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$n \rightarrow n'$ Transformation and Neutron Transition Magnetic Moment

Based on the paper to be submitted to arXiv by
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General theoretical framework:

neutron can spontaneously transform to “mirror” (dark, sterile) neutron with degenerate mass (Berezhiani and Bento: 2006):

$$m_n = m_{n'}$$

Mirror neutron can be part of Mirror Matter that can be a fraction or a whole of Dark Matter (Berezhiani, Comelli, Villante: 2001, …)

$$\mathcal{L}_{tot} = \mathcal{L}_{SM} + \mathcal{L}_{SM'} + \mathcal{L}_{mix}$$

with gravity common for both sectors

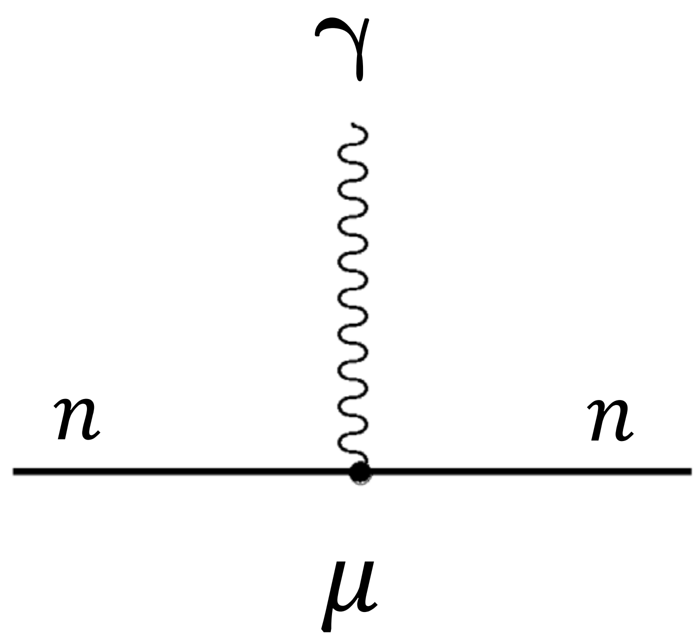
$\mathcal{L}_{mix} \rightarrow$ SM neutral singlets can transform between $SM \leftrightarrow SM'$, therefore $n \leftrightarrow n'$ violating Baryon number by 1 unit is possible.

Yesterday Z. Berezhiani discussed a variation of this model where $\Delta m = |m_n - m_{n'}| \sim 10^{-7}$eV. This conjecture will be easily tested (see talk of Leah Broussard). Here we will be back to the initial Mirror Matter assumption: $m_n = m_{n'}$

Will discuss:

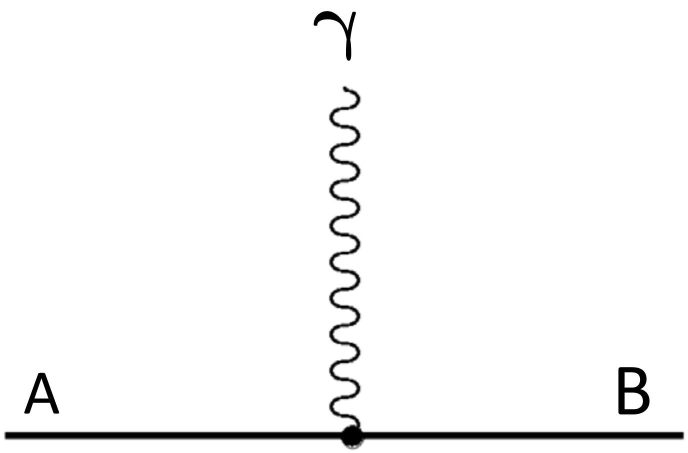
- what is neutron Transition Magnetic Moment (TMM)
- how it changes $n \to n'$ oscillations in magnetic field
- how TMM can influence n lifetime measurement
- how TMM effect can be measured

Neutron Magnetic Moment



μ makes n spin precession in magnetic field

Example of Transition Magnetic Moment



$\Sigma^0 \rightarrow \Lambda^0$

$$\mu_\Lambda = \mu_s \qquad \mu_s = -0.613\,\mu_N$$

$$\mu_{\Sigma^0} = (2\mu_u + 2\mu_d - \mu_s)/3$$

$$\mu_{\Sigma^0\Lambda} = (\mu_d - \mu_u)/\sqrt{3} \quad \rightarrow 1.63\,\mu_N$$

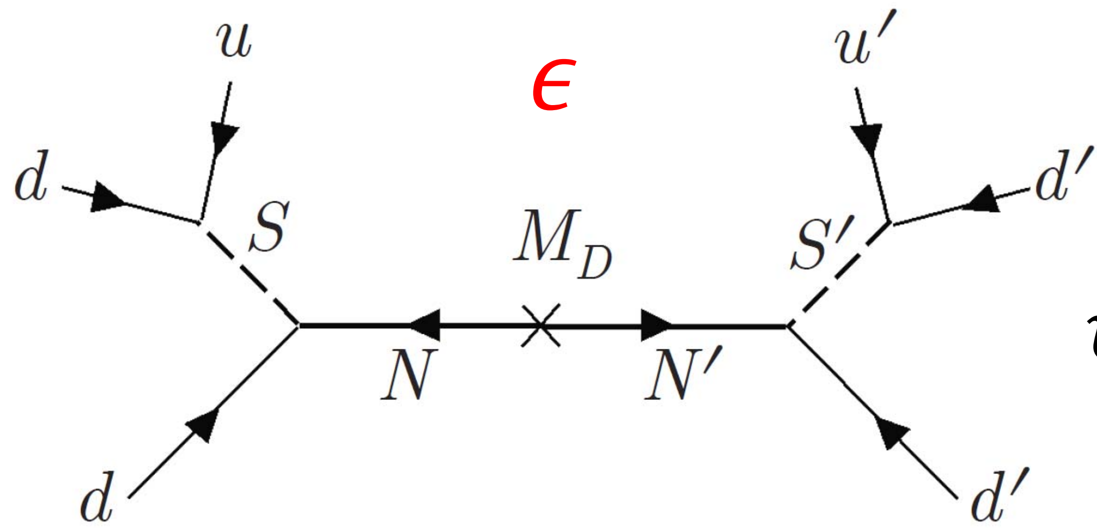
$$\mathrm{A} \neq \mathrm{B}$$

Interaction with magnetic photon $U = \mu_{\Sigma^0\Lambda}\boldsymbol{\sigma}\cdot\boldsymbol{B}$

