Amherst Center for Fundamental Interactions
Theoretical Innovations for Future Experiments Regarding Baryon Number Violation by Two Units
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# Searches for Neutron Oscillations to Sterile State $n \to n'$ and to Antineutron $n \to \bar{n}$


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On behalf of N-N′ Collaboration at ORNL and N-Nbar Collaboration at ESS

# Overview

- It is interesting to discuss new **easy-testable** physics effects; although they are hypothetical, but with high fundamental impact

- The $n \to n'$ is theoretical conjecture Z. Berezhiani et al (2006-2020) possibly related to the nature of Dark Matter (DM). QM oscillation $n \to n'$ is similar to $n \to \bar{n}$ with mixing $\epsilon_{n \to n'}$ different than $\epsilon_{n \to \bar{n}}$. It was noticed that $\tau_{nn'} = \hbar/\epsilon_{n \to n'}$ can be in the range of seconds.

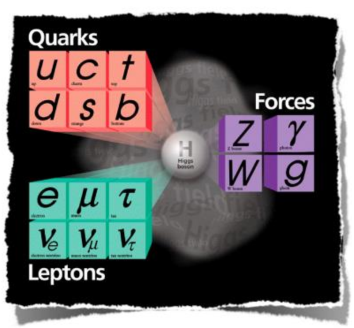
- New $n \to \bar{n}$ mechanism can arise as a second order process through $n \to n' \to \bar{n}$ Z. Berezhiani (2020), arXiv:2002.05609 [hep-ph]

- I will not discuss DM aspects of these ideas, but rather how to make the first step in the detection of these effects experimentally (if they exist) and the relevant plans made by ORNL-based NN′ and by ESS-based NNBAR Collaborations to study these processes.

Neutron transformation to sterile state $n \to n'$ would experimentally look like a disappearance process, where energy-momentum/ang. momentum disappear (you need some sterile carriers for these) and $\Delta\mathcal{B} = -1$ (however, that might be only the apparent BNV.)

The elegant Berezhiani's idea of $n'$ being the Mirror Matter neutron introduces the whole Mirror World with SM′ interactions similar to SM interactions, with known particle content, masses, gauge couplings, but with mirror matter (MM) not interacting with the ordinary matter (OM) except only by gravity (MM = DM) and possibly by some new BSM interactions mixing the neutral components of SM and SM′, e.g.

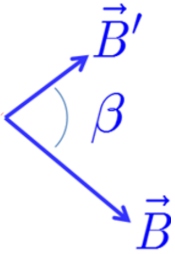
$\gamma \leftrightarrow \gamma'$, S. Glashow, (1985) Phys. Lett. B 167,35-36, B. Holdom, (1986) Phys. Lett. B 166,196
$\nu \leftrightarrow \nu'$, Z. Berezhiani and R. Mohapatra (1995), Phys. Rev. D 52, 6607
$n \leftrightarrow n'$, Z. Berezhiani and L. Bento (2006), Phys. Rev. Lett. 96, 081801




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

If the Global baryon number $\widetilde{\mathcal{B}} = (\mathcal{B} + \mathcal{B}')$ exists then $n \to n'$ can be a process without violation of $\widetilde{\mathcal{B}}$ and therefore it might not to be small like classical $n \to \bar{n}$

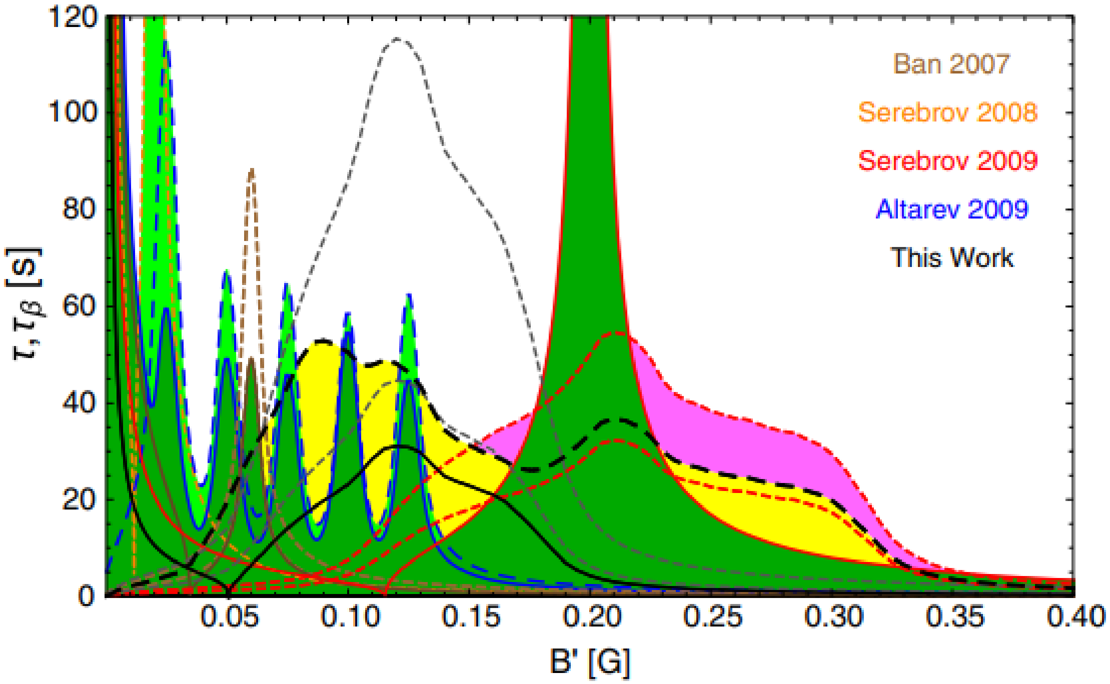
Accepting the concept of Mirror Matter with $\mathcal{L}_{mix}$ as a framework, one should also accept as part of MM phenomenology that the MM can be accumulated inside the planet and be present in the Earth experiments, as well as that the mirror magnetic field $B'$ should exist.

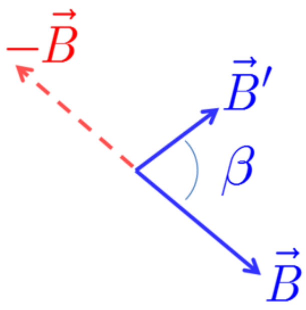



In Earth mag. field $\vec{B}$ : $U_n = \mu\vec{\sigma} \cdot \vec{B}$ ; $n'$ doesn't interact with $\vec{B}$.
In mirror mag. field $\vec{B}'$ : $U_{n'} = \mu'\vec{\sigma} \cdot \vec{B}'$ ; $n$ doesn't interact with $\vec{B}'$.
$\mu = \mu'$ as feature of MM model
For enhanced oscillations $U_n = U_{n'}$

European searches for $n \to n'$ disappearance for UCN neutron traps are summarized in the paper: Z. Berezhiani et al (2018), Eur. Phys. J. C78, no.9, 717

$$\tau_{nn'} = \frac{\hbar}{\epsilon}$$



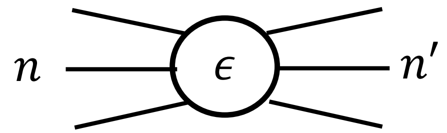

Exclusions $\tau$ for UCN $n \to n'$ search experiments.
For $B' < 0.25\ G$ $\tau_{nn'}$> 17 s are allowed
For $B' > 0.5\ G$ $\tau_{nn'}$> 1 s are allowed

