Storage modification of the crystal-diffraction nEDM experiment

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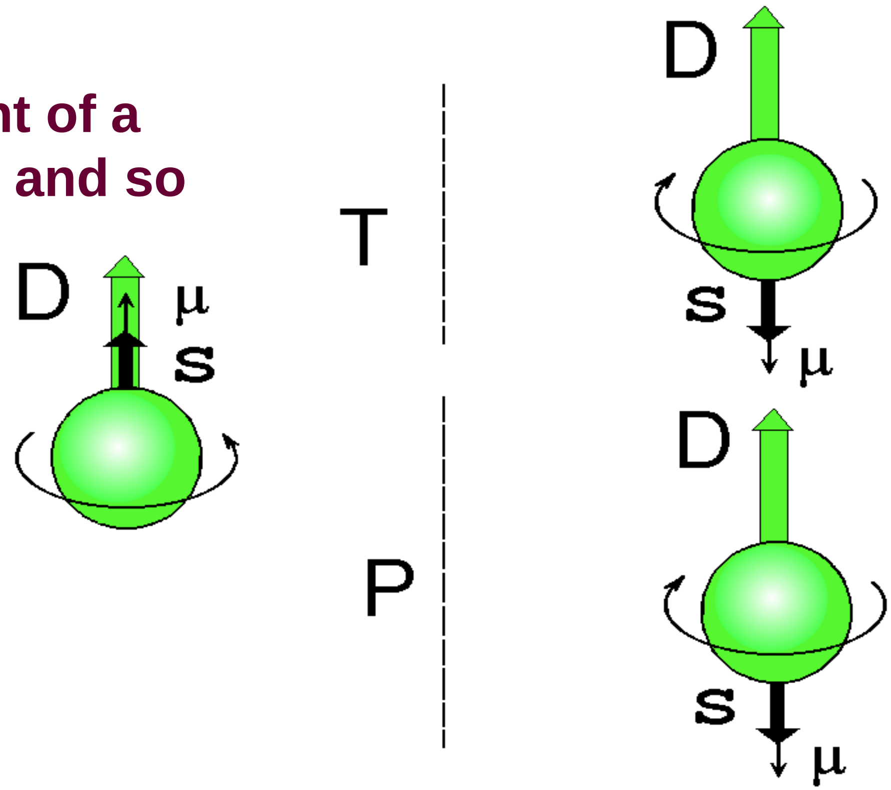
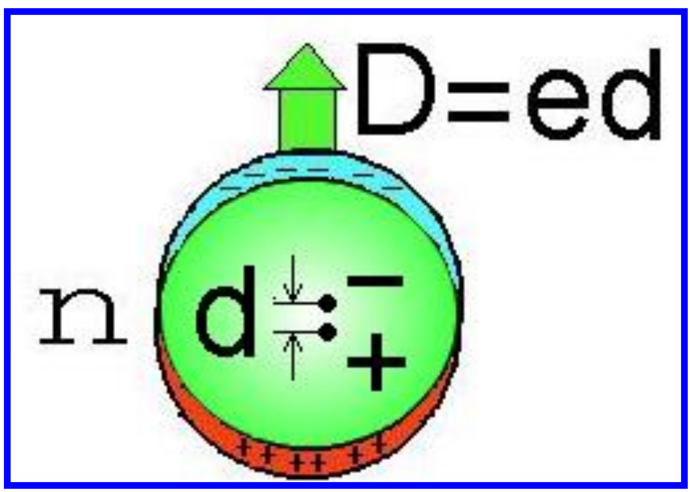
DNS-IV, Dubna, 06 – 07 December 2018

A few remarks. Why is it necessary to search for 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 ~ 30 years old results of PNPI and ILL: $d_n \leq 9,7{\cdot}10^{-26}$ e·cm, PNPI, 1989



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

Such a part of Earth radius is approximately ~ 2 μm !!!

The Standard Model (SM) perfectly well **explains** all observations **of CP and T violation** in **the K and B decays**.

Also **SM predicts the neutron EDM** 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}**.

According to Sakharov criteria (1967) only **theories beyond the SM,** suggesting **new channels for CP violation** as well as **violation of the baryon number conservation** are 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.**

So the measurements of the neutron EDM could provide a significant argument for these extensions to the SM.

Standard model

(the baryon asymmetry $n_b/n_\gamma \sim 10^{-20} - 10^{-25}$)

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

That is below of the current experimental limit by 6 – 8 orders of magnitude!!!

New physics beyond SM to explain the observable baryon asymmetry

(experiment - $n_b/n_\gamma \sim 10^{-8} - 10^{-10}$)

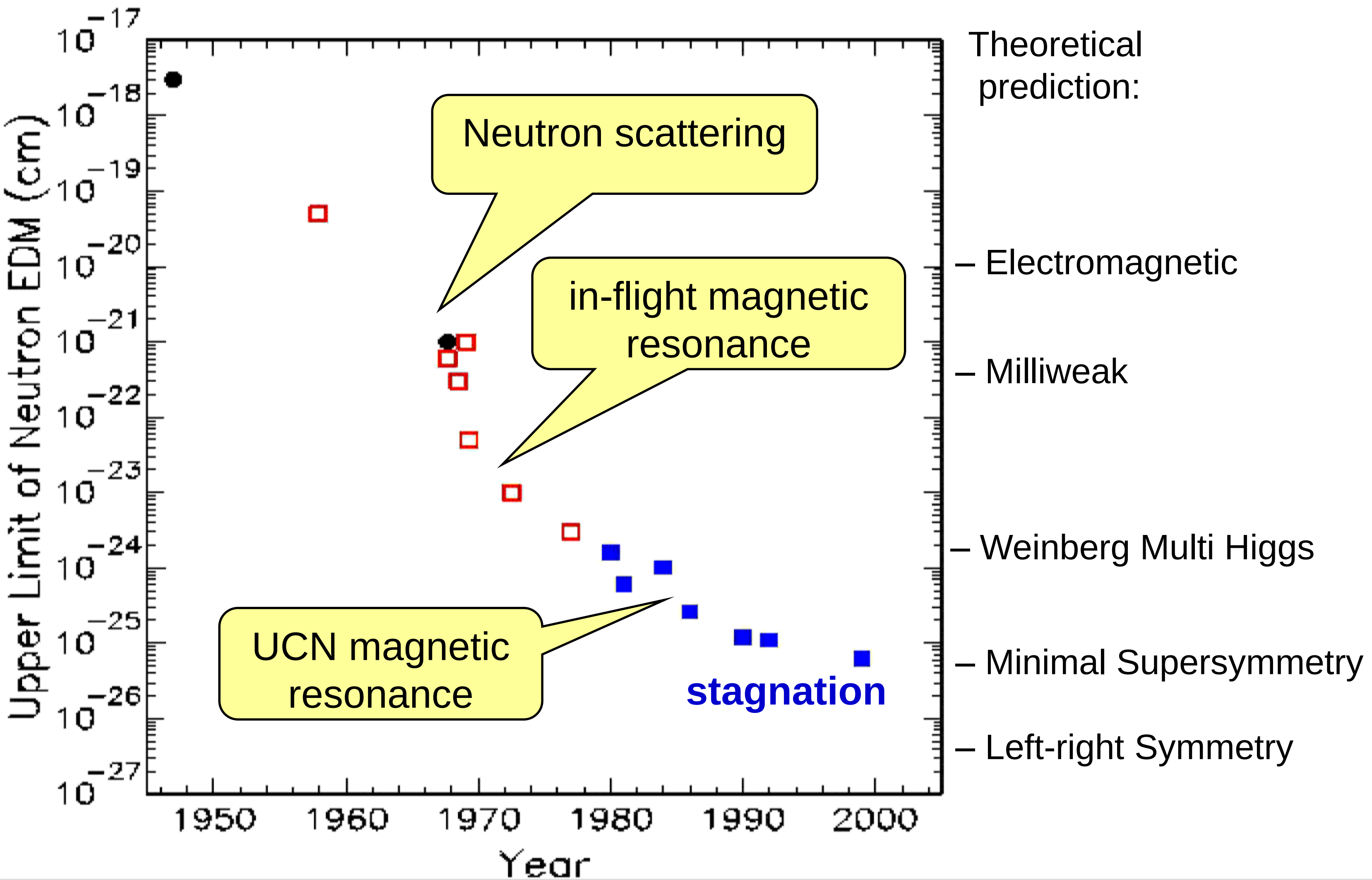
$d_n \sim (10^{-26} - 10^{-28})$ e cm

At the limit of current experimental feasibilities

For <u>last 30 years</u> there is some stagnation in the experimental sensitivity to neutron EDM – the sensitivity was **improved only about 3 times.**

Therefore it is important to develop the principally new methods and ideas to search for neutron EDM.

History of nEDM experiment from Ramsey pioneering work (measured in 1951, published in 1957)

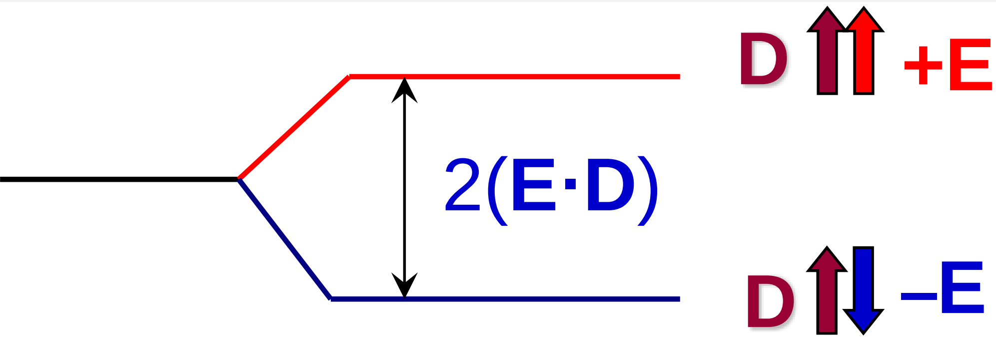


E.M. Purcell, and N.F. Ramsey, 1950, proposed to measure nEDM
Smith, J.H., 1951, PhD Thesis, measured nEDM
Smith, J.H., E.M. Purcell and N.F. Ramsey, 1957, Phys. Rev. 108, 120. Published

“It is fair to say that the neutron EDM has ruled out more theories (put forward to explain K_0 decay) than any experiment in the history of physics.”

Golub R., Lamoreaux S.K. Neutron electric-dipole moment, ultracold neutrons and polarized ^{3}He.
Phys. Rep., 237 (1994) 1– 62.

Sensitivity to neutron EDM



Interaction time with $\mathbf{E}$

A neutron spin precession angle due to interaction of the EDM with the electric field:

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

It is analogous to the spin precession angle due to interaction of magnetic moment with the magnetic field :

$$\varphi_\mu = 2(\mathbf{H}\cdot\boldsymbol{\mu})\tau/\hbar$$

Sensitivity to neutron EDM will be determined by the value of the effect $E\tau$ and the total number of accumulated events $\sqrt{N}$

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

Diffraction method to search for neutron EDM

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

UCN method

E ~ a few 10^4 V/cm

τ ~ 1000 s (time of life)

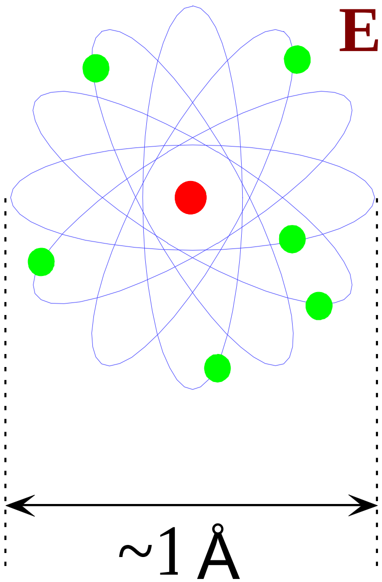
$(E\tau)_{max}$ ~ 10^7(V·s)/cm

Actual now

$E\tau \approx 10^6$ (V·s)/cm

Crystal-diffraction method

Electron bounding energy ~ **a few eV**



$\mathbf{E} = -\,\mathrm{grad}\, V_e \sim (1\text{-}10)10^8$ V/cm

τ_a ~ 0.01 c (absorption)

