Modern status of the crystal diffraction neutron EDM experiment

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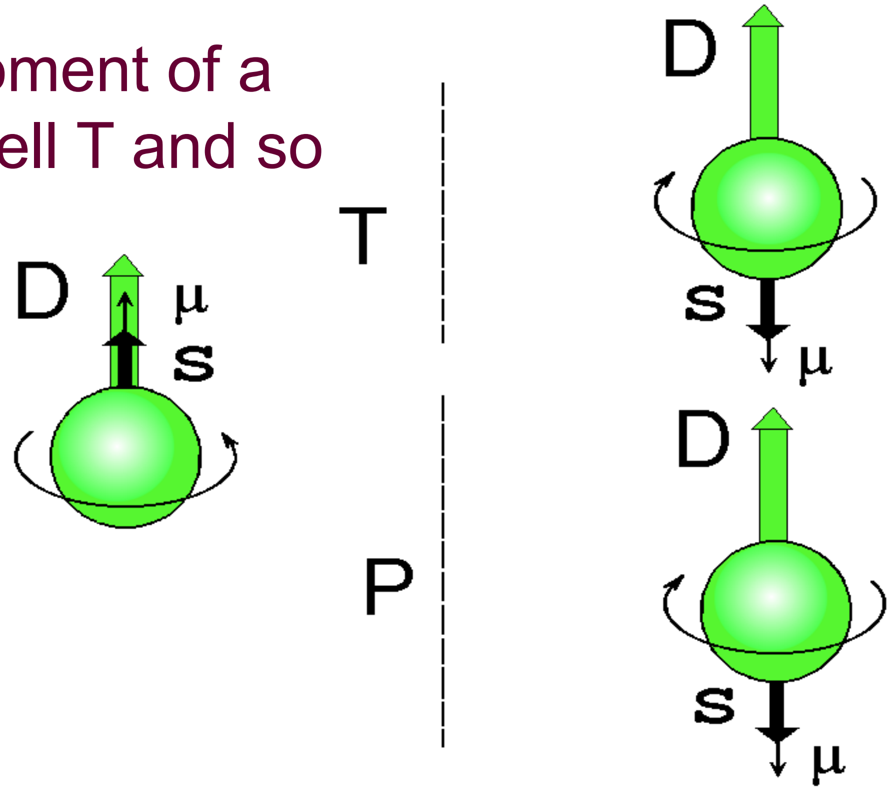
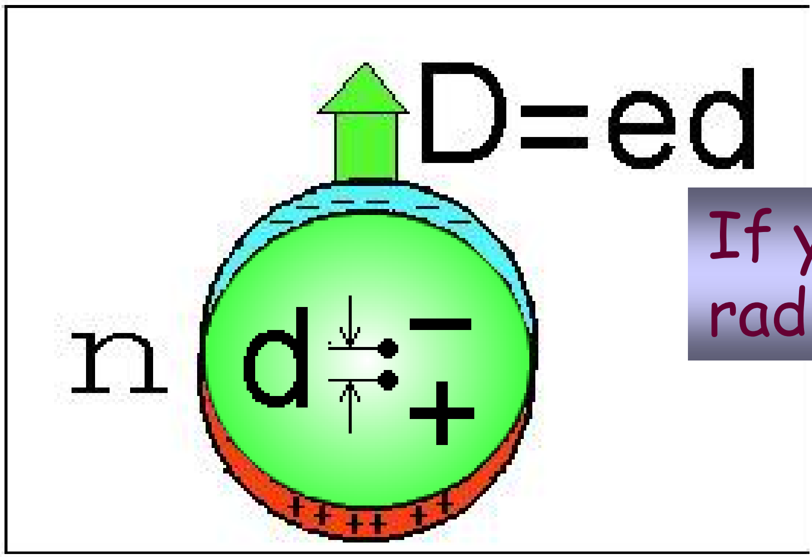
Neutron EDM

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

The last result $d_n \leq 3{\cdot}10^{-26}$ e·cм (ILL, RAL, Sussex Un.) PRL, 2006, 97, 131801) – is not much better 20 years old results of PNPI and ILL

$d_n \leq 9{,}7{\cdot}10\text{-}26$ e·cm, PNPI, 1989



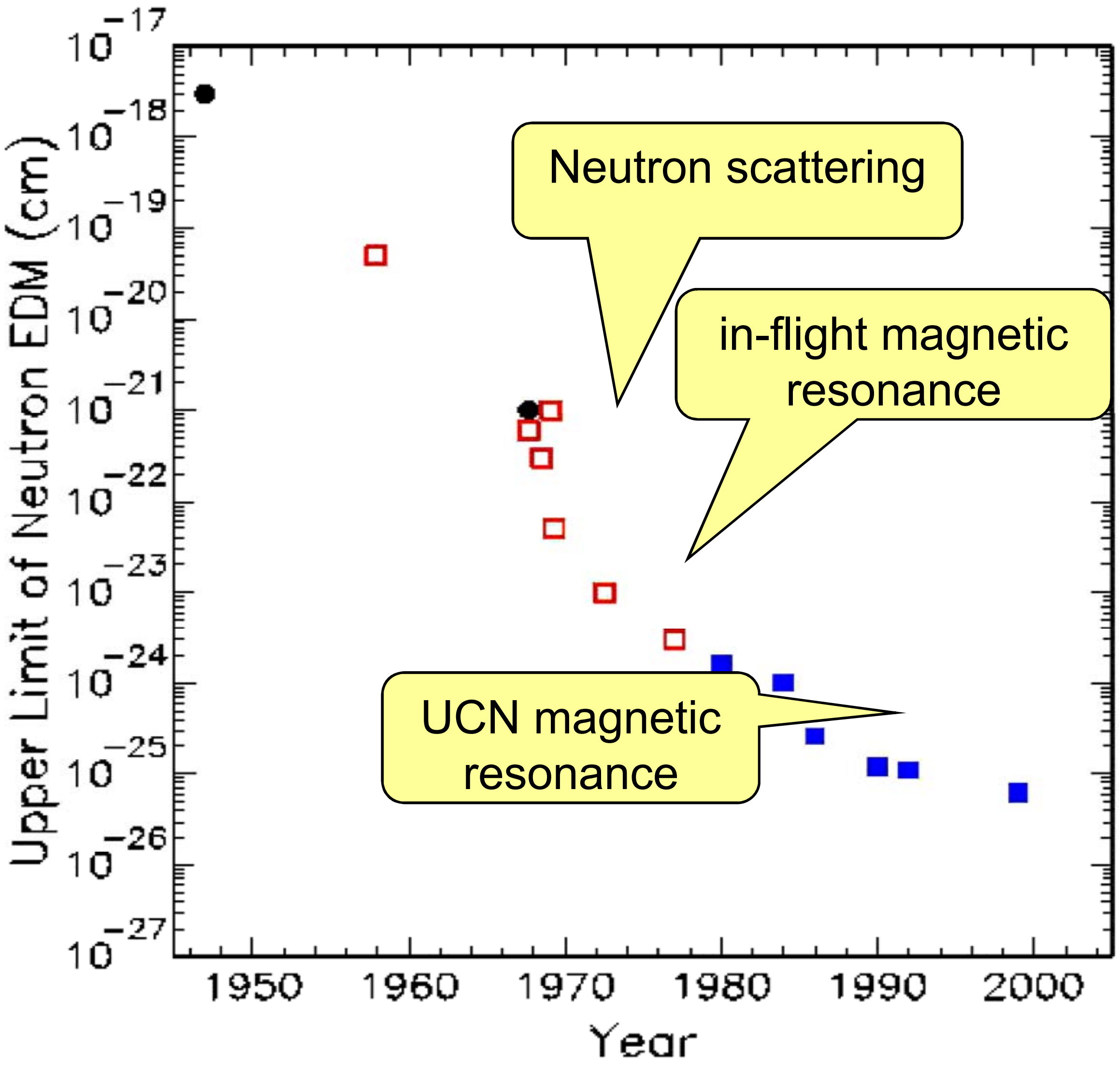


If you imagine a neutron as a sphere of radius R ~ 10^{-13} cm, than d/R ~ $3{\cdot}10^{-13}$.

Such a part of Earth radius is approximately ~ 2 μm

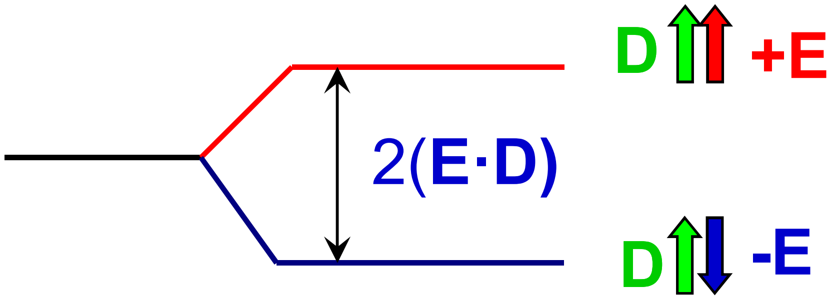
- In the Standard Model (SM) all observations of CP and T violation in the K and B decays can be explained perfectly well. The SM prediction for the neutron EDM is at the level, less than 10^{-31} e·cm, which is below of the current experimental limit by six orders of magnitude.
- However the SM cannot explain the baryon asymmetry of the Universe. It appears at the level 10^{-25} in SM, while observations give the value 10^{-10}.
- Only theories beyond the SM suggesting new channels for CP violation as well as violation of the baryon number (A.D.Sakharov) necessary to explain the baryon asymmetry in the Universe.
- In such theories (unification, supersymmetry) the predicted value of the neutron EDM is raised by up to seven orders of magnitude.
- Hence, measurements of the neutron EDM could provide a significant argument for these extensions to the SM. For the last two decades some stagnation in the experimental sensitivity to neutron EDM is observed (The sensitivity was improved only about 3 times during the last 20 years), therefore the development of principally new methods is extremely necessary.

Evolution of neutron EDM



stagnation

Sensitivity to neutron EDM



Interaction time with **E**

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

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

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.

