

CHANNELING 2016

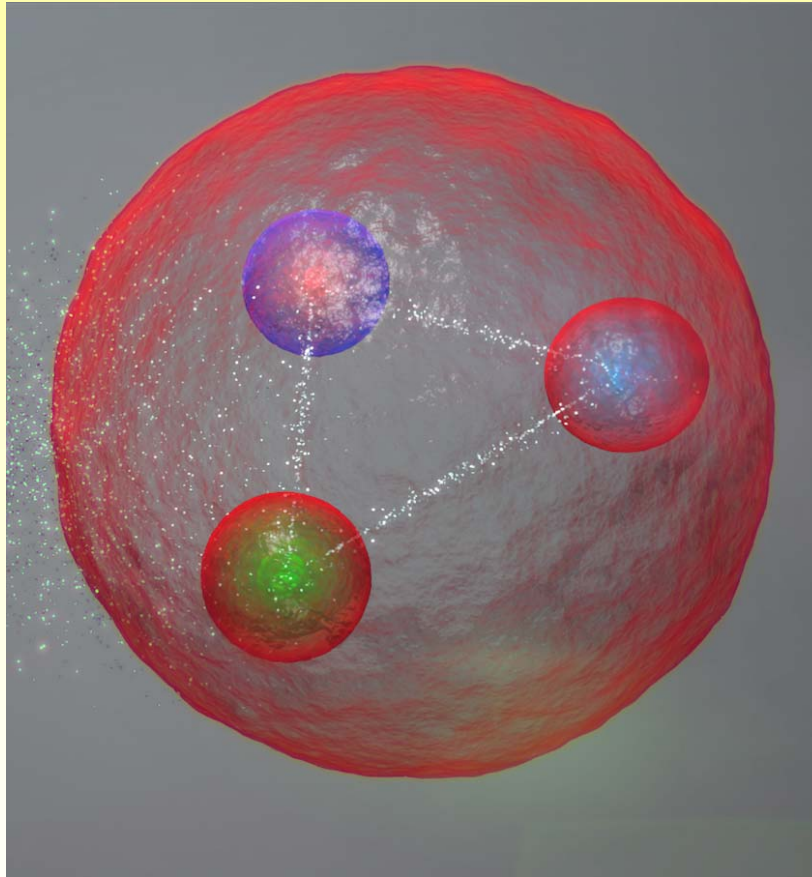
The phenomena of spin rotation and depolarization of high-energy particles in bent and straight crystals at Hadron Collider (LHC) and Future Circular Collider (FCC) energies and the possibility to measure the anomalous magnetic moments of short-lived particles (charm and beauty baryons) and quadrupole moment of Ω -hyperon

V.G. Baryshevsky



**Institute for Nuclear Problems,
Belarusian State University, Minsk, Belarus**

Magnetic moment - important characteristic of the nuclei and elementary particles



Picture of baryons according to CERN

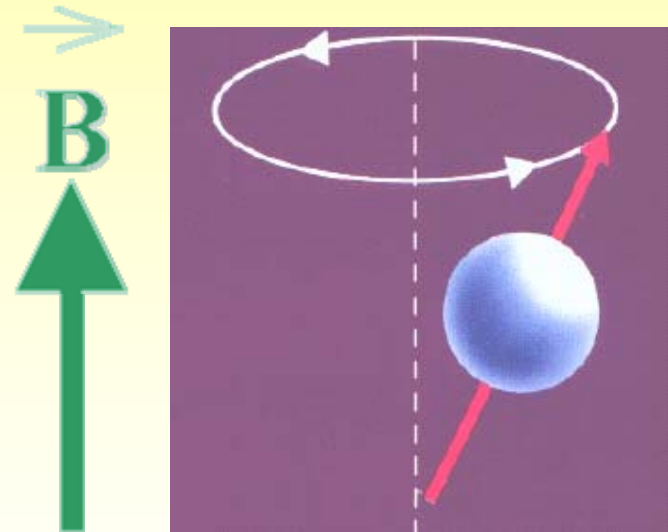
Magnetic moment - important characteristic of the nuclei and elementary particles

$$\mu = \frac{e\hbar}{2mc} gS = \mu_B gS \quad g - g \text{ factor} \quad \mu_B = \frac{e\hbar}{2mc}$$

Magnetic moment (spin) precesses in magnetic field .
Precession frequency

$$\Omega = \gamma_S B = \frac{g \mu_B B}{\hbar}$$

$$\gamma_S = g \mu_B = \frac{\mu}{S\hbar} - \text{gyromagnetic ratio}$$



So we can measure the magnetic moment

Majority of the elementary particles is unstable!

Characteristics

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

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

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

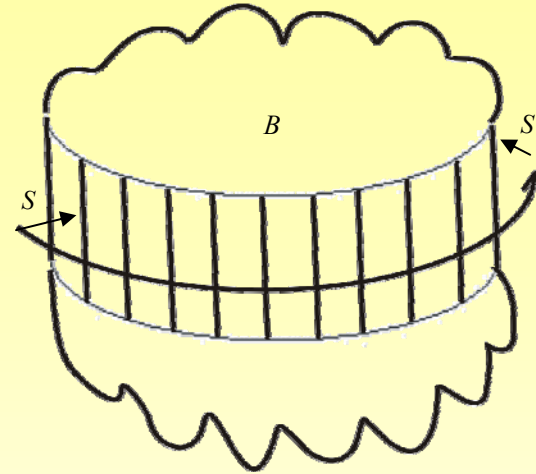
$$\Xi_b^- : \tau = 1.56 \cdot 10^{-12} s; \quad m = 5791 MeV; \quad l_d = 44.7 cm.$$

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

How can we measure μ for moving particle?