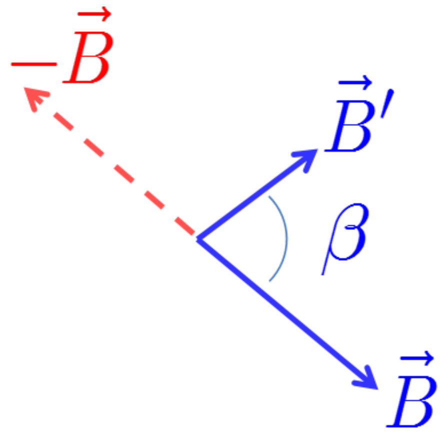
← Magenta color corresponds to not excluded 5.2 $\sigma$ anomaly obtained in the analysis paper: Z. Berezhiani and F. Nesti (2012), Eur. Phys. J. C72, 1974

# Neutron disappearance in the presence of $B'$

Z. Berezhiani (2009), Eur. Phys. J. C64, 421

$$\hat{H}_{nn'} = \begin{pmatrix} \mu\boldsymbol{\sigma}\boldsymbol{B} & \epsilon \\ \epsilon & \mu\boldsymbol{\sigma}\boldsymbol{B}' \end{pmatrix}$$




$$P_B(t) = p_B(t) + d_B(t) \cdot \cos\beta$$

$$p(t) = \frac{\sin^2\left[(\omega - \omega')t\right]}{2\tau^2(\omega - \omega')^2} + \frac{\sin^2\left[(\omega + \omega')t\right]}{2\tau^2(\omega + \omega')^2}$$

$$d(t) = \frac{\sin^2\left[(\omega - \omega')t\right]}{2\tau^2(\omega - \omega')^2} - \frac{\sin^2\left[(\omega + \omega')t\right]}{2\tau^2(\omega + \omega')^2}$$

where $\omega = \frac{1}{2}\left|\mu B\right|$ and $\omega' = \frac{1}{2}\left|\mu B'\right|$ ; $\tau$ - oscillation time

$$A_B^{\det}(t) = \frac{N_{-B}(t) - N_B(t)}{N_{-B}(t) + N_B(t)} = N_{collis} d_B(t) \cdot \cos\beta \leftarrow \quad \text{assymetry}$$

# More general look at the neutron oscillations

## 4-component neutron mixing in measurements

Z. Berezhiani (2020)
arXiv: 2002.05609

$$i\hbar\frac{\partial}{\partial t}\begin{pmatrix} n \\ \bar{n} \\ n' \\ \bar{n}' \end{pmatrix} = \begin{pmatrix} U_n + \mu\boldsymbol{\sigma B} & \epsilon & \alpha & \delta \\ \epsilon & U_{\bar{n}} - \mu\boldsymbol{\sigma B} & \delta & \alpha \\ \alpha & \delta & U_{n'} + \mu\boldsymbol{\sigma B}' & \epsilon' \\ \delta & \alpha & \epsilon' & U_{\bar{n}'} - \mu\boldsymbol{\sigma B}' \end{pmatrix}\begin{pmatrix} n \\ \bar{n} \\ n' \\ \bar{n}' \end{pmatrix}; \quad \psi_n(t=0) = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} \qquad (1)$$

For simplifies Hamiltonian in vacuum $U_i = 0$, no fields $B = B' = 0$

Classical $P_{n\to\bar{n}} = (\epsilon t/\hbar)^2 = (t/\tau_{n\bar{n}})^2$

$$P_{n\to n'} = (\alpha t/\hbar)^2 = (t/\tau_{nn'})^2$$

$$P_{n\to\bar{n}'} = (\delta t/\hbar)^2 = (t/\tau_{n\bar{n}'})^2$$

from ILL $n\bar{n}$ expteriment

$$\tau_{nn'}\tau_{n\bar{n}'} \gtrsim 100\ s^2(0.5G/B')^2$$

Suppressed if $\vec{\boldsymbol{B}} \neq \vec{\boldsymbol{B}}'$

Assuming mag. fields are present; no matter effects $U_i = 0$.

$$P_{n\to\bar{n}} = P(\epsilon,\alpha,\delta) = (t/\tau_{n\bar{n}})^2 + (t^2/\tau_{nn'}\tau_{n\bar{n}'})^2$$

Requires $\boldsymbol{B} = \boldsymbol{0}$

$\tau_{n\bar{n}} \gtrsim 3.5 \times 10^{+8}$ s

Considering all existing UCN limits and anomalies the $\tau_{nn'}\tau_{n\bar{n}'}$ can be in the range 100 -1000 $s^2$

$$P_{n\to\bar{n}} = (t/\tau_{n\bar{n}})^2 + (t^2/\tau_{nn'}\tau_{n\bar{n}'})^2$$

Let's take $t = 0.1$ s like in ILL expt. and calculate probabilities per sec in vacuum:

$$P_{n\to\bar{n}} \cong 10^{-19} + 10^{-8}\ s^{-1}$$

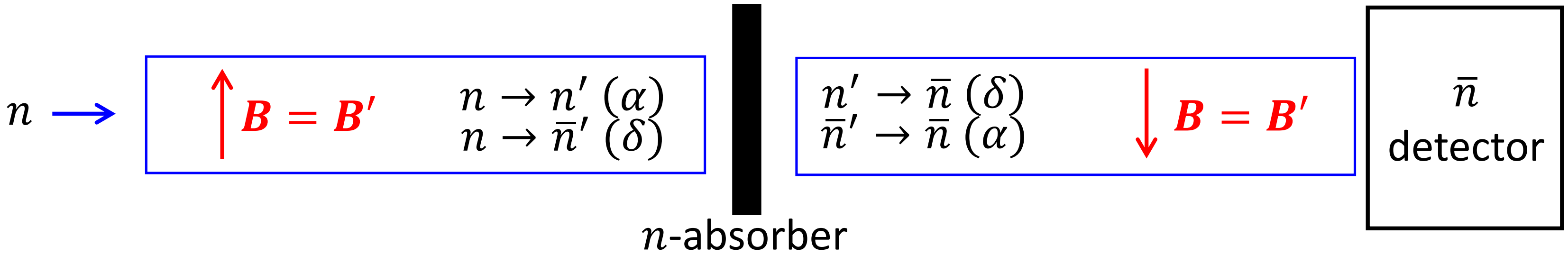
← This mechanism in vacuum might be dominant with the current $\tau_{nn'}\tau_{n\bar{n}'}$ limit

In above mentioned paper the S.E. (1) with $8 \times 8$ Hamiltonian was solved with the magnetic fields and for two polarizations. Assuming quasi-free conditions when $\mu(B - B')t < 1$, $\text{i.e.}\,(B - B') \lesssim 1\ m$G and taking into account angle $\beta$ between $\boldsymbol{B}$ and $\boldsymbol{B}'$ it was obtained:

$$P_{n\to\bar{n}} \lesssim \frac{sin^2\beta}{4}\left(\frac{t}{0.1\ s}\right)^4\left(\frac{B'}{0.5G}\right)^4 \times 10^{-8}$$

Imagine vertical neutron path with 1 km depth with UCN source on the top with average initial velocity of neutrons $\sim 10\,m/s$. Flight time $t\sim$10 s. Probability of $n \to \bar{n}$ transformation can be closer to ¼ with appropriate mag. field setting.

Experimentally this search can be addressed via regeneration method.




By systematic variation of magnitude of the magnetic field $B$, the resonance $B = B'$ can be found (with unknown angle $\beta$).

