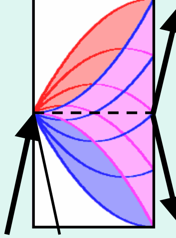

VERIFICATION OF THE WEAK EQUIVALENCE PRINCIPLE WITH LAUE DIFFRACTING NEUTRONS

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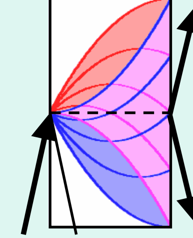
PNPI

ISINN-20

Motivation



- For Laue diffraction with Bragg angles close to the right one there is a significant diffraction enhancement factor of an external force affecting the neutron*:

$$K_d^{Si} \xrightarrow{\theta_B \sim 84\div 87^0} \left(10^7 \div 10^8\right)$$

- This factor can be used for observation of small external forces affecting the diffracting neutrons

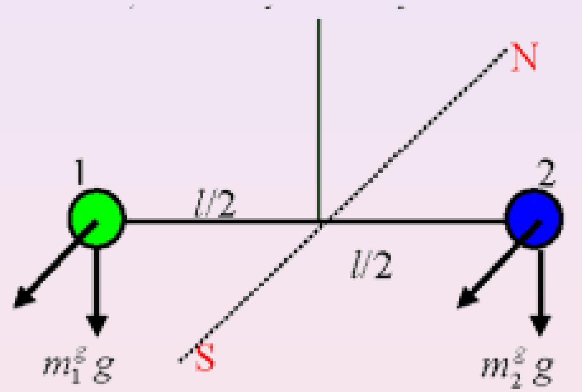
- For example, this enhancement can be used in $\boldsymbol{m^i/m^g}$ experiment with cold neutron ***(NGrav)***

*V.V. Fedorov et.al. JETP Lett. 85, 82 (2007)

Verification of WEP. Eötvös and novel EP tests

Torsion balance will be in equilibrium if

$$\frac{m_1^i}{m_1^g} = \frac{m_2^i}{m_2^g}$$



L. v. Eötvös (1908) $\leq 5 \cdot 10^{-9}$

Ann. Physik (Leipzig) 68 11 (1922)

Adelberger, et al. (1990) $\leq 0.8 \cdot 10^{-12}$

Phys. Rev. D 42 3267 (1990)

Baeßler, et al.(1999) $\leq 5 \cdot 10^{-13}$

Phys.Rev. Lett 83(18) 3585 (1999)

Earth Orbit (Projects)

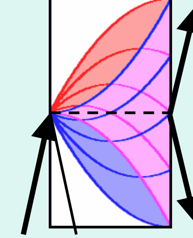
MiniSTEP (20??) $\leq 10^{-17}$; **MICROSCOPE** (201?) $\leq 10^{-16}$

Elementary particles (neutrons)

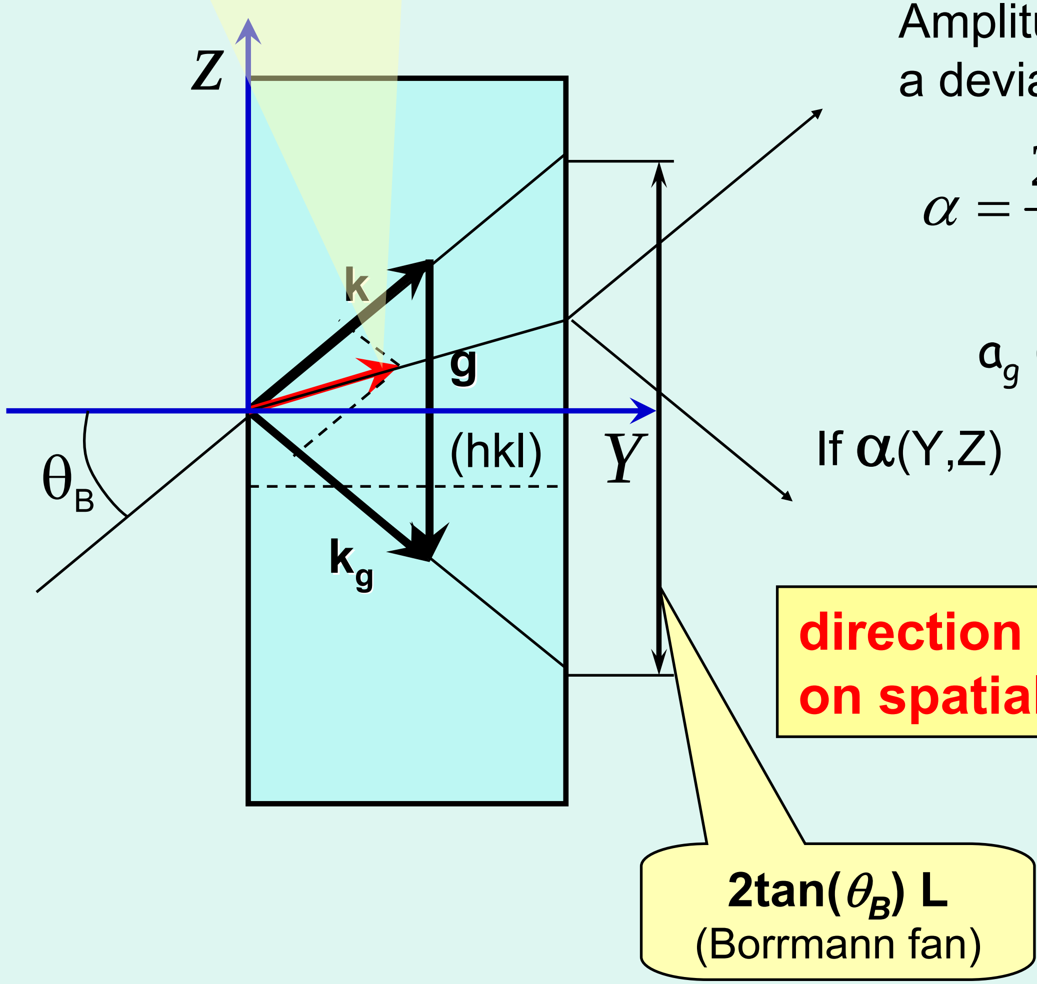
J. Schmiedmayer *(1989)* $\leq 2 \cdot 10^{-4}$; **A. Frank, et al. (Grav. Exp. with UCN)**