leads to decay $\Sigma^0 \rightarrow \Lambda^0 + \gamma$

Possible mechanism of $n \to n'$

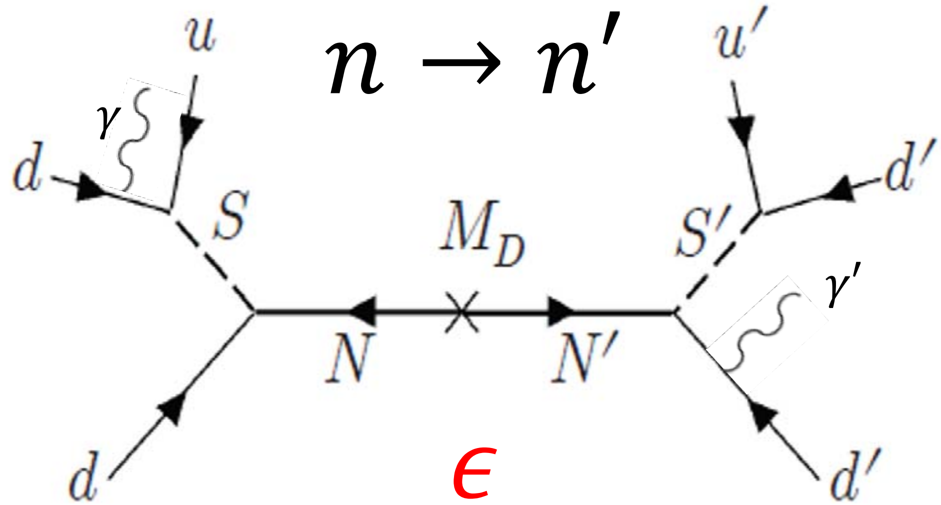
ϵ- mixing term in Hamiltonian $\begin{pmatrix} m & \epsilon \\ \epsilon & m \end{pmatrix}$



$$\psi = \begin{pmatrix} n \\ n' \end{pmatrix}$$

If this process exists, then photon γ and mirror photon γ' can interact with n and n'

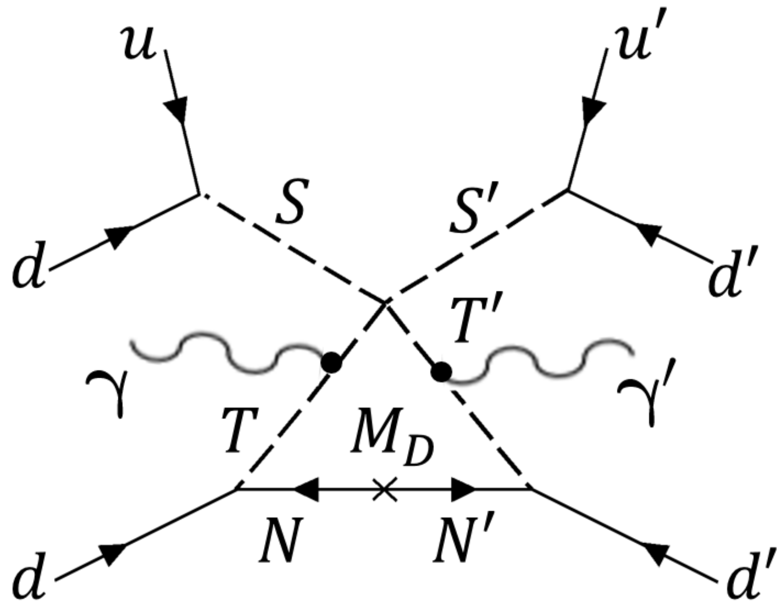
Neutron Transition Magnetic Moment TMM



Neutron and mirror neutron TMM $\kappa_n = \kappa_{n'} = \kappa$

is $\kappa = \kappa(\epsilon)$?

Origin of nTMM can be more complicated



$$\kappa_n = \kappa_{n'} \qquad \kappa \neq \kappa(\epsilon)$$

ϵ and κ can be two independent parameters

Magnitudes of ϵ and κ a priori not known,
but can be found or limited experimentally **!**

Notice, TMM for $n \to \bar{n}$ transformation is zero

Non-zero TMM for $n \to \bar{n}$ would violate rotational invariance (Berezhiani & Vainshtein 2018)

General form of $n \leftrightarrow n'$ Hamiltonian in the presence of $\boldsymbol{B}$ and $\boldsymbol{B}'$

$$\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_{int}$$

$$= \begin{pmatrix} E & \epsilon \\ \epsilon & E' \end{pmatrix} + \begin{pmatrix} \mu\boldsymbol{\sigma}\cdot\boldsymbol{B} & \kappa\boldsymbol{\sigma}\cdot[\boldsymbol{B}\pm\boldsymbol{B}'] \\ \kappa\boldsymbol{\sigma}\cdot[\boldsymbol{B}\pm\boldsymbol{B}'] & \mu'\boldsymbol{\sigma}\cdot\boldsymbol{B}' \end{pmatrix}$$

interaction of (n, n') system with $\boldsymbol{B}$ and $\boldsymbol{B}'$
$= 0$ if $\boldsymbol{B} = \boldsymbol{B}' = 0$

ϵ – mixing parameter of $n \leftrightarrow n'$: $\epsilon = 1/\tau$, where τ – oscillation time;

$\mu = \mu'$ usual neutron magnetic moment $\mu = -1.91\ \mu_N$

κ – transitional magnetic moment, sign is unknown, assume that $|\kappa| \ll |\mu|$

$\pm$ here is due to unknown possibly different relative parity of $\boldsymbol{B}$ and $\boldsymbol{B}'$

Assumptions:

if $n \rightarrow n'$ oscillations period is τ

Serebrov at al. (2009): $\tau > 448$ s at $B = 0$ assuming B'=0

It follows then that $\epsilon = \hbar/\tau$ is small $\epsilon \lesssim 10^{-18}\ eV$

In the $B = 0.5$G Earth magnetic field $\mu B \cong 3 \times 10^{-12}\ eV$

Let's assume that $\epsilon \ll \kappa B$ and we can neglect ϵ.
Also $\kappa B \ll \mu B$, so κ can be e.g. $\kappa \sim (10^{-3} - 10^{-5})\mu$