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

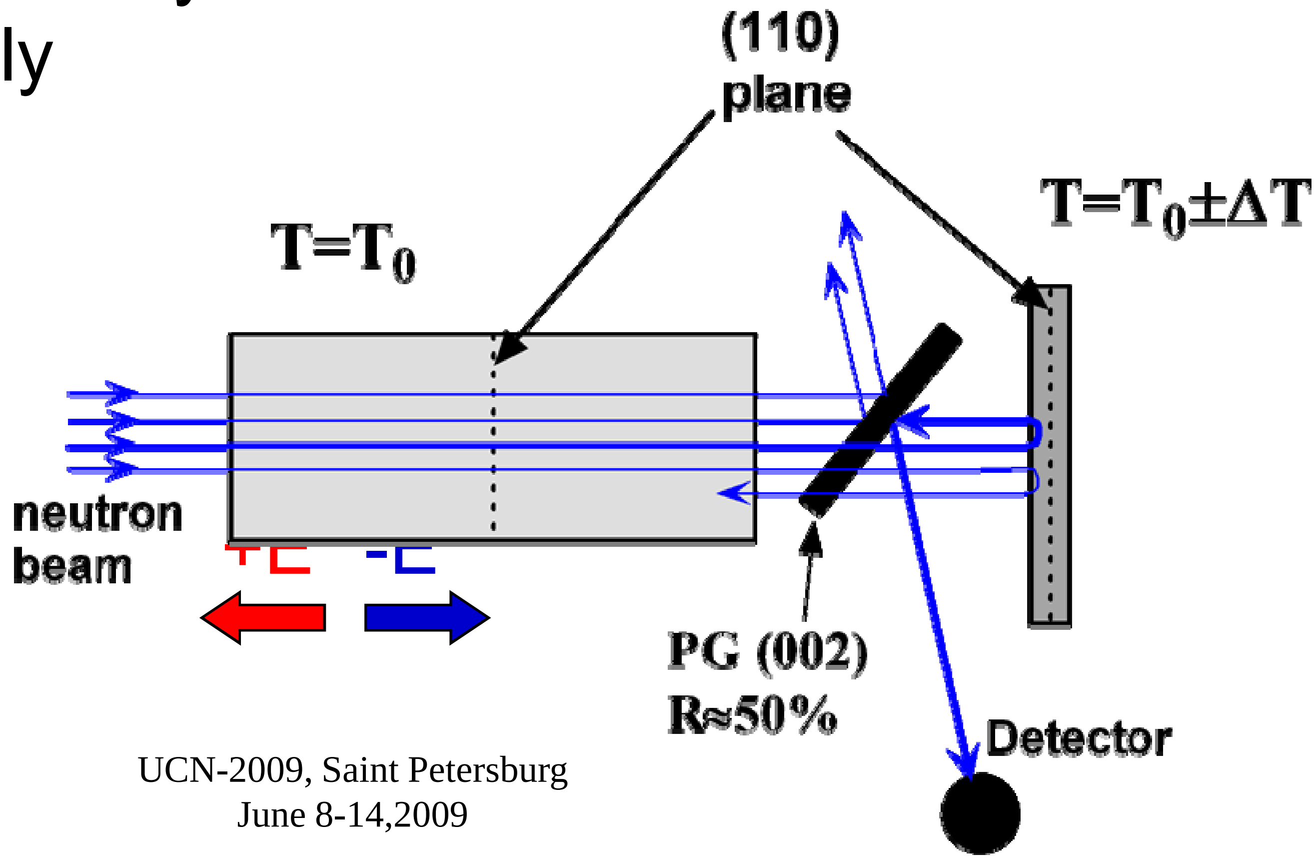
Essence of experiment

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

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

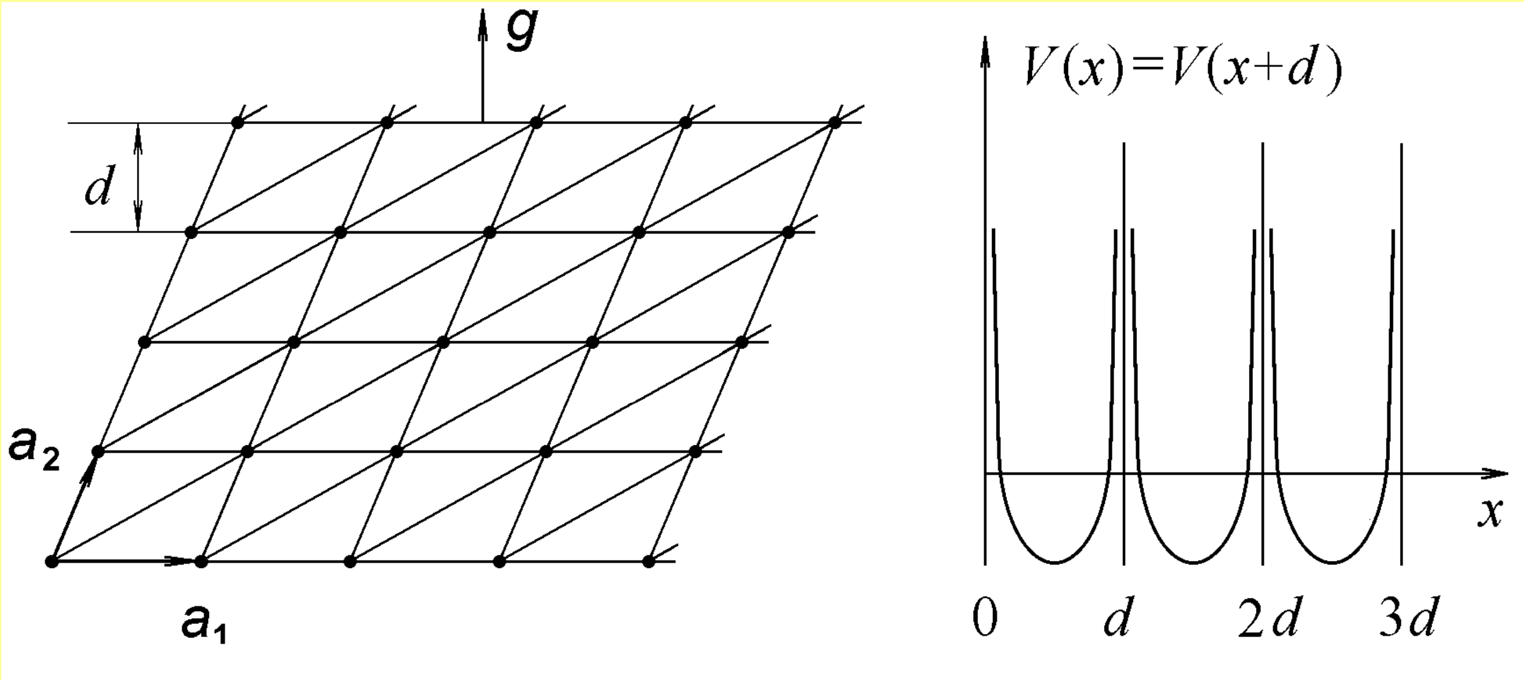
only the neutrons with $\lambda > \lambda_B$ and $\lambda < \lambda_B$ can pass through crystal and they will move in electric field –E and +E correspondingly

Changing λ (or d) one can control electric field acting on neutron



Nuclear and electric crystal potentials. Reciprocal lattice vectors

One can represent the crystal potential either as a sum of atomic potentials or as a sum of plane potentials. The last is called the reciprocal lattice vectors expansion



Periodic (along any *g* direction, *x* axis) potential of the some plane system can be expanded to Fourier series:

$$V_g(r) = \sum_n V_n \exp\left(\frac{2\pi i}{d} n x\right) = \sum_{g_n} V_{g_n} \exp(i g_n x)$$

$g_n = 2\pi n/d$. **Each harmonic can transfer only certain momentum $\hbar g_n$, so one can say that any harmonic describes its own plane system g_n.**
So we can consider the *n* order diffraction as the diffraction of the 1-st order but at the plane system with the interplanar distance $d_n = d/n$.

$$V(\vec{r}) = \sum_\alpha V_\alpha(\vec{r} - \vec{r}_\alpha) = \sum_g V_g e^{i\vec{g}\vec{r}} = V_0 + \sum_g 2 v_g \cos(\vec{g}\vec{r} + \phi_g)$$

$$V_g = V^*_{-g}$$

Because *V(**r**)* is real

$$V_g = v_g \exp(i\phi_g)$$

Essence of the phenomena

We can write the electric potential in the same way

$$V^E(\boldsymbol{r}) = 2V_g^E \cos(\boldsymbol{gr}) =$$

$$= V_g^E \exp(i\boldsymbol{gr}) + V_g^E \exp(-i\boldsymbol{gr})$$

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

$$\boldsymbol{E}(\boldsymbol{r}) = -\mathrm{grad}\ V^E(\boldsymbol{r}) =$$

$$= i\boldsymbol{g}V_g^E \exp(i\boldsymbol{gr}) - i\boldsymbol{g}V_g^E \exp(-i\boldsymbol{gr}) =$$

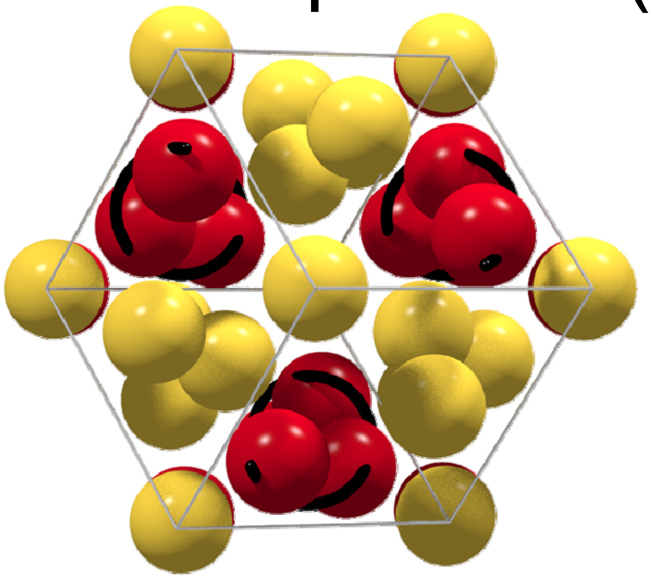
$$= 2V_g^E \boldsymbol{g} \sin(\boldsymbol{gr})$$

So electromagnetic scattering amplitude is imaginary

$$V^{EM}(\boldsymbol{r}) = \boldsymbol{ED} + \mu \frac{\boldsymbol{E} \times \boldsymbol{v}}{\boldsymbol{c}}$$

Essence of the phenomena

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



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

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

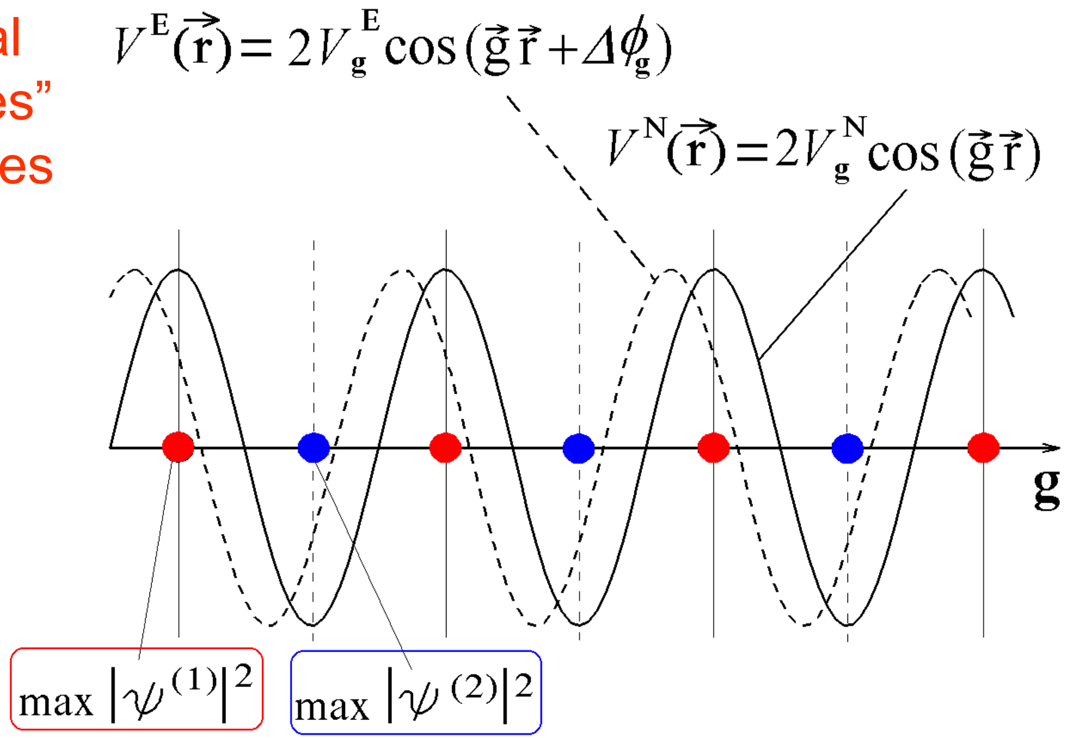
$$f_i^N(\mathbf{g}) = -a_i; \quad f_i^E(\mathbf{g}) = -2r_n \frac{Z_i - f_{ic}(\mathbf{g})}{\lambda_{cn}^2 g^2} .$$

Nuclear amplitudes determine nuclear potential

Electric amplitude determine electric potential

Essence of the phenomena

In the non-centrosymmetric crystal the positions of the "nuclear planes" are shifted from that of electric ones



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

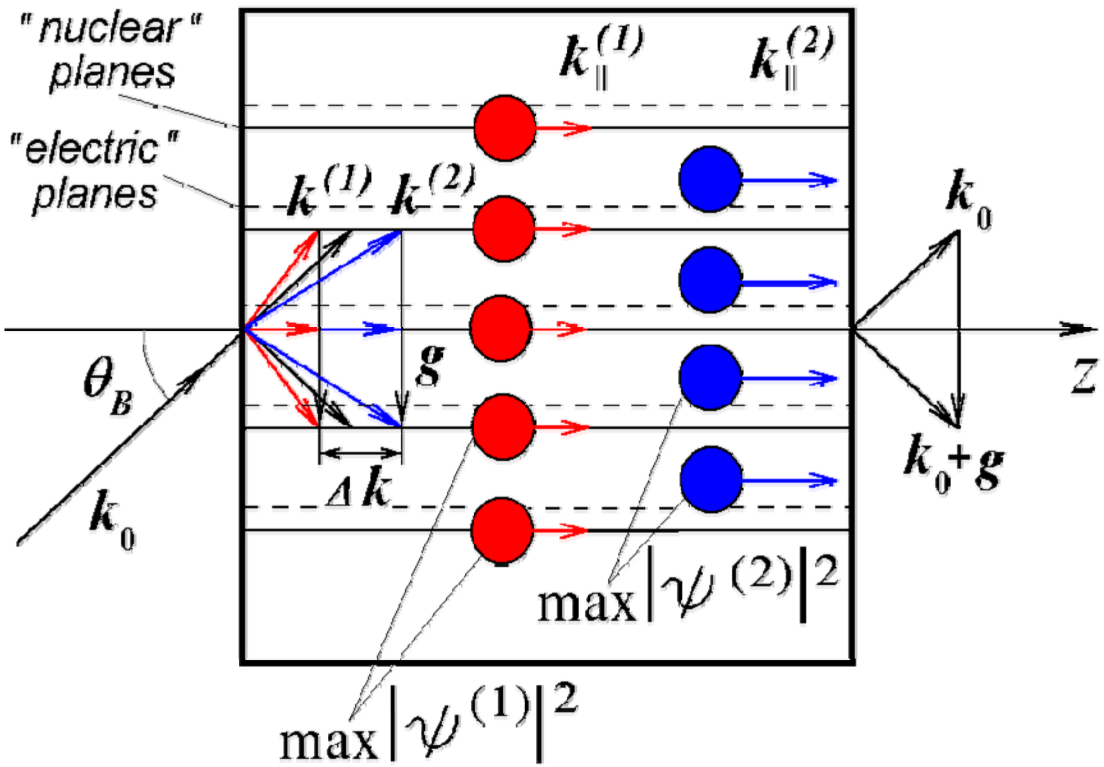
In the non-centrosymmetric crystal neutrons turn out to be under a strong electric field

$$\boldsymbol{E}(\boldsymbol{r}) = -\mathrm{grad}\, V^{E}(\boldsymbol{r}) = 2V_{g}^{E}\boldsymbol{g}\sin(\boldsymbol{g}\boldsymbol{r} + \Delta\phi_{g})$$

$$\boldsymbol{E}_{g} = \langle\psi^{(1)}|\boldsymbol{E}(\boldsymbol{r})|\psi^{(1)}\rangle = -\langle\psi^{(2)}|\boldsymbol{E}(\boldsymbol{r})|\psi^{(2)}\rangle = \boldsymbol{g}V_{g}\sin\Delta\phi_{g}$$

$E_g = (10^8 – 10^9)$ V/cm

Essence of the phenomena



Laue diffraction:

Bragg condition:

$|\mathbf{k}_0+\mathbf{g}|=|\mathbf{k}_0|$ or

$2d \sin \theta_B = \lambda$

$(|\mathbf{g}|=2\pi/d,\ |\mathbf{k}_0|= 2\pi/\lambda)$

$$\psi^{(1)} = \frac{\exp(i\boldsymbol{k}^{(1)}\boldsymbol{r}) + \exp(i(\boldsymbol{k}^{(1)} + \boldsymbol{g})\boldsymbol{r}}{\sqrt{2}} = \sqrt{2}\cos\left(\frac{\boldsymbol{g}\boldsymbol{r}}{2}\right)\exp\left[i\left(\boldsymbol{k}^{(1)} + \frac{\boldsymbol{g}}{2}\right)\boldsymbol{r}\right]$$

$$\psi^{(2)} = \frac{\exp(i\boldsymbol{k}^{(2)}\boldsymbol{r}) - \exp(i(\boldsymbol{k}^{(2)} + \boldsymbol{g})\boldsymbol{r}}{\sqrt{2}} = -i\sqrt{2}\sin\left(\frac{\boldsymbol{g}\boldsymbol{r}}{2}\right)\exp\left[i\left(\boldsymbol{k}^{(2)} + \frac{\boldsymbol{g}}{2}\right)\boldsymbol{r}\right]$$