$(E\tau)_{max}$ ~ 10^7(V·s)/cm

Crystal-diffraction nEDM project

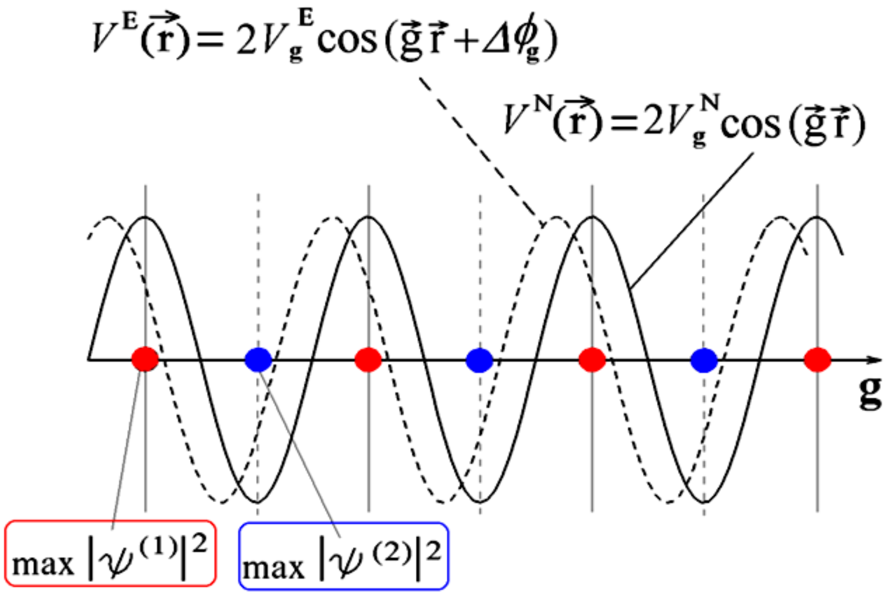
In the non-centrosymmetric crystal

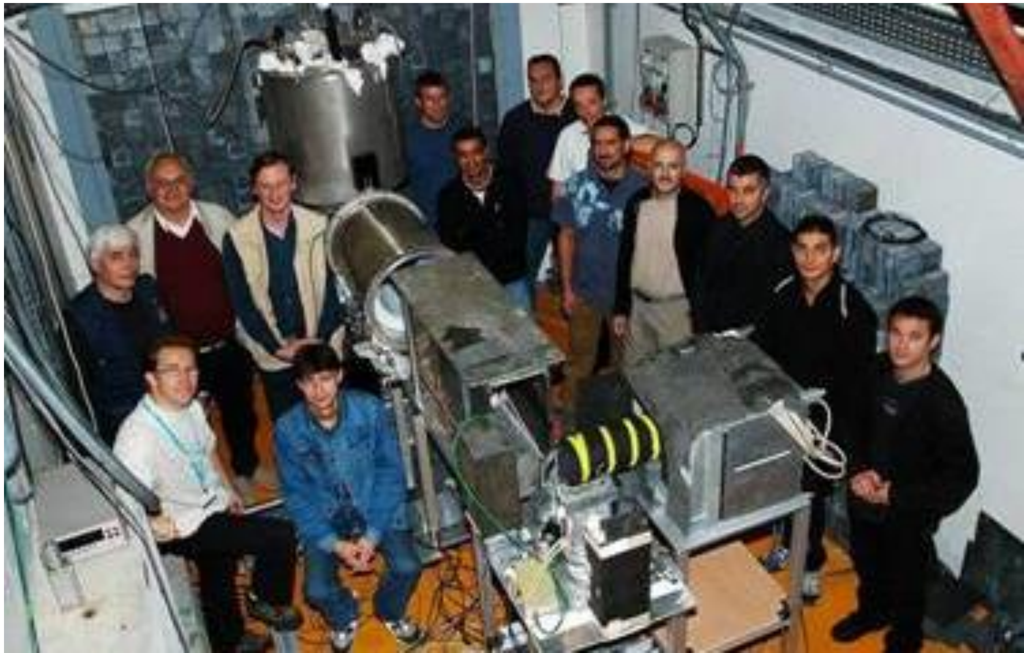
neutrons are moving under strong electric field (up to 10^9 V/cm).

The cause is that:

1. The neutron concentration on (or between) the nuclear planes

2. Shift of the electric planes relative to the nuclear ones





Test at ILL

PNPI

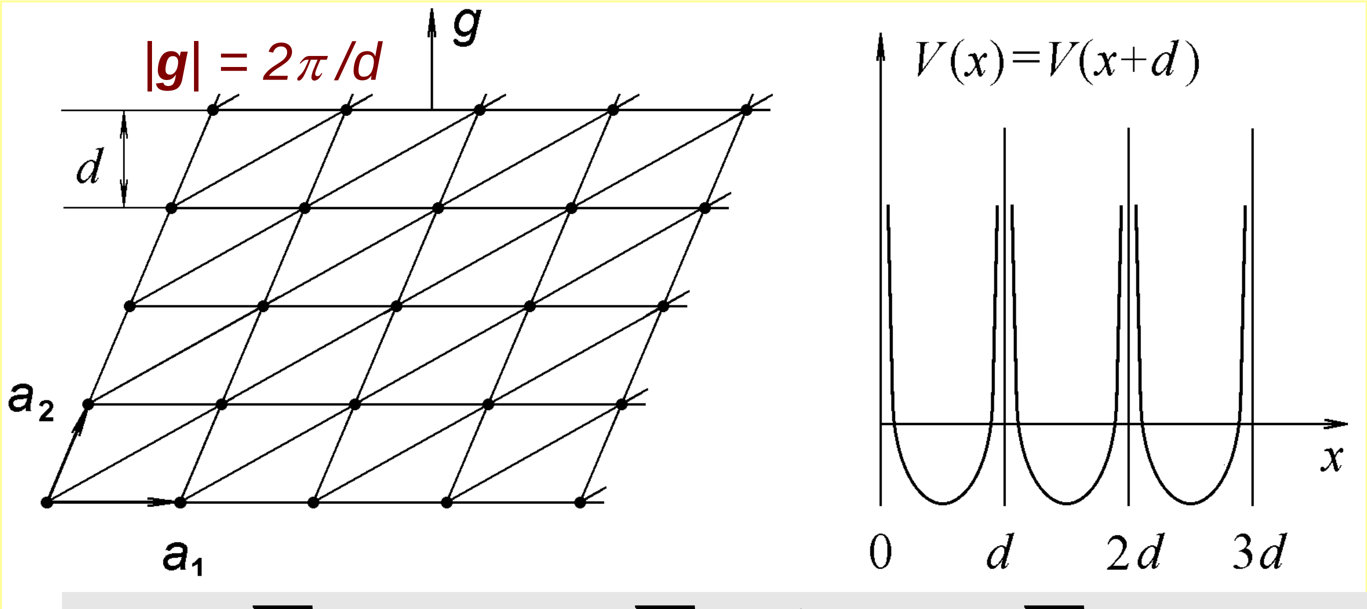
V.V. Fedorov,
E.G. Lapin,
I.A. Kusnetsov,
S.Yu. Semenikhin,
V.V. Voronin
Yu.P. Braginets

ILL

M. Jentschel,
E. Lelievre-Berna,
V. Nesvizhevsky,
A. Petoukhov,
T. Soldner

Any crystal potential (nuclear or electric)

Can be represented as a sum of atomic potentials or as a sum of crystal planes potentials. The last is called the reciprocal lattice vectors expansion



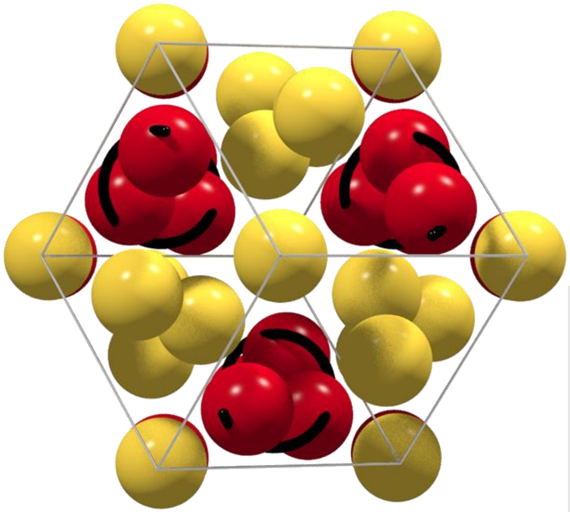
$$V(\mathbf{r}) = \sum_{\alpha} V_{\alpha}(\mathbf{r}-\mathbf{r}_{\alpha}) = \sum_{g} V_g e^{i\mathbf{g}\mathbf{r}} = V_0 + \sum_{g>0} 2\upsilon_g \cos(\mathbf{g}\mathbf{r}+\phi_g)$$

$V(\mathbf{r})$ **is real** ➡ $V_g = V^*_{-g}$, **and we put** $V_g = \upsilon_g \exp(i\phi_g)$

For centrosymmetric crystal, by choosing a center of symmetry as the origin of coordinates (so that $V(\mathbf{r}) = V(\mathbf{-r})$), one can **reduce to zero the phases of** the amplitudes **for all harmonics** of the total potential (and of each potentials individually):

$$\phi_g = \phi_g^N = \phi_g^E = \ldots \equiv 0,$$

Harmonic amplitudes V_g for both nuclear and electric potentials are determined by corresponding structure amplitudes F_g (sell scattering amplitudes):



$$V_g = \int_{V=1} d^3r\, e^{-i\mathbf{gr}} V(\mathbf{r}) = -\frac{2\pi\hbar^2}{m} N_c F_g,$$

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

<u>In NCS crystal</u> the phases of complex values V_g^N and V_g^E can be different that leads to shift of the electric potential maximums relative to the nuclear ones (shift of "electric planes" relative to "nuclear" ones)

Harmonic amplitude V_g^N of nuclear potential is determined by the nuclear scattering amplitudes (scattering lengths):

$$f_i^N(\mathbf{g}) = -a_i$$

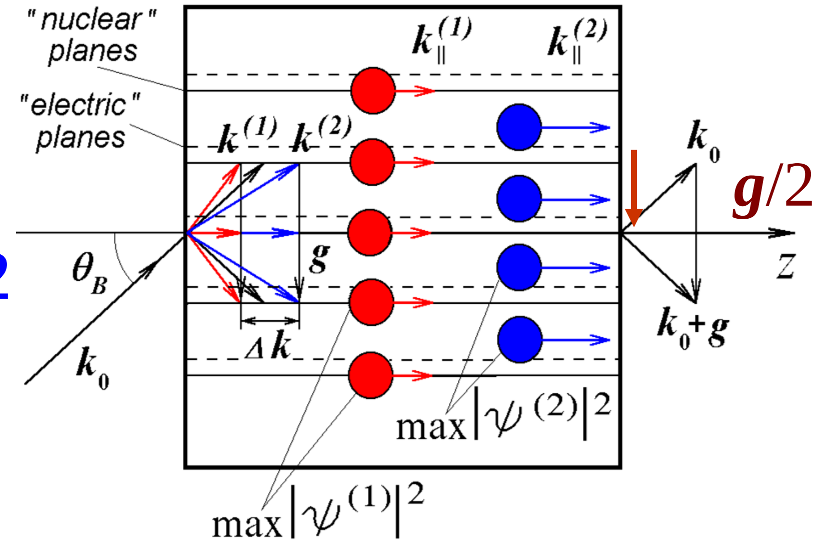
Harmonic amplitude V_g^E of electric potential is determined by the atomic scattering amplitudes for charged particle:

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

How a neutron concentration arises in crystal? Two wave approach

Periodic potential, containing $\cos \mathbf{gr}$, can transfer only momentum $\mathbf{q} = \hbar\mathbf{g}$.