Next talk by G. Kulin

Neutron trajectory for Laue diffraction



$$\mathbf{j} = \hbar/m\left(|a_g(\alpha)|^2 \mathbf{k_g} + |a_0(\alpha)|^2 \mathbf{k}\right)$$



Amplitudes a_g and a_0 depend on a deviation from exact Bragg condition

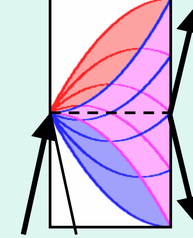
$$\alpha = \frac{2(\Delta\mathbf{k}_0 \cdot \mathbf{g})}{k_0^2}, \quad \Delta\mathbf{k}_0 = \mathbf{k}_0 - \mathbf{g}/2$$

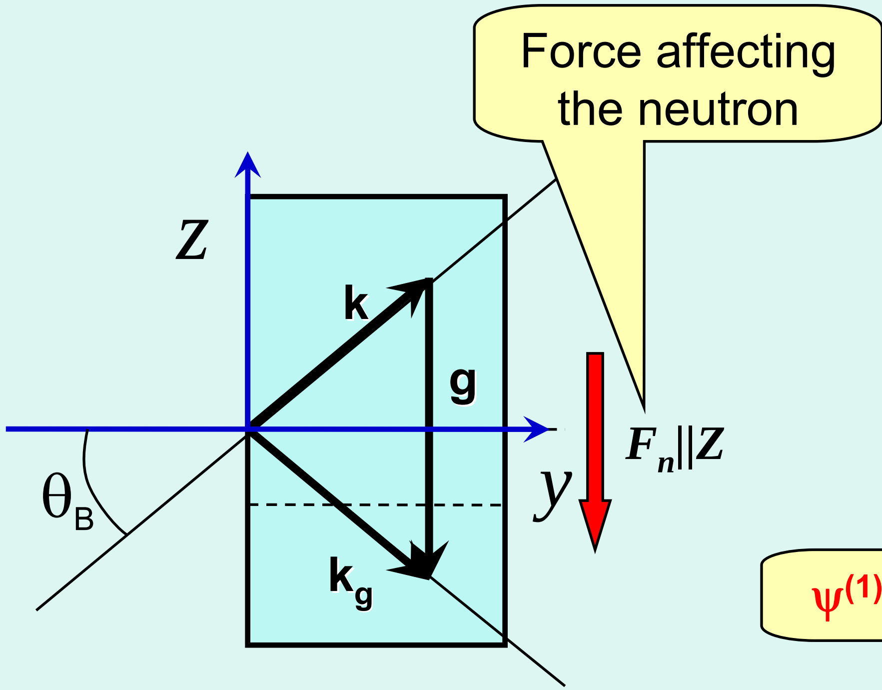
$a_g(\alpha)$ and $a_0(\alpha)$

If $\alpha(Y,Z)$ ⇒ $a_g(Y,Z)$ and $a_0(Y,Z)$

direction of neutron current depends on spatial coordinates j(Y,Z)