Nonrelativistic particle:

$$\mathcal{G} = \Omega t = \Omega \frac{L}{c} = \frac{2\mu B}{\hbar} \frac{L}{c} = \frac{2\mu B}{\hbar} \tau;$$



For example, for particle with $\mu = \mu_B$:

$$\mu = 5 \cdot 10^{-24}, B = 10^5, \tau = 10^{-12} \Rightarrow \mathcal{G} \simeq \frac{10^{-23}}{10^{-27}} B \tau = 10^4 \cdot 10^5 \cdot 10^{-12} = 10^{-3} \text{ rad}$$

Relativity: if $c\tau \leq 300\mu$ then for $\gamma = 10^3 \rightarrow L = c\tau\gamma = 30 \text{ cm}$.

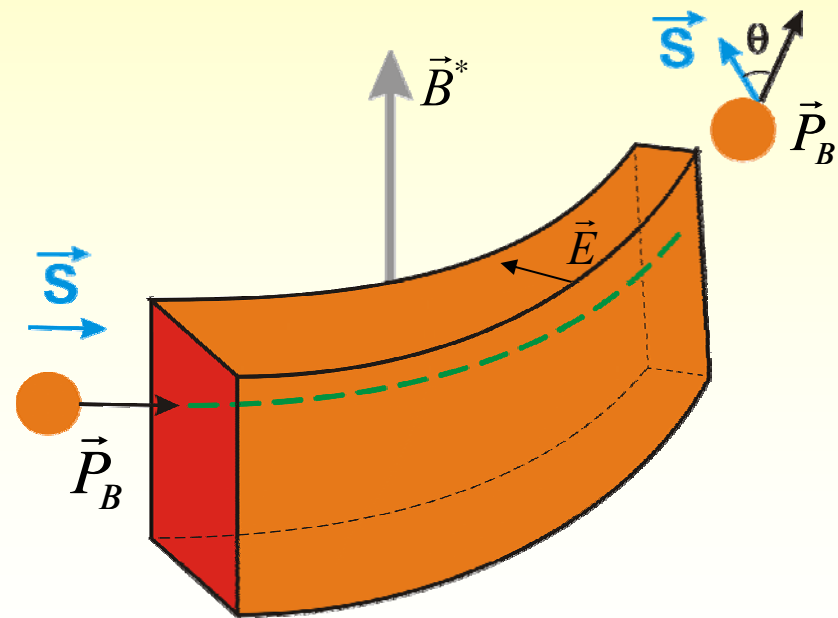
But creation of the magnetic field $B \sim 10^5$ in a big volume is a very complicated task.

If the pass length is small how can we measure μ ?

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

* 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]

* Baryshevsky V.G., 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.



Polarized particles spin rotation

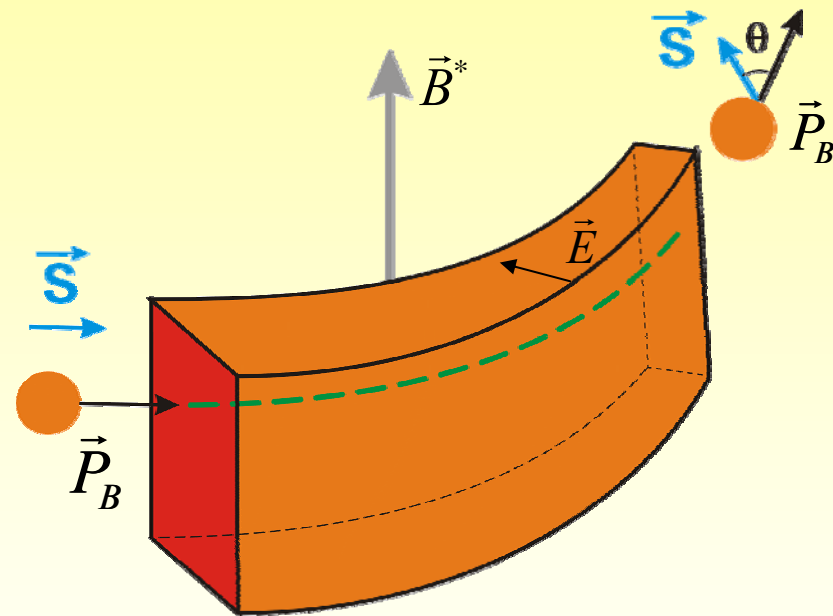
In particle rest frame

$$B^* \rightarrow \gamma E$$

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

In laboratory frame

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

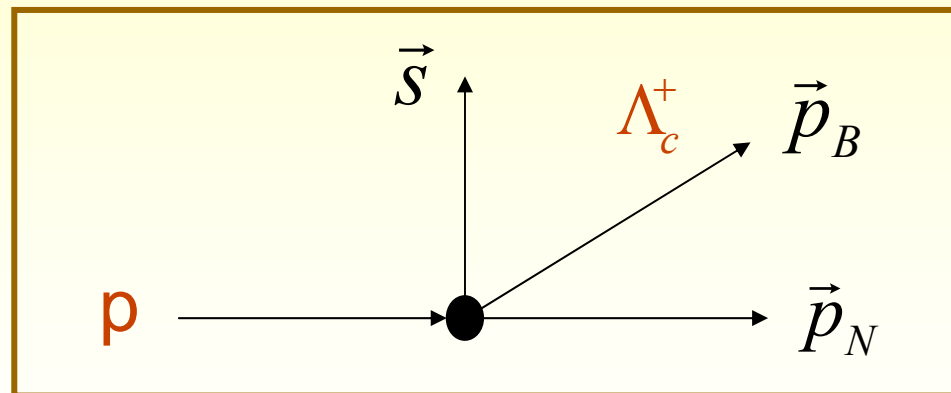


Polarization of Charm and Beauty baryons

Polarized particles are required for magnetic moment measurement.

