A search for nEDM and new constraints on short-range "pseudo-magnetic" interaction using neutron optics of noncentrosymmetric crystals

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Petersburg Nuclear Physics Institute of National Research Center “Kurchatov Institute” in Gatchina

Emperor Paul castle

Apostle Paul Cathedral

Venus Pavilion

fire-lookout tower

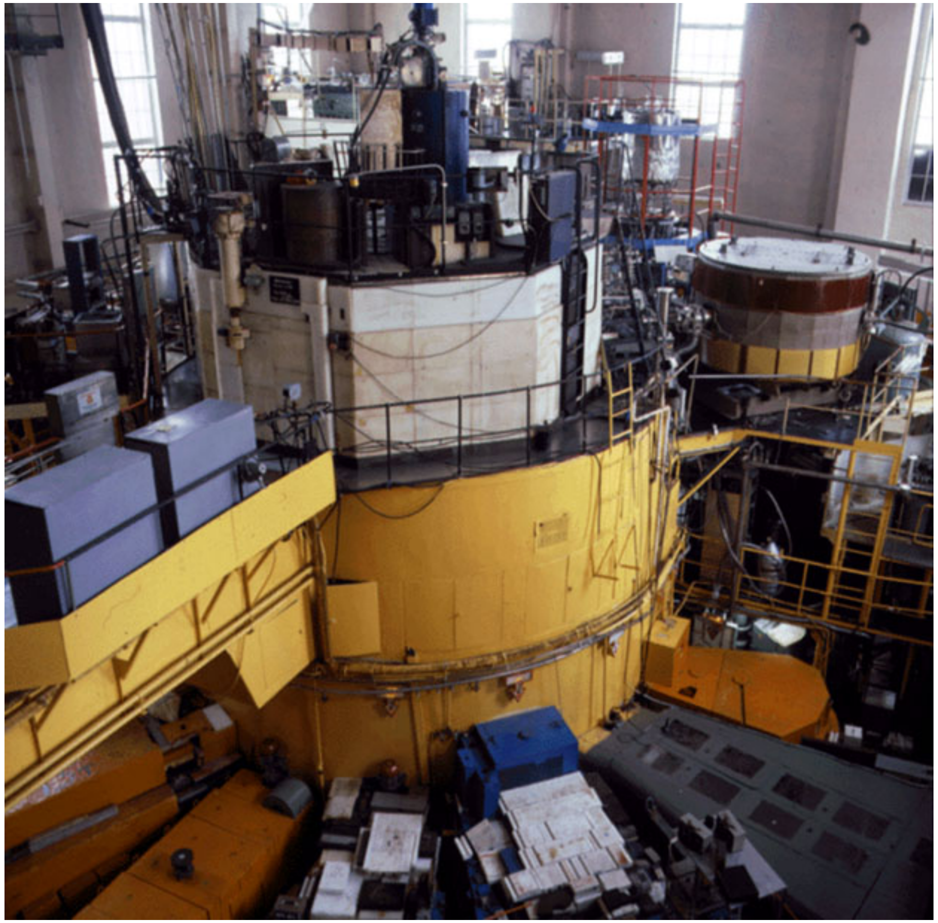
Prior Palace
(Order of the Knights of Malta)

Church of the Intercession
of the Holy Virgin

Reactor facilities of Petersburg Nuclear Physics Institute

Acting (from 1959) WWR-M
18 MW reactor

The 100 MW reactor PIK
(under construction)



Now reactor PIK has achieved important step in its construction:

The fuel elements were first loaded on February 28 last year. The reactor core was partly filled with the fuel assemblies.

Critical condition was achieved. First neutrons were obtained. **This fact provides inspiration for all future neutron beam users.**

Power increasing till designed 100 MW can be done step by step only when all the reactor buildings for auxiliary and alarm systems will be finalized in construction.

