Channeling tools for high energy and particle physics

High energy nuclear optics of polarized particles

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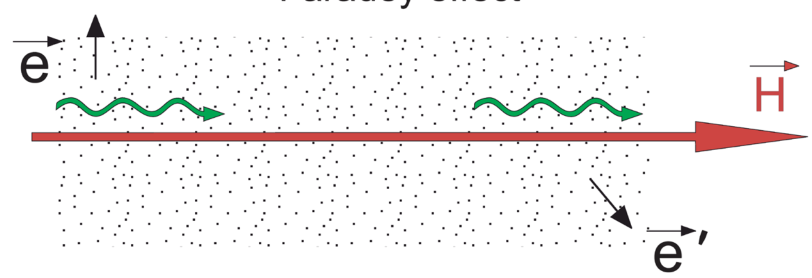
Photon plane rotation in optical anisotropy matter

Let photons with the linear polarization

$$\vec{e}_1 = -\frac{\vec{e}_+ - \vec{e}_-}{\sqrt{2}}$$ fall in a matter



N_+ N_-, N - refraction index

Polarization vector of a photon in matter

$$\vec{e}\,'_1 = -\frac{\vec{e}_+}{\sqrt{2}} e^{ikN_+L} + \frac{\vec{e}_-}{\sqrt{2}} e^{ikN_-L} =$$

$$= e^{\frac{1}{2}ik(N_+ + N_-)L} \left\{ \vec{e}_1 \cos\frac{1}{2}k(N_+ - N_-)L - \vec{e}_2 \sin\frac{1}{2}k(N_+ - N_-)L \right\}$$

L is the photon propagation length in a medium, $\vec{e}_2 \perp \vec{e}_1$

Photon polarization plane rotates in a matter and the angle of rotation

$$\vartheta = \tfrac{1}{2}\, k\ Re(N_+ - N_-)\ L$$

$\vartheta > 0$ corresponds to the right rotation of the light polarization plane (clockwise rotation)

$\vartheta < 0$ corresponds to the left rotation (i.e. counter-clockwise rotation)

Spin rotation and dichroism in the polarized target

Could the similar effect
exist for particles ?

Scattering amplitude in the polarized target, caused by strong interaction

$$f(0) = A + \overrightarrow{\sigma} \cdot \overrightarrow{g}$$, where $$\overrightarrow{g} = A_1 \overrightarrow{P} + A_2 \overrightarrow{n} \left(\overrightarrow{n} \cdot \overrightarrow{P} \right)$$

$$\overrightarrow{g} = (A_1 + A_2) \overrightarrow{P} \qquad \text{for } \overrightarrow{n} \parallel \overrightarrow{P}$$

$$\overrightarrow{g} = A_1 \overrightarrow{P} \qquad \text{for } \overrightarrow{n} \perp \overrightarrow{P}$$

$$f(0)_{\uparrow\uparrow} = A + g \qquad \text{for nucleon with spin parallel to } \overrightarrow{P}$$

$$f(0)_{\uparrow\downarrow} = A - g \qquad \text{for nucleon with spin antiparallel to } \overrightarrow{P}$$

Hence, the corresponding refractive indices are not equal to each other:

$$f(0)_{\uparrow\downarrow} \neq f(0)_{\uparrow\uparrow} \quad \Rightarrow \quad N_{\uparrow\uparrow} \neq N_{\uparrow\downarrow}$$

The index of refraction and effective potential energy of particles in matter

The wave number of the particle in vacuum is denoted *k*, $k' = kN$ is the wave number of the particle in medium.

boundary vacuum-medium

vacuum	medium
$E = \frac{\hbar^2 k^2}{2m}$	$E' = \frac{\hbar^2 k^2 N^2}{2m}$

$$N_{\uparrow\uparrow(\uparrow\downarrow)} = 1 + \frac{2\pi\rho}{k^2} f(0)_{\uparrow\uparrow(\uparrow\downarrow)}$$

$$N_{\uparrow\uparrow} \neq N_{\uparrow\downarrow}$$

$$f(0) = A + \vec{\sigma} \cdot \vec{g}$$

From the energy conservation condition we immediately obtain the necessity to suppose that a particle in medium possesses effective potential energy.

$$E = E' + U \qquad U = E - E' = -\frac{2\pi\hbar^2}{m} \rho f(0)$$

Spin splitting levels in the nuclear pseudo-magnetic field goes the same way as in the magnetic field. Spin rotation appears.

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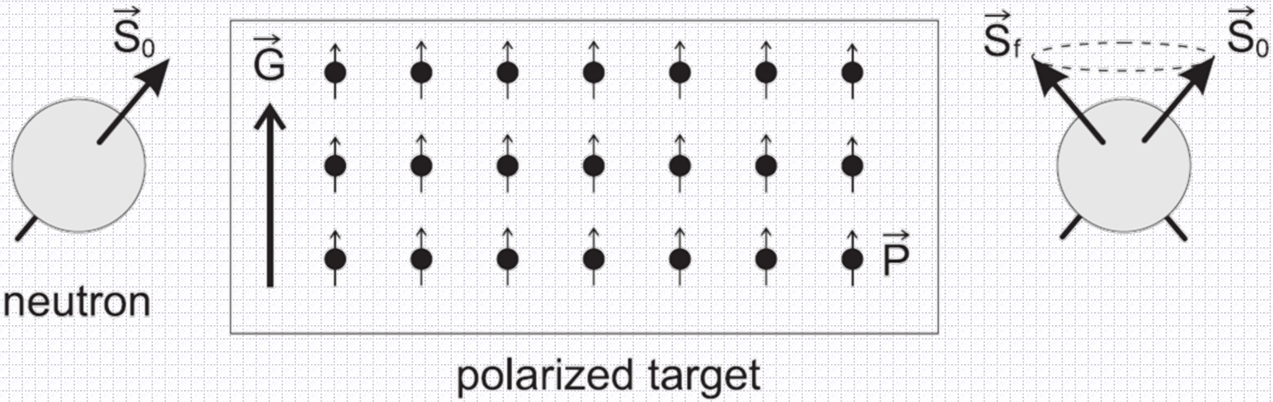
* Baryshevsky V.G., Podgoretskii, M.I. Nuclear precession of neutrons, Zh. Eksp. Teor. Fiz., 47 pp., 1050-1054, (1964).

Neutron nuclear precession (nuclear pseudomagnetism)

V. G. Baryshevskii and M. I. Podgoretskii, *Nuclear precession of neutrons,* ***Zh. Eksp.Teor. Fiz. 47 (1964) 1050 (Sov.Phys. JETP, 20 (1965) 704)***

$$\psi(\vec{r}) = \begin{pmatrix} c_1 \ \psi_+ \ (\vec{r}) \\ c_2 \ \psi_- \ (\vec{r}) \end{pmatrix} = c_1 e^{i\vec{k}_\perp \vec{r}_\perp} e^{ik_z n_+ z} \begin{pmatrix} 1 \\ 0 \end{pmatrix} + c_2 e^{i\vec{k}_\perp \vec{r}_\perp} e^{ik_z n_- z} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$



$$p_{nx} = \cos[k_z \mathtt{Re}(n_+ - n_-)z] e^{-k_z \mathtt{Im}(n_+ + n_-)z} \langle\psi|\psi\rangle^{-1} ,$$

$$p_{ny} = -\sin[k_z \mathtt{Re}(n_+ - n_-)z] e^{-k_z \mathtt{Im}(n_+ + n_-)z} \langle\psi|\psi\rangle^{-1} ,$$

$$p_{nz} = \frac{1}{2}(e^{-2k_z \mathtt{Im} n_+ z} - e^{2k_z \mathtt{Im} n_- z}) \langle\psi|\psi\rangle^{-1}$$

$$p_x^2 + p_y^2 + p_z^2 = 1 .$$

$$\theta = k_z \mathtt{Re}(n_+ - n_-)z = \frac{2\pi\rho}{k_z} \mathtt{Re}(f_+ - f_-)z$$

Neutron nuclear precession: experiments

Abragam, A., Bacchella, G.L.,Glattli, H. Meriel, P., Piesvaux, J., Pino, M. and Roubeau, P., C.R. Acad. Sci., (Paris) B274 (1972) 423

Forte,M, Nuovo Cimento A18,4 (1973) 726

Abragam, A. and Goldman, M., Nuclear Magnetism: Order and Disorder, Oxford University Press, 1982.

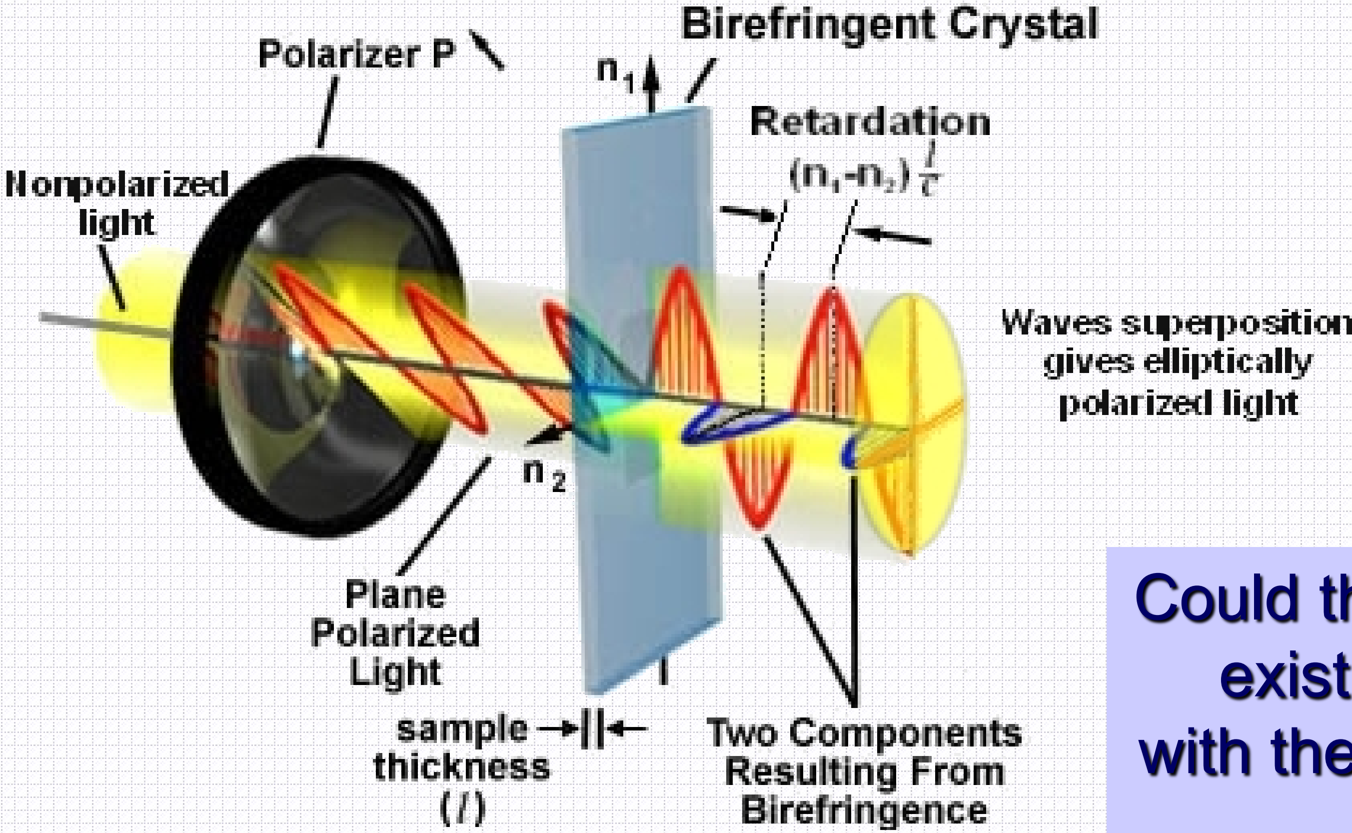
Piegsa, F.M. , van den Brandt, B., Glattli, H., Hautle, P., Kohlbrecher, J., Konter, J.A., Schlimme, B.S and Zimmer, O. A Ramsey apparatus for the measurement of the incoherent neutron scattering lengthof the deuteron, Nucl. Instrum. Methods A 589, 2 (2008) 318.

van den Brandt, B., Glattli, H., Hautle, P., Konter, J.A.,Piegsa, F.M. and   Zimmer, O. The measurement of the incoherent neutron scattering length of the deuteron, Nucl.Instrum. Methods A 611 (2009) 231.

Murman Tsulaya, Nuclear precession in a proton target, DUBNA. our days.

V.G.Baryshevsky, *High–Energy Nuclear Optics of Polarized Particles,* World Scientific, 2012.

Birefringence effect



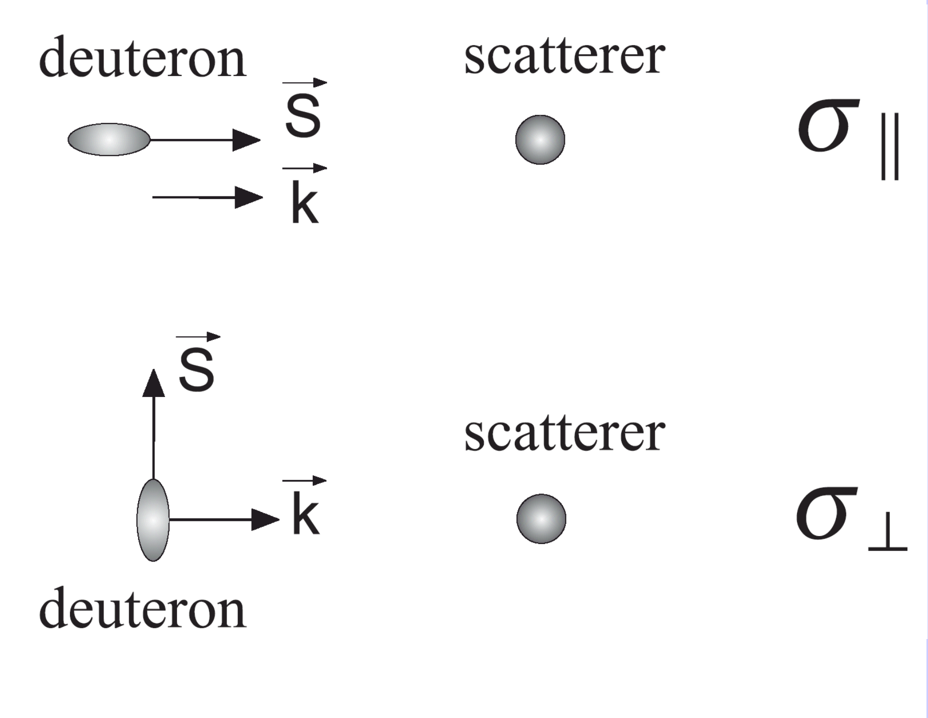
Could the similar effect exist for particles with the nonzero mass ?

V.G. Baryshevsky, *Birefringence of particles (nuclei, atoms) of spin S≥1 in matter*, **Phys. Lett. A 171, 5-6 (1992) 431**

V.G. Baryshevsky, *Spin oscillations of high-energy particles (nuclei) passingthrough matter and the possibility of measuring the spin-dependent part of the amplitude of zero-angle elasticcoherent scattering*, **J. Phys. G 19, 2 (1993) 273**

Deuteron (spin = 1) passing through a nonpolarized target
The phenomenon of birefringence in matter

Appearance of two refraction indices of deuteron can be easily explained



As the ground state of a deuteron is non-spherical, then the scattering cross-section depends on the angle between the spin and momentum of the deuteron

$$\mathrm{Im} f_{\parallel}(0) = \frac{k}{4\pi}\sigma_{\parallel} \neq \mathrm{Im} f_{\perp}(0) = \frac{k}{4\pi}\sigma_{\perp}$$

According to the dispersion relation
Re f(0) ~ Φ (Im f(0)), therefore

$$Re\ f_{\perp}(0) \neq Re\ f_{\parallel}(0)$$

Unlike optical birefringence, the birefringence effect for particles appear in isotropic matter (and even the spin of matter nuclei is either zero or unpolarized !). Anisotropy is provided by the particle itself (a particle with the spin S ≥ 1 and mass M ≠ 0 has the intrinsic anisotropy).

