VERIFICATION OF THE WEAK EQUVALENCE PRINCIPLE WITH LAUE DIFFRACTING NEUTRONS. CURRENT STATUS OF THE EXPERIMENT

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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*:

\[ K_d^{Si} \theta_B \sim 84° \div 87° \rightarrow 10^7 \div 10^8 \]

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

• For example, this enhancement can be used in \( m^i/m^g \) experiment with cold neutron (NGrav)

*V.V. Fedorov et.al. JETP Lett. 85, 82 (2007)
Verification of WEP. Eötvös and novel EP tests

L. v. Eötvös (1908) $\leq 5 \cdot 10^{-9}$
Ann. Physik (Leipzig) 68 11 (1922)

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

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

Earth Orbit (Projects):
MiniSTEP (202?) $\leq 10^{-16}$;
MICROSCOPE (201?) $\leq 10^{-15}$

Elementary particles (neutrons): L. Koester (1976) $\leq 2.5 \cdot 10^{-4}$

J. Schmiedmayer (1989) $\leq 1.8 \cdot 10^{-4}$; A. Frank, et al. (ongoing) $\leq 2 \cdot 10^{-3}$
Neutron trajectory for Laue diffraction

\[ j = \frac{\hbar}{m} \left( |a_g(\alpha)|^2 k_g + |a_0(\alpha)|^2 k \right) \]

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

\[ \alpha = \frac{2(\Delta k_0 \cdot g)}{k_0^2}, \quad \Delta k_0 = k_0 - g / 2 \]

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

If \(\alpha(Y,Z)\) \(\rightarrow\) \(a_g(Y,Z)\) and \(a_0(Y,Z)\)

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

\[ 2\tan(\theta_B) L \]  
(Borrmann fan)
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:

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

We obtain a gain factor for the diffracting neutron

For silicon (220) planes

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

\[
K_d = \tan^2 (\theta_B) \times 2 \cdot 10^5 \theta_B (84^0 \div 87^0) \rightarrow (10^7 \div 10^8)
\]

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

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Two-crystal scheme of Laue diffraction

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

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

The resolution for this setup is:

\[ W_F = \frac{m_0 E_n d}{\pi \tan^2 \theta_B L^2} \delta_S, \]

\( \delta_S \) – slit size

For (220) plane of Silicon:

\[ L = 10\,\text{cm}, \; \delta_S = 1\,\text{mm}, \; \theta_B = 86^\circ \]

\[ W_F \approx 1.5 \cdot 10^{-13} \, \text{eV/cm} \approx 10^{-5} \, m_n g \]

But, for such initial conditions a neutron should pass effectively through more than 3 meters of silicon \((2L/\cos(86^0))\).

\textbf{Is it possible?}
Experimental observation of Laue diffraction in the large silicon crystal ($L=220\; mm$)

Working crystallographic plane is $(220)$

\[ d = 1,92 \cdot 10^{-8}\; cm \]

\[ \Delta d / d \sim 10^{-8}\; cm^{-1} \]
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Experimental observation of Laue diffraction in the large silicon crystal (L=220 mm)

220 silicon plane intensity reflex

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

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

\[ \mu_{1,2} = \mu_0 \left( 1 \pm \varepsilon_g \right) \]
\[ \mu_1 = 0.05 \]
\[ \mu_2 < 0.003 \]

\[ L_{abs}^2 \sim 10L_{abs} \]

Theoretical prediction without taking Borrmann effect into account

One-crystal scheme

Two-crystal scheme

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Experimental test of the two-crystal setup possible resolution

\[ \theta_B = 78^\circ \]
\[ \delta_S = 15\,mm \]

Theta 86°, delta S = 2mm

\[ W_F^{\text{exp}} \approx 4 \cdot 10^{-11}\,eV/cm = 4 \cdot 10^{-2}\,m_n g \]

\[ W_F \approx 5 \cdot 10^{-13}\,eV/cm = 5 \cdot 10^{-4}\,m_n g \]

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

\[ \sigma F_{\text{ext}} \approx 5 \cdot 10^{-18}\,eV/cm \]
Idea of $m_i/m_g$ experiment with neutron (NGrav)

$F_G \approx m_g \ ; \ F_r \approx m_i$

$F_G = F_r$ for the Earth

$? \frac{m_i}{m_g} \neq \frac{m_i}{m_\odot} \ ?$

$F_G \neq F_r$ for the neutron

Possible appearance of the non zero force:

$$F_m = F_G - F_r = G \cdot \frac{m_g m_g}{R^2} \left( 1 - \frac{m_i / m_g}{m_\odot / m_\odot} \right) \approx 6 \cdot 10^{-13} \left( 1 - \frac{m_i}{m_g} \right) eV / cm$$

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

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

$F_m$ changes its sign in the laboratory coordinate system

Daily oscillations of the $F_m$ value

Our setup is sensitive to $F_m$ oscillations
**Value of the external force in $m_i/m_g$ experiment:**

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

**The possible sensitivity of the setup:**

$$\sigma \ F_{ext} \approx 5 \cdot 10^{-18} \text{eV/cm}$$

$$\delta_{i/G} \ (m_G - m_i) / m_G \approx 10^{-5}$$

Present accuracy $1.8 \cdot 10^{-4}$ (Schmiedmayer, 1989)

**More than one order better than the present day value**
Influence of noninertial forces*

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

2. Coriolis forces for cold neutron:
   Value $\sim 10^{-12}$ eV/cm
   Constant

The force we are looking for:
Value $\sim 10^{-17}$ eV/cm
Oscillation period=24 hours

Annual acceleration variations
cauian by possible EP violation

*estimations are presented in PNPI Preprint-2827 (2009)
Working crystal horizontality control. The inclinometer test

Reading spread of the DDYP.02 inclinometer (60 seconds)

Reading spread for 60 seconds of measurement \( \sim 10^{-8} \text{ rad} \)
Temperature uniformity

Simulation of the possible temperature gradients for the linear external thermal changes

$10 \times 10 \text{cm}^2$ (quartz crystal)

Rate of $T^0$ change $\approx 10^{-2} \text{ K/day}$

$\xi_T \leq 10^{-12} \text{ cm}^{-1}$

Influence $\sim 10^{-5} m_n g \ll W_F$

$10^{-7} \text{ K/sec} \ (\approx 0.01 \text{ K/day})$

for the working crystal

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Temperature uniformity. Test of the new thermostat

- Passive shielding (expanded foam)
- Active shielding (circulating water)
- Temperature control system (JULABO)
Temperature uniformity. Test of the new thermostat

Data from thermal sensors installed on the crystal surface

Dependence of the difference between installed sensors from the external temperature changes.

It is on the level $\sim 10^{-2} \, \text{K}$
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) in NGrav experiment can reach magnitude $\sim 10^{-5}$
- All of the external impacts can be controlled on acceptable level with available technical equipment
- Installation of improved NGrav setup on the 2\textsuperscript{nd} beam line of WWR-M - this autumn
- After test experiment – installation on a high flux research reactor (ILL, …)
Thanks for Your attention!