High Energy Nuclear Optics of polarized γ-quanta, nucleons and nuclei



Sergei Anishchenko, Vladimir Baryshevsky

Alexandra Gurinovich

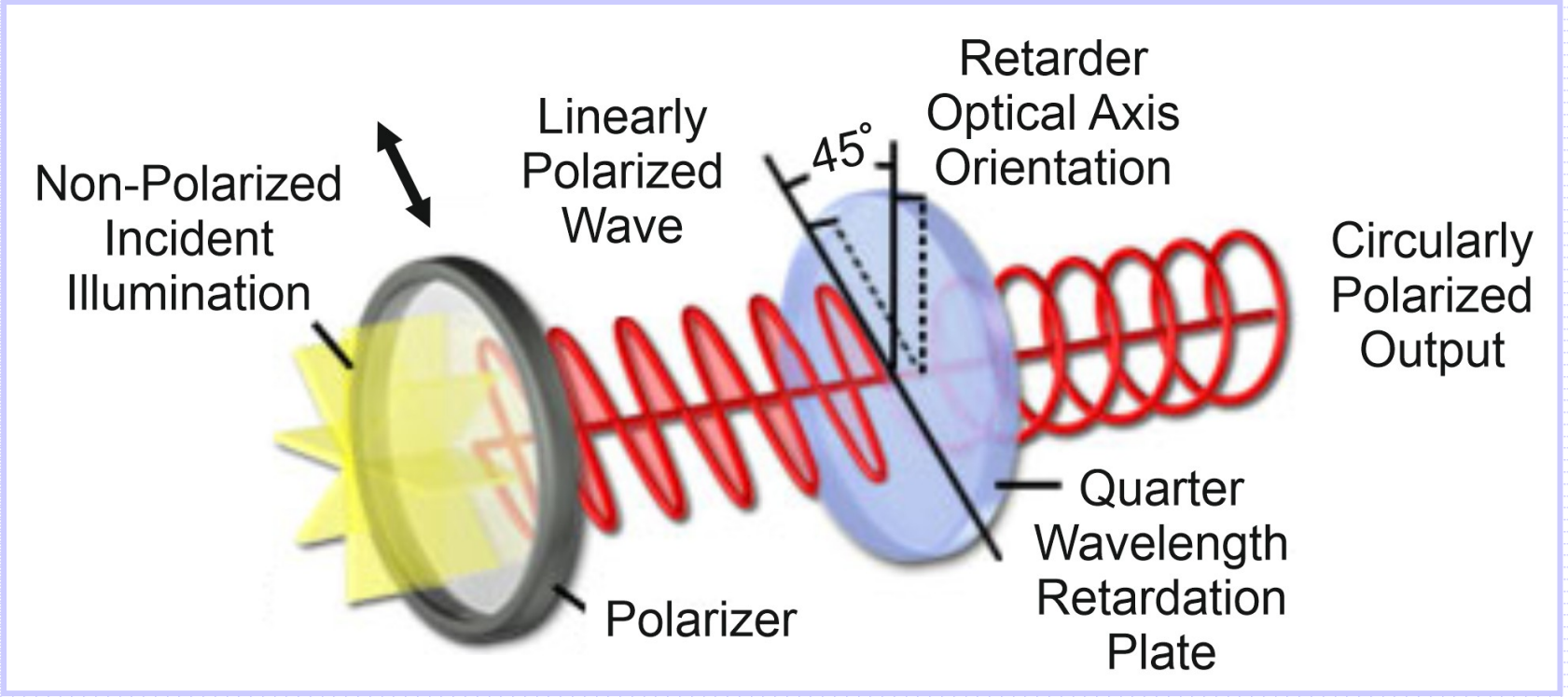
Research Institute for Nuclear Problems,

Belarusian State University, Minsk 220006, Belarus

Light optics

Birefringence effect

1669
E. Bartholin

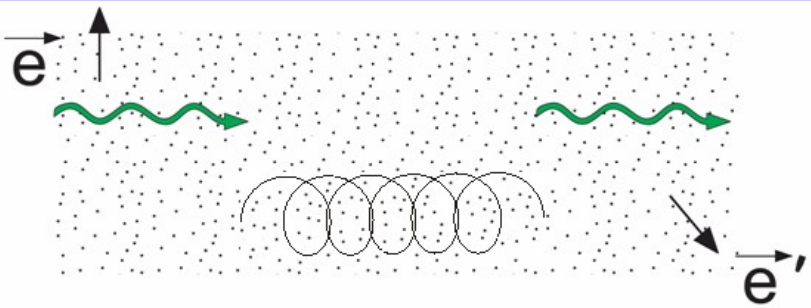


Natural optical activity

1811 D.F. Arago | **1812** J.B. Biot | **1817,1823** A. Fresnel

Linearly polarized photons in matter

$$\vec{e} = - \frac{e_+ - e_-}{\sqrt{2}}$$



Polarization vector of a photon in matter

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

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

Polarization plane of a photon, which passes length L in matter, rotates at angle ϑ

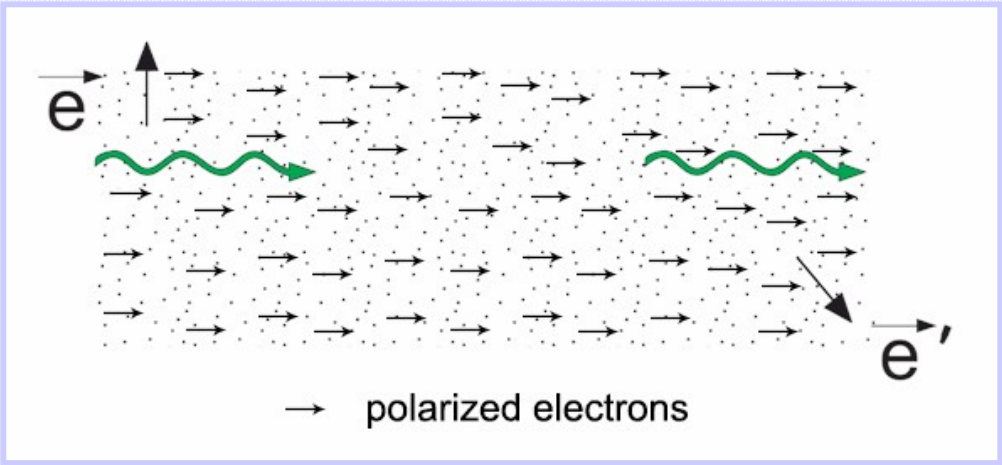
$$\vartheta = \tfrac{1}{2}\ k\ Re(N_+ - N_-)\ L$$

N_+ and N_- are the refraction indices.

Faradey effect (1845)

Gamma optics

Gamma quanta polarization plane rotation

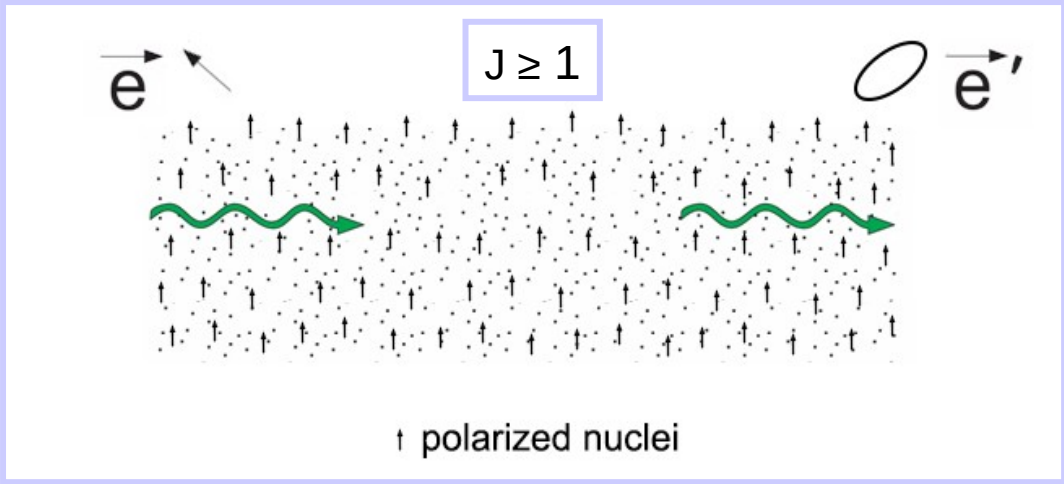


Belarusian State University, Minsk – JINR, Dubna
Scientific discovery N360

V.G. Baryshevsky, V.L. Lyuboshitz, *Rotation of the polarization plain of gamma quanta in passing through a polarized electron target,* Yad.Fiz., (1965)

350keV γ-quanta experiment: **V.M. Lobashev** (1971); **P. Bock**, **P. Luksch** (1971)

Birefringence of gamma quanta



When γ-quanta interact with matter, which comprises polarized nuclei with spin S≥1, the refractive index and the amplitude of coherent elastic forward scattering

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

$$f(0) = f_1(\omega)(\vec{e}\,'^{*}\ \vec{e}) + i\, f_2(\omega)\, \vec{p}\, [\vec{e}\,'^{*}\ \vec{e}] + f_3(\omega)\, Q_{ik} e_i'^{*} e_k + f_4(\omega) n_{\gamma i} n_{\gamma k} Q_{ik}$$

$\vec{p} = \mathrm{Tr}\hat{\rho}\vec{n}_S$ is the polarization vector of nuclei, $\vec{n}_S = \hat{\vec{S}}/S$, $\hat{\rho}$ is the spin density matrix of matter, $Q_{ik} = \mathrm{Tr}\hat{\rho}\,\hat{Q}_{ik}$ is the polarization tensor of rank two, $\vec{n}_\gamma$ is the unit vector along the γ-quanta momentum.

V.G. Baryshevsky, *On the birefringence of gamma quanta in a polarized nuclear target* , Yad.Fiz.,V.4 (1966)

The coherent elastic forward scattering amplitude

$$f(0) = f_1(\omega)(\vec{e}\,'^{*}\ \vec{e}) + i\, f_2(\omega)\, \vec{p}\, [\vec{e}\,'^{*}\ \vec{e}] + f_3(\omega)\, Q_{ik} e_i'^{*} e_k + f_4(\omega) n_{\gamma i} n_{\gamma k} Q_{ik}$$

$$f_1 = \left(\frac{\omega}{c}\right)^2 \alpha_0 \quad \text{(scalar)} \qquad f_2 = \left(\frac{\omega}{c}\right)^2 \alpha_\gamma \quad \text{(vector)} \qquad f_3 = \left(\frac{\omega}{c}\right)^2 \alpha_T \quad \text{(tensor)}$$

α_0, α_γ and α_T are the polarizabilities of nuclei introduced by A.M. Baldin

A.M.Baldin, *Optical Anisotropy of Atomic Nuclei*, Soviet Phys.JETP, **10** (1960) pp.142-148 [ЖЭТФ 37 №10 (1959) стр.202-211].