Deuteron spin dichroism: experiments

First observation of spin dichroism with deuterons up to 20 MeV in a carbon target **(LANL arxive: hep-ex/0501045 (2005))**

V. Baryshevsky, A. Rovba *(Research Institute of Nuclear Problems, Minsk, Belarus)*

R. Engels, F. Rathmann, H. Seyfarth, H. Stroher, T. Ullrich (*Institut fur Kernphysik, Forschungszentrum Julich, Germany)*

C. Duweke, R. Emmerich, A. Imig, J. Ley, H. Paetz gen. Schieck, R. Schulze, G. Tenckhoff, C. Weske (*Institut fur Kernphysik, Universitat zu Koln, Germany)*

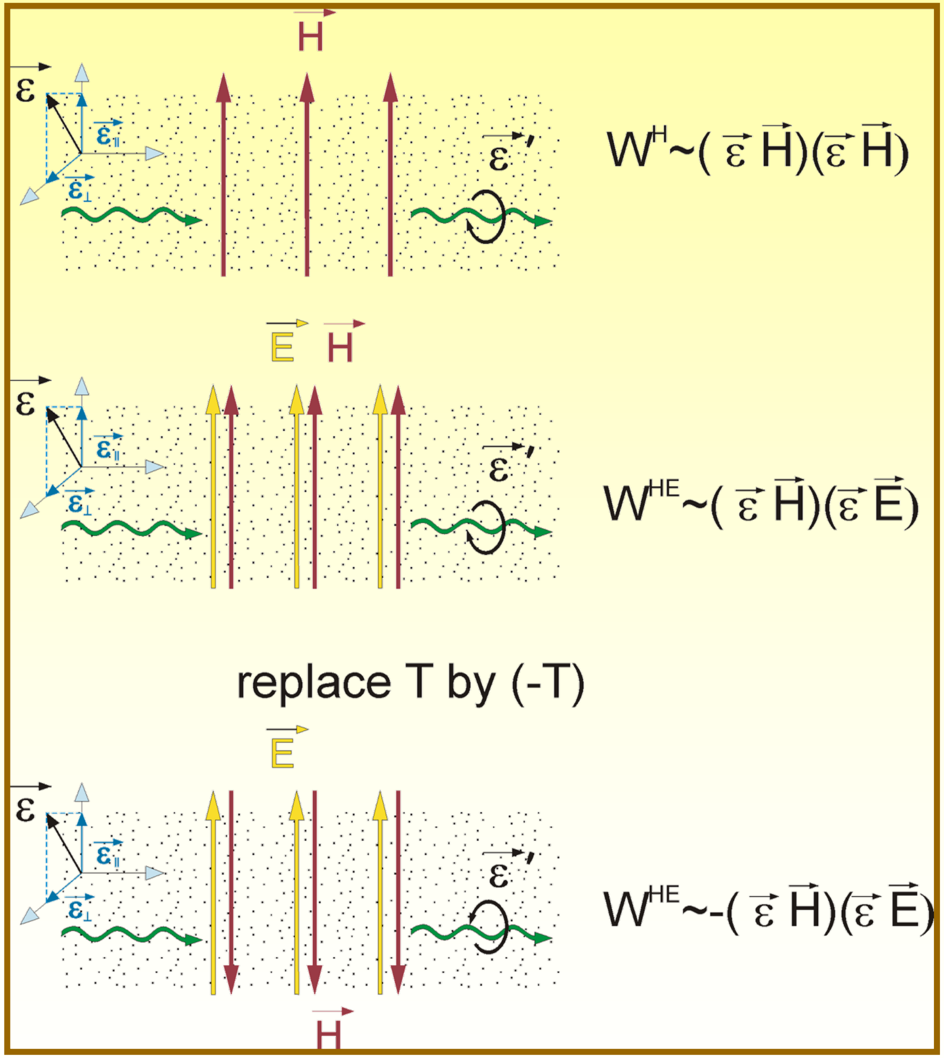
M. Mikirtytchiants, A. Vassiliev (*PNPI, Russia)*

H. Seyfarth, R. Engels, F. Rathmann, H. Stroher, V. Baryshevsky, A. Rouba, C. Duweke, R. Emmerich, A. Imig, K. Grigoryev, M. Mikirtychiants, and A. Vasilyev, *Production of a beam of tensor-polarized deuterons using a carbon target*, **Phys. Rev. Lett. 104, 22 (2010) 222501**.

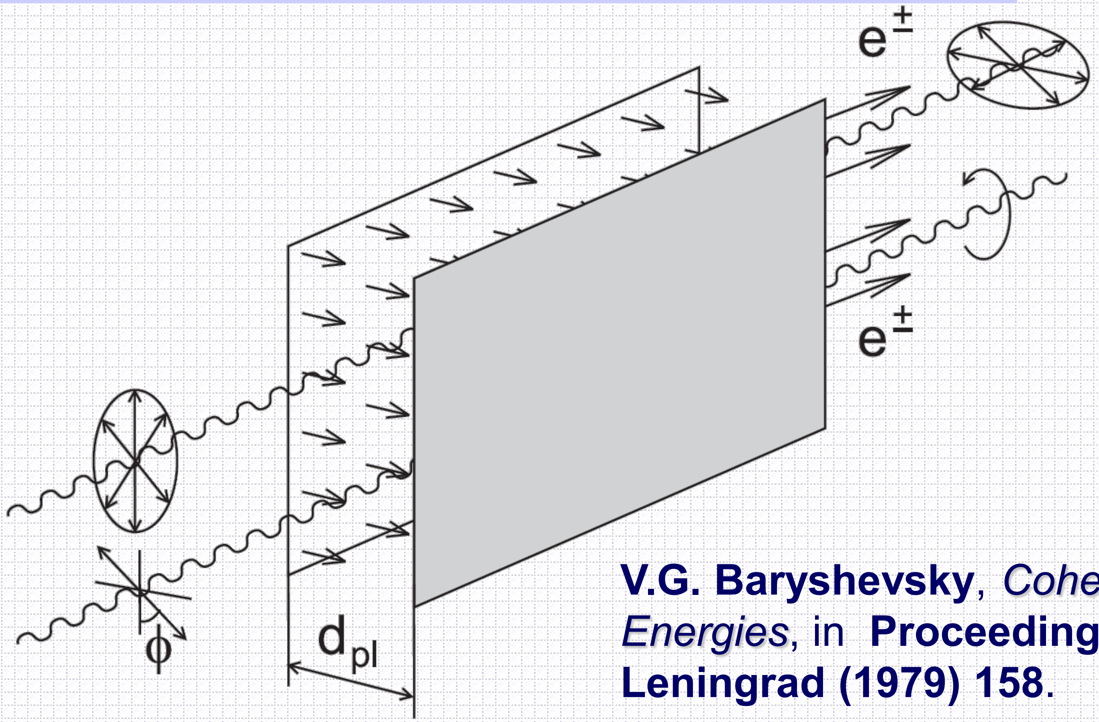
L. S. Azhgirei, Yu. V. Gurchin, A. Yu. Isupov, A.N. Khrenov, A. S. Kiselev, A.K. Kurilkin, P.K. Kurilkin, V.P. Ladygin, A.G. Litvinenko, V.F. Peresedov, S.M. Piyadin, S.G. Reznikov, P.A. Rukoyatkin, A.V. Tarasov, T.A. Vasiliev, V.N. Zhmyrov, and L.S. Zolin, *Observation of Tensor Polarization of Deuteron BeamTraveling through Matter*, **Physics of Particles and Nuclei Letters 5, 5 (2008) 432**.

Channeling and High energy nuclear optics of polarized particles in crystals
What is new?

Birefringence effect



High-energy gamma-quanta birefringence in crystals

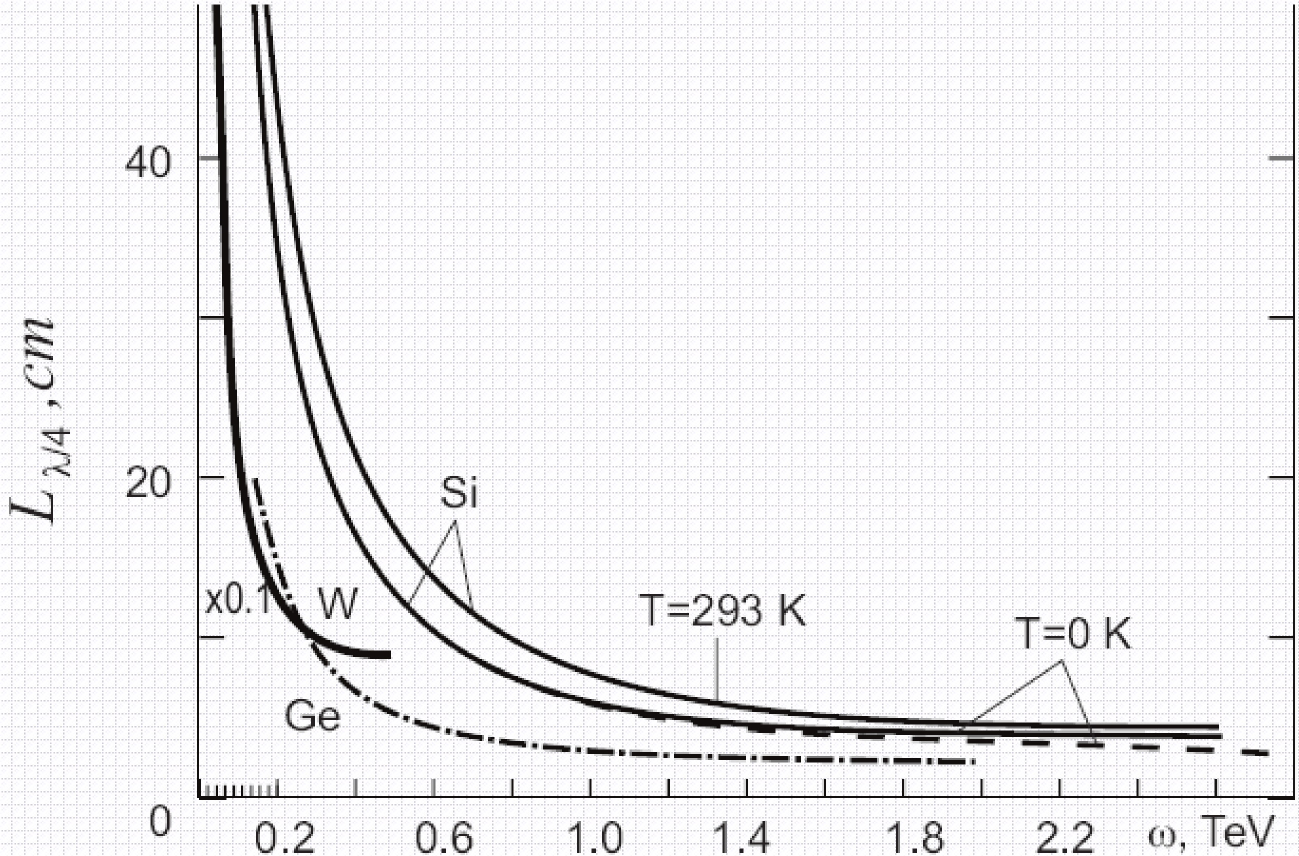


V.G. Baryshevsky, *Coherent Processes in Crystals at High Energies*, in **Proceedings of XIV Winter School LNPI, Leningrad (1979) 158**.

V.G. Baryshevsky and V.V. Tikhomirov, *Birefringenceof the high--energy γ-quanta in monocrystals*, **Yad.Fiz. 36 (1982) 697** [Sov. J. Nucl. Phys. 36 (1982) 408]

V.G. Baryshevsky and V.V. Tikhomirov, *Birefringence of the high--energy γ-quanta in monocrystals*, **Phys.Lett. A 90, 3 (1982) 153**

High-energy gamma-quanta birefringence in crystals



Energy dependence of birefringence effects for a linearly polarized beam and length of the quarter–wave plates for (110) planes of Ge and W crystals at T = 293 K, and also Si at T = 0 and at T = 293K.

Nuclear optics in crystals for high-energy electrons and positrons

V.G.Baryshevsky, *High–Energy Nuclear Optics of Polarized Particles,* **World Scientific, 2012**.

V.G.Baryshevsky, V.V.Tikhomirov, Synchrotron type radiation processes in crystals and polarization phenomena accompanying them, Sov. Phys. Usp. v.32,11,pp1013-1032(1989),

Uspekhi Fiz. Nauk v.159 (1989)pp529-565

Anomalous magnethic moment dependence on E

$$\frac{\mu'(\chi)}{\mu_B} = \frac{\alpha}{\pi}\int_0^\infty du \left(\frac{u}{\chi}\right)^{2/3} \frac{1}{(1+u)^3} \square \int_0^\infty dt \sin[\left(\frac{u}{\chi}\right)^{2/3} t + \frac{t^3}{3}]$$

$$\chi = \frac{\gamma E}{E_{cr}}, \; E_{cr} = 1.32 \cdot 10^{16} \; V/cm = 4.41 \cdot 10^{13}\, CGSE$$

Plane case

$$\chi = 1 \text{ if } \gamma = \frac{E_{cr}}{E} = \frac{1{,}32 \cdot 10^7}{z}$$

for tungsten z=74 $\gamma = 1.78 \cdot 10^5$

Axis case

$$\gamma_{ax} \approx 1.78 \cdot 10^4$$

The effect is huge for $e^{+/-}$. But calculations of $\mu'_B(E)$ are needed for baryons.

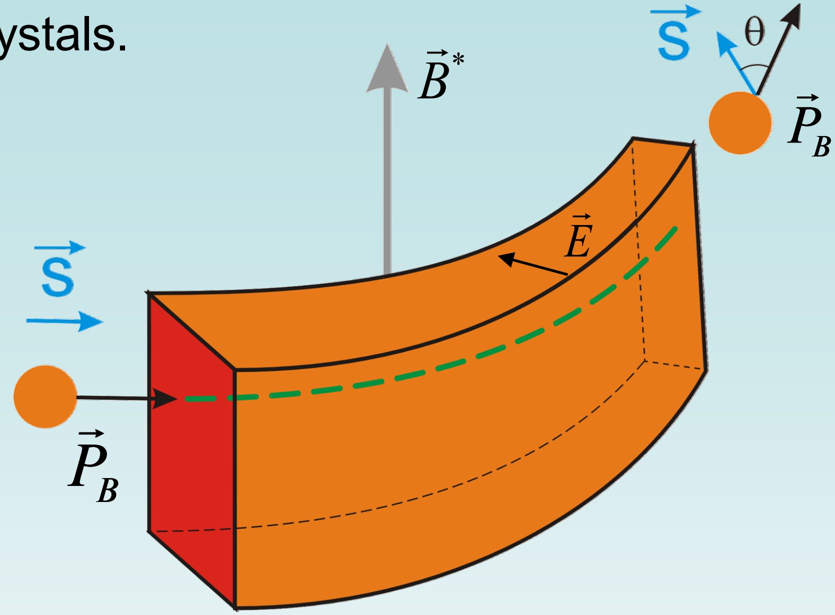
*Baryshevsky V.G., Grubich A.O., Dubovskaya I.Ya. Electromagnetic radiation from channeled particles in absorptive crystals, Izv. AN BSSR, 4, p 81, (1980).
* Baryshevsky V.G., High-Energy Nuclear Optics of Polarized Particles, World Scientific Publishing, Singapore, 2012.
* Baryshevskii V.G., Tikhomirov V.V. Synchrotron-type radiation processes in crystals and polarization phenomena accompanying them, Usp. Fiz. Nauk, 32, 1013–1032, (1989).
* Baryshevsky V.G. Channeling, radiation, and Reactions in Crystals at High Energies, BSU, Minsk, 1982, 256 p [in Russian].