Nowaday view of reactor PIK complex

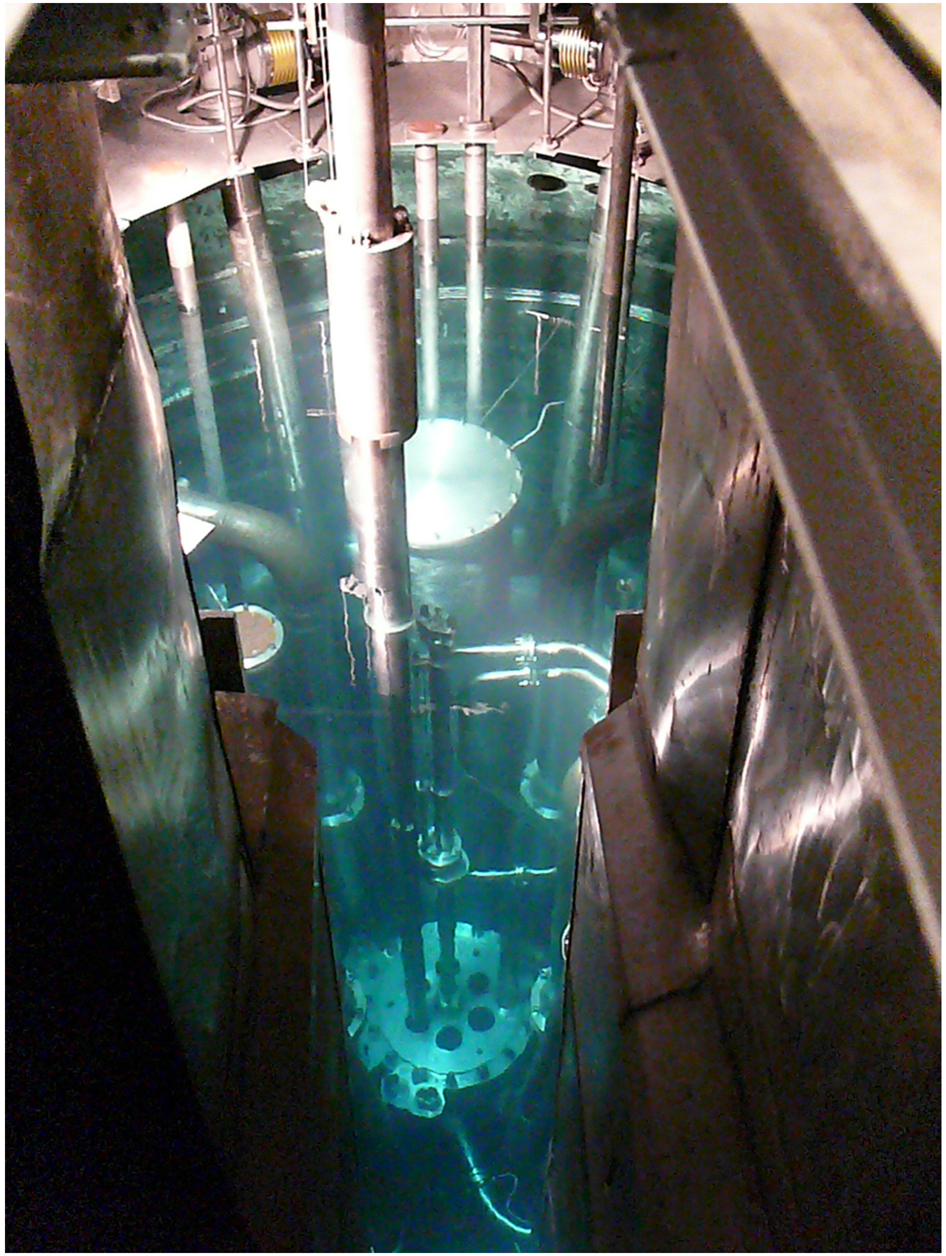
A

Technology hall.
Mounting of the reactor body

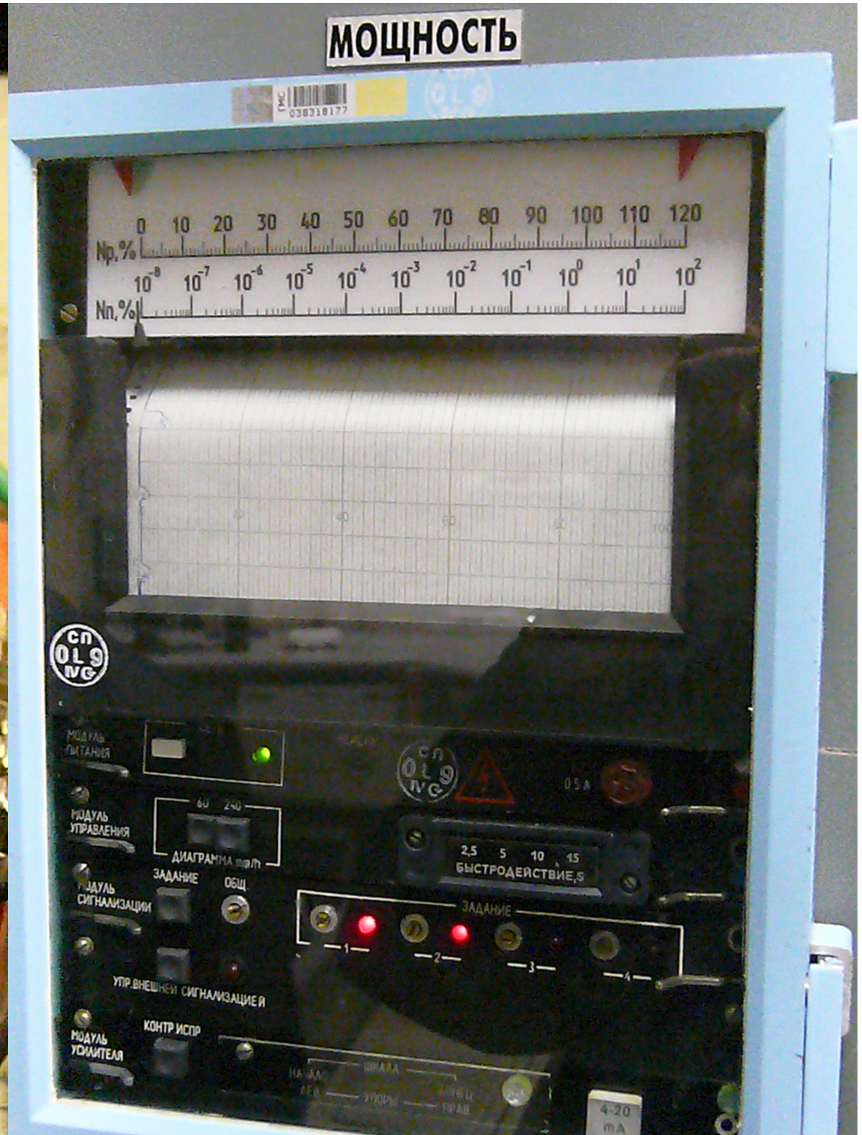
Sanitary inspection room

Reactor control panel

K.A. Konoplev. First fuel element to be loaded into ractor core



Loading the fuel elements



Recorder “sees” the neutrons

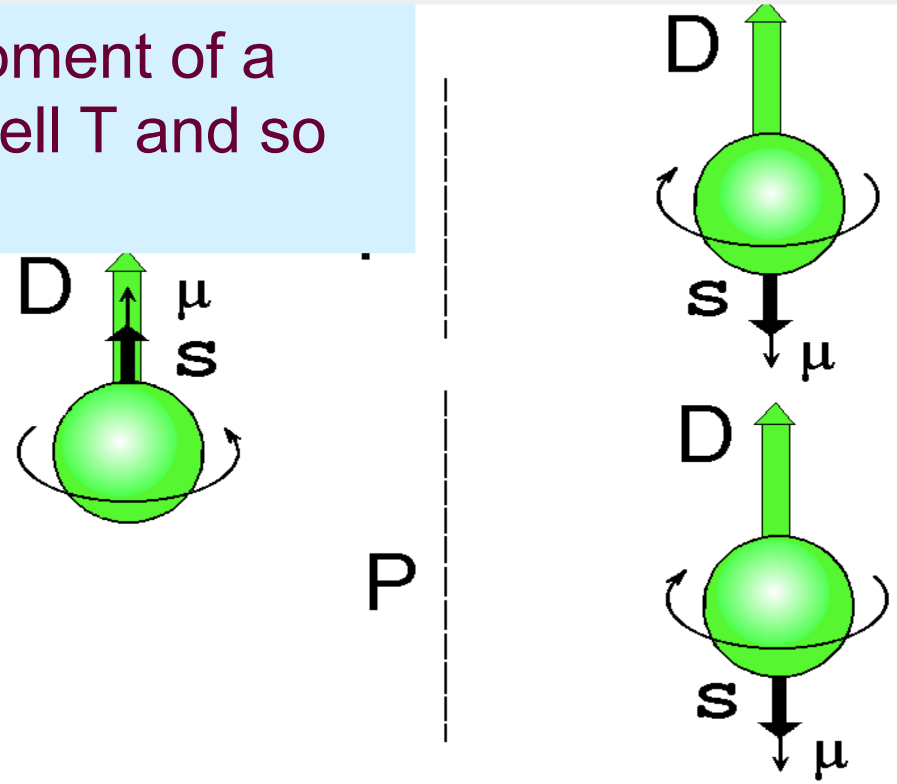
9 fuel elements were loaded

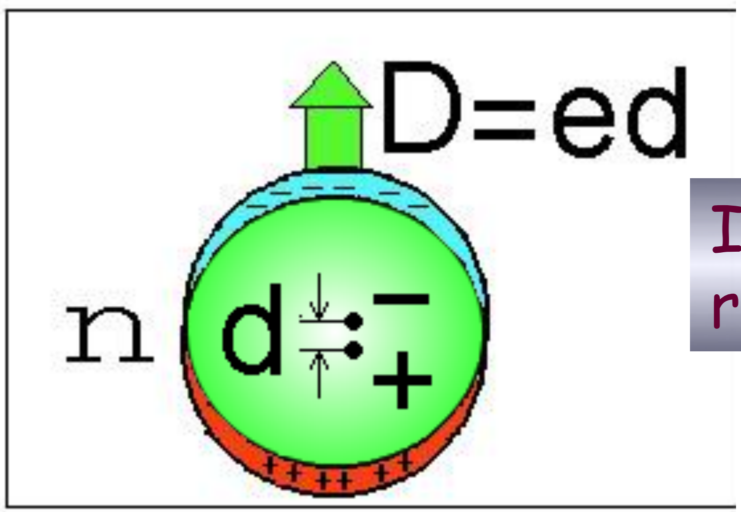
A few words about Neutron EDM

Existence of the Electric Dipole Moment of a particle violates P invariance as well T and so CP invariance

The last result $d_n \le 3\cdot10^{-26}$ e·cм (ILL, RAL, Sussex Un.) PRL, 2006, 97, 131801) – is not much better 23 years old results of PNPI and ILL

$d_n \le 9{,}7\cdot10^{-26}$ e·cm, PNPI, 1989





If you imagine a neutron as a sphere of radius R ~ 10^{-13} cm, than d/R ~ $3\cdot 10^{-13}$.

Such a part of Earth radius is approximately ~ 2 μm

History of nEDM experiment from Ramsey pioneering work (published in 1957)

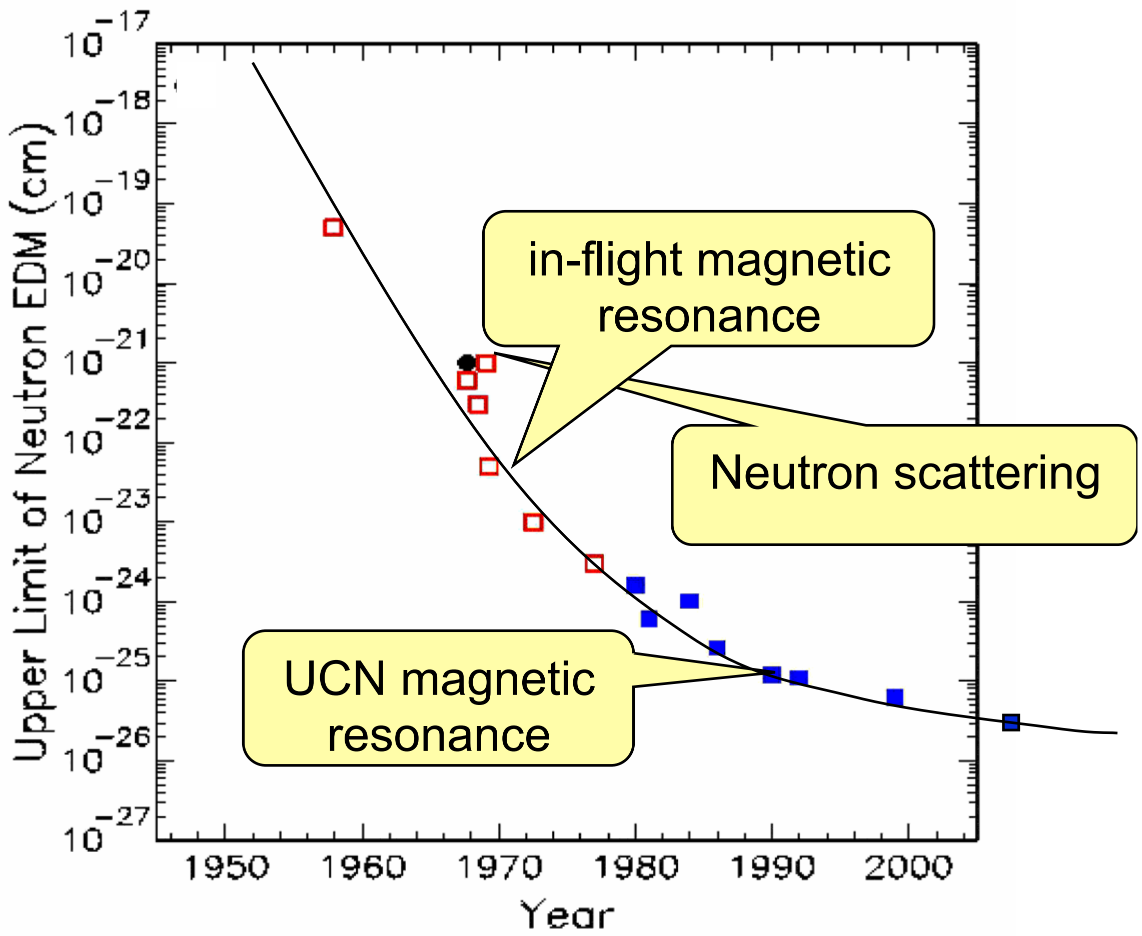
Standard model

$d_n \sim (10^{-31}-10^{-33})$ e cm

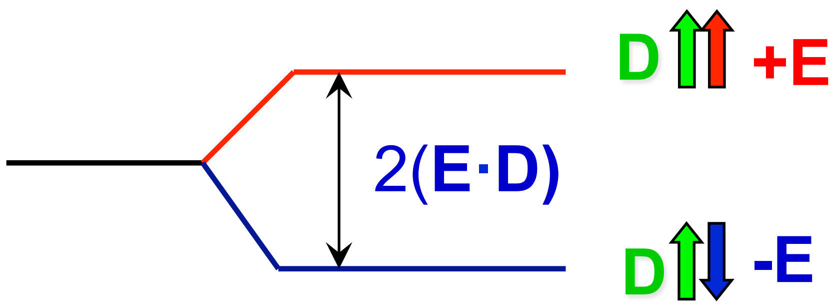
the baryon asymmetry
$n_b/n_\gamma \sim 10^{-25}$

New physics to explain the baryon asymmetry (experiment - $n_b/n_\gamma \sim 10^{-10}$)

$d_n \sim (10^{-26}-10^{-28})$ e cm



Sensitivity to neutron EDM



Interaction time with **E**

$$\varphi_D = 2(\mathbf{E}\cdot\mathbf{D})\tau / h$$

$$\sigma^{-1} \sim E\tau\sqrt{N}$$

Advantages of diffraction method of the nEDM search

- Strong electric field (**up to10^9 V/cm**), acts on neutron moving close to diffraction condition in a crystal without center of symmetry. It leads to spin rotation effects.

  (In lab only field ~**10^4 V/cm is available)**

- Direction of this field is perpendicular to crystallographic plane

- Feasibility of controlled changing the **sign and the value** of the electric field acting on neutron in crystal.

- A few ways to eliminate the false Schwinger effect

- The feasibility to use the assembling of a few different crystals to increase the interaction time

Comparison of Sensitivities

$$\sigma^{-1} \sim E\tau\sqrt{N}$$

UCN method

E ~ 10 kV/cm

τ_{max} ~ 1000 s (**neutron lifetime**)

$E\tau$ ~ 10^4(kV·s)/cm

(Current value

$E\tau \approx 10^3$ (kV·s)/cm)

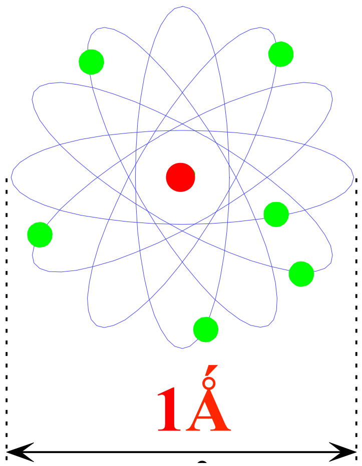
Crystal-diffraction method

E ~ (10^5- 10^6) kV/cm

τ_a ~ 0.01 c (absorption)

Ionization Energy

from few eV to tens eV



$E\tau$

10^4 (kV · s)/cm

Parameters of some NCS crystals

Crystal	Symmetry group	hkl	d, (Å)	E_g, 10^8V/cm	τ_a, ms	$E_g\,\tau_a$, (kV·s/cm)
α-quartz (SiO_2)	32(D^6_3)	111	2.236	**2.3**	**1**	**230**
		110	2.457	**2.0**		**200**
$Bi_{12}SiO_{20}$	I23	433	1.75	4.3	**4**	**1720**
		312	2.72	2.2		**880**
$Bi_4Si_3O_{12}$	-43m	242	2.10	4.6	2	**920**
		132	2.75	3.2		**640**
PbO	P c a 21	002	2.94	10.4	**1**	**1040**
		004	1.47	10		**1000**
BeO	6mm	011	2.06	5.4	7	**3700**
		201	1.13	6.5		**4500**

!!! We should looking for new NCS crystal !!!

Essence of experiment

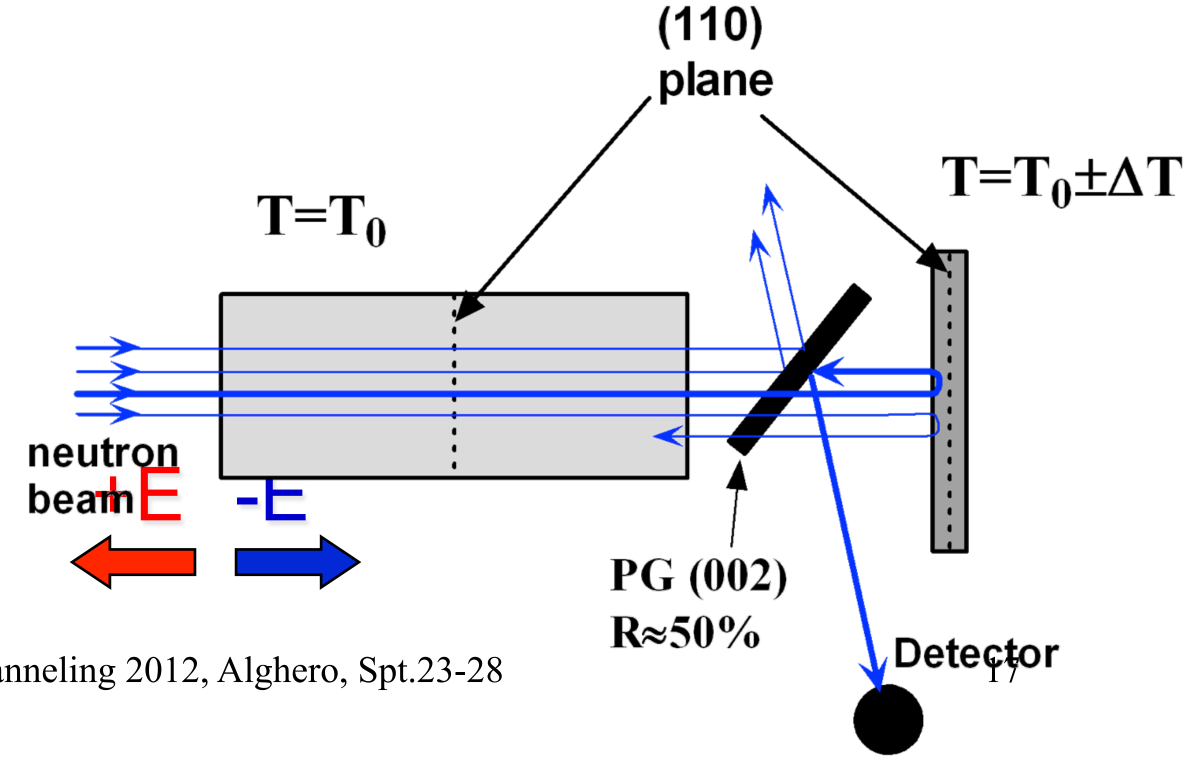
The neutrons with $\lambda_B = 2d_0 \sin\theta_B$ reflect from crystal.