Energy conservation ➡ **Bragg condition**



final energy — initialal energy

$$|\mathbf{k}_0 + \mathbf{g}|^2 = |\mathbf{k}_0|^2 \quad \text{or} \quad k_{0y} \equiv k_{\perp} = -g/2$$

that equal to usual: $2d \sin\theta_B = \lambda$

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

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

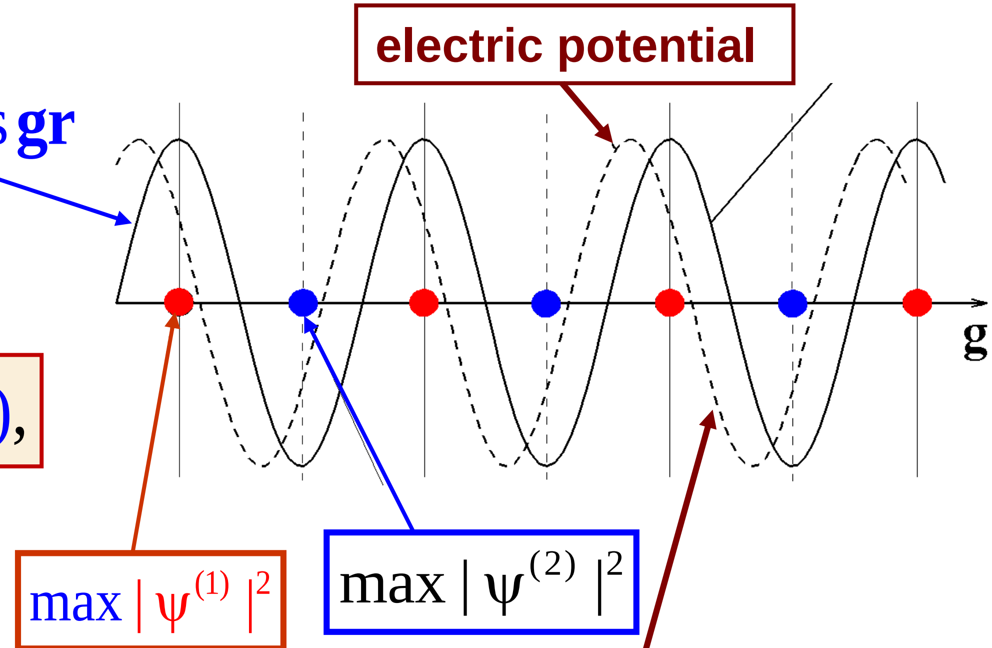
$$\psi^{(2)} = \frac{\exp\left(i\mathbf{k}^{(2)}\mathbf{r}\right) - \exp\left[i(\mathbf{k}^{(2)} + \mathbf{g})\mathbf{r}\right]}{\sqrt{2}} = -i\sqrt{2}\sin\left(\frac{\mathbf{gr}}{2}\right)\exp\left[i\left(\underbrace{\mathbf{k}^{(2)} + \frac{\mathbf{g}}{2}}_{k_{\parallel}}\right)\mathbf{r}\right]$$

Neutrons are moving along the crystal planes with the velocity:

$$|\mathbf{v}_{\parallel}| = \frac{\hbar k \cos\theta_B}{m} = \upsilon\cos\theta_B \approx \upsilon\left(\frac{\pi}{2} - \theta_B\right) \quad \text{при} \quad \theta_{\text{B}} \approx \frac{\pi}{2}$$

The **behavior of neutrons** in crystal **is determined by the nuclear interaction**, so the **periodic potential** responsible for diffraction has a form (we put $\phi_g^N = 0$):

$$V^N(\mathbf{r}) = 2\upsilon_g^N \cos \mathbf{gr}$$



Neutron "density" in crystal for **symmetric state** is

$$|\psi^{(1)}|^2 = 2\cos^2(\mathbf{gr}/2) = 1 + \cos(\mathbf{gr}),$$

the neutrons are concentrated **on the "nuclear" planes**.

$$V^E(\mathbf{r}) = 2V_g^E \cos(\mathbf{gr} + \Delta\phi_g)$$

For **antisymmetric state** neutrons are concentrated **between the "nuclear" planes:**

$$|\psi^{(2)}|^2 = 1 - \cos(\mathbf{gr})$$

$$\mathbf{E}(\mathbf{r}) = -\mathrm{grad}\ V^E(\mathbf{r}) = 2\upsilon_g^E \mathbf{g} \sin\left(\mathbf{gr} + \Delta\phi_g\right)$$

In noncentrosymmetric crystal

$\Delta\phi_g \neq 0$, therefore

$$\mathbf{E}_g = \left\langle \psi^{(1)} | \mathbf{E}(\mathbf{r}) | \psi^{(1)} \right\rangle = -\left\langle \psi^{(2)} | \mathbf{E}(\mathbf{r}) | \psi^{(2)} \right\rangle = \mathbf{g}\upsilon_g^E \sin\Delta\phi_g .$$

In noncentrosymmetric (NCS) crystals there are strong electric fields, which act on neutron, moving in a crystal

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**
		444	**1.46**	**4.65**		**1860**
$Bi_{12}GeO_{20}$	I23	433	**1.74**	**4.65**	**1**	**465**
		444	**1.46**	**4.8**		**480**

Historical review on NCS crystal study

- **Abov Yu.G., Gulko A.D., Krupchitsky,P.A**. *Polarized Slow Neutrons*; Atomizdat; Moscow, **1966**
  Interference term of the nuclear and spin-orbit amplitudes in a noncentrosymmetric crystal
- **Forte M.** J., Phys. G (**1983**) **9** 745. Idea to search for neutron EDM by measuring a spin rotation in NCS crystal
- **Baryshevskii V.G. and Cherepitsa S.V.,** Phys. Stat. Sol., (**1985**) **128**, 379 Neutron spin precession and spin dichroism of nonmagnetic unpolarized single crystals
- **Fedorov V.V., Voronin V.V. et al.** Nucl. Instr. and Meth. A (**1989**) **A284** 181. First measurements of electric field in Laue diffraction geometry
- **Forte M., Zeyen C.M.E.** Nucl. Instr. and Meth. A (**1989**) **A284** 147 Observation of the spin effect NCS crystal
- **Fedorov V.V., Voronin V.V., E.G. Lapin,** J. Phys. G, **1992** **18** 1133 On a search for nEDM via Pendellosung fringe in NCS crystal
- **Fedorov V.V., Lapin E.G., Semenikhin S.Yu., Voronin V.V.** , JETP Letters, **72 (**6) (**2000**) 308
  Observation of a Neutron Beam Depolarization in NCS crystal for the Laue Diffraction
- **Fedorov V.V., Lapin E.G., Semenikhin S.Yu., Voronin V.V.** JETP Letters, **74** (5) (**2001**) 251
  Observation of neutron spin rotation in neutron optics of NCS crystal
- **Claude M.E. Zeyen, Yoshie Otake**, Nuclear Instruments and Methods in Physics Research A 440 (**2000**) 489. Note about BGO crystal for nEDM
- **PNPI, ILL team** – (**2006-2010**) – series of the experiments to test the nEDM search technique using NCS quartz crystal.
  $d_n = (2.5 \pm 6.5\text{stat} \pm 5.5\text{syst}) \cdot 10^{-24}$ e cm. (**V.V. Fedorov et al**, Physics Letters B 694 (2010) 22)
- **V.V. Fedorov, V.V. Voronin.** JPS Conf. Proc. 22, 011007 (2018) Modern Status of Searches for nEDM, using Neutron Optics and Diffraction in Noncentrosymmetric Crystals

Neutron optics. Perturbation theory

If the Bragg condition is not satisfied for any plane system the neutron wave function in the crystal can be written as

$$\psi(\mathbf{r}) = e^{i\mathbf{kr}} + \sum_{g'} \frac{V_{g'}^N}{E_k - E_{k_{g'}}} e^{i\mathbf{k}_{g'}\mathbf{r}} \approx e^{i\mathbf{kr}}\left[1 - \frac{1}{\Delta_B} e^{i\mathbf{gr}}\right], \quad E_k = \hbar^2\mathbf{k}^2/2m, \quad \mathbf{k}_g = \mathbf{k} + \mathbf{g},\ E_{k_g} = \hbar^2\mathbf{k}_g^2/2m,$$

only one reflected wave for plane system **g**, most close to Bragg conditon

$$\Delta_B = \frac{E_k - E_{k_g}}{V_g^N} = \frac{2(E_k - E_B)}{V_g^N}$$

the deviation parameter from the Bragg condition

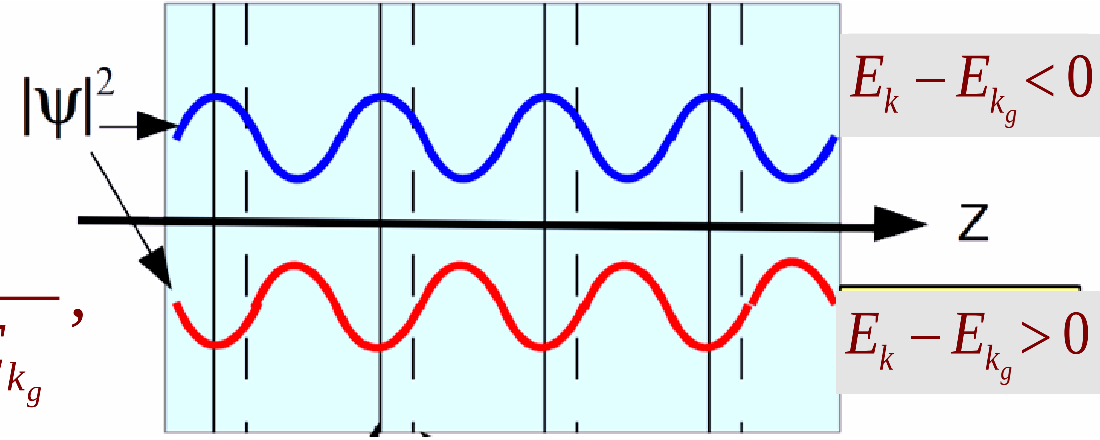
$$V^N(\mathbf{r}) = 2\upsilon_g^N \cos \mathbf{gr}, \qquad |\psi(\mathbf{r})|^2 = 1 - \frac{2}{\Delta_B}\cos \mathbf{gr},$$

$$V^E(\mathbf{r}) = 2\upsilon_g^E \cos\left(\mathbf{gr} + \Delta\phi_g\right)$$

Electric field, acting on neutron

$$\mathbf{E} = \langle \psi | \mathbf{E}(\mathbf{r}) | \psi \rangle = \mathbf{E}_g \frac{2\upsilon_g^N}{E_k - E_{k_g}},$$

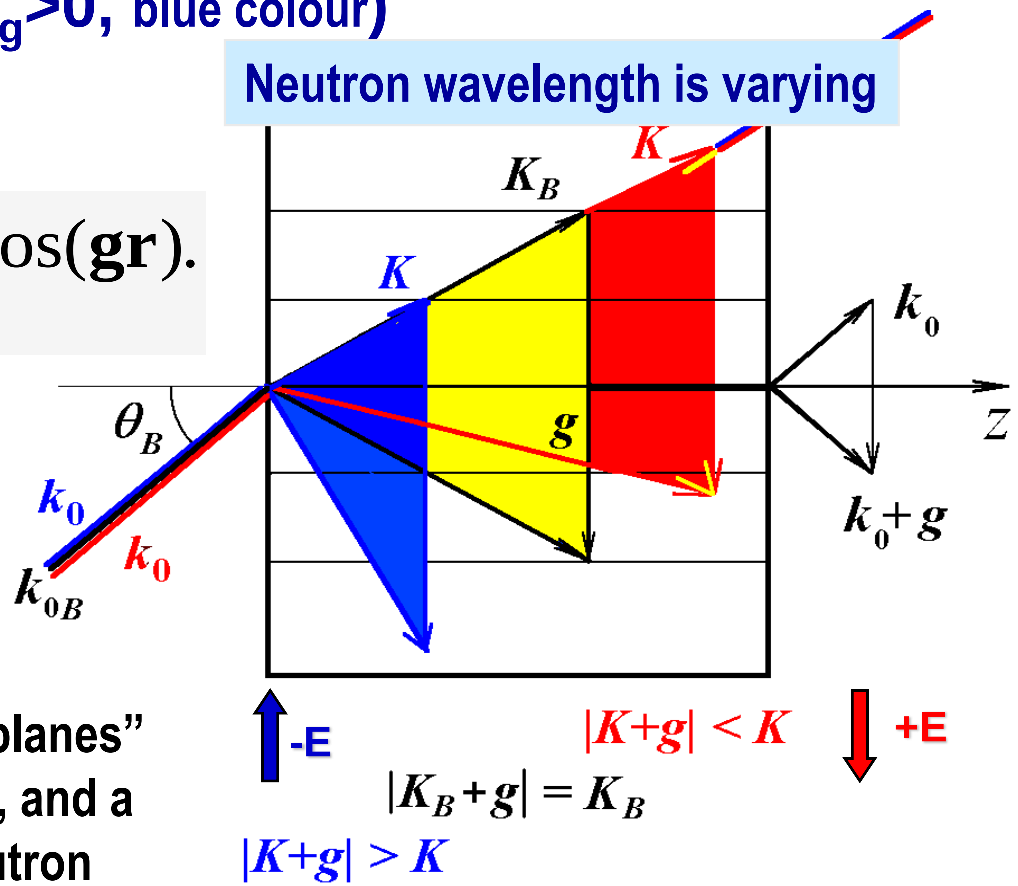
$$\mathbf{E}_g = \mathbf{g}\upsilon_g^E \sin \Delta\phi_g .$$



Changing the neutron wavelengths one can change the sign and value of the deviation parameter from the Bragg condition $\Delta_g = |K+g|^2 - K^2$, so the neutrons will 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)

$$V_{per}^{N}(\mathbf{r}) = \sum_{g\neq 0} V_g^N e^{i\mathbf{gr}} = \sum_{g>0} 2\upsilon_g^N \cos(\mathbf{gr}).$$