Radiative self-polarization

$e^{+/-}$ spin radiative self-polarization in bent crystals.

$$\zeta_z(t) = \zeta_0(0)\, e^{-t/T_0} + 8(5\sqrt{3})^{-1}(1 - e^{-t/T_0})$$

$$T_0^{-1} = (5\sqrt{3}/8)\,\alpha \left(\frac{\hbar\gamma}{mc}\right)^2 \left(\frac{\gamma}{R}\right)^3 \cdot c$$

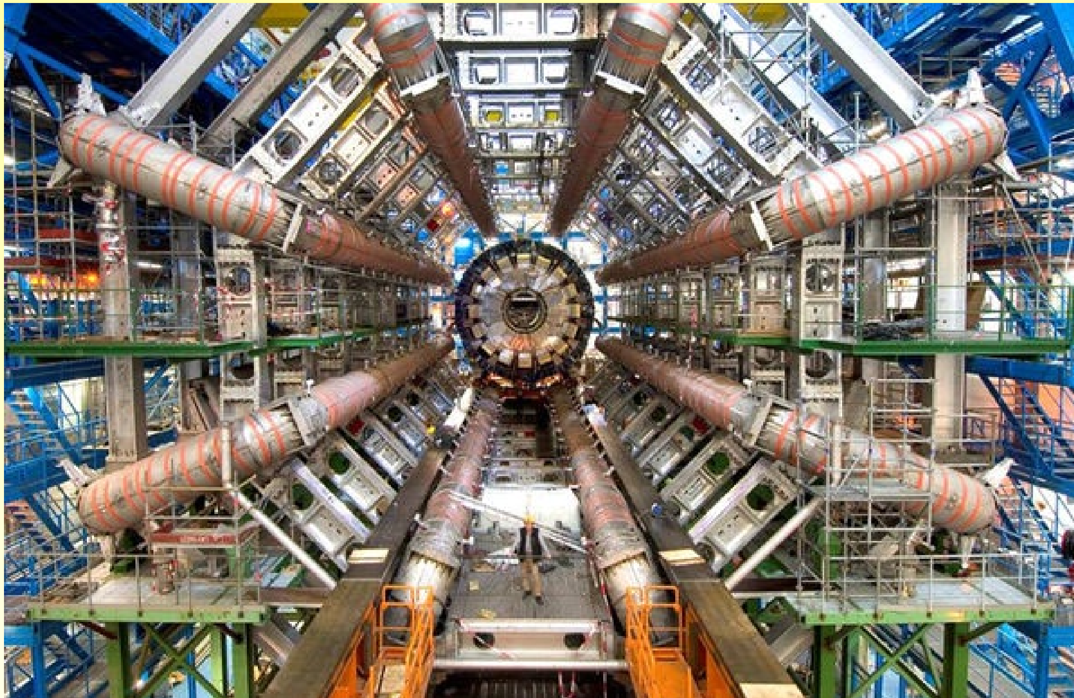


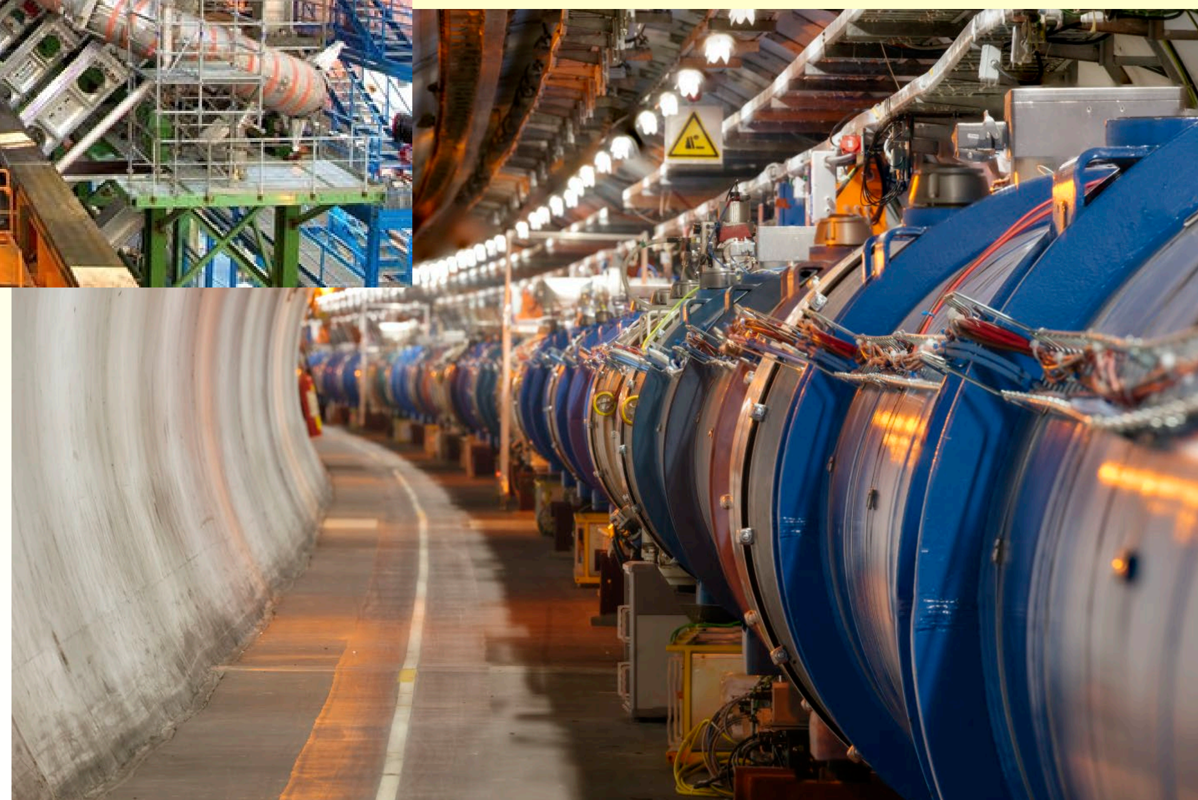
During $t > T_0$ independently from initial polarization $\zeta_z = 8(5\sqrt{3})^{-1} \approx 0.924$.

The beam polarizes along crystal bending axis – one photon is being radiated.

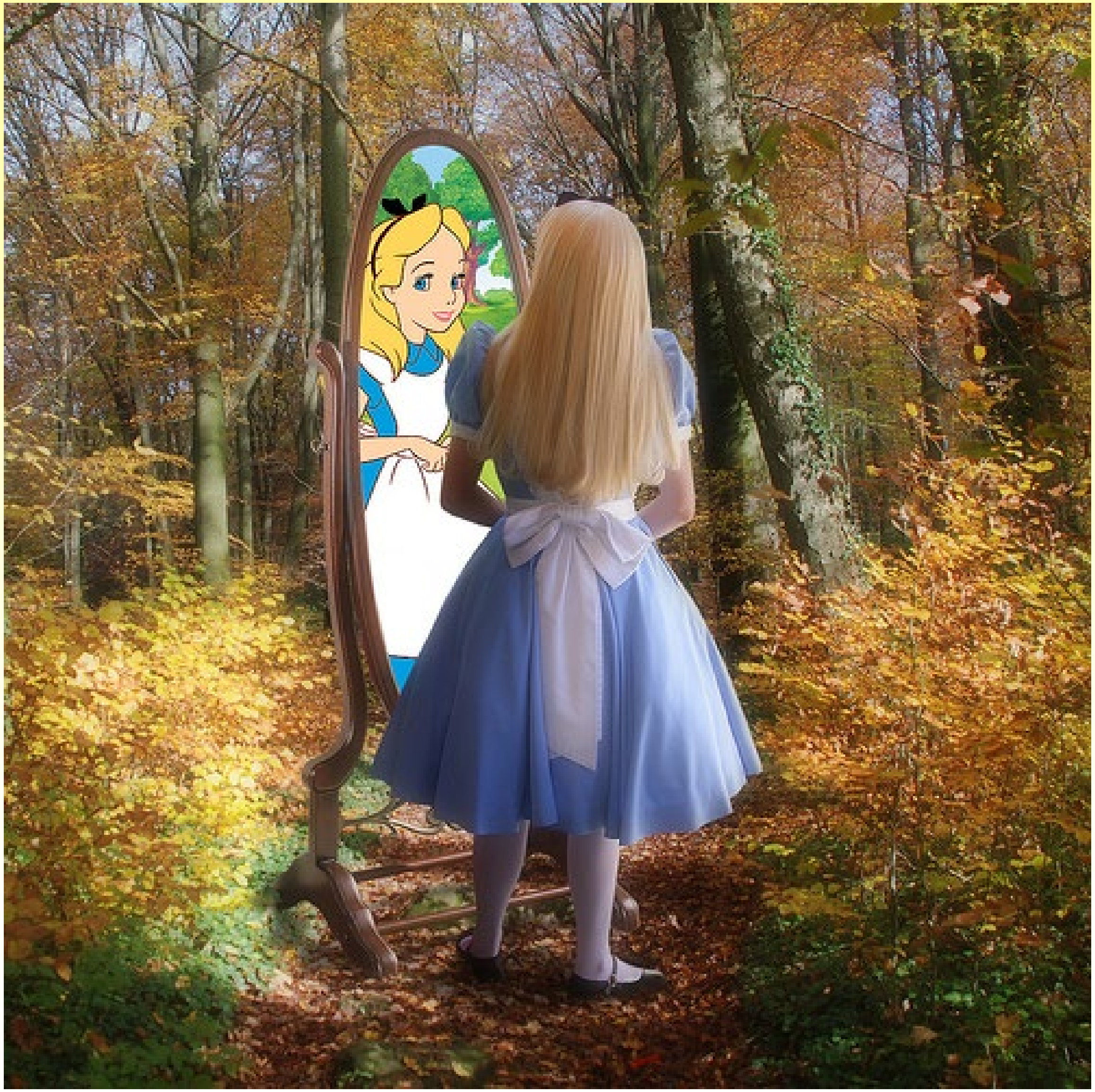
* Baryshevsky V.G., Radiative self-polarization and spin precession of particle moving in crystals, Dokl. Akad. Nauk BSSR, 23, 5, pp 438, (1979).
* Baryshevsky V.G., High-Energy Nuclear Optics of Polarized Particles, World Scientific Publishing, Singapore, 2012.
* Baryshevskii V.G., Tikhomirov V.V. Synchrotron-type radiation processes in crystals and polarization phenomena accompanying them, Usp. Fiz. Nauk, 32, 1013–1032, (1989).
*Baryshevsky V.G., Grubich A.O., Dubovskaya I.Ya. Electromagnetic radiation from channeled particles in absorptive crystals, Izv. AN BSSR, 4, p 81, (1980).
* Baryshevsky V.G. Channeling, radiation, and Reactions in Crystals at High Energies, BSU, Minsk, 1982, 256 p [in Russian].

Parity (P) and time T (CP) non-invariance at LHC and FCC

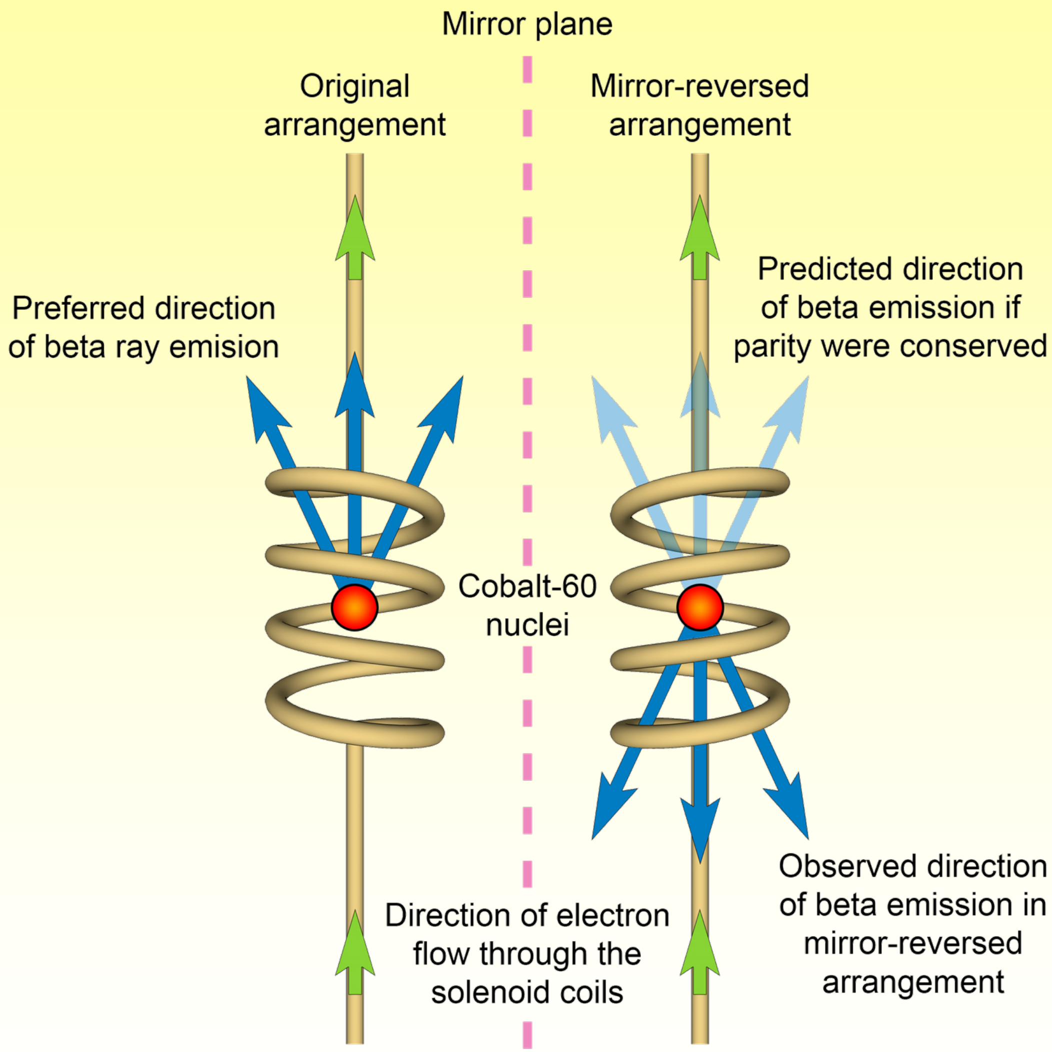




P non-invariance



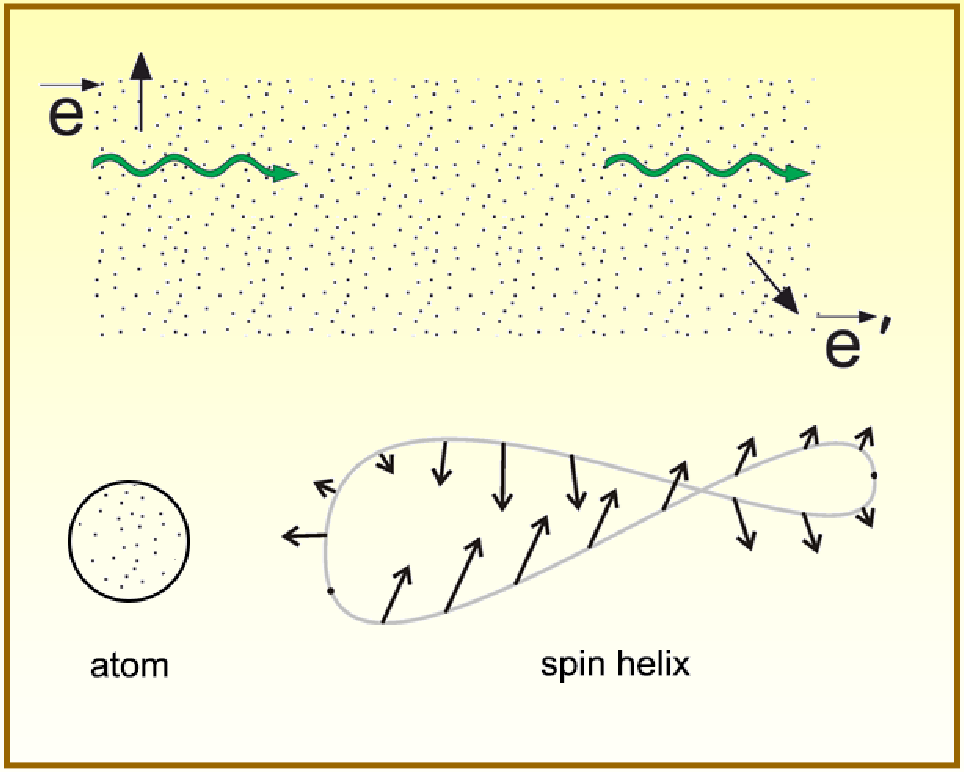
The Wu experiment



The Wu experiment, conducted in 1956 by the Chinese American physicist Chien-Shiung Wu in collaboration with the Low Temperature Group of the US National Bureau of Standards.

Tsung-Dao Lee and Chen-Ning Yang, the theoretical physicists who originated the idea of parity nonconservation and proposed the experiment, received the 1957 Nobel Prize in physics for this result.