For simplification we also assume that $B' = 0$ and

consider neutrons with only one polarization

$$\mathcal{H} = \begin{pmatrix} E + \mu B & \epsilon + \kappa B \\ \epsilon + \kappa B & E' \end{pmatrix} = \begin{pmatrix} x & d \\ d & y \end{pmatrix}$$

This is real Hermitian matrix with eigenvalues determining the energy levels of two oscillating components:

$$\mathcal{E}_{1,2} = \frac{x+y}{2} \pm \sqrt{\left(\frac{x-y}{2}\right)^2 + d^2} \qquad d = \epsilon + \kappa B \cong \kappa B$$

$$\Omega = \frac{\mathcal{E}_1 - \mathcal{E}_2}{2} = \sqrt{\left(\frac{x-y}{2}\right)^2 + d^2}$$ oscillation frequency

$$\frac{x-y}{2} = \frac{E + \mu B - E'}{2} \cong \frac{\mu B}{2}$$ in constant mag. field B

$$\Omega = \sqrt{(\mu B/2)^2 + (\kappa B\,)^2} \cong \mu B/2 \qquad\qquad d \cong \kappa B$$

$$\boxed{P_{n\to n'}(t) = \frac{d^2}{\Omega^2} sin^2(\Omega t)}$$

Solution in a constant magnetic field

for initial neutron condition $\binom{1}{0}$

- For $B = 0$: $P_{n\to n'}(t) = sin^2(\epsilon t)$ oscillation with $\tau > 448$ s

- In UCN storage experiments $\langle \Delta t \rangle \sim 0.1$s between collisions with walls, and $\langle sin^2(\Omega t)\rangle$ =1/2 at B > few mG

$$P_{n\to n'}(t) = \frac{2\kappa^2}{\mu^2} = 2 \cdot (10^{-3} - 10^{-5})^2$$

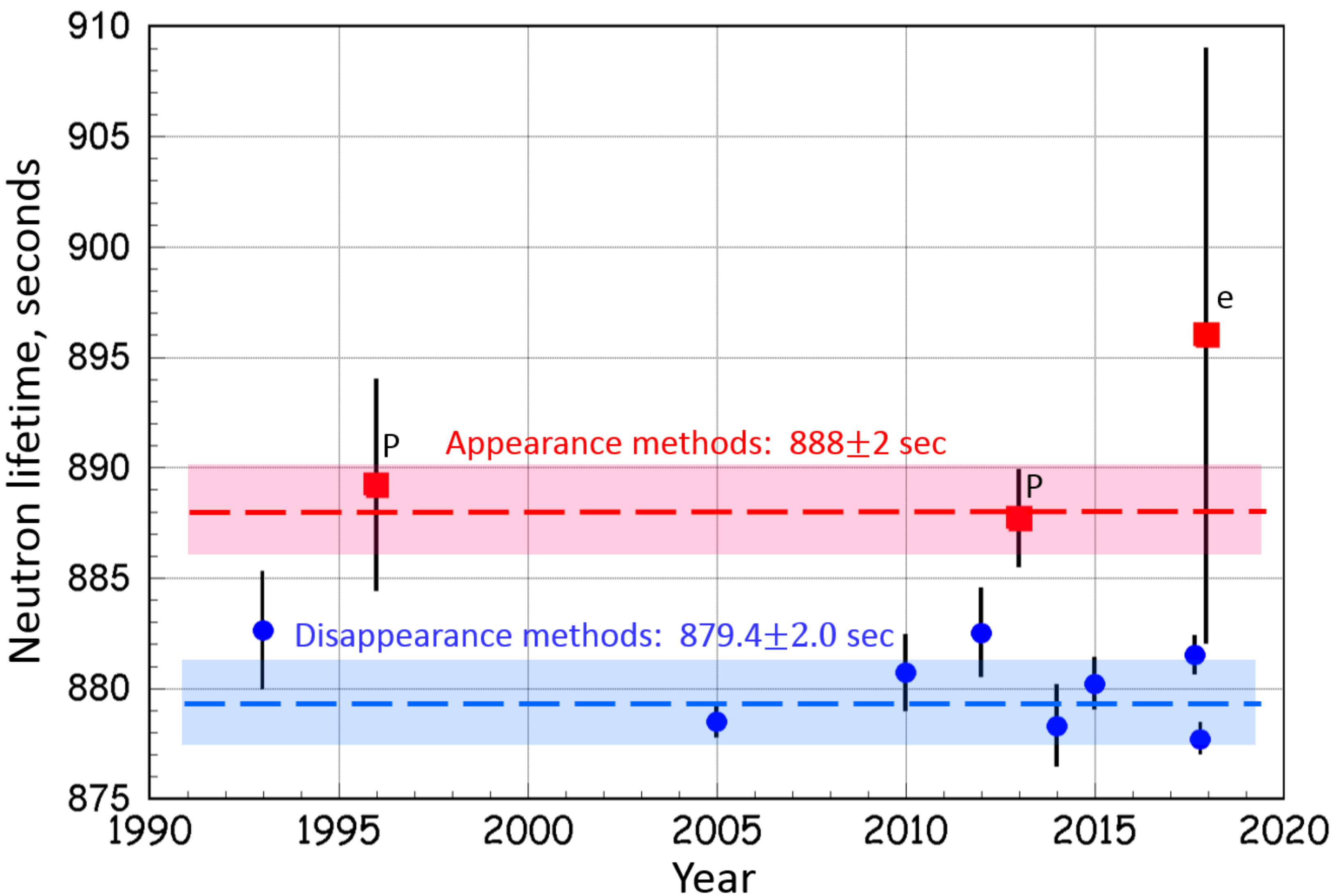
Interesting Result: In MM model with nTMM

for B > few mG

$$\boxed{P_{n\to n'}(t) = \frac{2\kappa^2}{\mu^2}}$$

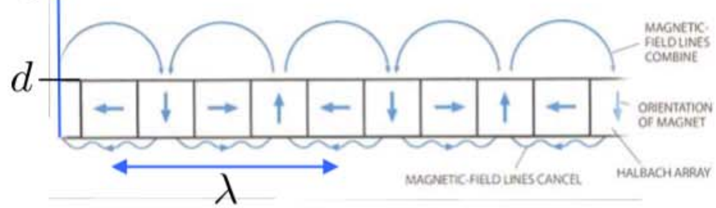
- Probability of $n \to n'$ is constant independent on B;
- $P_{n\to n'} \lesssim 10^{-6}$;
- Oscillation frequency Ω increases with B;
- Probability is the same for both n polarizations;
- If $B = 0$, but $B' >$ few mG – same effect;
- If $B' \neq 0$ resonance at $\boldsymbol{B} = \boldsymbol{B}'$ is possible - enhanced by $\kappa B' > \epsilon$

