# Present status and future prospects of n→n′ search

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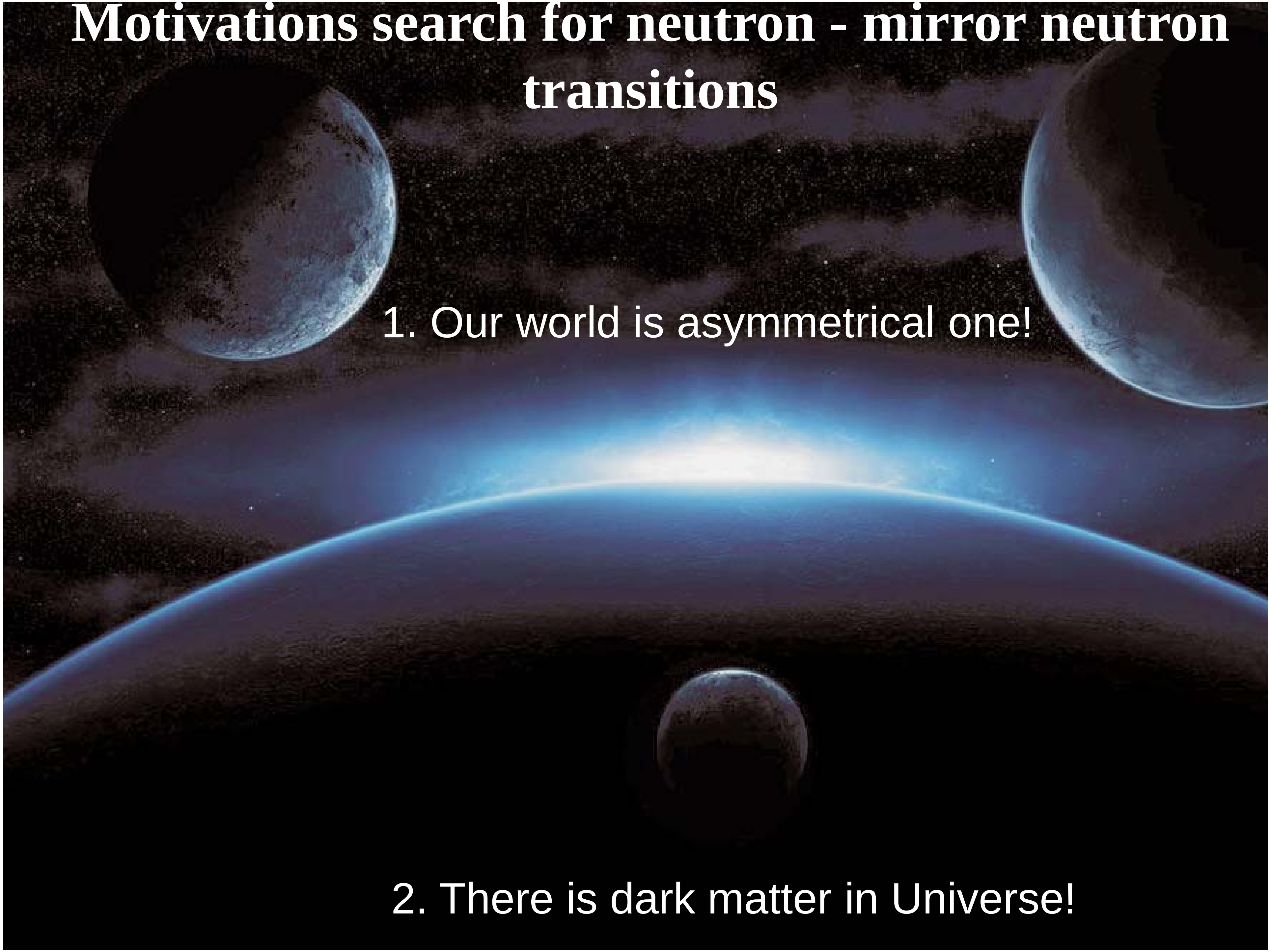
Search for Baryon and Lepton Number Violations
International Workshop
September 20-22, 2007

# Motivations search for neutron - mirror neutron transitions



1. Our world is asymmetrical one!

2. There is dark matter in Universe!

# History of mirror ideas

The concept of mirror world as a hidden duplicate of the observable particle world and concept of mirror parity was introduced by I.Yu.Kobzarev, L.B.Okun and I.Ya.Pomeranchuk (Yad. Fiz. 3, 1154 (1966)

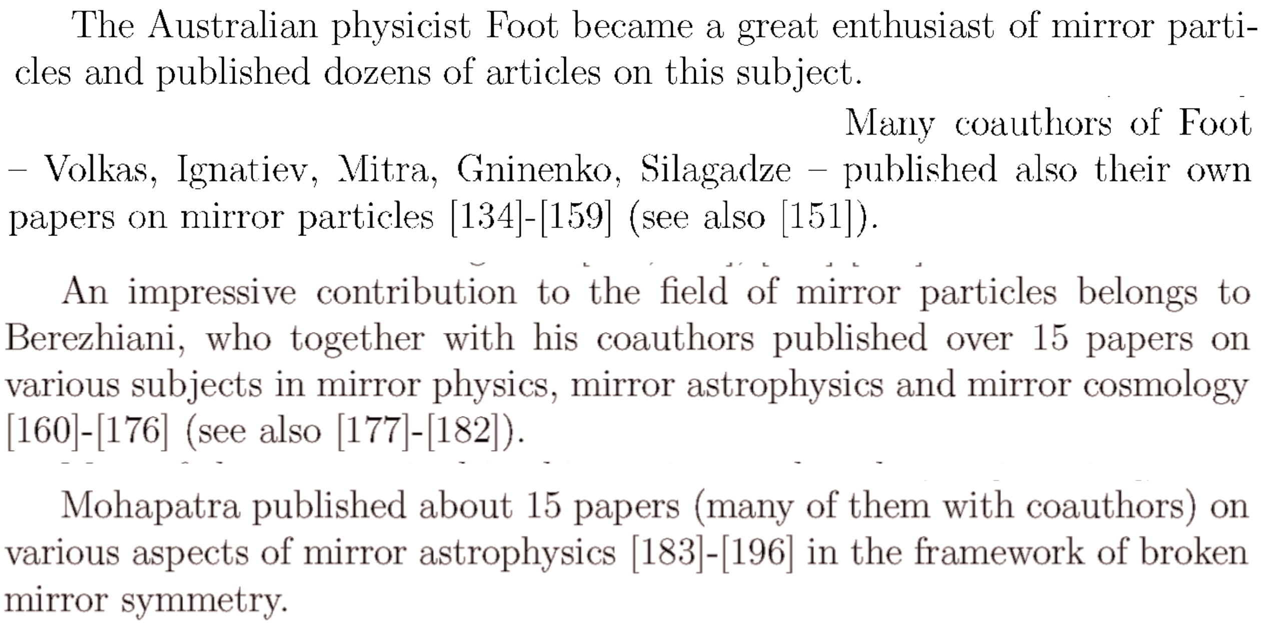
| | |
|---|---|
| mirror particles | particles |
| mirror antiparticles | antiparticles |