Optical gyrotropy caused by P-violating interactions

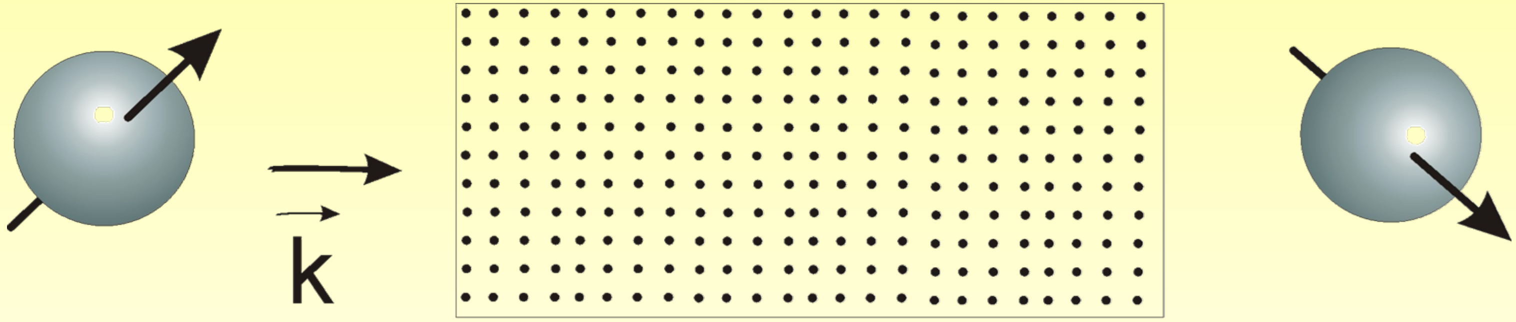


1957 Zeldovich I.B.
1978 Barkov L.M., Zolotarev M.S.

Neutral weak currents were later discovered in SLAC at deeply nonelastic electrons scattering by deutons.

Neutron optical spin rotation

$$\psi(\vec{r}) = \begin{pmatrix} c_1 \ \psi_+ \ (\vec{r}) \\ c_2 \ \psi_- \ (\vec{r}) \end{pmatrix} = c_1 e^{i\vec{k}_\perp \vec{r}_\perp} e^{ik_z n_+ z} \begin{pmatrix} 1 \\ 0 \end{pmatrix} + c_2 e^{i\vec{k}_\perp \vec{r}_\perp} e^{ik_z n_- z} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

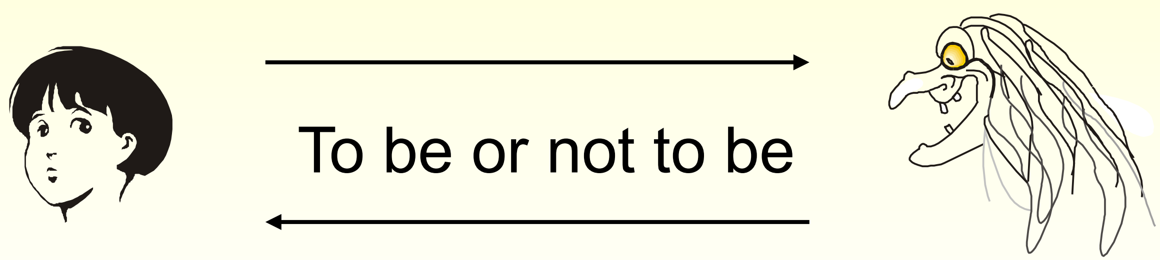


$$p_{nx} = \cos[k_z \mathtt{Re}(n_+ - n_-)z] e^{-k_z \mathtt{Im}(n_+ + n_-)z} \langle\psi|\psi\rangle^{-1},$$
$$p_{ny} = -\sin[k_z \mathtt{Re}(n_+ - n_-)z] e^{-k_z \mathtt{Im}(n_+ + n_-)z} \langle\psi|\psi\rangle^{-1},$$

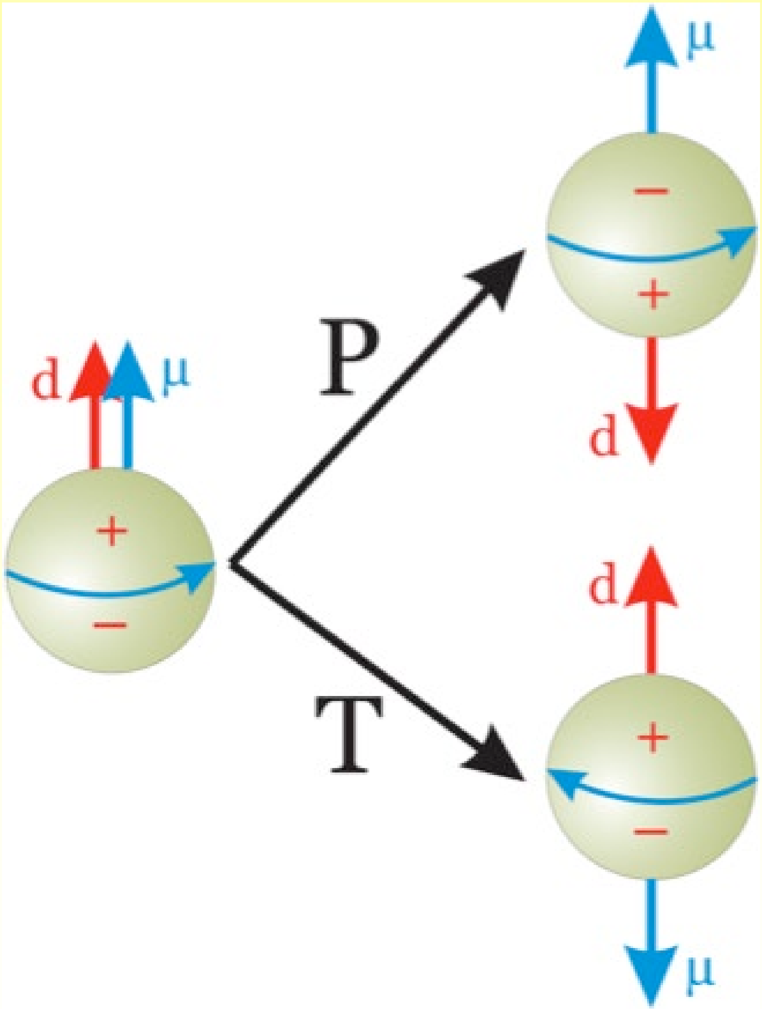
$$\theta = k_z \mathtt{Re}(n_+ - n_-)z$$

• Forte, M. (1980). Parity violation effects in neutron scattering and capture, *Lett. Nuovo Cimento* **28**, 16, pp. 538–540.
• Michel, F. C. (1964). Parity nonconservation in nuclei, *Phys. Rev.* **133**, 2B, pp. B329–B349.

T non-invariance



T non-invariance



Non-Relativistic Hamiltonian

$$H = \underbrace{-\vec{\mu}\vec{B}}_{\substack{C-even \\ P-even \\ T-even}} - \underbrace{\vec{d}\vec{E}}_{\substack{C-even \\ P-odd \\ T-odd}}$$

Assume $\vec{\mu} = \mu \frac{\vec{J}}{J}$ and $\vec{d} = d \frac{\vec{J}}{J}$

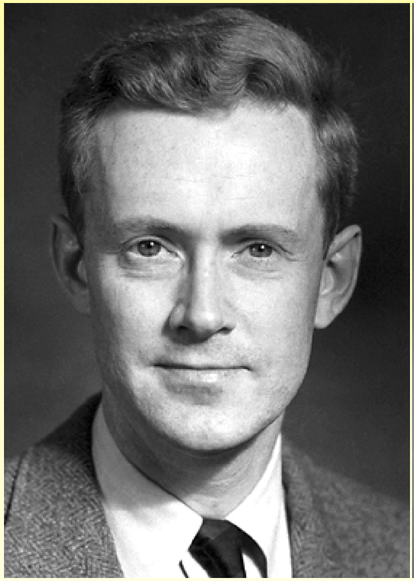
Role of CP violation in the matter/antimatter asymmetry of the Universe

Sakharov Criteria:

Particle Physics can produce matter/antimatter asymmetry in the early universe IF there is:

- Baryon Number Violation
- CP & C violation
- Departure from Thermal Equilibrium

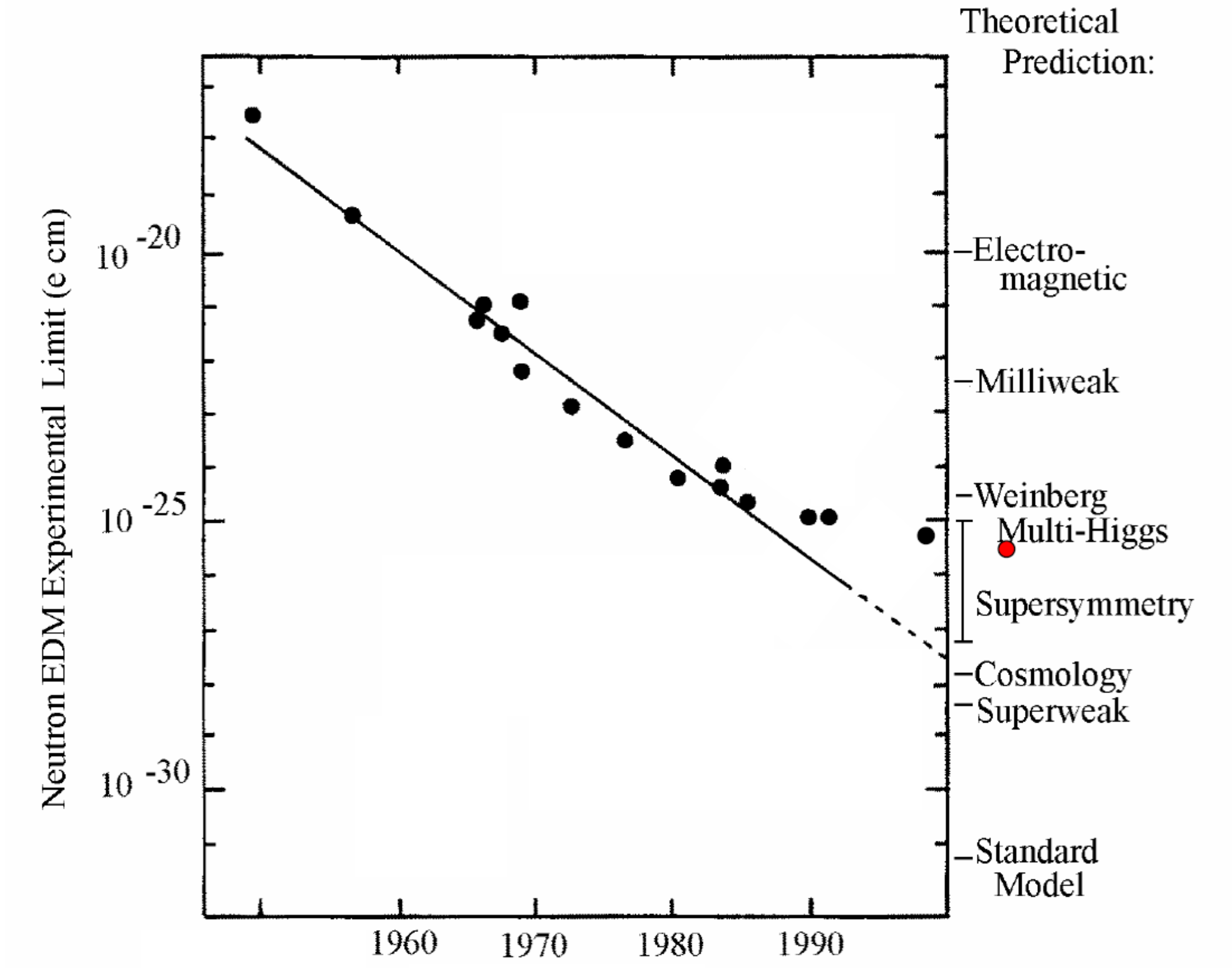
First result for neutron EDM




E.M. Purcell and N.F. Ramsey, Phys. Rev. 78, 807 (1950)

Pioneered Neutron Beam Magnetic Resonance

n-EDM vs Time



Theoretical
Prediction:
Neutron EDM Experimental Limit (e cm)
10^{-20}
10^{-25}
10^{-30}
1960
1970
1980
1990
Electro-
magnetic
Milliweak
Weinberg
Multi-Higgs
Supersymmetry
Cosmology
Superweak
Standard
Model

Electrical dipole moment of heavy charm and beauty baryons

It was recently stated that heavy baryons EDM can be as great as the value $d \sim 10^{-17}$.

- F. Sala, JHEP 03, 061, (2014)
- A.E. Blinov, et all, Nucl. Phys. Proc. Suppl., 1 89, 257, (2009)
- Cordero-Cid, et all, J. Phys. G, 35, 02504, (2008)

Characteristics. MDM and EDM = ?

Charmed baryons

$$\Lambda_c^+ : \tau = 0.2 \cdot 10^{-12} s; \quad m = 2286.46 MeV; \quad l_d = l_{decay} = \tau c \gamma = 6 cm.$$

$$\Xi_c^+ : \tau = 0.44 \cdot 10^{-12} s; \quad m = 2467.8 MeV; \quad l_d = 13.2 cm.$$

$$\Xi_c^0 : \tau = 0.1 \cdot 10^{-12} s; \quad m = 2470.88 MeV; \quad l_d = 3.3 cm; \quad \gamma = 10^3$$

$$\Omega_c^0 : \tau = 7 \cdot 10^{-14} s; \quad m = 2695 MeV; \quad l_d = 2.1 cm.$$

Bottom baryons

$$\Lambda_b^0 : \tau = 1.425 \cdot 10^{-12} s; \quad m = 5619.4 MeV; \quad l_d = 42.7 cm; \quad \gamma = 10^3.$$

$$\Xi_b^0 : \tau = 1.49 \cdot 10^{-12} s; \quad m = 5788 MeV; \quad l_d = 44.7 cm.$$

$$\Xi_b^- : \tau = 1.56 \cdot 10^{-12} s; \quad m = 5791 MeV; \quad l_d = 44.7 cm.$$

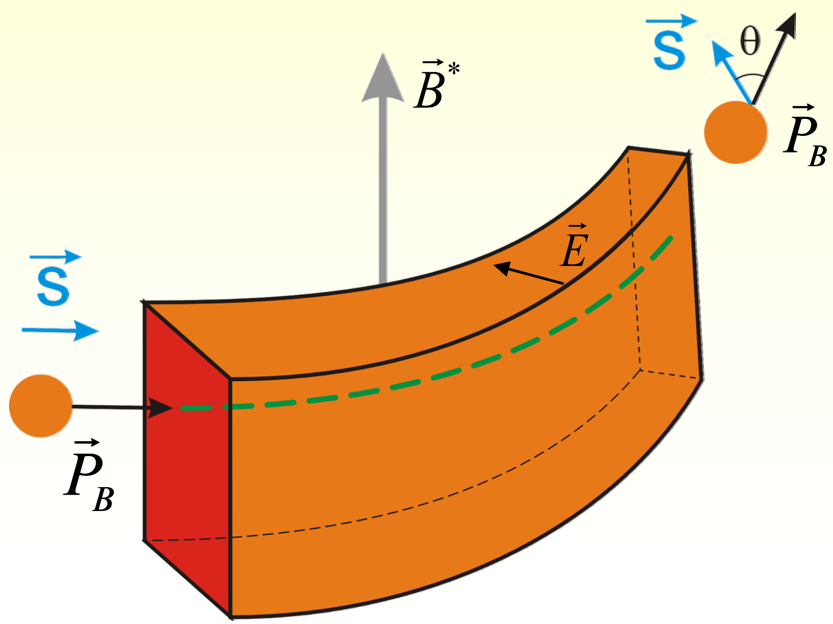
$$\Omega_b^- : \tau = 1.1 \cdot 10^{-12} s; \quad m = 6071 MeV; \quad l_d = 33 cm.$$

Spin rotation effect of ultrarelativistic particles passing through a crystal

- **V.G. Baryshevsky**, Spin rotation of ultrarelativistic particles passing through a crystal, Pis'ma Zh. Tekh. Fiz., 5, 3 (1979), pp 182-184.

* **V.G. Baryshevsky**, High-Energy Nuclear Optics of Polarized Particles, World Scientific Publishing, Singapore, 2012.

* **V.G. Baryshevsky**, The possibility to measure the magnetic moments of short-lived particles (charm and beauty baryons) at LHC and FCC energies using the phenomenon of spin rotation in crystals, Physics Letters B, V. 757, 2016, pp 426–429.