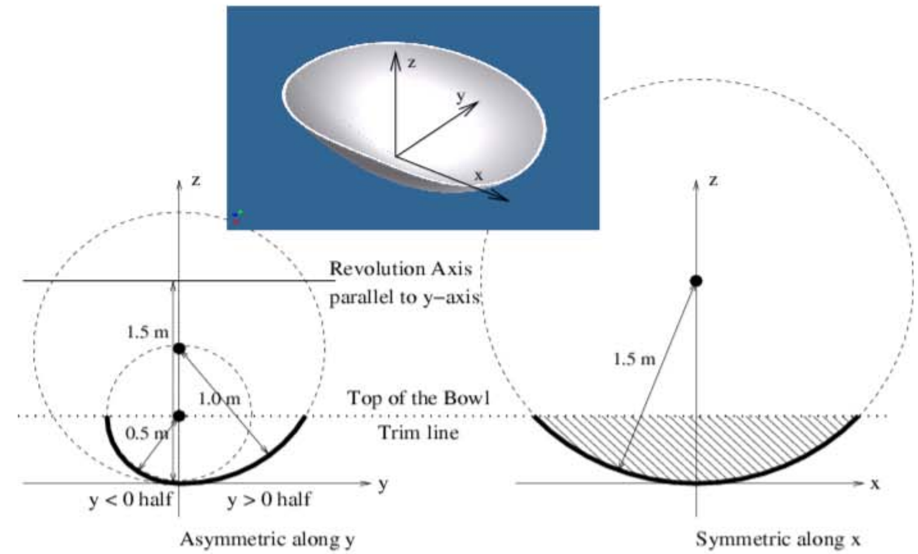
Can we relate TMM effect to n lifetime experiments?



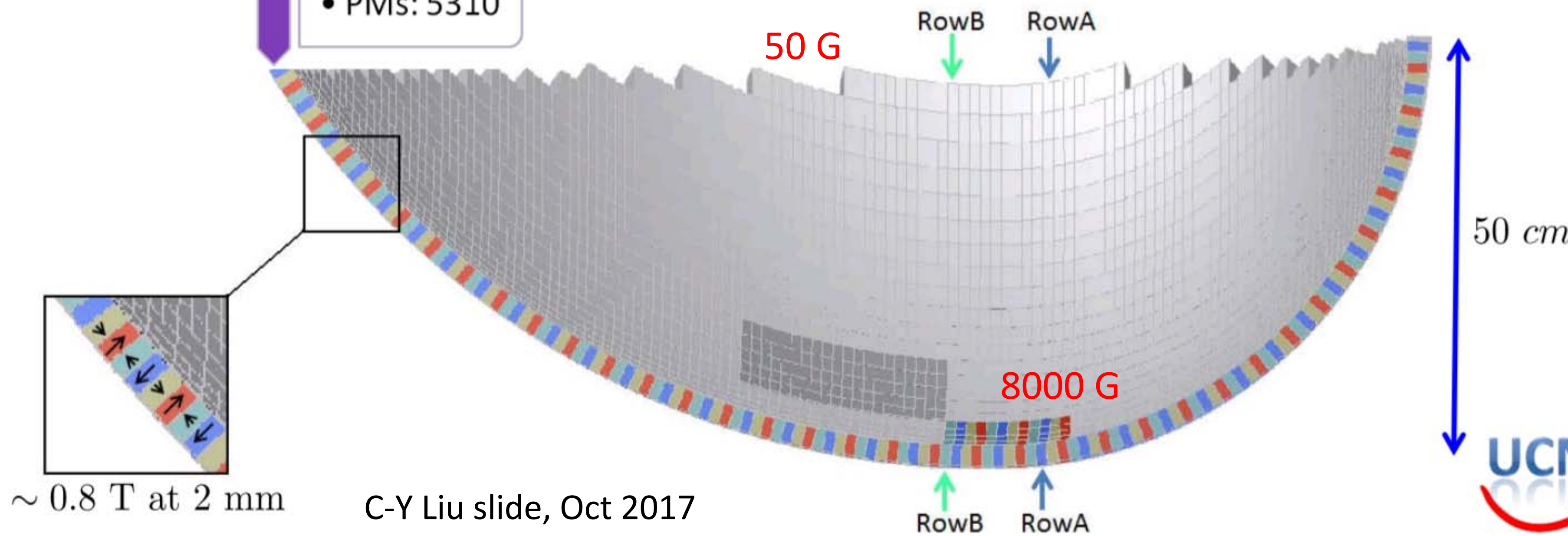
Halbach Magnetic Array in UCNτ experiment

$$|\mathbf{B}| \approx B_{\mathrm{rem}}(1 - e^{-2\pi d/\lambda})\, e^{-2\pi y/\lambda}$$