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

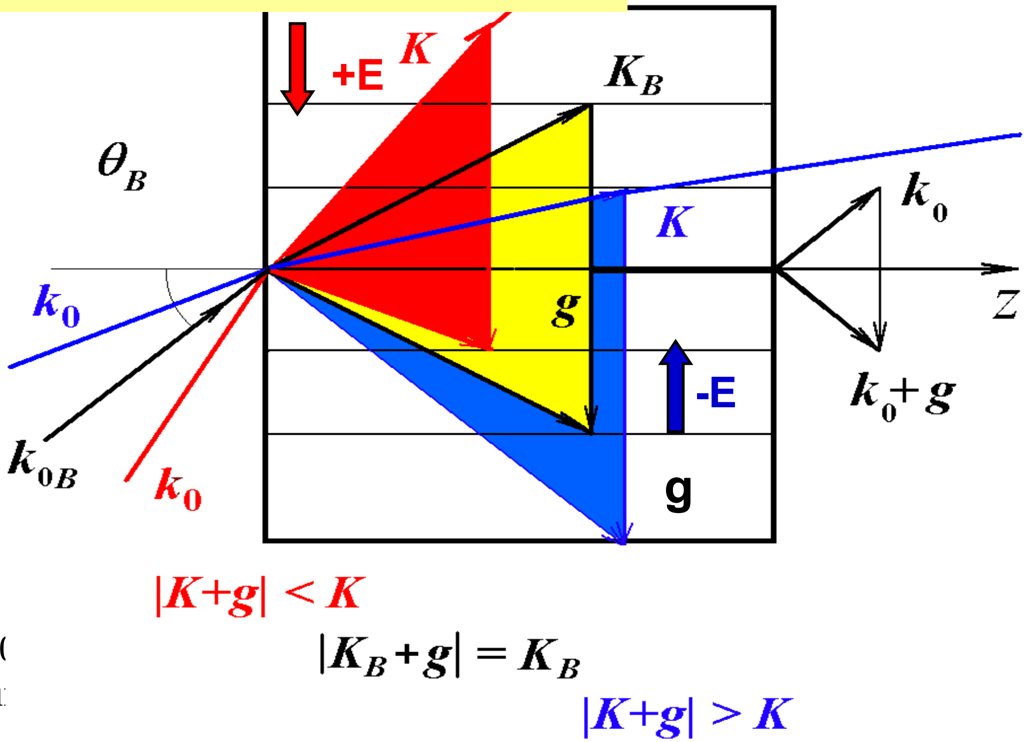
$$\psi = e^{i\mathbf{K}\mathbf{r}} + \sum_g \frac{V_g}{E_K - E_{K+g}} \cdot e^{i(\mathbf{K}+\mathbf{g})\mathbf{r}} =$$

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

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

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

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

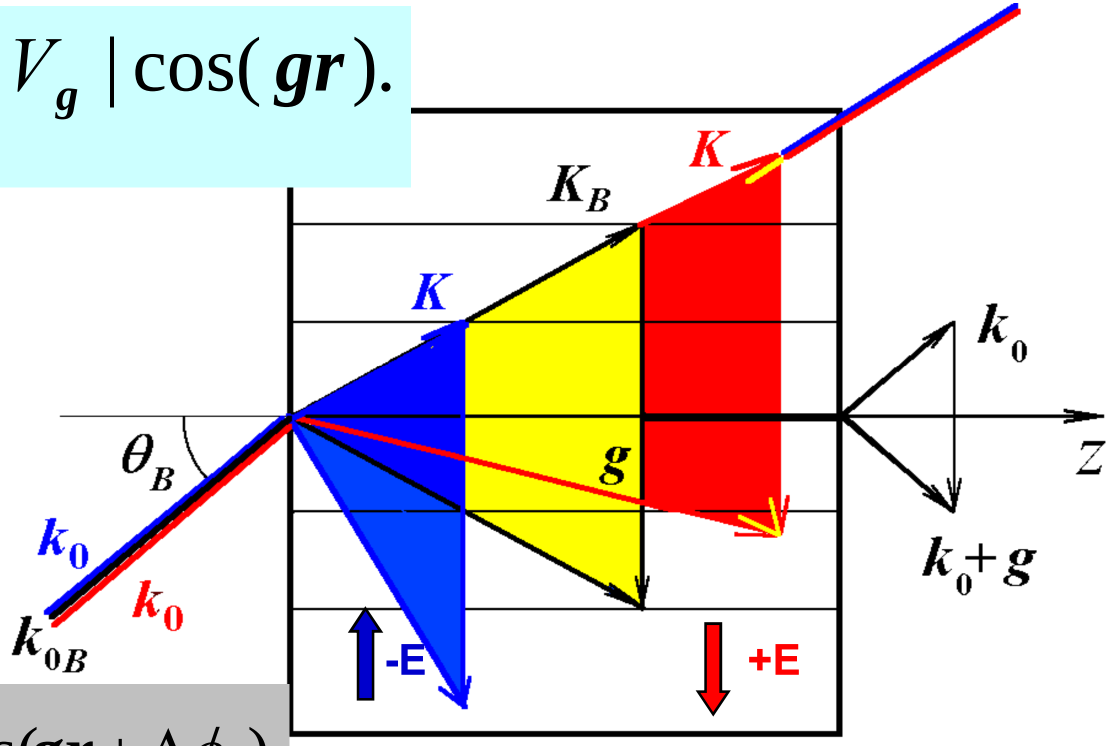


Depending on the sign of the deviation parameter from the Bragg condition $2\Delta_g = |\mathbf{K}+\mathbf{g}|^2 - \mathbf{K}^2$, the neutrons concentrate on the nuclear planes or between them (on the maxima of nuclear potential ($\Delta_g < 0$, red colour), or on its minima ($\Delta_g > 0$, blue colour)

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

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

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

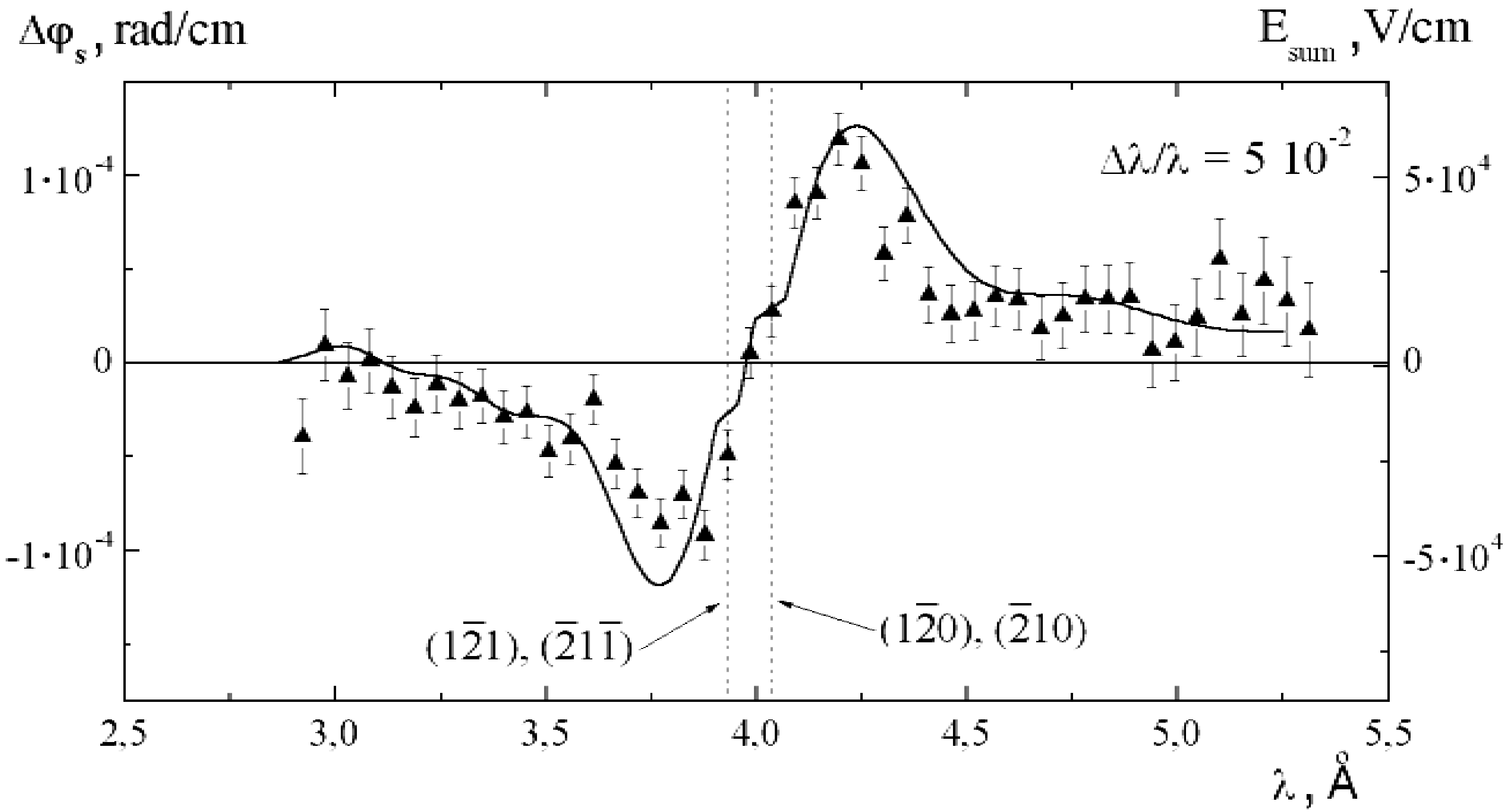
$$\Delta\varphi_S = \frac{2}{\hbar c v}\mu\boldsymbol{\sigma}\cdot\left[\mathbf{E}_{\mathbf{sum}}\times\mathbf{v}\right]$$

$$\mathbf{E}_{sum} = \sum_g \frac{2v_g^N}{\Delta_g^\varepsilon} v_g^E \mathbf{g}\sin\Delta\phi_g$$ For $\Delta\lambda/\lambda=5\cdot10^{-2}$

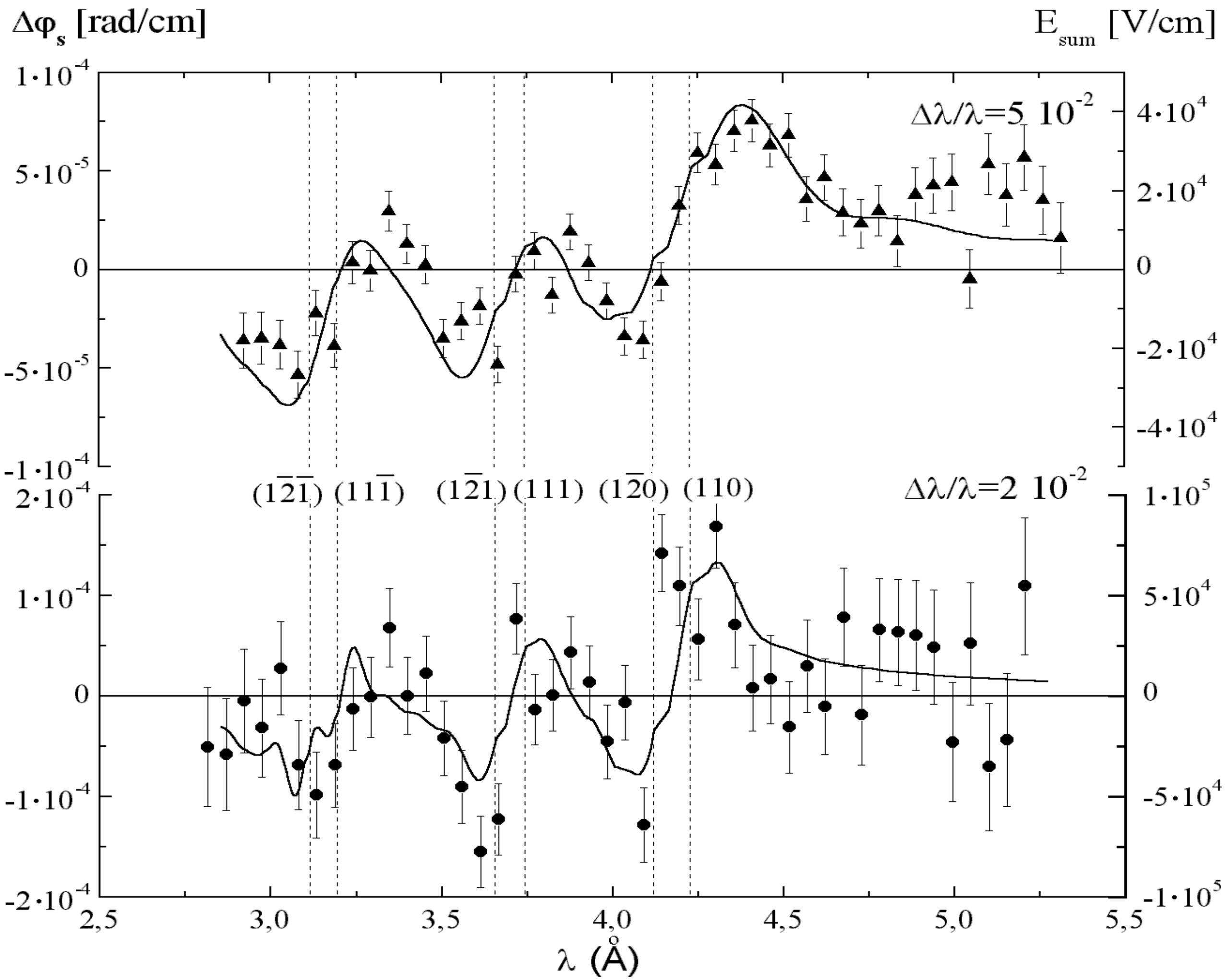
For α-quartz $\mathbf{E}_{sum}$~10^5 V/cm $\Rightarrow \Delta\varphi_S \sim 10^{-4}$ rad/cm

For $PbTiO_3$ $\mathbf{E}_{sum}$~10^6 V/cm $\Rightarrow \Delta\varphi_S \sim 10^{-3}$ rad/cm