For $\theta_B \approx \pi/2 \rightarrow \lambda_B \approx 2d_0\,[1-(\pi/2-\theta_B)^2]$

Notice, that only the neutrons with $\lambda > \lambda_B$ and $\lambda < \lambda_B$ can pass through crystal and they will move in electric field **–E** and **+E** correspondingly.

We can select this passed neutrons by the second crystal - reflector (analyzer) with controlled interplanar spacing

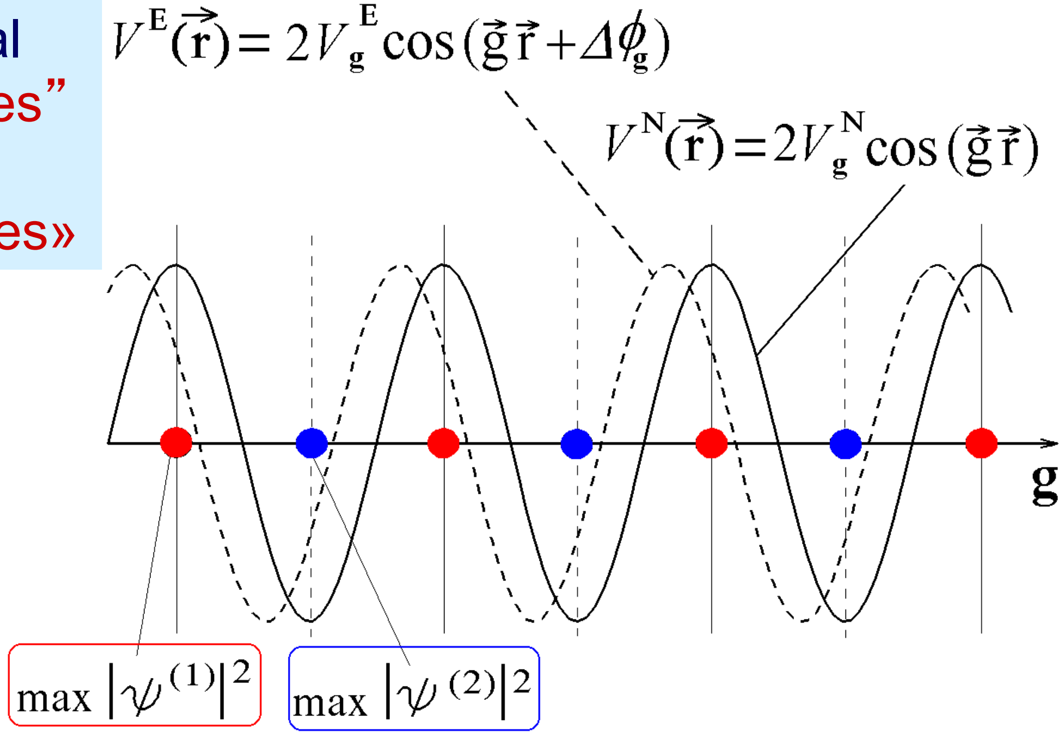
Changing ***d*** of analyzer (by heating or cooling) one can control electric field acting on neutron



Essence of the phenomena

In the non-centrosymmetric crystal the positions of the "nuclear planes" are shifted from that of «charge ones», and also from «mass planes»

Neutrons are concentrated on the "nuclear planes" or between them (on the maxima or on the minima of the nuclear potential).



In the non-centrosymmetric crystal neutrons turn out to be under a strong electric field (and also «pseudomagnetic» field)

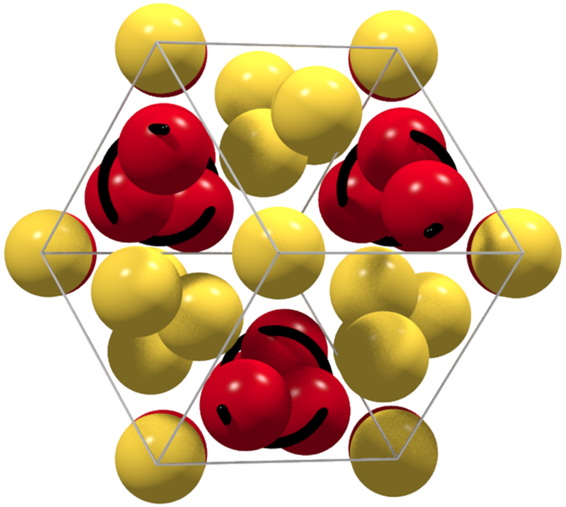
$$E(r) = -\text{grad } V^E(r) = 2V_g^E \boldsymbol{g} \sin(\boldsymbol{g}\boldsymbol{r} + \Delta\phi_g)$$

$$\boldsymbol{E}_g = \langle \psi^{(1)} | \boldsymbol{E}(\boldsymbol{r}) | \psi^{(1)} \rangle = -\langle \psi^{(2)} | \boldsymbol{E}(\boldsymbol{r}) | \psi^{(2)} \rangle = \boldsymbol{g} V_g \sin \Delta\phi_g$$

$E_g = (10^8 - 10^9)$ V/cm

Essence of the phenomena

Harmonic amplitudes V_g are determined by structure amplitudes F_g (sell scattering amplitude):



$$V_g = -\frac{2\pi h^2}{m} N_c F_g,$$

$$F_g = \sum_i e^{-W_{ig}} f_i(\mathbf{g}) e^{-i\mathbf{g}\mathbf{r}_i}.$$

$$f_i^N(\mathbf{g}) = -a_i; \quad f_i^E(\mathbf{g}) = -2r_n \frac{Z_i - f_{ic}(\mathbf{g})}{D_{cn}^2 g^2}.$$

Nuclear amplitudes determine nuclear potential

Electric amplitude determine electric potential (charge distribution)

Essence of the phenomena

We can write the electric potential in the same way

$$V^E(\boldsymbol{r}) = 2V_g^E \cos(\boldsymbol{g}\boldsymbol{r}) =$$
$$= V_g^E \exp(i\boldsymbol{g}\boldsymbol{r}) + V_g^E \exp(-i\boldsymbol{g}\boldsymbol{r})$$

The electromagnetic neutron interaction contains electric field (not a potential)

$$V^{EM}(\boldsymbol{r}) = D(\boldsymbol{\sigma}\mathbf{E}) + \mu \frac{(\boldsymbol{\sigma}[\mathbf{E}\times\mathbf{v}])}{c}$$

$$\mathbf{E}(\boldsymbol{r}) = -\mathrm{grad}\ V^E(\boldsymbol{r}) =$$
$$= i\boldsymbol{g}V_g^E \exp(i\boldsymbol{g}\boldsymbol{r}) - i\boldsymbol{g}V_g^E \exp(-i\boldsymbol{g}\boldsymbol{r}) =$$
$$= 2V_g^E \boldsymbol{g}\sin(\boldsymbol{g}\boldsymbol{r})$$

So electromagnetic scattering amplitude is imaginary

Neutron scattering amplitude for short range Yukawa-type potential of fermion-fermion interaction due to exchange of pseudoscalar light particle (J.E.Moody and Frank Wilczek, Phys.Rev.D **30** (1984) 130 **is also imaginary as the electric one**

Direct calculation for neutron-nucleon interaction gives

$$V_{sp}(g) = -\frac{i\hbar^2 g_s g_p}{2m}\frac{g\lambda^2}{1+g^2\lambda^2}(\boldsymbol{\sigma}\mathbf{n}_{\mathbf{g}})$$

$$\mathbf{n}_{\mathbf{g}} = \mathbf{g}/|\mathbf{g}|$$

It seems as interaction of spin with some pseudo magnetic field that is gradient of pseudo magnetic potential

g-harmonics of neutron interaction with the crystal will be

$$\hat{V}_g^{SP} = -iF_g^{SP}e^{i\Phi_g^{SP}}\frac{\hbar^2 g_s g_p}{2mV_c}\frac{g\lambda^2}{1+g^2\lambda^2}(\boldsymbol{\sigma}\mathbf{n}_g)$$

$$f_g^{SP} \equiv F_g^{SP}e^{i\Phi_g^{SP}} = \sum_i A_i \cdot e^{i\mathbf{g}\mathbf{r}_i}$$

is a structure factor determined by mass distribution

A_i is a mass number of i nucleus

Neutron optics in the crystal without center of symmetry

One can write the neutron wave function in crystal, using the perturbation theory for directions and energies far from the Bragg ones, in the following form

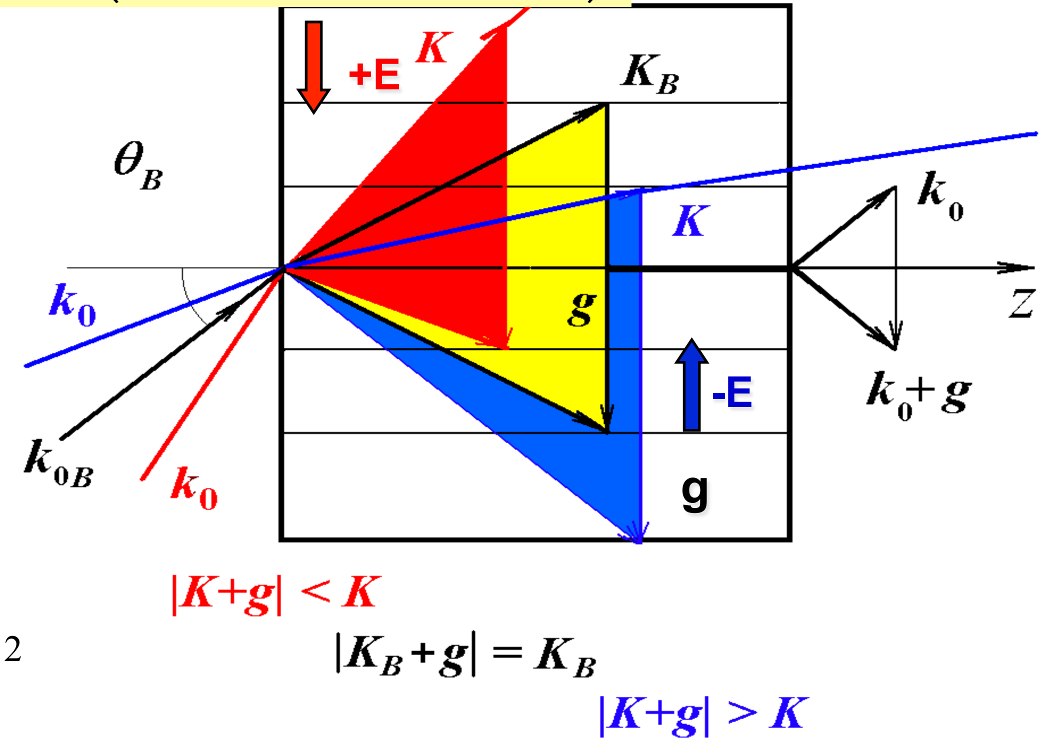
$$\psi = e^{i\mathbf{Kr}} + \sum_g \frac{V_g}{E_K - E_{K+g}} \cdot e^{i(\mathbf{K}+\mathbf{g})\mathbf{r}} =$$

$$= e^{i\mathbf{Kr}}\left(1 - \sum_g \frac{V_g}{\Delta_g^{\varepsilon}} \cdot e^{i\mathbf{gr}}\right) = e^{i\mathbf{Kr}}\left(1 - \sum_g \frac{1}{w_g} \cdot e^{i\mathbf{gr}}\right)$$