- Rows: 141
- PMs: 5310

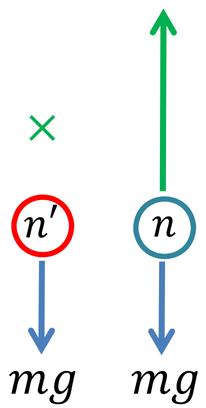


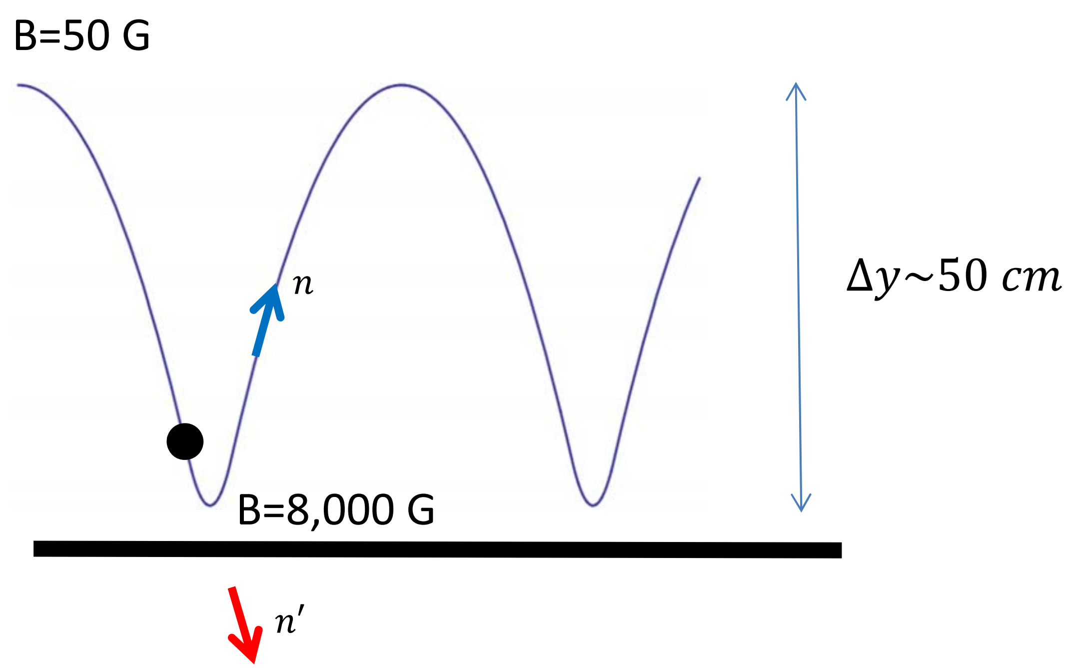
C-Y Liu slide, Oct 2017

Neutron bouncing in non-uniform magnetic field without touching walls

$\begin{pmatrix} n \\ n' \end{pmatrix}$ $\quad U = \mu \boldsymbol{\sigma} \cdot \boldsymbol{B}(y) = \mu B(y)$ polarized beam

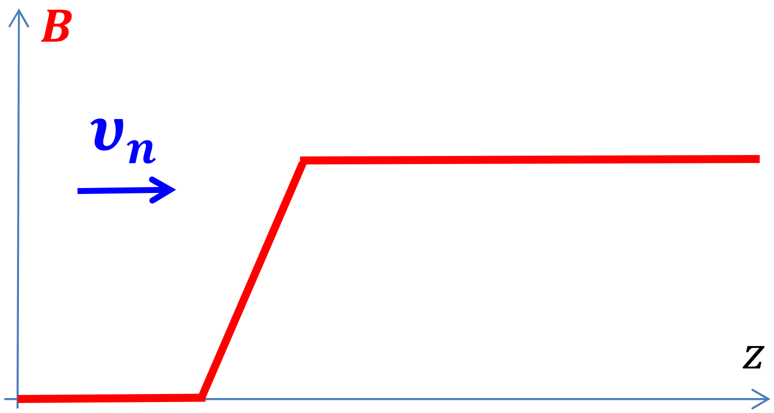
$$F = -\frac{\partial U}{\partial y}$$





Decoherence measures nn' system

What minimum B – gradient is needed to “measure” nn' system?



nn' in unusual QM system where magnetic field gradient is exerted only on one component of the system.

At some value of gradient $G = dB/dz$ decoherence will “measure” the nn' system. <u>We can assume that this will occur when the separation of energy levels due to gradient will exceed the energy width of nn' wave packet.</u>

What minimum B – gradient is needed to "measure" nn' system?

$\binom{1}{0}$ $\leftarrow \boldsymbol{G} = d\boldsymbol{B}/dz$ $\begin{pmatrix} n(t_{12}) \\ n'(t_{12}) \end{pmatrix}$

1 $\boldsymbol{v}_n \rightarrow$ 2

$$\Delta E_{wp} \sim 1/\Delta t_{12}$$

If for time Δt_{12}: $\mu \Delta B > \Delta E_{wp}$ ←Decoherence condition

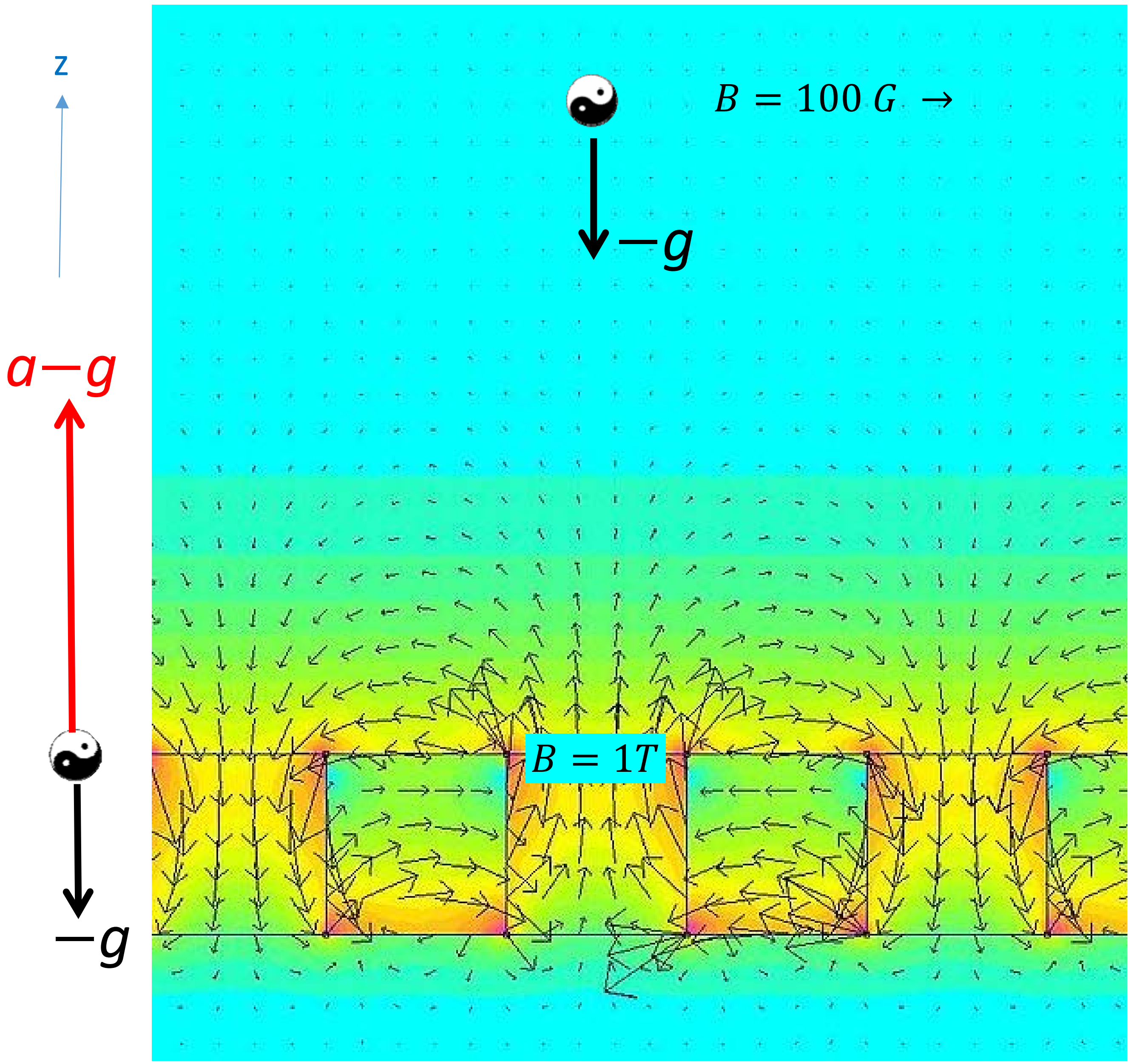
$$\mu G v \Delta t_{12} > \frac{\hbar}{\Delta t_{12}}$$