## Mirror particles and mirror matter: 50 years of speculation and search

L.B. Okun
ITEP, Moscow, Russia

Review (259 references)
hep-ph/0606202 v2 Dec 2006

1991-2006



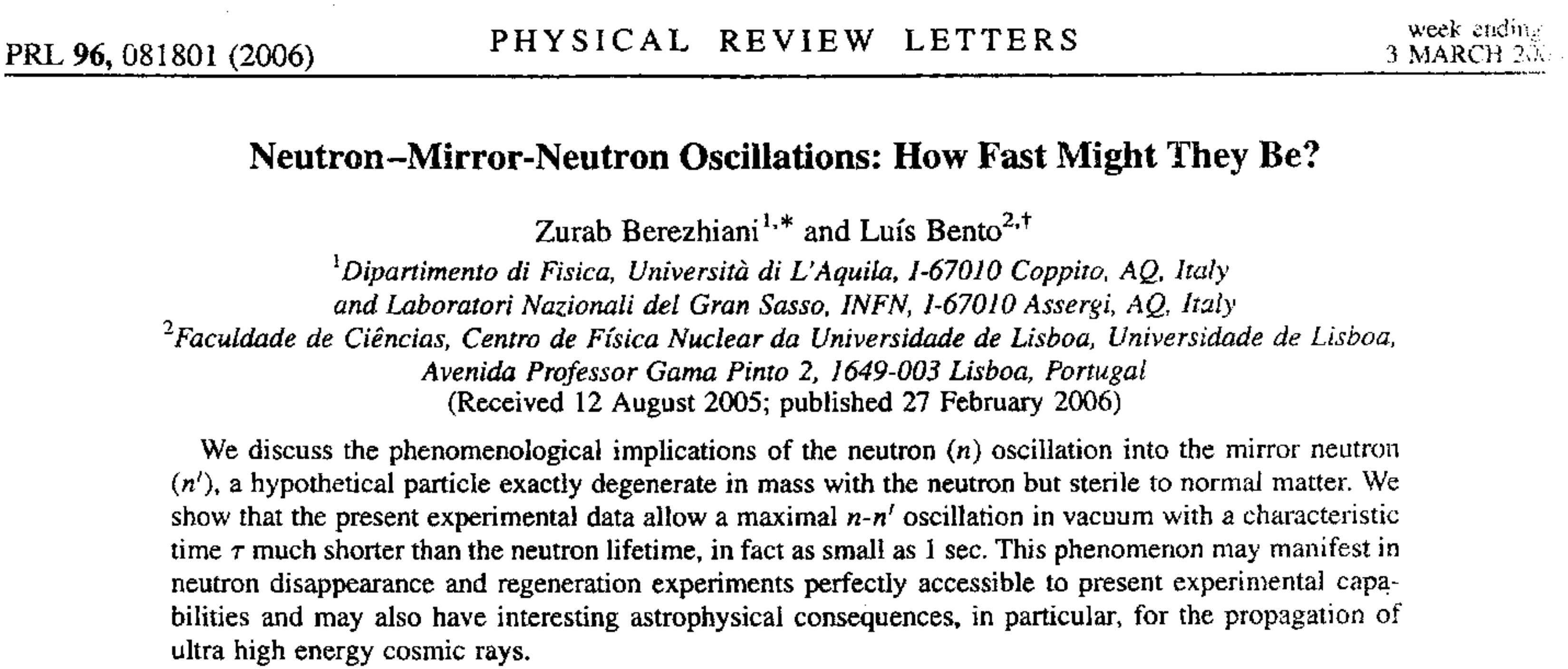
The Australian physicist Foot became a great enthusiast of mirror particles and published dozens of articles on this subject.

Many coauthors of Foot – Volkas, Ignatiev, Mitra, Gninenko, Silagadze – published also their own papers on mirror particles [134]-[159] (see also [151]).

An impressive contribution to the field of mirror particles belongs to Berezhiani, who together with his coauthors published over 15 papers on various subjects in mirror physics, mirror astrophysics and mirror cosmology [160]-[176] (see also [177]-[182]).

Mohapatra published about 15 papers (many of them with coauthors) on various aspects of mirror astrophysics [183]-[196] in the framework of broken mirror symmetry.

# Recent theoretical publications



PRL **96,** 081801 (2006) PHYSICAL REVIEW LETTERS
week ending
3 MARCH 2

## Neutron–Mirror-Neutron Oscillations: How Fast Might They Be?

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(Received 12 August 2005; published 27 February 2006)

We discuss the phenomenological implications of the neutron ($n$) oscillation into the mirror neutron ($n'$), a hypothetical particle exactly degenerate in mass with the neutron but sterile to normal matter. We show that the present experimental data allow a maximal $n$-$n'$ oscillation in vacuum with a characteristic time $\tau$ much shorter than the neutron lifetime, in fact as small as 1 sec. This phenomenon may manifest in neutron disappearance and regeneration experiments perfectly accessible to present experimental capabilities and may also have interesting astrophysical consequences, in particular, for the propagation of ultra high energy cosmic rays.

$$\tau_{\substack{\mathrm{osc}\\ \mathrm{nn'}}} > 1\ \mathrm{s}$$

# Recent experimental publications

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## On the experimental search for neutron → mirror neutron oscillations

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Available online 13 June 2006

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**Abstract**

Fast neutron → mirror neutron ($n \to n'$) oscillations were proposed recently as the explanation of the GZK puzzle. We discuss possible laboratory experiments to search for such oscillations and to improve the present very weak constraints on the value of the $n \to n'$ oscillation probability.

*PACS:* 11.30.Er; 14.20.Dh; 28.20.-v

*Keywords:* Reflection symmetry; Mirror world; Neutron oscillations; Neutron lifetime; Ultracold neutrons

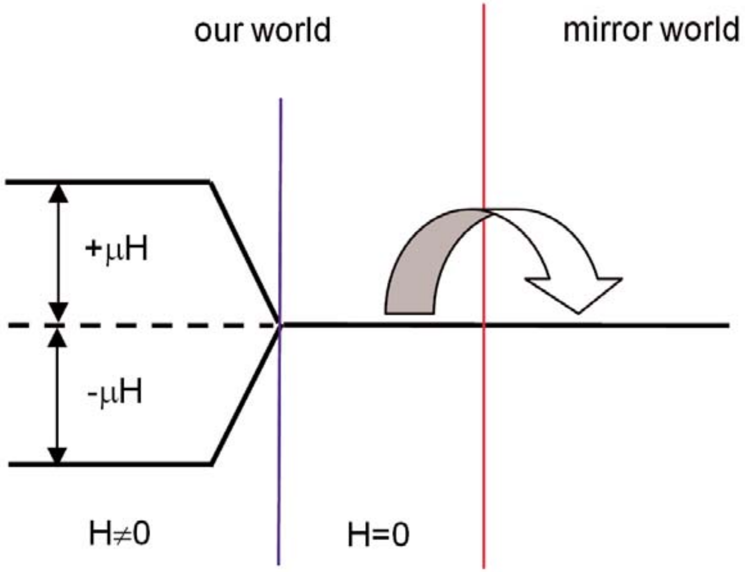
# Present experimental status

| | |
|---|---|
| 1. talk of U.Schmidt (this Workshop) | $\tau_{osc} \geq 2.7$ s |
| 2. G.Ban et al., arXiv:0705.2336v1 [nucl-ex] | $\tau_{osc} \geq 103$ s (95% C.L.) |
| 3. A.Serebrov et. al., arXiv:0706.3600v1 [nucl-ex] | $\tau_{osc} \geq 414$ s (90% C.L.) |

# How to observe n-n′ transitions

The evolution of nonrelativistic n-n′ system in the external magnetic field B is described by the effective Hamiltonian :

$$H = \begin{pmatrix} m + \frac{P^2}{2m} - i\frac{\Gamma}{2} + \mu(\sigma \cdot B) + V & \delta m \\ \delta m & m' + \frac{P^2}{2m'} - i\frac{\Gamma'}{2} + V' \end{pmatrix}$$



Energy states of ordinary and mirror neutron are degenerated when magnetic field H=0, and transitions are possible. Due to magnetic field energy states of neutron can be shifted and transitions to mirror state will be suppressed.

# Phenomenology of n → n′ oscillations, estimation of "zero" magnetic field and "suppressing" magnetic field

$$n'(t)=\frac{n_0}{1+(\omega\tau_{osc})^2}\sin^2\left(\sqrt{1+(\omega\tau_{osc})^2}\cdot\frac{t}{\tau_{osc}}\right)$$

$\omega=\frac{\Delta E}{\hbar}$; $2\Delta E$ is the energy difference of the neutron and mirror neutron states = $\mu B$

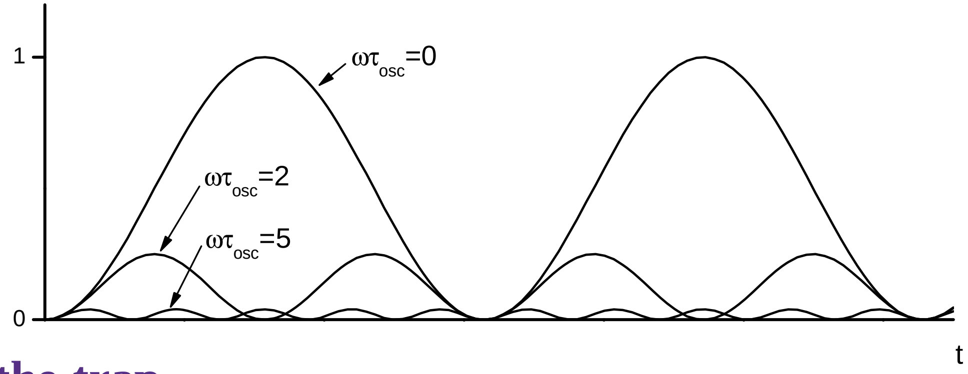
$\tau_{osc}$ is the oscillation time

$\omega_{min}=1\ s^{-1}\quad(2\cdot10^{-4}\ G)$

$(\omega\tau)^2>>1\quad\tau_{osc}>3\ s$

$\mu=6\cdot10^{-12}\ eV/G$

$\omega=4.8\cdot10^3\cdot H$



t is the time of flight between collisions in the trap

$$n'(t)=\frac{n_0}{(\omega\tau_{osc})^2}\sin^2(\omega t)$$

$n_0\left(\frac{t}{\tau_{osc}}\right)^2;\quad\omega<<1$

$\frac{n_0}{2(\omega\tau_{osc})^2};\quad\omega t>>1$

$\omega_{min}t=0.1,\ t=0.1\ s,\ H_{min}=2\cdot10^{-4}\ G$

$\omega_{max}t=10,\ t=0.1\ s,\ H_{max}=2\cdot10^{-2}\ G$

"zero" magnetic field $2\cdot10^{-4}$ G

"suppressing" magnetic field $2\cdot10^{-2}$ G

# Estimation of sensitivity of n → n′ experiment

**"zero" magnetic field**

$$\tau_0^{-1} = \tau_n^{-1} + \mu\nu + \left(\frac{t}{\tau_{osc}}\right)^2 \nu$$

**"suppressing" magnetic field**

$$\tau_H^{-1} = \tau_n^{-1} + \mu\nu + \boxed{\frac{1}{2(\omega_{max}\tau_{osc})^2}\nu} \rightarrow 0$$

$$\Delta\tau_{H-0}^{-1} = \left(\frac{\Delta t}{\tau_{osc}}\right)^2 \nu = \frac{1}{\nu\tau_{osc}^2}$$