Result: Spectral dependence of a spin rotation angle



Spectral dependence of a spin rotation angle



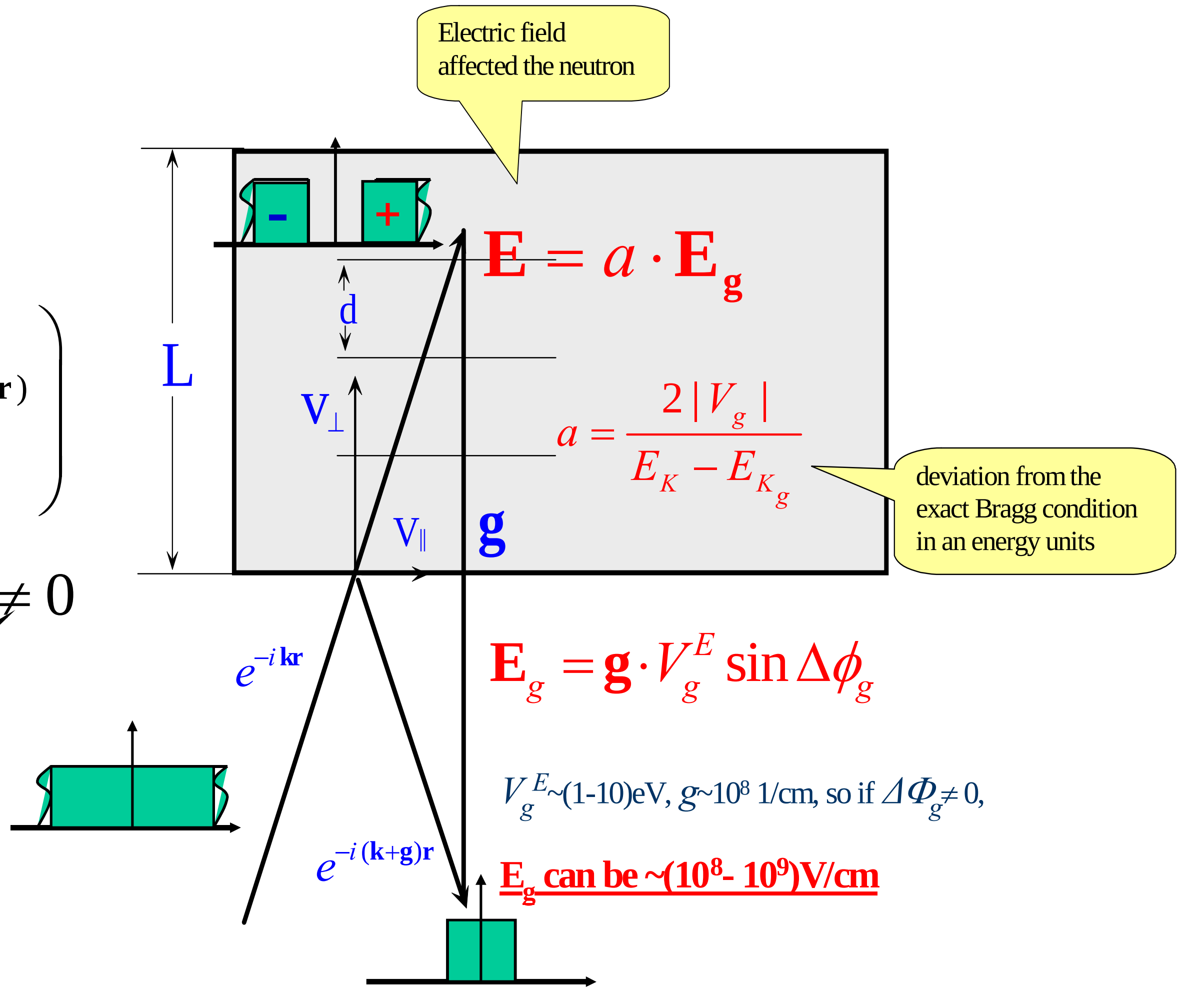
Simple Bragg diffraction case

Neutron wave function

$$\psi(\mathbf{r}) = e^{i(\mathbf{kr})}\left(1 + \frac{V_g}{E_K - E_{K_g}} e^{i(\mathbf{gr})}\right)$$

$$E = \langle \psi(\mathbf{r}) | \mathbf{E}(\mathbf{r}) | \psi(\mathbf{r}) \rangle \neq 0$$

NCS crystal

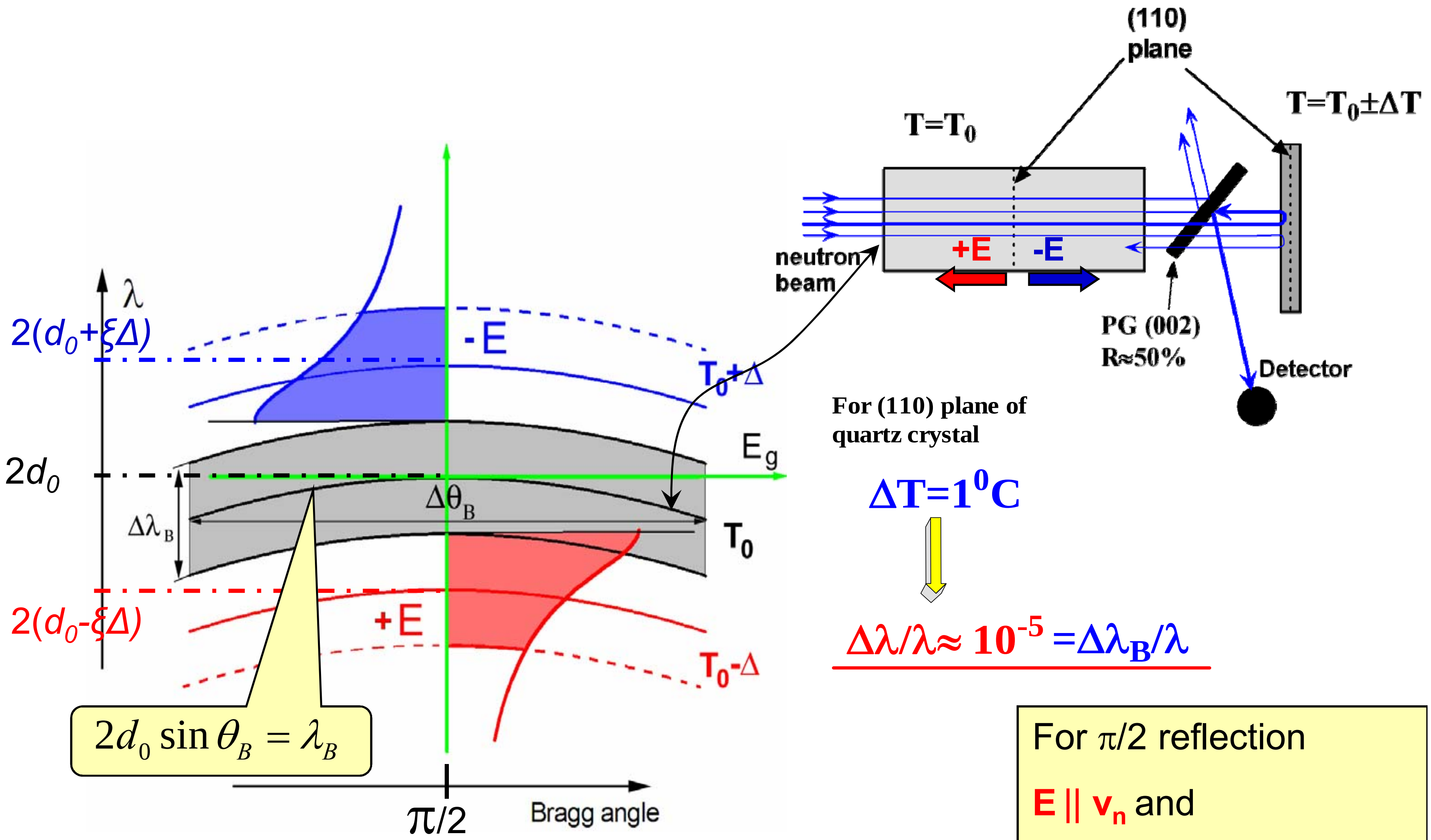


Parameters of some NCS crystals

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 !!!

Changing ***d*** of analyzer we can select the neutrons passed the crystal under given electric field



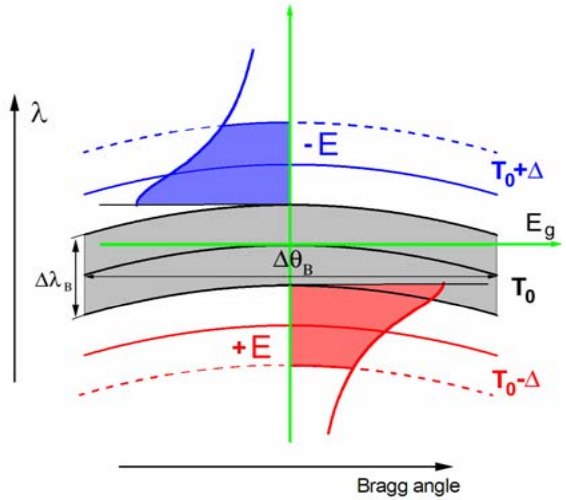
For π/2 reflection

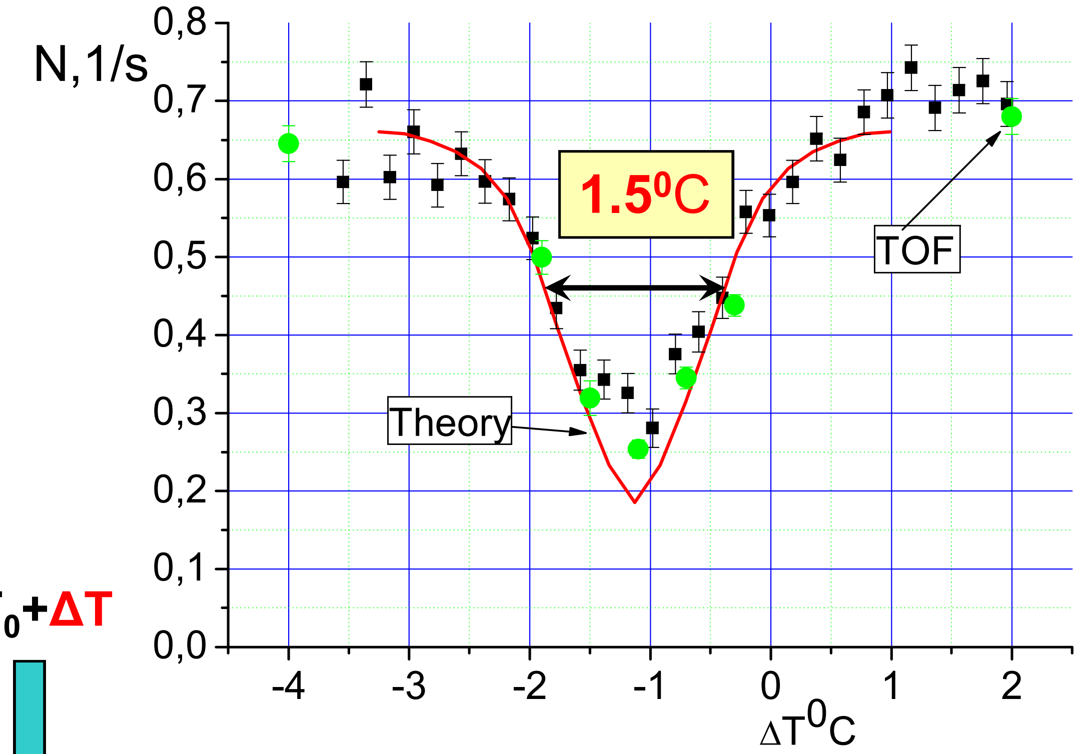
E || v_n and

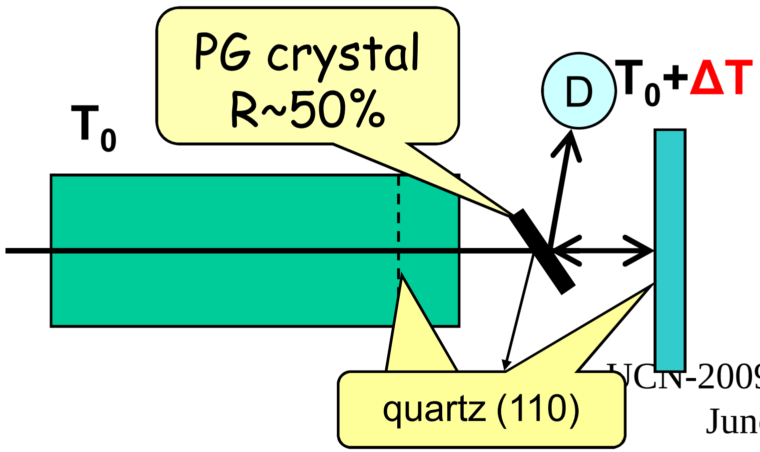
H_s~[E x v_n]≈0

Experimental test

Two crystal line (ΔT)

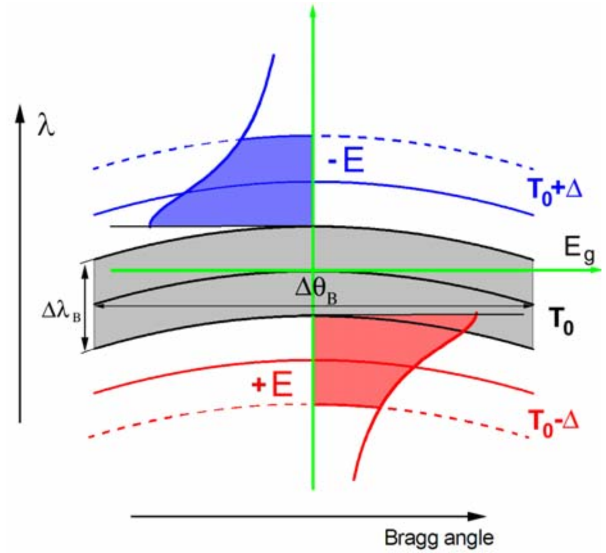




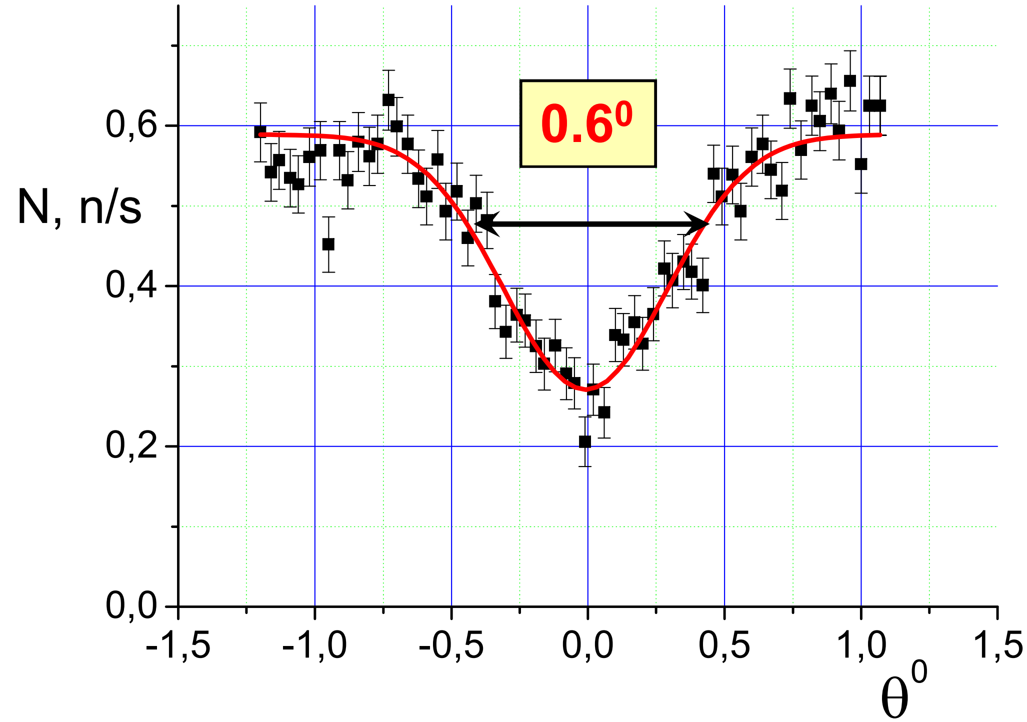


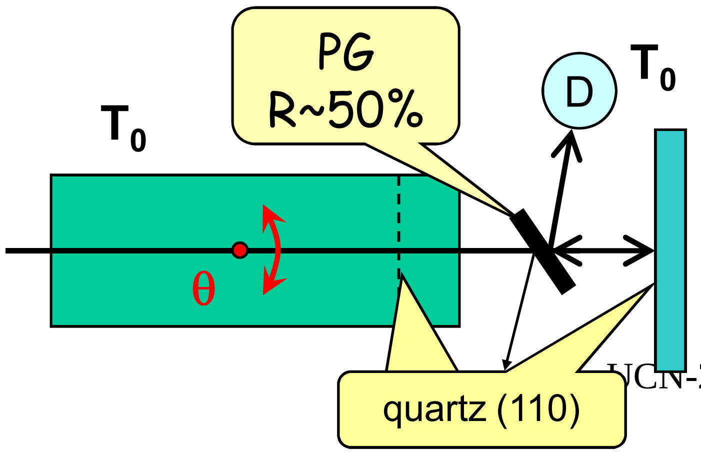
We can control the deviation parameter by the temperature of crystal.