Amplitude of reaction: $f = f_0 + \vec{s} [\vec{p}_N \times \vec{p}_B]$

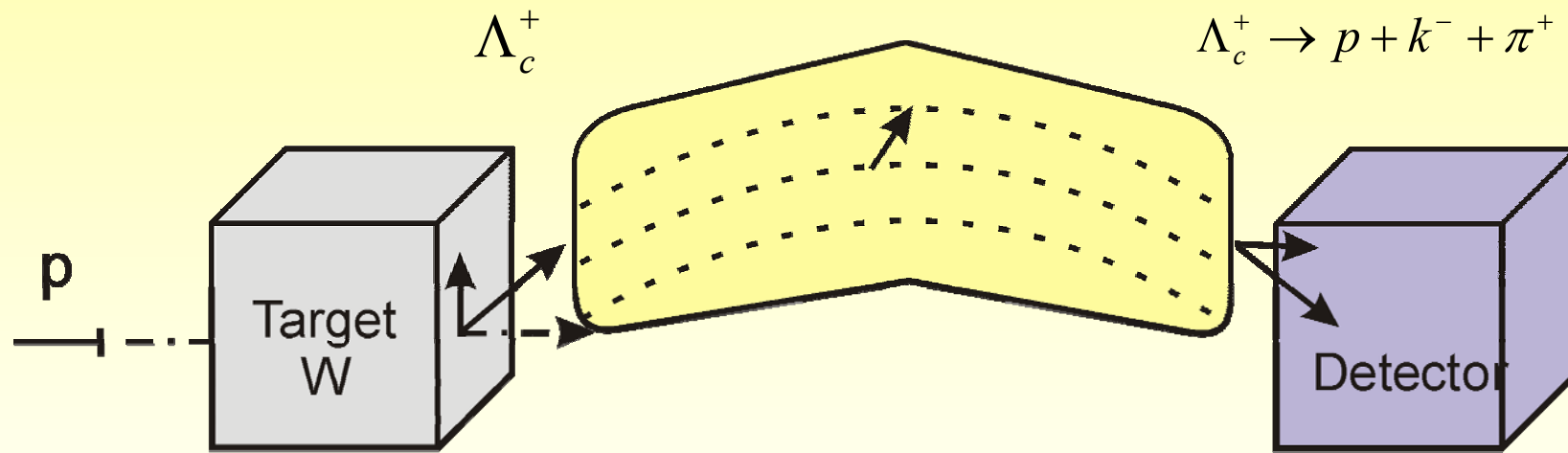
Particles in reactions are born polarized.



Production plane formed by \vec{p}_N and \vec{p}_B

How to measure orientation?

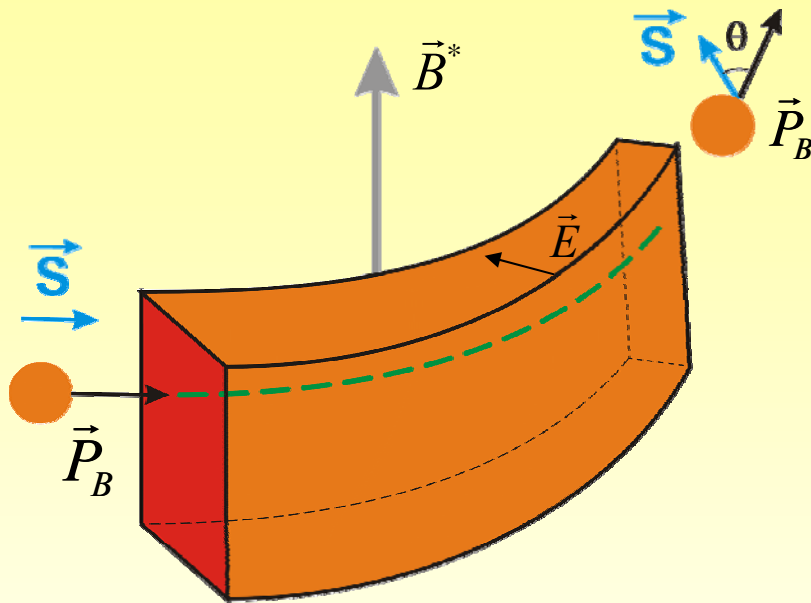
As a result of parity violation in weak decays asymmetry relative to baryon production plane exists. The momentum direction of decay products follows the spin direction.



$$\Lambda_c^+ \rightarrow p + k^- + \pi^+ \rightarrow k^0 + p + \pi^+ + \pi^- \rightarrow \Lambda^0 + \pi^+ + \pi^+ + \pi^-$$

$$\Lambda_c^+ \rightarrow \Lambda^+ + \pi^+$$

First experiment for measurement (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

"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.

Polarized particles spin rotation

Rotation angle for $L=1$ cm :

$$g_{s1} = \frac{g-2}{2} \frac{\gamma}{R}$$

and

$$g_{s1}^{\max} = \frac{g-2}{2} \frac{U'_{\max}}{mc^2}$$

where U is the channel potential energy.

Does not depend on energy!

Polarized particles spin rotation

$$\mathcal{G}_{s1} = \frac{g-2}{2} \frac{U'_{\max}}{mc^2} \frac{R_{cr}}{R} = \mathcal{G}_{s1}^{\max} \frac{R_{cr}}{R}$$

For constant ratio $\frac{R_{cr}}{R}$ angle \mathcal{G}_{s1}
does not depend on energy.