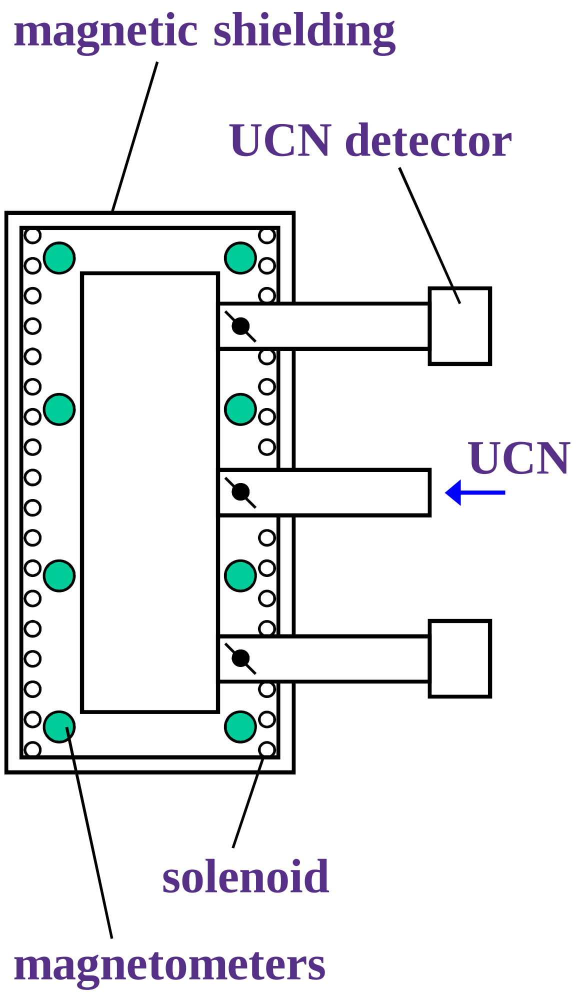
$$\tau_{osc} = \left[\frac{\tau}{\nu}\cdot\left(\frac{\Delta\tau}{\tau}\right)^{-1}\right]^{\frac{1}{2}}$$

$$\tau_{osc} \geq 0.66\left[\frac{\tau}{\nu}\cdot\left(\frac{\Delta\tau}{\tau}\right)^{-1}\right]^{\frac{1}{2}} \quad (90\%\ \text{C.L.})$$

**μ - probability of losses per one collision**

**ν - frequency of collisions**

# Estimation of sensitivity of n → n′ experiment



$$\tau_{osc} \geq 0.66\left[\frac{\tau}{\nu}\cdot\left(\frac{\Delta\tau}{\tau}\right)^{-1}\right]^{\frac{1}{2}} = 3\left(\frac{\Delta\tau}{\tau}\right)^{-\frac{1}{2}} = 300\ \text{s}$$

$$\tau_{storage} \approx 200\ \text{s};\ \nu \approx 10\ \text{s}^{-1};\ \left(\frac{\Delta\tau}{\tau}\right) \approx 10^{-4}$$

$$\frac{\Delta\tau}{\tau} \approx \frac{2}{\sqrt{N}};\ \text{N}=\rho\text{V}\frac{\text{T}}{\left(\tau_{st}+\tau_{fill}+\tau_{empt}\right)} = 3.3\cdot 10^{9}$$

$\rho = 5\ \text{n/cm}^3$ - UCN density

$\text{V} = 200\ \text{l}$ - trap volume

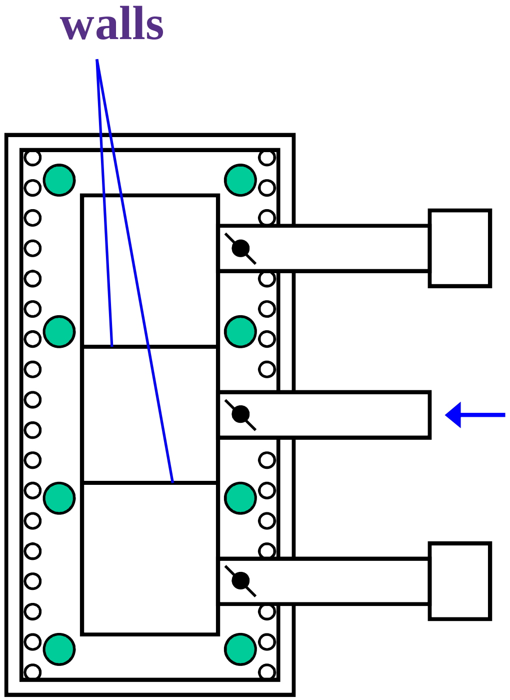
$\text{T} = 10^6\ \text{s}$ - time of experiment

$\left(\tau_{st}+2\tau_{fill}+2\tau_{empt}\right) \approx 300\ \text{s}$ - time of one measurement

$$\frac{\Delta\tau}{\tau} = 3.5\cdot 10^{-5}$$

**Lower limit $\boxed{\tau_{osc}^{90\%} \geq 500\ \text{s}}$ can be installed!**

# Estimation of sensitivity of $n \to n'$ experiment with regeneration ($n \to n' \to n$)



$\Phi$ - flux on trap surface $= 8 \cdot 10^5$ $s^{-1}$

$\Phi'$ - leakage of flux from the trap due to $n \to n'$

$\Phi''$ - flux to detectors due to $n \to n' \to n$

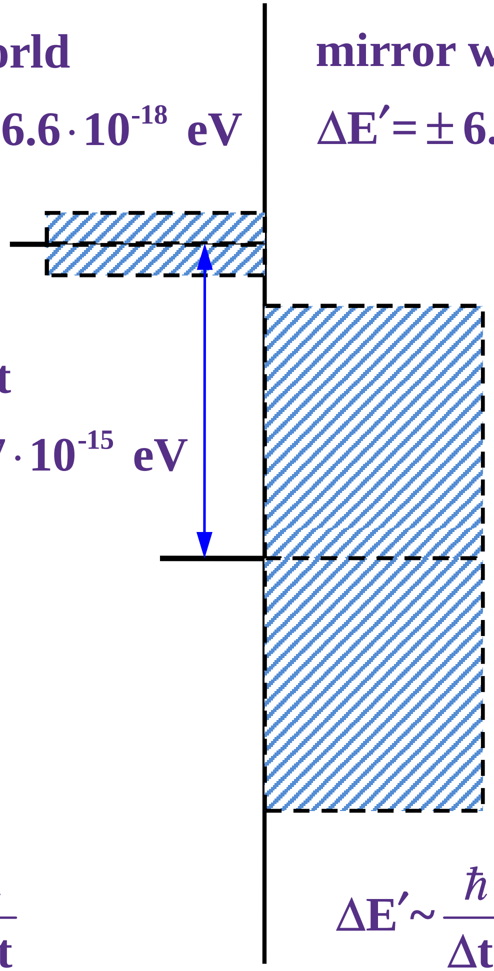
| $\tau_{osc}$ | 1 s | 10 s | 50 s | 100 s |
|---|---|---|---|---|
| $\Phi'$ | $8 \cdot 10^3$ | 80 | 3.2 | 0.8 |
| $\Phi''$ | 80 | $8 \cdot 10^{-3}$ | $1.3 \cdot 10^{-5}$ | $8 \cdot 10^{-7}$ |

background $\approx 10^{-2} \div 10^{-3}$ $s^{-1}$

experiment is sensitive to $n \to n' \to n$ if

$$\boxed{\tau_{osc} \leq 30 \text{ s}}$$

# Small shift of n-n′ degenerated states in UCN experiment



**our world**

$\Delta E = \pm 6.6 \cdot 10^{-18}$ eV

**mirror world**

$\Delta E' = \pm 6.6 \cdot 10^{-15}$ eV

**shift**

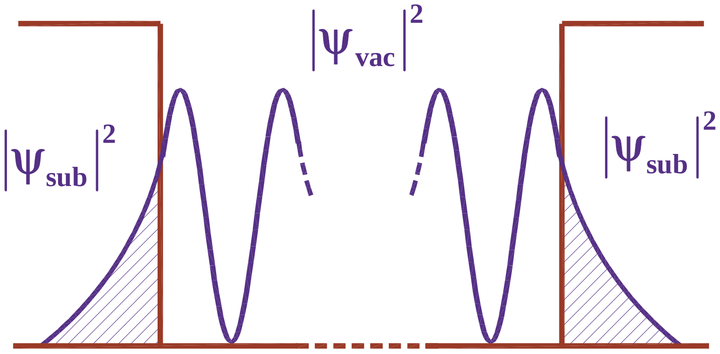
$\bar{U} = 7 \cdot 10^{-15}$ eV

$\Delta E \sim \dfrac{\hbar}{\Delta t}$

$\Delta E' \sim \dfrac{\hbar}{\Delta t'}$

$\Delta t \sim 100$ s - storage time

$\Delta t' \sim 0.1$ s - flight time between wall collisions



$$|\psi_{sub}|^2 = \frac{4E_\perp}{U_0} e^{-2æz} \qquad æ = \frac{1}{\hbar}\sqrt{2m\left(E_\perp - U_0\right)}$$

$$|\psi_{vac}|^2 = 4\sin^2 kz \qquad k = \frac{1}{\hbar}\sqrt{2mE_\perp}$$

$$\bar{U} = U_0 \frac{\int |\psi_{sub}|^2 dV}{\int |\psi_{vac}|^2 dV} \approx E_\perp ƛ \frac{S}{V}$$