Diffraction enhancement factor





Neutron “Kato trajectory” equation (± stands for different Bloch waves):

$$\frac{\partial^2 z}{\partial y^2} = \pm \frac{\tan^2(\theta_B)}{m_0} \frac{\pi}{d} \frac{F_n}{2E_n}$$

Equation for freely flighting neutron:

$$\frac{\partial^2 z}{\partial y^2} = \frac{F_n}{2E_n}$$

$\psi^{(1)}$ or $\psi^{(2)}$

We obtain a gain factor for the diffracting neutron

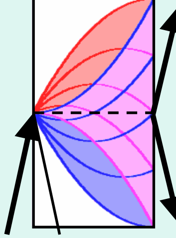
$$K_d = \pm \frac{\tan^2(\theta_B)}{m_0} \frac{\pi}{d}$$

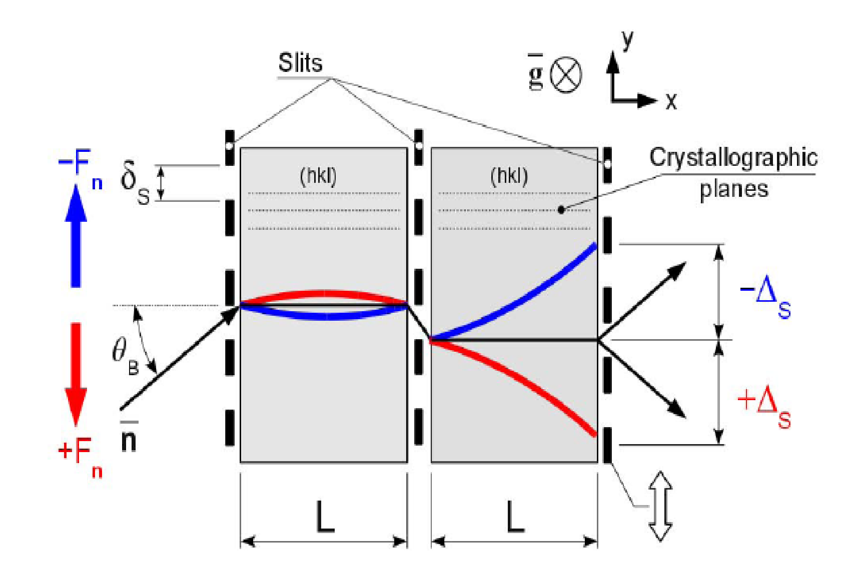
For silicon (220) planes

$$K_d = \tan^2(\theta_B) \times 2 \cdot 10^5 \xrightarrow{\theta_B (84^0 \div 87^0)} (10^7 \div 10^8)$$

Additional enhancement factor due to neutron delay inside the crystal (Bragg angle close to π/2)

Two-crystal scheme of Laue diffraction





External force shifts the spot of the neutron beam at the exit surface:

$$\Delta_F^1(1,2) = \pm \frac{\pi \tan^2(\theta_B) L^2}{m_0 d E_n} F_n \equiv \pm \Delta_F^1$$

The resolution for this setup is:

$$W_F = \frac{m_0 E_n d}{\pi \tan^2(\theta_B) L^2} \delta_S,$$

δ_S – slit size

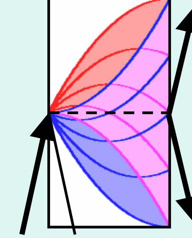
For (220) plane of Silicon:

$$L = 10\,cm,\ \delta_S = 1\,mm,\ \theta_B = 86^\circ \quad \Rightarrow \quad W_F \approx 1{,}5 \cdot 10^{-13}\ eV/cm \approx 10^{-5} m_n g$$

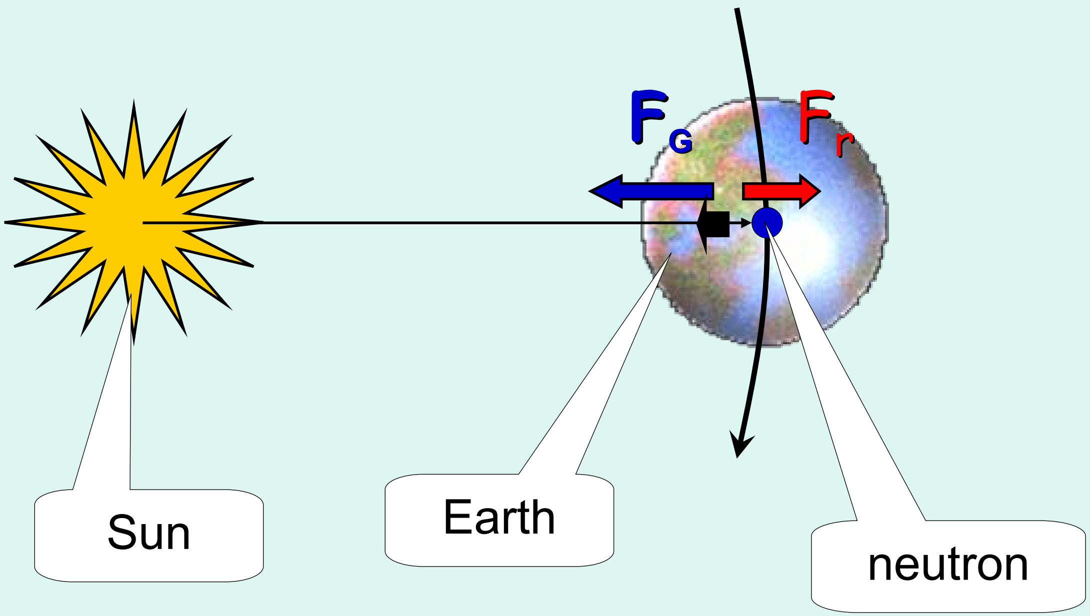
The possible sensitivity of the setup for 100 days of statistic accumulation (with high flux neutron beam):