According to Biryukov* for Si

$$U' = 5 \text{ GeV} / \text{cm}$$

$$\mathcal{G}_s = \mathcal{G}_{s1} L \quad L \leq L_D \quad \text{- dechanneling length}$$

Hence, using the evaluation of g-factor for Λ_c^+

$$g \simeq 1,36 - 2,45$$

For $L = 10 \text{ cm}$, $\mathcal{G}_s \simeq 1 \text{ rad}$, if $\frac{R_{cr}}{R} = \frac{1}{3}$

* Biryukov V.M., Chesnokov Yu.A., Kotov V.I., Crystal channeling and its application at high-energy accelerators, Springer, Berlin, 1997

Polarized particles spin rotation

With the growth of energy $\mathcal{G}_L \sim \frac{1}{\sqrt{\gamma}}$ everything complicates,

but during the particle production $\delta\mathcal{G} \sim \frac{1}{\gamma}$

Therefore trapped particles part is increasing: $\frac{\mathcal{G}_L}{\delta\mathcal{G}} \sim \sqrt{\gamma}$

With the growth of energy production cross section σ_r increases, but how?

According to J. Appel and J. Russ

$$\sigma_r \sim \gamma$$

*J. Appel, in: Proc. of the CHARM 2000 Workshop, FERMILAB-CONF-94/190, Fermilab, June 7–9, 1994, Batavia, IL, p. 4.

*J. Russ, in: Proc. of the CHARM 2000 Workshop, FERMILAB-CONF-94/190, Fermilab, June 7–9, 1994, Batavia, IL, p. 111.

Polarized particles spin rotation

But the latest experiments with Λ_c^+ at 7 TeV had shown that the increase is weaker.

LHCb Collaboration, R. Aaij, et al., J. High Energy Phys. 12 (2013) 090.

LHCb Collaboration, R. Aaij, et al., LANL e-print, arXiv:1302.2864v1 [hep-ex].

LHCb Collaboration, R. Aaij, et al., Nucl. Phys. B 871 (2013) 1.

Therefore let us assume $\sigma_r \sim \alpha(\gamma)\gamma$; with $\alpha(\gamma) < 1$.

As a result, the number of particles N that experienced channeling is

$$N \sim \alpha(\gamma)\gamma^{\frac{3}{2}}$$

The running time

$$T \sim \frac{1}{\sqrt{N}} = \frac{1}{\sqrt{\alpha(\gamma)\gamma^{\frac{3}{2}}}}$$

Running time

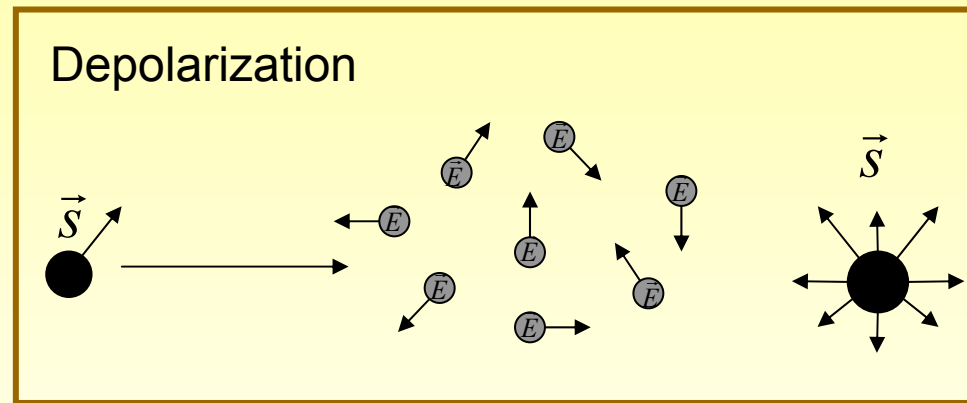
For 7Tev LHC energies the running time required for measuring the magnetic moment of short lived particles is 2-16 hours.

* Baryshevsky V.G., 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.

That works well for positively charged particles, but what should be done with negatively charged ones?

Spin depolarization in amorphous target

In amorphous target electric fields possess various values and directions.

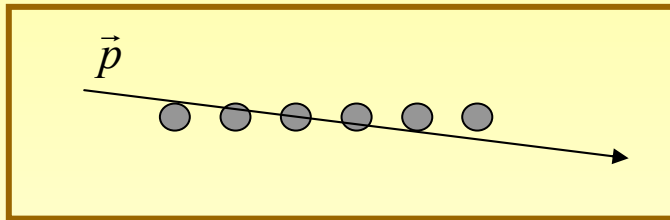


The degree of depolarization is small : less than 1% on nuclear absorption length.

* 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 $\langle g_p^2 \rangle_{cr}$ becomes much bigger in crystals



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

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

$$\langle g_{p1}^2 \rangle_{cr} \sim \frac{1}{\gamma^2}$$

$$\langle g_{s1}^2 \rangle_{cr}$$

Mean-square angle of multiple scattering per unit length

Does not depend on γ

* 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.

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

Enables measurement of magnetic moment of negative beauty 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].

Neutral baryons spin depolarization in crystals

The scattering cross section on neutral baryons in crystal can be analyzed using the following expression for differential cross section

$$\frac{d\sigma_{cr}}{d\Omega} = \frac{d\sigma}{d\Omega} \frac{1}{N} \left| \sum_{n=1}^N \exp(i \vec{q} \vec{r}_n) \right|^2$$

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

$f(\vec{q})$ the amplitude of elastic scattering of the spin \vec{S} particle by the nucleus

ρ spin density matrix of the particle

According to Dyumin, Baryshevsky * for neutrons with energies up to several MeV the cross section σ_{cr} increases by a factor ten compared with σ in amorphous matter.

* A.N. Dyumin, I.Ya. Korenblim, V.A. Ruban, B.B. Tokarev, Electromagnetic (Schwinger) scattering of fast neutrons in crystals, JETP Lett. 31, 7 (1980) 384.

* V.G. Baryshevsky, A.M. Zaitseva, Izv. VUZov, Fizika, 3 (1985) 103–104.