A.M.Baldin and S.F.Semenko, *On the Theory of the Optical Anisotropy of Atomic Nuclei*, Soviet Phys.JETP, **12** (1961) pp.306-307 [ЖЭТФ **39** (1960) стр.434-437].

$$f_4 = \left(\frac{\omega}{c}\right)^2 \alpha_{T2}$$

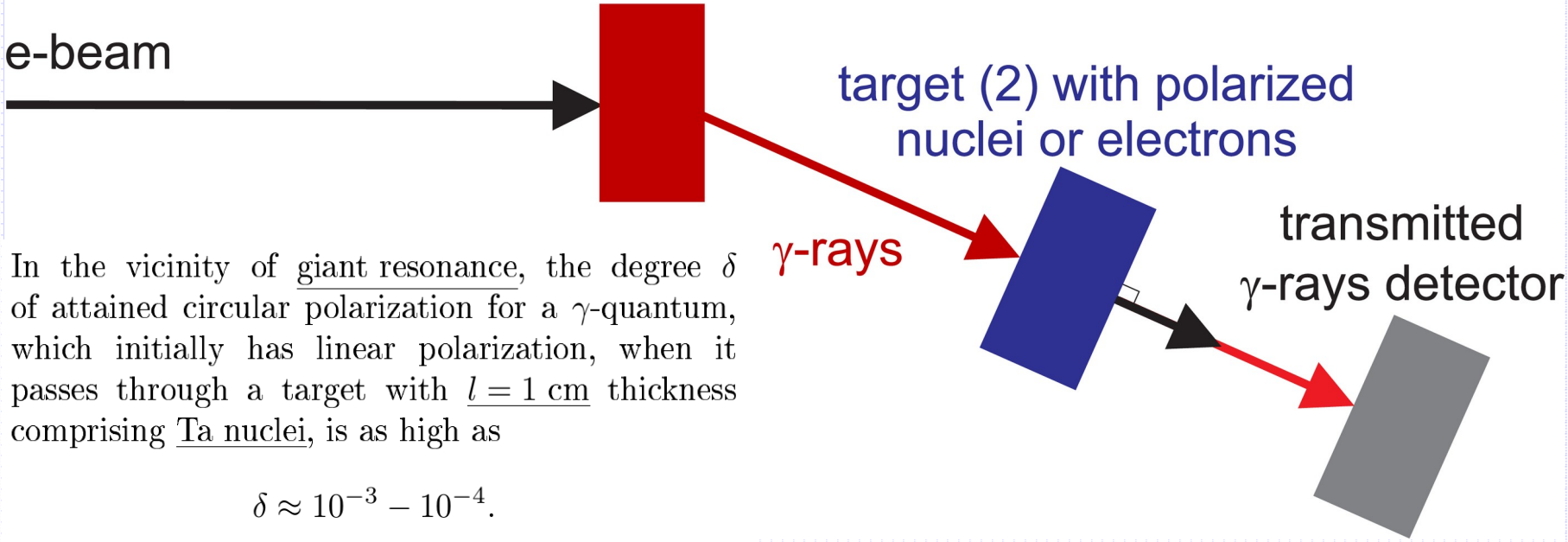
α_{T2} is the polarizability of nuclei introduced by V.G.Baryshevsky

В.Г. Барышевский, Ядерная оптика поляризованных сред, Энергоатомиздат, 1995

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

Transmission experiment @ LINAC-200 (800)

target (1) for polarized γ-ray production
(bremsstrahlung or coherent bremsstrahlung in a crystal)



In the vicinity of giant resonance, the degree δ of attained circular polarization for a γ-quantum, which initially has linear polarization, when it passes through a target with $l = 1$ cm thickness comprising Ta nuclei, is as high as

$$\delta \approx 10^{-3} - 10^{-4}.$$

For a target comprising polarized deuteron nuclei polarization degree could be evaluated as

$$\delta \approx 4 \cdot 10^{-5}\, l,$$

assuming that γ-quanta energy is about few MeV and deuteron tensor polarizability is evaluated by its static polarizability $\alpha_T \approx 10^{-40}\,\mathrm{cm}^3$.

Baryshevsky arXiv: 2602.16470v1 [hep-ph]

Refraction at high energies

The following statements, similar to those recently expressed by a reviewer of a distinguished journal still appear:

”... and the whole classical concept of a refractive index, which underpins this calculation, requires a beam of light coherent over some spatial extent much larger than the distance between the scatterers so that the (forward) scattered radiation interferes constructively to produce a phase-shifted beam – it is not a obvious that the gamma-ray beam at, say, MAMI satisfies this ...”

Baryshevsky V. High Energy Nuclear Optics of polarized nucleons and nuclei: research at complex Nuclotron M- NICA. ArXiv: 2602.16470 [hep-ph].

Quasi-optical phenomena for low-energy particles

Neutron spin precession (nuclear pseudomagnetism)

Refraction of neutrons:

$$N^2 = 1 + \frac{4\pi}{k^2} \sum_i \rho_i f_i(0)$$

ρ_i is the density of particles of the i-th type (the number of particles in cm^3)

$f_i(0)$ is the amplitude of coherent elastic scattering in forward direction for particles of the i-th type

E. Fermi, Nuclear Physics, Course Notes Complied by Jay Orear, Rosenfeld and R. A. Schulter ,University of Chicago Press (1950)

M. Lax, Rev. Mod. Phys. 23, 287 (1951)

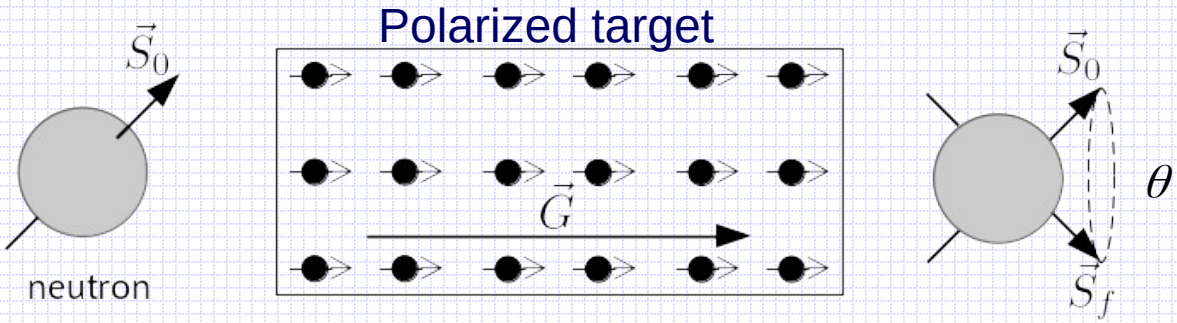
I.I. Gurevich, L.V. Tarasov, Low-energy neutron physics, ed. by R.I.Sharp, S. Chomet, Amsterdam: North - Holland Publishing Co. 1968.

Neutron spin precession (nuclear pseudomagnetism)

Belarusian State University, Minsk – JINR, Dubna
Scientific discovery N 244 from April 3, 1964

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

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



For neutron spin orthogonal to polarization vector of nuclei

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

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

$$\theta = k_z\,\mathrm{Re}(N_+ - N_-)\,z = \frac{2\pi\rho}{k_z}\mathrm{Re}(f_+ - f_-)\,z$$

Neutron spin precession (nuclear pseudomagnetism)

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

M. Forte, Nuovo Cimento A18, v4 (1973) 726-736.

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

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

Neutron spin precession (nuclear pseudomagnetism)

Another view on spin precession phenomenon

$$U_{\pm} = \frac{\hbar^2 k_z^2}{2m}(1 - N_{\pm}^2) = -\frac{2\pi\hbar^2}{m}\rho f_{\pm}(0)$$

In perfect analogy with spin behavior in a magnetic field, the non-zero difference $U_+ - U_-$ leads to the neutron spin precession about the direction of the nuclear polarization vector with the frequency:

$$\omega = \left|\mathrm{Re}\frac{U_+ - U_-}{\hbar}\right| = \frac{4\pi\hbar\rho}{m}\mathrm{Re}\beta Jp$$

$$\hat{U} = u_0 - \mu\vec{\sigma}\vec{B}_{\mathrm{eff}} \qquad B_{\mathrm{eff}} = \hbar\omega/(2\mu)$$

For a completely polarized proton target $\omega = 5\cdot10^8$ s^{-1}, $B_{\mathrm{eff}} \approx 3\cdot10^4$ Gs = 3T (*which exceeds by two orders of magnitude the ordinary magnetic field created by polarized magnetic moments of protons*).

For thermal neutrons $v = 2.2\cdot10^5$ cm/s and the full turn of spin will occur over the length $L \approx 10^{-3}$ cm.

Neutron spin precession (nuclear pseudomagnetism)

Neutron spin precession at high energies

Precession frequency $\omega \sim Re(f_+ - f_-)$

Rotation angle $\theta = \omega T = \omega L / v$

For thermal neutrons velocity $v = 2.2 \cdot 10^5$ cm/s and, thus, spin full turn occurs at length $L \approx 10^{-3}$ cm.

Velocity grows with the energy growth approaching speed of light *c* . Therefore, at the constant value of difference the length L, at which spin full turn occurs, increases 10^5 times to be as long as 100 cm.

With particle energy growth the nuclear spin phenomenon becomes available for positively charged particles and nuclei (Coulomb repulsion does not prevent nuclear interactions in this case).

Spin precession in pseudomagnetic nuclear field for high-energy particles

Evaluation for spin rotation effect

$$\theta = k\,\mathrm{Re}(N_+ - N_-)\,L = \frac{2\pi\rho}{k}\mathrm{Re}(f_+ - f_-)\,L$$

Scattering amplitude relates to scattering matrix T(E) as follows:

$$f(E,0) = -(2\pi)^2\,\frac{m\gamma}{\hbar^2}\,T(E)$$

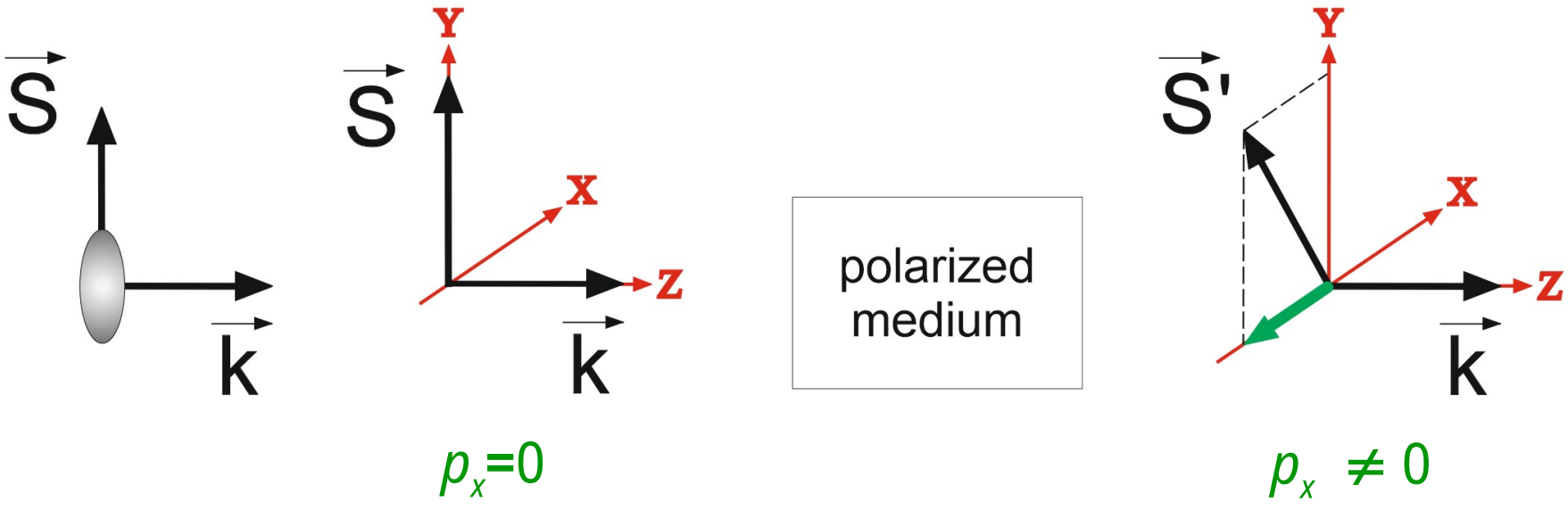
$$\theta = 2\pi\rho\lambda_c\frac{(f_+ - f_-)\,L}{\gamma}$$

λ_c is the Compton wavelength of the particle, $f' = f/\gamma \sim T(E)$.

For example, for NH_3 target the density of polarized protons (the number of particles per cm^3) is as high as $\rho = 5\cdot10^{22}$ cm^{-3}. For protons with the use of evaluation for $f' = f/\gamma \approx 10^{-13}$ cm the value of spin rotation angle is as high as $\theta = 3\cdot10^{-3}$ rad for target thickness L=30 cm.

Nuclear precession (rotation in pseudomagnetic field)

Polarized particles (protons, deuterons, nuclei) moving in a polarized target

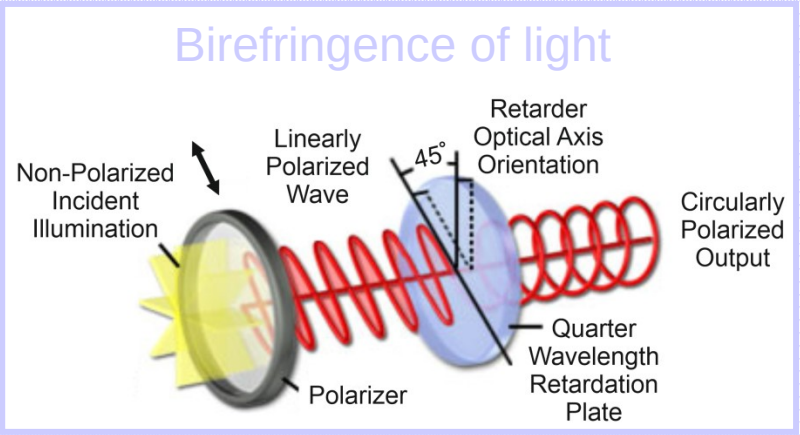


Example. Effect evaluation for a polarized external target (NH_3, ND_3) at Nuclotron.

Part.	Target	N_b	σ, b	L, cm	Δσ/σ	Re(Δf)/Im(Δf)	$\|p_x\|$	$T_{1\%}$
p	NH_3	10^{10}	0.5	30	0.02	~0.5	$\sim 2\cdot 10^{-3}$	30 hours
p	ND_3	10^{10}	0.6	30	0.04	~0.5	$\sim 4\cdot 10^{-3}$	8 hours

Birefringence of particle (nuclei) with spin $S \geq 1$

Birefringence effect: dichroism and spin rotation



Could the effect similar to birefringence of light exist for particles with nonzero mass ?