Two crystal line (angular)



For Bragg angle ~ 45⁰ the Bragg width ~ 0.0005⁰



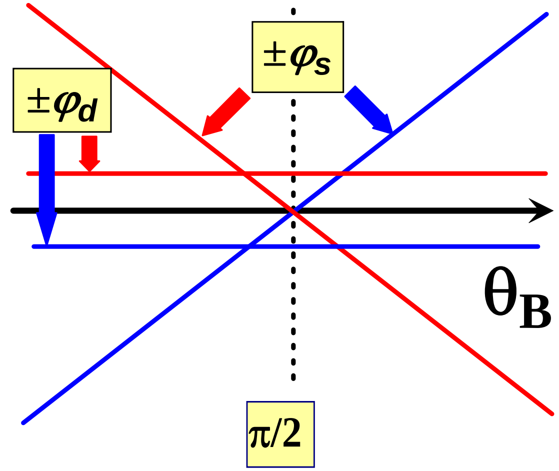


We can increase the EDM effect by using a series of the crystals.

π/2 reflection → “zero” Schwinger

EDM effect doesn't depend on a Bragg angle

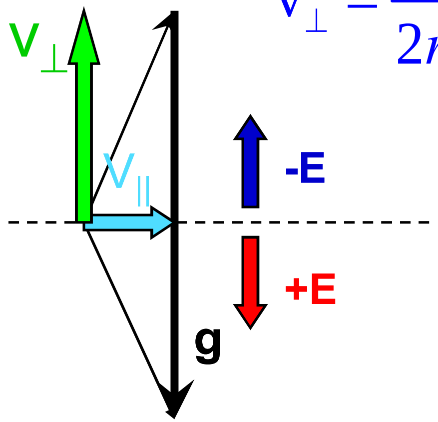
$$\varphi_d = \frac{\mathbf{E}\cdot d_n \cdot L}{\hbar \mathrm{v}_\perp}$$



For π/2 reflection

E || v$_n$ and

H$_s$~[E x v$_n$]≈0

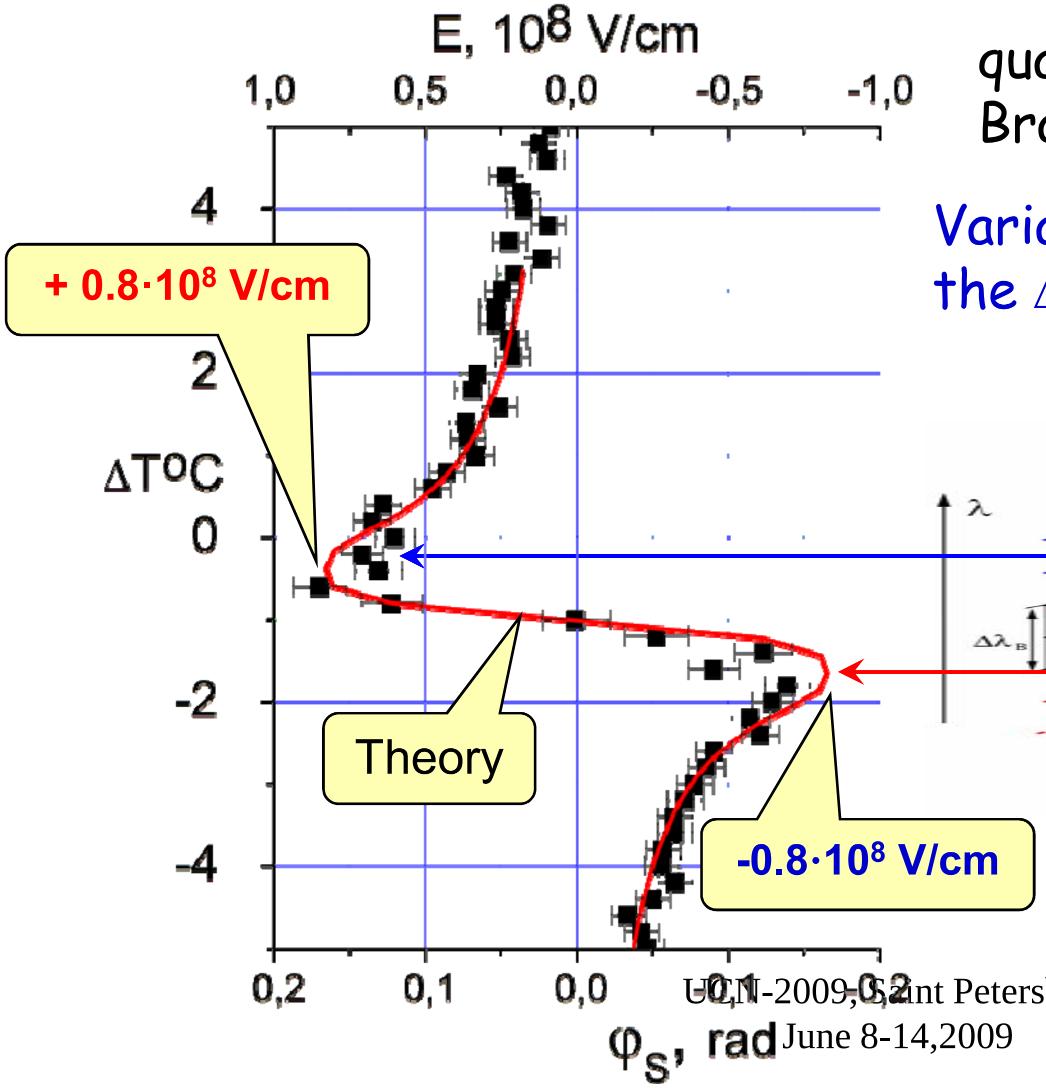


$$\mathrm{v}_\perp = \frac{\hbar g}{2m} \equiv const$$

Schwinger effect can be decreased down to zero for the Bragg angle close to π/2

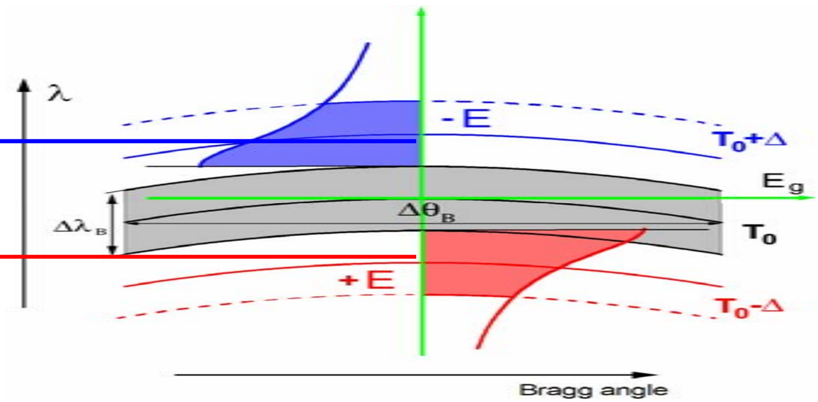
$$\varphi_s = \frac{\mathbf{E}\cdot v_{\parallel}\cdot \mu \cdot L}{c\hbar \mathrm{v}_\perp} = \frac{\mathbf{E}\cdot \mu \cdot L}{c\hbar} ctg(\theta_B) \xrightarrow[\theta_B \to \pi/2]{} 0$$

Electric field

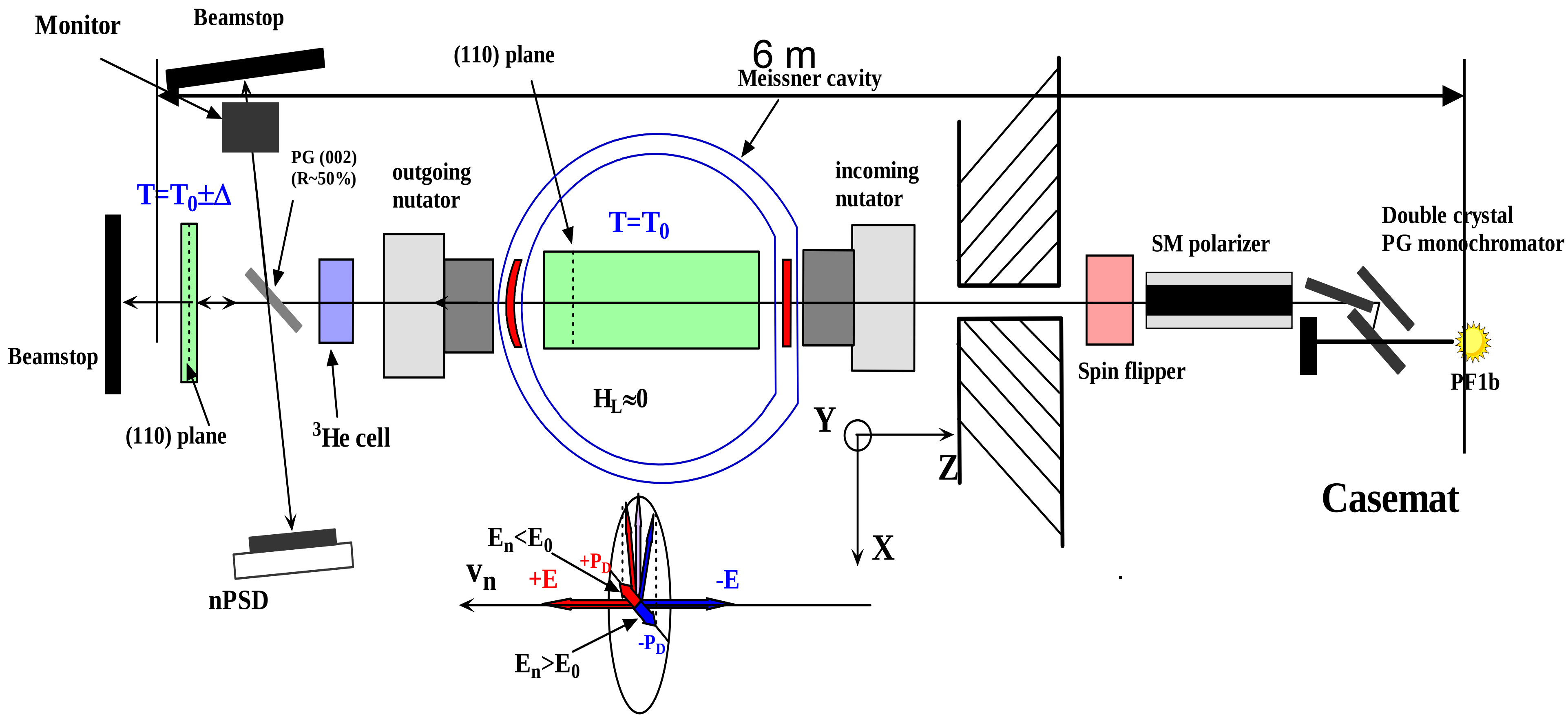


quartz (110) plane L_c=14 cm
Bragg angle ≈ 86^0

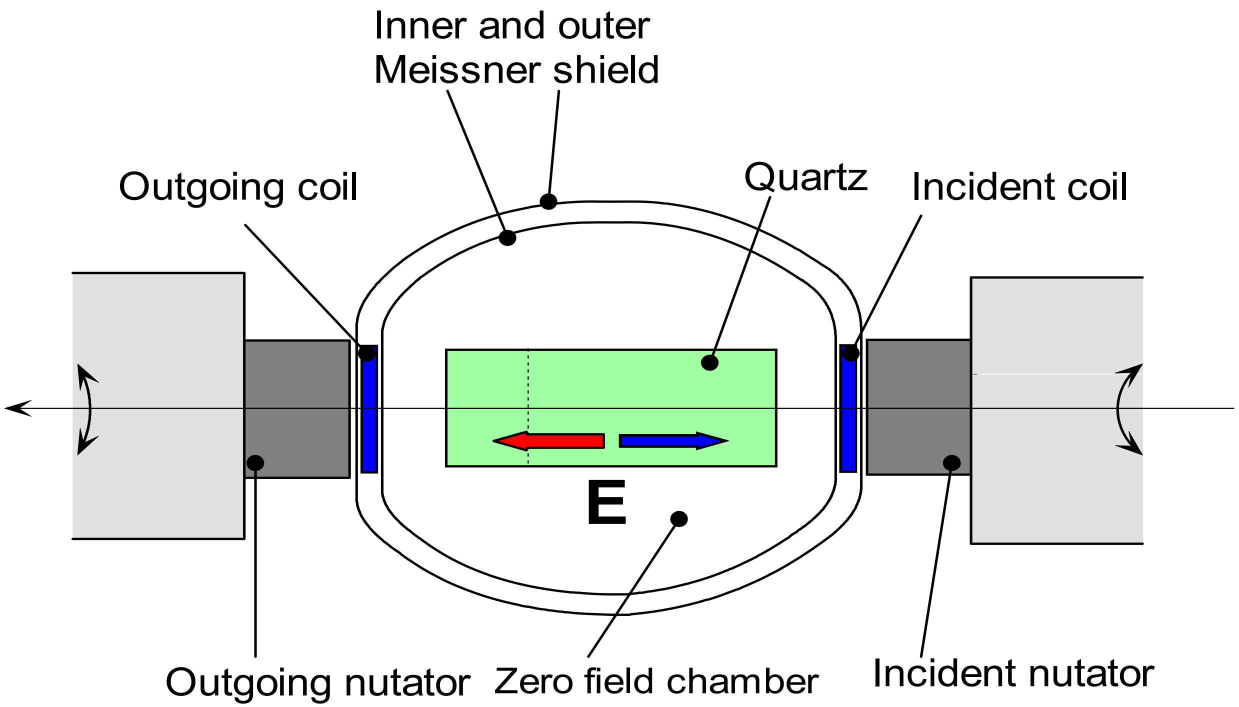
Variation of the ΔT on $\pm 1^0$ ⇒ $E \approx \pm 10^8$ V/cm



