the barrier at a small angle close to the Lindhard angle can be expressed as a sum:

$$\hat{U}(\vec{\rho}) = \hat{U}^{coul}(\vec{\rho}) + \hat{U}^{sp.-orb.}(\vec{\rho}) + \hat{U}_{eff}^{nucl}(\vec{\rho}) + \hat{U}^{magn}(\vec{\rho}) \tag{6}$$

where $\hat{U}^{coul}$ is the potential energy of particle Coulomb interaction with the crystallographic plane (axis), $\hat{U}^{sp.-orb.}$ is the energy of spin-orbit interaction with the Coulomb field of the plane (axis) and spin-orbit nuclear interaction with the effective nuclear field of the plane (axis), $\hat{U}_{eff}^{nucl}$ is the effective potential energy of nuclear interaction of the incident particle with the crystallographic plane (axis)

$$\hat{U}_{eff}^{nucl}(\vec{\rho}) = -\frac{2\pi\hbar^2}{M\gamma}N(\vec{\rho})\hat{f}(0), \tag{7}$$

where $N(\vec{\rho})$ is the nuclei density in the point $\vec{\rho}$ of the crystallographic plane (axis), $\vec{\rho} = (x, y)$, the axis z is directed along the crystal axis (along the velocity component parallel to the crystallographic plane in the case of plane channelling), $\hat{f}(0)$ is the amplitude of elastic coherent forward scattering, which depends on the incident particle spin and nucleus polarization, $\hat{U}^{magn}(\vec{\rho})$ is the energy of magnetic interaction of the particle with the magnetic field created by electrons (nuclei).

Thus, several contributions to the energy of interaction should be considered for a high-energy particle elastically scattered in a crystal.

Let us consider first the influence of the electromagnetic field induced by the crystallographic planes (axes) on the particle spin.

3 Spin rotation of relativistic particles in a crystal

Thus, let a high-energy particle travels through a crystal. Inasmuch as in this case the particle wavelength is much less then typical inhomogeneities in the electric fields in crystals, so to describe spin motion in these fields a quasi-classical approximation can be used. The equations describing particle spin motion in an electromagnetic field were obtained by Bargmann et. al. [12].

$$\frac{d\vec{P}}{dt} = \left[\vec{\Omega}\vec{P}\right], \tag{8}$$

where $\vec{P}$ is the vector polarization of the particle,

$$\Omega = -\frac{e}{Mc}\left\{\left(\frac{g-2}{2} + \frac{1}{\gamma}\right)\vec{B} - \frac{g-2}{2}\,\frac{\gamma-1}{\gamma}\frac{(\vec{v}\vec{B})\vec{v}}{v^2} - \left(\frac{g-2}{2} + \frac{1}{\gamma+1}\right)\left[\vec{\beta}\times\vec{E}\right]\right\}$$

is the angular velocity of particle spin precession at the particle location point at time moment t, $\vec{\beta} = \frac{\vec{v}}{c}$, $\vec{v}$ is the particle velocity, e is the particle charge, M is its mass, c is the speed of light, γ is the particle Lorentz factor, g is the gyromagnetic ratio (g-factor). In the absence of magnetic field the angular velocity of particle momentum rotation at the moment t is:

$$\Omega_0 = \left[\vec{n}\frac{d\vec{n}}{dt}\right] = -\frac{e}{Mc}\frac{\gamma}{\gamma^2-1}\left[\vec{E}\times\vec{\beta}\right],$$

where $\vec{n} = \vec{v}/v$.

If $\gamma \gg 1$

$$\Omega_0 = -\frac{e}{Mc\gamma}\left[\vec{E}\times\vec{\beta}\right] = -\frac{e}{Mc\gamma}\left[\vec{E}\times\vec{n}\right]$$

and

$$\Omega = \left(\frac{g-2}{2} + \frac{1}{\gamma}\right)\gamma\Omega_0.$$

We should also recall that the anomalous magnetic moment of a particle μ' is in the following relation to (g-2):

$$\mu' = \frac{e(g-2)}{2Mc}\hbar S,$$

where S is the particle spin.