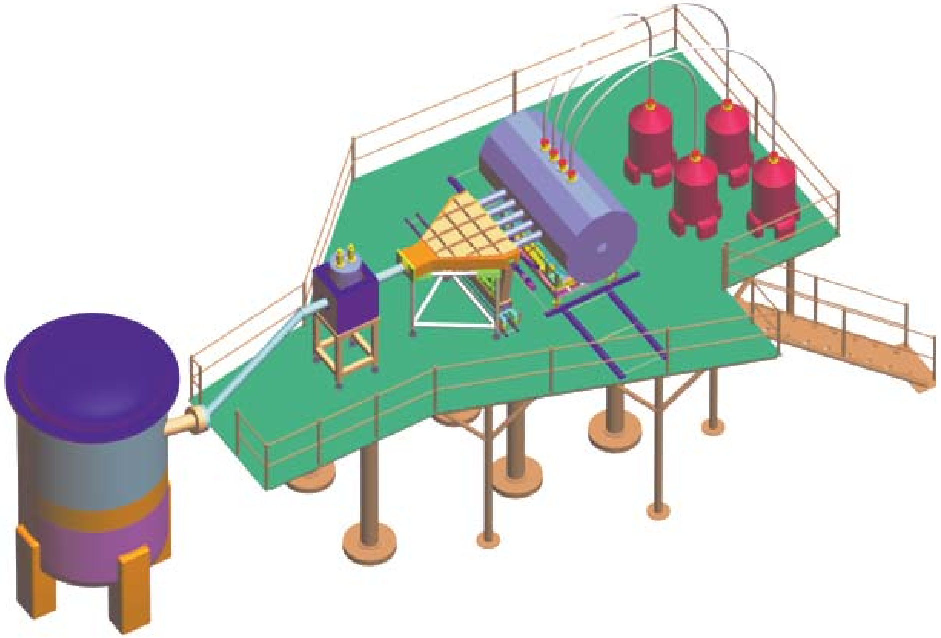
$$ƛ = \frac{1}{\hbar}\sqrt{2m\left(U_0 - E_\perp\right)}$$

$$\bar{U} \approx 7 \cdot 10^{-15}\ \text{eV} \qquad \left(H = \frac{\bar{U}}{\mu} \approx 100\ \text{nT}\right)$$

factor of suppression ~ 10%

# Proposal of PNPI for n → n′ experiment

Experiment for n → n′ oscillations
can be realized using PNPI EDM spectrometer



$\tau_{\text{storage H=0}}$ (without magnetic field)

$\tau_{\text{storage H}\neq 0}$ (with magnetic field)

$\Delta\tau = \tau_{\text{storage H}\neq 0} - \tau_{\text{storage H=0}} = (\neq)0$

It is the main question

# PNPI-ILL-PTI collaboration

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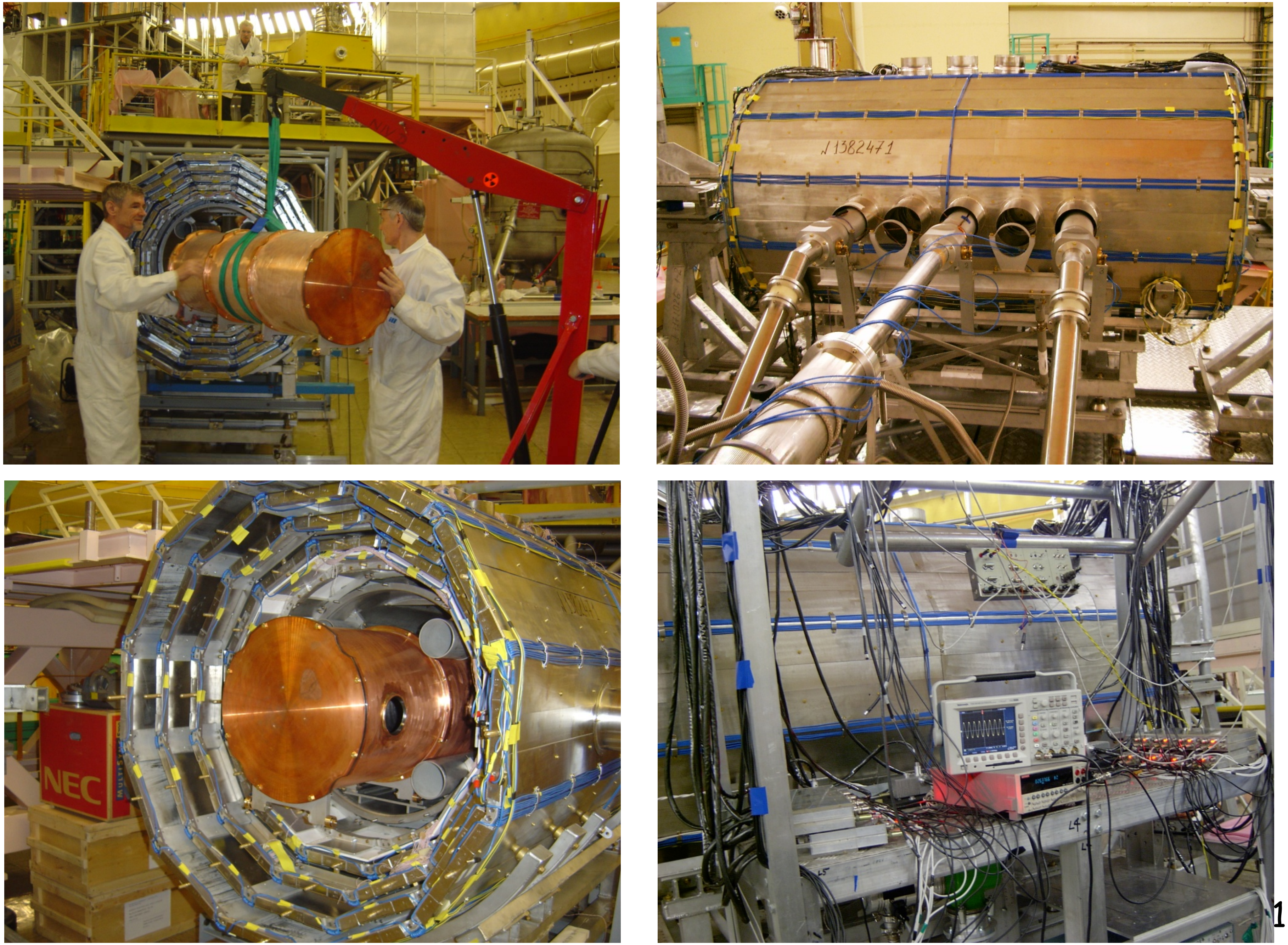
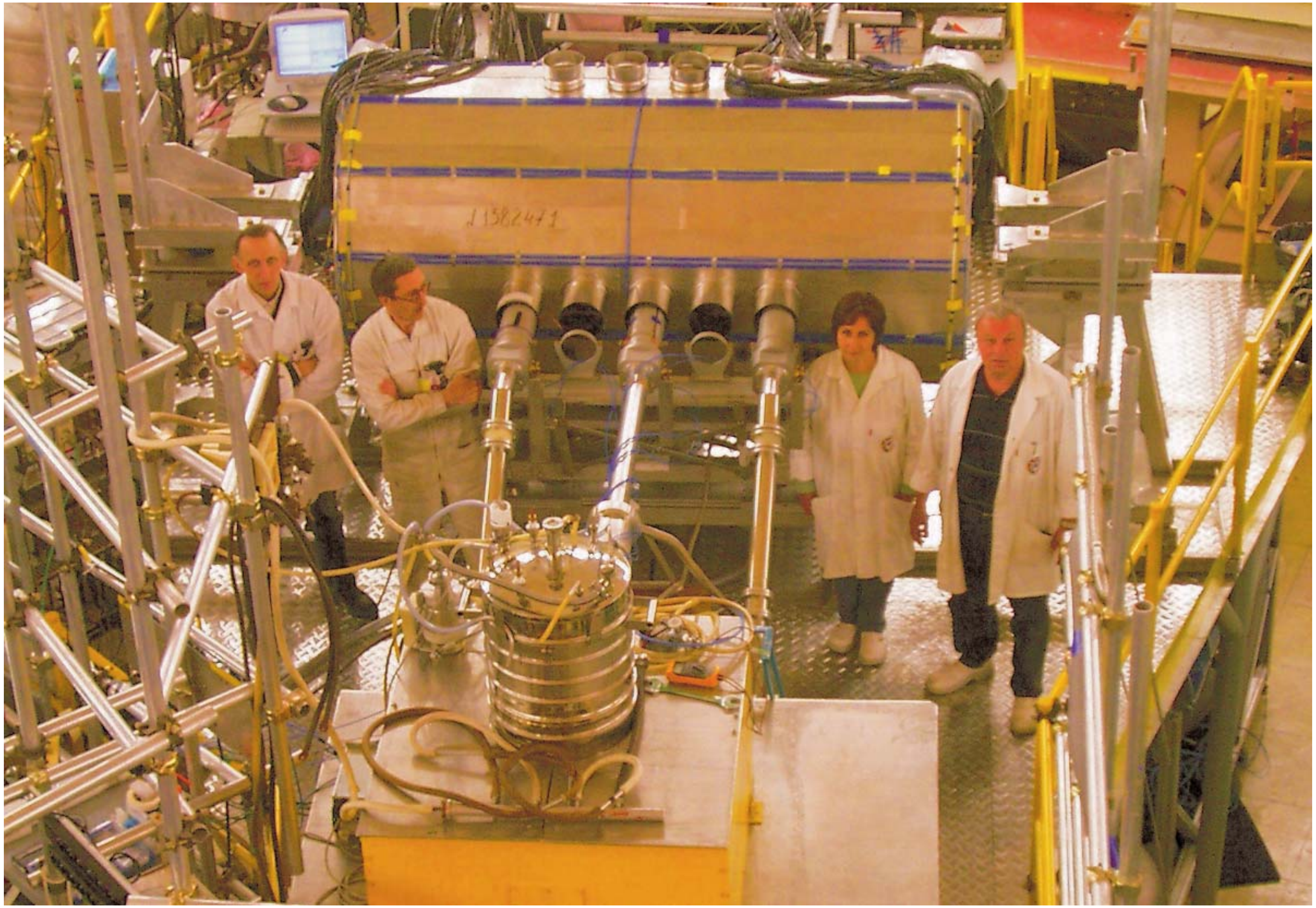
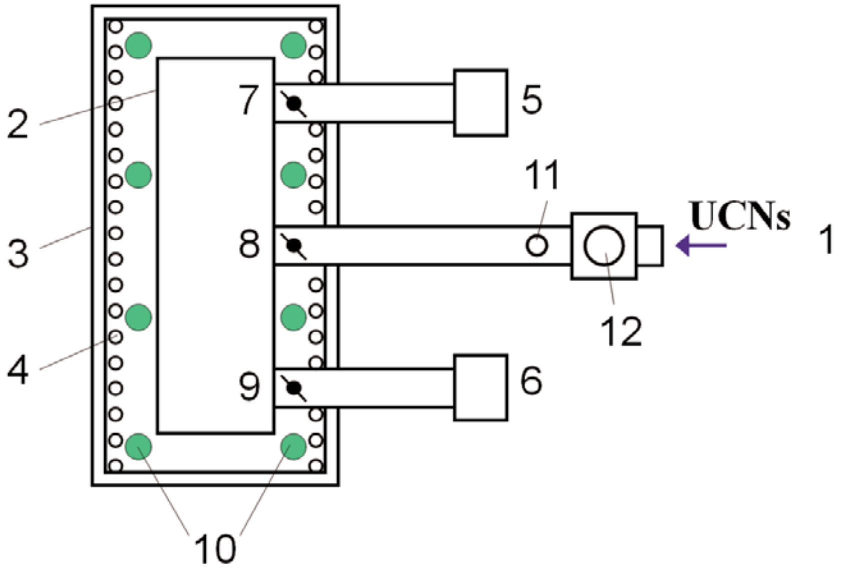
# Preparation of n → n′ experiment at ILL