$$\sigma(F_{ext}) \approx 1{,}5 \cdot 10^{-18}\ eV/cm$$

100 kg ⟺ 1 metre



Idea of m^i/m^g experiment with neutron (I)



$F_G \sim m^g$; $F_r \sim m^i$

$F_G = F_r$ for the Earth

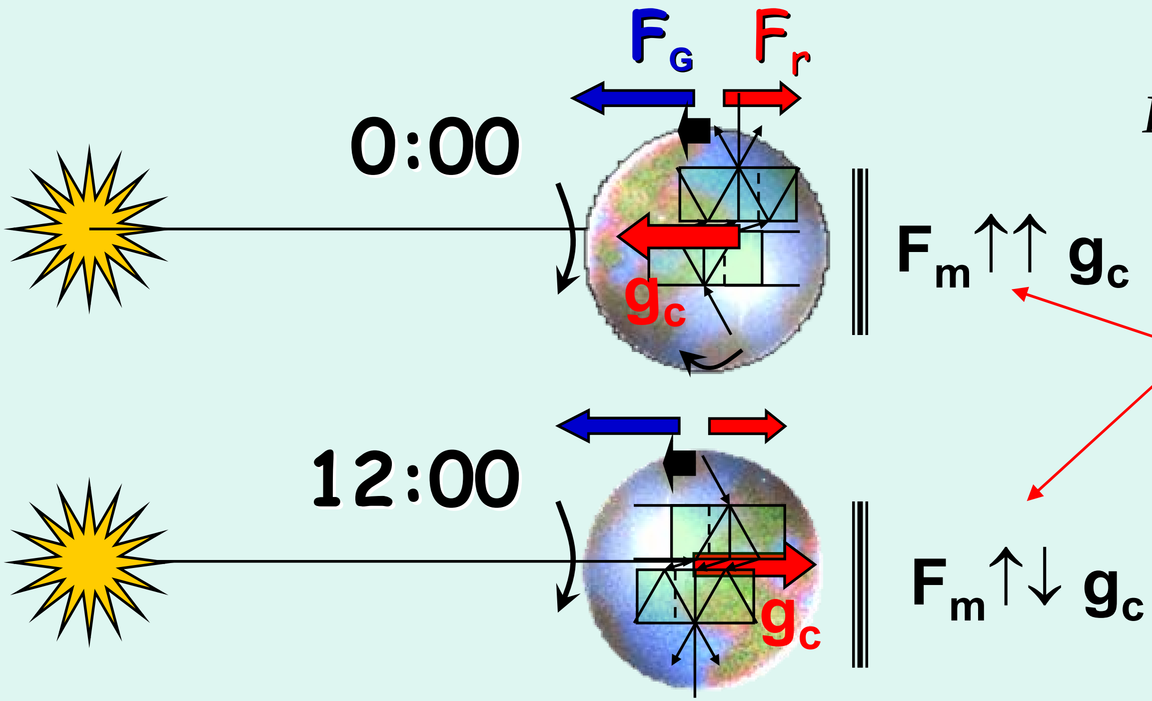
$$? \; \frac{m_n^i}{m_n^g} \neq \frac{m_\otimes^i}{m_\otimes^g} \; ?$$

$F_G \neq F_r$ for the neutron

Possible appearance of the non zero force:

$$F_m \equiv F_G - F_r = G \cdot \frac{m_\otimes^g m_n^g}{R^2}\left(1 - \frac{m_n^i / m_n^g}{m_\otimes^i / m_\otimes^g}\right)\Bigg|_{m_\otimes^i / m_\otimes^g \equiv 1} \approx 6 \cdot 10^{-13}\left(1 - \frac{m_n^i}{m_n^g}\right) eV/cm$$