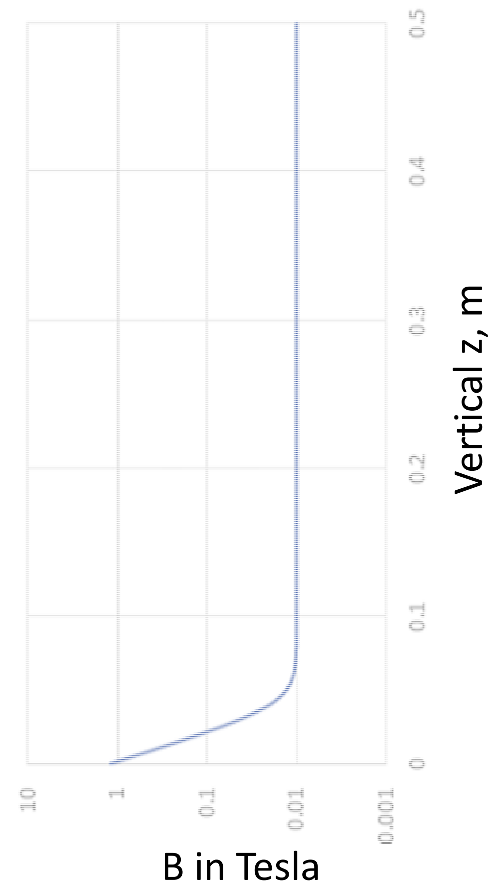
Minimal gradient:

$$\boxed{G > \frac{\hbar}{\mu v (\Delta t_{12})^2} = \frac{\hbar v}{\mu (\Delta z_{12})^2}}$$

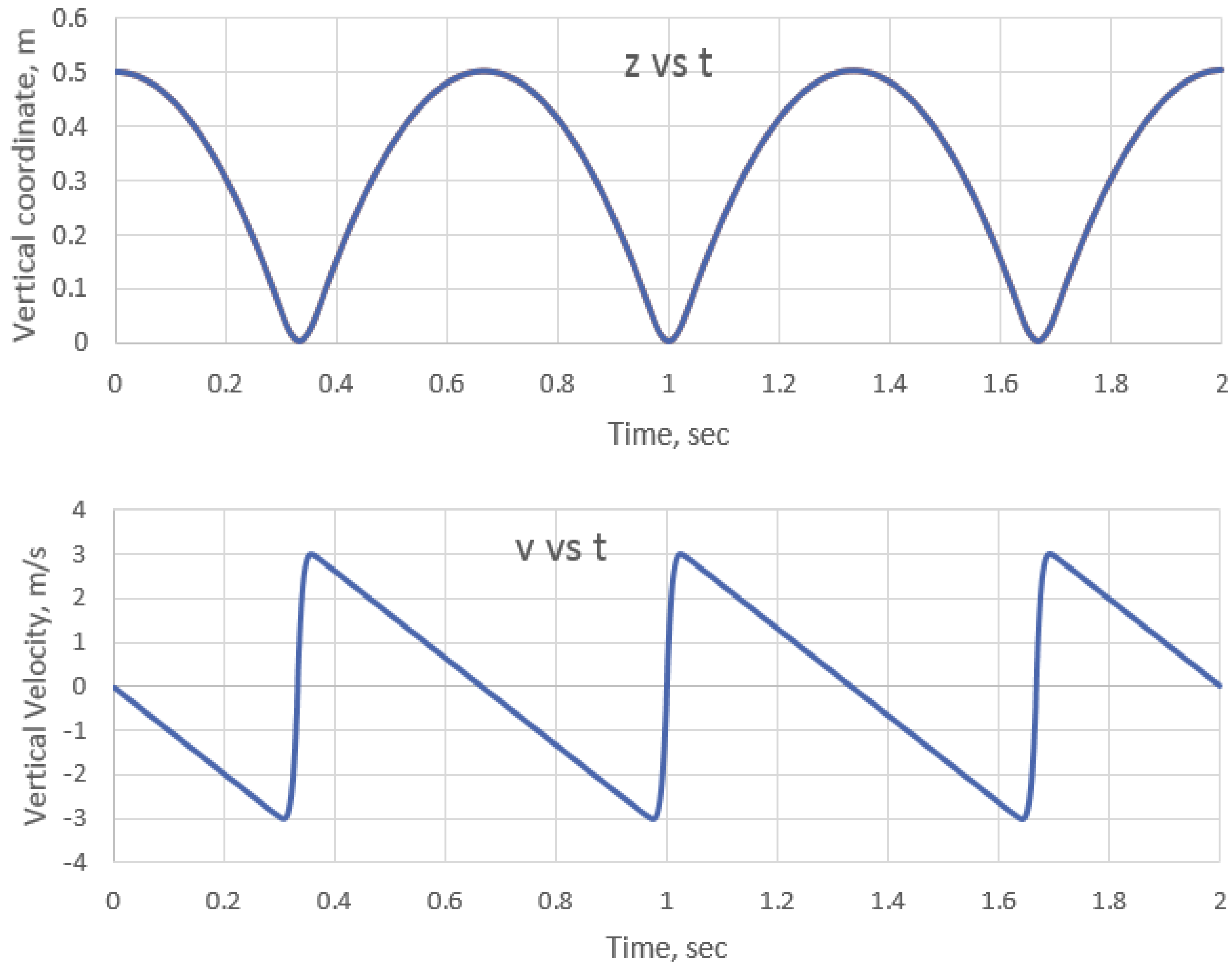
Neutron in Halbach Array in UCNτ at LANL