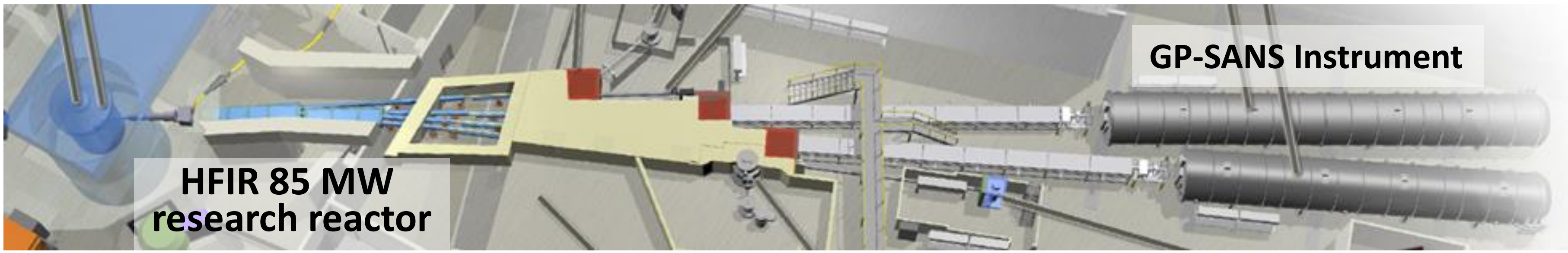
$$P_{n\bar{n}}(t) = 2P_{nn'}P_{n\bar{n}'} = \frac{sin^2\beta}{2}\left(\frac{t}{0.1\ s}\right)^4\left(\frac{B'}{0.5G}\right)^4 \times 10^{-8}$$

Also, angle $\beta$ can be found by 3D rotation of mag. field $\boldsymbol{B}$

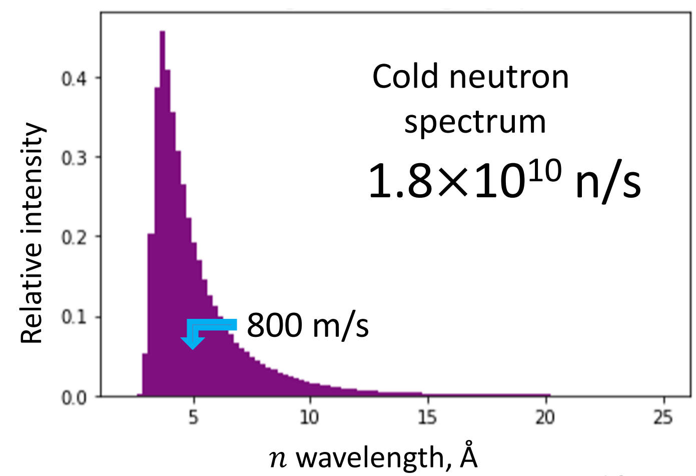
This is an idea behind $NN'$ (ORNL) research program (2020-2023) that will grow later into NNBAR (ESS) research program (2023-2027) with extended sensitivity. Before the classical $n \to \bar{n}$ in zero magnetic field will be tested after 2030, possibly much larger effect can be sought in magnetic field in the years 2022-2027 at HFIR and then at ESS.

- Advantages of cold beam vs UCN is much higher neutron flux, the absence of wall collisions, and the possibility of regeneration observations with low background.
- All neutrons sources at ORNL are neutron scattering user's facilities. Max beamtime available for dedicated experiment is ~ 10-20 days per year.

ORNL HFIR Cold-Neutron Beam Facility (more in the talk of M. Demarteau)

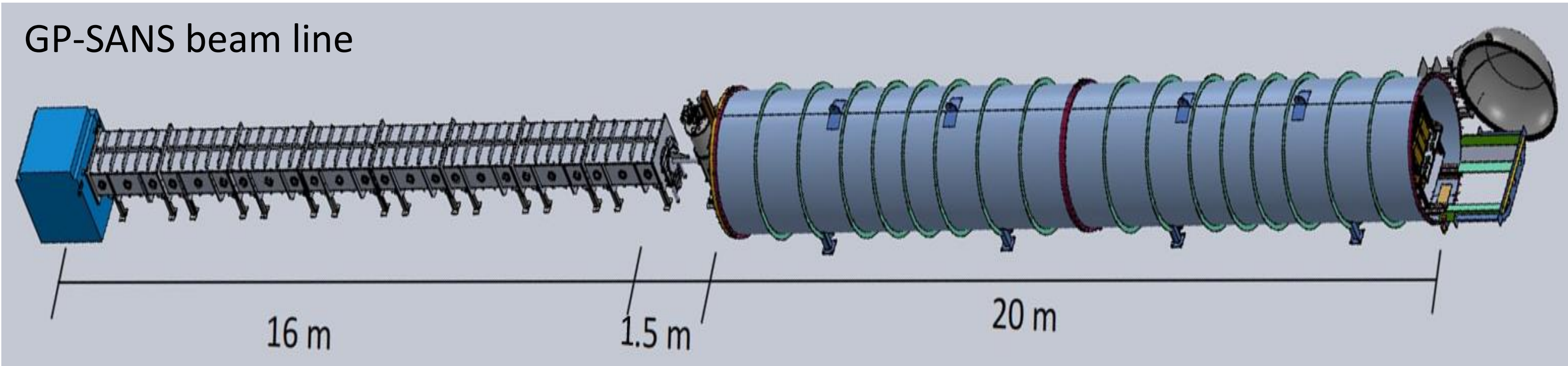


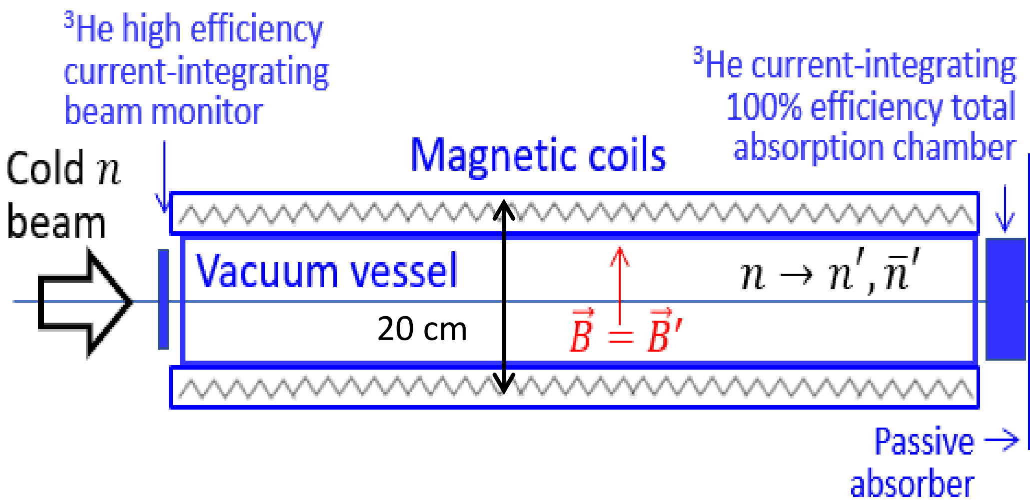

- We have to design removable experiment with minimal impact on the $n$-scattering program.
- Infrastructure support. ORNL neutron experts support.
- We are developing a program of several small experiment at HFIR GP-SANS facility for 2020-2023 with extension to ESS > 2023