Idea of ***m***



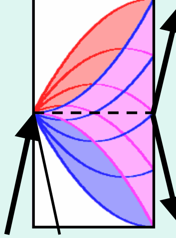
$$F_m \approx 6 \cdot 10^{-13} \left(1 - \frac{m_n^i}{m_n^g}\right) eV / cm$$

F_m changes its sign in the laboratory coordinate system

Daily oscillations of the *F_m value*

Our setup is sensitive to F_m oscillations

m^i/m^g experiment with cold neutron (III)



Value of the external force in m^i/m^g experiment:

$$F_m \equiv F_G - F_r = G\cdot\frac{m_\otimes m_n^g}{R^2}\left(1-\frac{m_n^i/m_n^g}{m_\otimes^i/m_\otimes^g}\right)\Bigg|_{m_\otimes^i/m_\otimes^g\equiv 1} \approx 6\cdot 10^{-13}\left(1-\frac{m_n^i}{m_n^g}\right) eV/cm$$

The possible sensitivity of the setup:

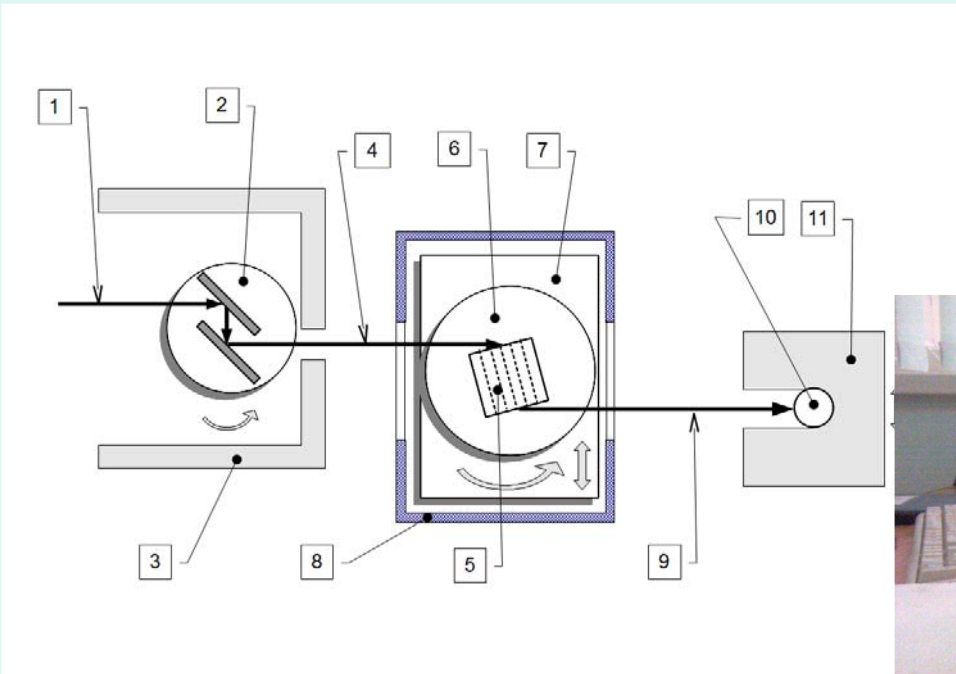
$$\sigma\left(F_{ext}\right)\approx 1,5\cdot 10^{-18}\,eV/cm$$

$$\delta_{i/G}\left(\left(m_G-m_i\right)/m_G\right)\approx 2,5\cdot 10^{-6}$$

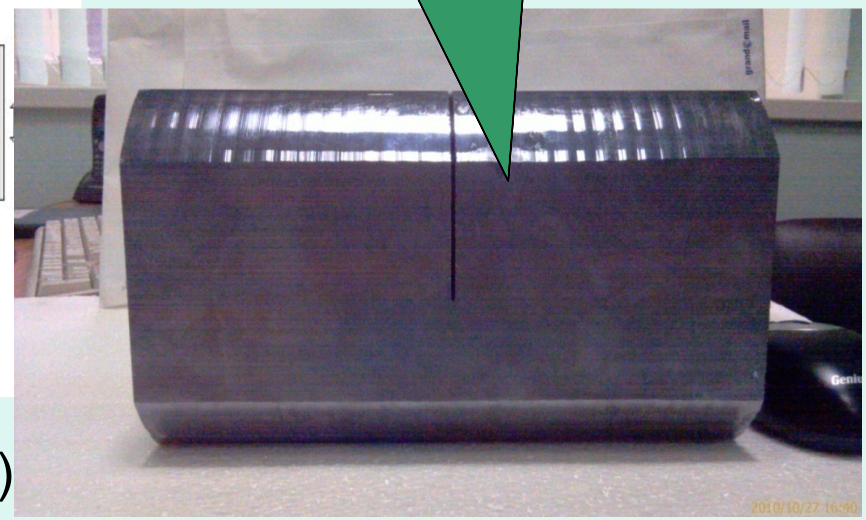
Two orders better than the best modern result

