Sterile Neutron Searches at ORNL

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ESS - ILL Topical workshop on Fundamental and Particle Physics
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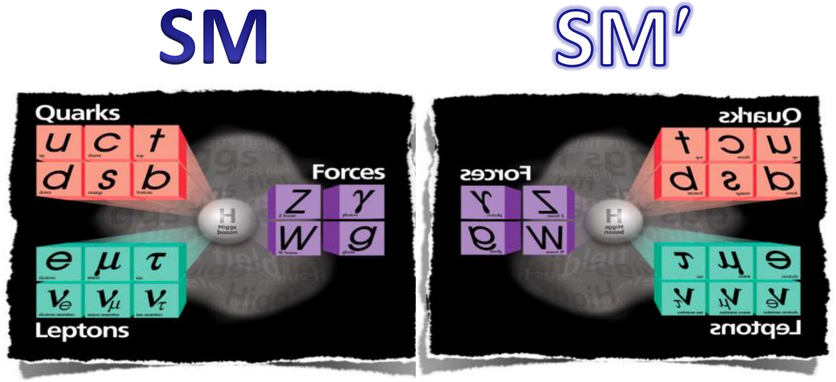
Oak Ridge National Laboratory High Flux Isotope Reactor

Overview

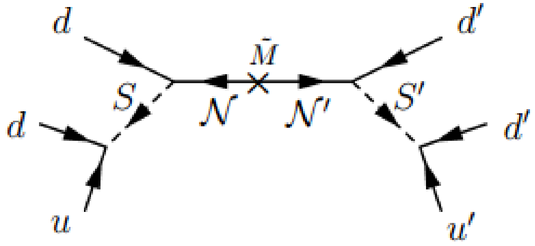
- Neutrons might disappear into a sterile partner, and experimentally this is not strongly constrained
- Relationship to important science questions, such as dark matter and lack of antimatter in the universe, or anomalies, such as the neutron lifetime discrepancy
- Previous searches use ultracold neutrons—cold neutrons offer a robust and complementary approach
- We can use existing infrastructure to perform these searches at ORNL

Motivation

- What is dark matter? We've been searching a long time; we need new avenues to explore! Cosmic Visions 2017 Community Report
- Mirror matter: identical copy of SM with opposite parity [Phys.Usp. **50** (2007) 380-389, From Fields to Strings **3** (2015) 2147]
  - Mirror sector was proposed to restore L-R symmetry [Phys.Rev. **104** (1956) 254-258]
  - No new parameters. Z_2 symmetry
  - MM and SM don't interact via known SM interactions except gravity [Sov.J.Nucl.Phys. **3** (1966) 6]
- MM a viable DM candidate [PLB **503** (2001) 362, IJMPA **29** (2014) 1430013]
  - Possibly related to sterile neutrino anomaly, GZK limit
- Predictions of nn' mixing in Mirror Matter models PRL 96 081801 (2006)
  - Apparent BNV: Global $\mathcal{B} = \mathcal{B} + \mathcal{B}'$?
- Neutron could be one of a very few portals to a dark sector



Neutron Oscillations



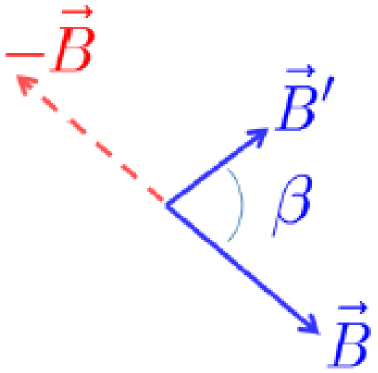
- Similar concept to $n - \bar{n}$: mixing of neutron with sterile twin
  - Less demanding magnetic field requirements
- Small mirror magnetic field $\boldsymbol{B}'$ possible from MM captured by earth

$$\mathcal{H}_{int} = \begin{pmatrix} m + \mu\boldsymbol{\sigma} \cdot \boldsymbol{B} & \epsilon \\ \epsilon & m' + \mu'\boldsymbol{\sigma} \cdot \boldsymbol{B}' \end{pmatrix} \qquad \text{oscillation time } \tau_{nn'} = \frac{1}{\epsilon}$$

- $n - n'$ mass splitting (10^{-24} GeV) or magnetic field (mG) can strongly suppress oscillation: no oscillations in a neutron star, nucleus, earth's magnetic field…
- Not sensitive to large $\Delta m_{nn'}$ in laboratory, control $\vec{B}$ for resonance in probability:

$$\mathrm{P}(n \to n') = \frac{\sin^2[(\omega-\omega')t]}{[(\omega-\omega')]^2 2\tau^2} + \frac{\sin^2[(\omega+\omega')t]}{(\omega+\omega')^2 2\tau^2} + \cos\beta \left[\frac{\sin^2[(\omega-\omega')t]}{(\omega-\omega')^2 2\tau^2} - \frac{\sin^2[(\omega+\omega')t]}{(\omega+\omega')^2 2\tau^2}\right]$$

$$\omega = \frac{1}{2}|\mu B|,\ \omega' = \frac{1}{2}|\mu' B'|,\ \ \mu = \mu' \text{ and } \tau = \frac{1}{\varepsilon}$$