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 $S \geq 1$ and mass $M \neq 0$ has the intrinsic anisotropy).

V.G. Baryshevsky, *Birefringence of particles (nuclei, atoms) of spin $S \geq 1$ 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 elastic coherent scattering*, **J. Phys. G 19**, 2 (1993) 273.

Refractive index for particles in matter

$$N = 1 - \frac{2\pi}{k^2} \sum_i \rho_i f_i(0)$$

ρ_i is the density of particles of the i-th type (the number of particles in cm^3)

$f_i(0)$ is the amplitude of coherent elastic scattering in forward direction for particles of the i-th type

E. Fermi, Nuclear Physics, Course Notes Complied by Jay Orear, Rosenfeld and R. A. Schulter ,University of Chicago Press (1950)

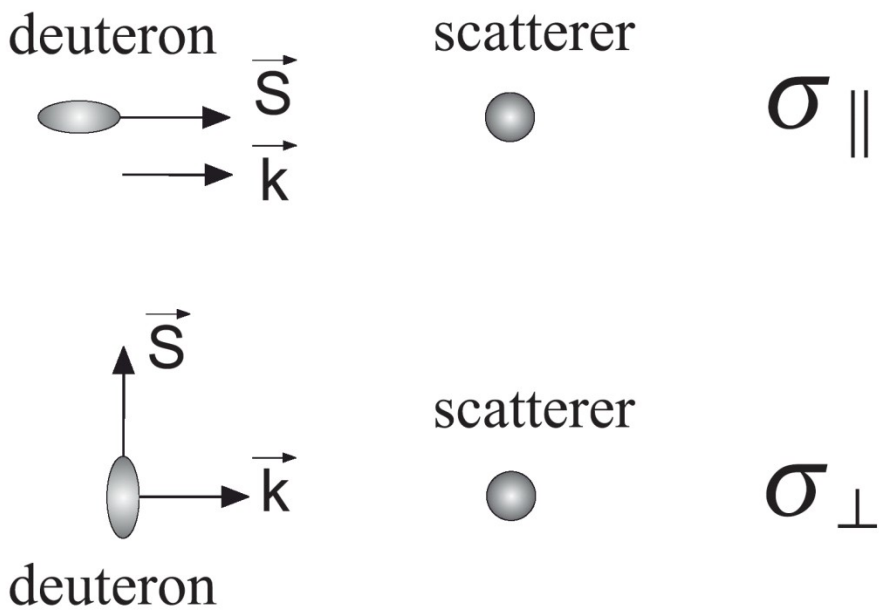
M. Lax, Rev. Mod. Phys. 23, 287 (1951)

I.I. Gurevich, L.V. Tarasov, Low-energy neutron physics, North - Holland Publishing Co. 1968.

M.L. Goldberger, K.M. Watson, Collision Theory, Wiley, New York, 1984

Birefringence phenomenon

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

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

Birefringence phenomenon

Forward scattering amplitude of a particle in a nonpolarized target (oz || particle momentum, contribution of weak interactions is omitted) reads:

$$\hat{f}(0) = d + d_1 S_z^2 + d_2 S_z^4 \ldots + d_s S_z^{2s}$$

For particles with spin 1 and 3/2

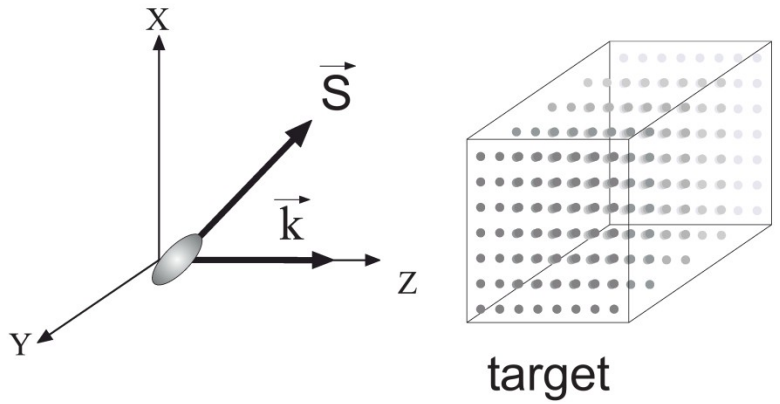
$$N(m) = 1 + \frac{2\pi\rho}{k^2}(d + d_1 m^2)$$

index of refraction

$$\psi = \sum_{m=\pm 1,0} a^m \chi_m = \left\{ \begin{array}{c} a^1 \\ a^0 \\ a^{-1} \end{array} \right\} = \left\{ \begin{array}{c} a\, e^{i\delta_1} e^{ikN(m=1)z} \\ b\, e^{i\delta_0} e^{ikN(m=0)z} \\ c\, e^{i\delta_{-1}} e^{ikN(m=-1)z} \end{array} \right\} = \left\{ \begin{array}{c} a\, e^{i\delta_1} e^{ikN_1 z} \\ b\, e^{i\delta_0} e^{ikN_0 z} \\ c\, e^{i\delta_{-1}} e^{ikN_1 z} \end{array} \right\}$$

Deuteron (spin = 1) in nonpolarized target

Let us look for the mean value of the spin operator in state ψ.



Plane (xz) coincides with that formed by polarization vector $\vec{p}$ and deuteron momentum $\vec{k}$ before entering the target

In this case $\delta_1 - \delta_0 = 0$ at $z=0$, $\langle p_x \rangle \neq 0$, $\langle p_y \rangle = 0$

$$< p_x >= \sqrt{2} e^{-\frac{1}{2}\rho(\sigma_0+\sigma_1)z} b(a+c) \cos\left[\frac{2\pi\rho}{k} Re(d_1) z\right] / |\psi|^2,$$

$$< p_y >= -\sqrt{2} e^{-\frac{1}{2}\rho(\sigma_0+\sigma_1)z} b(a-c) \sin\left[\frac{2\pi\rho}{k} Re(d_1) z\right] / |\psi|^2,$$

$$< p_z >= e^{-\rho\sigma_1 z}(a^2 - c^2)/|\psi|^2,$$

$$|\psi|^2 = (a^2 + c^2) e^{-\rho\sigma_1 z} + b^2 e^{-\rho\sigma_0 z}$$

z is the pathlength of particle inside medium.

Deuteron (spin = 1) in nonpolarized target

Spin-dependent part of $f_m(0)$

$$\mathrm{Re}\ d_1 = -\frac{3}{\pi}\left(\mathrm{Re}\ f_p(0)\sigma_n + \mathrm{Re}\ f_n(0)\sigma_p\right) G$$

$$\mathrm{Im}\ d_1 = \left(\frac{24}{k}\mathrm{Re}\ f_p(0)\ \mathrm{Re}\ f_n(0) - \frac{3k}{8\pi^2}\sigma_p\sigma_n\right) G\,.$$

Cross-section difference

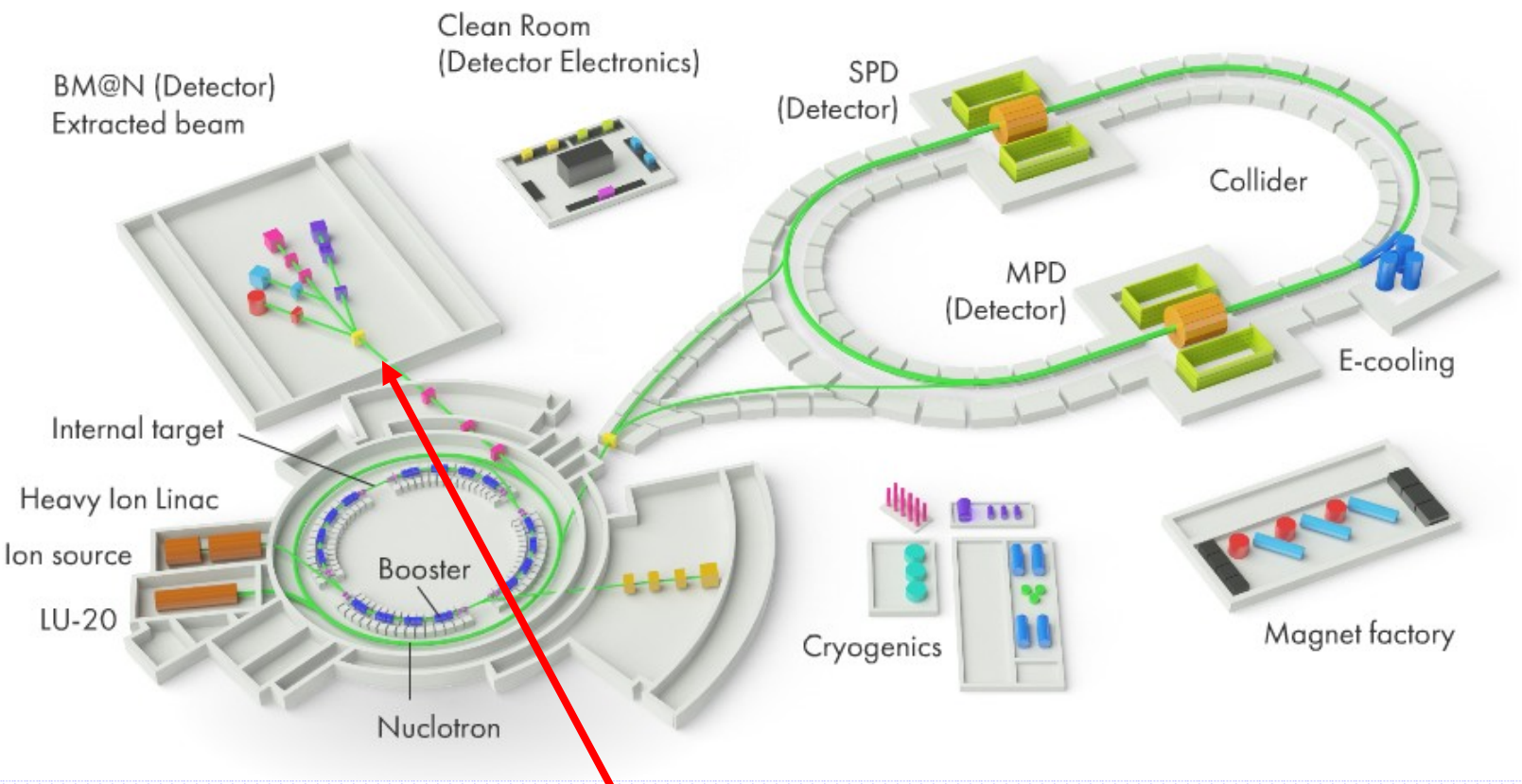
$$\Delta\sigma = \sigma_0 - \sigma_{\pm 1} = -\frac{4\pi \mathrm{Im} d_1}{k}$$

Here, $\sigma_{p(n)}$ is the total scattering cross section of a proton and a neutron by a nucleus, respectively,

$$G = \int_0^\infty \left(\frac{1}{\sqrt{2}}\frac{u(r)W(r)}{r^2} - \frac{1}{4}\frac{W^2(r)}{r^2}\right) dr\,.$$

Sensitive to u(r) and W(r) behavior in the vicinity of r=0

Nuclotron. External target



Deuteron spin dichroism
External target

Nonpolarized deuterons in nonpolarized target

Optical theorem (m=±1, 0)

$$\mathrm{Im} f_m(0) = \frac{k_z}{4\pi}\sigma_m$$

Amplitudes of the coherent forward scattering

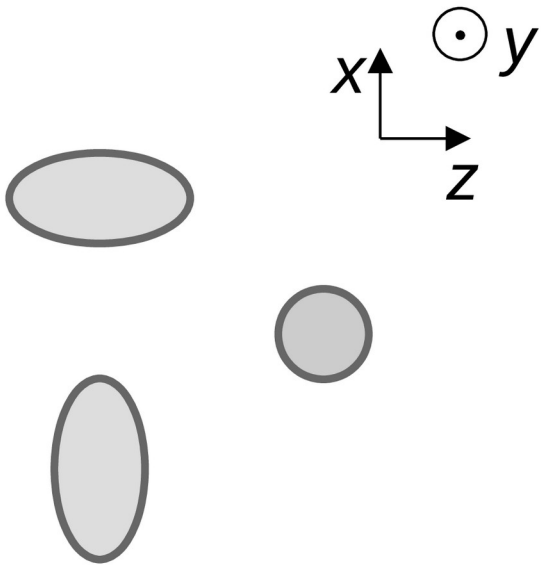
$$f_m(0) = d_0 + d_1 m^2$$

Tensor polarization p_{zz} after passing through a target with density ρ (the number of scatterers per unit volume) and thickness l is expressed via intensities $\boldsymbol{I_{\pm 1}}$ and $\boldsymbol{I_0}$ for deuterons with spin projection m=±1 and 0 as follows