Neutral baryons spin depolarization in crystals

The degree of longitudinal (transverse) depolarization of neutral baryons in crystal :

$$\eta_{\parallel(\perp)}^{cr}(\mathcal{G}_0) \simeq \frac{\sigma_{cr}(\mathcal{G}_0)}{\sigma} \eta_{\parallel(\perp)am}$$

$\sigma_{cr}(\mathcal{G}_0)$ the total scattering cross section in crystal due to spin-orbit interaction (Schwinger scattering),

σ the total spin-orbital Schwinger scattering cross section by nucleus in the amorphous medium.

* V.G. Baryshevsky, Nucl. Instrum. Methods B, 44, 266-272, 1990.

* 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.

Neutral baryons spin depolarization in crystals

When energy grows, σ_{cr} grows. As a result the degree of depolarization of hyperons at LHC and FCC energies reaches tens percent at several cm length.

Running time for charm baryons 2-20 hours.

Running time for more heavy bottom baryons – tens of hours (up to 200 hours).

**Short-lived particle interaction with crystal
containing polarized nucleus**

**Opportunities for measuring spin-dependent
interactions of short lived elementary particles
with nucleus and measurement of particle
polarization**

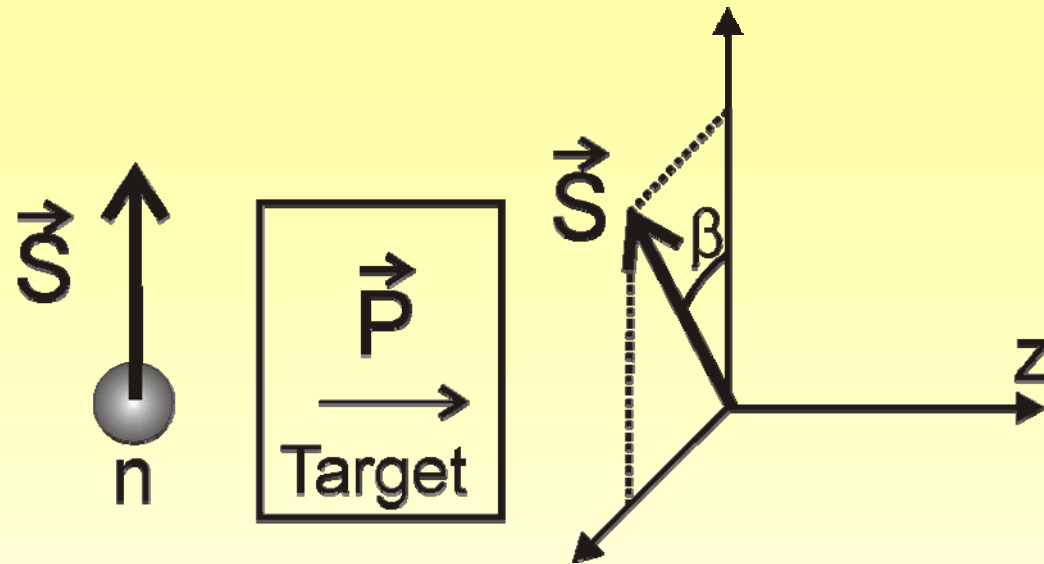
Spin rotation and dichroism in the polarized target

The elastic scattering amplitude at zero angle depends on the spin operators of an incident particle and that of a target, and also on the momentum of the incident particle.

$$f(0) = A + A_1(\vec{S} \cdot \vec{P}) + A_2(\vec{S} \cdot \vec{n})(\vec{n} \cdot \vec{P})$$

Where \vec{P} is polarization vector of the target nuclei, \vec{n} - unit vector in momentum direction.

Spin rotation and dichroism in the polarized target



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

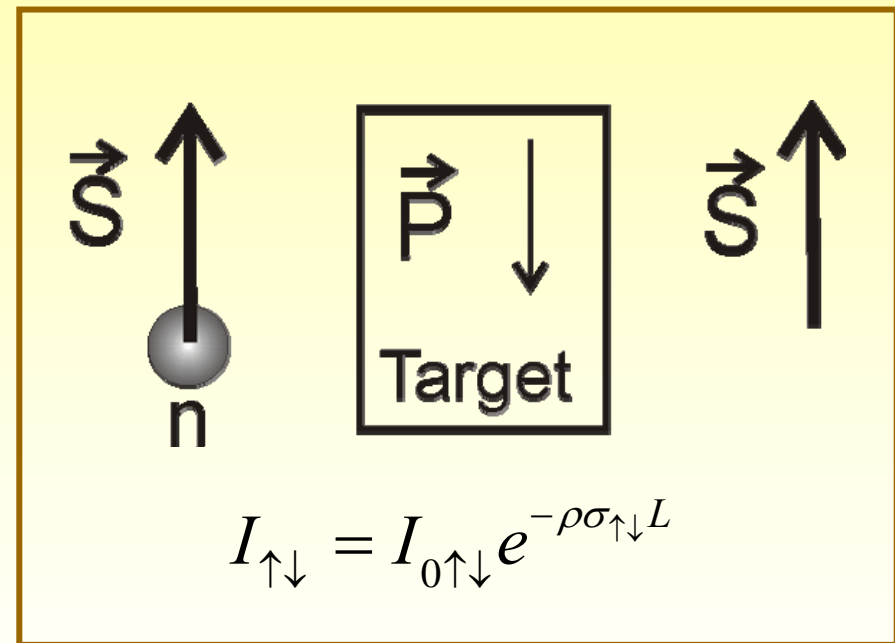
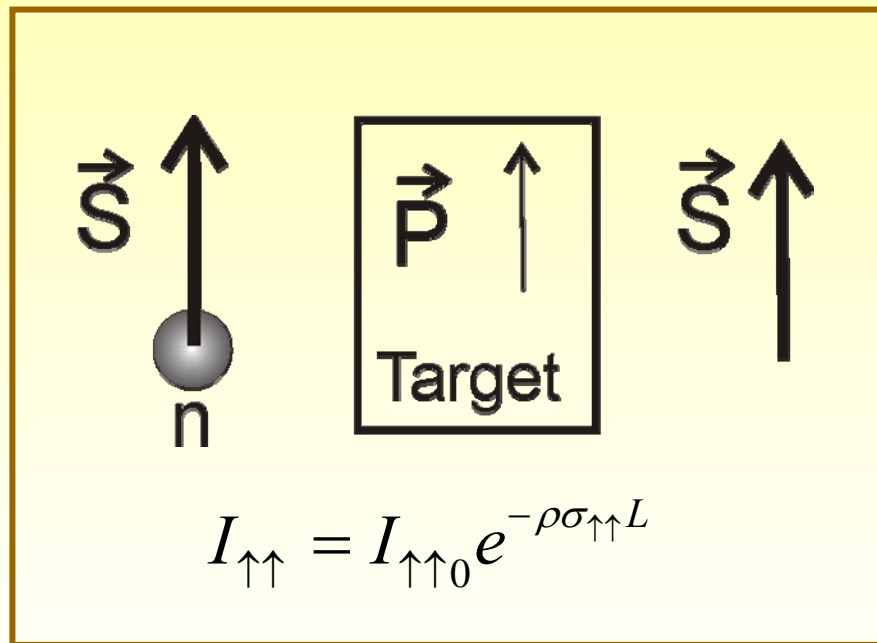
* Abragam A., et al, C.R. Acad. Sci. (Paris) B274, pp. 423--433, (1972).