only one polarization of neutron is bouncing

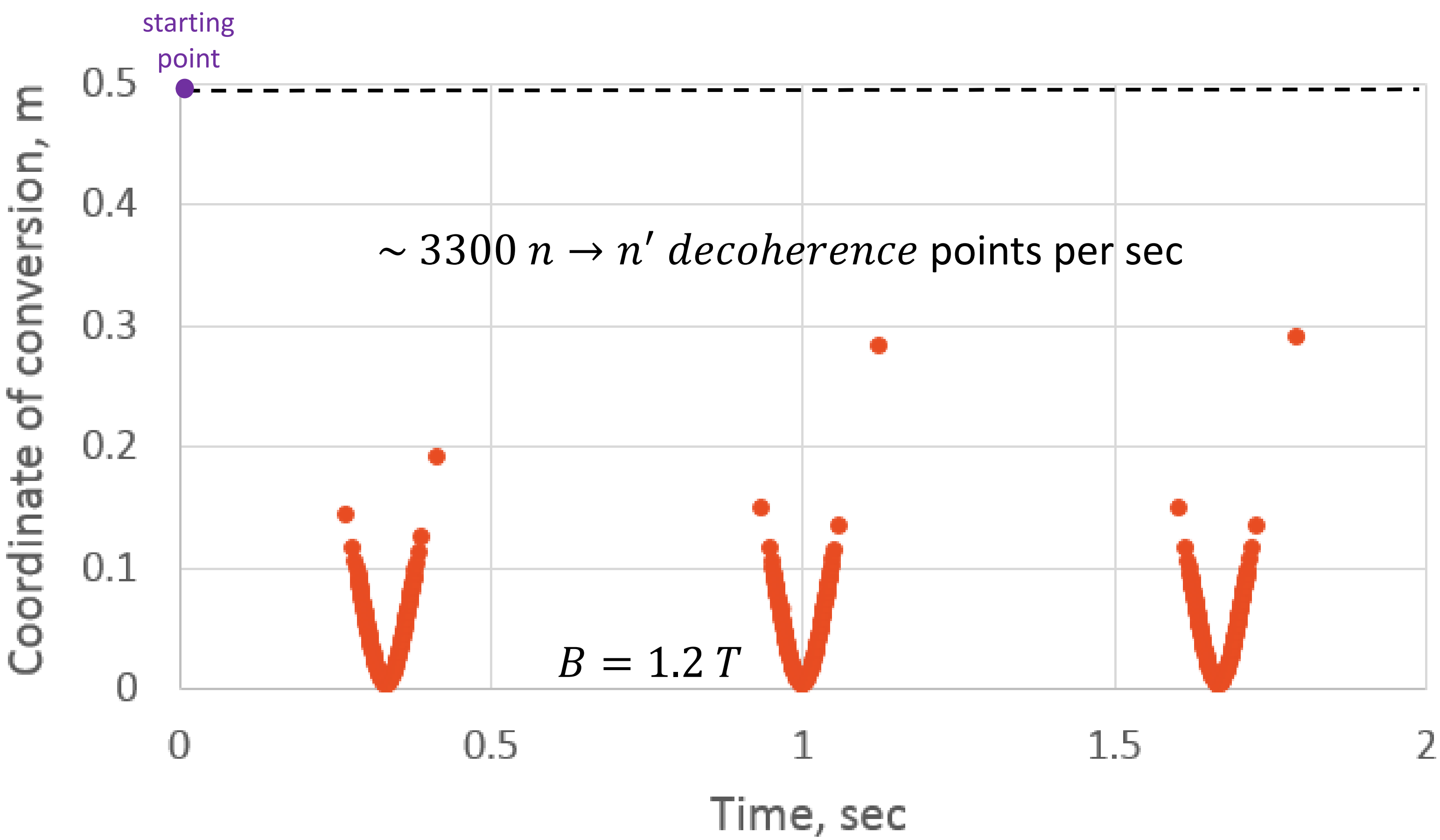




Simplified B description of UCNτ $(LANL)$ −neutron motion



Simplified B-description of UCNτ $(LANL)$



With $\boldsymbol{\kappa \cong 4 \times 10^{-5}\ \mu}$ this can explain the n lifetime difference between UCNτ and NIST experiments (even, if $B' \neq 0$).

$P_{n'}(t) \cong \frac{2\eta^2}{\mu^2} = 3.2 \times 10^{-9}$ (realistic UCNτ simulations can be useful)

By braking of coherence, the wave packet will collapse (n, n') system to pure interaction states $\longrightarrow$ either to remain as n or become n'

$$\frac{dB}{dx} > \frac{\hbar}{\mu v (\Delta t)^2} = \frac{\hbar v}{\mu (\Delta x)^2}$$

For UCN gravity trap: $\Delta t = 0.1\ s$ and $v = 3$ m/s
decoherence collapse requires $dB/dx > 3.7$ mG/m

In the magnetically un-shielded UCN gravity trap expts. such gradients can lead to in-volume loss of neutrons due to $n \to n'$.