Particles spin rotation in bent crystal

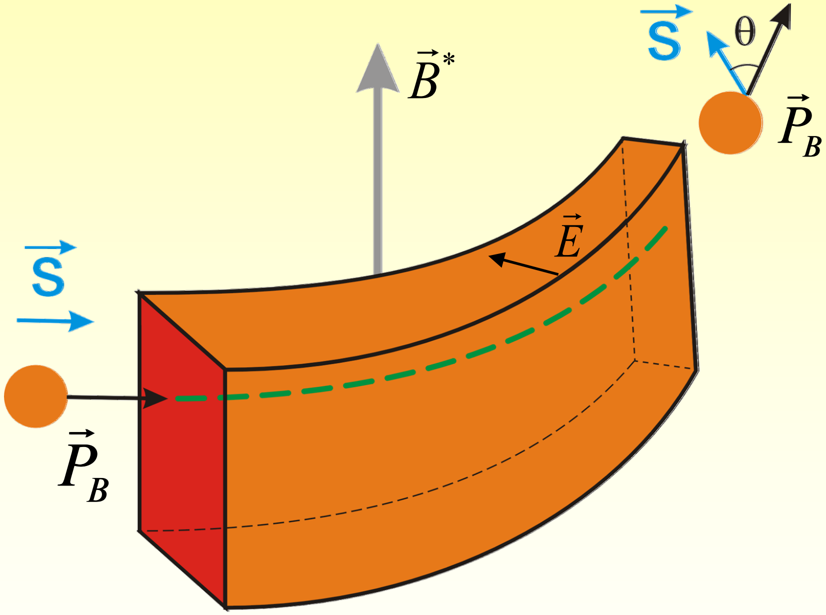
In particle rest frame

$$B^* \to \gamma E$$

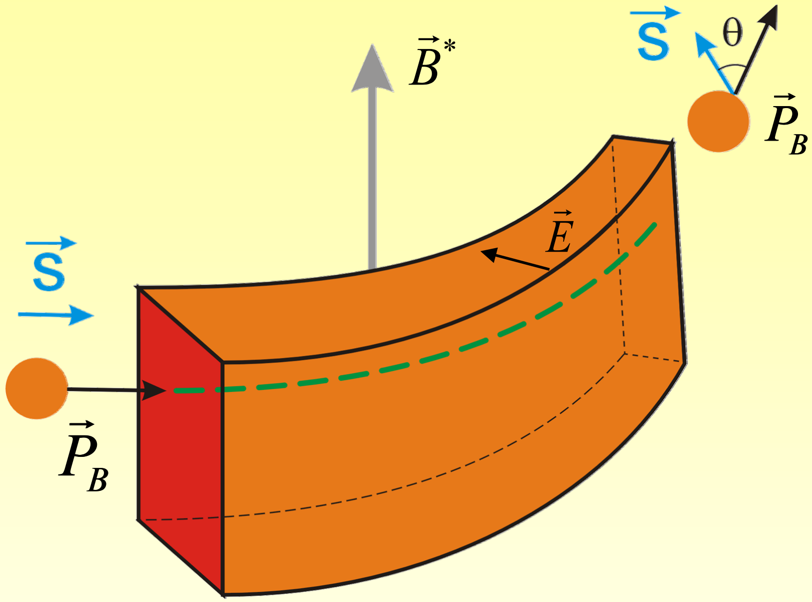
$$\omega' = \frac{2\mu' B^*}{\hbar} = \frac{2\mu' \gamma E}{\hbar}$$

In laboratory frame

$$\omega = \frac{\omega'}{\gamma} = \frac{2\mu' E}{\hbar}$$



First experiment to measure (g-2) rotation



E761 Collaboration, FERMILAB

"First observation of spin precession of polarized Σ^+ hyperons channeled in bent crystals", LNPI Research Reports (1990-1991) 129.

Energy of Σ^+ : 200 – 300 GeV

D. Chen et all

"First Observation of Magnetic Moment Precession of Channeled Particles in Bent Crystals", Phys. Rev. Lett. 69 (1992) 3286.

A.V. Khanzadeev, V.M. Samsonov, R.A. Carrigan, D. Chen

"Experiment to observe the spin precession of channeled relativistic Σ^+ hyperons" NIM 119 (1996) 266.

Electromagnetic dipole moment and particles spin rotation in bent crystals at Large Hadron Collider

Non-Relativistic Hamiltonian

$$H = \underbrace{-\vec{\mu}\vec{B}}_{\substack{C-even\\ P-even\\ T-even}} - \underbrace{\vec{d}\vec{E}}_{\substack{C-even\\ P-odd\\ T-odd}}$$

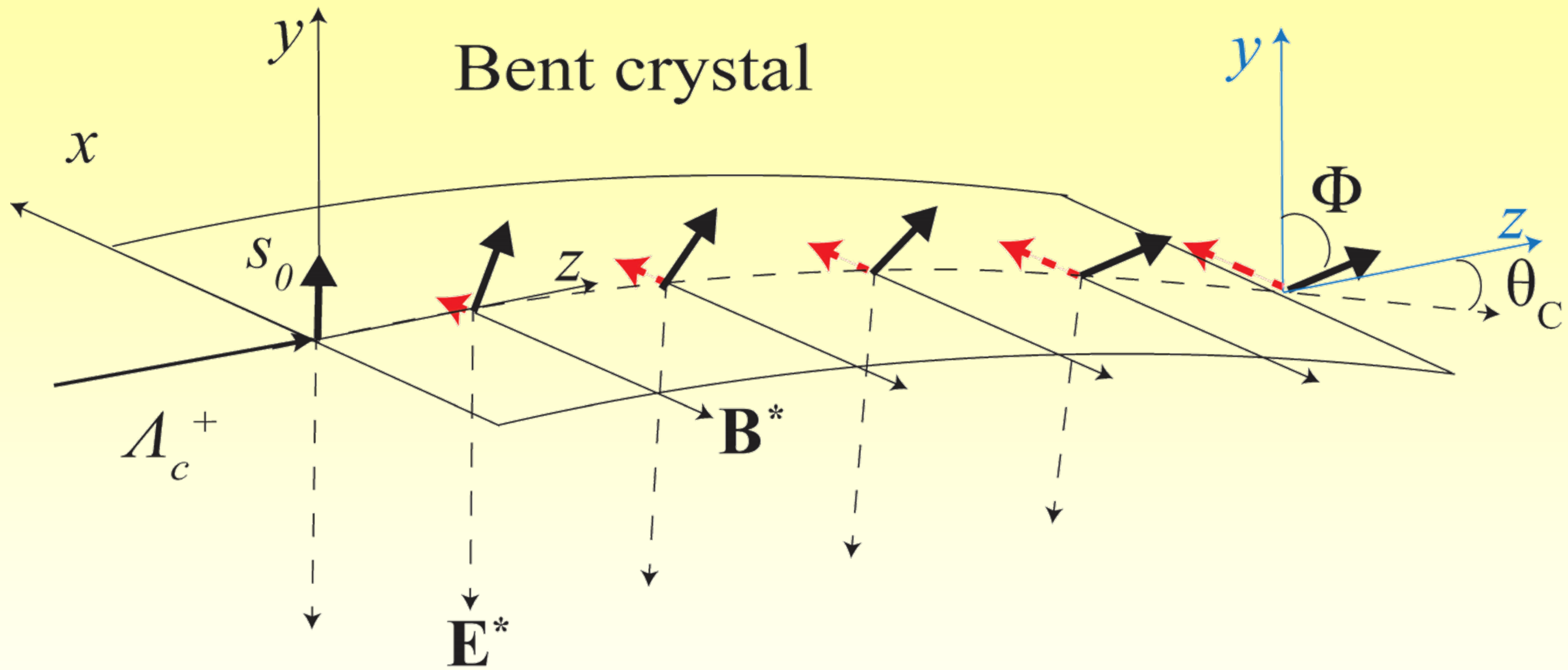
Relativistic equation

$$\frac{d\vec{S}}{dt} = -\frac{e(g-2)}{2mc}\left[\vec{S}\times\left[\vec{\beta}\times\vec{E}\right]\right] + \frac{d}{\hbar S}\left[\vec{S}\times\vec{E}\right].$$

- Botella F. J., Garcia Martin L. M., Marangotto D., et all, On the search for the electric dipole moment of strange and charm baryons at LHC, *Eur. Phys J.C.* **77**, 181 (2017), DOI 10.1140/epjc/s10052-017-4679-y.

- Bagli E., Bandiera L., Cavoto G., et all, Electromagnetic dipole moments of charged baryons with bent crystals at the LHC, *Eur. Phys J.C.*, (2017) 77:828, p. 1-19.

Electromagnetic dipole moment and particles spin rotation in bent crystals at Large Hadron Collider



Behavior of the spin rotation caused by magnetic moment and EDM. The figure is reprinted from Botella et all, On the search for the electric dipole moment of strange and charm baryons at LHC, *Eur. Phys J.C.* 77, 181 (2017). Black arrows represent spin rotation caused by magnetic dipole moment, red arrows represent spin rotation caused by electric dipole moment.

T non-invariance interactions at LHC and FCC

- **V.G. Baryshesky**, Electromagnetic dipole moment and time reversal invariance violating interactions of high energy short-lived particles in bent and straight crystals, Phys.Rev Accelerators and Beams 22,081004 (2019)

- **V.G. Baryshesky**, Electromagnetic dipole moments and time reversal violating interactions for high energy charged baryons in bent crystals, Eur.Phys.J.C (2019) 79:350.

The index of refraction and effective potential energy of relativistic particles in matter

The wave number of the particle in vacuum is denoted *k*, *k'* = *kn* is the wave number of the particle in medium.

$$n = 1 + \frac{2\pi N}{k^2} f(0)$$

Expression for n does not contain ħ.

Boundary vacuum-medium

vacuum

medium

$$E = \sqrt{\hbar^2 k^2 c^2 + m^2 c^4}$$

$$E_{med} = \sqrt{\hbar^2 k^2 n^2 c^2 + m^2 c^4}$$

Kinetic energy of a particle in vacuum is not equal to that in medium.

Effective potential energy of particle interaction in matter

From the energy conservation condition we immediately obtain the necessity to suppose that a particle in medium possesses effective potential energy. This energy can be found easily from the evident equality:

$$E = E_{med} + U_{eff}$$

$$U_{eff} = E - E_{med} = -\frac{2\pi\hbar^2}{m\gamma} N f(E,0) = (2\pi)^3 N T_{aa}(\vec{k}' - \vec{k} = 0)$$

$$f(E,0) = -(2\pi)^2 \frac{E}{c^2\hbar^2} T_{aa}(\vec{k}' - \vec{k} = 0) = -(2\pi)^2 \frac{m\gamma}{\hbar^2} T_{aa}(\vec{k}' - \vec{k} = 0)$$

Effective potential energy of particle interaction with crystal

$$U(\vec{r}) = \sum_{\vec{\tau}} U(\vec{\tau}) e^{i\vec{\tau}\vec{r}} \qquad U(\vec{\tau}) = \frac{1}{V} \sum_{j} U_j(\vec{\tau}) e^{i\vec{\tau}\vec{r}_j}$$

$$U_j(\vec{\tau}) = -\frac{2\pi\hbar^2}{m\gamma} F_j(\vec{\tau})$$

$$F_j(\vec{k}' - \vec{k}) = f_j(\vec{k}' - \vec{k}) - i\frac{k}{4\pi}\int f_j^*(\vec{k}'' - \vec{k}') f_j(\vec{k}'' - \vec{k}) d\Omega_{k''}$$

Effective potential energy of particle interaction with plane and axis

For plane:

$$\hat{U}(x) = -\sum_{\tau_x} \frac{2\pi\hbar^2}{m\gamma V} \hat{F}(q_x = \tau_x, q_y = q_z = 0) e^{i\tau_x x} =$$

$$= -\frac{2\pi\hbar^2}{m\gamma V d_y d_z} \sum_{X_n} \hat{F}(x - X_n, q_y = q_z = 0)$$

$$\hat{F}(\vec{q}) = \int \hat{F}(\vec{r}\,') e^{-i\vec{q}\vec{r}\,'} d^3 r'$$

For axis:

$$\hat{U}(\vec{\rho}) = -\frac{2\pi\hbar^2}{m\gamma V} \sum_{\tau_x, \tau_y} \hat{F}(q_x = \tau_x, q_y = \tau_y, q_z = 0) e^{i\tau_\perp \vec{\rho}} =$$

$$= -\frac{2\pi\hbar^2}{m\gamma d_z} \sum_{R_{n\perp}} \hat{F}(\vec{\rho} - \vec{R}_{n\perp}, q_z = 0)$$

Scattering amplitude of a particle with spin 1/2

$$\hat{F}(\vec{q}) = A_{coul}(\vec{q}) + A_s(\vec{q}) + (B_{magn}(\vec{q}) + B_S(\vec{q}))\vec{\sigma}[\vec{n}\times\vec{q}] +$$
$$+(B_{we}(\vec{q}) + B_{wnuc}(\vec{q}))\vec{\sigma}\vec{N}_w + (B_{EDM}(\vec{q}) + B_{Te}(\vec{q}) + B_{Tnuc}(\vec{q}))\vec{\sigma}\vec{q}$$

$$\vec{q} = \vec{k}' - \vec{k},\ \ \vec{n} = \frac{\vec{k}}{k},\ \vec{N}_w = \frac{\vec{k}' + \vec{k}}{|\vec{k}' + \vec{k}|}$$

Effective potential energy determined by the anomalous magnetic moment

$$\hat{F}^{(1)}_{magn}(q) = B_{magn}(q)\vec{\sigma}[\vec{n}\times\vec{q}]$$

$$\hat{U}^{(1)}_{magn} = -\frac{e\hbar}{2mc}\frac{g-2}{2}E_{xplane}(x)\vec{\sigma}\vec{N}$$

$$\vec{N} = [\vec{n}_x \times \vec{n}],\ \vec{n}_x \parallel \vec{E}(x),\ \vec{n}_x \perp \vec{n},\ \vec{n} = \frac{\vec{k}}{k}$$

Effective potential energy determined by the anomalous magnetic moment

$$\hat{F}^{(2)}(\vec{q}=\vec{\tau}) = i\frac{k}{4\pi\hbar^2 c^2}\iint e^{-i\vec{\tau}\vec{r}_\perp}\left\{\overline{\left[\int \hat{V}(\vec{r}_\perp, z)dz\right]^2} - \left[\int \overline{\hat{V}(\vec{r}_\perp, z)dz}\right]^2\right\} d^2 r_\perp$$

$$\hat{V}(\vec{r}_\perp, z) = V_{coul}(\vec{r}_\perp, z) + \hat{V}_{magn}(\vec{r}_\perp, z)$$

$$\hat{U}^{(2)}_{magn}(x) = -i\frac{1}{4d_y d_z mc^2}\left(\frac{g-2}{2}\right)\frac{\partial}{\partial x}\overline{\delta V^2{}_{coul}(x)}\vec{\sigma}\vec{N}$$

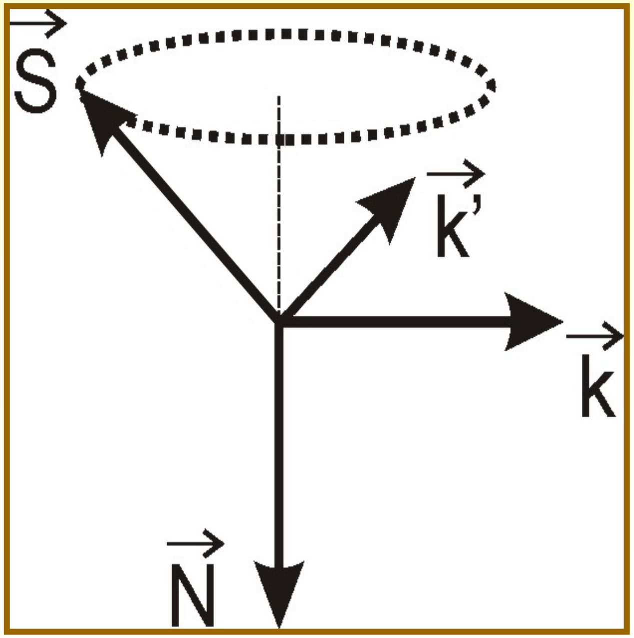
$$\hat{U}_{magn}(x) = -(\alpha_m(x) + i\delta_m(x))\vec{\sigma}\vec{N}$$

Effective potential energy determined by spin-orbit interaction

$$\hat{F}_{ssp-orb}(\vec{q}=\vec{\tau}) = B_s(\vec{\tau})\vec{\sigma}[\vec{n}\times\vec{\tau}]$$

$$\hat{U}_{ssp-orb} = -(\alpha_s + i\delta_s)\vec{\sigma}\vec{N}$$

Spin structure of $\hat{U}_s(x)$ is similar to the one of $\hat{U}_{magn}(x)$.