Present accuracy $2\cdot 10^{-4}$ (Schmiedmayer, 1989)

m^i/m^g *experiment with cold neutron (IV)*



Large silicon crystal
(220 mm)

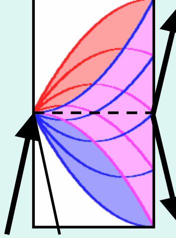


Working crystallographic plane is (220)

$$d = 1{,}92 \cdot 10^{-8} cm$$

$$\Delta d / d \sim 10^{-8}\ cm^{-1}$$

Experimental observation of Laue diffraction in the large silicon crystal (L=220 mm)



220 silicon plane intensity reflex

$$N_{1,2} \sim \exp\left(-L_{eff}\,\mu_{1,2}\right)$$

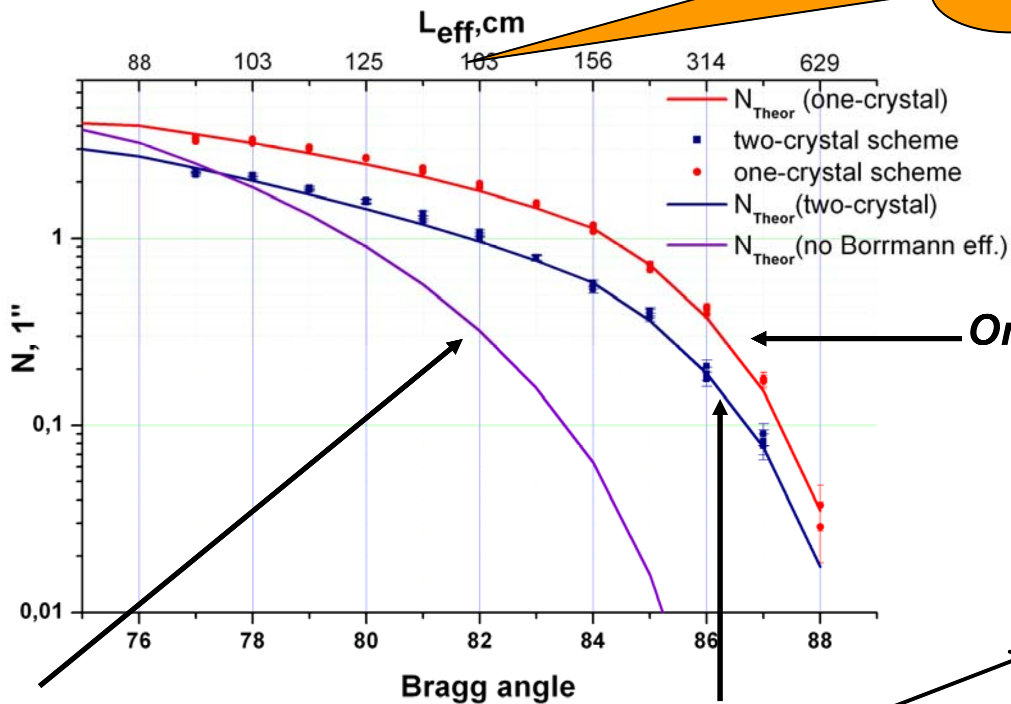
Effective crystal length ($L/\cos(\theta_B)$) can reach few meters