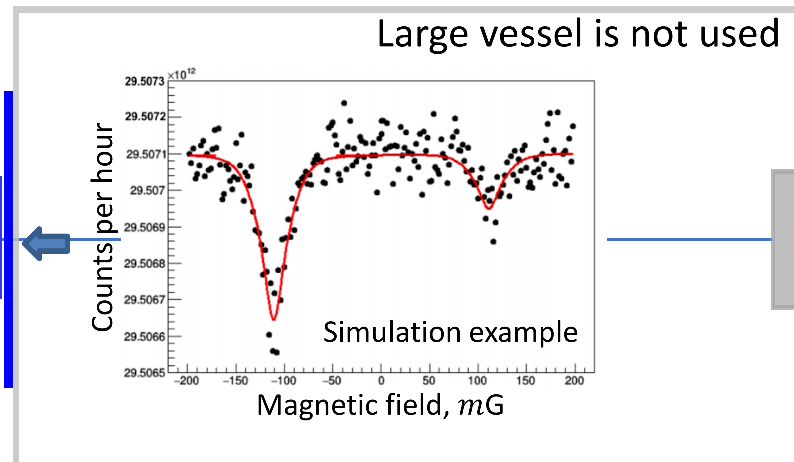


# ① HFIR disappearance experiment in 16-m guide vessel





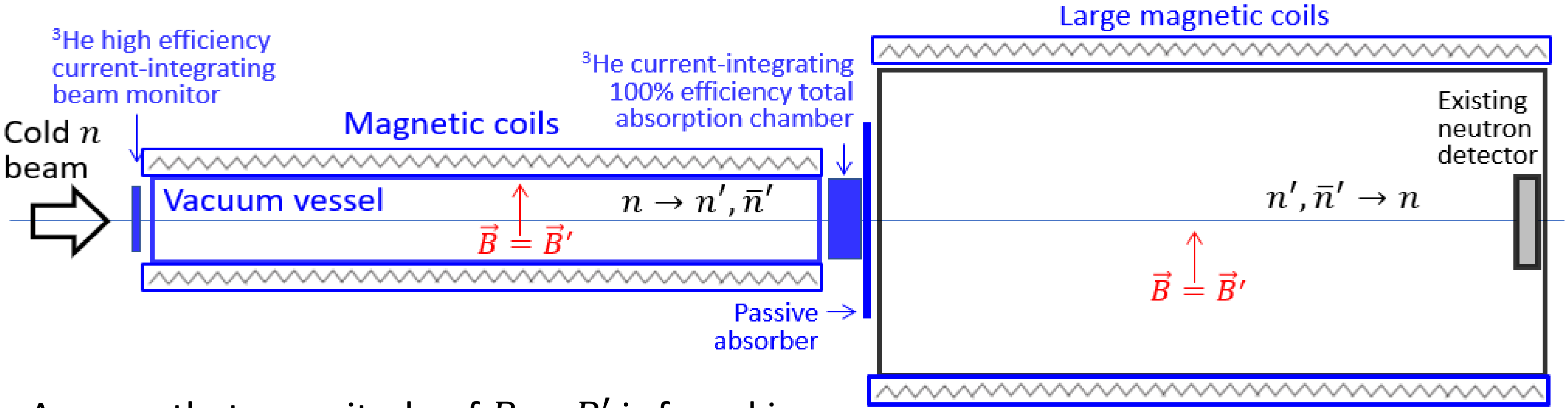




Detailed scan in the range of mag. field $\pm 1.0$ Gauss with resolution few $m$G.

For 10 days beam time sensitivity reach $\tau_{nn'} > 24\ s$ @95% CL. (Detecting fraction~$10^{-7}$)

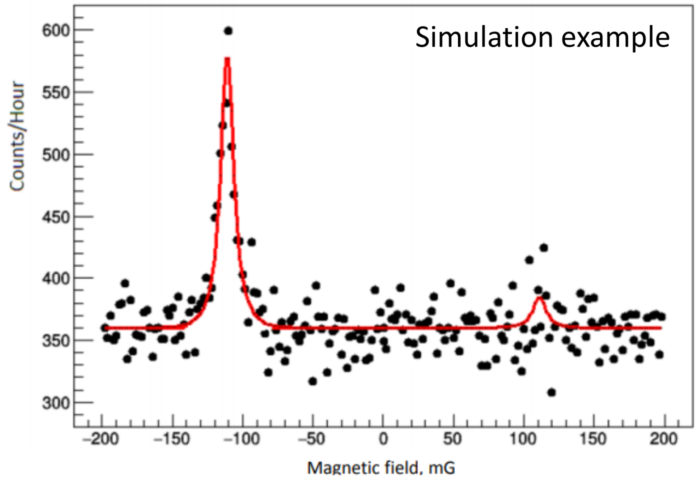
L. Broussard et al, arXiv:1912.08264 [physics.ins-det]

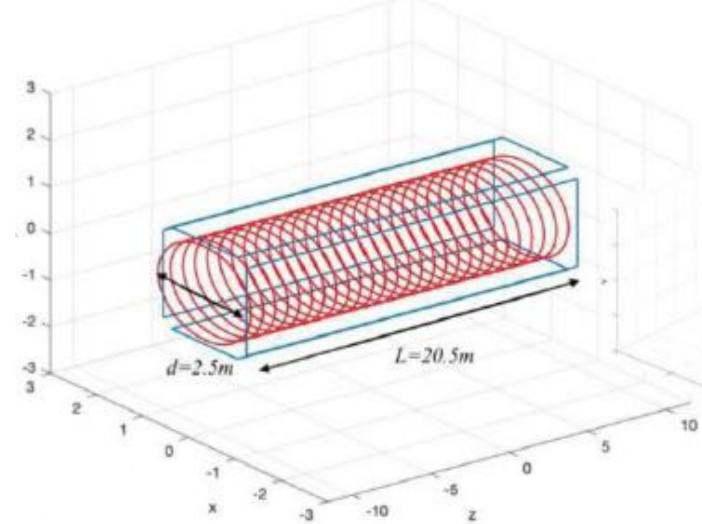
# ② GP-SANS regeneration experiment $n \to n' \to n$



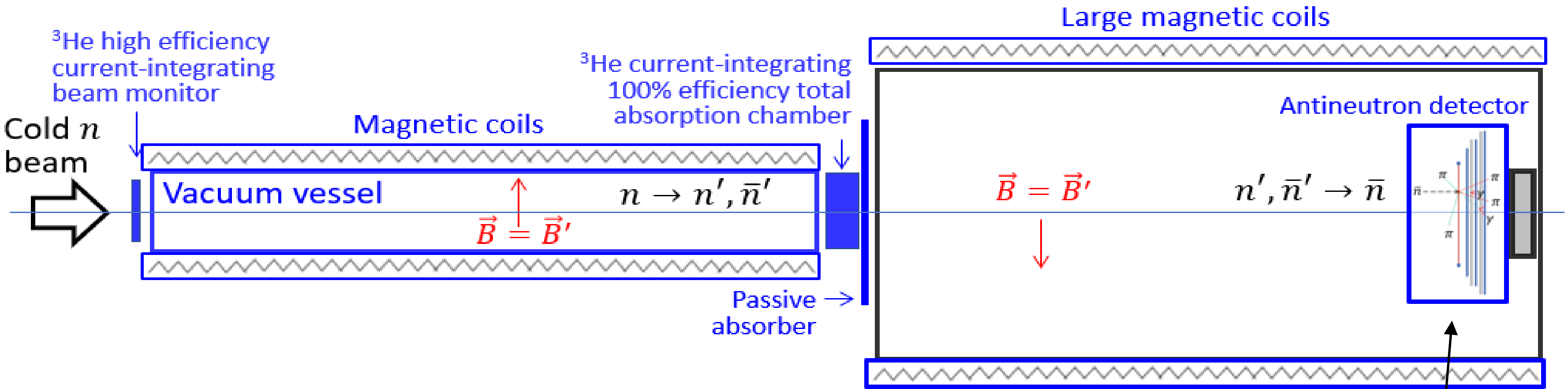

Assume that magnitude of $B = B'$ is found in the previous experiment. For 10 days run limit can be set $\tau_{nn'} > 20.4\ s$ with 95% CL