* Forte M., Neutron spin precession in polarized nuclear targets, Nuovo Cimento A, V.18 , Iss. 4, pp. 726—736, (1973).

* Baryshevsky V.G., High-Energy Nuclear Optics of Polarized Particles, World Scientific Publishing Company, 640 p., (2012).

Short-lived particle interaction with polarized nucleus. Spin dichroism in the polarized target

$$\text{Im } f(0)_{\uparrow\uparrow} \neq \text{Im } f_{\downarrow\downarrow}(w) \quad \text{Im } f(0)_{\uparrow\uparrow(\uparrow\downarrow)} = \frac{k}{4\pi} \sigma_{\uparrow\uparrow(\uparrow\downarrow)tot} \quad \sigma_{\uparrow\downarrow} \neq \sigma_{\downarrow\uparrow}$$



I - intensity

This allows us to measure total section $\sigma_{\uparrow\uparrow}$ and $\sigma_{\uparrow\downarrow}$ in transmitting (not scattering!) experiments.

Short-lived particle interaction with polarized nucleus

Spin dichroism in the polarized target

When a particle with a negative charge, for example beauty baryon, is moving in the vicinity of the crystal plane or axes, then

$$\rho_{pl(ax)} \gg \rho_{av}, \quad \rho_{pl} \simeq 10^2 \rho_{av}, \quad \rho_{ax} \simeq 10^4 \rho_{av}$$

In the crystal axes case $L=0.1$ cm

The growth exists for positively charged particles too.

Measurement of hyperon quadrupole moment

Deuteron and Ω hyperon are examples of particles with $S=1$ and $S=3/2$.

Deuteron has quadrupole moment.

What is about quadrupole moment of Ω hyperon ?

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 :

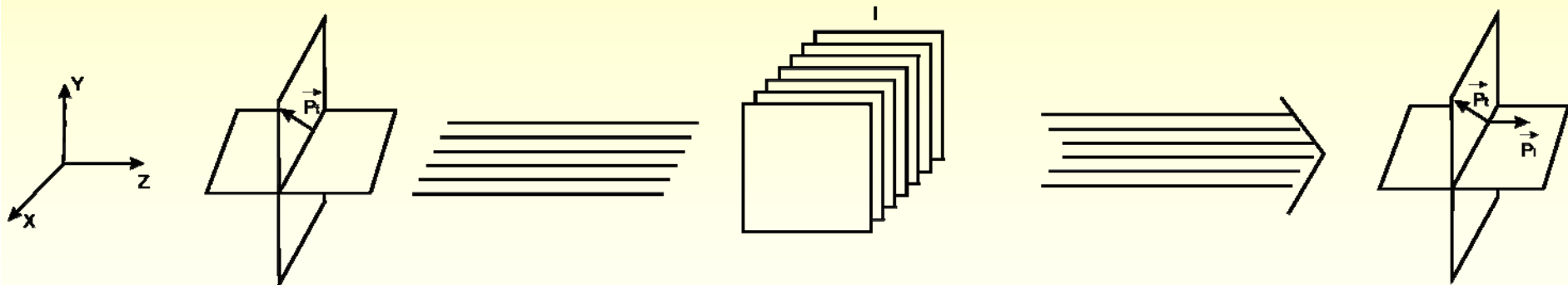
$$\hat{W}_Q = \frac{1}{6} \hat{Q}_{ik} \frac{\partial E_i}{\partial x_k}$$

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

S is the value of the particle spin $\hat{S}_{ik} = \hat{S}_i \hat{S}_k + \hat{S}_k \hat{S}_i$

The possibility of quadrupole moment measurement of hyperons moving in crystal

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



* Baryshevsky V.G., Shechtman A.G., Spin oscillations and possibility of quadrupole moment measurement for Ω - hyperons moving in a crystal, NIM B, 83, (1993)

The possibility of quadrupole moment measurement of hyperons moving in crystal

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

With the growth of energy of protons grows the number of the produced Ω^- hyperons. That allows to measure even smaller values of the quadrupole moment Q .