$E_K = \hbar^2 K^2/2m,$

$E_{K+g} = \hbar^2 |K+g|^2/2m$

$$\frac{1}{w_g} = \frac{V_g}{\Delta_g^{\varepsilon}} = \frac{\gamma_B}{\Delta\theta} = \frac{\Delta\lambda_B}{\Delta\lambda}$$

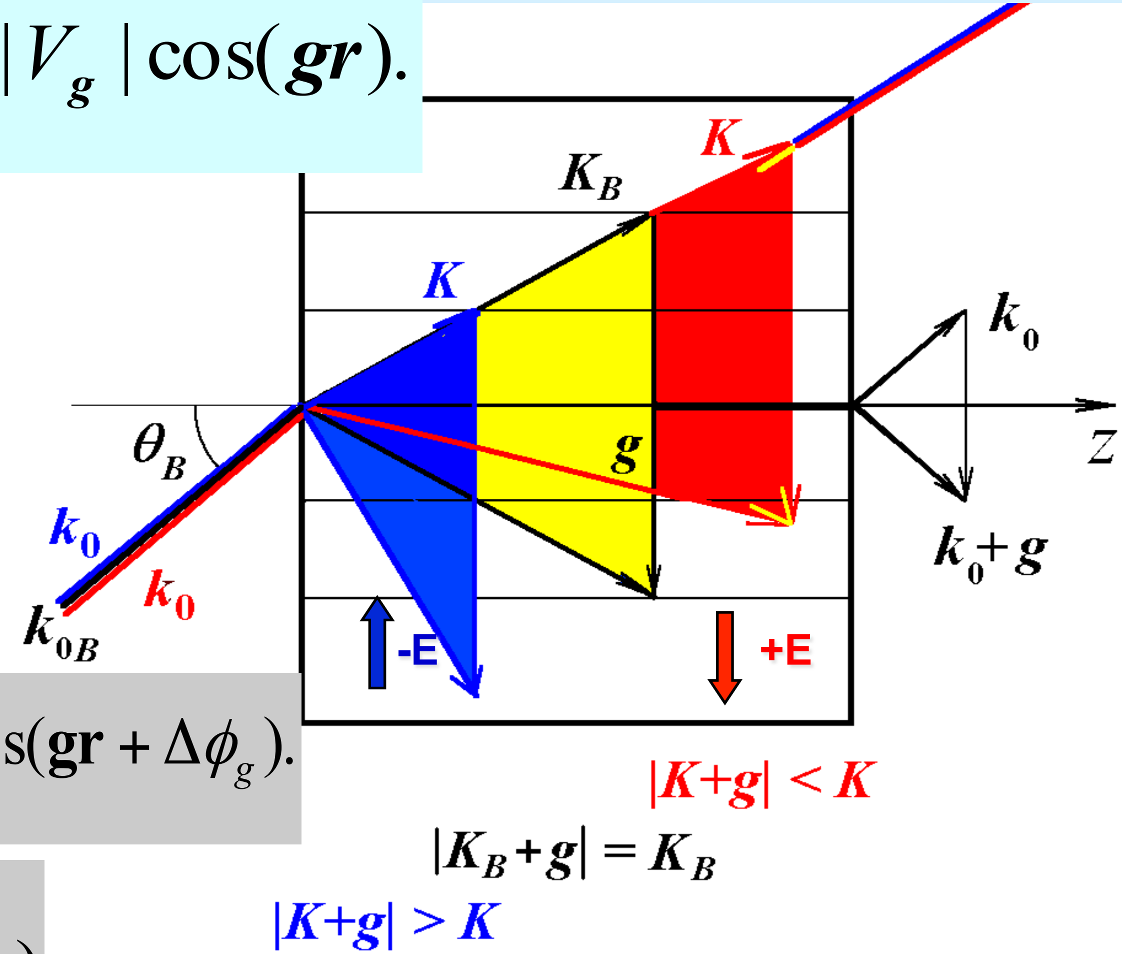


Depending on the sign of the deviation parameter from the Bragg condition **$2\Delta_g=|K+g|^2-K^2$**, the neutrons concentrate on the nuclear planes or between them (on the maxima of nuclear potential **($\Delta_g<0$, red colour)**, or on its minima **($\Delta_g>0$, blue colour)**

$$V^N(\boldsymbol{r}) = \sum_g V_g e^{i\boldsymbol{gr}} = \sum_g 2|V_g|\cos(\boldsymbol{gr}).$$

$$|\psi|^2 = 1 - \sum_g \frac{2v_g^N}{\Delta_g^\varepsilon}\cos\mathbf{gr}$$

For noncentrosymmetric crystal "electric planes" are shifted relatively to the "nuclear" ones



$$V^E(\mathbf{r}) = \sum_g V_g^E e^{i\mathbf{gr}} = \sum_g 2|V_\mathbf{g}|\cos(\mathbf{gr}+\Delta\phi_g).$$

$$\mathbf{E}_{sum} = \sum_g \frac{2v_g^N}{\Delta_g^\varepsilon} v_g^E \mathbf{g}\sin(\Delta\phi_g)$$

A spin rotation angle due to Shwinger interaction is

$$\Delta\varphi_S = \frac{2}{\hbar c v}\mu\boldsymbol{\sigma}\cdot\left[\mathbf{E}_{\mathbf{sum}}\times\mathbf{v}\right]$$

$$\mathbf{E}_{sum} = \sum_g \frac{2v_g^N}{\Delta_g^{\varepsilon}} v_g^E \mathbf{g}\sin\Delta\phi_g$$

In the considered case only one system of crystallographic planes **g** is essential

$$\mathbf{E}_g^{(1,2)} = \pm\frac{1}{\sqrt{1+w_g^2}} v_g^E \mathbf{g}\sin\Delta\phi_g = \pm\frac{E_g}{\sqrt{1+w_g^2}}$$

"Pseudomagnetic" field also is determined by the shift of "pseudomagnetic" planes relative to nuclear ones

$$\hat{V}_{SP} = <\psi(\mathbf{r})|V_{SP}(\mathbf{r})|\psi(\mathbf{r})> = \frac{U_g^N}{\Delta_g}|\hat{V}_g^{SP}|\sin\Phi_g^{SP} =$$

$$= \frac{U_g^N}{\Delta_g} F_g^{SP} \frac{h^2 g_s g_p}{2mV_c} \frac{g\lambda^2}{1+g^2\lambda^2}(\sigma\mathbf{n}_g)\sin\Phi_g^{SP} \equiv V_{SP}(\sigma\mathbf{n}_g).$$

deviation from Bragg condition

phase shift

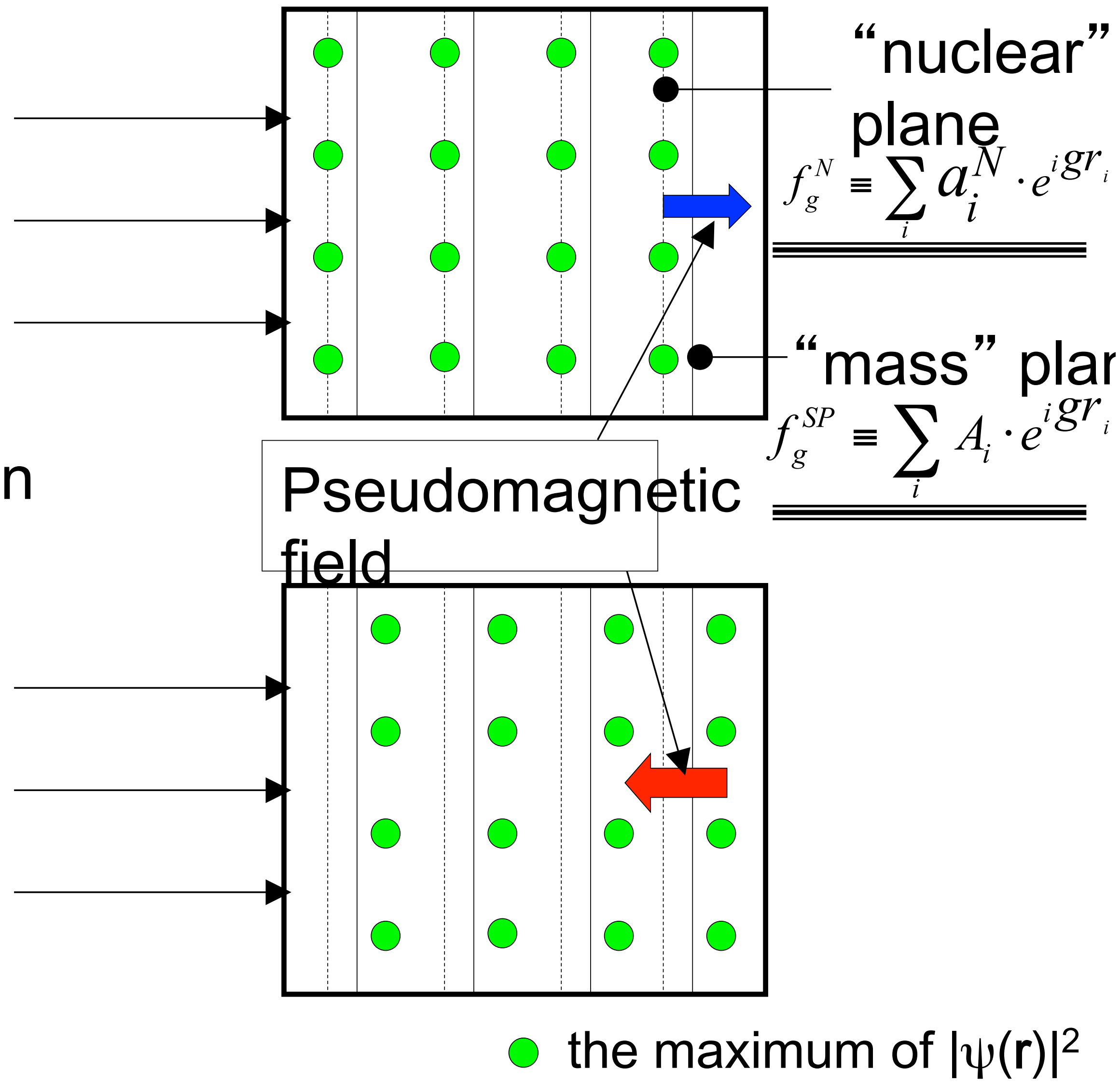
Time of neutron passage through the crystal

Angle of neutron spin rotation $\varphi_{SP} = \frac{2V_{SP}}{h}\tau$

For crystal with a center of symmetry $\varphi_{SP} \equiv 0$ because $\Phi_g^{SP} \equiv 0$