Let us consider first the simplest case for the sake of more clear understanding. Suppose a particle move in a planar channelling mode in the plane x, z in a crystal bent about the y-axis. In this case from (8) it follows that

$$\frac{dP_x}{dt} = \Omega_y(t)P_z,\ \frac{dP_z}{dt} = \Omega_y(t)P_x,\ \frac{dP_y}{dt} = 0, \tag{9}$$

where the frequency of particle precession about the y-axis is:

$$\Omega_y(t) = \left(\frac{g-2}{2} + \frac{1}{\gamma}\right)\gamma\Omega_{0y}(t), \tag{10}$$
$$|\Omega_y| = \left(\frac{g-2}{2} + \frac{1}{\gamma}\right)\frac{e}{Mc}E(t),$$

here E is the magnitude of the electric field of the crystallographic plane at the particle location point at time moment t (let us recall that in the case under consideration the direction of this field is practically orthogonal to the particle velocity).

From (9) it follows that during motion in a bent crystal the particle spin rotates about the direction of the momentum [2,3] and owing to the large magnitude of field E ($E \sim 10^7 - 10^8$ CGSE), making the particle following the bending of the crystal, the frequencies Ω_y for $(g-2) \sim 1$ are large $\Omega_y \approx 10^{11} - 10^{13}$ s^{-1} and the angle of rotation by one centimeter could reach values as large as $10 - 10^3$ rad/cm.

An important relation between the spin rotation angle θ_s and the momentum rotation angle θ_m in case of planar motion follows from (11)

$$\theta_s = \int_0^T \Omega_y(t')dt' = \left(\frac{g-2}{2} + \frac{1}{\gamma}\right)\gamma\theta_m,$$
$$\theta_m = \int_0^T \Omega_{0y}(t')dt' \tag{11}$$

Let, for example, the curvature radius of a bent crystal be 10^2 cm , then for $\gamma = 10^2$ and $(g-2) \sim 1$, $\theta_s = 1$ rad/cm, that is obviously observable.

With the help of (11) we can measure the magnitudes $(g-2)$ for a particle without making use concrete models, which describe the distribution of intracrystalline fields. It is sufficient to measure θ_m and θ_s:

$$g - 2 = \frac{2}{\gamma} \frac{\theta_s - \theta_m}{\theta_m} \tag{12}$$

If $(g-2) \sim 1$ and $\gamma \gg 1$, then $(g-2) \approx 2\theta_s/\gamma\theta_m$.

4 Spin rotation of relativistic particles in the presence of quadrupole interactions and birefringence effect in pseudoelectric and electric fields

If a particle has the spin $S \geq 1$ then interaction $\hat{W}_Q$ of its electric quadrupole moment with an inhomogeneous electric field of crystallographic planes (axis) [9,10] and the birefringence effect in pseudoelectric nuclear and electric fields could appear important [13]-[18].

Remember also that a particle with the spin $S \geq 1$ possesses the electric and magnetic polarizabilities.

Let an electric field $\vec{E}(\vec{r})$ acts on a particle (nucleus) ($\vec{r}$ is the particle coordinate). The energy $\hat{V}_{\vec{E}}$ of interaction of the particle with the electric field due to the electric polarizability tensor can be written as [17]:

$$\hat{V}_{\vec{E}} = -\frac{1}{2} \hat{\alpha}_{ik} (E_{eff})_i (E_{eff})_k, \tag{13}$$

where $\hat{\alpha}_{ik}$ is the electric polarizability tensor of the particle , $\vec{E}_{eff} = (\vec{E} + \vec{\beta} \times \vec{B})$ is the effective electric field; the expression (13) can be rewritten as follows:

$$\hat{V}_{\vec{E}} = \alpha_S E_{eff}^2 - \alpha_T E_{eff}^2 \left(\vec{S} \vec{n}_E \right)^2, \; \vec{n}_E = \frac{\vec{E} + \vec{\beta} \times \vec{B}}{|\vec{E} + \vec{\beta} \times \vec{B}|} \tag{14}$$

where α_S is the scalar electric polarizability and α_T is the tensor electric polarizability of the particle.