3D magnetic field $\pm 1\ G$ around 2.5-m dia vacuum vessel



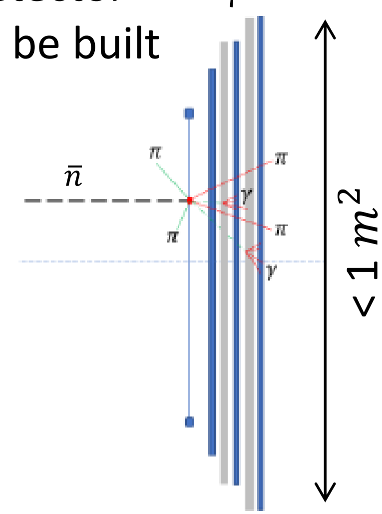



# ③ GP-SANS transformation experiment $n \to n' \to \bar{n}$



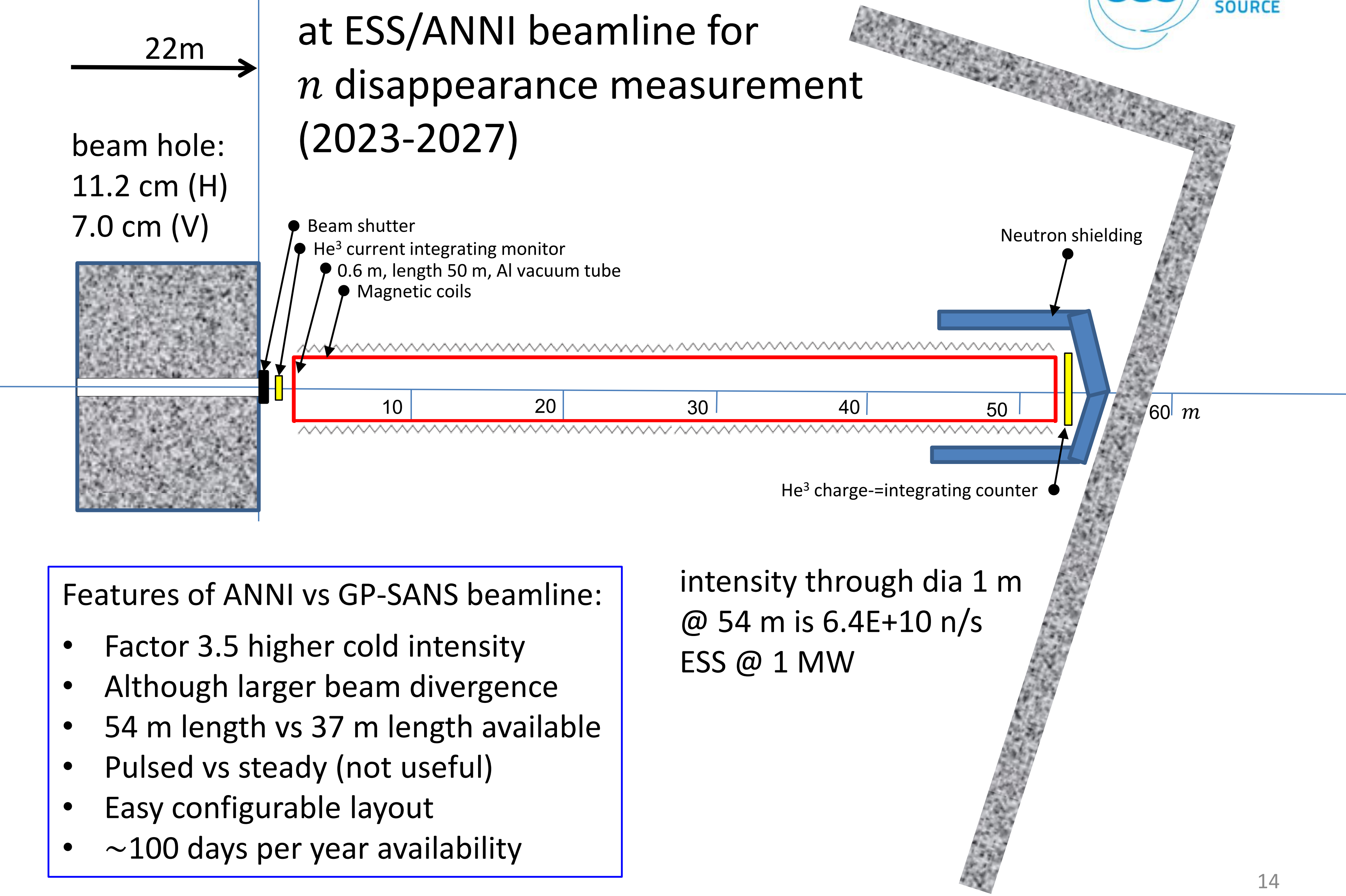

For 10-20 days run at $B = B'$
assuming low background 1/h, the limit
can be set at $\tau_{nn'}\tau_{n\bar{n}'} \gtrsim 1{,}000\ s^2$

Removable $\bar{n}$ detector to be built




These 3 experiments can be repeated with higher sensitivity at ESS ANNI beamline in the HIBEAM experiment of NNBAR Collaboration

# HIBEAM Experiment Layout at ESS/ANNI beamline for $n$ disappearance measurement (2023-2027)




Features of ANNI vs GP-SANS beamline:

- Factor 3.5 higher cold intensity
- Although larger beam divergence
- 54 m length vs 37 m length available
- Pulsed vs steady (not useful)
- Easy configurable layout
- ~100 days per year availability

intensity through dia 1 m @ 54 m is 6.4E+10 n/s ESS @ 1 MW

Comparison of sensitivities of experiments for GP-SANS/HFIR and ANNI/ESS

| Experiment / limit → | GP-SANS/HFIR | HIBEM/ESS |
|---|---|---|
| ① Disappearance $n \to n'$ | $\tau_{nn'} > 24$ s | $\tau_{nn'} > 200$ s |
| ② Regeneration $n \to n' \to n$ | $\tau_{nn'} > 20.4$ s | $\tau_{nn'} > 80$ s |
| ③ Transformation $n \to n' \to \bar{n}$ | $\tau_{nn'}\tau_{n\bar{n}'} \gtrsim 1{,}100\ s^2$ | $\tau_{nn'}\tau_{n\bar{n}'} \gtrsim 3{,}300\ s^2$ |

If positive effects will be detected within the range of sensitivity that would mean:

- Demonstration of $n \leftrightarrow n'$ system oscillation (not a decay in disappearance)
- Resonance at $B = B'$ is demonstration of mirror photon field (another component of MM=DM)
- Finding direction of $B'$ is demonstration of vector character of mirror photons.
- Demonstration of a new $n \to MM \to \bar{n}$ mechanism

In the case of null-effect observation:

- Essential part of motivated region of $\alpha$ and $\delta$–mixings will be excluded

# Testing variations of $n \leftrightarrow n'$ hypothesis: $n$TMM-1

Transformation $n \leftrightarrow n'$ can be also due to neutron Transition Magnetic Moment (nTMM) introducing non-diagonal operator

$$\eta\, F_{\mu\nu}\, \overline{n}\sigma^{\mu\nu} n' + \eta'\, F'_{\mu\nu}\, \overline{n}\sigma^{\mu\nu} n' \;+\; \text{h.c.}$$