Scheme of the experiment



Main elements CRYOPAD and position sensitive detector



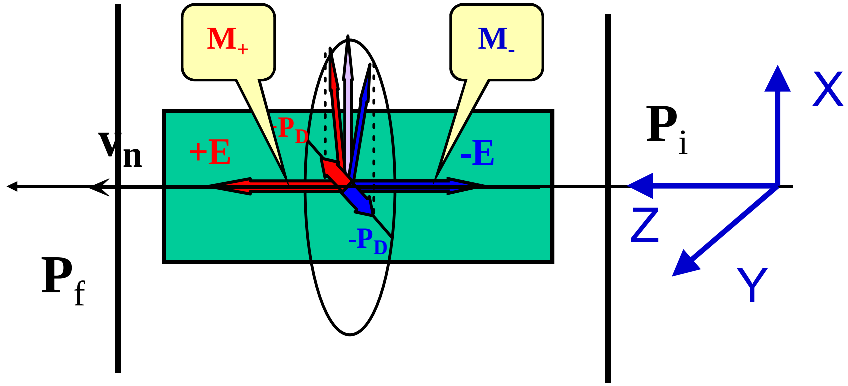
Current accuracy of spin orientation is

~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**

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

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

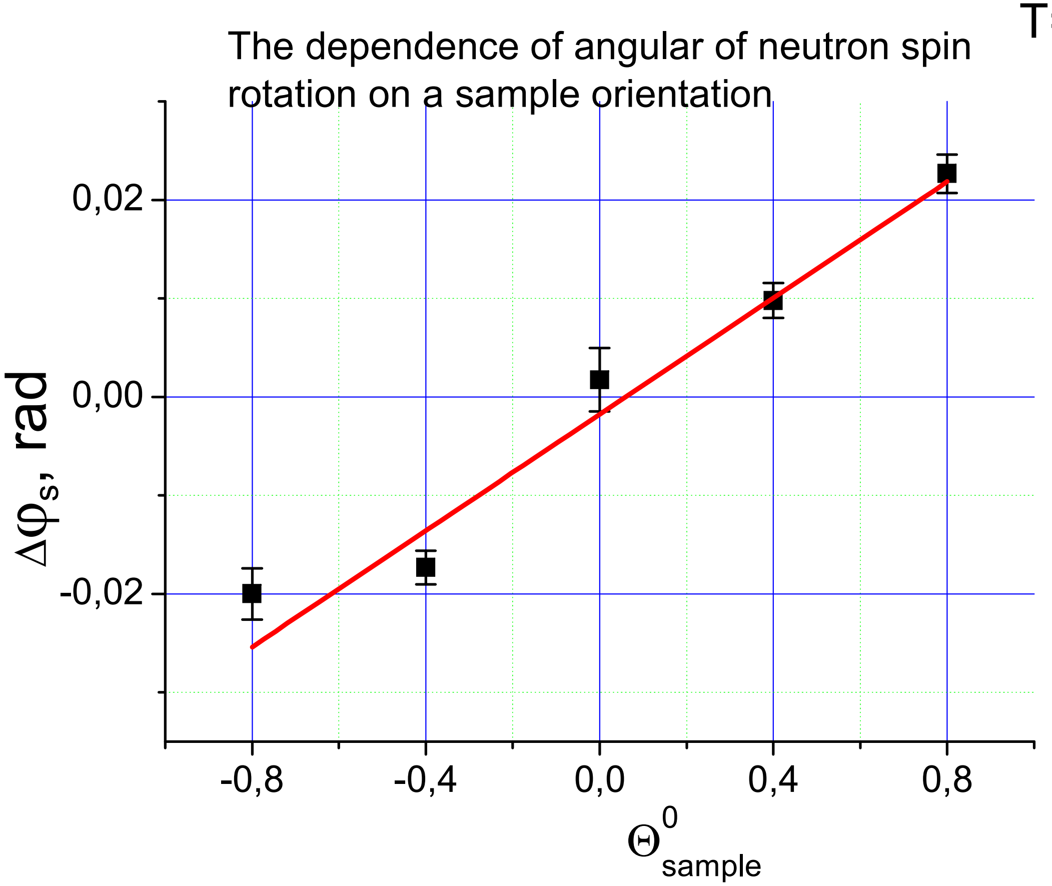
$$\mathbf{M}_{+} - \mathbf{M}_{-} \equiv \Delta\mathbf{M} = g_n\tau_0\left[\begin{pmatrix} 0 & -H_e & 0 \\ H_e & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \begin{pmatrix} 0 & 0 & H_{sy} \\ 0 & 0 & -H_{sx} \\ -H_{sy} & H_{sx} & 0 \end{pmatrix} + \Delta\tau/\tau_0\begin{pmatrix} 0 & -H_z & H_y \\ H_z & 0 & -H_x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