A particle with the spin $S \geq 1$ also has the magnetic polarizability, which is described by the magnetic polarizability tensor $\hat{\beta}_{ik}$ and interaction of the particle with the magnetic field due to the magnetic polarizability tensor is as follows [18]:

$$\hat{V}_{\vec{B}} = -\frac{1}{2} \hat{\beta}_{ik} (B_{eff})_i (B_{eff})_k, \tag{15}$$

where $(B_{eff})_i$ are the components of the effective magnetic field $\vec{B}_{eff} = (\vec{B} - \vec{\beta} \times \vec{E})$; $\hat{V}_{\vec{B}}$ can be expressed as:

$$\hat{V}_{\vec{B}} = \beta_S B_{eff}^2 - \beta_T B_{eff}^2 \left(\vec{S}\vec{n}_B\right)^2, \; \vec{n}_B = \frac{\vec{B} - \vec{\beta} \times \vec{E}}{|\vec{B} - \vec{\beta} \times \vec{E}|}. \tag{16}$$

where β_S is the scalar magnetic polarizability and β_T is the tensor magnetic polarizability of the particle.

When a particle with the spin $S \geq 1$ passes through an unpolarized medium, the medium refraction index depends on particle spin orientation to its momentum [13,14]. As a result, for a particle moving in a crystal with the nonpolarized nuclei the effective potential energy $\hat{U}^{nucl}$ depends on the spin orientation [13,14,18]

$$\hat{U}^{nucl} = -\frac{2\pi\hbar^2}{M\gamma} N(\vec{\rho}) \hat{f(0)}, \tag{17}$$

Substituting $\hat{f(0)}$ in its explicit form one can obtain [13,14]:

$$\hat{U}^{nucl} = -\frac{2\pi\hbar^2}{M\gamma} N(\vec{\rho}) \left(d + d_1 \left(\vec{S}\vec{n}\right)^2\right), \tag{18}$$

where $\vec{n}$ is the unit vector along the particle momentum direction, for $S > 1$ the summands with higher degrees of S could present in (18) (they are omitted here for simplicity, so strictly speaking (18) is applicable for $S = 1$ and $S = \frac{3}{2}$).

Let the quantization axis z is directed along $\vec{n}$ and m denotes the magnetic quantum number. Then, for a particle in the state that is an eigenstate of the operator S_z of spin projection onto the z-axis, the efficient potential energy can be written as:

$$\hat{U}^{nucl} = -\frac{2\pi\hbar^2}{M\gamma} N(\vec{\rho}) \left(d + d_1 m^2\right). \tag{19}$$

According to (19) splitting of the particle energy levels in a matter is similar to splitting of atom energy levels in an electric field aroused by the quadratic Stark effect. Therefore, the above effect could be considered as caused by splitting of the spin levels of the particle in the pseudoelectric nuclear field of a matter. Rotation and oscillations of deuteron vector and tensor polarization in matter, along with the spin dichroism (birefringence effect), appear due to the above interaction. Spin dichroism was observed in the experiment [15].

Thus, considering evolution of the spin of a particle in a crystal one should take into account several interactions:

1. interactions of the magnetic dipole moment with the electromagnetic field of a bent crystal;

2. interaction (13) of the particle with the crystal due to the tensor electric polarizability;

3. interaction of the particle with the crystal due to the tensor magnetic polarizability;

4. interaction (18) of the particle with the pseudoelectric nuclear field of matter;

5. interaction $\hat{W}_Q$ of the quadrupole moment with the inhomogeneous crystallographic electric field.

Therefore, the equation for the particle spin wavefunction is:

$$i\hbar\frac{\partial\Psi(t)}{\partial t} = \left(\hat{H}_0 + \hat{W}_Q + \hat{U}_{nucl} + \hat{V}_E + \hat{V}_B\right)\Psi(t) \tag{20}$$

where $\Psi(t)$ is the particle spin wavefunction, $\hat{H}_0$ is the Hamiltonian describing the spin behavior caused by interaction of the magnetic moment with the electromagnetic field (equation (20) with the only $\hat{H}_0$ summand converts to the Bargman-Myshel-Telegdy equation).

It is important that the terms $\hat{W}_Q$, $\hat{U}_{nucl}$, $\hat{V}_E$ and $\hat{V}_B$ cause oscillations and rotation of spin even in a straight (non-bent) crystal.

Multiple scattering and depolarization can be substantial for processes in crystals and complete description of these processes can be done by the density matrix formalism (see [17,19]).