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



For noncentrosymmetric crystal “electric planes” are shifted relatively to the “nuclear” ones, and a strong electric field appears, acting on neutron

$$V_{periodic}^{E}(\mathbf{r}) = \sum_{g\neq 0} V_g^E e^{i\mathbf{gr}} = \sum_{g>0} 2\upsilon_g^E \cos(\mathbf{gr} + \Delta\phi_g).$$

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

To increase the field we should use much more monochromatic neutrons and minimal deviation parameters

Essence of experiment

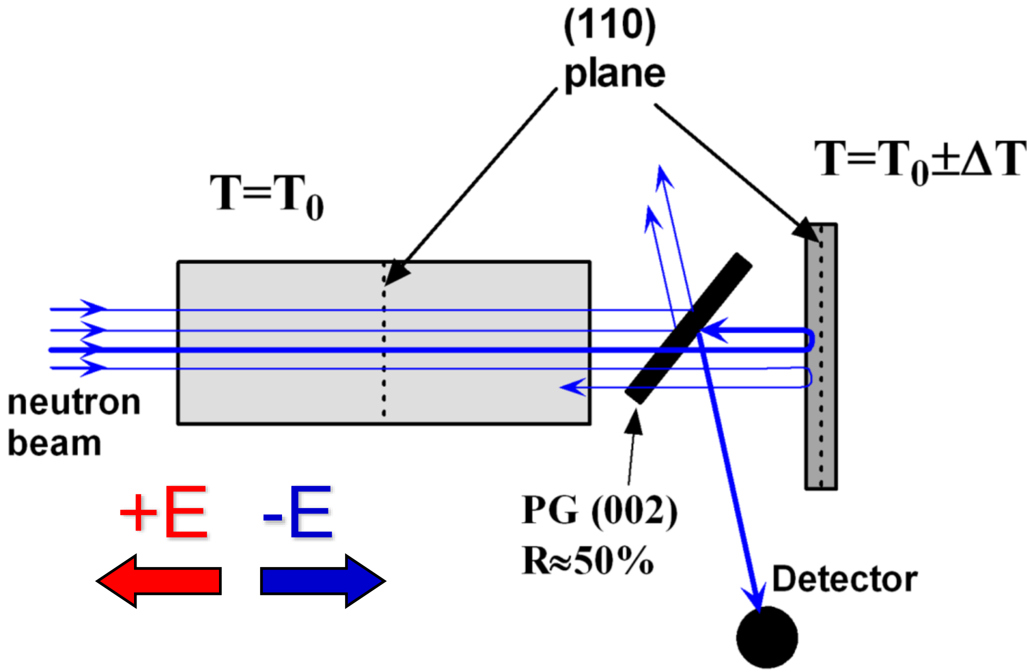
The neutrons with $\lambda_B = 2d_0 \sin\theta_B$ will completely reflect from the crystal. For $\theta_B \approx \pi/2 \rightarrow \lambda_B \approx 2d_0\,[1-(\pi/2-\theta_B)^2]$

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

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

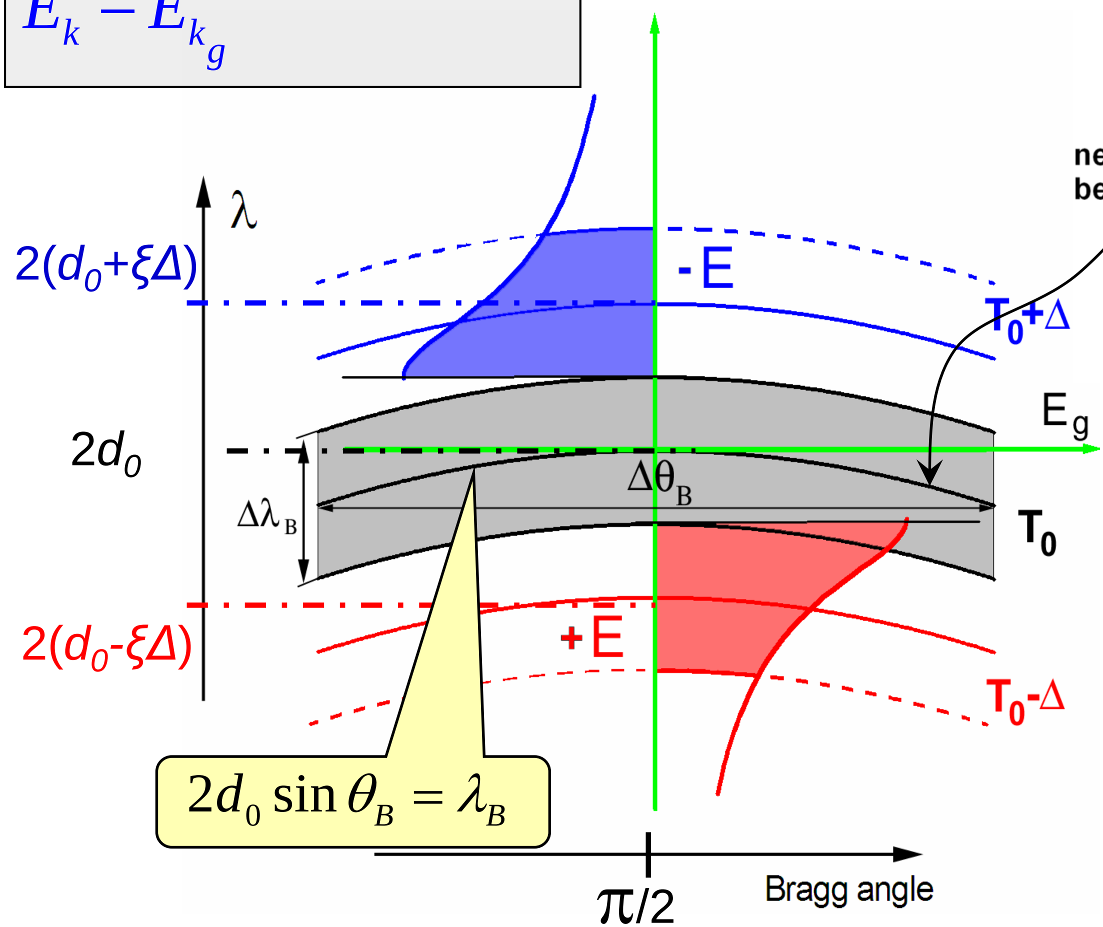
Changing *d* of analyzer (by heating or cooling) one can control electric field acting on neutron

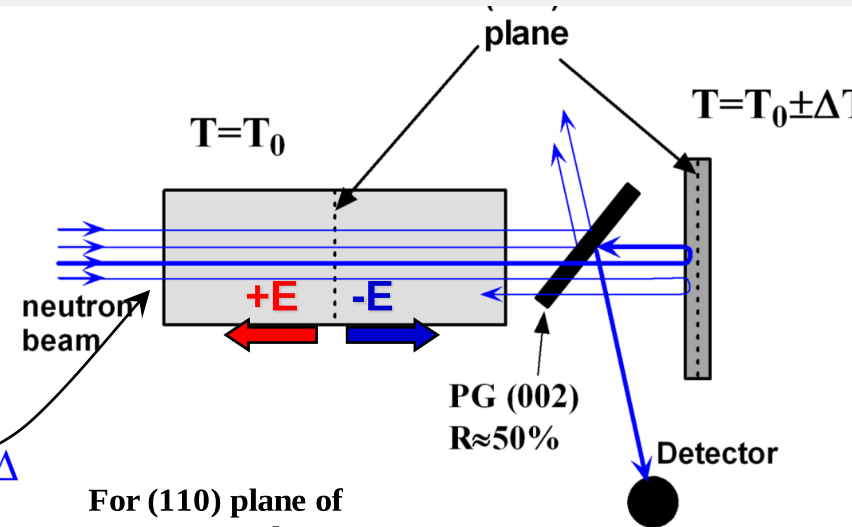
$$\frac{2V_g^N}{E_k - E_{k_g}} \sim (0.5 \div 0.3)$$



Changing ***d*** of a crystal-analyzer we can **select** the neutrons passed the crystal with the **given energy** and so **under the given electric field** (without monochromatization of the incident beam)

$$\frac{2V_g^N}{E_k - E_{k_g}} \sim (0.5 \div 0.3)$$





For (110) plane of quartz crystal

$$\Delta T = 1^0 C$$

$$\Delta\lambda/\lambda \approx 10^{-5} = \Delta\lambda_B/\lambda$$

For $\pi/2$ reflection

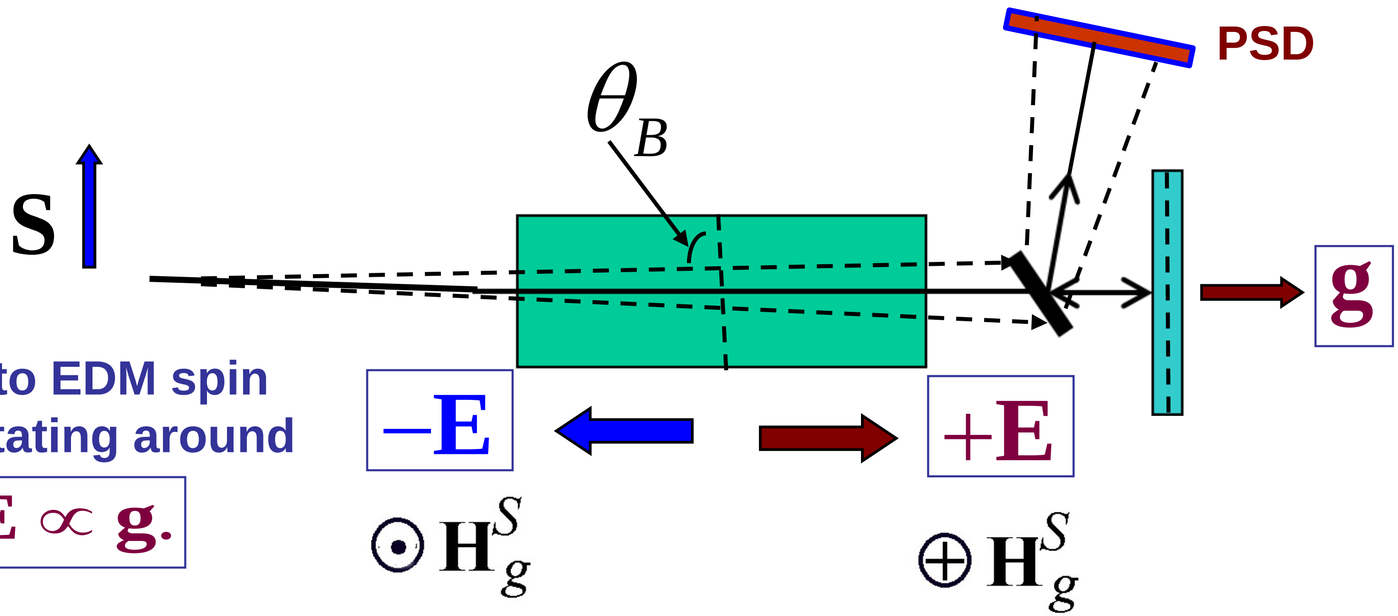
E || v_n and

H_s~[E x v_n]≈0

DNS-IV, Dubna, 6 – 7 December 2018

$$\theta_B = \frac{\pi}{2} \pm \Delta\theta,$$

$$\mathbf{H}^S = \frac{1}{c}\left[\mathbf{E}\times\mathbf{v}\right] \longrightarrow H^S = \pm\frac{E\upsilon}{c}\sin\Delta\theta_B$$