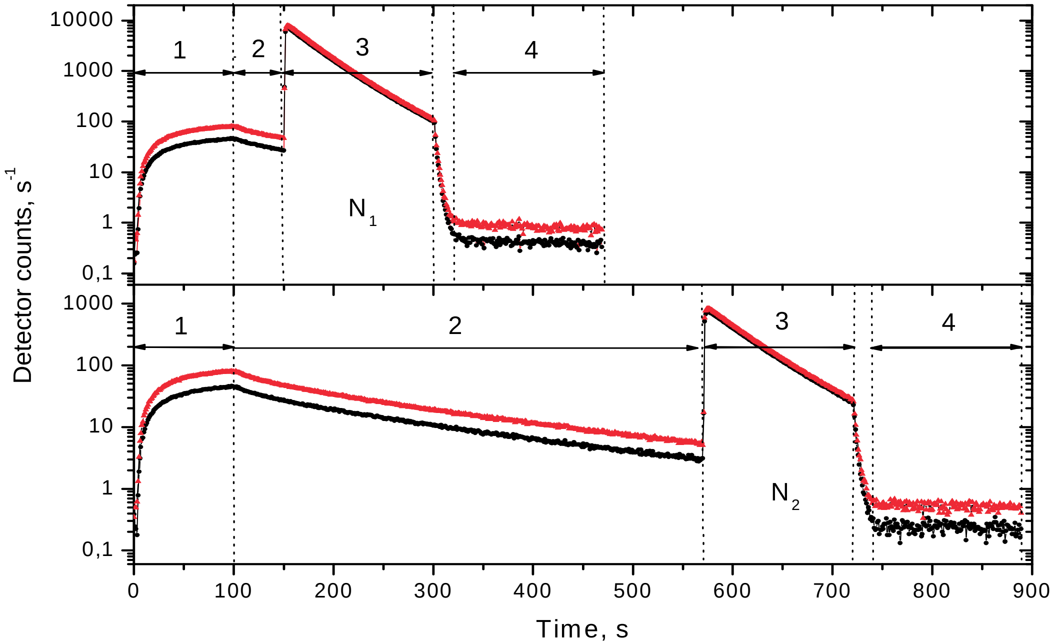


# Experimental installation search for n-n′ oscillation and some members of PNPI-ILL-PTI collaboration



# Scheme of experimental installation to search for n-n' transitions

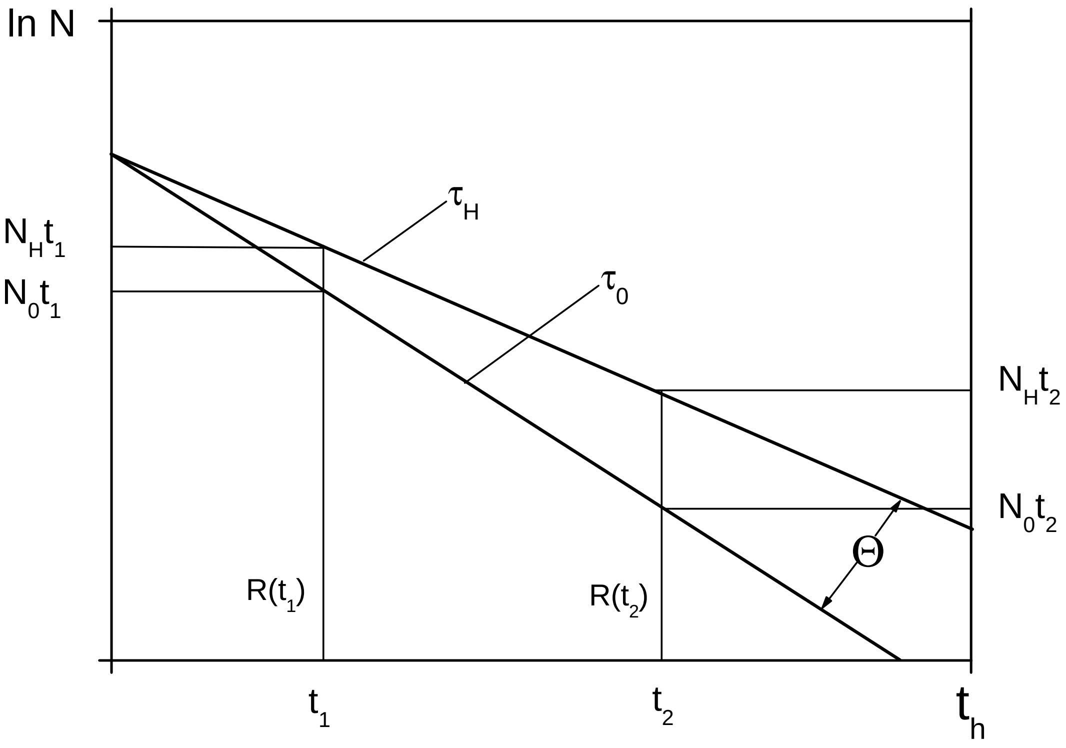




1: UCN input guide; 2: UCN storage chamber; 3: magnetic shielding; 4: solenoid; 5-6: UCN detectors; 7-9: valves; 10: Cs-magnetometers, 11: monitor detector, 12: entrance valve.