Interactions contributing to the spin motion of a particle

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

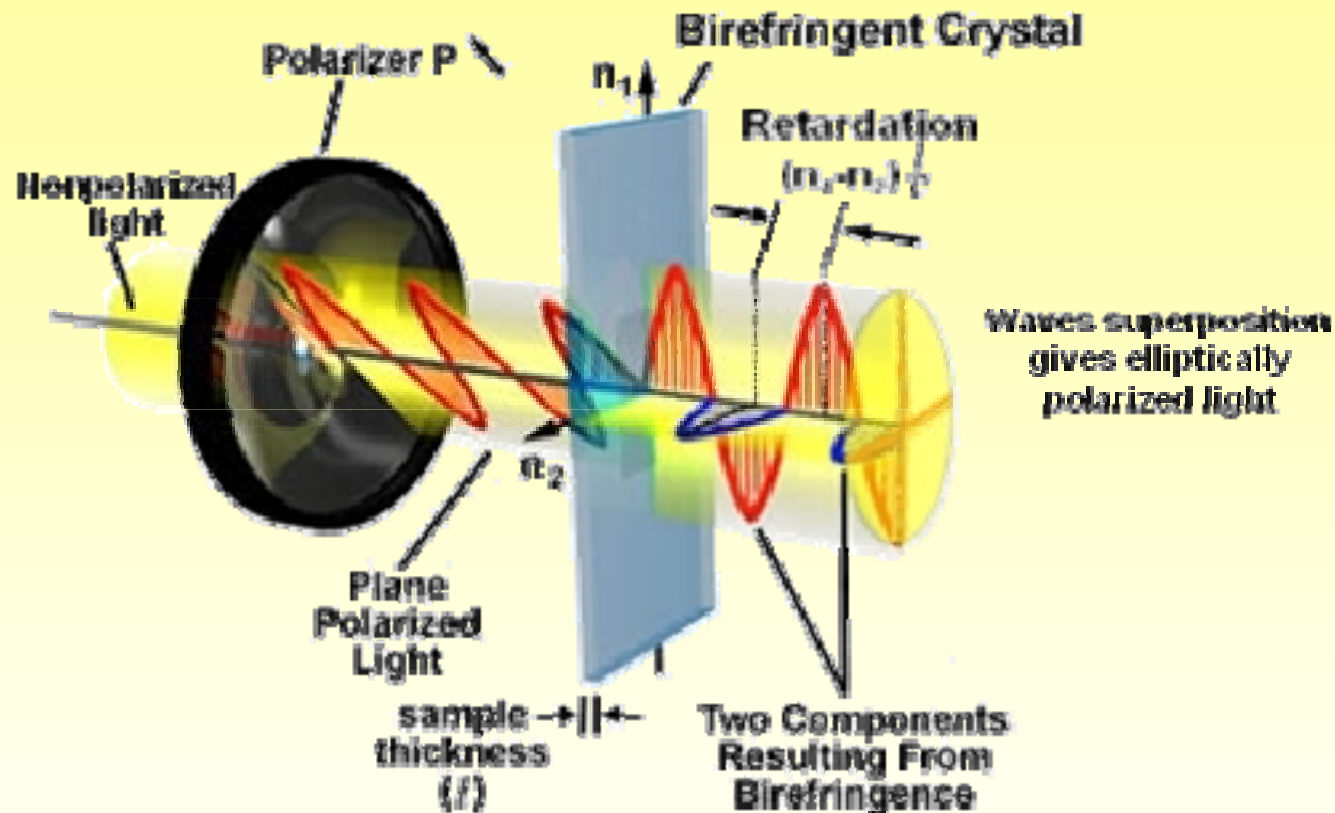
- interaction of the quadrupole moment with an inhomogeneous electric field;
- Spin – orbital interaction of the particle with nucleus
- interaction due to birefringence effect.

The birefringence effect allows to measure quark rescattering processes in Ω hyperons and to avoid a background of single scattering.

* Baryshevsky V.G., Batrakov K.G., Cherkas S.L., J.Phys. G, V.24, pp2049-2064, 1998

What is the birefringence effect?