Due to EDM spin is rotating around

$$\mathbf{E} \propto \mathbf{g}.$$

Due to μ – around

$$\mathbf{H}^S \propto \mathbf{g}\times\mathbf{v},.$$

$$\varphi_D = \frac{Ed_n}{\hbar}\frac{L}{\upsilon_{\perp}}.$$

$$\upsilon_{\parallel} = \upsilon\sin\Delta\theta_B,$$

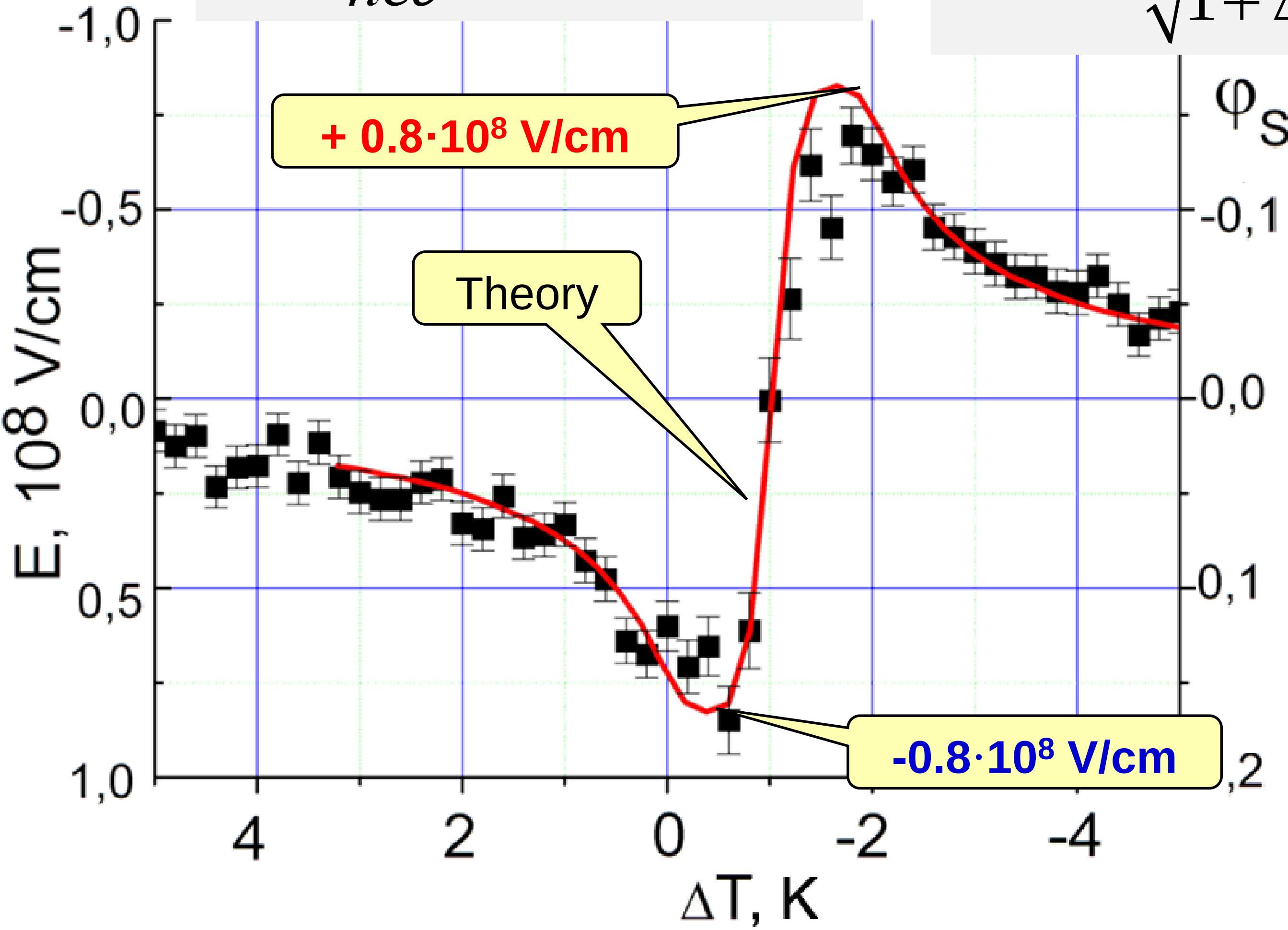
$$\upsilon_{\perp} = \upsilon\cos\Delta\theta_B$$

$$\varphi_S = \frac{E\mu}{\hbar}\cdot\frac{\upsilon_{\parallel}}{c}\cdot\frac{L}{\upsilon_{\perp}} \propto \frac{\pi}{2} - \theta_B \xrightarrow[\theta_B\to\pi/2]{} 0$$

Electric field measurement, using Schwinger interaction

$$\varphi_S = \frac{2}{\hbar c \upsilon} \mu \boldsymbol{\sigma} \cdot [\mathbf{E} \times \mathbf{v}] L_c; \qquad \mathbf{E} = \mathbf{E}_g \frac{\Delta_B}{\sqrt{1+\Delta_B^2}}$$

In 2-wave approx.



quartz (110) plane
L_c = 14 cm
Bragg angle ≈ 86⁰

Variation of the ΔT by ±1K

E ≈ ± 10⁸ V/cm

Fedorov V.V., Lapin E.G., Semenikhin S.Yu., Voronin V.V. JETP Lett**., 74 (**5) (2001) 251–254.
Observation of neutron spin rotation in neutron optics of NCS crystal

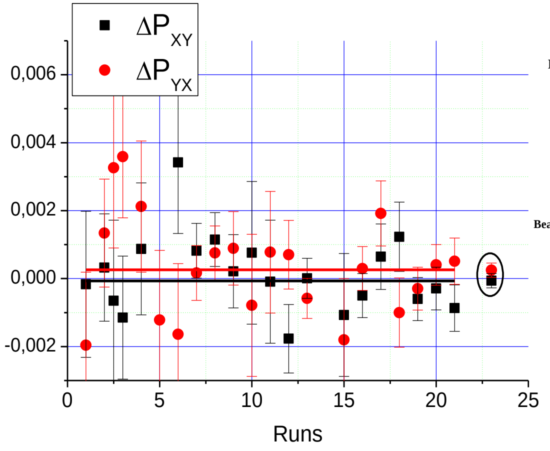
nEDM test experiment (PNPI-ILL)

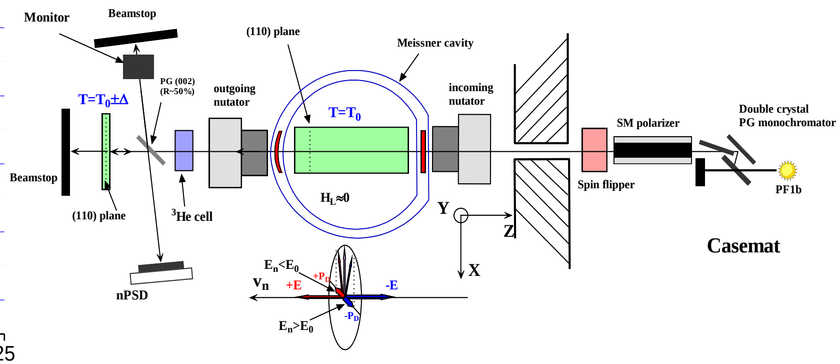
1. Field value coincide with the theory **E = (0.7±0.1) 10^8 V/cm for (110) quartz plane**
2. The statistical sensitivity was **~ $1.6 \cdot 10^{-23}$ e·cm/day.**

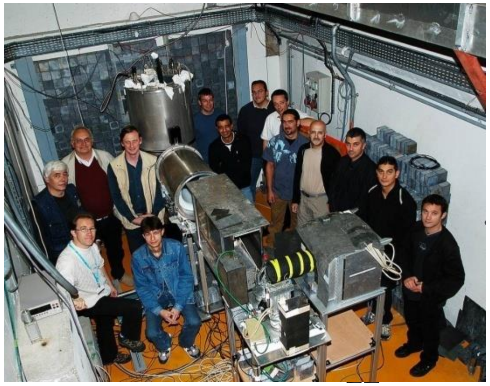
$$d_n = \left(2.5 \pm 6.5^{stat} \pm 5.5^{syst}\right) \cdot 10^{-24} e \cdot cm.$$

V.V. Fedorov et al, Physics Letters B 694 (2010) 22

3. The sensitivity can be improved **by a factor of 65** and reach about **$2.5\ 10^{-25}$ e cm/day for the full scale experiment**, mainly by increasing the divergence acceptance of the installation, the beam size, and the crystal length.







Sensitivity for the quartz crystal

For the 100x100x500 mm^3 (110) quartz plane it can be 2 10^{-26} e см per 100 day

How to improve this sensitivity?

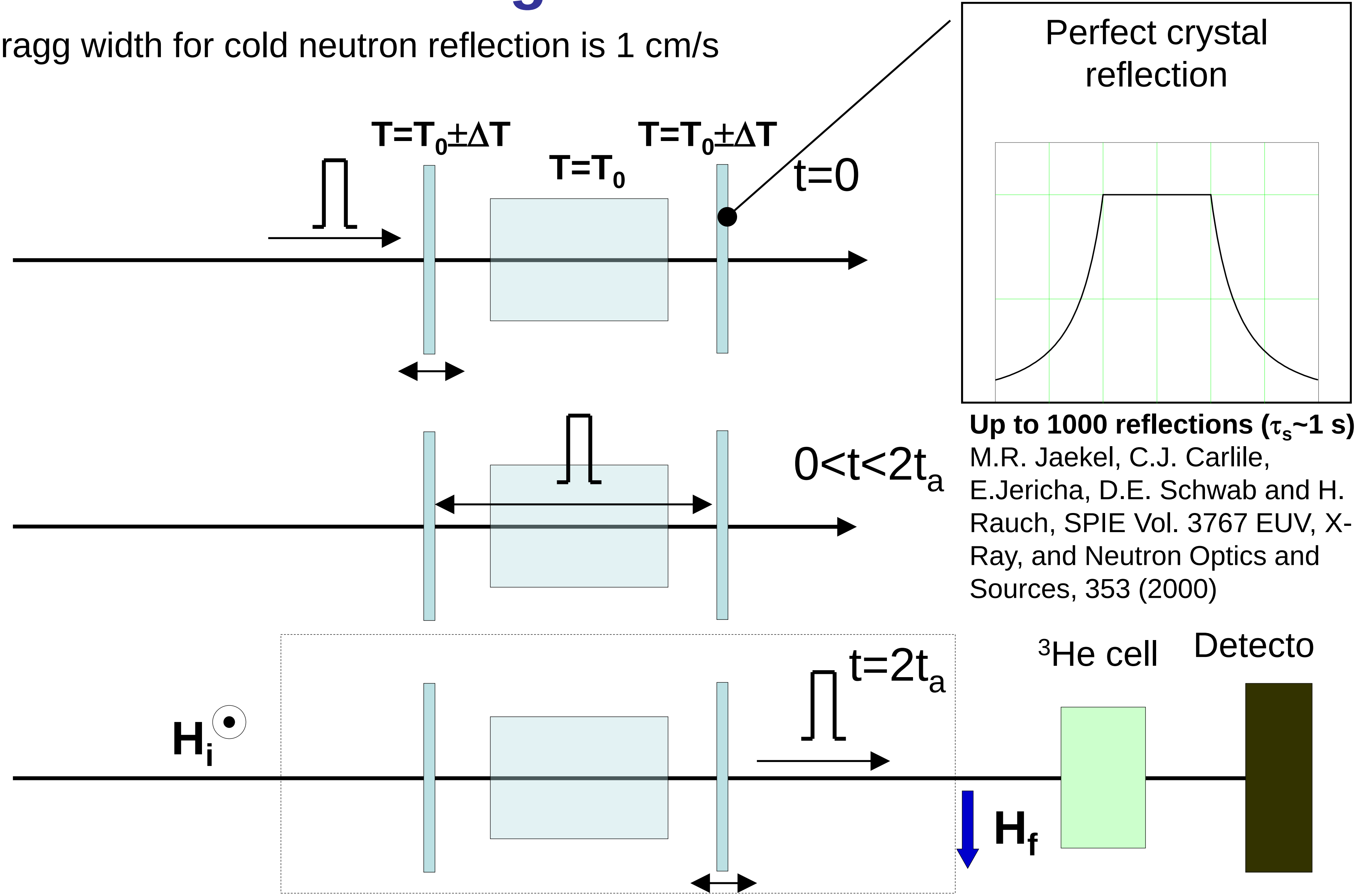
To improve the sensitivity we need new NCS crystal

- **Low neutron absorption**
- **No center of symmetry**
- **Elements with** large **Z** to increase electric field
- **Perfect crystal (Δ*d/d* < Bragg width (~10^{-5}))**
- **Large crystal** >100x100x100mm^3 **or**
- **Multiple passage** through thin crystal

  (storage variant)

Storage variant

Bragg width for cold neutron reflection is 1 cm/s



Up to 1000 reflections (τ_s~1 s)
M.R. Jaekel, C.J. Carlile, E.Jericha, D.E. Schwab and H. Rauch, SPIE Vol. 3767 EUV, X-Ray, and Neutron Optics and Sources, 353 (2000)

V.V. Fedorov, V.V. Voronin, Yu.P. Braginetz Physica B **406** (2011) 2370

Statistical sensitivity estimation

	E_g, 10^8V/cm	τ, ms	Count rate	K_{inp}	σ_d, 10^{-25} e·cm per day
α-quartz (110) in-flight	**2.0**	**0.6** (L=50cm we have)	**10^4 n/s** (ILL PF1b)		**2-3**
$Bi_{12}SiO_{20}$ (444) Storage	**4.65**	**8**	**10^3 n/s** (ESS, LP)	**10**	**0,2**
			500 n/s (J-PARK, SP)	**7**	**0,3**
$Bi_{12}GeO_{20}$ (444) Storage	**4,8**	**2**	**10^3 n/s** (ESS, LP)	**2,5**	**0,7**
			500 n/s (J-PARK, SP)	**1,8**	**1**
Isotope crystal **$Bi_{12}{}^{76}GeO_{20}$** Storage	**4,8**	**~20 (50 Hz)**	**~10^3 n/s**	**~20**	**~0.1**