Count rates of UCN detectors (5 and 6) in log scale during measurements. The filling time is 100 s. Holding times were $t_1$ = 50 s and $t_2$ = 470 s. Empting time is 150 s. The time of background measurement is 150 s. The region 3 in these plots is used to deduce the numbers $N_1$ and $N_2$ required for the determination of the storage time, respectively the ratio $R$ (after background subtraction). This picture was obtained after 130 cycles. $\tau_{\text{fill}}$ = 35 s, $\tau_{\text{emp}}$ = 30 s after holding time 50 s, $\tau_{\text{emp}}$ = 38 s after holding time 470 s.

# Two method of determination of $\tau_{\text{osc}}$



$$\tau_{\text{osc}}^{-2} = \frac{\theta}{\left\langle t_{\text{f}}^{2} \right\rangle \nu} \cdot \tau_{\text{st}}^{-2}$$

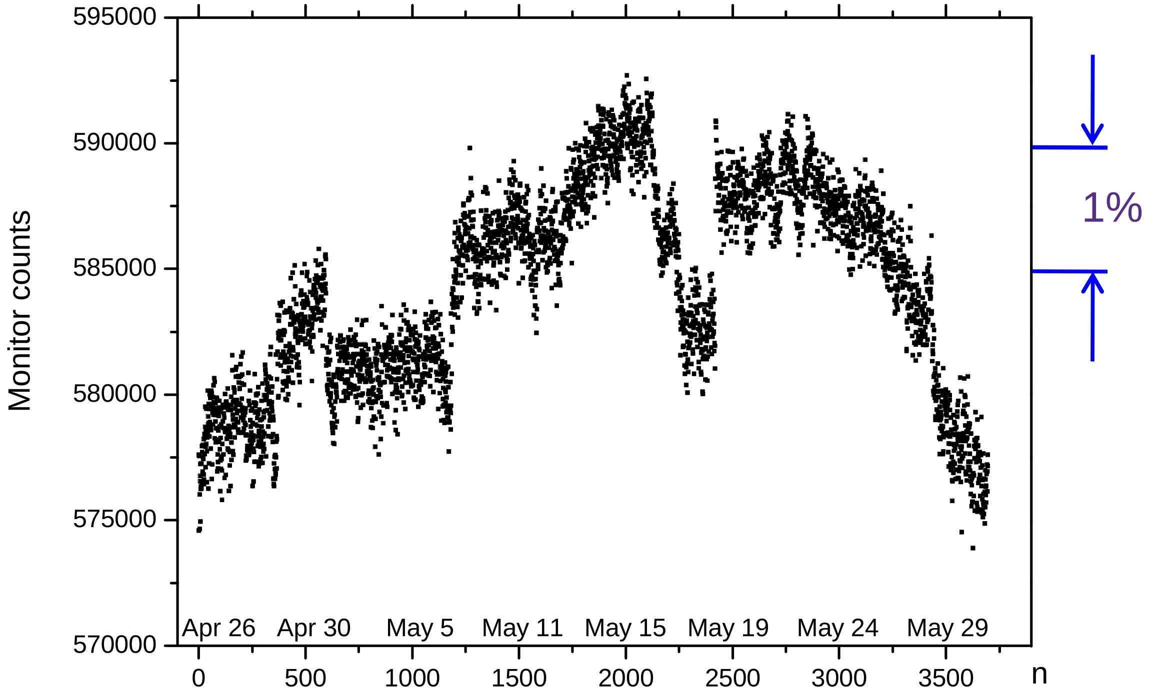
$$\theta = \tau_{\text{st},H} - \tau_{\text{st},0}$$

$$\tau_{\text{osc}}^{-2} = \frac{r}{\left\langle t_{\text{f}}^{2} \right\rangle \nu \left( t_{\text{h}} + \tau_{\text{fill}} + \tau_{\text{emp}} \right)}$$

$$r = 1 - R$$

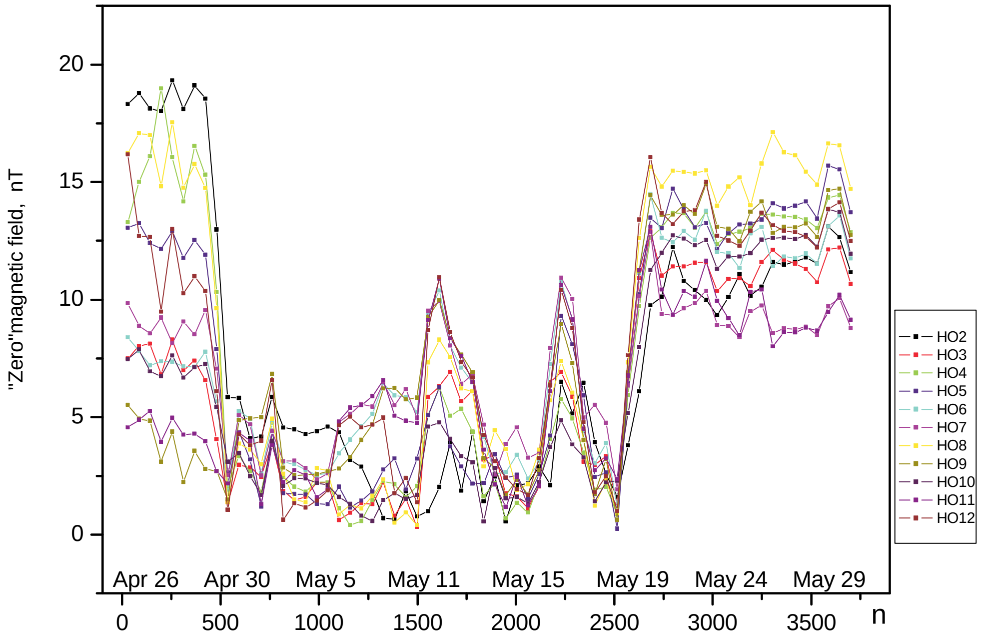
$$R \equiv N_0 / N_H = e^{-\left\langle t_{\text{f}}^{2} \right\rangle \nu \left( t_{\text{h}} + \tau_{\text{fill}} + \tau_{\text{emp}} \right) / \tau_{\text{osc}}^{2}} = 1 - \left\langle t_{\text{f}}^{2} \right\rangle \nu \left( t_{\text{h}} + \tau_{\text{fill}} + \tau_{\text{emp}} \right) / \tau_{\text{osc}}^{2}$$

# Stability of intensity of UCN beam

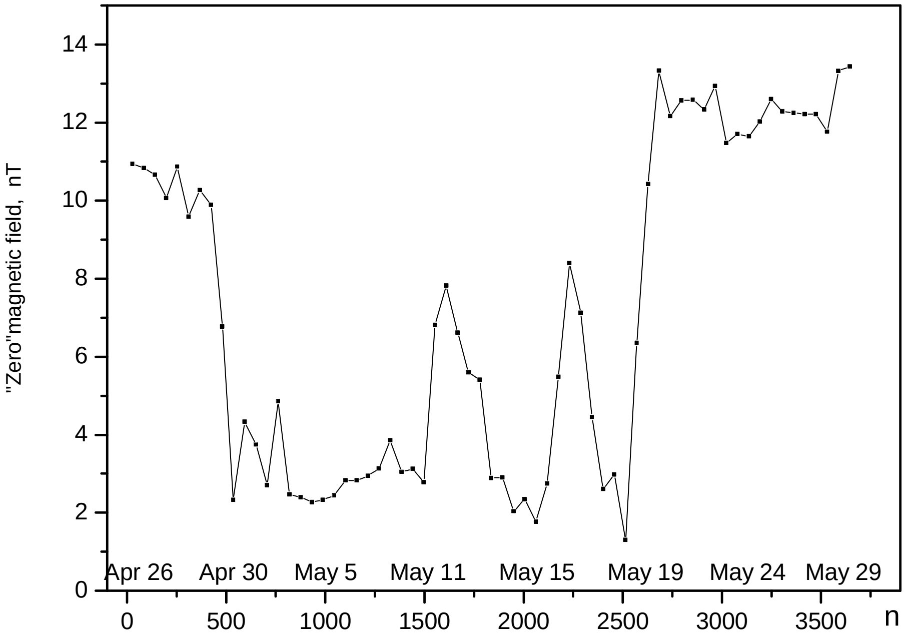


Counts recorded with the monitor detector during the measurements. n counts the number of each procedure including UCN filling, UCN keeping and empting.