Neutron passage through the crystal, Bragg angle close to the right one

$E_n > E_g$

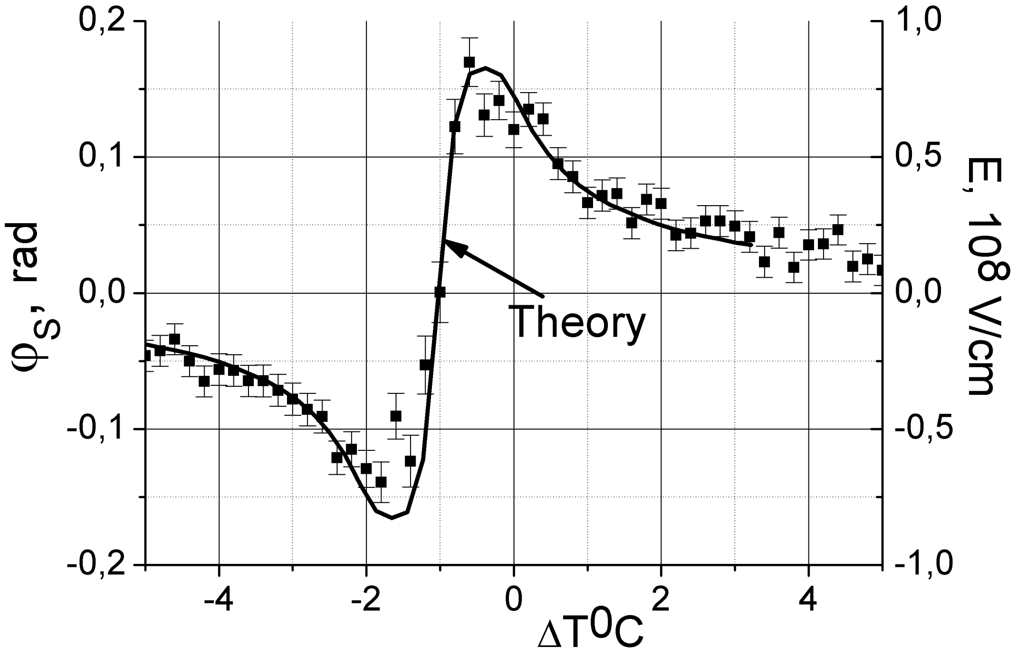


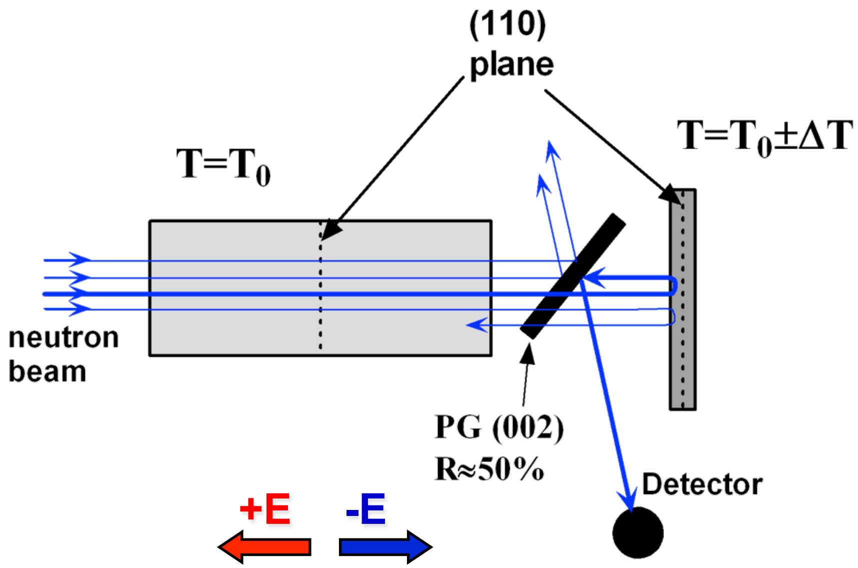
Neutron energy
of exact Bragg condition

$$E_g = h^2 g^2 / 8m$$

$E_n < E_g$

Test experiments (WWR-M, HFR)



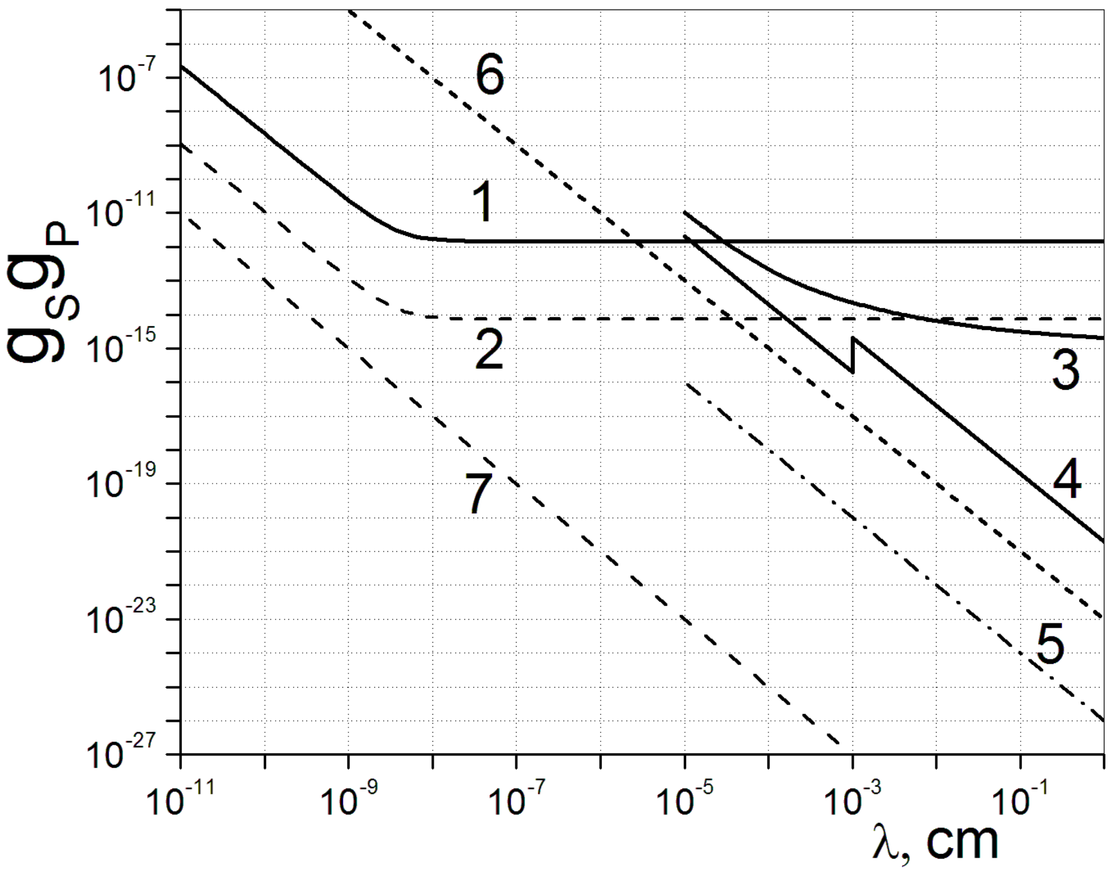


Dependence of interplanar electric field, acting on neutron, on the temperature difference of two crystals (quartz (110) plane, L_c=14 cm, Bragg angle ≈ 86^0

From the test experiment it follows that the sensitivity to measure the EDM is ~ 2 · 10^{-25} e·cm/day (3 times better than in ILL UCN experment)

Simultaneously we can search for short range Yukawa-type fermion-fermion "pseudomagnetic" interaction due to exchange of pseudo scalar light (axion-like) particle

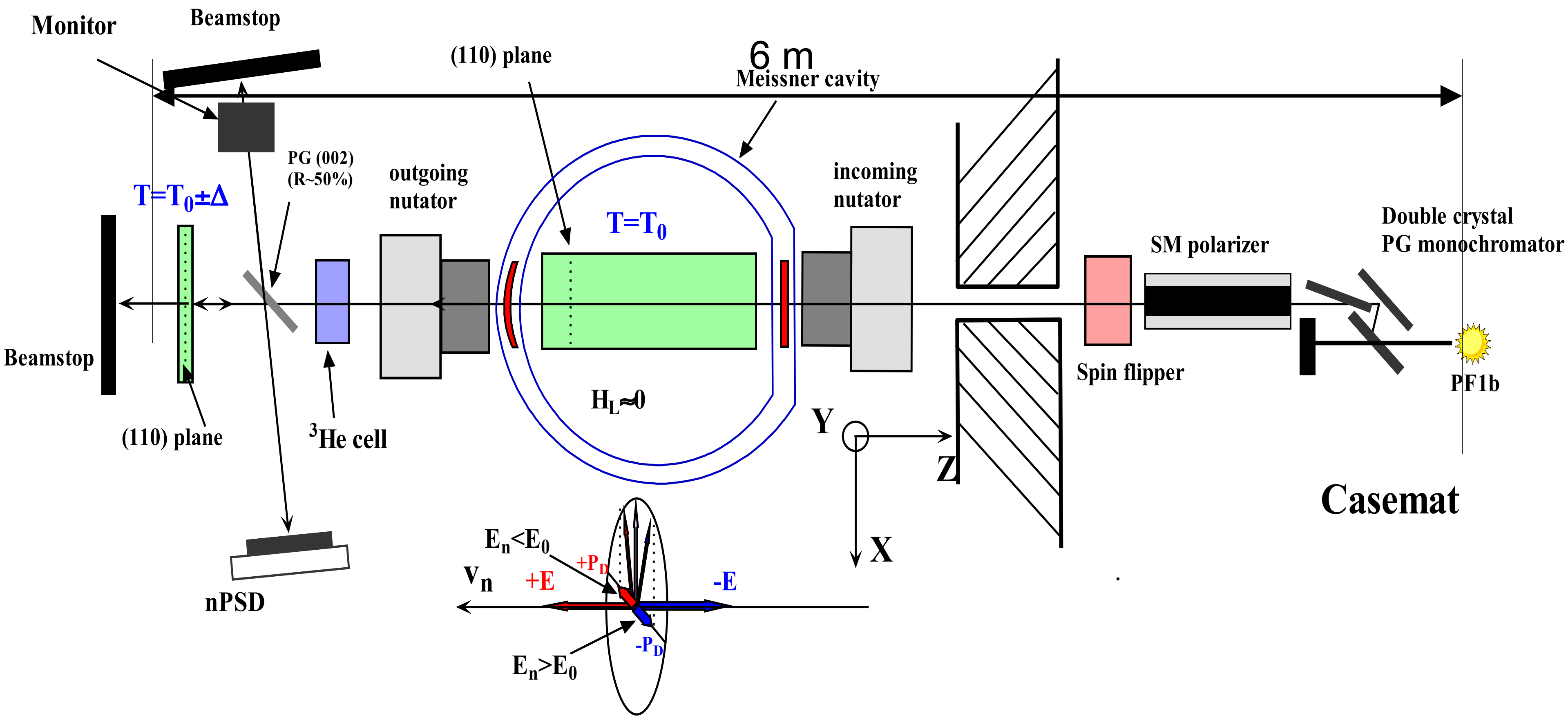
Constraints on the ($g_s g_p$;λ) from the test experiment



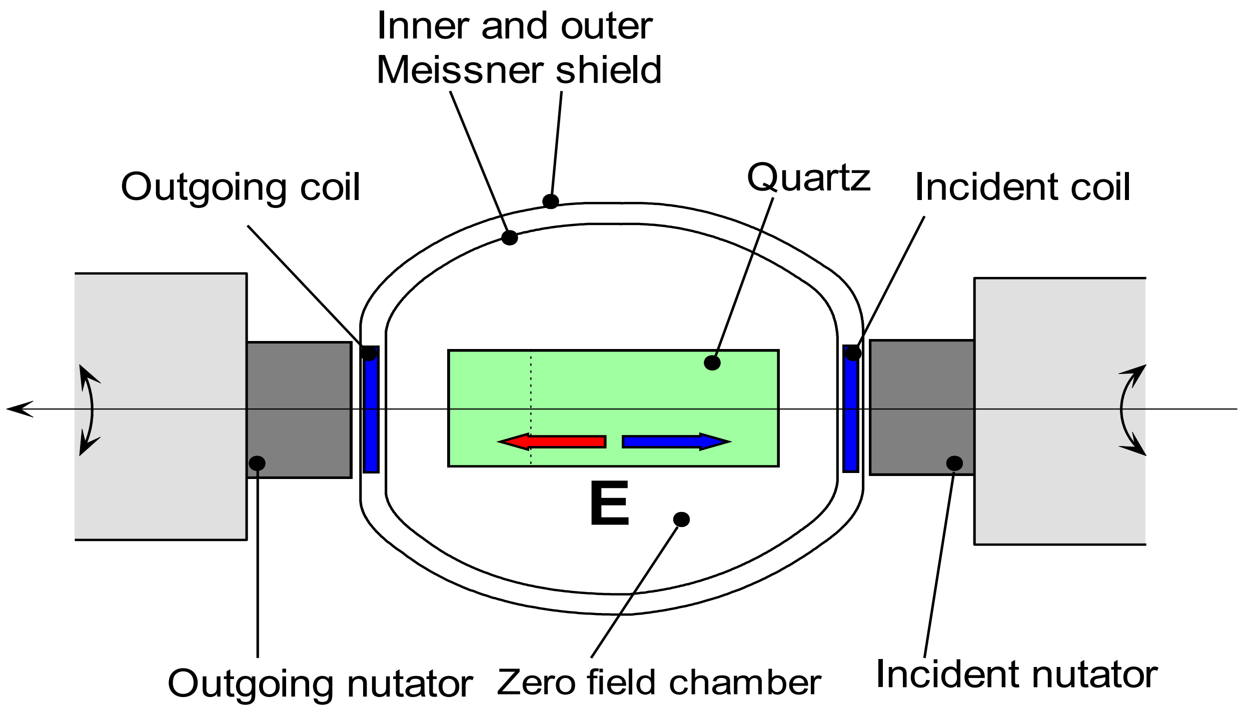
(1) this work
(2) is possible improvement of this method,
(3) is gravitational level experiment [1]
(4) is the UCN depolarization [2]
(5) is proposal [3],
(6) and (7) are the predictions of axion model with $\theta \sim 1$ and $\theta \sim 10^{-10}$ correspondingly [2]

[1] S.Baessler, V.V.Nesvizhevsky, K.V.Protasov, A.Yu.Voronin, Phys.Rev.D **75** (2007) 075006.
[2] A.P. Serebrov, ArXiv:0902.1056v1 [nucl-ex] 6 Feb 2009.
[3] O. Zimmer, ArXiv:0810.3215v1 [nucl-ex] 17 Oct 2008.