$$\vec{N} = [\vec{n}_x \times \vec{n}]$$

$$\alpha_s = -\frac{2\pi\hbar^2}{m\gamma d_y d_z}\frac{\partial N_{nuc}}{\partial x}B''$$

$$\delta_s = \frac{2\pi\hbar^2}{m\gamma d_y d_z}B'\frac{\partial N_{nuc}}{\partial x}$$

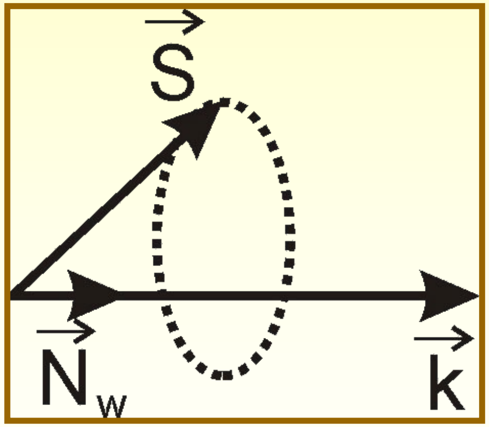
Effective potential energy determined by P-odd and T-even interactions

$$\hat{F}_w(\vec{q}) = (B_{we}(\vec{q}) + B_{wnuc}(\vec{q}))\vec{\sigma}\vec{N}_w$$

$$\hat{U}_w(x) = \hat{U}_{we}(x) + \hat{U}_{wnuc}(x) = -(\alpha_w(x) + i\delta_w(x))\vec{\sigma}\vec{N}_w$$

$$\alpha_w(x) = \alpha_{we}(x) + \alpha_{wnuc}(x)$$

$$\delta_w(x) = \delta_{we}(x) + \delta_{wnuc}(x)$$



$$\alpha_w(x) = \frac{2\pi\hbar^2}{m\gamma d_y d_z}(\tilde{B}'_{we}(0)N_e(x) + \tilde{B}'_{wnuc}(0)N_{nuc}(x))$$

$$\delta_w(x) = \frac{2\pi\hbar^2}{m\gamma d_y d_z}(\tilde{B}''_{we}(0)N_e(x) + \tilde{B}''_{wnuc}(0)N_{nuc}(x))$$

Effective potential energy determined by the electric dipole moment and other T-nonivariant interactions

$$\hat{F}_T(q) = (B_{EDM}(q) + B_{Te}(q) + B_{Tnuc}(q))\vec{\sigma}\vec{q}$$

$$\vec{q} = \vec{k}\,' - \vec{k}$$

$$\hat{U}_T(x) = \hat{U}_{EDM} + \hat{U}_{Te} + \hat{U}_{Tnuc} = -(\alpha_T(x) + i\delta_T(x))\vec{\sigma}\vec{N}_T$$

$$\hat{U}_{EDM}(x) = -(\alpha_{EDM}(x) + i\delta_{EDM}(x))\vec{\sigma}\vec{N}_T,\ \vec{N}_T = \vec{n}_x$$

$$\alpha_T(x) = \alpha_{EDM} + \alpha_{Te} + \alpha_{Tnuc}$$

$$\delta_T(x) = \delta_{EDM} + \delta_{Te} + \delta_{Tnuc}$$

$$\alpha_{Te(nuc)} = \frac{2\pi\hbar^2}{m\gamma d_y d_z}\tilde{B}''_{Te(nuc)}\frac{dN_{e(nuc)}(x)}{dx}$$

$$\delta_{Te(nuc)} = \frac{2\pi\hbar^2}{m\gamma d_y d_z}\tilde{B}'_{Te(nuc)}\frac{dN_{e(nuc)}(x)}{dx}$$

P and CP violating spin rotation in bent crystals

$$i\hbar \frac{\partial |\Psi(t)>}{\partial t} = \hat{U}_{eff} |\Psi(t)>$$

$$\vec{\xi} = \frac{<\Psi(t)|\vec{\sigma}|\Psi(t)>}{<\Psi(t)|\Psi(t)>}$$

P and CP violating spin rotation in bent crystals

$$\frac{d\vec{\xi}}{dt} = \left[\vec{\xi}\times\vec{\Omega}_{mso}\right] - \frac{2}{\hbar}(\delta_m(x)+\delta_{s0}(x))\{\vec{N}_m - \vec{\xi}(\vec{N}_m\vec{\xi})\} +$$

$$+\left[\vec{\xi}\times\vec{\Omega}_T\right] + \frac{2}{\hbar}(\delta_{EDM}(x)+\delta_{Te}(x)+\delta_{Tnuc}(x))\{\vec{N}_T - \vec{\xi}(\vec{N}_T\vec{\xi})\} +$$

$$+\left[\vec{\xi}\times\vec{\Omega}_w\right] - \frac{2}{\hbar}\delta_w\{\vec{n} - \vec{\xi}(\vec{n}\vec{\xi})\}.$$

$$\vec{\Omega}_{mso} = \vec{\Omega}_{MDM} + \vec{\Omega}_{so} = -\left(\frac{e(g-2)}{2mc}E_x(x) + \frac{2}{\hbar}\alpha_{so}(x)\right)\vec{N}_m,$$

$$\vec{\Omega}_T = \vec{\Omega}_{EDM} + \vec{\Omega}_{Ten} = \frac{2}{\hbar}(dE_x(x)+\alpha_{Te}(x)+\alpha_{Tnuc}(x))\vec{N}_T,$$

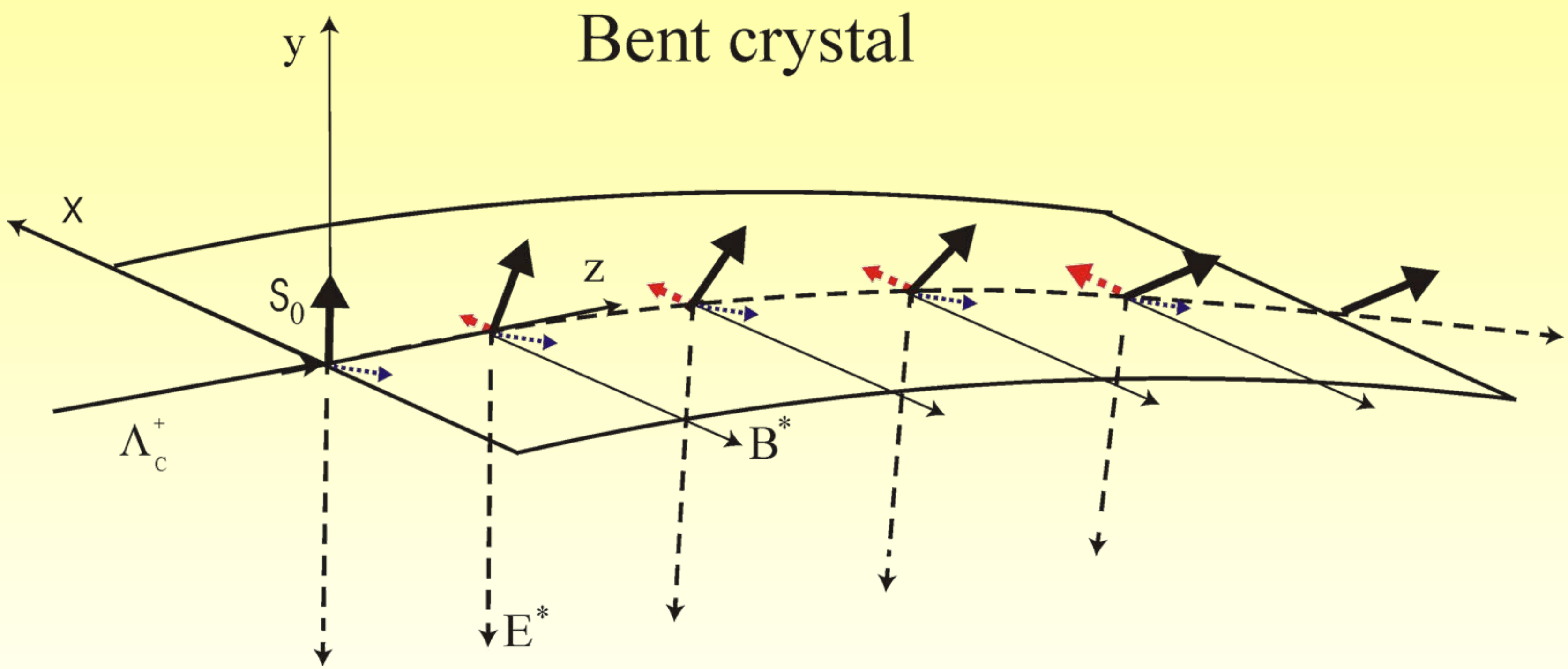
$$\vec{\Omega}_w = \frac{2}{\hbar}\alpha_w\vec{n}.$$

$$\vec{N}_m = [\vec{n}\times\vec{n}_x],$$

$$\vec{N}_T = \vec{n}_x,$$

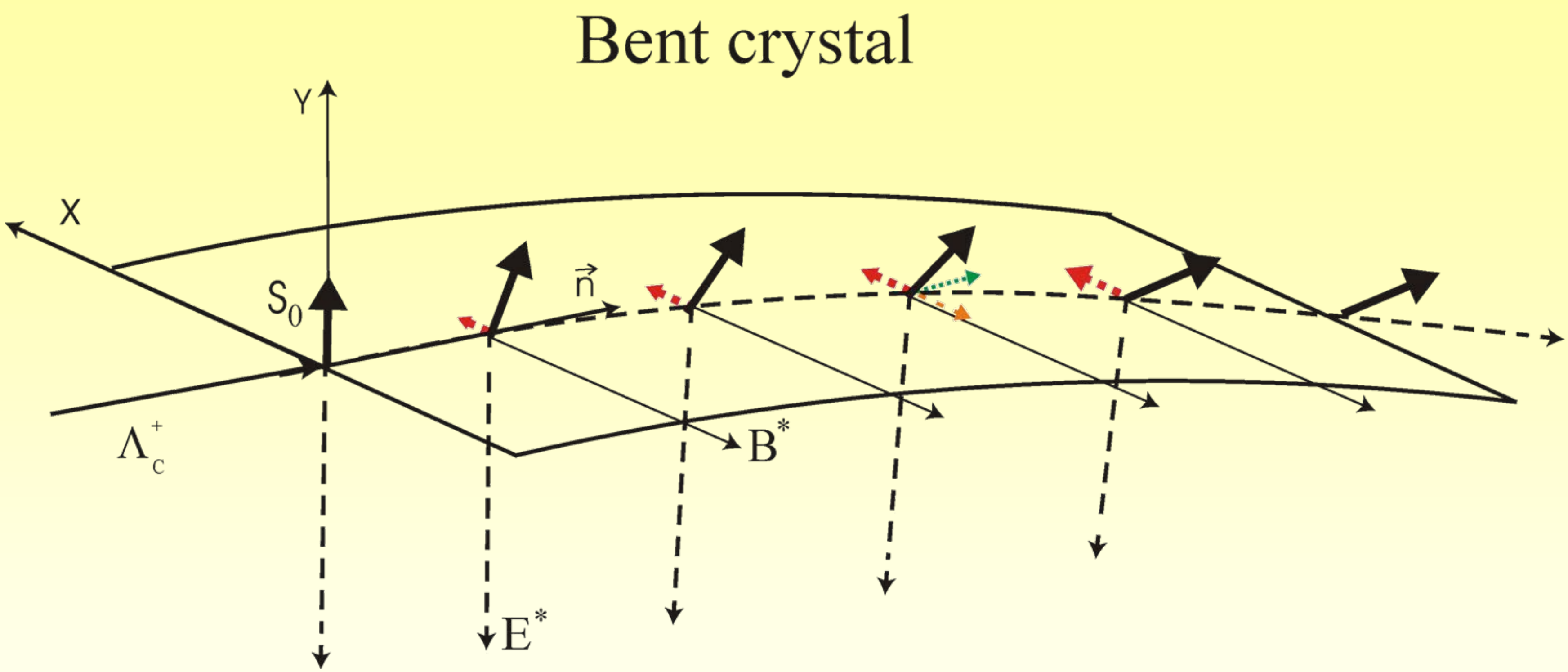
$$\vec{n} = \frac{\vec{k}}{k}$$

P and CP violating spin rotation in bent crystals



Behavior of the spin rotation caused by magnetic moment and T-reversal violation interactions. Black arrows represent spin rotation about effective magnetic field (about bent axis, direction $\vec{N}_m$), red arrows represent spin rotation about electric field (direction $\vec{N}_T$), purple arrows represent effect of magnetic spin rotation in direction $\vec{N}_m$. (Rotation owing to T-reversal violation and P-violating interactions, is not shown here for simplicity.)

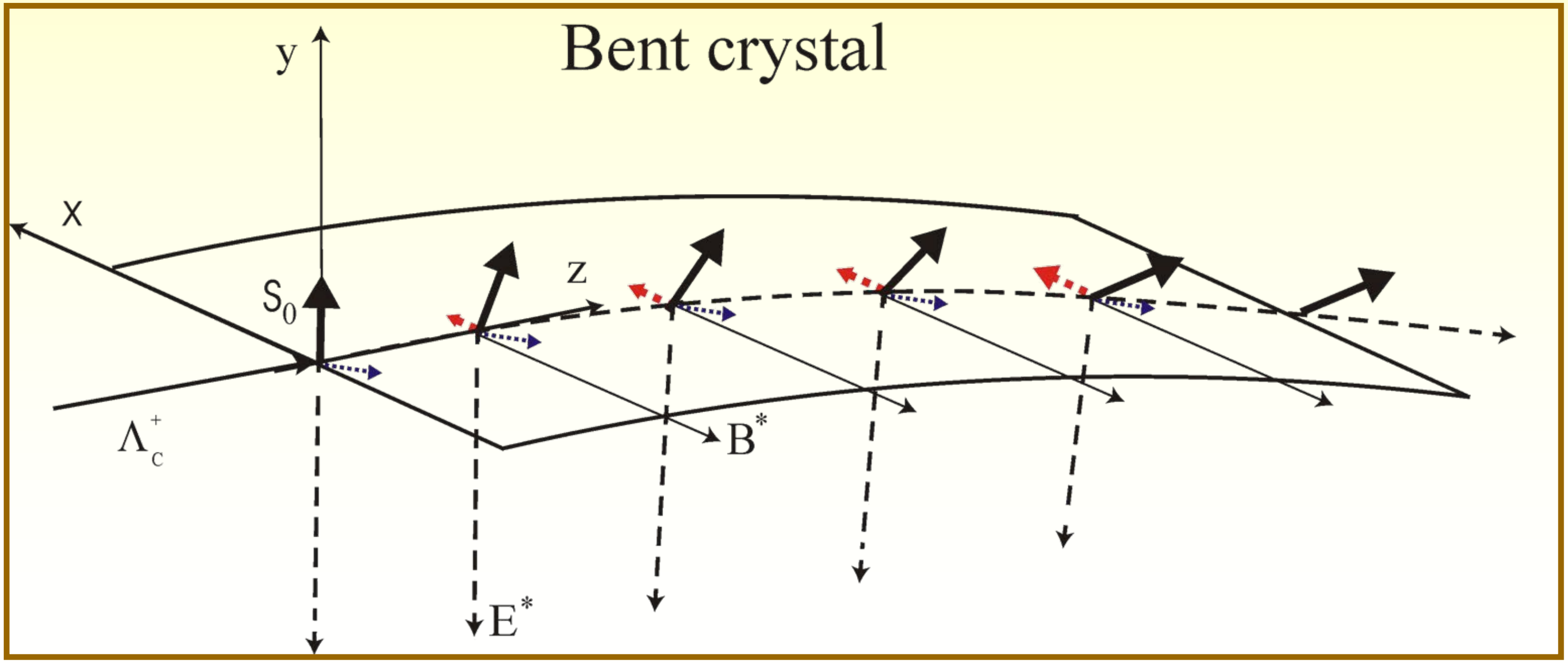
P and CP violating spin rotation in bent crystals



Behavior of the spin rotation caused by magnetic moment, T-reversal violation interactions (including EDM) and P-violation spin rotation about direction $\vec{n}$ and rotation in direction $\vec{n}$ (orange and green arrows). Rotation in direction $\vec{N}_m$ and direction $\vec{N}_T$ is not shown for simplicity.
It is obvious that P-odd T-even interactions can imitate EDM rotation.