$$\mu_{1,2} = \mu_0\left(1 \pm \varepsilon_g\right)$$

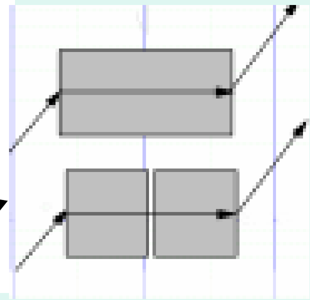
$$\mu_1 = 0,05$$

$$\mu_2 < 0,003$$

$$L_{abs}^{\psi(2)} \sim 10\,L_{abs}$$

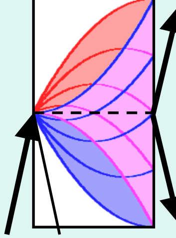


One-crystal scheme

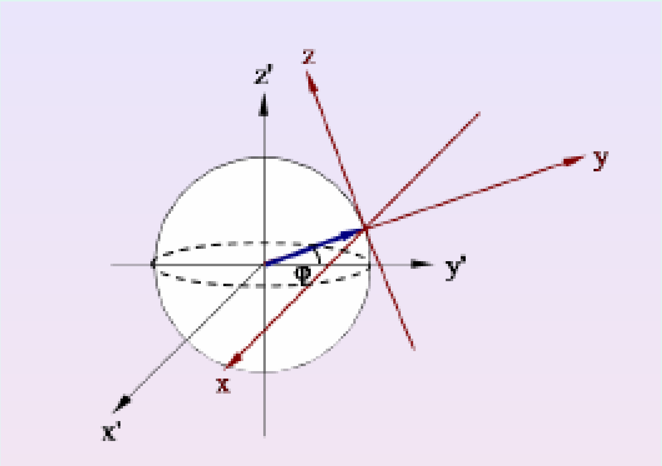


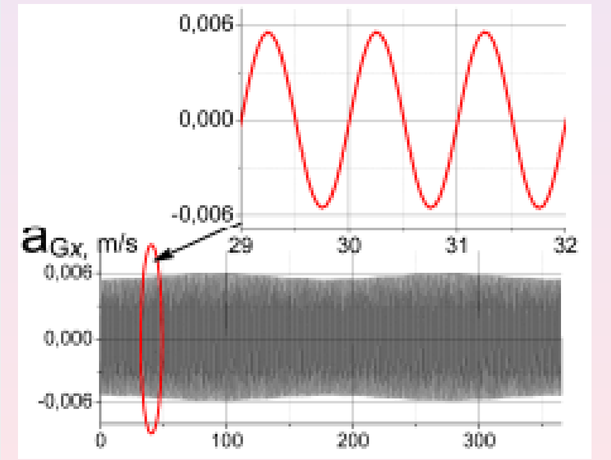
Two-crystal scheme

Theoretical prediction without taking Borrmann effect into account



*Influence of noninertial forces**





1. Tidal forces:
Value ~ 10^{-17} eV/cm
Period 12 hours

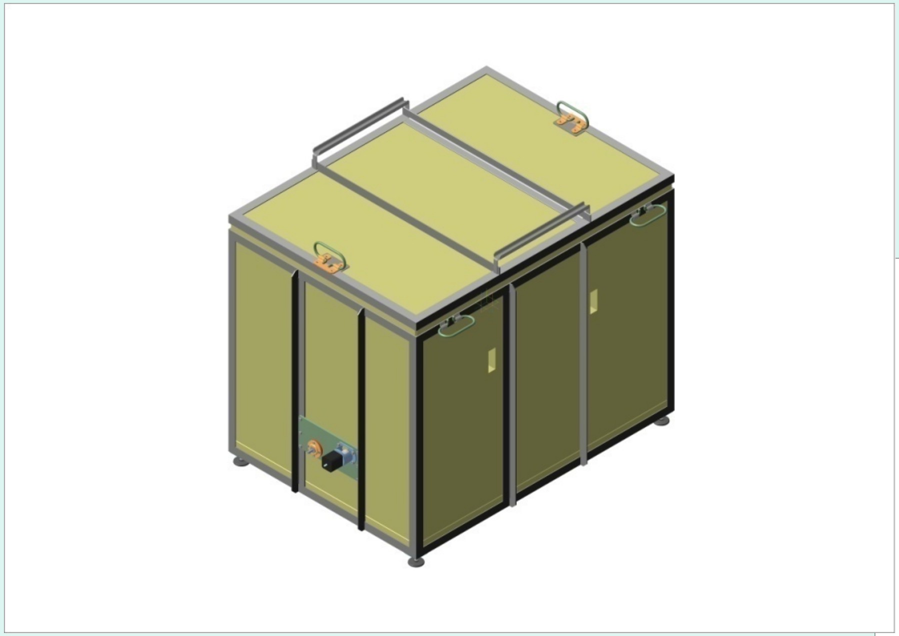
2. Coriolis forces for cold neutron:
Value ~10^{-12} eV/cm
Period 12 hours