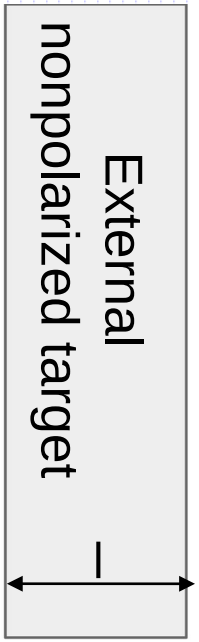
$$p_{zz}(l) = \frac{I_{+1}(l) + I_{-1}(l) - 2\cdot I_0(l)}{I_{+1}(l) + I_{-1}(l) + I_0(l)} \approx \frac{2}{3}\rho\, l(\sigma_0 - \sigma_1) = -\frac{8\pi}{3}\,\rho\, l\frac{\mathrm{Im}(d_1)}{k}$$

First experimental observations of deuteron dichroism

20 MeV – Köln, Minsk, Juelich
5 GeV/c – JINR



Non-polarized deuterons ($p_{zz}=0$)





Tensor polarized deuterons ($p_{zz}\neq0$)

Cross sections

$$\sigma = \frac{1}{3}\sigma_0 + \frac{2}{3}\sigma_{\pm1}$$

$$\Delta\sigma = \sigma_0 - \sigma_{\pm1}$$

Target	N_{bunch}	σ, b	ρl, g·cm^{-2}	Δσ/σ	p_{zz}	Reference
C	5·10^8-3·10^9	0.63	83	0.06	0.1	Azhgirey et al., 2008, 2010

Deuteron spin dichroism: experiments

First observation of spin dichroism with deuterons up to 20 MeV in a carbon target

V. Baryshevsky, A. Rovba, 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. Mikirtytchiants, A. Vassiliev *(LANL arxive: hep-ex/0501045)*

Proceedings of the 17th Int. spin phys. symp.,SPIN 2006, Kyoto, Japan, 2–7 October 2006. / AIP Conf. Ser, v.915 (2007) 777-780

Production of a beam of tensor-polarized deuterons using a carbon target

Phys. Rev. Lett. 104, 22 (2010) 222501

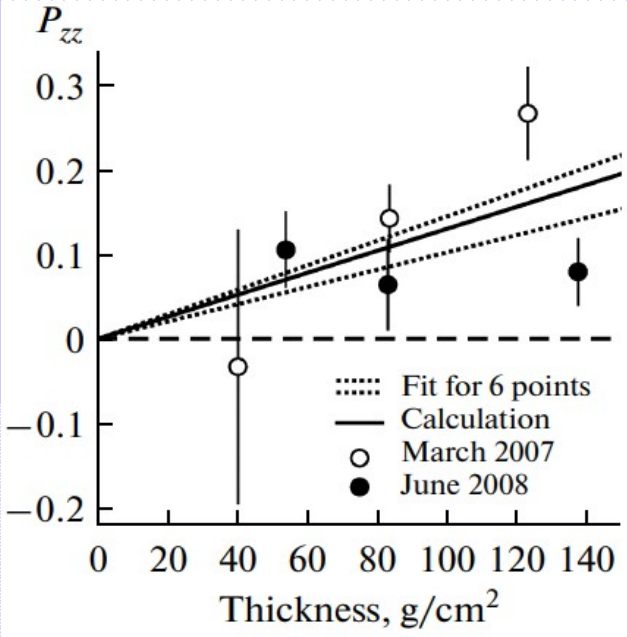
JINR experiments 5 GeV/c 2008-2010 years

Observation of Tensor Polarization of Deuteron Beam Traveling through Matter
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,

Physics of Particles and Nuclei Letters 5, 5 (2008) 432.

Measurement of tensor polarization of a deuteron beam passing through matter

Phys. of Particles and Nuclei Lett. 7, 1 (2010) 27–32.



Tensor polarization of deuterons vs. thickness of target The dashed region shows the error corridor, the solid curve is the calculation result.

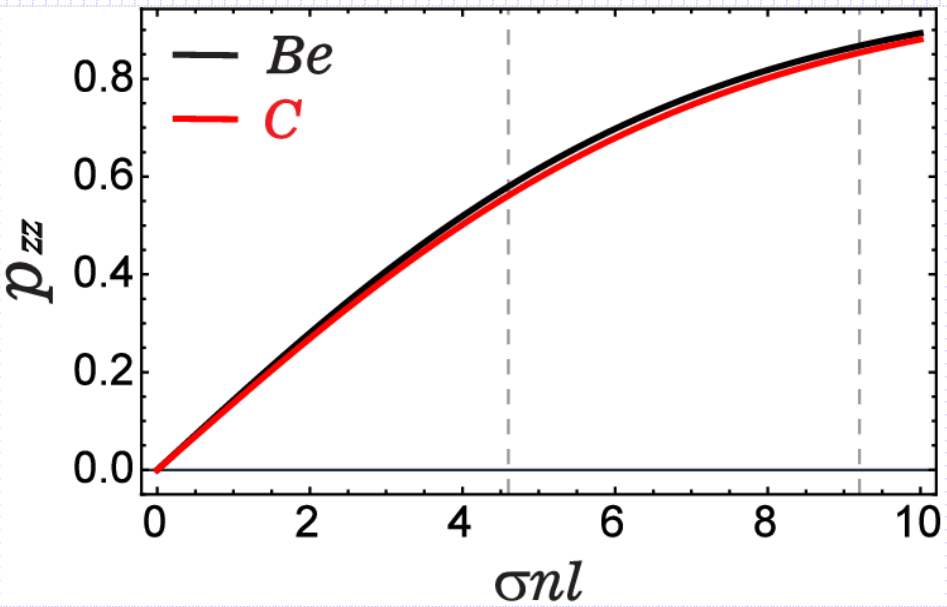
External nonpolarized fixed target@Nuclotron
Nonpolarized beam of heavy nuclei with spin S≥1

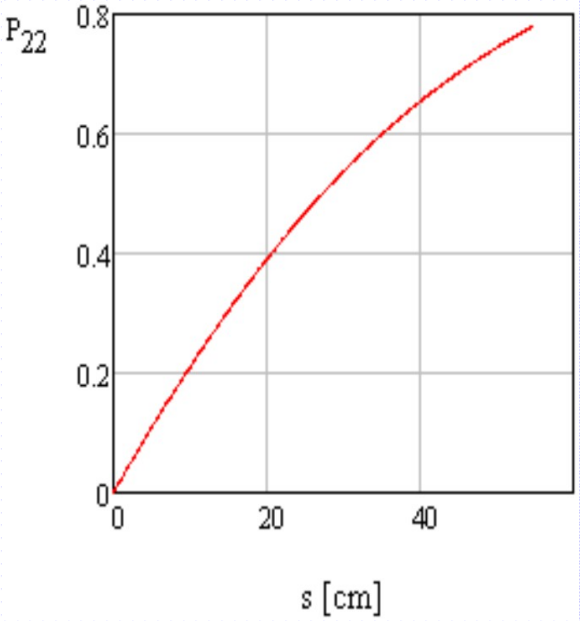
Spin dichroism effect evaluation: for nonpolarized heavy nuclei with high spherical asymmetry (for example, Ne or Eu) passing through the external carbon target of thickness about 40 g/cm^2 at Nuclotron the value of tensor polarization is as high as:

$$p_{zz} \sim 0.5 .$$

Great value of tensor polarization appearing due to spin dichroism for many nuclei, gave possibility to V.Lebedev and S.Shimansky to formulate an idea for application of nuclei, which acquire tensor polarization at low energies, for further acceleration and bringing into NICA ring. Therefore, one gains possibility to study reactions induced at collisions of tensor polarized nuclei beams.

External nonpolarized fixed target@Nuclotron
Nonpolarized beam of ^{21}Ne nuclei with spin S=3/2





Baryshevsky V. arXiv: 2602.16470 [hep-ph]

Ladygin V.P. SPIN-2025, Qingdao, China

N/N_0	σnl	p_{zz}(Be)	p_{zz}(C)
10^{-2}	4.6	0.58	0.56
10^{-4}	9.2	0.87	0.85

Nuclei spin rotation in nonpolarized target

Nonpolarized external fixed target@Nuclotron

Deuteron spin rotation in nonpolarized target

Only spin dichroism for deuterons was observed in the first experiment at Nuclotron. Deuteron spin rotation is not measured yet.

Angle of rotation for polarization vector (polarization tensor) for a deuteron beam passing distance l in a target with density ρ (the number of nuclei per cm^3) reads

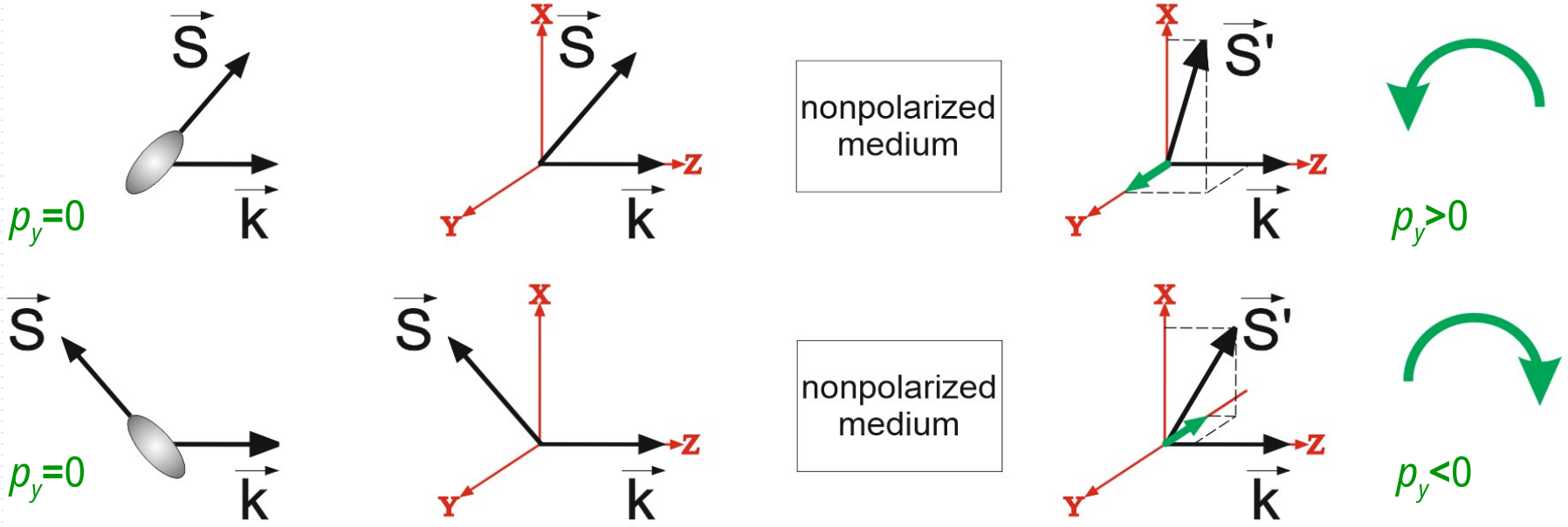
$$\vartheta = 2\pi\rho l\lambda_c \frac{1}{\gamma}\mathrm{Re}d_1 \quad \text{, where} \quad \lambda_c = \frac{\hbar}{Mc}$$

Analysis shows that for deuterons of several GeV energies passing through a carbon target with thickness of several nuclear interaction lengths angle of polarization vector (polarization tensor) rotation is about

$$\vartheta \sim 1 \cdot 10^{-2}\ \mathrm{rad}$$

Deuteron (spin = 1) in nonpolarized target

Rotation for an acute and obtuse angles between spin and momentum occurs in opposite directions



$$p_y = -\frac{2\sqrt{2}e^{-\rho(\sigma_1+\sigma_0)z/2}b(a-c)\sin(2\pi\rho\mathrm{Re}d_1 z/k)}{|\psi|^2}$$

$$p_{yz} = -\frac{3\sqrt{2}e^{-\rho(\sigma_1+\sigma_0)z/2}b(a+c)\sin(2\pi\rho\mathrm{Re}d_1 z/k)}{|\psi|^2}$$

c=0

Target	N_{bunch}	σ, b	ρl, g·cm^{-2}	Δσ/σ	|Re(d_1)/Im(d_1)|	|p_y|	|p_{yz}|	$T_{1\%}$
C	10^{10}	0.6	83	0.06	0.1	$4\cdot10^{-3}$	$6\cdot10^{-3}$	8 hours