# “Zero” magnetic field



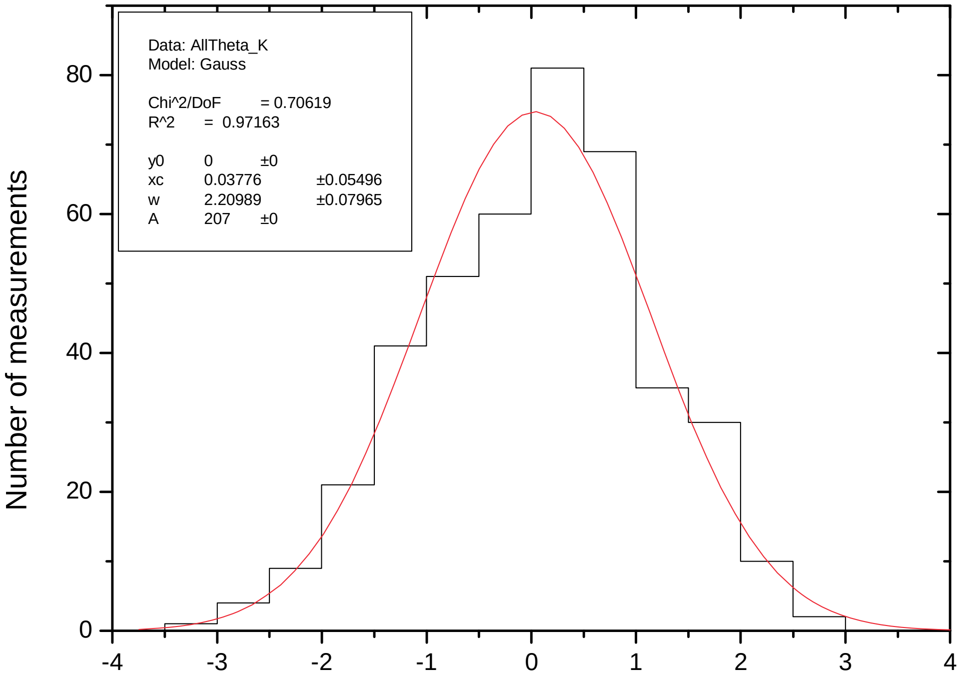
Instability of the “zero” magnetic field measure with 11 Cs-magnetometers



Averaged value

During all measurements at “zero” magnetic field its actual value did not exceed 20 nT, corresponding to a value of $\omega t_f$ less than 0.1, which is still acceptable to perform the experimental search for neutron – mirror neutron transitions.

# θ-method



Histogram of *θ*-measurements. The solid line shows a Gaussian fit. $\delta\theta_{st}$ is the statistical error of each measurement by means both detectors for the following the sequence ($t_1$, $t_2$, $t_2$, $t_1$) at “zero” magnetic field and at the “suppressing” magnetic field *H*. The width of distribution is 2σ = 2.21 i.e. it is widened with respect to the statistical one by the factor 1.1.

| $k$ | $\tau_{osc}^{-2}$ | $\Delta(\tau_{osc}^{-2})_{dis}$ | $\delta(\tau_{osc}^{-2})_{st}$ | $t_1$ [s] | $t_2$ [s] |
|---|---|---|---|---|---|
| 1 | 12.80 | 10.77 | 11.39 | 50 | 350 |
| 2 | -1.141 | 8.567 | 8.067 | 50 | 470 |
| 3 | 5.778 | 15.60 | 14.48 | 50 | 350 |
| 4 | 21.77 | 11.90 | 11.26 | 50 | 250 |
| 5 | -1.557 | 11.96 | 10.39 | 50 | 350 |
| 6 | -2.677 | 14.54 | 14.54 | 50 | 350 |
| 7 | 3.291 | 11.88 | 11.88 | 50 | 350 |
| 8 | 18.42 | 23.08 | 15.19 | 150 | 470 |
| 9 | 54.62 | 43.94 | 34.70 | 150 | 250 |
| 10 | -5.958 | 11.82 | 11.82 | 150 | 470 |

Result of *θ*-measurements: $\tau_{osc}^{-2}$ and its distributions are given in units $10^{-6}$ $s^{-2}$. *k* is the number of each run with about three days length, $\Delta(\tau_{osc}^{-2})_{dis}$ is the uncertainty of measurement deduced from the dispersion of the data of each run, $\delta(\tau_{osc}^{-2})_{st}$ is the counting statistical error of measurement. The total result was calculated with $\Delta(\tau_{osc}^{-2})_{dis}$.

Result of 10 runs of *θ*-measurement is $\tau_{\text{osc},\,\theta}^{-2} = \left(+7.05 \pm 5.66\right) \times 10^{-6}\ \text{s}^{-2}$

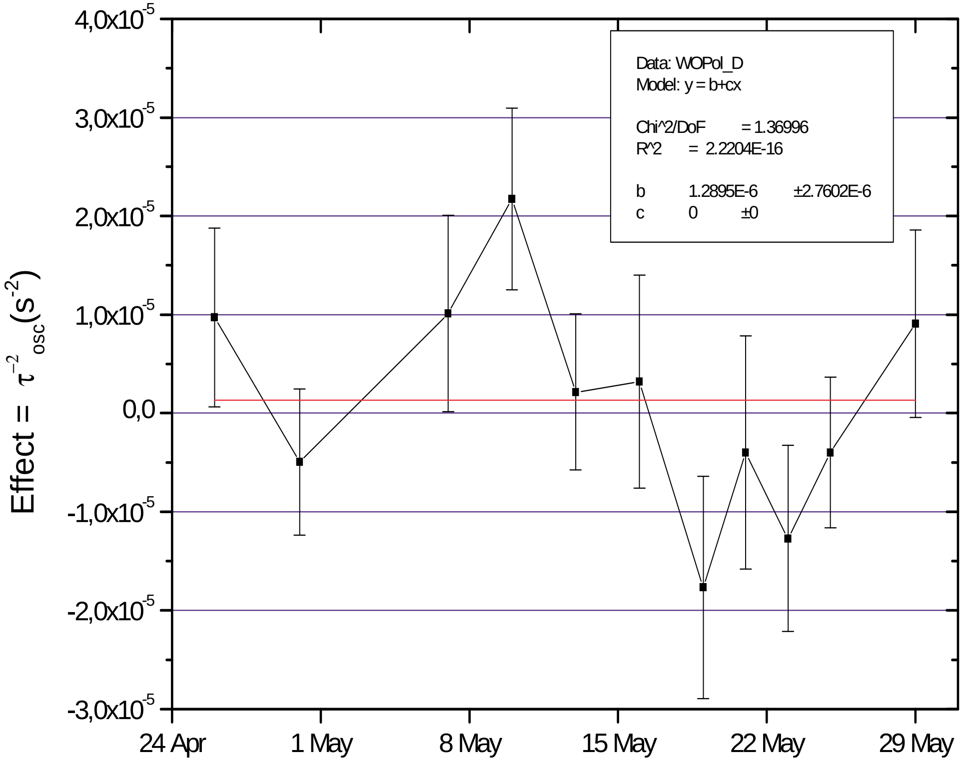
$$\tau_{\text{osc},\,\theta}\left(90\%\ \text{C.L.}\right) \geq 247\ \text{s}$$

# r-method

| $k$ | $\tau^{-2}_{\mathrm{osc}}$ | $\Delta(\tau^{-2}_{\mathrm{osc}})_{\mathrm{dis}}$ | $\delta(\tau^{-2}_{\mathrm{osc}})_{\mathrm{st}}$ | $t_1$ [s] | $t_2$ [s] |
|---|---|---|---|---|---|
| 1 | 9.711 | 9.082 | 8.272 | 50 | 350 |
| 2 | -4.95 | 7.396 | 6.734 | 50 | 470 |
| 3 | 10.12 | 9.969 | 8.560 | 50 | 350 |
| 4 | 21.73 | 9.204 | 8.189 | 50 | 250 |
| 5 | 2.147 | 7.908 | 7.583 | 50 | 350 |
| 6 | 3.202 | 10.81 | 10.62 | 50 | 350 |
| 7 | -17.66 | 11.27 | 8.651 | 50 | 350 |
| 8 | -4.006 | 11.82 | 8.386 | 150 | 470 |
| 9 | -12.70 | 9.438 | 8.476 | 150 | 250 |
| 10 | -5.256 | 10.89 | 8.622 | 150 | 470 |
| 11 | 9.090 | 9.514 | 8.234 | $t_{\mathrm{h}} = 350$s | |

Result of data treatment by *r*-method

$$\tau^{-2}_{\mathrm{osc},\, r} = (+1.29 \pm 2.76) \times 10^{-6} \ \mathrm{s}^{-2}$$



The result of measurement of the normalized *r*-value ($\tau_{\mathrm{osc}}^{-2}$). The measurement errors for different runs were calculated from dispersion of measurements inside each run.

$$\tau_{\mathrm{osc},\, r}\,(90\%\ \mathrm{C.L.}) \geq 414\ \mathrm{s}$$

# New experimental limit

As a result of measurements carried out in this work a new lower limit for the time of neutron mirror neutron oscillations was established:

$$\tau_{\mathrm{osc}}\left(90\%\ \mathrm{C.L.}\right) \geq 414\ \mathrm{s}$$

This limit is already not too far from the neutron lifetime but might still be too low to provide restriction of the mechanism of appearance of high-energy protons above the GZK-cutoff in cosmic radiation due to n-n' oscillations.