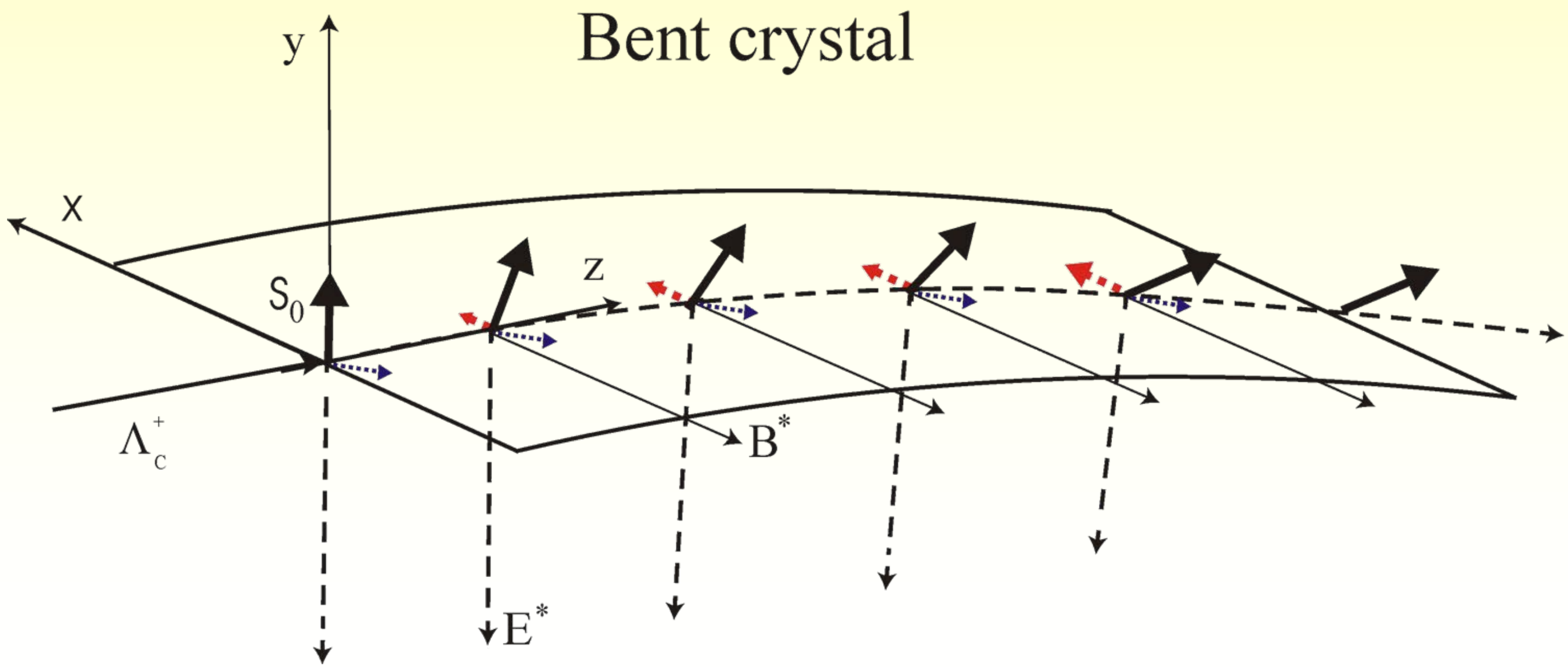
P and CP violating spin rotation in bent crystals

- Thus baryon spin rotates around three axes: effective magnetic field direction $\vec{N}_m \sim \left[\vec{n} \times \vec{E}\right]$, electric field direction $\vec{N}_T \sim \vec{E}$ and momentum direction $\vec{n}$.
- Contribution to rotations is determined by several types of interactions.
- Nonelastic processes in crystals result in the addition effects: terms proportional to δ lead to rotation of the polarization vector in directions of vectors $\vec{N}_m$, $\vec{N}_T$ and $\vec{n}$



Magnetic spin rotation and EDM measuring

The following estimation for the value δ_m can be obtained: $\delta_m \sim 10^8 - 10^9 \sec^{-1}$. The charm baryon EDM is predicted to be as large as $d \sim 10^{-17}$. Spin rotation frequency Ω_{EDM} determined by such charmed baryon EDM is $\Omega_{EDM} \sim 10^6 - 10^7 \sec^{-1}$. As a result, the nonelastic processes, which are caused by magnetic moment scattering, can imitate the EDM contribution.



P violating spin rotation in bent crystals

Precession frequency Ω_w is determined by the real part of the amplitude of baryon weak scattering by an electron (nucleus). This amplitude can be evaluated by Fermi theory for the energies, which are necessary for W and Z bosons production or smaller:

$$ReB: \quad G_F k = 10^{-5}\frac{1}{m_p^2}k = 10^{-5}\frac{\hbar}{m_p c}\frac{m\gamma}{m_p} = 10^{-5}\lambda_{cp}\frac{m\gamma}{m_p}$$

For different particle trajectories in a bent crystal the value of precession frequency Ω_w could vary in the range $\Omega_w \sim 10^3 - 10^4 \sec^{-1}$. Therefore, when a particle passes $10\,cm$ in a crystal, its spin undergoes additional rotation around momentum direction at angle $\vartheta_p \sim 10^{-6} - 10^{-7}\,rad$. The effect grows for a heavy baryon as a result of the mechanism similar to that of its EDM growth.

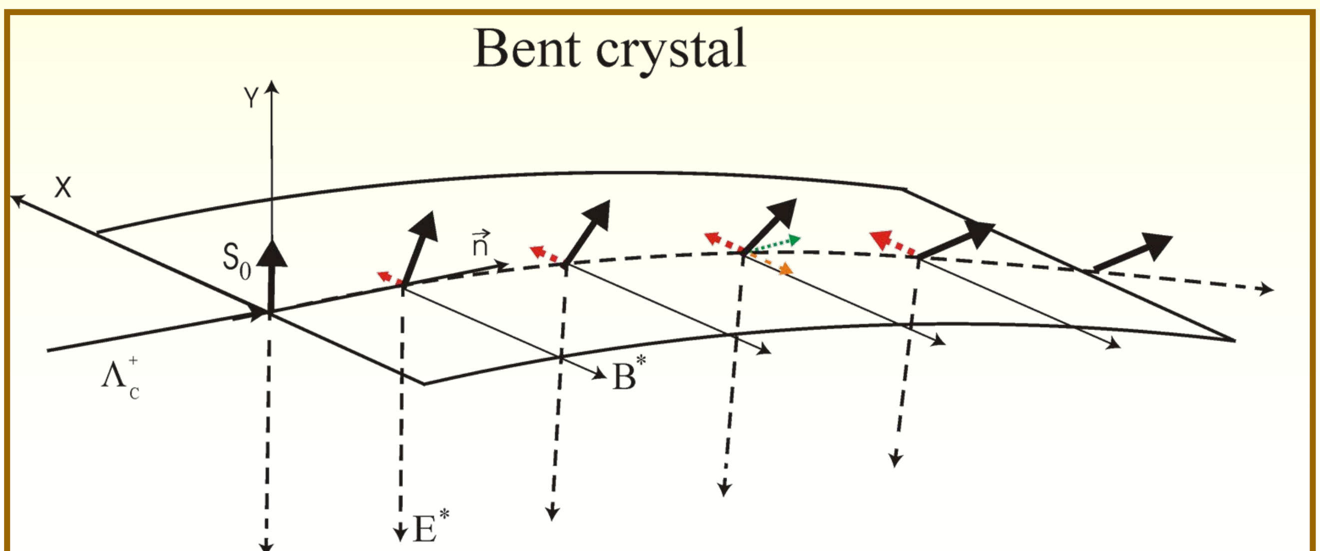
P violating spin rotation in bent crystals

Absorption caused by parity violating weak interaction also contributes to change in spin direction. This rotation is caused by the imaginary part of weak scattering amplitude and is proportional to the difference of total scattering cross-sections $\sigma\uparrow\uparrow$ and $\sigma\downarrow\uparrow$.

$$\sigma_{\uparrow\uparrow(\downarrow\uparrow)} = \int | f_{c(nuc)} + B_{0w} \pm B_w |^2 \, d\Omega$$

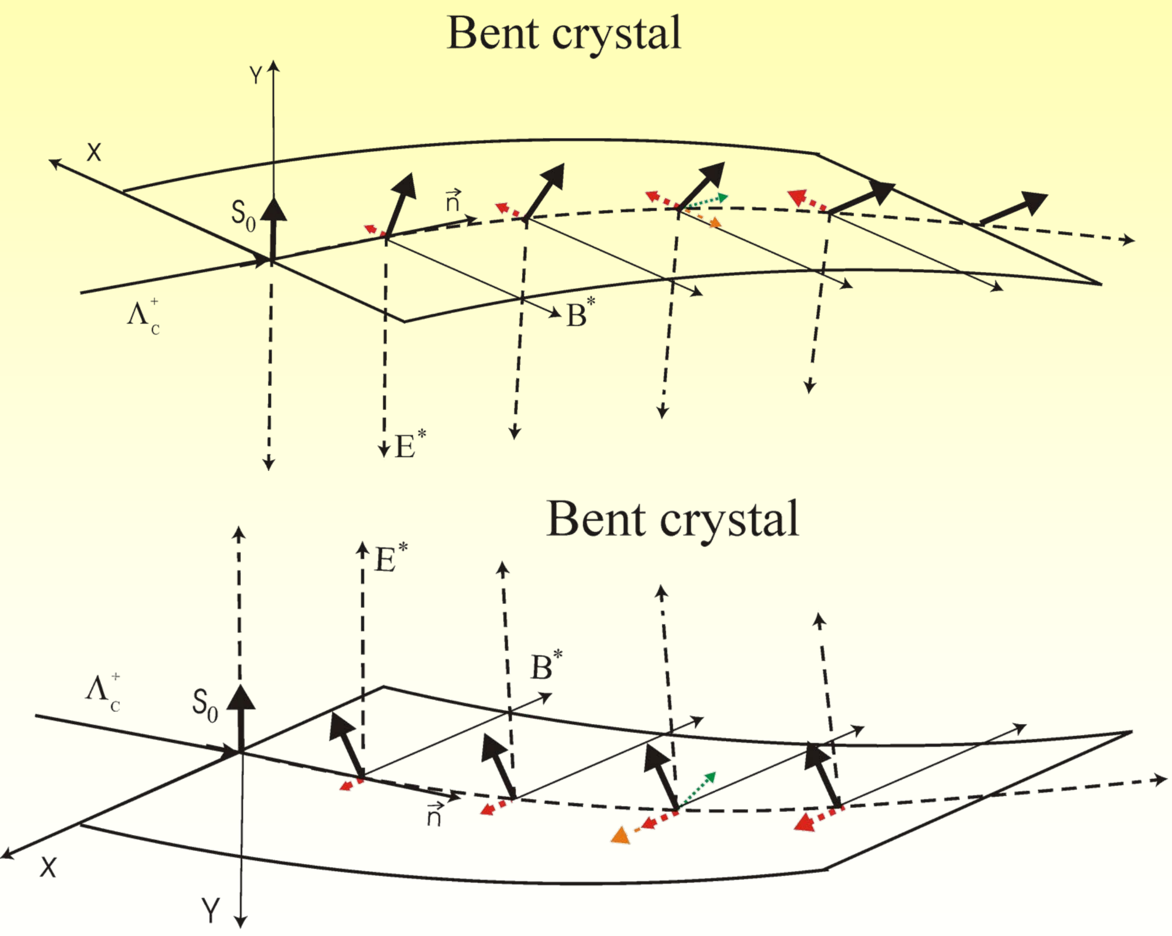
$$\sigma_{\uparrow\uparrow} - \sigma_{\downarrow\uparrow} = 2\int [(f_{c(nuc)} + B_{0w})B^* + (f_{c(nuc)} + B_{0w})^* B] d\Omega$$

When baryon trajectory passes in the area, where collisions with nuclei are important (this occurs in the vicinity of potential barrier for positively charged particles), the value $\delta_w \sim 10^6 - 10^7 \sec^{-1}$. Similar to the real part *ReB* for the case of heavy baryons the difference in cross-sections grows.



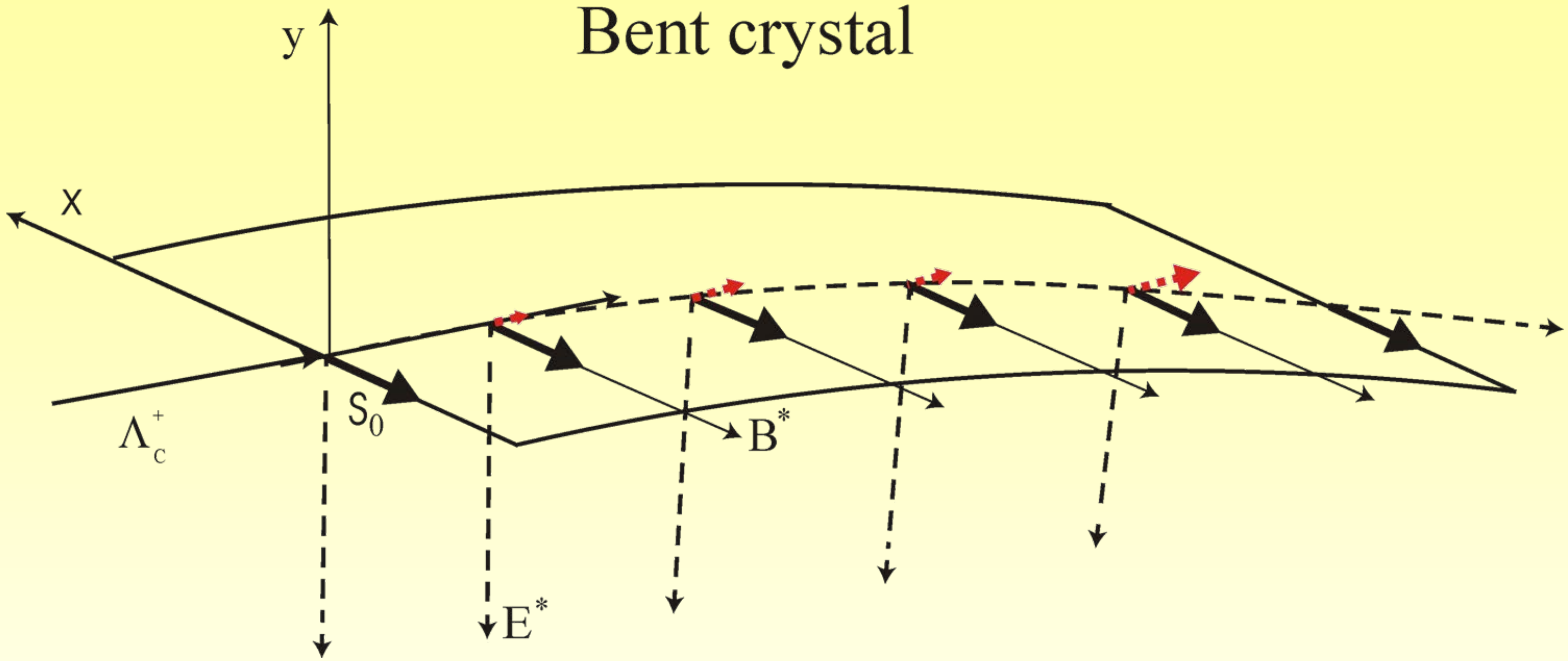
P and CP violating spin rotation in bent crystals

Separation of P and CP violating spin rotation



By turning the crystal 180◦ around the direction of incident baryon momentum One could observe that P_{odd} spin rotation does not change, while the sign of MDM and To_{dd} spin rotations does due to change of the electric field direction. Subtracting results of measurements for two opposite crystal positions one could obtain the angle of rotation, which does not depend on P_{odd} effect.

Separation of MDM and T-odd effects



Separation of the contributions caused by MDM and T-odd spin rotation is possible when comparing experimental results for two initial orientations of polarization vector $\vec{\xi}$. Namely: $\vec{\xi} \parallel \vec{N}_m$ and $\vec{\xi} \parallel \vec{N}_t$, i.e. the initial $\vec{\xi}$ is parallel to the bending axis of the crystal or $\vec{E}$.

In real situation rotating the crystal by 90^o so that direction of S_0 is parallel to B^* can be more convenient.

P and CP violating spin rotation in bent crystals

- Experiment on measuring EDM provides information on contributions of several T noninvariant interactions.Spin precession in bent crystals at LHC gives unique possibility for measurement CP violating and P violating interactions of charm, beauty and strange baryons

- Effect, which is caused by nonelastic processes, arises – spin rotation to the direction of the bend axis, the direction of the electric field and the direction of the particle momentum. This effect can imitate T noninvariant rotation.