- Oscillation between vector and tensor polarizations

Oscillation between vector and tensor polarizations

Wave function

$$\psi = \sum_{m=\pm 1,0} a^m \chi_m = \left\{ \begin{array}{c} a^1 \\ a^0 \\ a^{-1} \end{array} \right\} = \left\{ \begin{array}{c} a\, e^{i\delta_1} e^{ikN(m=1)z} \\ b\, e^{i\delta_0} e^{ikN(m=0)z} \\ c\, e^{i\delta_{-1}} e^{ikN(m=-1)z} \end{array} \right\} = \left\{ \begin{array}{c} a\, e^{i\delta_1} e^{ikN_1 z} \\ b\, e^{i\delta_0} e^{ikN_0 z} \\ c\, e^{i\delta_{-1}} e^{ikN_1 z} \end{array} \right\}$$

The vector and tensor polarization oscillate when c=a and $\delta_1 - \delta_0 = \delta_0 - \delta_{-1} = \pi/2$.

$$\begin{aligned} p_x &= 0, \\ p_y &= \frac{\sqrt{2} e^{-\frac{1}{2}\rho(\sigma_0+\sigma_1)Z} 2ba \cos\left(\frac{2\pi\rho}{k} \mathrm{Re} d_1 Z\right)}{\langle \Psi \mid \Psi \rangle}, \\ p_{xz} &= \frac{\frac{3}{\sqrt{2}} e^{-\frac{1}{2}\rho(\sigma_0+\sigma_1)Z} 2ab \sin\left(\frac{2\pi\rho}{k} \mathrm{Re} d_1 Z\right)}{\langle \Psi \mid \Psi \rangle} \end{aligned}$$

Part.	Target	N_{bunch}	σ, b	ρl, g·cm^{-2}	Δσ/σ	|Re(d_1)/Im(d_1)|	|p_{xz}|	$T_{1\%}$
d	C	10^{10}	0.6	83	0.06	0.1	$4 \cdot 10^{-3}$	5 hours

Spin rotation and oscillation between vector and tensor polarizations for ^{21}Ne nuclei.

^{21}Ne spin rotation in nonpolarized target

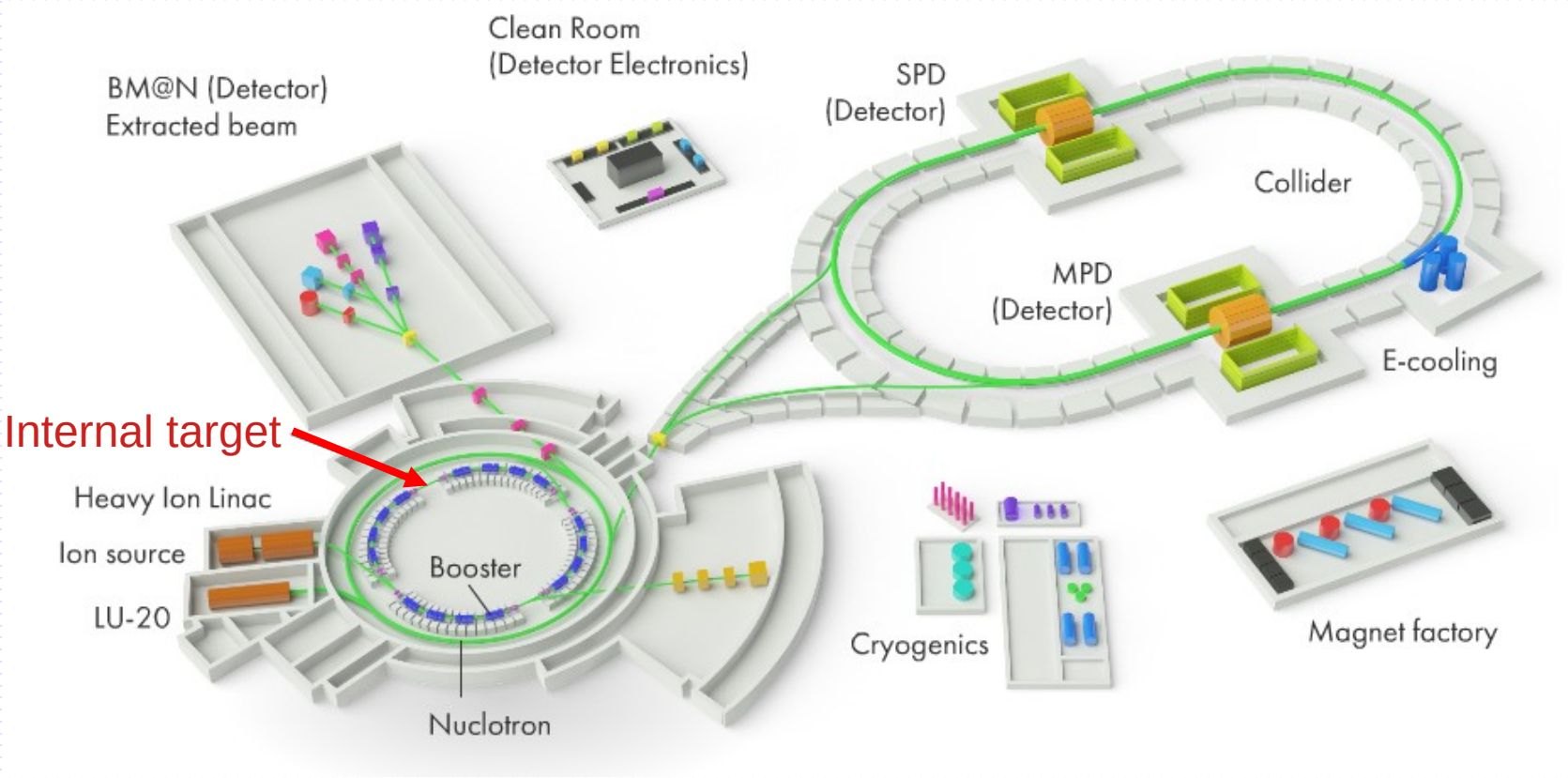
Angle of rotation for polarization vector (polarization tensor) for a ^{21}Ne beam passing distance l in a target with density ρ (the number of nuclei per cm^3) reads

$$\vartheta = 2\pi\rho l\lambda_c \frac{1}{\gamma}\mathrm{Re}d_1 \quad \text{, where} \quad \lambda_c = \frac{\hbar}{Mc}$$

Analysis shows that for ^{21}Ne nuclei of several GeV energies passing through a carbon target with thickness of several nuclear interaction lengths angle of polarization vector (polarization tensor) rotation is about

$$\vartheta \sim 1 \cdot 10^{-2}\ \mathrm{rad}$$

Nuclotron. Internal target

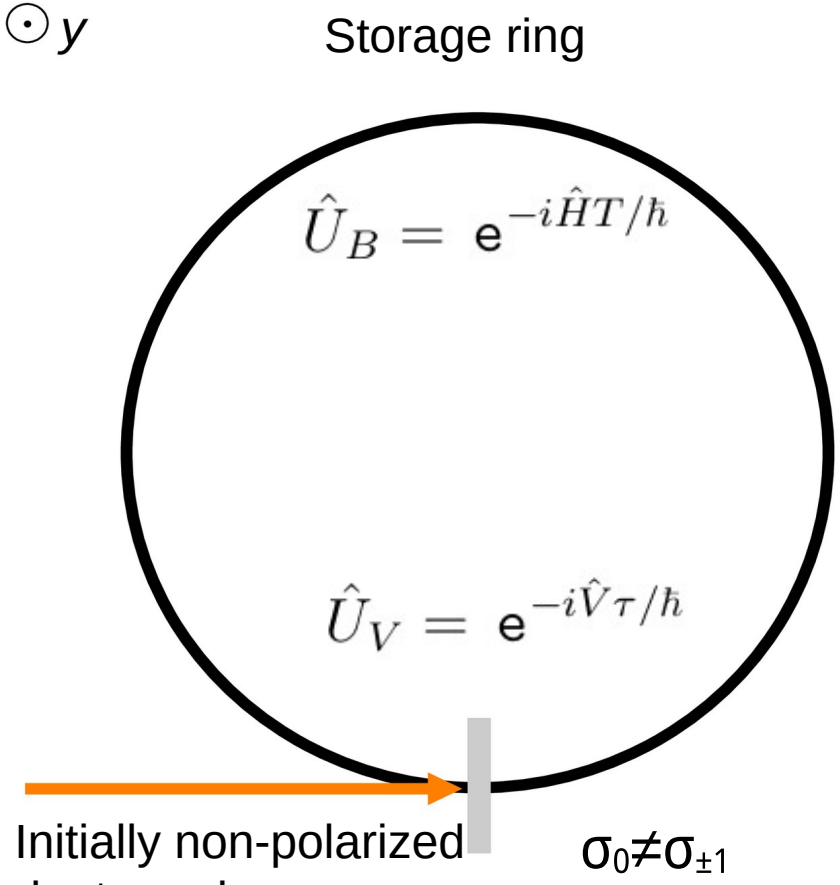


Internal nonpolarized fixed target@Nuclotron

Measurements of spin dichroism at the internal target is important for testing and verification of polarization measurements at NICA for colliding beams of nuclei (deuterons and other).

S.V. Anischenko, V.G. Baryshevsky, A.A. Gurinovich, V.P. Ladygin, *About possibility to observe spin dichroism effect (the effect of tensor polarization acquiring) for a nonpolarized deuteron beam passing through the nonpolarized internal target of Nuclotron*, arXiv:2508.11718 [nucl-th]

Deuteron dichroism at internal target



Spin-dependent Hamiltonian in the storage ring

$$\hat{H} = -\frac{e\hbar}{Mc}\left(\frac{g-2}{2} + \frac{1}{\gamma}\right) B_y \hat{S}_y$$

Spin-dependent Hamiltonian in the target

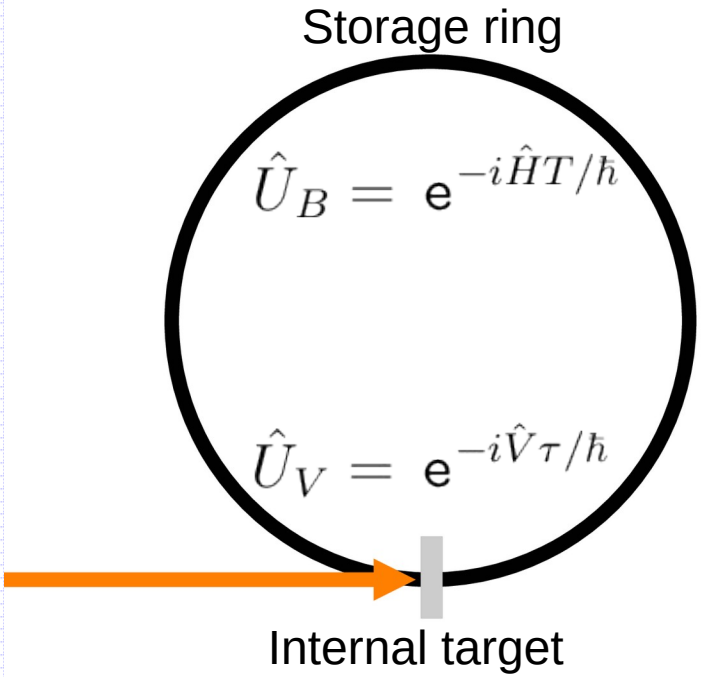
$$\hat{V} = -\frac{2\pi\hbar^2 N}{M\gamma}\hat{f}(0)$$

$$= -\frac{2\pi\hbar^2}{M\gamma}\sum_i N_i \hat{f}_i(0)$$

N is the number of molecules per cm^3
N_i is the number of atoms of type i per cm^3

Tensor rotation in magnetic field!