Scheme of the experiment



Main elements CRYOPAD and position sensitive detector



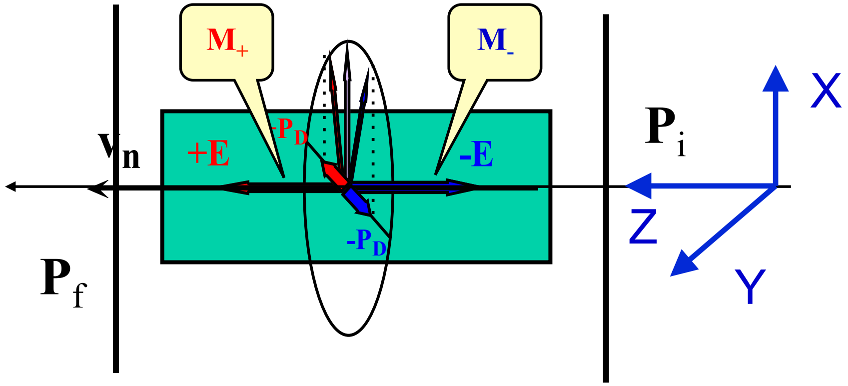
Current accuracy of spin orientation is

~10^{-2} rad for routine experiment

~10^{-3} rad can be reached for special cases

F. Tasset, P.J. Brown, E. Lelie`vre-Berna, T. Roberts, S. Pujol, J. Allibon, E. Bourgeat-Lami, Physica B, **267-268** (1999) 69-74

3-D spin analysis allows to select different contributions



$\tau_\pm$ ⟸ time of the neutron stay in the crystal for ± E

$$\Delta\tau = (\tau_+ - \tau_-)/2 \qquad \tau_0 = (\tau_+ + \tau_-)/2$$

$$\mathbf{P}_f = \mathbf{M}_\pm \mathbf{P}_i$$

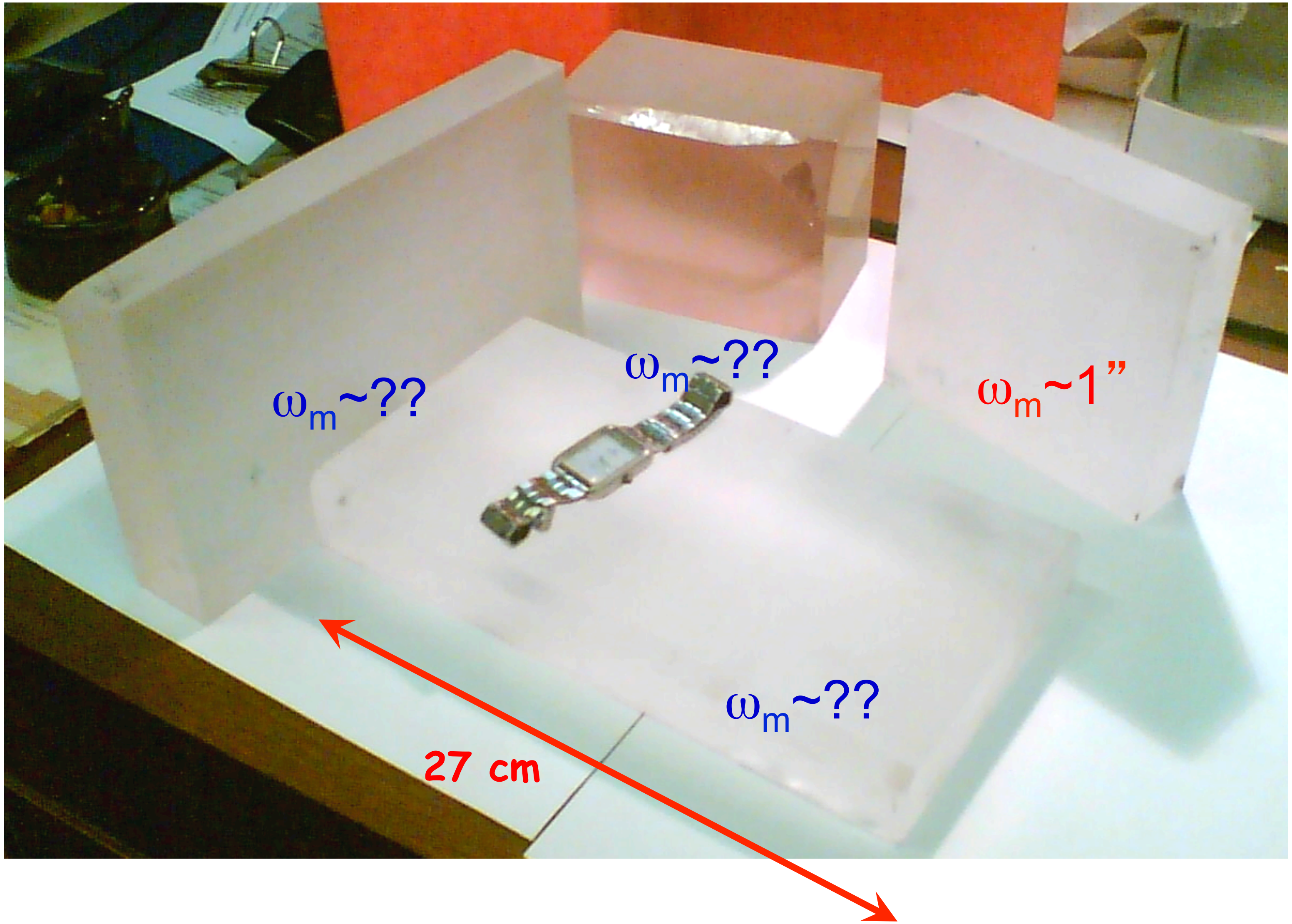
$$\mathbf{M}_+ - \mathbf{M}_- \equiv \Delta\mathbf{M} = g_n\tau_0\left[\begin{pmatrix} 0 & -H_e & 0 \\ H_e & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \begin{pmatrix} 0 & 0 & H_{sy} \\ 0 & 0 & -H_{sx} \\ -H_{sy} & H_{sx} & 0 \end{pmatrix} + \Delta\tau/\tau_0 \begin{pmatrix} 0 & -H_z & H_y \\ H_z & 0 & -H_x \\ -H_y & H_x & 0 \end{pmatrix}\right]$$

$$H_e = (E\, d_n)/\mu_n$$

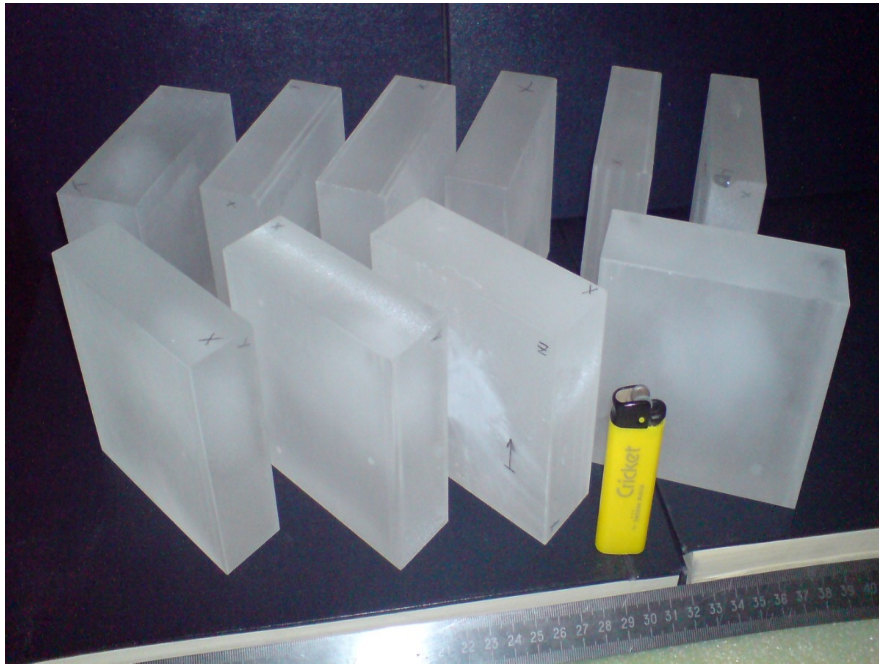
EDM **Schwinger** **Residual magnetic field**

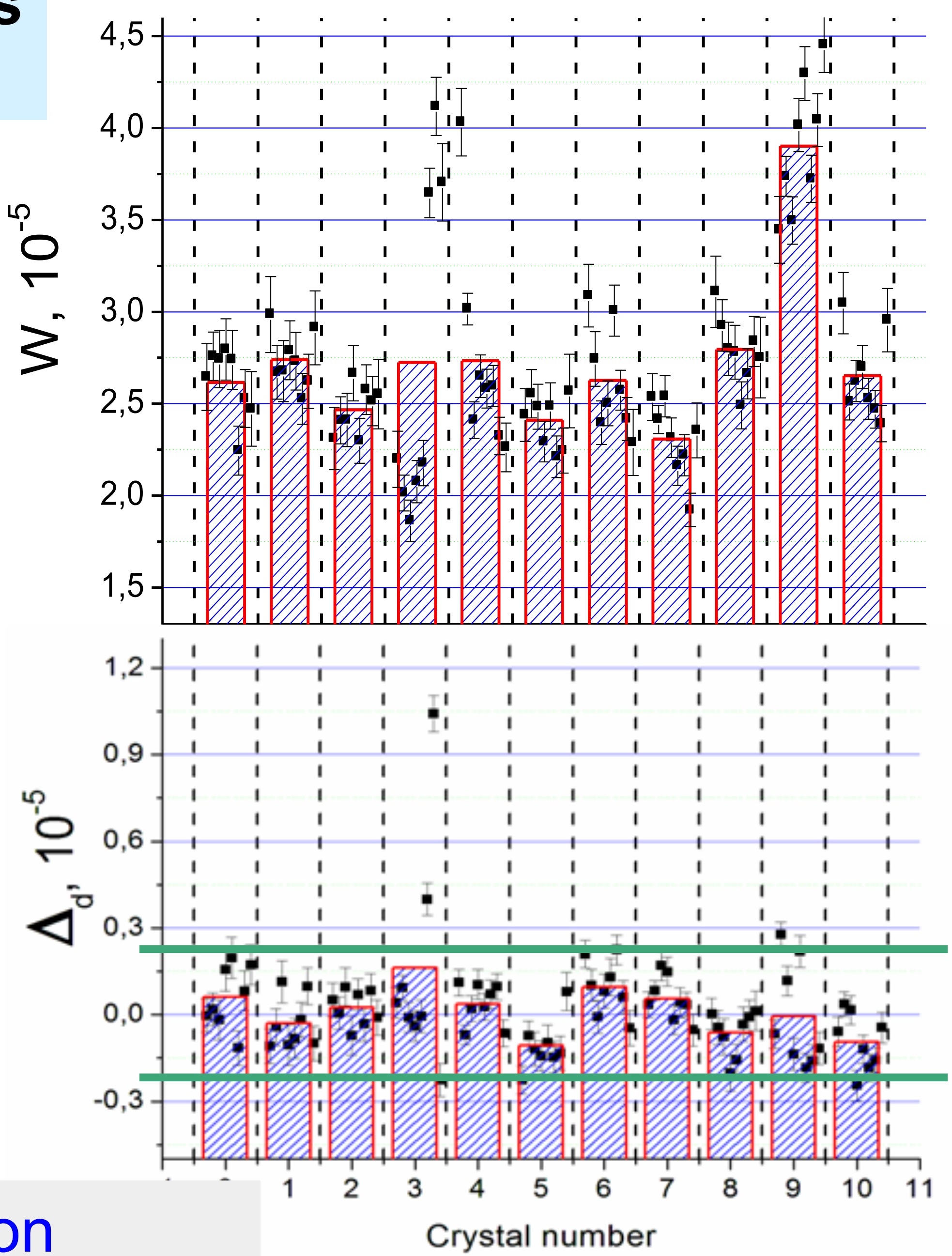
$g_n = 1.8 \cdot 10^4$ [1/Gs/s]

Photo of quartz crystals



Tests of the series of crystals from Aleksandrov factory





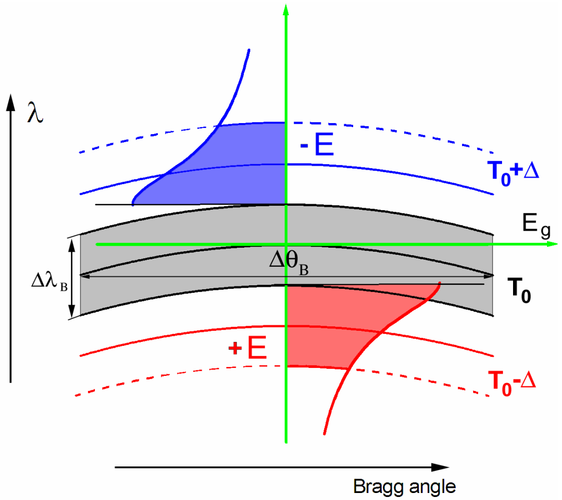
Crystals No.3 and 9 turned to be not sutable.