Z. Berezhiani, R. Biondi, Y.K., and L. Varriano, *MDPI Physics* 1 (2019) 2, 271

$$\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_{int} = \begin{pmatrix} E & \epsilon \\ \epsilon & E \end{pmatrix} + \begin{pmatrix} V + \mu\boldsymbol{\sigma}\cdot\boldsymbol{B} & \eta\boldsymbol{\sigma}\cdot[\boldsymbol{B} \pm \boldsymbol{B}'] \\ \eta\boldsymbol{\sigma}\cdot[\boldsymbol{B} \pm \boldsymbol{B}'] & V' + \mu'\boldsymbol{\sigma}\cdot\boldsymbol{B}' \end{pmatrix}$$

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

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

$\eta$ – transition magnetic moment, sign is unknown, assumed that $|\eta| \ll |\mu|$

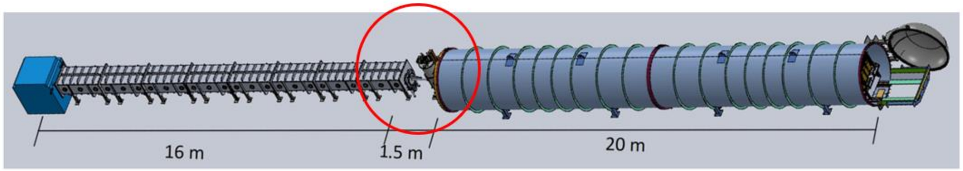
$\pm$ is due to unknown possibly different relative parity of $\boldsymbol{B}$ and $\boldsymbol{B}'$

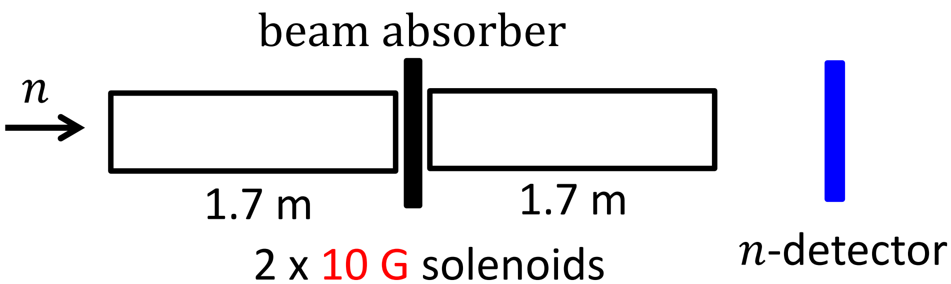
Presence of magnetic fields in the non-diagonal terms will enhance oscillation probability and in the diagonal terms will suppress it. Thus, it can be constant dependent on the magnitude of $n$TMM $\eta$.

$$P_{nn'}(t) \cong \frac{2\eta^2}{\mu^2}$$

with $n$TMM in the range $\eta/\mu \lesssim 10^{-4} - 10^{-5}$ from existing limits

# ④ Regeneration with $n$TMM at GP-SANS




Let' assume $B' = 0$, $V' = 0$, and one polarization of neutron beam

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

$V_F = 0.06\ eV$ for air @NTP can be exactly compensated by 10 G mag.field

$$P_{nn'} = \exp(-L/20m) \times sin^2\left[(\epsilon + \eta B)\, t/\hbar\right]$$

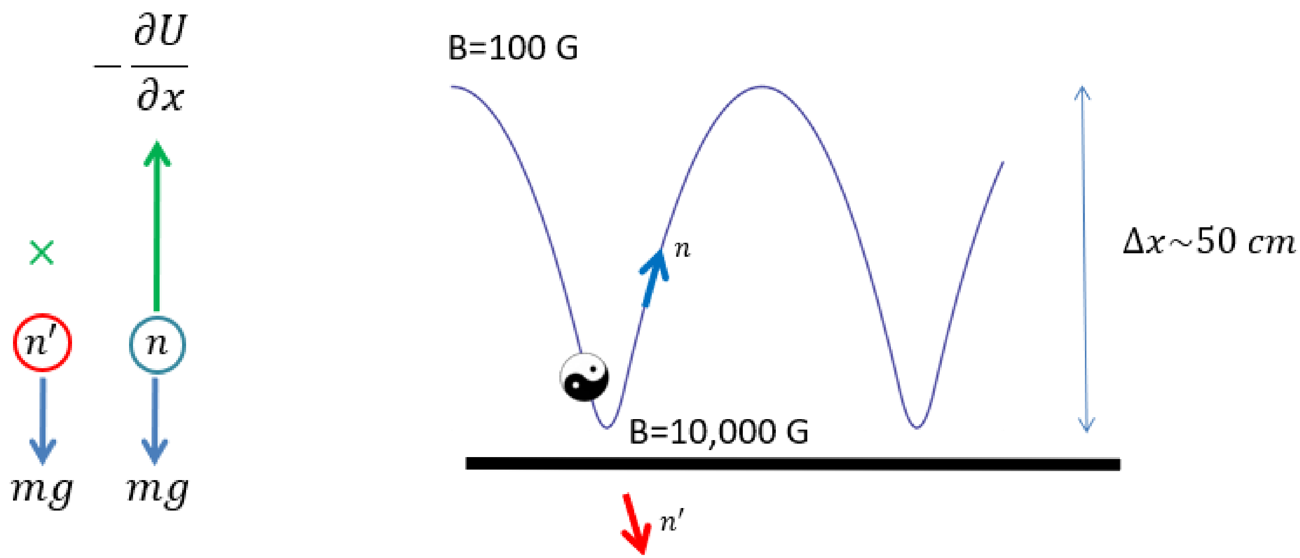
$n$TMM can be detected down to $\eta \leq 10^{-5}\mu$

Mismatch of $V_F - \mu B = 0$ might allow measurement of small $B' \neq 0$ and/or $V' \neq 0$

# Testing variations of $n \leftrightarrow n'$ hypothesis: $n$TMM -2

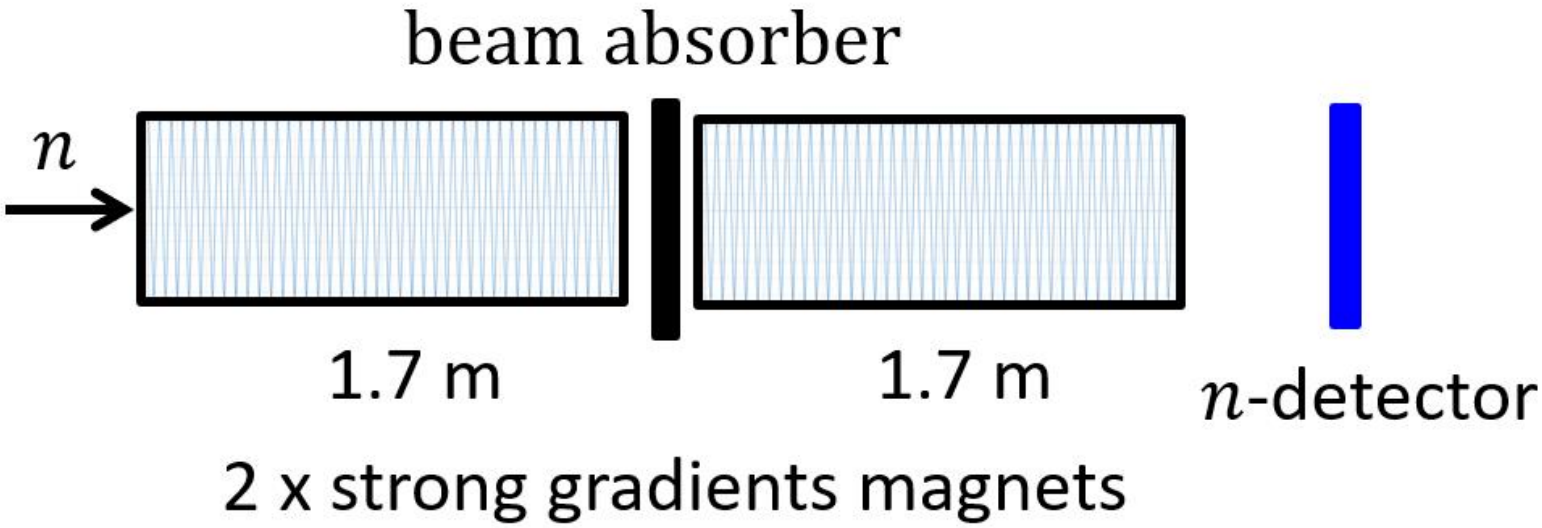
## $(n, n')$ system bouncing in non-uniform magnetic field without touching walls (UCN-$\tau$)

$$U = \mu \boldsymbol{\sigma} \cdot \boldsymbol{B}(x) = \mu B(x) \text{ polarized beam} \qquad \boldsymbol{F} = -\frac{dU}{dx}\boldsymbol{i}$$