Tensor polarization



One turn: $\hat{U}_1 = \hat{U}_B \hat{U}_V$

n turns: $\hat{U}^{(n)} = \hat{U}_1^n$

Density matrix: $\hat{\rho}^{(n)} = \hat{U}^{(n)} \hat{\rho}_0 \hat{U}^{(n)+}$

Tensor polarization: $p_{ij} = \dfrac{\mathrm{Sp}(\hat{\rho}^{(n)} \hat{Q}_{ij})}{\mathrm{Sp}(\hat{\rho}^{(n)})}$

Cross sections

$$\sigma = \frac{1}{3}\sigma_0 + \frac{2}{3}\sigma_{\pm 1}$$

$$\Delta\sigma = \sigma_0 - \sigma_{\pm 1}$$

Linear approximation

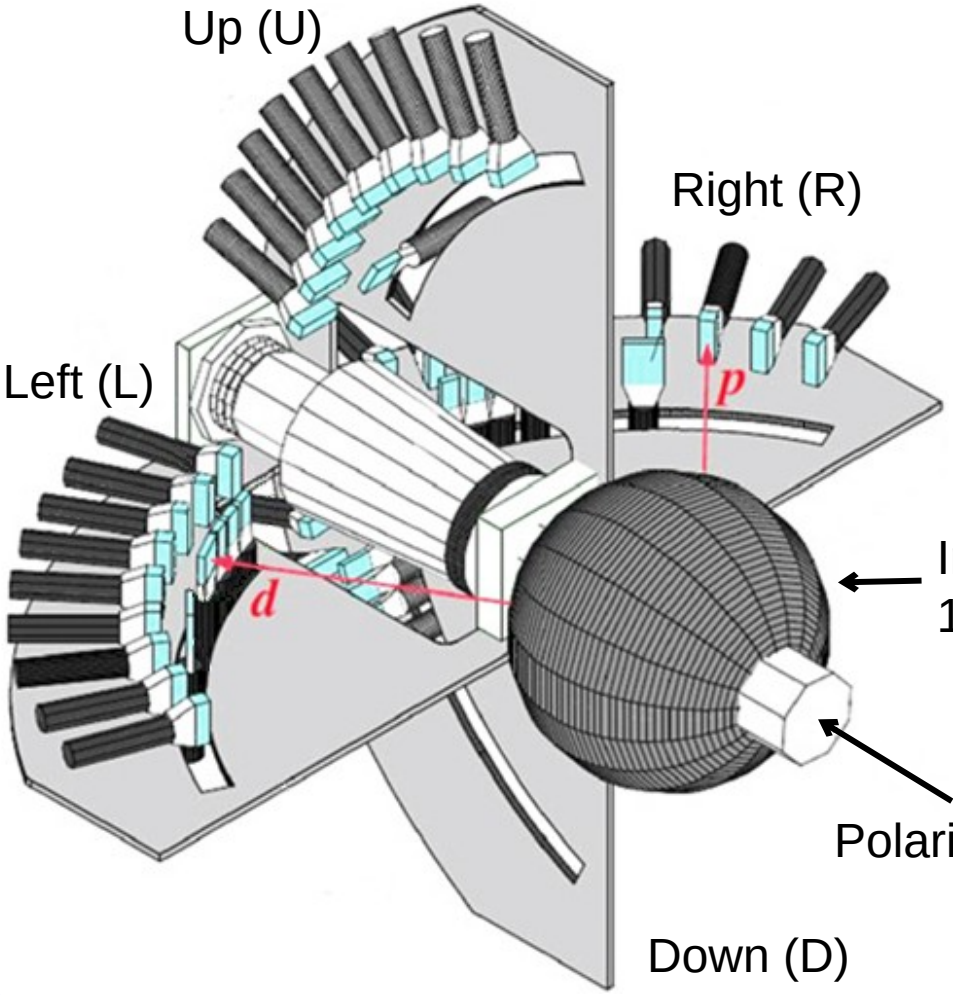
$$p_{zz} \approx \frac{\Delta\sigma}{\sigma}\frac{N\sigma z}{6}$$

Averaging over z

$$\bar{p}_{zz} \approx \frac{\Delta\sigma}{6\sigma}$$

p_{zz} is 4 times smaller due to tensor rotation in magnetic field!!!

Detectors and analyzing powers



Flux difference

$$\frac{U+D-R-L}{U+D+R+L} = \frac{1}{2}(A_{yy} - A_{xx})p_{zz}$$

Tensor analyzing powers

Internal target station (ITS)
10 μm CH_2

Polarized deuteron beam

Malakhov A.I. et. al. NIM A 440 (2000) 320.

270 MeV: Kurilkin P.K. et. al. NIM A. 642 (2011) 45; Satou Y. et al. Phys. Lett. B 549 (2002) 307

Asymmetry in up (down) and left (right) fluxes

Target: 10 μm CH2

Deuteron energy 270 MeV

The number of detected particles:

$N_{det}=N_U+N_D+N_R+N_L$

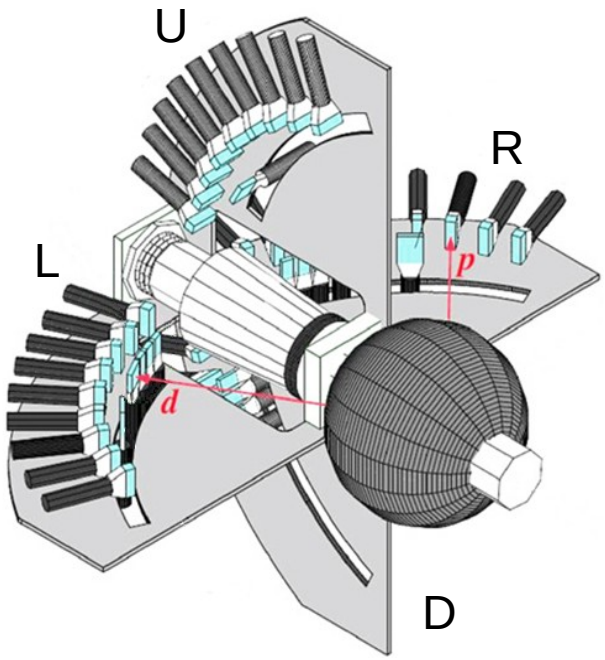
$$N_{det} \sim \frac{N_0}{\sigma} \int \frac{d\sigma_{el}}{d\Omega} d\Omega \approx 5 \cdot 10^{-5} N_0$$

Flux difference ($\Delta\sigma/\sigma=0.01$):

$N_{diff}=N_U+N_D-N_R-N_L$

$$N_{diff} \sim \frac{N_0 \bar{p}_{zz}}{\sigma} \int \frac{d\sigma_{el}}{d\Omega} (A_{yy} - A_{xx}) d\Omega \approx 5 \cdot 10^{-8} N_0$$

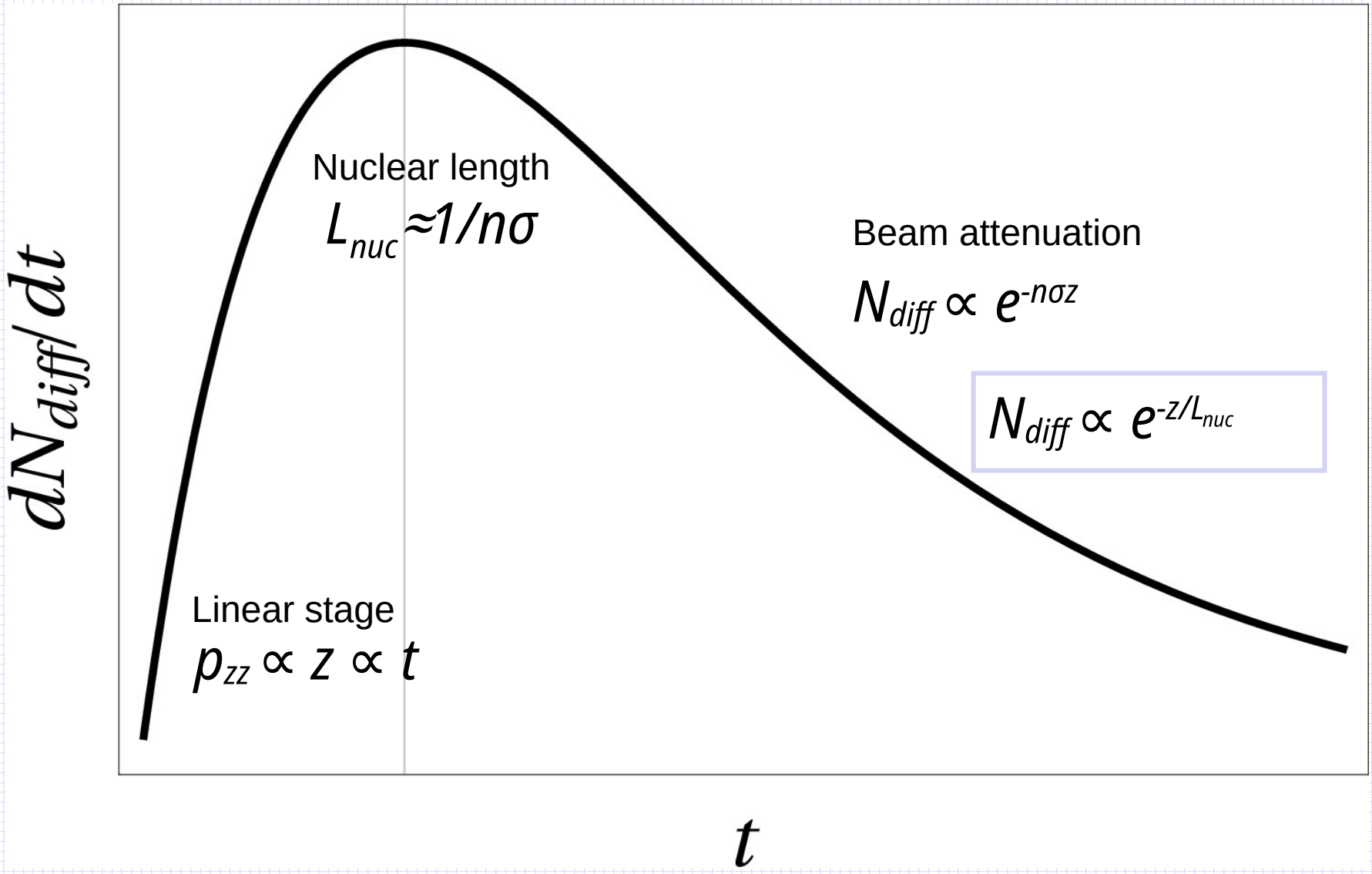
Statistical error: $\Delta N=N_{det}^{1/2}$



Internal target station

Target	Δσ/σ	N_0	N_{diff}	ΔN	p_{zz}	$T_{1\%}$
CH_2	0.01	10^{10}	500	700	0.002	30 hours
CH_2	0.06	10^{10}	3000	700	0.01	~1 hour

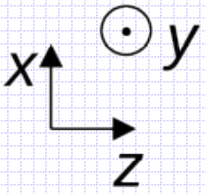
Detector counts



Deuteron dichroism (internal nonpolarized target)

Magnetic field presents in the ring and it is parallel to y-axis. It rotates spin component, which is parallel to the particle motion plane (xz).

TOP VIEW



Nonpolarized deuterons ($p_{zz}=0$)

$N_{+1}=N_{-1}=N_0$

Internal nonpolarized target

Deuterons with nonzero tensor polarization ($p_{zz}\neq 0$)

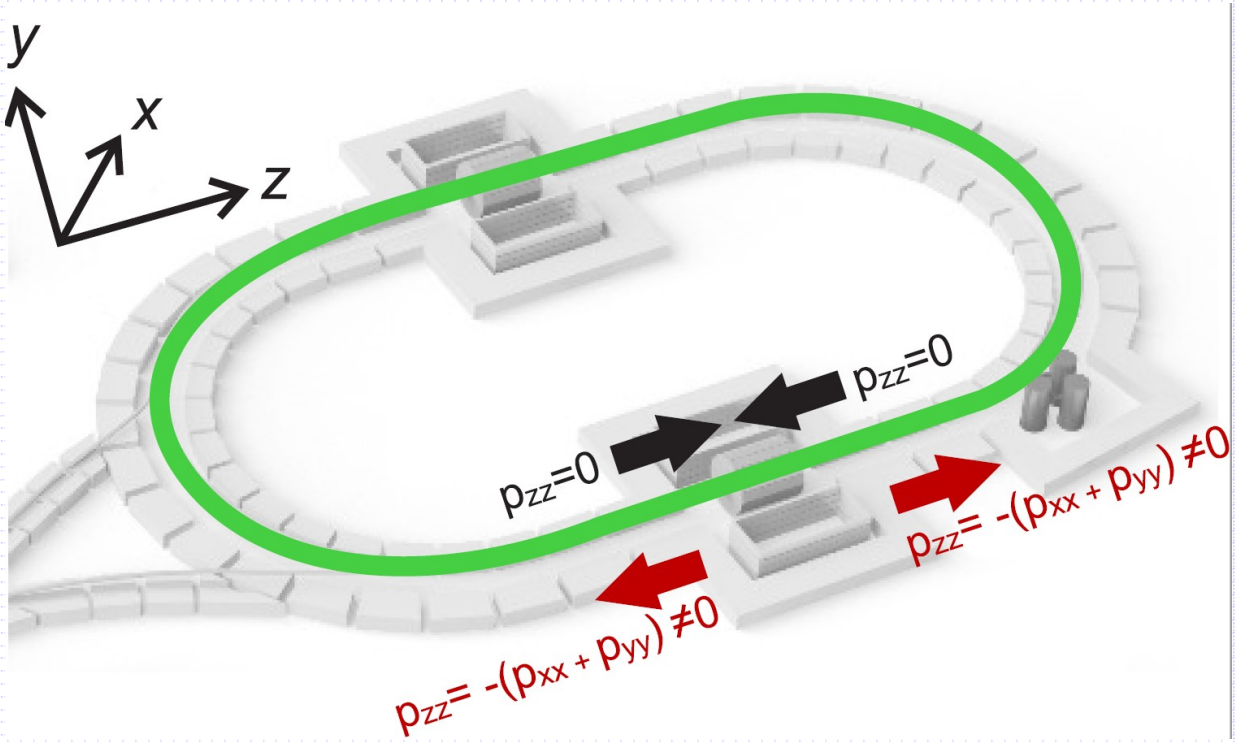
$N_{+1}=N_{-1}\neq N_0$

Particle	Target	E, MeV	N_{bunch}	σ, b	Δσ/σ	$\langle p_{zz}\rangle$	$T_{1\%}$
d	CH_2	270	10^{10}	0.8	**0.06**	$1\cdot10^{-2}$	~1 hour
d	CH_2	270	10^{10}	0.8	**0.01**	$2\cdot10^{-3}$	30 hours
d	C	3700	10^{10}	0.6	**0.06**	$1\cdot10^{-2}$	~hours
d	C	270	10^{10}	0.6	**0.06**	$1\cdot10^{-2}$	~hours