Spin oscillations and possibility of quadrupole moment measurement, birefringence, P and CP noninvariant interactions for Ω^{-+} hyperons moving in a crystal

V.G. Baryshevsky, A.G. Shechtman, "Spin oscillations and possibility of quadrupole moment measurement for Ω^{-} hyperons moving in a crystal" NIM B83 (1993)

V.G.Baryshevsky, K.G.Batrakov, S.Cherkas, **The effect of spin oscillation of relativistic particles passing through substance and the possibility of constituent quark rescattering observation at Ω^{-+} hyperon–proton collision,** J. Phys. G: Nucl. Part. Phys. **24** (1998) 2049–2064.

V.G. Baryshevsky, Electromagnetic dipole, quadrupole moments and parity and time reversal invariance interactions of $\Omega\pm$ baryons in bent and straightcrystals,
arXiv:20040 . 01900v1[hep-ph] (2020)

Interactions contributing to the spin motion of a particle

Ω^- hyperon is an example of a particle with S > 1/2 .

Considering evolution of the spin ($S \geq 1$) of a particle we should take into account several addition interactions:

- interaction of the magnetic moment with an electric field of the crystal planes and axes;
- interaction of the quadrupole moment with an inhomogeneous electric field;
- interaction due to birefringence effect
- EDM interaction with a crystal electric field and P and CP-odd interactions

What effects arise from the above interactions?

When a particle with S=3/2 (S>1/2) moves in a straight and bent crystal the effects of spin rotation and vector-to-tensor (tensor-to-vector) polarization conversion appear due to the interactions W_Q, V_{bir}, $W_{p(cp)}$ along with the spin rotation caused by (g-2) and EDM.

Interaction of the particle quadrupole moment with an inhomogeneous electric field

For a particle with the quadrupole moment Q the energy of spin interaction with an inhomogeneous electric field E

$$\hat{W}_Q = \frac{1}{6}\hat{Q}_{ik}\frac{\partial E_i}{\partial x_k}$$

, where

$$\hat{Q}_{ik} = \frac{3Q}{2S(2S-1)}\left(\hat{S}_{ik} - \frac{2}{3}S(S+1)\delta_{ik}\right)$$

is the quadrupole interaction operator of the particle, Q is the quadrupole moment, S is the value of the particle spin, $\hat{S}_{ik} = \hat{S}_i\hat{S}_k + \hat{S}_k\hat{S}_i$ is the spin operator.

The possibility of quadrupole moment measurement of hyperons moving in crystal

The relativistic equation of spin motion in this case has the following form (EDM, P and CP odd interaction terms is not written):

$$\frac{d\hat{I}_i}{dt} = \varepsilon_{ijk}\left(\Omega_j \hat{I}_k + \frac{1}{3} e\varphi_{il}\hat{Q}_{kl}\right)$$

Ω_j is a component of the vector:

$$\vec{\Omega} = \left[\frac{1}{2}(g-2)\gamma + \frac{\gamma}{(\gamma+1)}\right] v^2 \vec{\Omega}_0 \, , \; \vec{\Omega}_0 = -\left(\frac{e}{m}\right)\left(\frac{\gamma}{(\gamma^2-1)}\right)\left(\vec{E}\times\vec{\upsilon}\right), \quad \varphi_{ik} = \frac{d^2U}{dx_i dx_k}$$

$$\frac{d\hat{I}_z}{dt} = \Omega_x \hat{I}_y - \Omega_y \hat{I}_x + \frac{\varphi_{xx} eQ}{2I(2I-1)} \hat{I}_{xy}$$

$$\frac{d\hat{I}_y}{dt} = \Omega_z \hat{I}_x - \Omega_x \hat{I}_z + \frac{\varphi_{xx} eQ}{2I(2I-1)} \hat{I}_{zx}$$

$$\frac{d\hat{I}_x}{dt} = \Omega_x \hat{I}_z - \Omega_z \hat{I}_y$$

The possibility of quadrupole moment measurement of hyperons moving in crystal

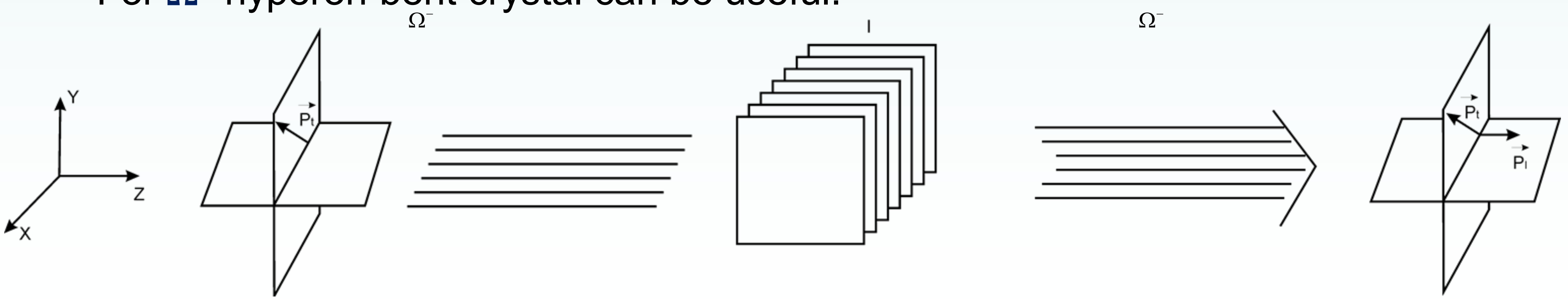
When a particle with quadrupole moment moves in a straight or bent crystal, not only spin oscillations and rotation appear, but also the transitions between tensor P_{ik} and vector $\vec{P}$ polarizations of the particle.

In experiments for an Ω^- hyperon beam with the Lorentz factor $\gamma = 100$, intensity $N \approx 10^6$ particles/s and the beam divergence angle $\theta_{div} < 0.4\,mrad$ it is possible to measure the quadrupole moment Q of an Ω^- hyperon on the level $10^{-27}\ cm^2$ in a tungsten crystal of length $l = 20cm$. Time for measurement approximately 250 hour.

For the realization of this measuring procedure it is quite sufficient to have a crystal with a mosaic spread χ < 0.4 mrad or a set of crystals arranged with an exactness of not more than χ < 0.4 mrad relative to the chosen family of crystallographic planes.

So such the measurement possibilites of the Ω^- hyperon quadrupole moment study requires neither a high quality crystal nor a monochromatic hyperon beam.

For Ω^+ hyperon bent crystal can be useful.



Angular asymmetry and polarization of the scattered particles

Elastic scattering angular distribution of a particle with spin 1/2

Elastic scattering of a particle with spin 1/2

$$\hat{F}(\vec{q}) = A(\vec{q}) + B(\vec{q})\vec{\sigma}\vec{N} + B_{0w}(\vec{q}) + B_w(\vec{q})\vec{\sigma}\vec{N}_w + B_T\vec{\sigma}\vec{N}_T$$

$$\vec{q} = \vec{k}' - \vec{k}, \quad \vec{n} = \frac{\vec{k}}{k}, \quad \vec{N}_w = \frac{\vec{k}' + \vec{k}}{|\vec{k}' + \vec{k}|}, \quad \vec{N} = \frac{\left[\vec{k} \times \vec{k}'\right]}{\left\|\left[\vec{k} \times \vec{k}''\right]\right\|}, \quad \vec{N}_T = \frac{\vec{q}}{q}.$$

$$\frac{d\sigma}{d\Omega} = tr\rho\hat{F}^{+}(\vec{q})\hat{F}(\vec{q})$$

$$\vec{\xi} = \frac{tr\rho F^{+}\vec{\sigma}F}{tr\rho F^{+}F} = \frac{tr\rho F^{+}\sigma F}{\frac{d\sigma}{d\Omega}}$$

$$\vec{\xi} = \vec{\xi}_{so} + \vec{\xi}_w + \vec{\xi}_T$$

Scattering of a particle with spin 1/2 in crystals

$$\vec{\xi}_{so} = \left\{ (|\overline{A}|^2 - |B|^2)\vec{\xi}_0 + 2Im(\overline{A}B^*)[\vec{N}\vec{\xi}_0] + 2|B|^2\ \vec{N}(\vec{N}\vec{\xi}_0) + 2\vec{N}Re(\overline{A}B^*) \right\} \cdot \left(\frac{d\sigma}{d\Omega} \right)^{-1}$$

$$\vec{\xi}_w = \left\{ (|\overline{A}|^2 - |B_w|^2)\vec{\xi}_0 + 2Im(\overline{A}B_w^*)[\vec{N}_w\vec{\xi}_0] + 2|B_w|^2\ \vec{N}_w(\vec{N}_w\vec{\xi}_0) + 2\vec{N}_w Re(\overline{A}B_w^*) \right\} \cdot \left(\frac{d\sigma}{d\Omega} \right)^{-1}$$

$$\vec{\xi}_T = \left\{ (|\overline{A}|^2 - |B_T|^2)\vec{\xi}_0 + 2Im(\overline{A}B_T^*)[\vec{N}_T\vec{\xi}_0] + 2|B_T|^2\ \vec{N}_T(\vec{N}_T\vec{\xi}_0) + 2\vec{N}_T Re(\overline{A}B_T^*) \right\} \cdot \left(\frac{d\sigma}{d\Omega} \right)^{-1}$$

$$\frac{d\sigma}{d\Omega} = tr\rho F^+F = |\overline{A}|^2 + |B|^2 + |B_w|^2 + |B_T|^2 + 2Re(\overline{A}B^*)\vec{N}\vec{\xi}_0 + + 2Re(\overline{A}B_w^*)\vec{N}_w\vec{\xi}_0 + 2Re(\overline{A}B_T^*)\vec{N}_T\vec{\xi}_0$$

Both rotation around $\vec{N}, \vec{N}_W, \vec{N}_T$ and components in directions of $\vec{N}, \vec{N}_W, \vec{N}_T$ appear.

Scattering of particles in crystals

Scattering of particles on crystal axes (planes) gives unique possibility for measurement of EDM and constants determining T_{odd}, P_{odd} (CP) violating interactions and P_{odd}, T_{even} interactions of negative, positive and neutral baryons with electrons and nucleus (nucleons).

V.G. Baryshesky, Electromagnetic dipole moment and time reversal invariance violating interactions of high energy short-lived particles in bent and straight crystals, Phys.Rev Accelerators and Beams 22,081004 (2019)

V.G. Baryshesky, Electromagnetic dipole moments and time reversal violating interactions for high energy charged baryons in bent crystals, Eur.Phys.J.C (2019) 79:350.

Spin depolarization of particles in crystals

Baryshevsky V.G., Spin rotation and depolarization of relativistic particles traveling through a crystal, Nucl. Instrum. Methods B, 44, 3 (1990), 266-272.

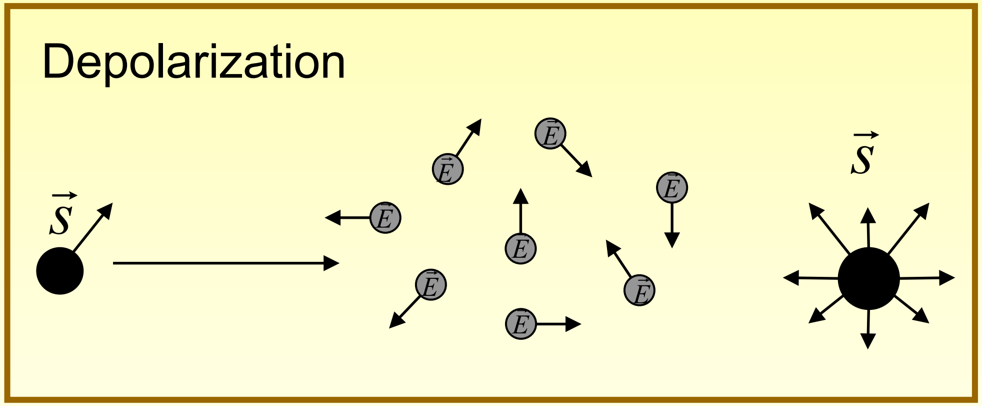
V.G. Baryshevsky, High-Energy Nuclear Optics of Polarized Particles, World Scientific, 2012.

Baryshevsky V.G. Spin rotation and depolarization of high-energy particles in crystals at Hadron Collider (LHC) and Future Circular Collider (FCC) energies and the possibility to measure the anomalous magnetic moments of short-lived particles, arXiv:1504.06702 [hep-ph].

V.G. Baryshevsky, Depolarization of high-energy neutral particles in crystals and the possibility to measure anomalous magnetic moments of short-lived hyperons, arXiv:1608.06815v1 [hep-ph], 2016.

Spin depolarization in amorphous target

In amorphous target electric fields possess various values and directions.

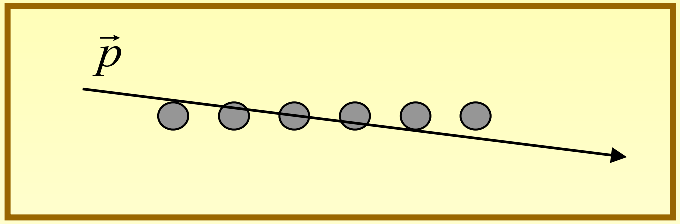


The degree of depolarization is small : less than 1% on nuclear absorption length.

* Lyubosihtz, V.L., (1980b). Depolarization of fast particles travelling through matter, *Sov. J. Nucl. Phys.* **32**, 3, pp. 362–365.

Spin depolarization in crystals

Mean-square angle of multiple scattering $\left\langle \vartheta_p^2 \right\rangle_{cr}$ becomes much bigger in crystals



$$\zeta_{\parallel} = \zeta_z(0) e^{-\frac{1}{2}\left\langle \vartheta_{s1}^2 \right\rangle_{cr} l}$$

$$\left\langle \vartheta_{s1}^2 \right\rangle_{cr} = \left(\frac{g-2}{2} \right)^2 \gamma^2 \left\langle \vartheta_{p1}^2 \right\rangle_{cr}$$

$\left\langle \vartheta_{p1}^2 \right\rangle_{cr} \sim \frac{1}{\gamma^2}$

$\left\langle \vartheta_{s1}^2 \right\rangle_{cr}$

Mean-square angle of multiple scattering per unit length
Does not depend on γ

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* Baryshevsky V.G., Spin rotation and depolarization of relativistic particles traveling through a crystal, Nucl. Instrum. Methods B, 44, 3 (1990), 266-272.

Spin depolarization in crystals

Depolarization in crystal is increasing up to dozens percent on 1 cm.

$$\left|g-2\right| = \sqrt{\frac{8}{\gamma^2 \left\langle \vartheta_p^2(l) \right\rangle_{ch}} \ln \frac{\left\langle \zeta_z(0) \right\rangle}{\left\langle \zeta_z(l) \right\rangle}}$$

Enables measurement of magnetic moment of negative beauty baryons and neutral baryons.

* Baryshevsky V.G., Spin rotation and depolarization of relativistic particles traveling through a crystal, Nucl. Instrum. Methods B, 44, 3 (1990), 266-272.

•Baryshevsky V.G. Spin rotation and depolarization of high-energy particles in crystals at Hadron Collider (LHC) and Future Circular Collider (FCC) energies and the possibility to measure the anomalous magnetic moments of short-lived particles, arXiv:1504.06702 [hep-ph]

•. V.G. Baryshevsky, Depolarization of high-energy neutral particles in crystals and the possibility to measure anomalous magnetic moments of short-lived hyperons, arXiv:1608.06815v1 [hep-ph], 2016.

Conclusion

High-energy particles channeling and scattering on crystal axes (planes) gives unique possibility for measurement of MDM, EDM and constants determining T_{odd}, P_{odd} (CP) violating interactions and P_{odd}, T_{even} interactions of negative, positive and neutral baryons with electrons and nucleus (nucleons).

V.G. Baryshevsky, High-Energy Nuclear Optics of Polarized Particles, World Scientific, 2012.

V.G. Baryshesky, Electromagnetic dipole moment and time reversal invariance violating interactions of high energy short-lived particles in bent and straight crystals,

Phys.Rev Accelerators and Beams 22,081004 (2019)

V.G. Baryshesky, Electromagnetic dipole moments and time reversal violating interactions for high energy charged baryons in bent crystals, Eur.Phys.J.C (2019) 79:350.

Thank you for your attention