Due to $n$TMM oscillation amplitude doesn't depend on the magnetic field ***B.*** High gradients of magnetic field can lead to the system decoherence through separation of the wave packets of the oscillating $n \leftrightarrow n'$ system.

⑤ Study decoherence due to strong gradients of $nn'$ system with $n$TMM



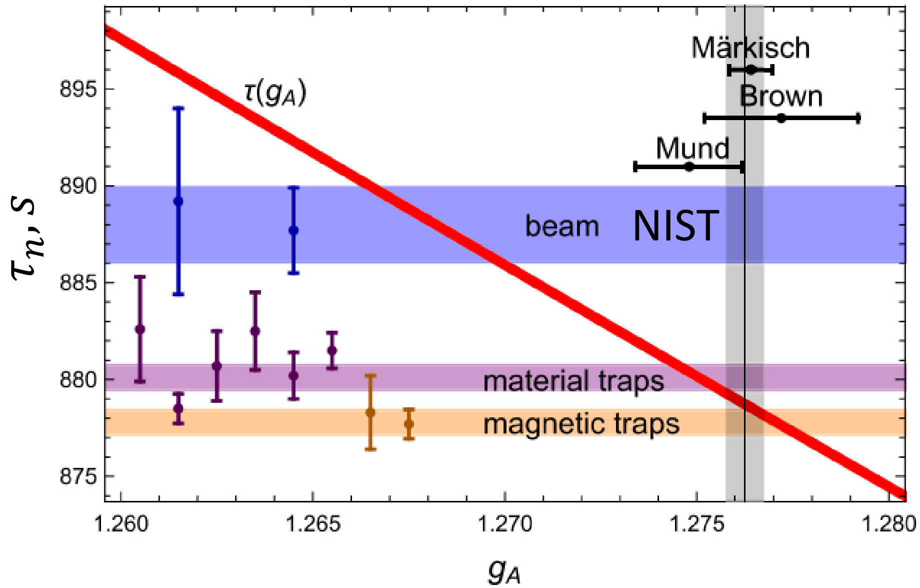

High-gradient fields can be obtained by opposite-B-direction coils, by Halbach arrays, by large-field superconducting magnets

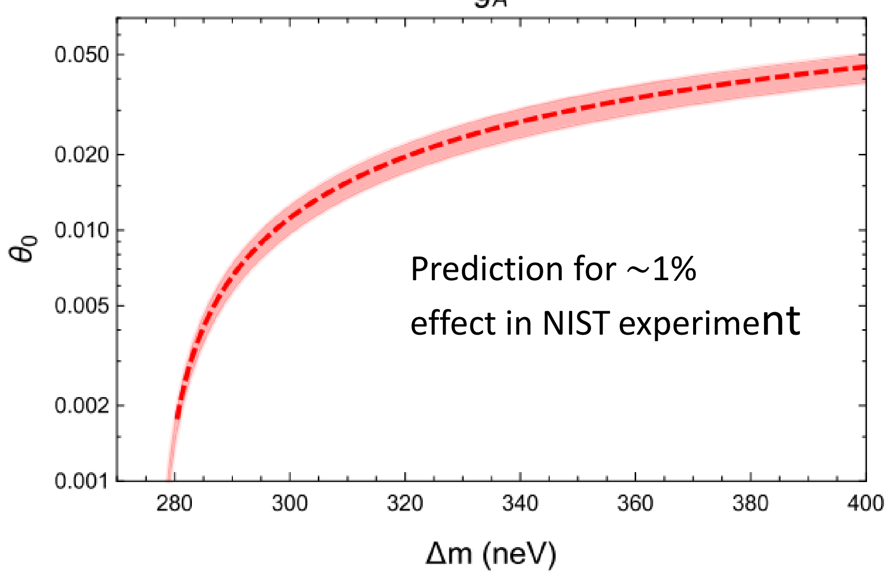
Separation by decoherence can be used as regeneration method
$n$TMM can be detected down to $\eta \leq 10^{-5}\mu$

If $\eta > 10^{-5}\mu$, this mechanism can be used for the explanation of the neutron lifetime anomaly by disappearance of UCN neutrons stored in the magnetic and material traps.

# Testing variations of $n \leftrightarrow n'$ hypothesis: $\Delta m = m_{n'} - m_n \sim 10^{-7}\ eV$ Model

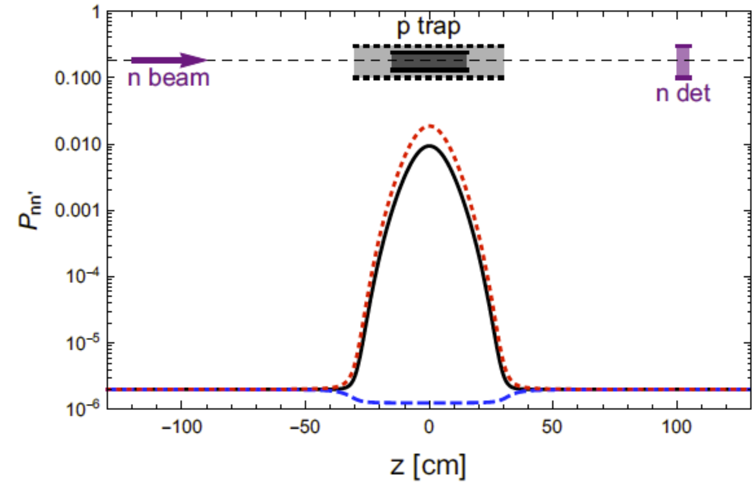
[Z. Berezhiani (2019), Eur. Phys. J. C79, 484](#)