Magnetic gradients inside the buildings:

In my Stockholm hotel room:

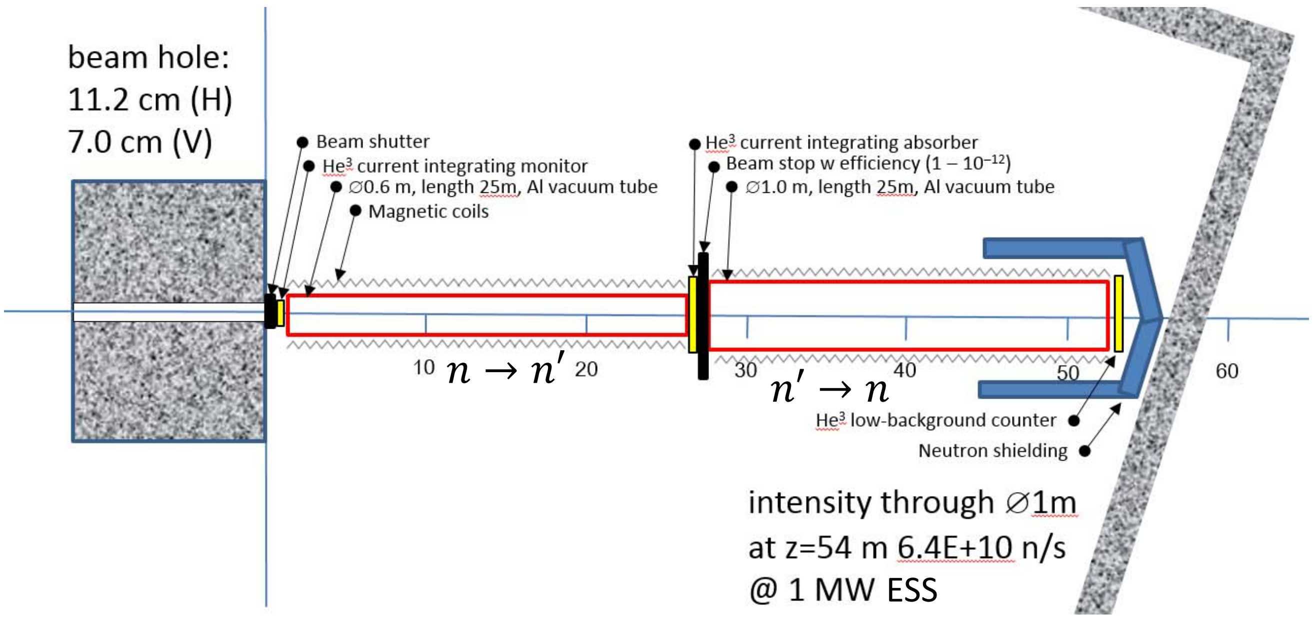
$$\frac{dB}{dx} = 33\ \frac{mG}{m}; \quad \frac{dB}{dy} \uparrow = 170\ \frac{mG}{m}; \quad \frac{dB}{dz} = 120\ \frac{mG}{m}$$

In this lecture hall:

$$\frac{dB}{dx} = 20\ \frac{mG}{m}; \quad \frac{dB}{dy} \uparrow = 140\ \frac{mG}{m}; \quad \frac{dB}{dz} = 50\ \frac{mG}{m}$$

How TMM effects can be measured?

First method: with high-intensity cold beam by the regeneration method using high magnetic field gradients:



E.g. high-field superconducting magnets with neutron absorber in the center, or special gradient magnets (discussed by Leah Broussard today). Due to TMM the probability of $n \to n'$ transformation doesn't depend on mag. field B.

Second TMM detection method:

All previous was in vacuum. Now, let's consider another possibility: neutron propagation in gas, e.g. in air

$$\mathcal{H} = \begin{pmatrix} V_F - \mu B & \epsilon + \kappa B \\ \epsilon + \kappa B & 0 \end{pmatrix} \to \begin{pmatrix} 0 & \epsilon + \kappa B \\ \epsilon + \kappa B & 0 \end{pmatrix}$$

$V_F(air) \sim 0.12$ neV; at $B^* = V_F/\mu \approx 20G \to \Omega = d$

With constant and uniform magnetic field for one of polarizations of neutron beam one can compensate effect of V_F

Elastic scattering at angle $\theta \neq 0$ and absorption will work decoherently. However, in air at STP these result in $\sim$5% intensity loss per m

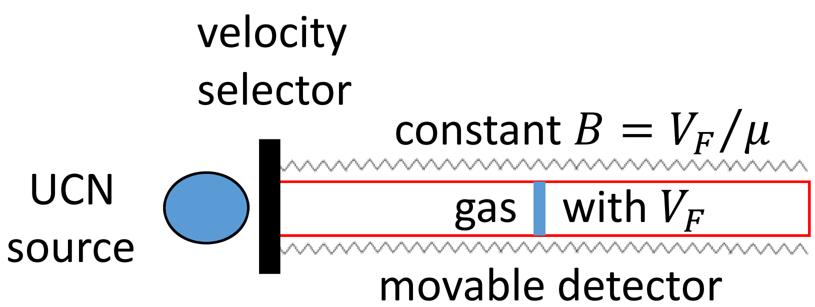
$$P_{n\to n'}(t) = \frac{d^2}{\Omega^2} sin^2(\Omega t) = sin^2[(\epsilon + \kappa B)t]$$

It is like "quasi-free" unsuppressed oscillations

$$P_{n\to n'}(t) = sin^2[(\epsilon + \kappa B)t] \approx sin^2[\kappa B t]$$

Probability grows quadratically with B (with gas compensation) and with time without decoherence collapse; it will have a maximum at

$$\kappa B t/\hbar = \pi/2$$



With $\kappa = 10^{-5}\mu$ at one polarization one can see large oscillation effect with UCN at short distances a la Serebrov's $\bar{\nu}$

Should be also easy measurable effect with cold beam e.g. at 1000 m/s. Beam-gas elastic scattering and absorption will result is some losses. Hopefully effect still can be easy visible. Gas/pressure can be optimized.

In MM model $n \to n'$ with nTMM + compensated gas

$$P_{n\to n'}(t) = sin^2[(\epsilon + \kappa B)t]$$

- $P_{n\to n'} \lesssim 10^{-6}$ in vacuum without magnetic field;
- Probability increases with B as $\sim B^2$;
- Probability is for only one gas-compensated polarization;
- More interesting effects if $B' \neq 0$ will be found

ESS ANNI beam at initial low intensity opens up interesting possibilities for $n \to n'$search with simple and non-expensive experiments
(more details in the talk of Josh Barrow today)