Conclusion

The absence of the center of symmetry in crystal

- Results in arising a series of new spin effect in neutron optics (Pendelosung shift, spin rotation, depolarization, …)

AND

- Opens a new field in the studying of a symmetry fundamental interactions:
  - T violation and nEDM. Ultimate sensitivity to nEDM can be better than **10^{-27} e·cm** for modern neutron fluxes and special crystals
  - Studying the CP-violating forces at short ranges

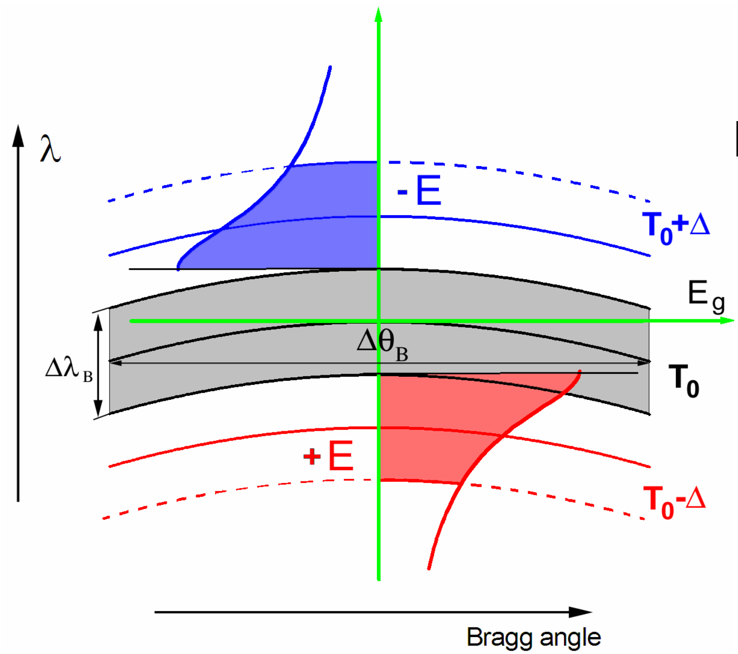
Thank you
for attention !

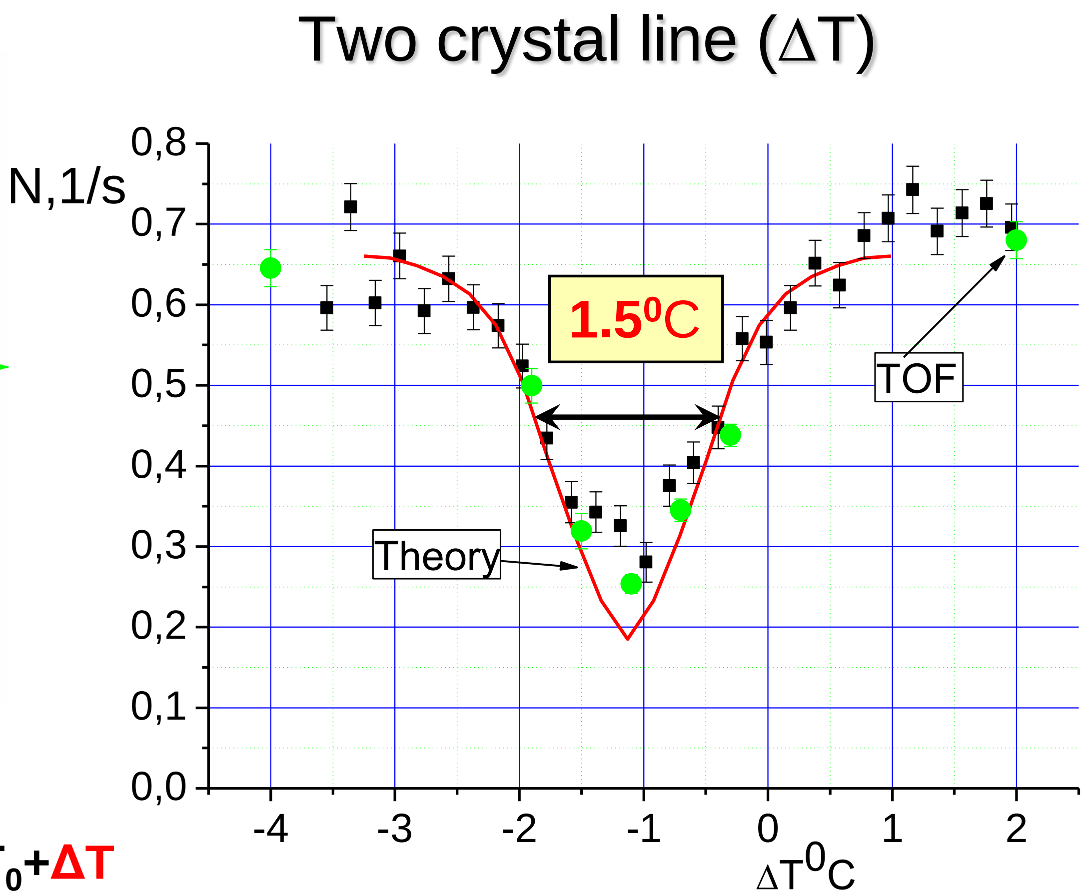
Summary of the systematic

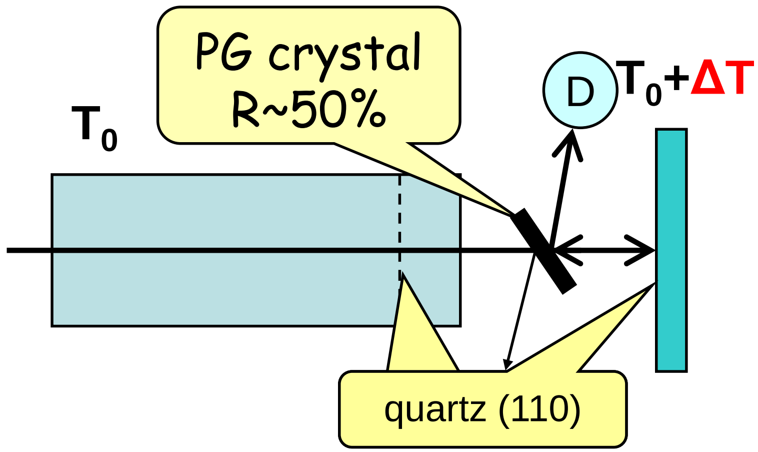
Residual magnetic field Value	$\mathbf{H}_r \sim 10^{-4}\, Gs$
Time stability	$\Delta\mathbf{H}_r \sim 10^{-5}\, Gs / hour$
3D polarization analysis	$\delta_y \sim 10^{-3}\, rad$
The crystals alignment	~ 0.02^0
The ΔT^0 control	~ 0.01^0C

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

Experimental test

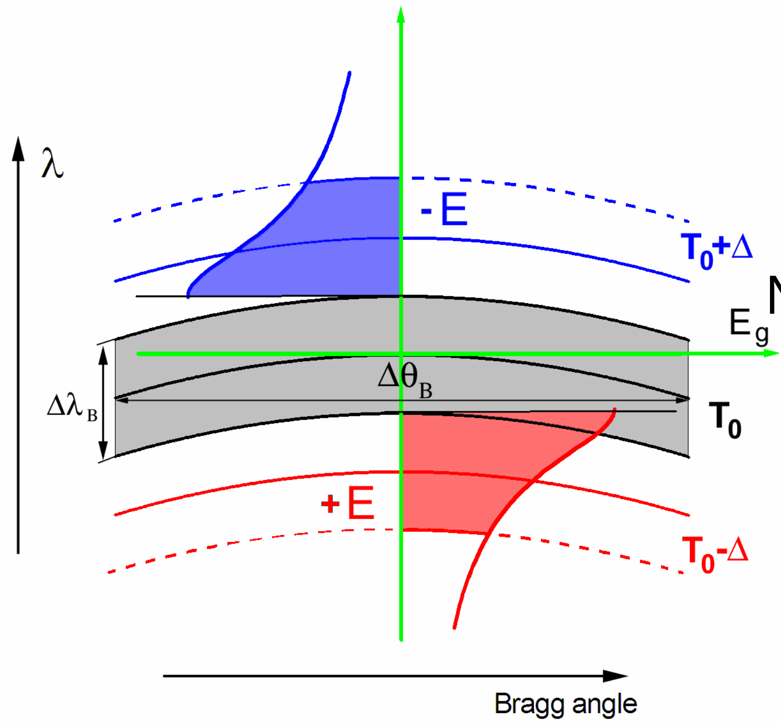


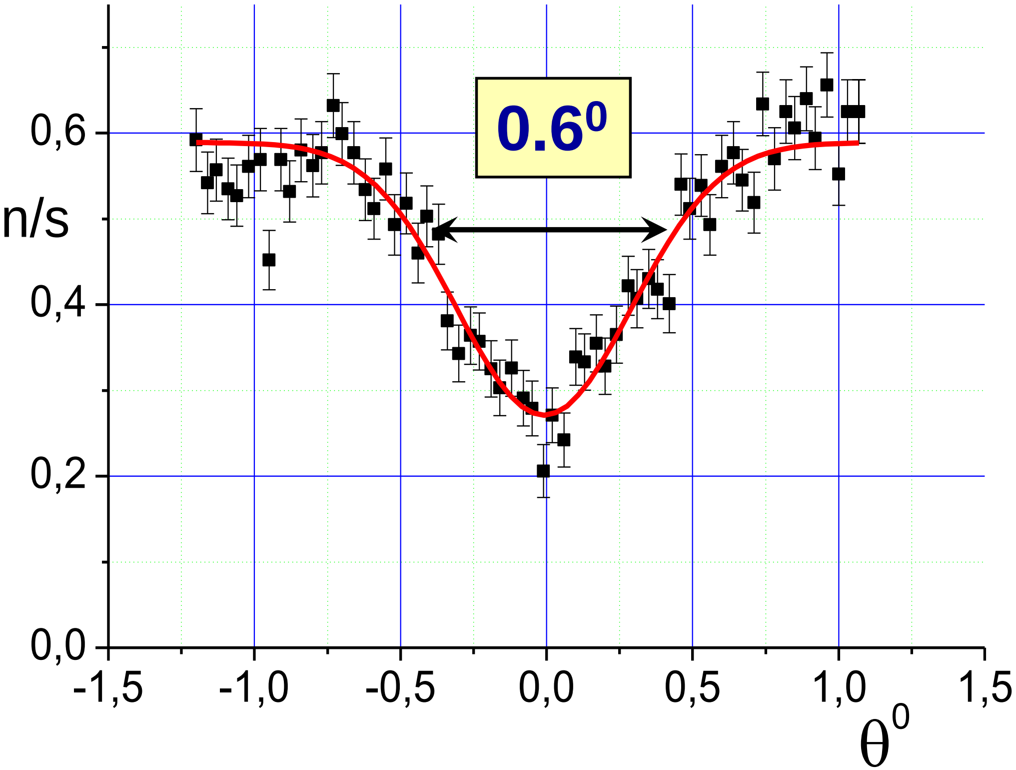


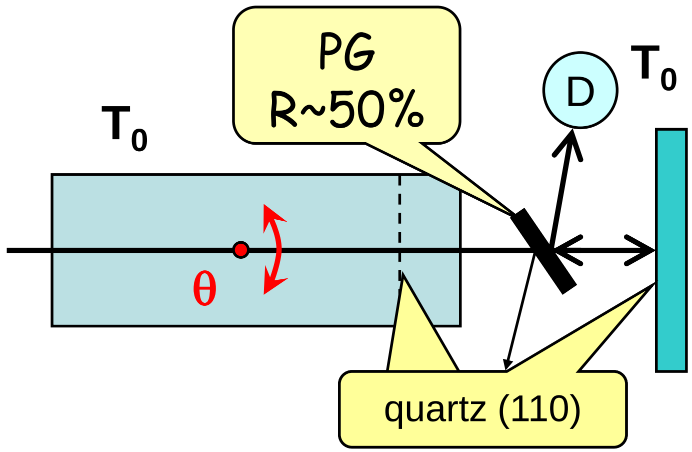


We can control the deviation parameter by the temperature of crystal-analiser.