Experiments at Nuclotron M– NICA

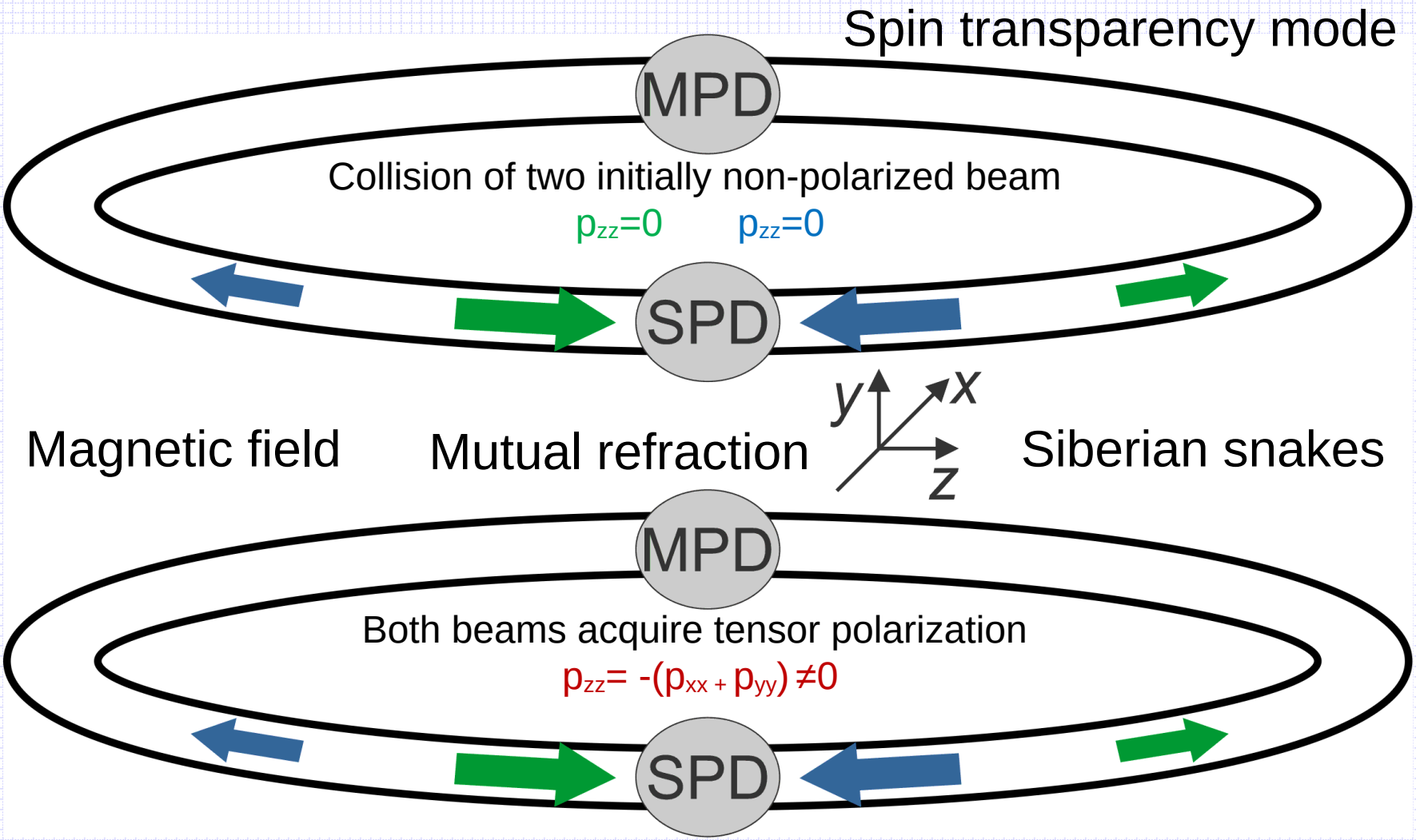
Due to the presence of not only unpolarized particles, but also polarized ones, it is possible to study not only spin dichroism, but also the effects of rotation and oscillations of the vector and tensor polarization of particles, arising as a result of nuclear precession and birefringence

Spin dichroism effects: evaluations for NICA



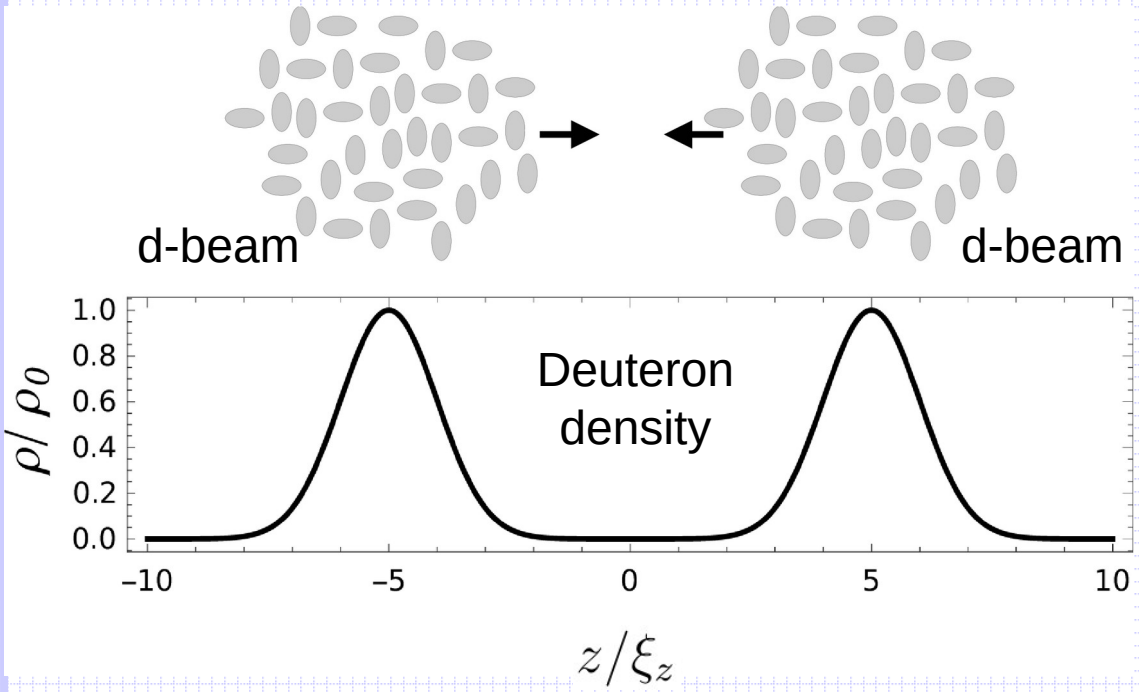
Particles	N per beam	σ, b	L, $cm^{-2}s^{-1}$	Δσ/σ	p_{zz}	T
d-d	$1.3 \cdot 10^{13}$	0.2	$4 \cdot 10^{31}$	0.01	$3 \cdot 10^{-5}$	2 hours
Ne-Ne	$4.4 \cdot 10^{10}$	1.4	10^{27}	0.1	$6 \cdot 10^{-5}$	10 hours
Ne-d	$4.4 \cdot 10^{10}$ (Ne)	0.7	$2 \cdot 10^{29}$	0.1	$1.2 \cdot 10^{-3}$ (Ne)	2 hours

Spin dichroism at collision of two initially non-polarized deuteron beams at NICA



Two collision points at SPD and MPD locations !!!

Collision of bunches



Tensor polarization in homogeneous target

$$p_{zz} = \frac{2}{3}\Delta\sigma\rho l$$

Deuteron density in the beam

$$\rho = \rho_0 \exp\left(-\frac{x^2}{2\xi_x^2} - \frac{y^2}{2\xi_y^2} - \frac{z^2}{2\xi_z^2}\right)$$

Average tensor polarization after one collision

$$\bar{p}_{zz}^{(1)} = \sqrt{\frac{2\pi}{9}}\Delta\sigma\rho_0\xi_z$$

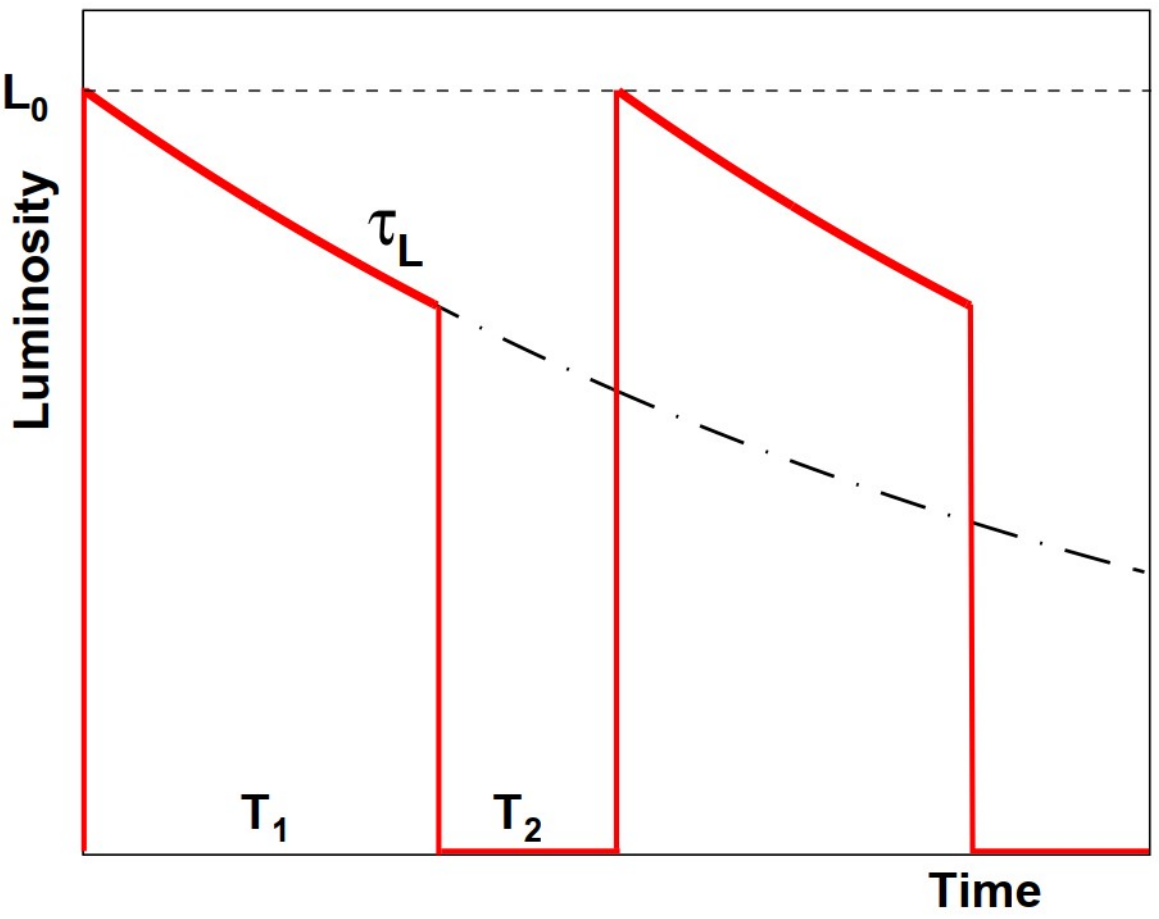
Tensor polarization averaged over time T expressed via the number of particles in the ring N and luminosity L

$$\bar{p}_{zz} = \frac{2}{3}\frac{\Delta\sigma}{\sigma}\frac{\sigma LT}{N}$$

Total cross-section σ is the sum of cross-section of elastic scattering and cross-section of a reaction.