Birefringence effect

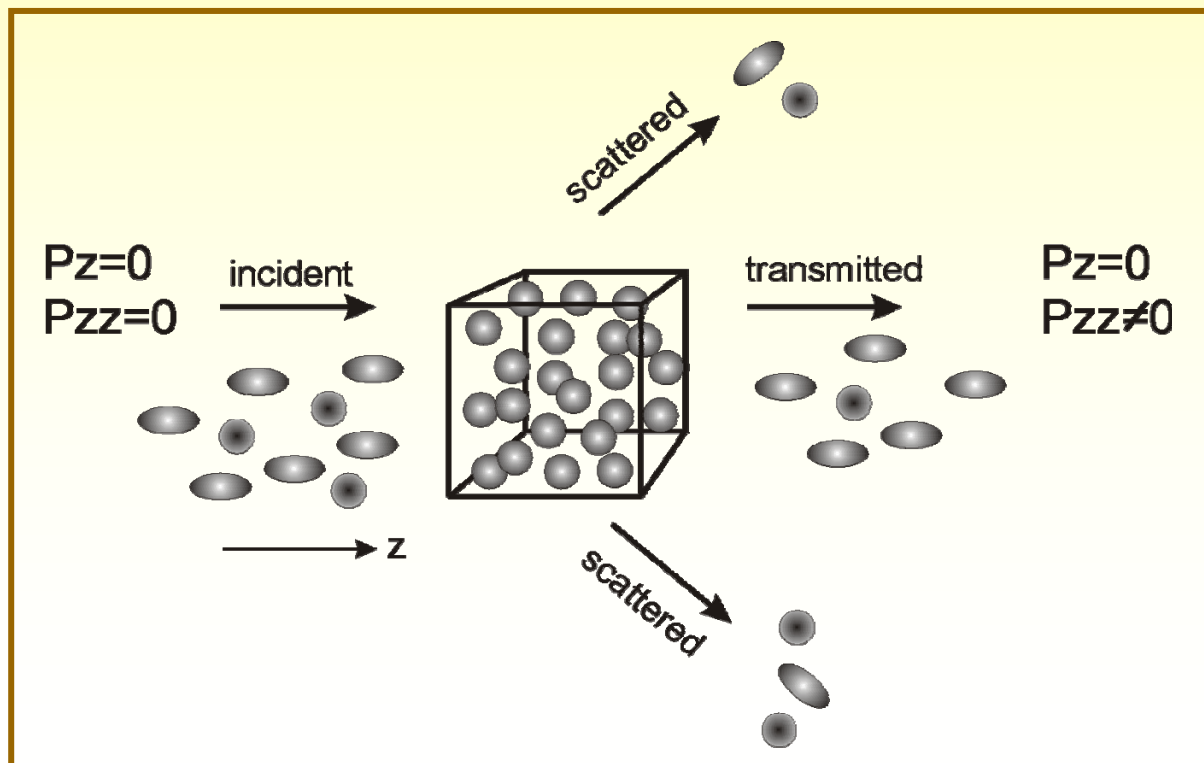
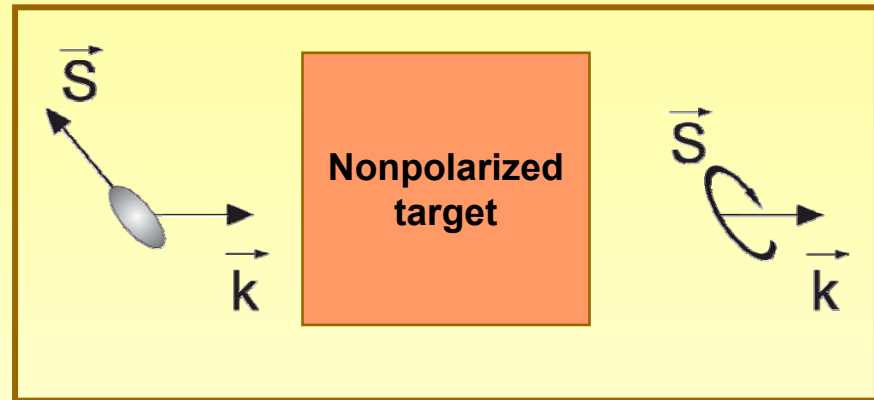
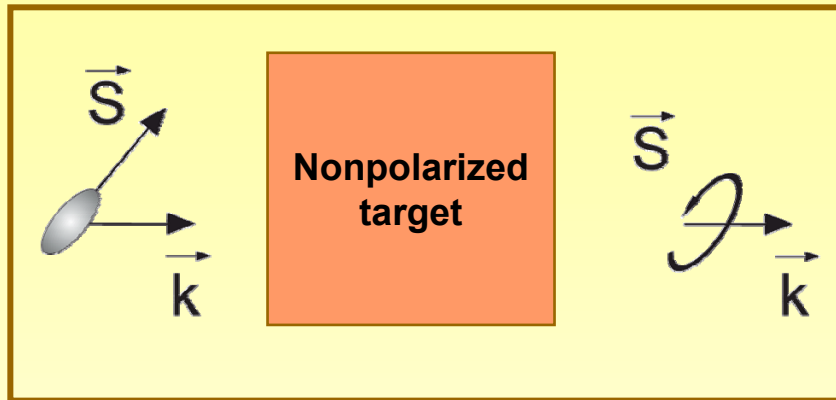


Could the similar effect exist for particles with the nonzero mass ?

* Baryshevsky V.G., Phys. Lett. A, 171, (1992), 431; Baryshevsky V.G., J. Phys. G, 19, (1993), 273.

Birefringence effect.

Spin rotation and dichroism in nonpolarized matter



First observation of spin dichroism with deuterons up to 20 MeV

* Baryshevsky V.G., A. Rouba, R. Engels, F. Rathmann, H. Seyfarth, H. Stroher, T. Ullrich, C. Duweke, R. Emmerich, A. Imig, J. Ley, H. Paetz gen. Schieck, R. Schulze, G. Tenckhoff, C. Weske, M. Mikirtychiants, A. Vassiliev, First observation of spin dichroism with deuterons up to 20 MeV in a carbon target, LANL e-print arxiv: hep-ex/0501045, 2005.

* H. Seyfarth, R. Engels, F. Rathmann, H. Ströher, V. Baryshevsky, A. Rouba, C. Düweke, R. Emmerich, A. Imig, K. Grigoryev, M. Mikirtychiants, A. Vasilyev, Production of a beam of tensor-polarized deuterons using a carbon target, Phys. Rev. Lett., Vol.104, 2010.

Spin dichroism with deuterons energies up to 5 GeV

*Azhgirey L.S., Ladygin V.P., Tarasov A.V., Zolin L.S. Observation of tensor polarisation of deuteron beam travelling through matter. DSPIN2007, Dubna, Russia, September 3-7, 2007.

*L. S. Azhgirey et al, Observation of tensor polarization of deuteron beam traveling through matter, Phys. of Part. and Nucl. Lett., 2008, Vol. 5, No. 5, P. 432–436.

*L. S. Azhgirei et al, Measurement of tensor polarization of a deuteron beam passing through matter, Phys. of Part. and Nucl. Lett., 2010, Vol. 7, No. 1, P. 27–32.

Conclusion

High-energy particles interaction with crystals provides us with unique opportunities for measuring important spin-dependent characteristics of elementary particles.

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

Thank you!