Two crystal line (angular)



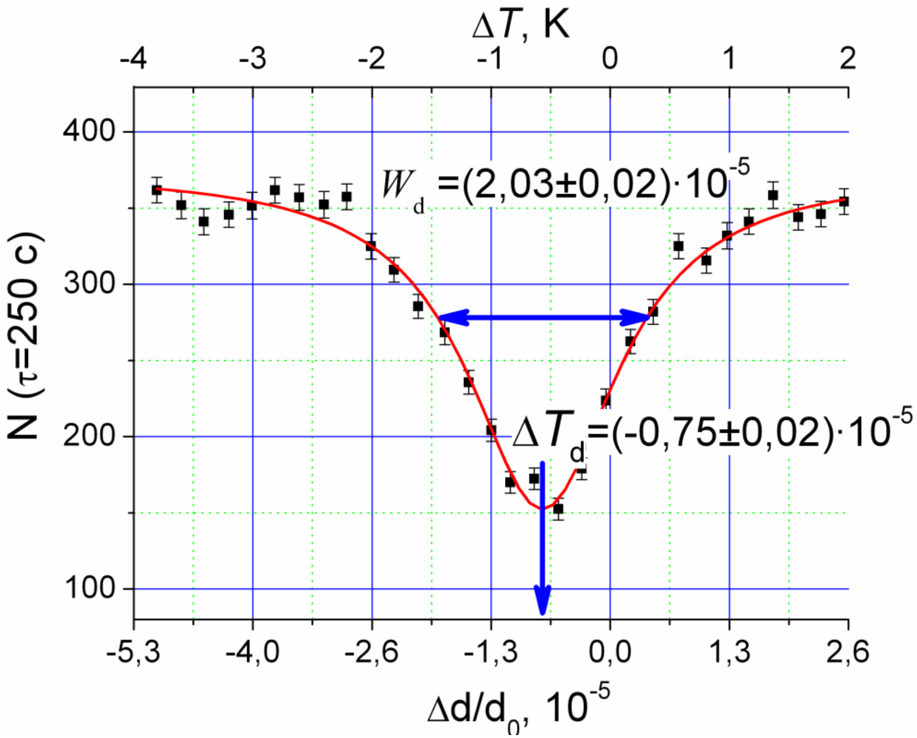


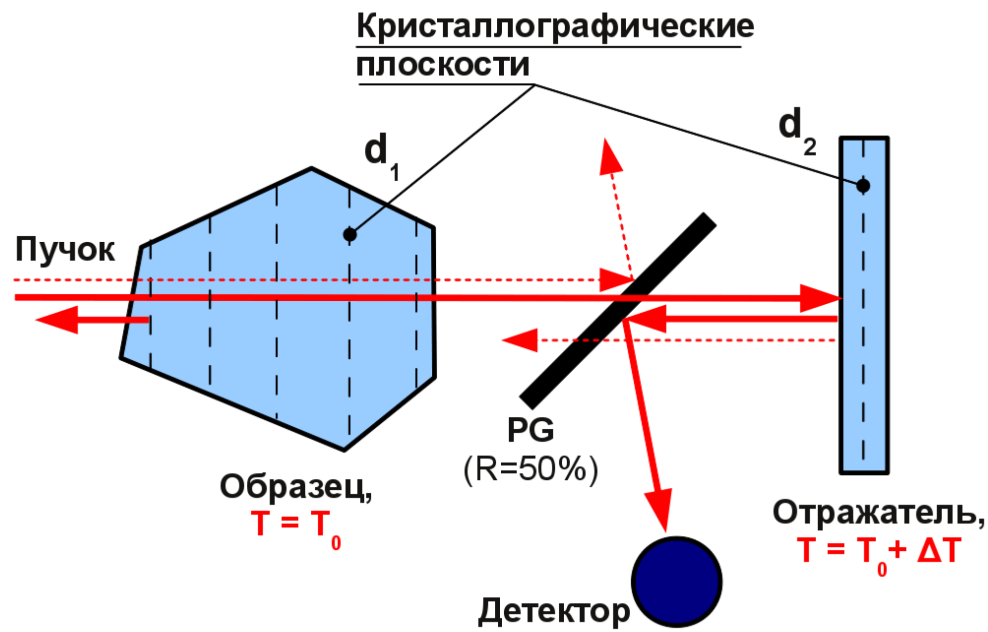


For Bragg angles ~ 45⁰ the angular Bragg width ~ 0.0005⁰

So we can increase the EDM effect by using assembled crystal (from a series of the crystals).

Новый метод объемного контроля деформации кристалла

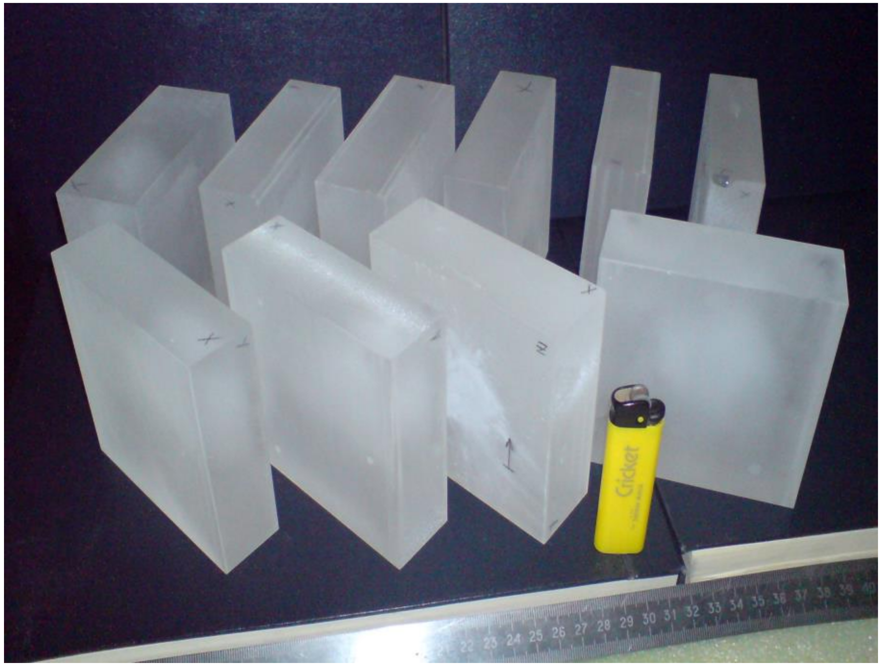


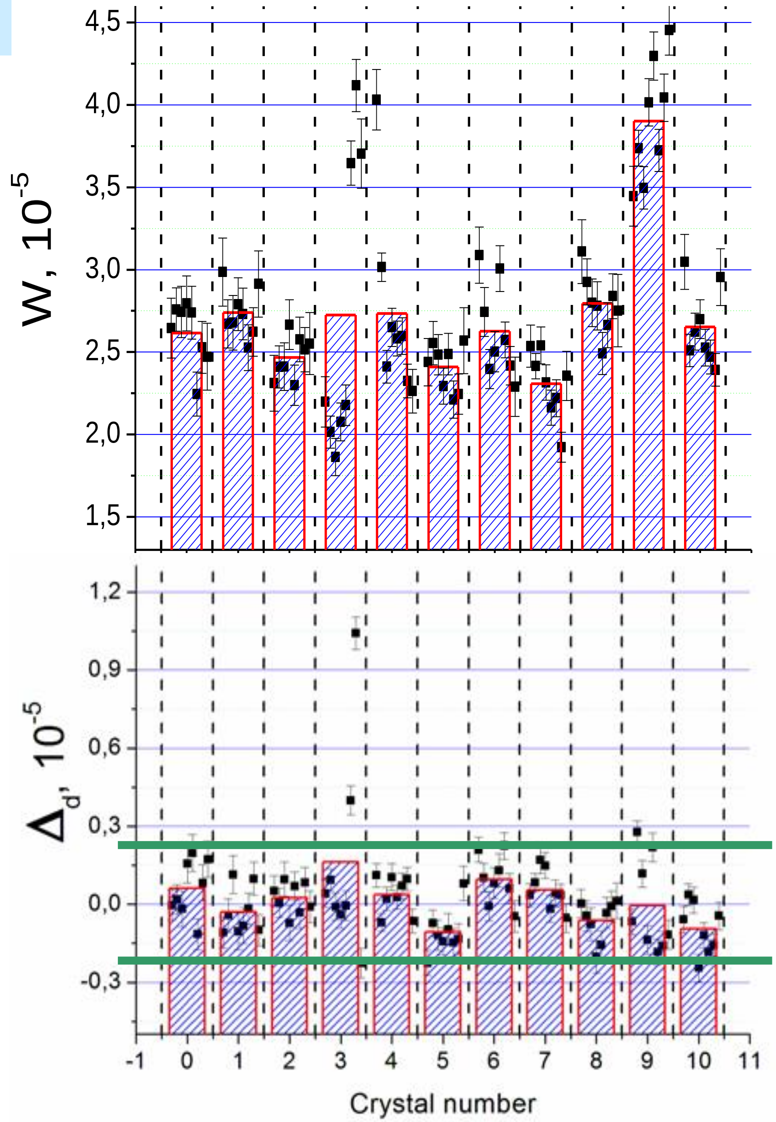


Новый метод относительного измерения межплоскостных расстояний монокристаллов, основанный на использовании дифракции нейтронов под углом Брэгга ~90^{O}, обладающий следующими достоинствами:

- Относительная точность измерения может превосходить **$\Delta d/d$ ~ 10^{-7}.**
- Тестирование по **всему объему кристалла**. Размер исследуемого кристалла ограничен длиной поглощения нейтрона (для кварца ~50 см).
- **Не требуется предварительная подготовка кристалла**. Можно исследовать образцы любой формы и огранки.
- **Не требуется высокая точность предварительной угловой юстировки кристаллов**.

Результаты теста первой партии кристаллов (2008) из Александрова для дифракционного ЭДМ-эксперимента





Суммарный размер кристаллов 105x100x500 мм³ (15 шт. по 35x100x100)

Ожидаемая чувствительность ~ 2 ·10^{-25} e·см/сутки

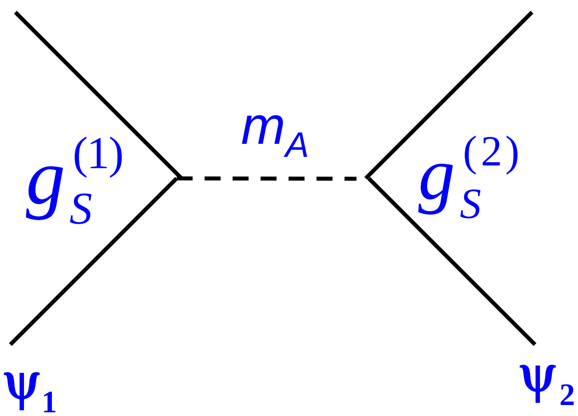
разброс межплоскостного расстояния протестирован новым методом (патент на изобретение №2394228, 03 февраля 2009)

Δd/d < 3·10-6

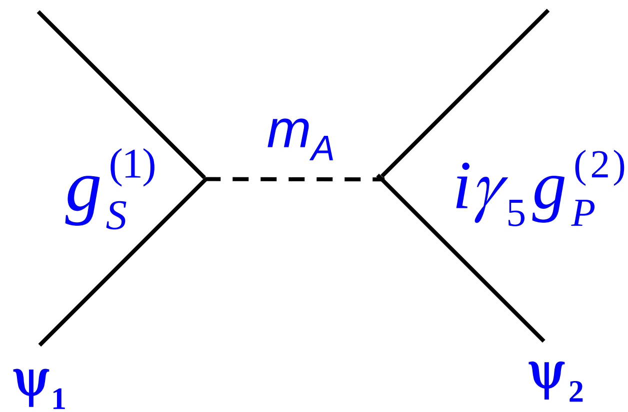
Axion-like CP violating nucleon-nucleon interaction

A.A. Anselm
JETP Lett. v.36, N2 (1982)

J.E. Moody and Frank Wilczek
Phys. Rev. D v.30, N1 (1984)



$\lambda_A = \hbar/m_A c$



$$V(\mathbf{r}) = -\frac{g_S^{(1)} g_S^{(2)}}{4\pi r} e^{-\frac{r}{\lambda_A}}$$

$$V_{SP}(\mathbf{r}) = \frac{\hbar^2 g_S^{(1)} g_P^{(2)}}{8\pi m} \frac{(\mathbf{r}\cdot\boldsymbol{\sigma})}{r} \left(\frac{1}{r\lambda} + \frac{1}{r^2}\right) e^{-r/\lambda}.$$

Add-ons to gravity

Pseudomagnetic interaction

g-harmonics of CP-odd pseudomagnetic N-N interaction, which arises due to exchange by pseudoscalar axion-like particle

$$V_g^{PS} = -\int_{V=1} V^{PS}(\mathbf{r}) e^{-i\mathbf{g}\mathbf{r}} d^3 r = -i \frac{\hbar^2 g_S g_P}{2mV_c} \frac{\lambda^2 (\boldsymbol{\sigma}\mathbf{g})}{1+g^2\lambda^2},$$