So, when a particle moves in a bent crystal the effects of spin rotation and vector-to-tensor (tensor-to-vector) polarization conversion appear due to the interactions $\hat{W}_Q$, $\hat{U}_{nucl}$, $\hat{V}_E$ and $\hat{V}_B$ along with the spin rotation caused by $(g-2)$. These effects can be used for measurement Q, α_T, β_T and d_1. It is of the essence that the above quantities can be measured even in straight crystal, but bent crystals could provide higher electric fields E.

One more additional consequence [20] follows from (8): if the gyromagnetic ratio satisfies the condition $1 < g < 2$, then the electric field does not influence on the spin of a particle with the energy $\epsilon_0 = \frac{g}{g-2}mc^2$ (the angular velocity of the spin precession appears equal to 0, whereas the magnetic moment is nonzero). This effect is purely relativistic and caused by cancellation of "dynamical" precession by Thomson precession. When the energy of the particle is less then ϵ_0, the spin rotates in the same direction as the momentum does. Otherwise (when the energy of the particle is greater then ϵ_0), the spin and momentum rotate in different directions. The requirement $1 < g < 2$ can be fulfilled for a deuteron ($g = 1.72$ and $\epsilon_0 = 11.5$ GeV) and some nuclei (^{6}Li has g=1.64). In such conditions spin rotation and oscillations appears caused only by interactions $\hat{W}_Q$, $\hat{U}_{nucl}$, $\hat{V}_E$ and $\hat{V}_B$.

Let us consider the possibility to measure the tensor electric and magnetic polarizabilities α_T, β_T. The typical frequency of spin rotation (oscillations) caused by the considered interaction due to the particle electric polarizability is:

$$\omega_\alpha = \frac{\alpha_T E^2}{\hbar}, \tag{21}$$

the corresponding rotation angle (phase of oscillations) is:

$$\varphi = \omega_\alpha \frac{L}{v}, \tag{22}$$

where L is the length of the particle pass inside the crystal, therefore:

$$\varphi = \frac{\alpha_T E^2 L}{\hbar v}. \tag{23}$$

Hence, φ measurement implies α_T measurement. The angle of momentum rotation in a bent crystal is:

$$\theta_0 = \frac{eEL}{Mc^2\gamma}, \tag{24}$$

from here

$$E = \frac{Mc^2\gamma}{eL}\theta_0, \tag{25}$$

therefore

$$\varphi = \frac{\alpha_T\gamma^2}{\lambda_c r_0 L}{\theta_0}^2, \tag{26}$$

here λ_c is the Compton wavelength, $r_0 = \frac{e^2}{Mc^2}$ is the electromagnetic radius of the particle. And finally, measuring φ, θ_0, L and γ we can find α_T:

$$\alpha_T = \frac{\lambda_c r_0 L}{\gamma^2}\frac{\varphi}{{\theta_0}^2}, \tag{27}$$

Let us evaluate α_T could be measured when a particle passes through a crystal. Suppose that the experimentally measured angle of rotation is about $\varphi \approx 10^{-4}$. The strength of the electric field can be achieved in a bent crystal is about $E \approx 10^9$ CGSE. Therefore we can obtain the estimation $\alpha_T = \frac{\hbar c\varphi}{E^2 L} = \frac{3}{L}10^{-39}$ cm^3. The electric polarizability of a deuteron can be evaluated as $\alpha_T \approx 10^{-40}$ cm^3 [21]. The similar estimations can be obtained for β_T [21].

Then, it seems possible to measure of the tensor polarizability of deuterons (nuclei) and as well as to get limits for polarizability of elementary particles (for example, Ω hyperon).

5 Particle motion in a polarized crystal

Suppose now that the crystal nuclei are polarized. The cross-section of high-energy particle scattering by a nucleus (the amplitude of zero-angle scattering) in a crystal with the polarized nuclei depends on the particle spin orientation with respect to target polarization. Therefore, the absorption coefficient also depends on particle spin orientation. Let a particle moves in a crystal at a small angle to the crystallographic plane (axis) close to the Lindhard angle. In this case the coefficient of particle absorption by nuclei appears greater than the absorption coefficient for the particle moving in the crystal at a large angle to the crystallographic plane (axis). Let us discuss the possibility to use a polarized crystal to obtain a polarized beam of high energy particles and to analyze the polarization state of high energy particles [22].