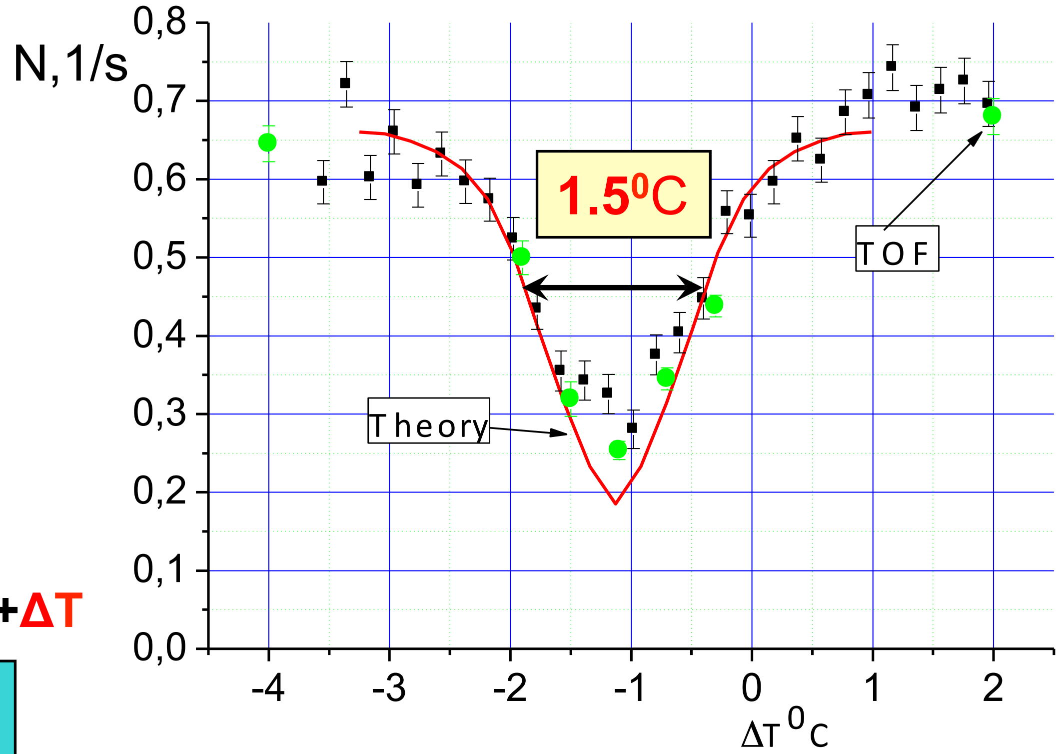
The rest ones had $\Delta d/d < 3 \cdot 10^{-6}$

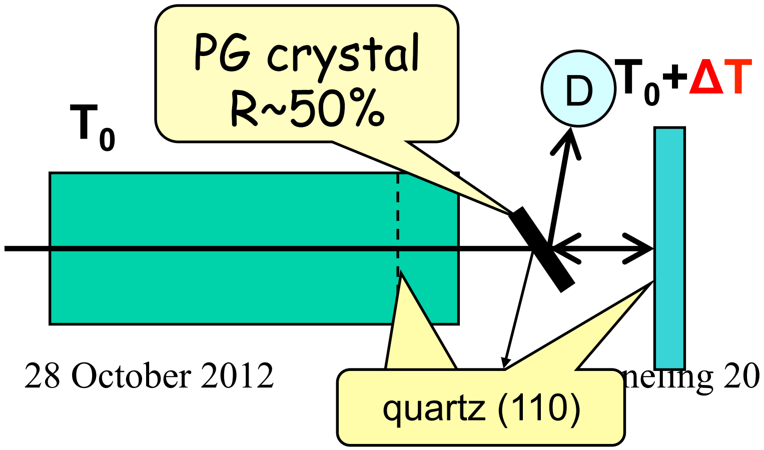
Full assembled crystal dimention 105x100x500 mm^3 (15un. 35x100x100)

Experimental test

Two crystal line (ΔT)



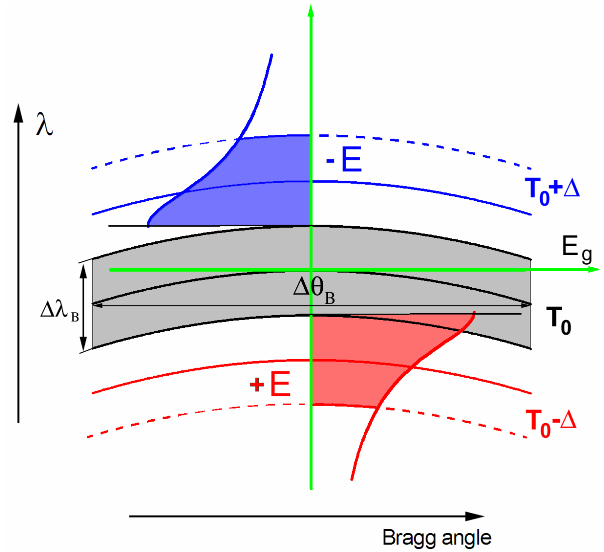


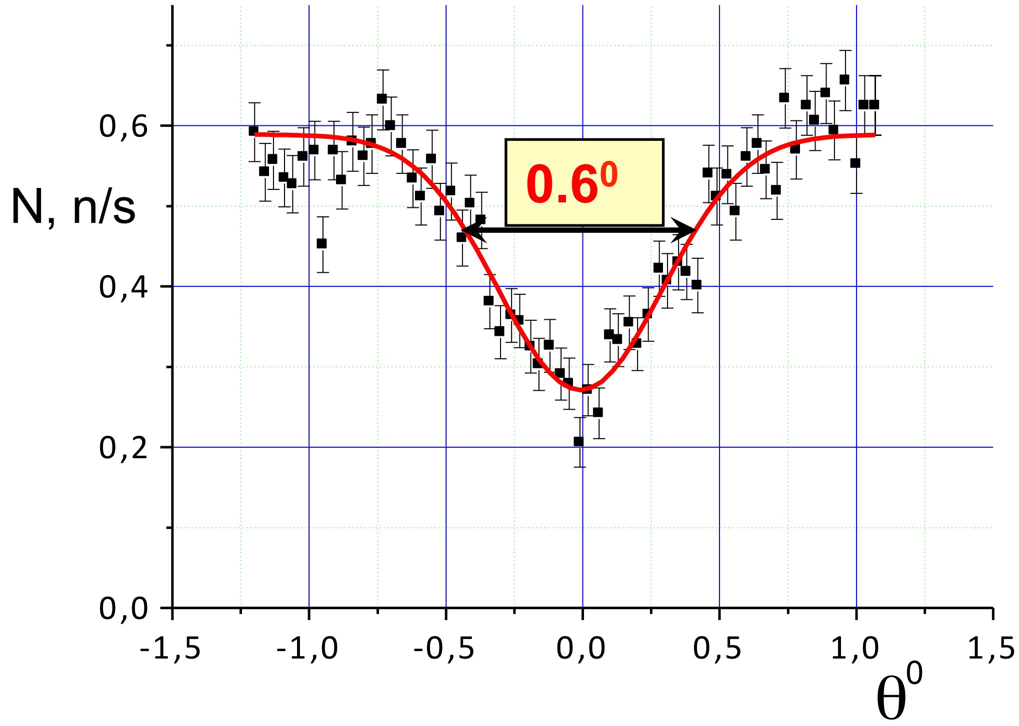


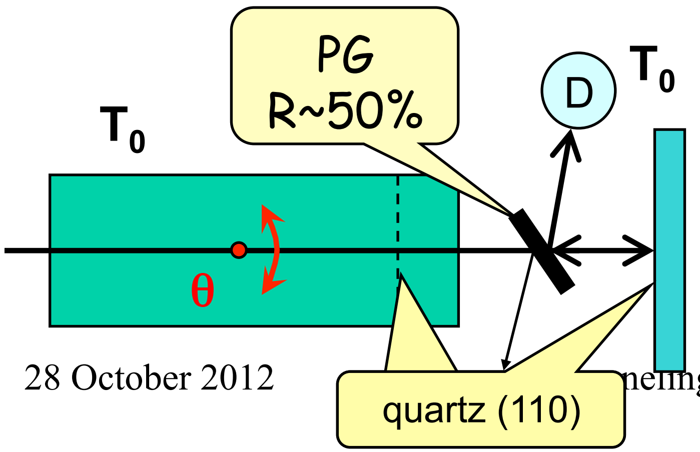
We can control the deviation parameter by the temperature of crystal.

Two crystal line (angular)