The same situation as for neutron EDM interaction

$$V_g^{PS} = -i\varphi_g^H (\mathbf{g}\,\boldsymbol{\sigma})$$

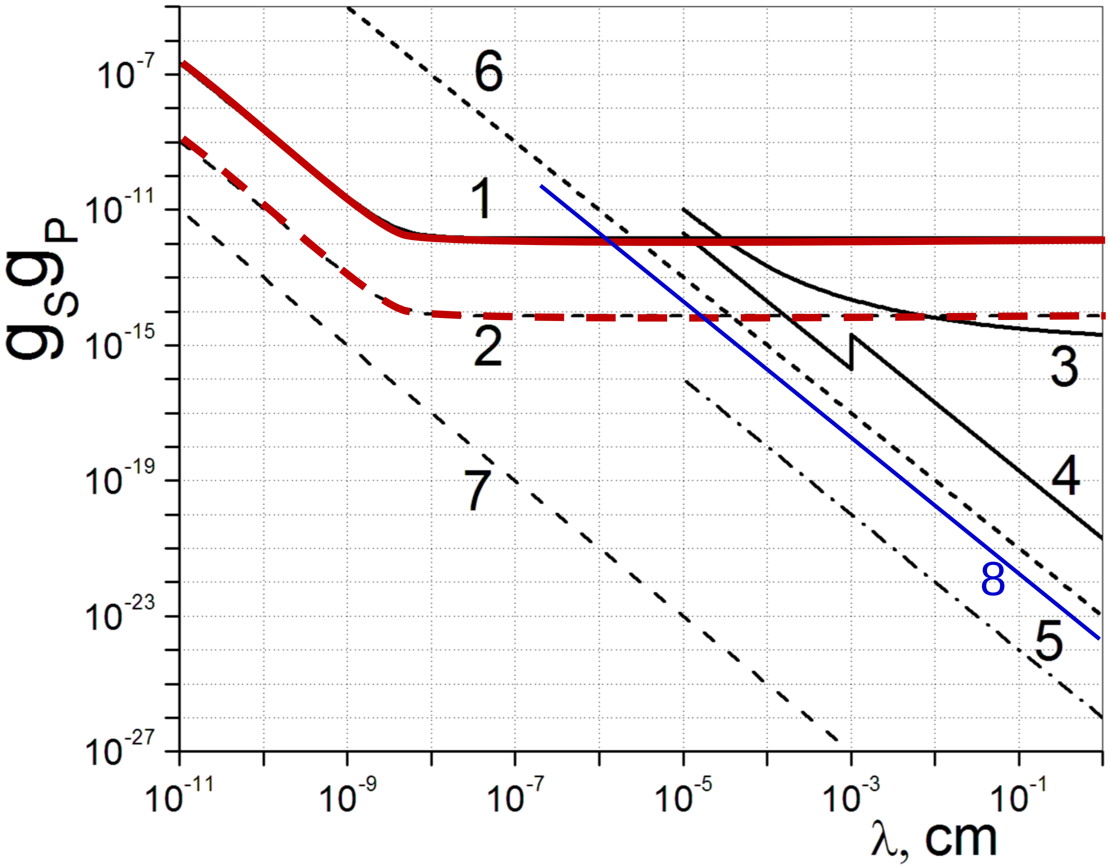
Is determined by distribution of nuclear mass number in crystal

$$V_g^{EDM} = i \cdot \upsilon_g^E d_n (\mathbf{g}\,\boldsymbol{\sigma})$$

Is determined by distribution of electric charge in crystal

We should measure the effects for two different crystallographic planes to separate these phenomenon.

Constraint on the $(g_s g_p;\lambda)$ from the test experiment



(1) NCS crystal neutron optics,
V.V. Voronin, V.V. Fedorov, I.A. Kuznetsov, JETP Letters (2009) **90** 5

(2) Possible progress.

(3) gravitational level experiment,
S.Baessler, V.V.Nesvizhevsky, K.V.Protasov, A.Yu.Voronin, Phys.Rev.D **75** (2007) 075006

(4) the UCN depolarization,
A.P. Serebrov, ArXiv:0902.1056

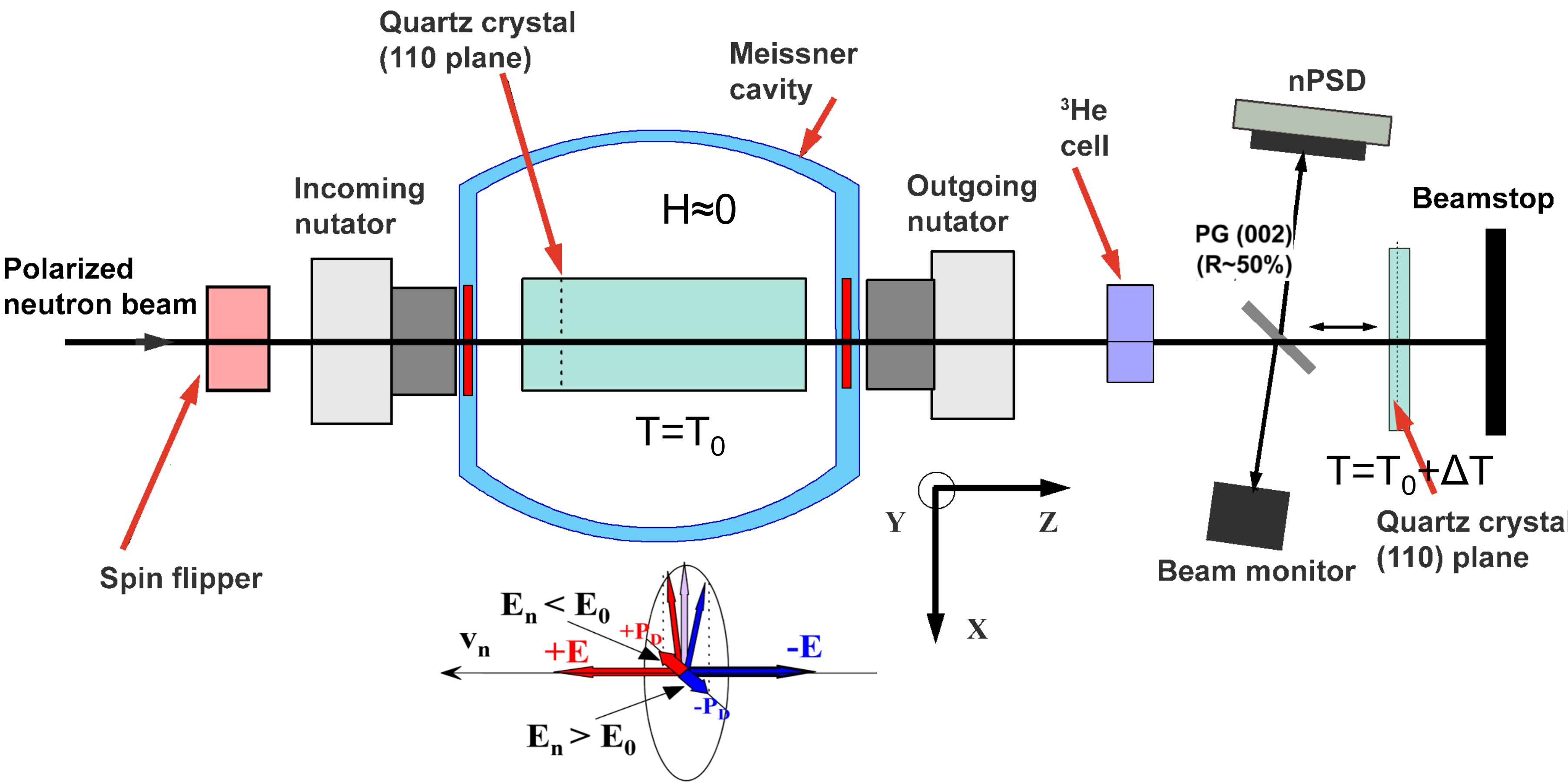
(5) proposal O. Zimmer, ArXiv:0810.3215

(6) and (7) are the predictions of axion model with $\theta \sim 1$ and $\theta \sim 10^{-10}$

(8) ^{3}He polarization, M. Guigue, D. Jullien, A. K. Petukhov and G. Pignol, Phys.Rev. D92 (2015), 114001

$$V_{SP}(\mathbf{r}) = \frac{\hbar^2 g_S^{(1)} g_P^{(2)}}{8\pi m} \frac{(\mathbf{r}\cdot\boldsymbol{\sigma})}{r}\left(\frac{1}{r\lambda}+\frac{1}{r^2}\right)e^{-r/\lambda}.$$

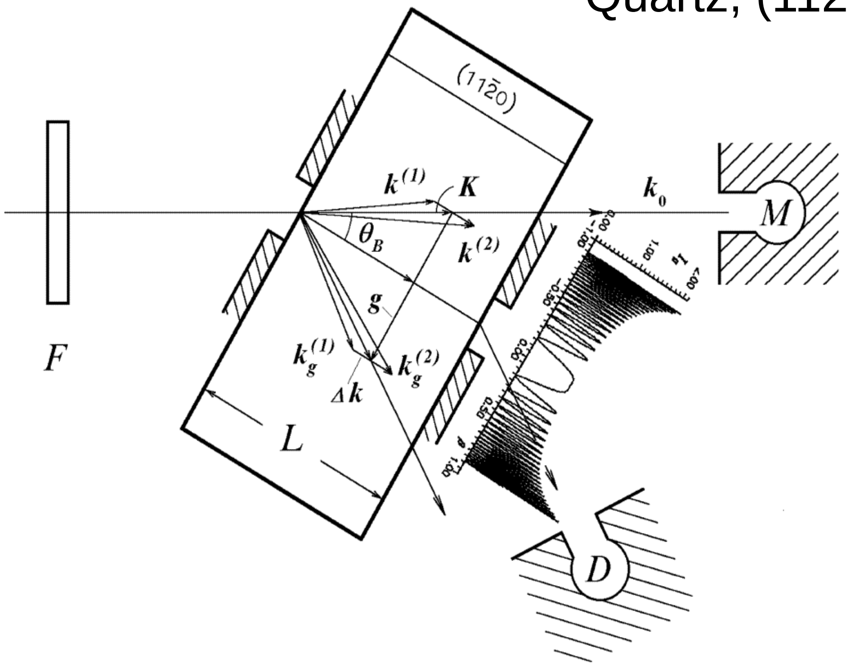
nEDM search test experiment

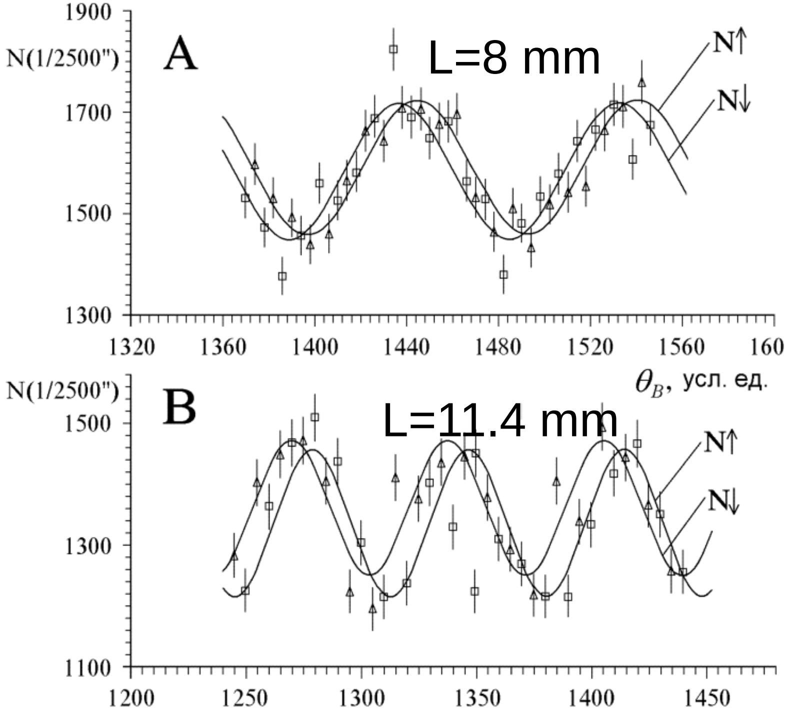


V.V. Fedorov et al, Physics Letters B 694 (2010) 22

First measurement of electric field

Quartz, $(11\bar{2}0)$ plane





First measurement of the electric field of noncentrosymmetric crystal (quartz)

$$E_{(11\bar{2}0)} = 2.1 \pm 0.12(0.23) \cdot 10^{8}\ V/cm$$

V.L. Alekseev, V.V. Voronin, E.G. Lapin et al. Sov. Phys. JETP 69, 1083 (1989)