In the case of consideration a positively charged high-energy particle moves close to the top of the potential barrier, therefore, it moves in the range with the nuclei density higher than that for an amorphous medium. If it moves at a small angle to the crystallographic plane, then the growth is described by $\frac{a}{a_0} \approx 10^2$, here a is the lattice period, a_0 is the amplitude of the nucleus thermal oscillations. If it moves at a small angle to the crystallographic axis, then the growth is described by $(\frac{a}{a_0})^2 \approx 10^4$.

The polarization degree after passing the polarized crystal with the thickness L is

$$P = \frac{e^{-\rho\sigma_{\uparrow\uparrow}L} - e^{-\rho\sigma_{\uparrow\downarrow}L}}{e^{-\rho\sigma_{\uparrow\uparrow}L} + e^{-\rho\sigma_{\uparrow\downarrow}L}} \tag{28}$$

where $\sigma_{\uparrow\uparrow}$ is the total scattering cross-section for the particle with the spin parallel to the polarization vector of nuclei and $\sigma_{\uparrow\downarrow}$ is the total scattering cross-section for the particle with the spin anti-parallel to the polarization vector of nuclei. The effect magnitude is determined by the parameter $A = \rho(\sigma_{\uparrow\uparrow} - \sigma_{\uparrow\downarrow})L$ ($A = \rho_{av} \cdot 10^2 \Delta\sigma L$ for a plane and $A = \rho_{av} \cdot 10^4 \Delta\sigma L$ for an axis, ρ_{av} is the average density of nuclei in the crystal).

The length L_1 corresponding to $A = 1$ is equal to $L_1 = \frac{1}{\rho\Delta\sigma}$. If suppose $\rho_{av} \approx 10^{22}$, $\Delta\sigma \sim 10^{-25}\ cm^2$ then for a plane $L_1 \approx 10\ cm$; for an axis $L_1 \approx 10^{-1}\ cm$

Let positively charged particles move parallel to a crystallographic plane then the most of them appear close to the bottom of the potential well and far from nuclei, therefore, the absorption coefficient is smaller comparing that for average crystal absorption.

In contrast to the positively charged particles a negatively charged particle (for example Ω^- hyperon, antiproton), being channelled, moves in the range with high density of nuclei,therefore, even a very thin polarized crystal ($L \approx 10^{-1}$ cm) can be an effective polarizer and polarization analyzer.

Moreover, for a negatively charged channelled particle the angle of spin rotation in the nuclear pseudomagnetic field of the polarized crystal [13,14,19] can be larger comparing with that for amorphous matter (for example, for the particle energy $\sim 10\ GeV$ in channelling conditions in the crystal of $\approx 10^{-1}$ cm length the angle of spin rotation is about $\vartheta \sim 10^{-1}$ rad). Similarly the birefringence effect in pseudoelectric nuclear field and electric field also grows for Ω^- hyperon channelled in a crystal (or for any other channelled particle with the negative charge). This is the reason for the thin polarized crystals to be used as nuclear-optical elements can guide polarization of high-energy particle beams.

To increase interaction of a positively charged particle with a nucleus a bent crystal could be used. In this case the centrifugal forces push the channelled beam to the range with the high density of nuclei.

Thus, both the straight and bent crystals provide methods for getting the polarized beams of high-energy particles, rotating the particle spin and analyzing particle polarization state.

Note that spin-orbit interaction also leads to particle polarization as well as to the left-right asymmetry in polarized particles scattering. The density of nuclei near the axis is much higher than the density of amorphous target. This makes the induced polarization (left-right asymmetry) for particles scattered by the crystal axes noticeably higher, as compared with amorphous matter, due to interference of the Coulomb and effective nuclear potentials of the axis [22].

6 Conclusion

Thus, particle motion in a bent (straight) crystal is accompanied by particle spin rotation and oscillations that allows to measure the tensor electric polarizability of nuclei and elementary particles.

Channelling of particles in either straight or bent crystal with the polarized nuclei could be used for polarization or analyzing polarization of high energy particles. The beam of nonpolarized particles extracted from the storage ring could be significantly polarized by applying the additional polarized bent (straight) crystal.

This work is prepared in the framework of INTAS Project# 03-52-6155.

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