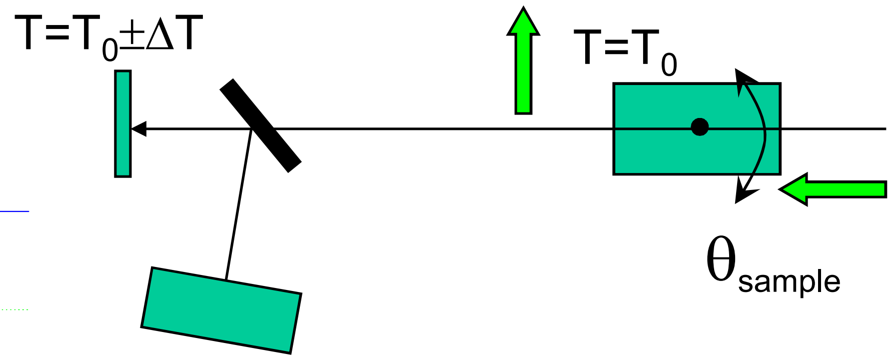
$$H_e = (E\,d_n)/\mu_n$$

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

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

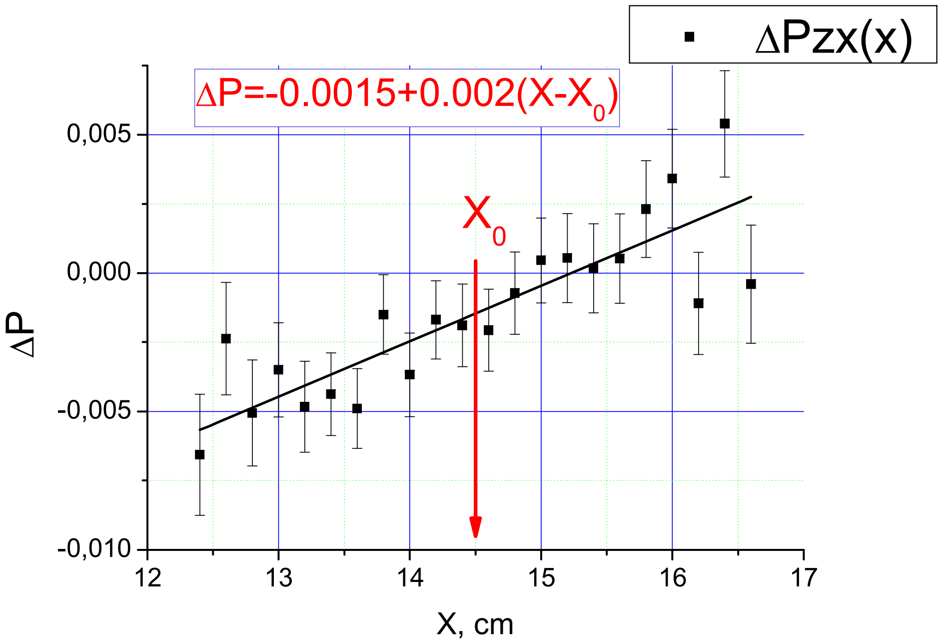
Measurement of Schwinger effect

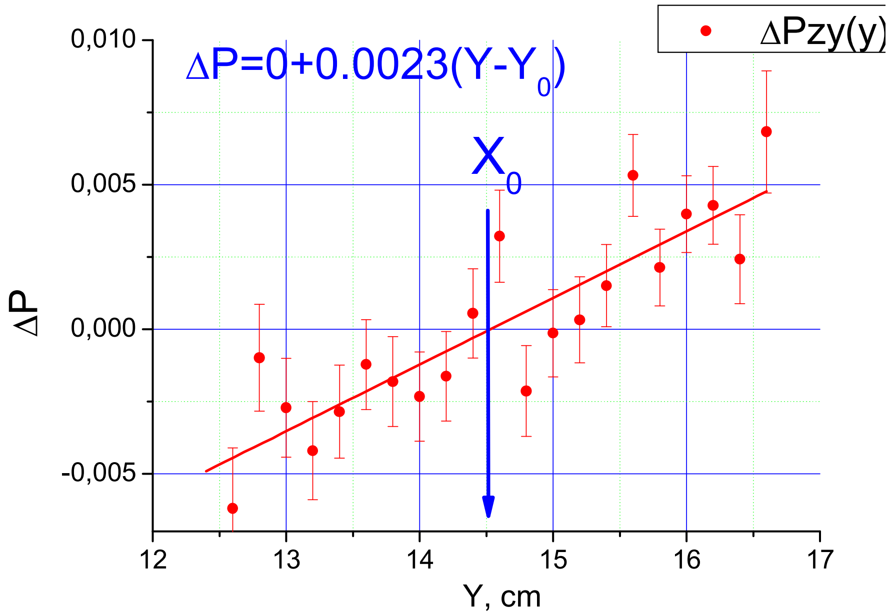


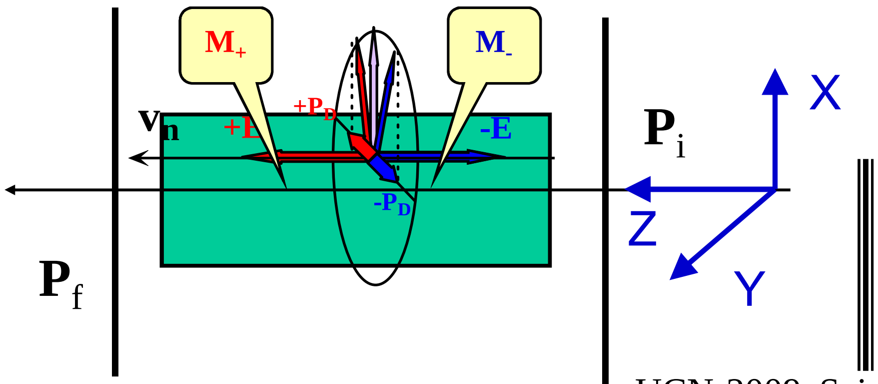


1. **Schwinger effect is zero for $\theta_B=90^0$**
1. **E~ 0.7 10^8 V/cm**

Spatial distribution of Schwinger effect in position sensitive detector



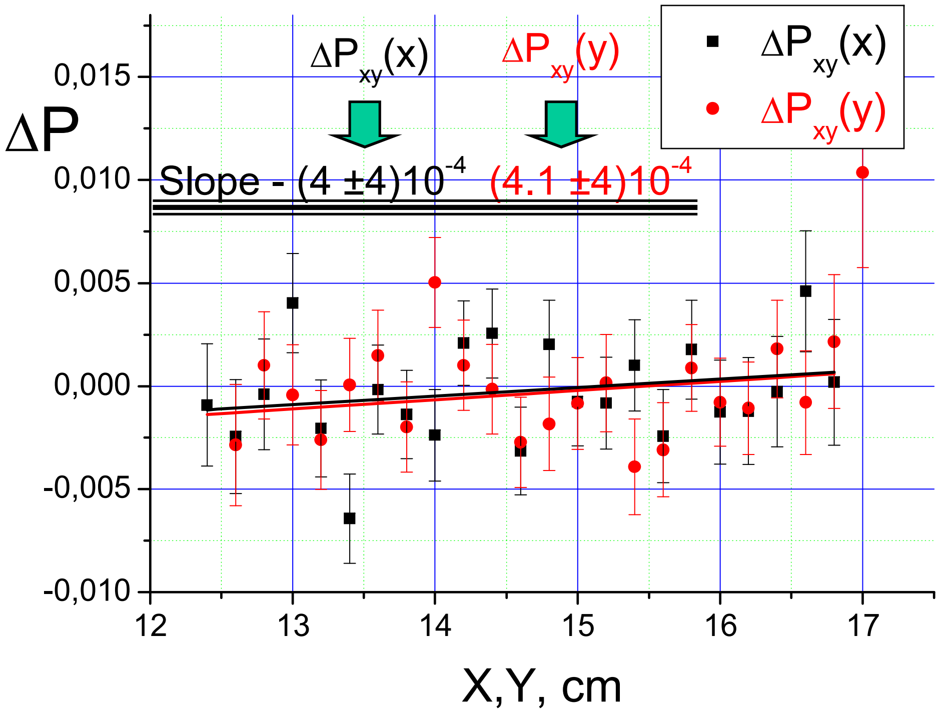


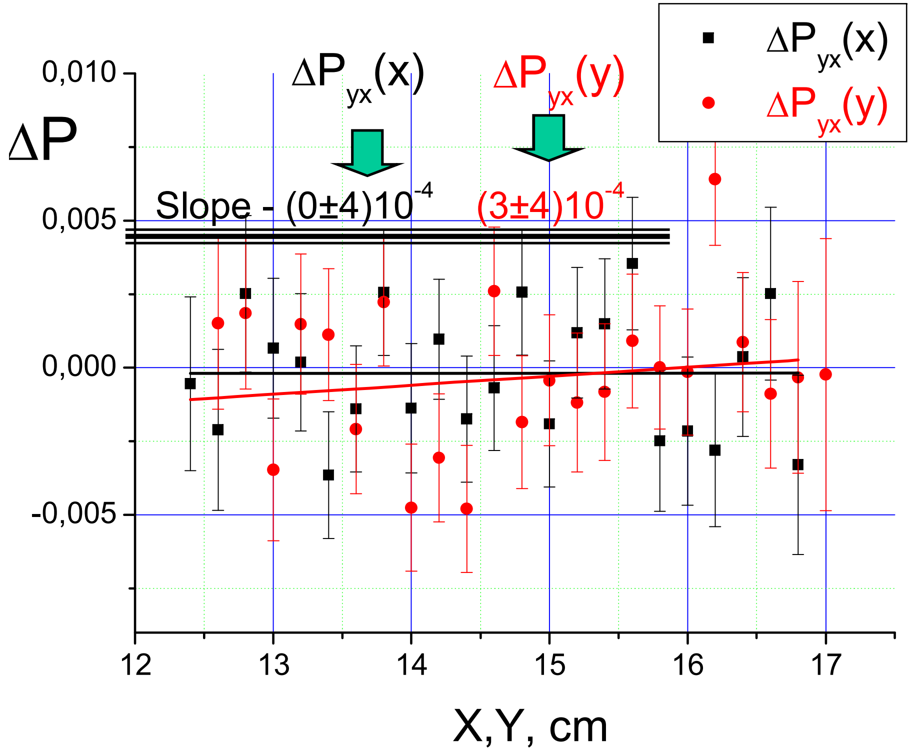


$$\Delta P = P(\Delta T_+) - P(\Delta T_-)$$

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

nEDM effect spatial distribution





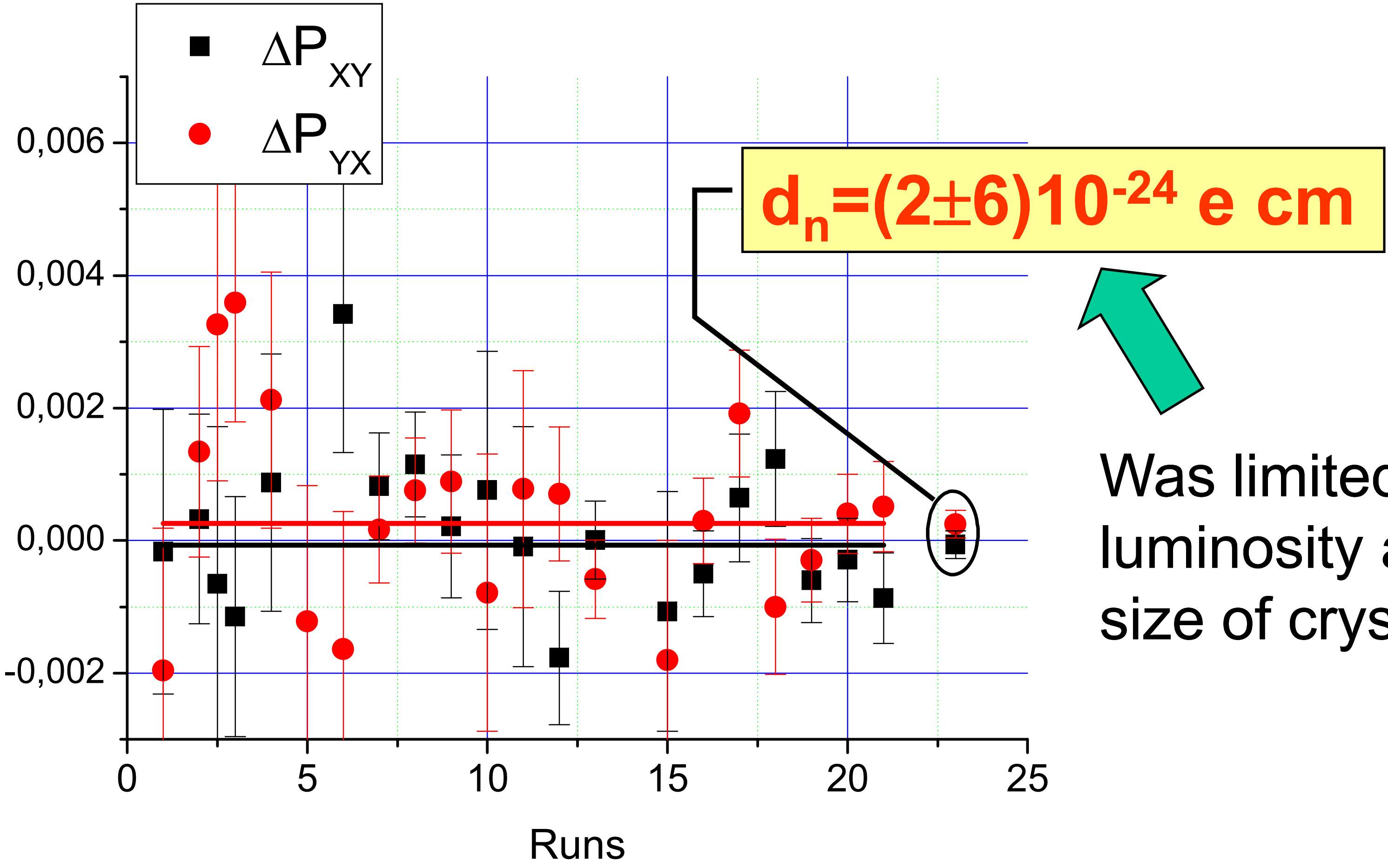
Schwinger $\Delta P_s < 1.1\ 10^{-4}$

stat. accuracy is

$\Delta P \sim 1.5\ 10^{-4}$

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

nEDM measurement



Was limited by low luminosity and size of crystal

Statistical sensitivity (1)

$$\sigma^{-1} \sim E\tau\sqrt{N} = E\frac{L_c}{\text{v}}\sqrt{\Delta\lambda_B e^{-L_c/L_a}\Phi(\lambda)S_b \cdot P \cdot K_{exp}}$$

Bragg width

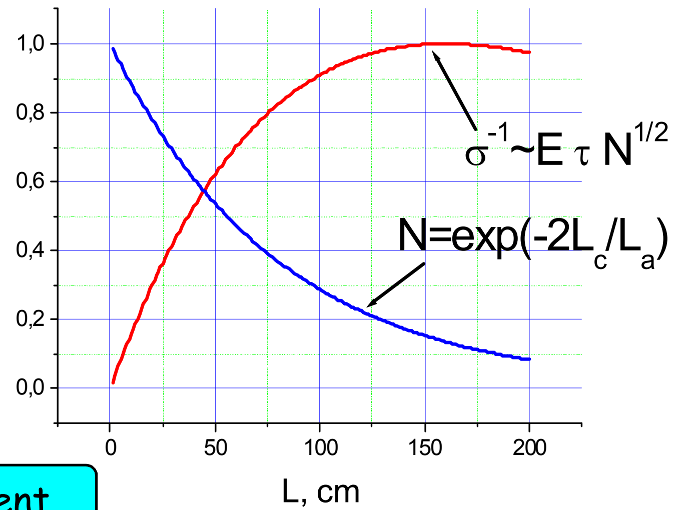
Unpolarized beam flux

Loses for polarization

Absorption

Beam square

Setup coefficient



Optimal length of crystal is the two absorption length.

$$\mathbf{E} \approx 1\cdot 10^8\,\text{V/cm}$$

$L_a = 80\text{cm}$ for λ = 4.9 Å

For crystal thickness L_c=50 cm

$$\varphi_d \approx 1.7\cdot 10^{-5}\,\text{rad}$$

for $d_n = 10^{-25}\,e\cdot cm$

Statistical sensitivity (2)

$\Phi=10^9$ n/(cm^2 Å s) (λ=5 Å, PF1B of ILL reactor)
$S=6\times12$ cm^2, $P=1/10$, $K_{exp}=1/8$ **$N=2.1\ 10^4$ n/s**

$$\sigma_d = 1.3\cdot10^{-25}\ e\cdot cm\ per\ day$$

quartz SiO_2
$E_g\sim 10^8$ V/cm
$\tau_a\sim1$ ms

Current sensitivity to nEDM in UCN method

~ 6 10^{-25} e·cm/day

$\sigma_d \sim 10^{-26}$ *e cm per day*

PbO
$Bi_{12}SiO_{20}$
????

$\sigma_d \sim 10^{-27}$ *e cm per day*

?? Fantasy - ^{208}PbO??
$E_g\sim10^9$ V/cm
$\tau_a\sim10$ ms

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 ω_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

100 day

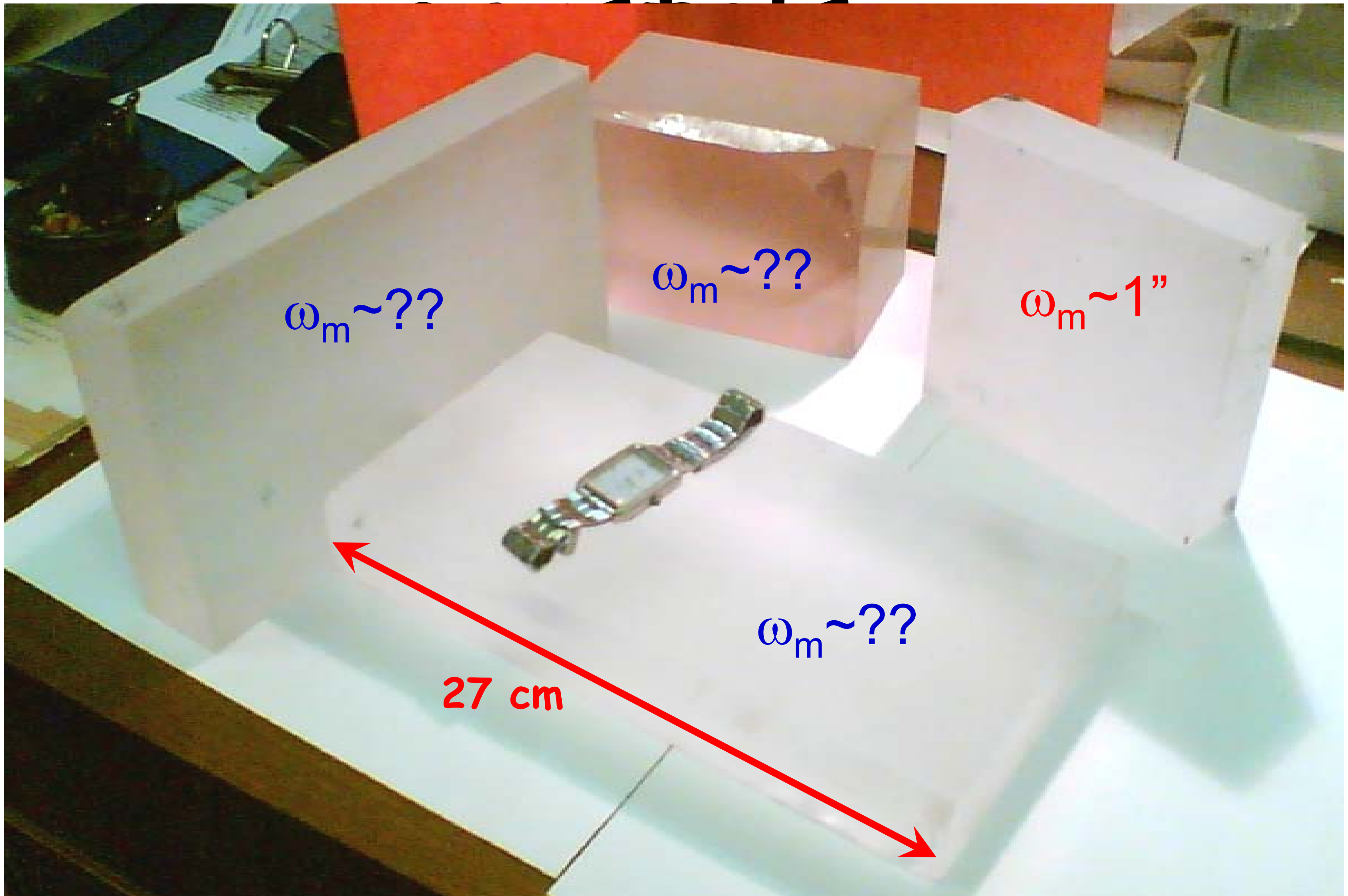
⇨ $\sigma_d \sim 1.3 \cdot 10^{-26}\ e \cdot cm$