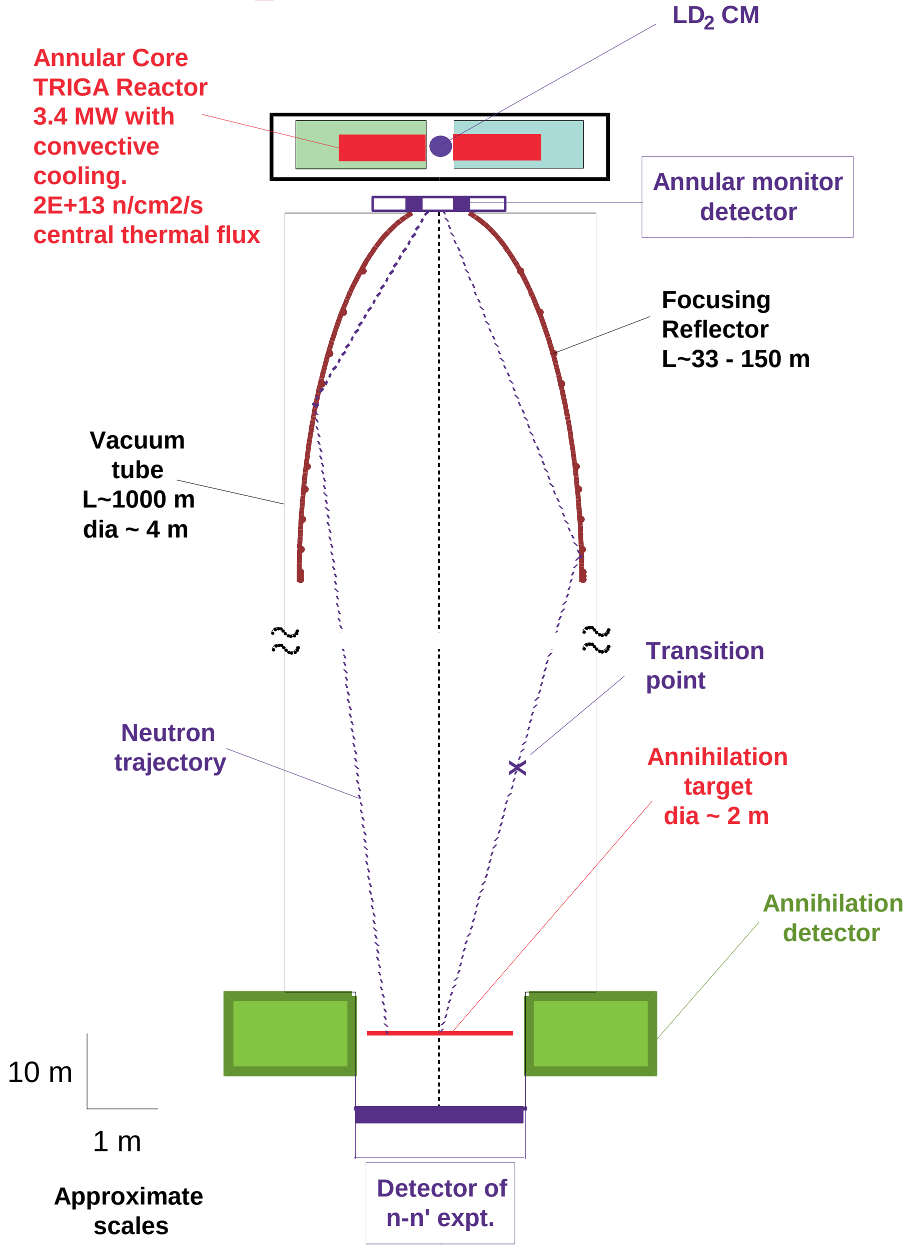
# Prospects of UCN n-n′ experiment

In this work it was shown that UCN storage is indeed a very effective experimental method to search for the n-n' transitions. An improvement by a factor 2 may be reached due to increasing the storage volume to a trap diameter of 1 m. Another factor 3 will be available when a UCN density of $10^3$ $cm^{-3}$ will be available from new powerful UCN sources.

# Prospects of beam n-n′ experiment

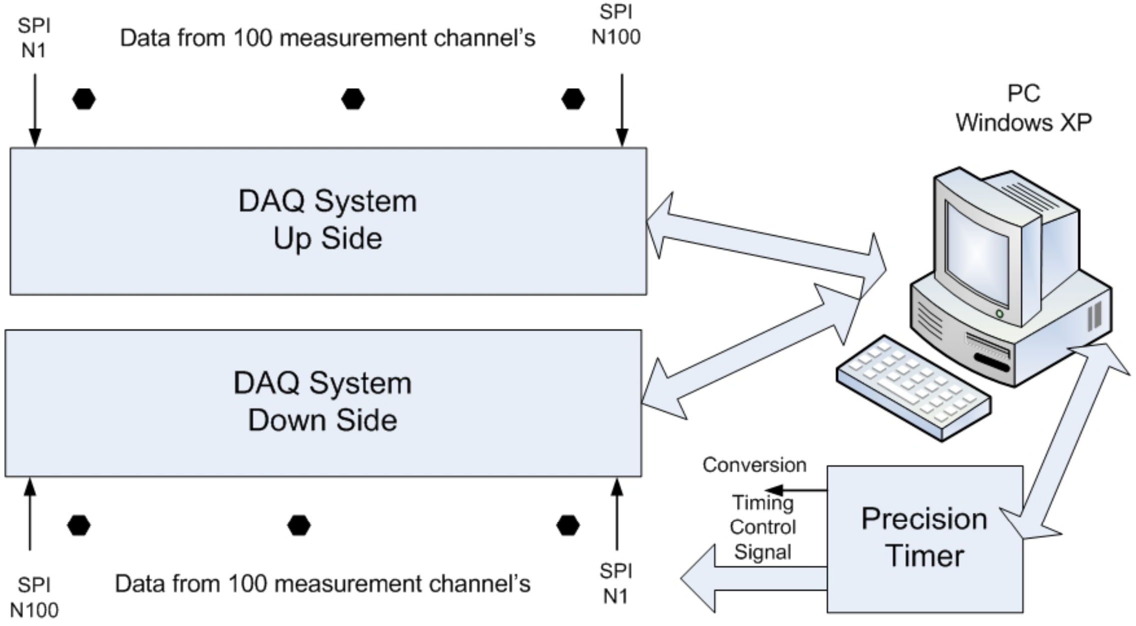
More substantial improvement in the search for n-n′ transitions might be realized in a new-proposed neutron-antineutron transition search for DUSEL laboratory. This project assumes the preparation of a vertical path (1 km) with time of flight of cold neutrons about 1 s and with a neutron beam intensity $10^{12}$ s-1. The same installation with small modification can be used for the n-n′ experiment.

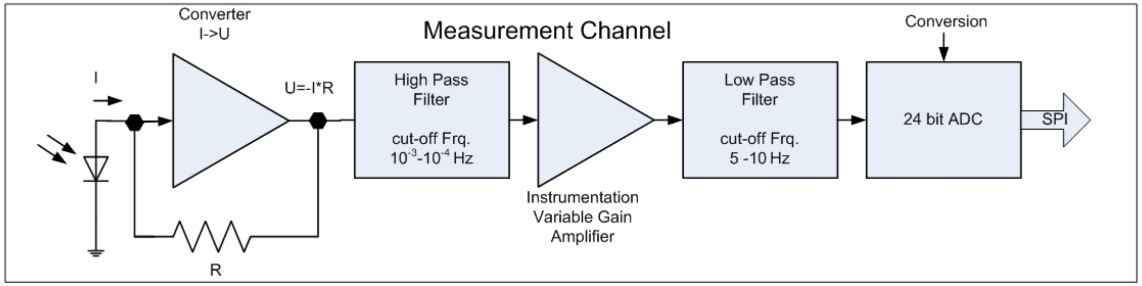
Possible sensitivity for $\tau_{osc}$ is $10^4$-$10^5$ s!



# The most important experimental task is

to suppress reactor fluctuations down to the level of statistical fluctuations.





Fortunately, positive experience in such type of tasks exist, for example, in experimental search for circular polarization in n+p→d+γ reaction at PNPI reactor. (This experiment has been carried out also with inter reactor target.)

# Instead of conclusion

The window to mirror world is not opened yet! The discussions about mirror particles and mirror matter proceed 50 years. However it is very probable that humanity tended to search for other dimensions much earlier. In any event it is written on the board of the monastery Chartreux: “La recherche d′une outré dimension”.