Approximation: all scattered particles leave the orbit!
However, small-angle scattering requires special consideration!

NICA operation cycles



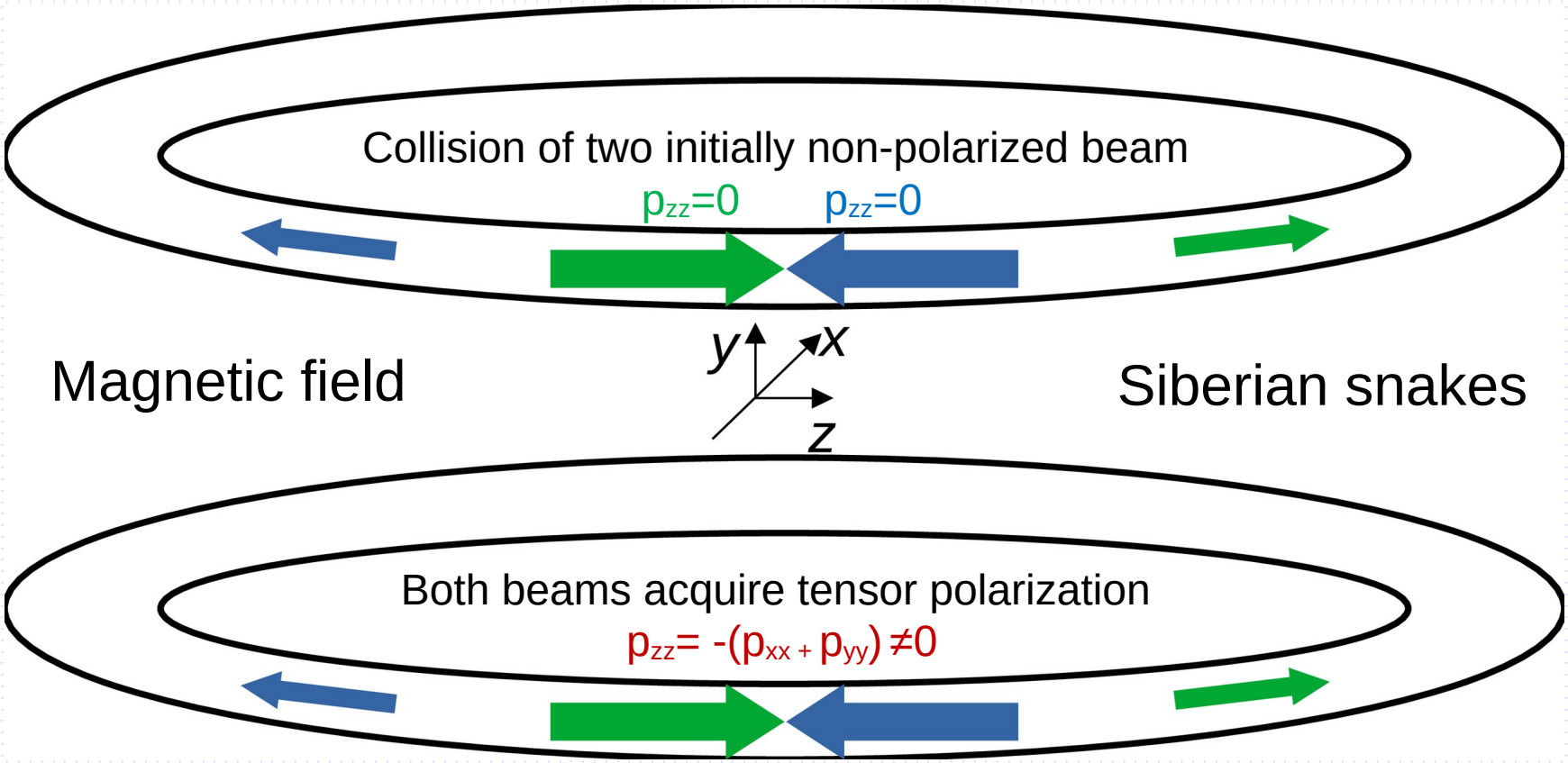
d-d colisions:

T_1 = 2 hours

Figure 3.4 (design report): Cycle of the collider operation // Abazov V., et al. Natural Sci. Rev. 1 (2024) 1.

Spin dichroism effects: evaluations for NICA

Spin transparency mode



Particles	N per beam	σ, b	L, $cm^{-2}s^{-1}$	Δσ/σ	p_{zz}	T
d-d	$1.3 \cdot 10^{13}$	0.2	$4 \cdot 10^{31}$	0.01	$3 \cdot 10^{-5}$	2 hours
d-d	$1.3 \cdot 10^{13}$	0.2	$4 \cdot 10^{31}$	**0.06**	$2 \cdot 10^{-4}$	2 hours

Statistically reliable effect value

Tensor polarization

$$\bar{p}_{zz} = \frac{2}{3}\frac{\Delta\sigma}{\sigma}\frac{\sigma LT}{N}$$

The number of reactions ($\sigma_r \sim \sigma$)

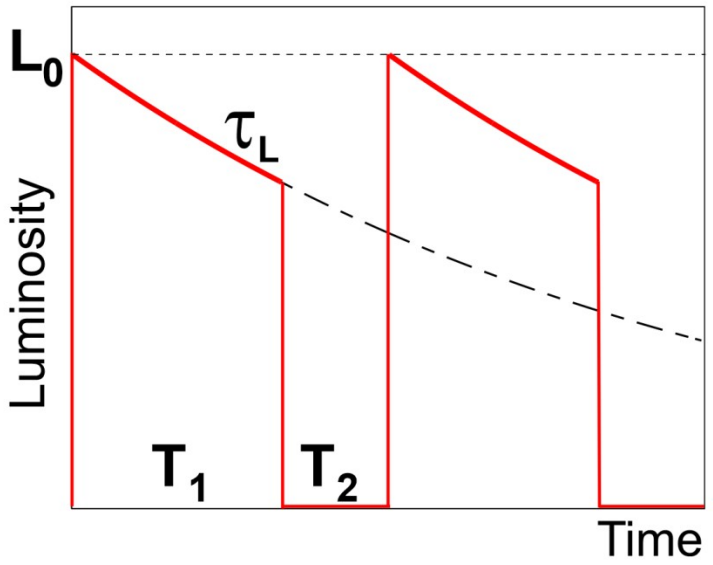
$$N_r = \sigma_r LT$$

Effect

$$N_{diff} \sim A_r N_r \bar{p}_{zz}$$

Statistical error

$$\Delta N_r \sim \sqrt{\sigma_r LT}$$



Observation time:

$T=N(T_1+T_2)$,

where N is the number of cycles.

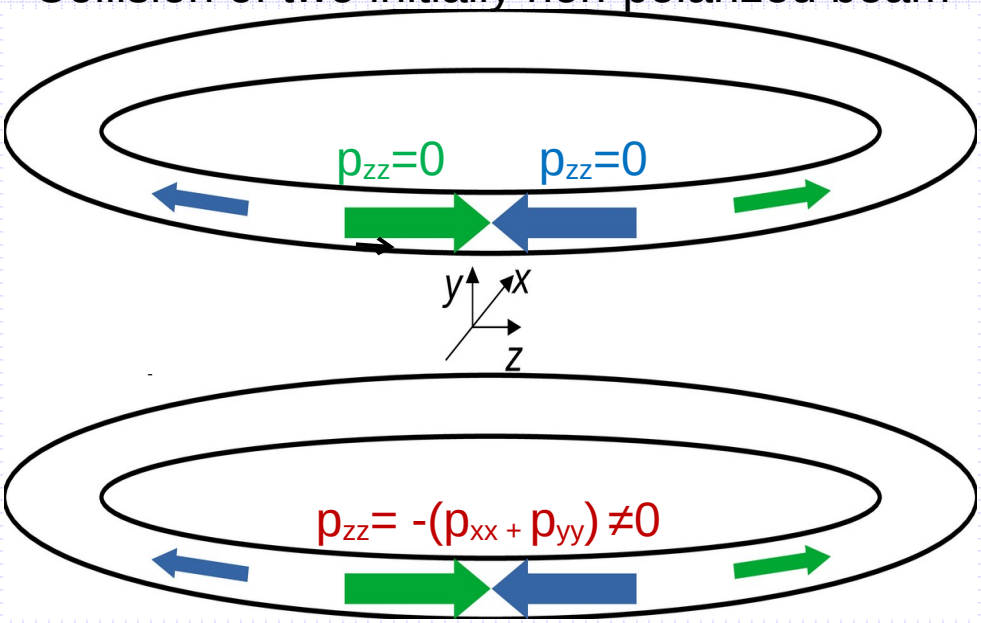
For T=1 month, we have

$\Delta N_r/N_{diff} \sim 2\cdot10^{-3}/A_r - 10^{-2}/A_r$

Part.	σ,b	Δσ/σ	N	N_{diff}	ΔN_r	p_{zz}	$T=T_1$
d-d	0.2	0.01	$1.3\cdot10^{13}$	$2\cdot10^6 A_r$	$2\cdot10^5$	$3\cdot10^{-5}$	2 hours
d-d	0.2	**0.06**	$1.3\cdot10^{13}$	$10^7 A_r$	$2\cdot10^5$	$2\cdot10^{-4}$	2 hours

Spin dichroism effects: evaluations for NICA

Collision of two initially non-polarized beam



Both beams acquire tensor polarization

There are no siberian snakes and spin transparency mode.

Nevertheless, the effect could be observed, while its value is 4 times lower

Particles	N per beam	σ, b	L, $cm^{-2}s^{-1}$	Δσ/σ	p_{zz}	T
d-d	$1.3 \cdot 10^{13}$	0.2	$4 \cdot 10^{31}$	**0.01**	$3 \cdot 10^{-5}$ **/4**	2 hours
d-d	$1.3 \cdot 10^{13}$	0.2	$4 \cdot 10^{31}$	**0.06**	$2 \cdot 10^{-4}$ **/4**	2 hours

P-odd and T-odd,P-odd T-even, P-even T-odd phenomena

Investigation of T-odd P-odd, T-odd P-even, T-even P-odd contributions in coherent quasi-optical phenomena to obtain constraints on parameters characterizing these contributions.

Forward scattering amplitude for a particle with spin S

Refractive index for particles with spin S: $\hat{N} = 1 + \frac{2\pi\rho}{k^2}\hat{f}(0)$

where $\hat{f}(0) = \mathrm{Tr}\hat{\rho}_J\hat{F}(0)$; $\hat{\rho}_J$ is the spin matrix of the scatterer; $\hat{F}(0)$ is the operator. Amplitude of forward scattering that acts in the spin space of the particle and the scatterer with spin *J* reads as follows:

$$\hat{F} = A + A_1 S_i J_i + A_2 S_i J_k n_i n_k + A_3 J_i J_k n_i n_k$$
$$+ A_4 S_i S_k n_i n_k + A_5 S_i S_k J_i J_k + A_6 S_i S_k n_i n_k J_l J_m n_l n_m + \ldots$$
$$\ldots + BS_i n_i + B_1 S_i I_m e_{iml} n_l + B_2 S_i n_i S_l J_l + B_3 S_i S_l n_i n_l J_m n_m$$
$$+ B_4 J_i n_i + B_5 S_i J_m e_{iml} n_l S_p n_p + \ldots$$

terms containing products of S_i and J_i up to *2S* and *2J*

- terms proportional to amplitudes *A* are P- and T-even;
- those proportional to B, B_2, B_3, B_4 are P-odd and T-even;
- one proportional to B_1 is P- and T-odd;
- one proportional to B_5 is P-even and T-odd;

В.Г. Барышевский, Ядерная физика, т.38 (1983) стр.1162-1169.
V.G. Baryshevsky, Phys. Lett. B 120 (1983) pp.267-269.
В.Г. Барышевский, Ядерная оптика поляризованных сред, Энергоатомиздат, 1995.
V.G.Baryshevsky, *High–Energy Nuclear Optics of Polarized Particles,* World Scientific, 2012.

Conclusion

The following can be proposed for starting investigations of nuclear optical phenomena at the Nuclotron-M NICA complex :

1. Investigation of spin dichroism effect and transformation vector polarization into tensor one for deuterons at Nuclotron with the internal target.
2. Detection and study of spin dichroism, rotation of spin and tensor polarization, and oscillations between vector and tensor polarizations for deuterons passing through an unpolarized target with the use of the extracted beam at Nuclotron.
3. Observation of tensor polarization acquiring by heavy nuclei (for example, Ne) when passing through an external target at Nuclotron.
4. Observation of spin dichroism effect for deuterons during collisions of nonpolarized deuteron beams at NICA.
5. The nuclear optics effects for polarized particles should be taken into account when studying various reactions since they can reveal as systematic errors.

Thank you for attention!!