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	$\sim 0.01^0C$

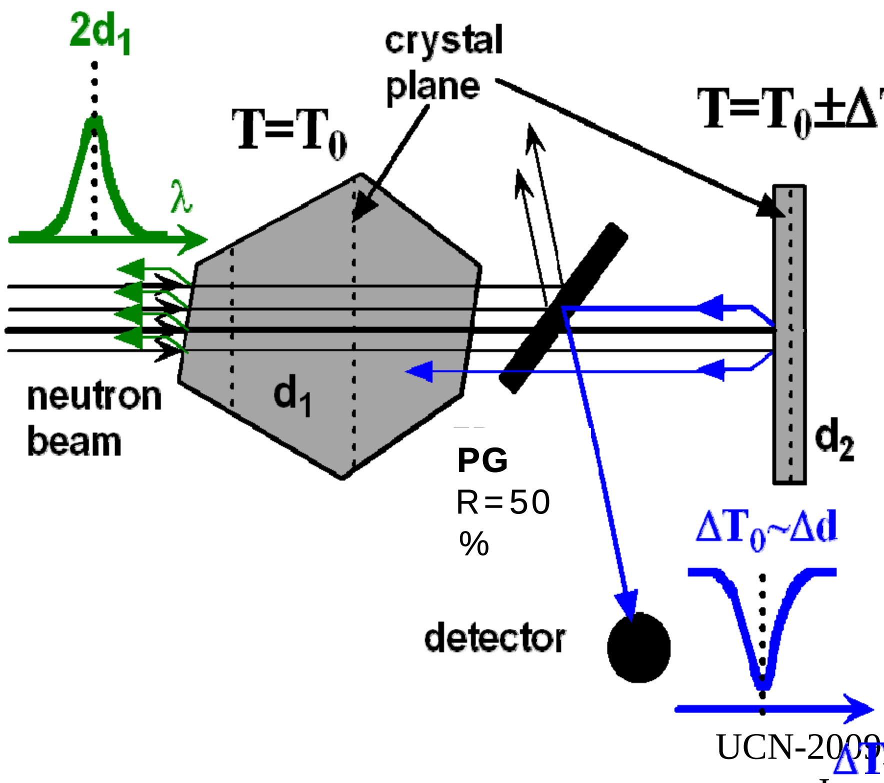
$\sigma_d < 6\ 10^{-27}$e cm

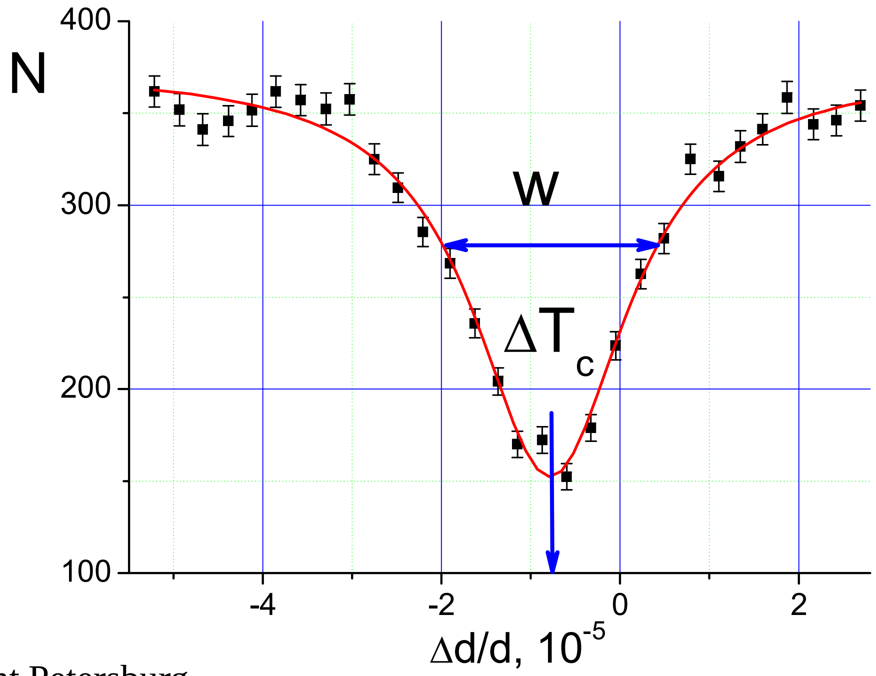
Photo of quartz



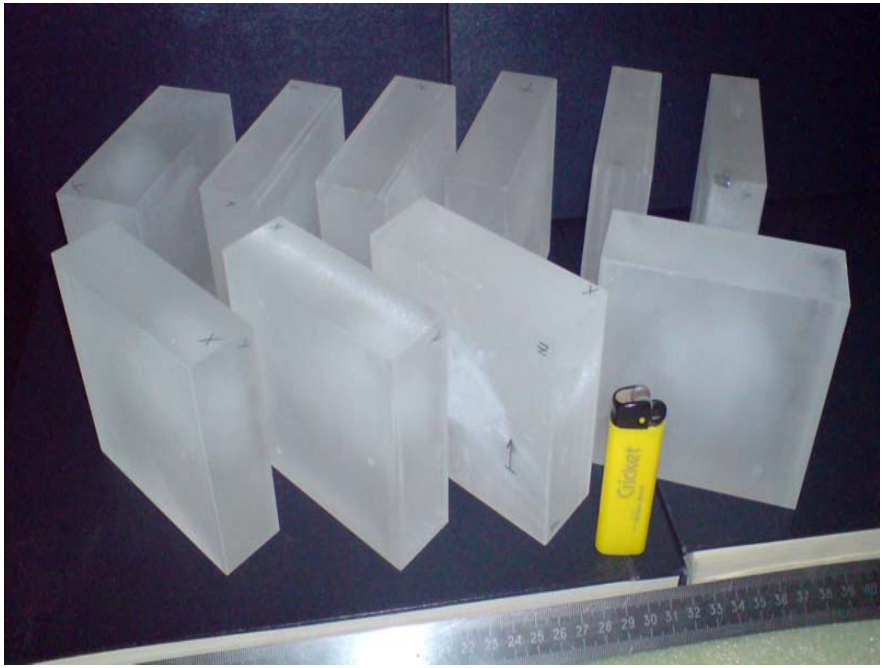
It turns out to be new method of testing the crystal quality in volume

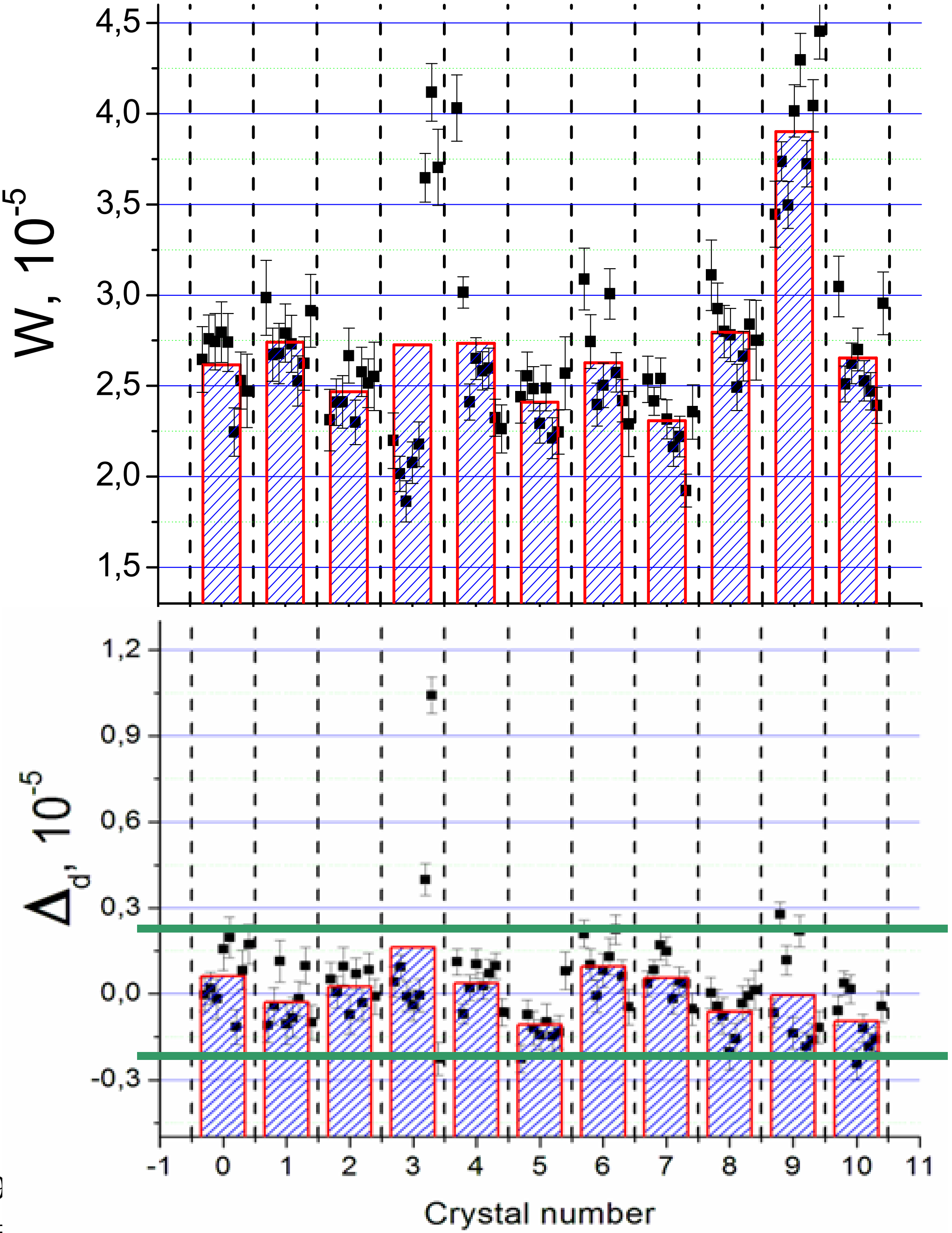
- One can test the quartz samples up to 50 cm thickness (limited by absorption length).
- Precision $\Delta d/d \sim 10^{-7}$





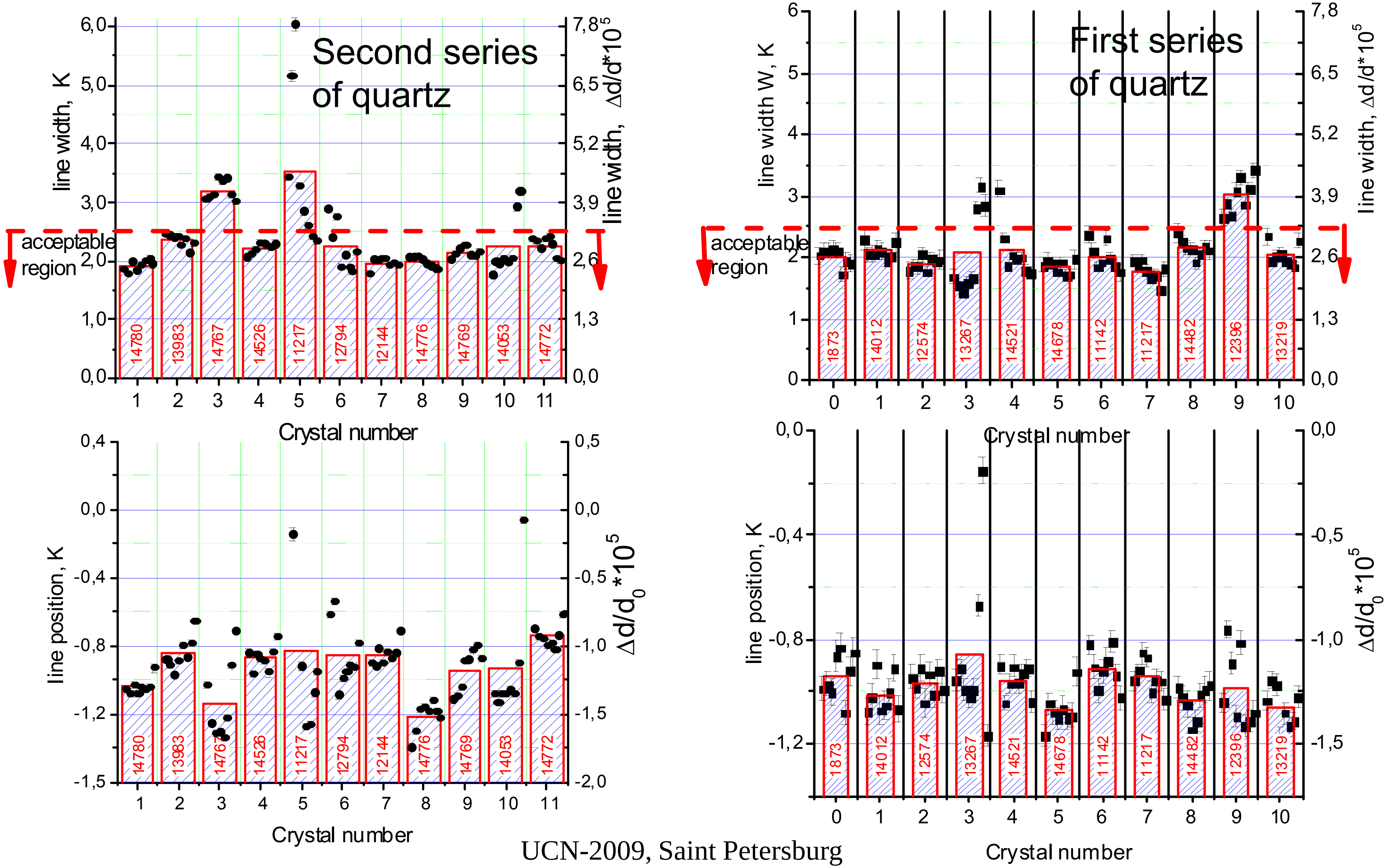
Tests of the series of crystals from Aleksandrov factory





Crystals No. 3 and 9 tuned to be not sutable the last ones had $\Delta d/d = \pm 2 \cdot 10^{-6}$

Quartz test



UCN-2009, Saint Petersburg
June 8-14,2009

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- **1966** **Abov Yu.G., Gulko A.D., Krupchitsky,P.A.** *Polarized Slow Neutrons*; Atomizdat; Moscow, 1966
  Interference of the nuclear and spin-orbit amplitudes in a non-centrosymmetric crystal.
- **1967** **Shull,C.G.; Nathans,R.** Phys. Rev. Lett.1967 **19** 384.
  Bragg reflection by CdS centrosymmetrical crystal for nEDM search: $d_n<7\ 10^{-22}$e cm
- **1972** **Golub R., Pendlebury G.M.**, Contemp. Phys. (1972) **13** 519.
  The idea to use the atomic electric fields for the neutron EDM search. But how?
- **1983** **Forte M. J.,** Phys. G (1983) **9** 745.
  Idea to search for neutron EDM by measuring a spin rotation angle for the Bragg diffraction scheme.
- **1989** **Forte M., Zeyen C.M.E.** Nucl. Instr. and Meth. A (1989) **A284** 147.
  Experiment on the neutron spin-orbit rotation in the Bragg scheme of the diffraction.
- **1989** **Fedorov V.V., et al.** Nucl. Instr. and Meth. A (1989) **A284** 181.
  First measurements of electric field of NCS crystal. Eg≈2 108 V/cm for quartz crystal.
- **1992** **Fedorov V.V., Voronin V.V., Lapin E.G.** J. Phys. G (1992) **18** 1133.
  Laue diffraction for the neutron EDM search. Spin dependence of pendulum phase.
- **1997** **Fedorov V.V., Voronin V.V., Lapin E.G., Sumbaev O.I**. Tech.Phys. Lett. (1995) **21** (11) 881; Physica B (1997) **234--236** 8.
  Depolarization in Laue diffraction scheme and sensitivity to neutron EDM search.
- **1997-2009** **Fedorov V.V. et al**
  Series of the test experiments on observation of spin e ffects in neutron optics and diffraction

Last publications

- V.V. Fedorov, V.V. Voronin. Neutron diffraction and optics in noncentrosymmetric crystals. New feasibility of a search for neutron EDM, Nuclear Instruments and Methods in Physics Research B, **201** (1) 230-242 (2003)

- V.V. Fedorov, E.G. Lapin, E. Lelievre-Berna, V.V. Nesvizhevsky, A.K. Petoukhov, S.Yu. Semenikhin, T. Soldner, F. Tasset and V. V. Voronin, The Laue diffraction method to search for a neutron EDM. Experimental test of the sensitivity, Nuclear Instruments and Methods in Physics Research B, **227** (1-2) 11-15 (2005)

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