The force we are looking for:
Value~10^{-13}eV/cm
Oscillation period=24 hours

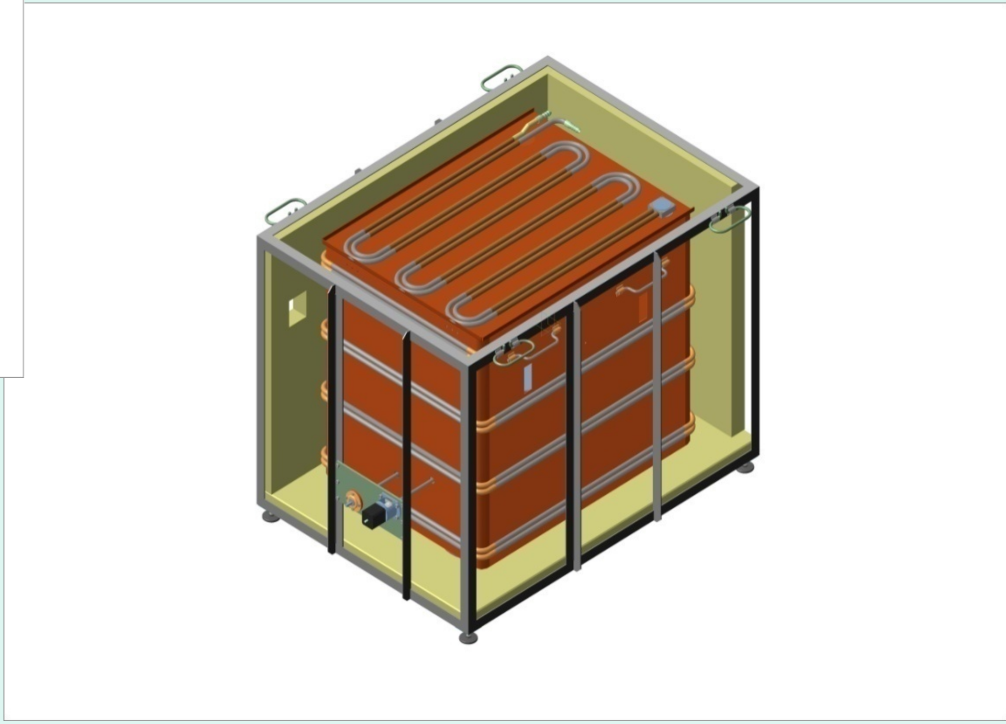
Annual acceleration variations caused by possible EP violation

*estimations are presented in PNPI Preprint-2827 (2009)

m^i/m^g *experiment with cold neutron.*
Improvement of the experimental setup

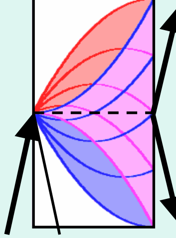


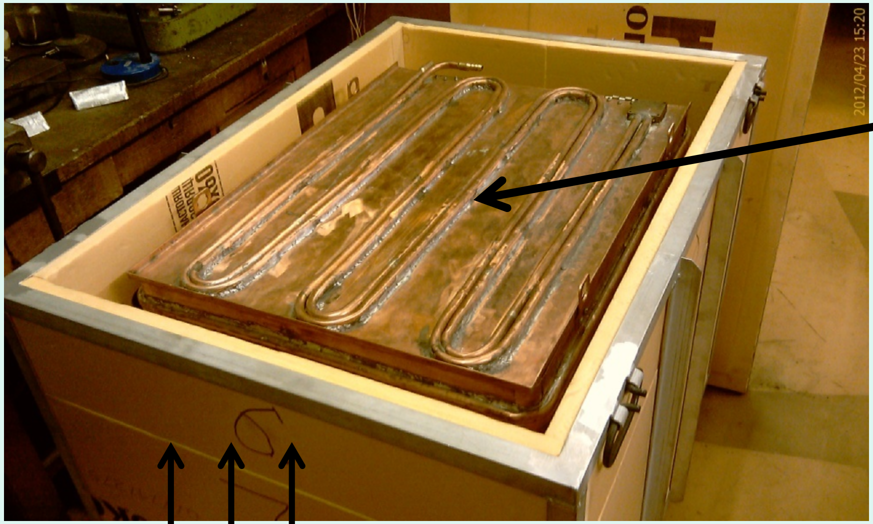
New “double-layer” thermostat was made (start of temperature stability tests – August 2012)



10^{-7} K/sec (≈0.01 K/day)
for the working crystal

Our brand new “double-layer” thermostat

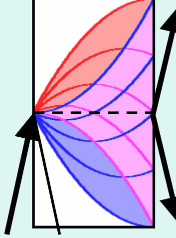




Active shielding (flowing water)

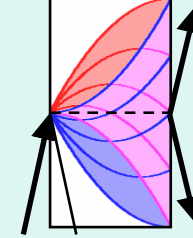
Passive shielding (expanded foam)

Still crucial issue – placement of the rotating stages and other heat emitting mechanisms



Summary and future plans

- *Two-crystal scheme of the Laue diffraction with Bragg angles close to the right one is a very sensitive experimental instrument (resolution to the external force reaches 10^{-13}eV/cm)*
- *The uncertainty of measuring inertial to gravitational mass ratio for the neutron (test of WEP) can reach magnitude ~10^{-6}*
- *All observed experimental results coincide with theoretical predictions*
- *Temperature stability tests of the new thermostat – at the present time*
- *Installation of improved setup on the 2nd beam line of WWR-M - end of 2012*
- *After test experiment – installation on high flux research reactor (ILL, PIK,…)*



Thanks for Your attention!