For Bragg angle ~ 45^0 the Bragg width ~ 0.0005^0

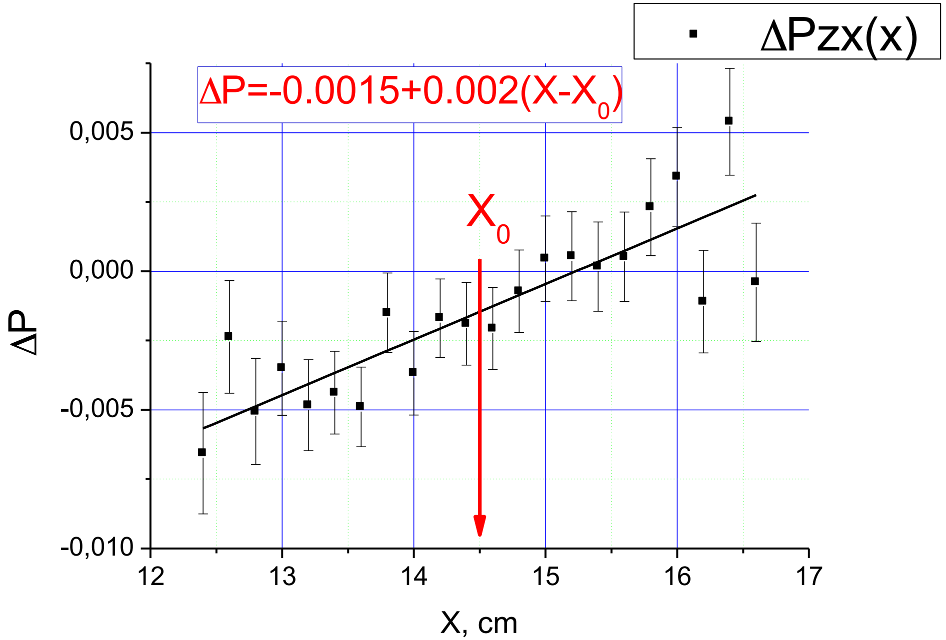


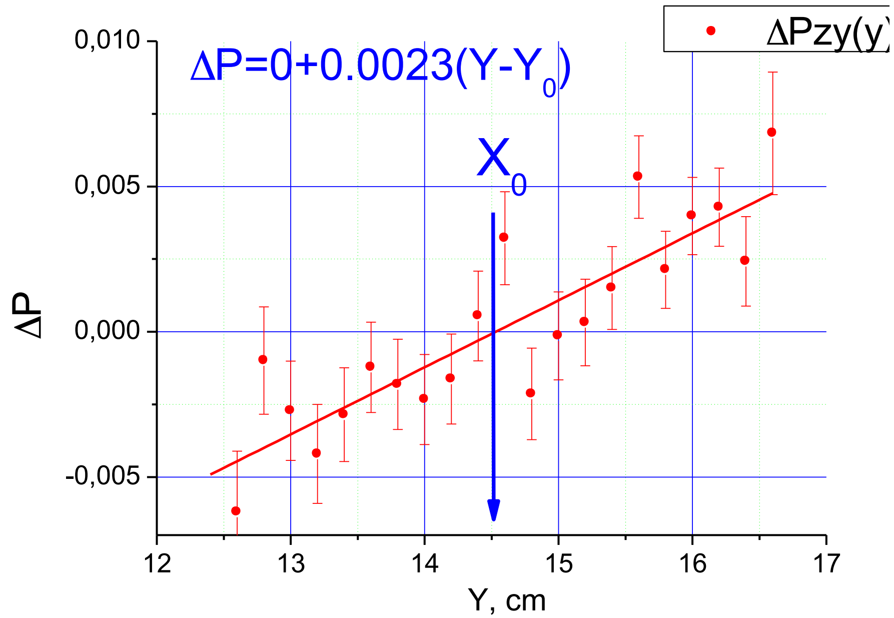


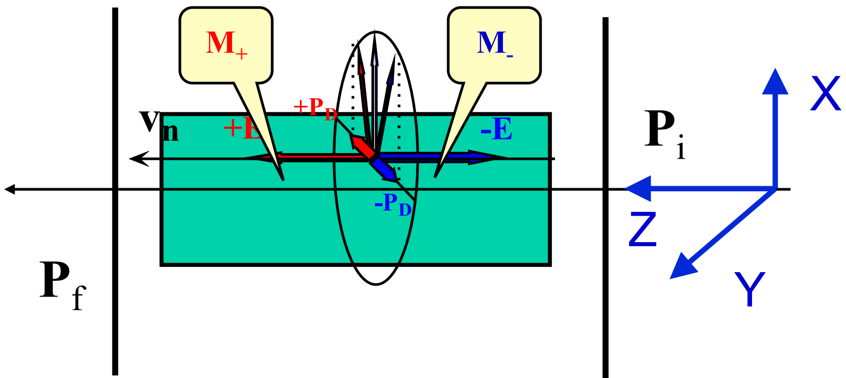


We can increase the EDM effect by using assembly of the crystals.

Spatial distribution of Schwinger effect in position sensitive detector



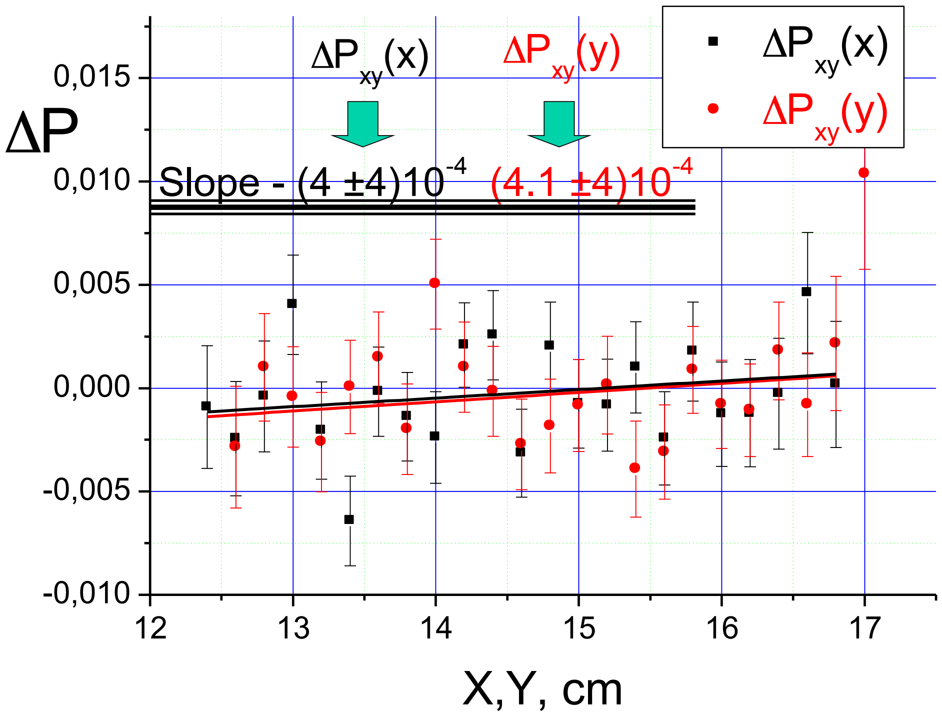


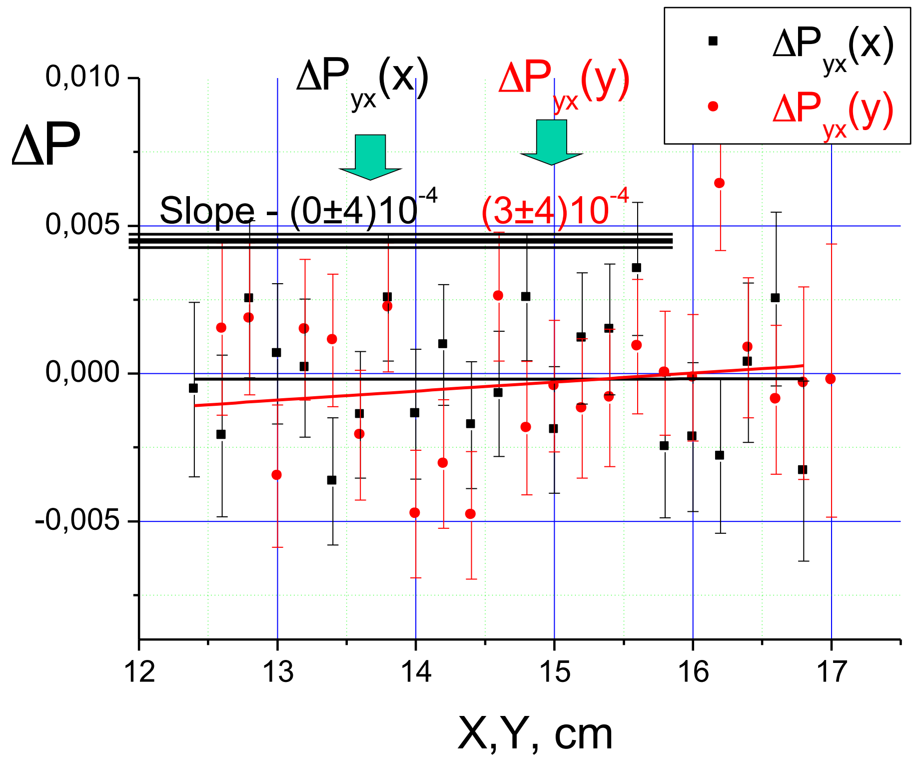


$\Delta P = P(\Delta T_+) - P(\Delta T_-)$

We should observe the same dependence for Pxy and Pyx components responsible for nEDM

nEDM effect spatial distribution

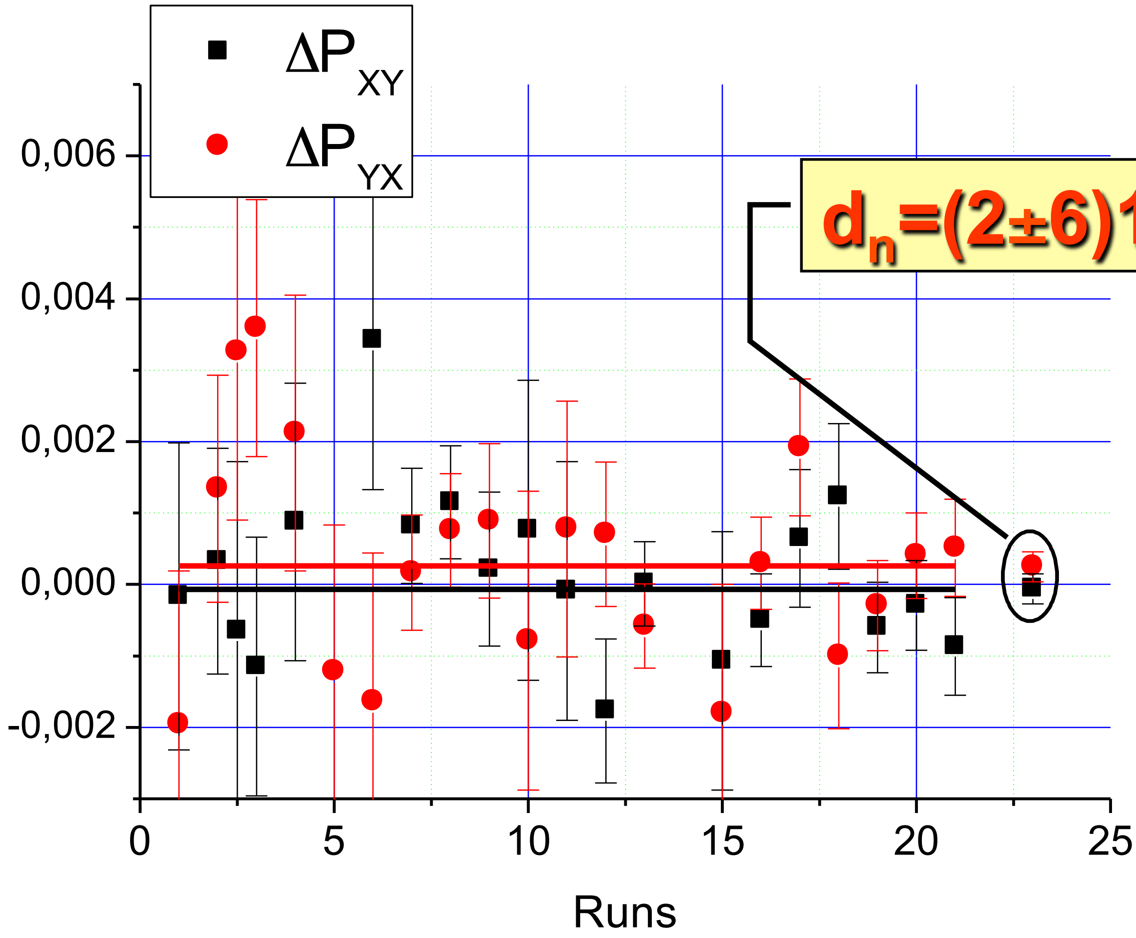




Schwinger $\Delta P_s < 1.1\ 10^{-4}$
stat. accuracy is
$\Delta P \sim 1.5\ 10^{-4}$

We don't see the spatial dependence of Pxy and Pyx components.

nEDM measurement



$d_n=(2\pm6)10^{-24}$ e cm

Was limited by low luminosity and size of crystal

Summary of the experimental scheme

- Possibility to reverse of the electric field.
- "Zero" Schwinger effect.
- Possibility to control and suppress the systematic.
- Low influence of crystal quality. (For $\omega_m >> \Delta\theta$ the effects ~ $\Delta\theta / \omega_m$. Intensity ~ ω_m). ⇨ New kinds of NSC crystals
- One can increase the effect by using a series of crystals

For	**quartz crystal,**
for thickness	**L_c=50 cm**
statistics	**100 day**

⇨

$$\sigma_d \sim 1.3 \cdot 10^{-26} \; e \cdot cm$$

Summary of the systematic

Residual magnetic field	
Value	$\mathbf{H}_r \sim 10^{-4}\, Gs$
Time stability	$\Delta\mathbf{H}_r \sim 10^{-5}\, Gs / hour$
3D analysis of polarization	$\delta_y \sim 10^{-3}\, rad$
The crystals alignment	$\sim 0.02^0$
The ΔT^0 control	$\sim 0.01^0 C$

$\sigma_d < 6\ 10^{-27} e\ cm$

Historical review

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Thank you for attention