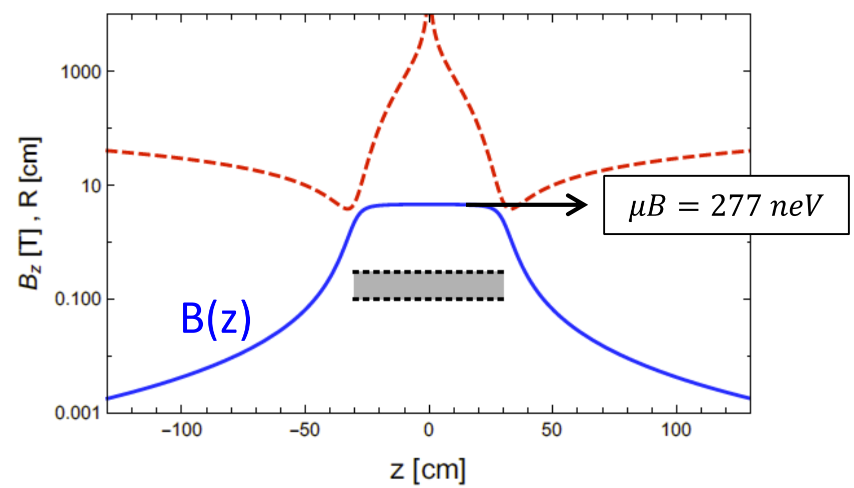



Hamiltonian for one n-polarization

$$H = \begin{pmatrix} V + \mu B - \Delta m & \epsilon \end{pmatrix}$$

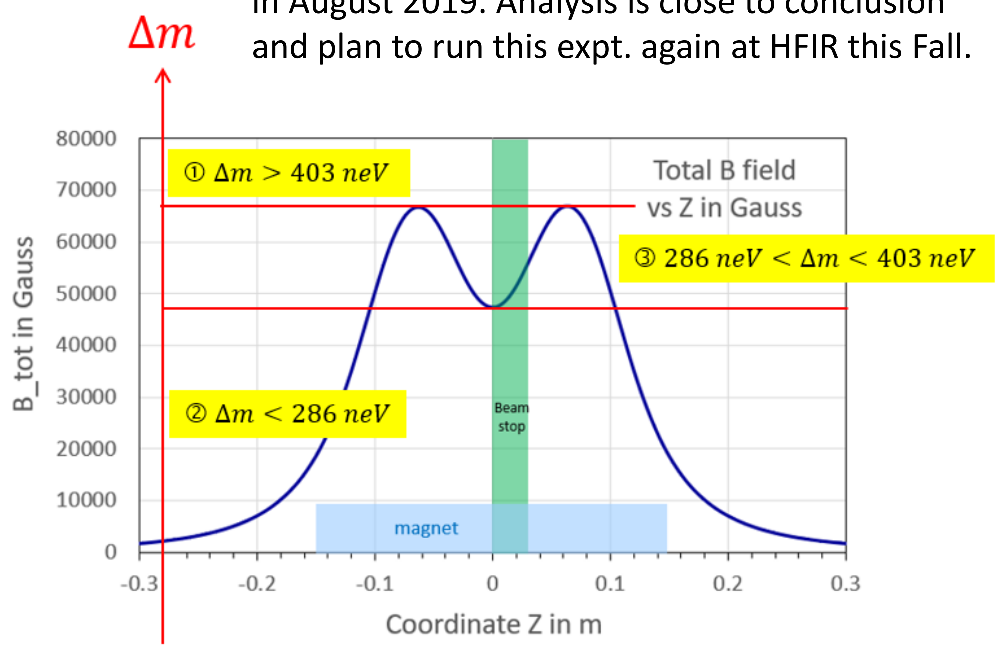


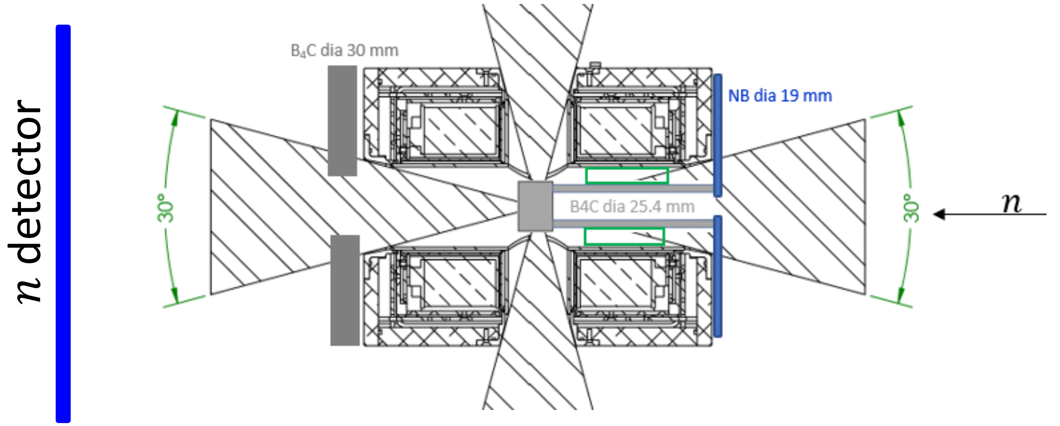



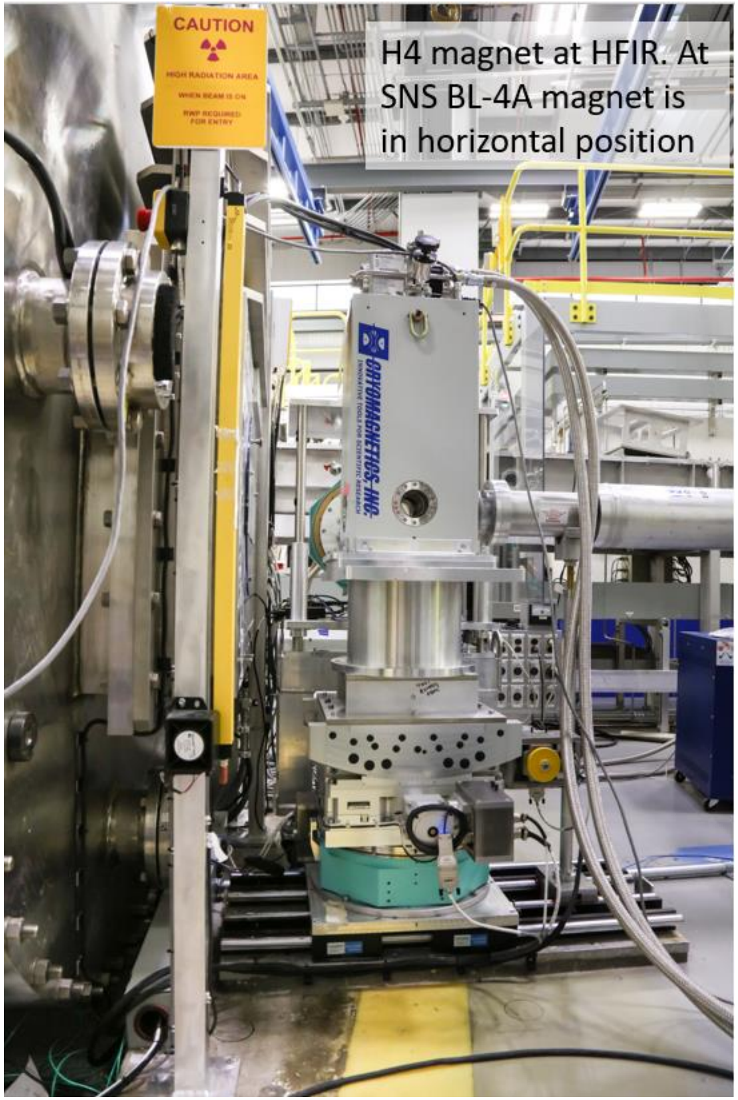

For NIST beam expt. magnet

# ⑥ Search $n \to n'$ in MM model with small $\Delta m$

Experiment was performed at SNS beamline 4A in August 2019. Analysis is close to conclusion and plan to run this expt. again at HFIR this Fall.



# Conclusions

- Neutrons with lifetime 880 s are excellent tool to look for new physics
- $n \to n'$ and $n \to MM \to \bar{n}$ is reach phenomenology field with many experimental possibilities that can be tested
- Physics that can be addressed with neutrons: BNV, BAU, origin of DM
- Collaborations around ORNL and ESS in Europe are building up with short and long-term plans to develop neutron oscillation physics