- Near resonance $\mathrm{P}(n \to n') \propto \left(\frac{t}{\tau}\right)^2$. Signal maximum when $\cos\beta = 1$

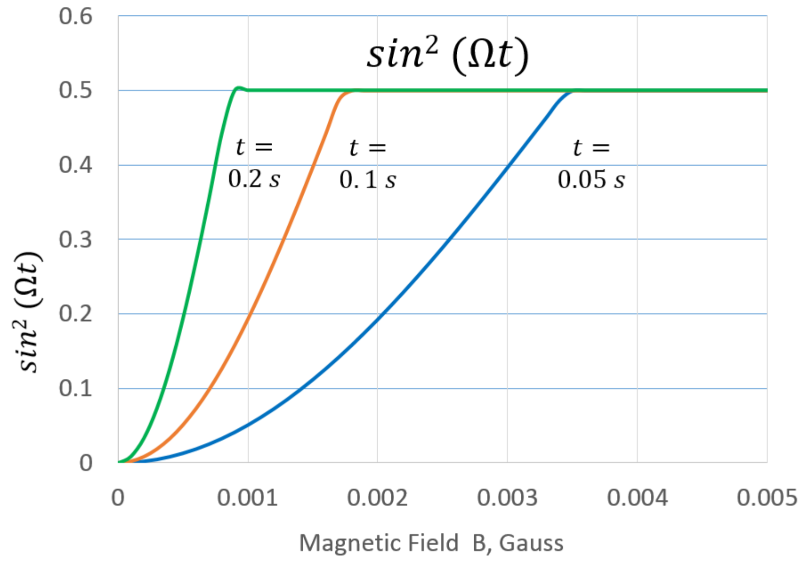
Transition Magnetic Moment (TMM)

- Include off-diagonal operators: TMM η MDPI Phys **1** (2019) 271

$$\eta F_{\mu\nu}\bar{n}\sigma^{\mu\nu}n' + \eta' F'_{\mu\nu}\bar{n}\sigma^{\mu\nu}n' + \text{HC} \qquad \mathcal{H}_{int} = \begin{pmatrix} m + \mu\boldsymbol{\sigma}\cdot\boldsymbol{B} & \eta\boldsymbol{\sigma}\cdot[\boldsymbol{B} \pm \boldsymbol{B}'] \\ \eta\boldsymbol{\sigma}\cdot[\boldsymbol{B} \pm \boldsymbol{B}'] & m' + \mu'\boldsymbol{\sigma}\cdot\boldsymbol{B}' \end{pmatrix}$$

- Assume $\eta \ll \mu$; $[B \pm B']$ depends on Z_2 parity
- Magnetic field suppresses oscillation due to mass-splitting, but with TMM off-diagonal enhances probability
- For $\omega t \gg 1$ probability of TMM transition becomes nearly constant

$$P_{nn'} \approx \frac{2\eta^2}{\mu^2}$$



Mixing with Antineutrons

- Transformation $n \rightarrow \bar{n}$ would provide evidence of $\mathcal{B}$-violation, a yet unseen Sakharov Condition, needed to explain matter-antimatter asymmetry in universe
  - Connection to cobaryogenesis IntJModPhysA **33** 1844034 (2018)
- Sterile neutrons provide shortcut for neutron-antineutron oscillations arXiv:2002.05609
- Straightforward extension of formalism to consider $n \rightarrow \bar{n}, n', \bar{n}'$

$$|\phi_n\rangle = \begin{vmatrix} n \\ n' \\ \bar{n}' \\ \bar{n} \end{vmatrix}\rangle$$

- Classic signature: single mixing term $\varepsilon_{n\bar{n}}$ without dark sector
- $\alpha_{nn'}$ -- mixing with sterile neutron
- Shortcut via new term $\delta_{n\bar{n}'}$

$$\mathcal{H}_{int} = \begin{pmatrix} m + \mu\boldsymbol{\sigma}\cdot\boldsymbol{B} & \varepsilon_{n\bar{n}} & \alpha_{nn'} & \delta_{n\bar{n}'} \\ \varepsilon_{n\bar{n}} & m - \mu\boldsymbol{\sigma}\cdot\boldsymbol{B} & \delta_{n\bar{n}'} & \alpha_{nn'} \\ \alpha_{nn'} & \delta_{n\bar{n}'} & m' + \mu'\boldsymbol{\sigma}\cdot\boldsymbol{B}' & \varepsilon_{n\bar{n}} \\ \delta_{n\bar{n}'} & \alpha_{nn'} & \varepsilon_{n\bar{n}} & m' - \mu'\boldsymbol{\sigma}\cdot\boldsymbol{B}' \end{pmatrix}$$

$$P_{n\bar{n}'} \sim \left(\frac{t}{\tau_{n\bar{n}'}}\right)^2$$

- From ILL $n \rightarrow \bar{n}$ search and UCN limits/anomalies can estimate $\tau_{n\bar{n}'}\tau_{nn'} > 100 - 1000\ \mathrm{s}^2$

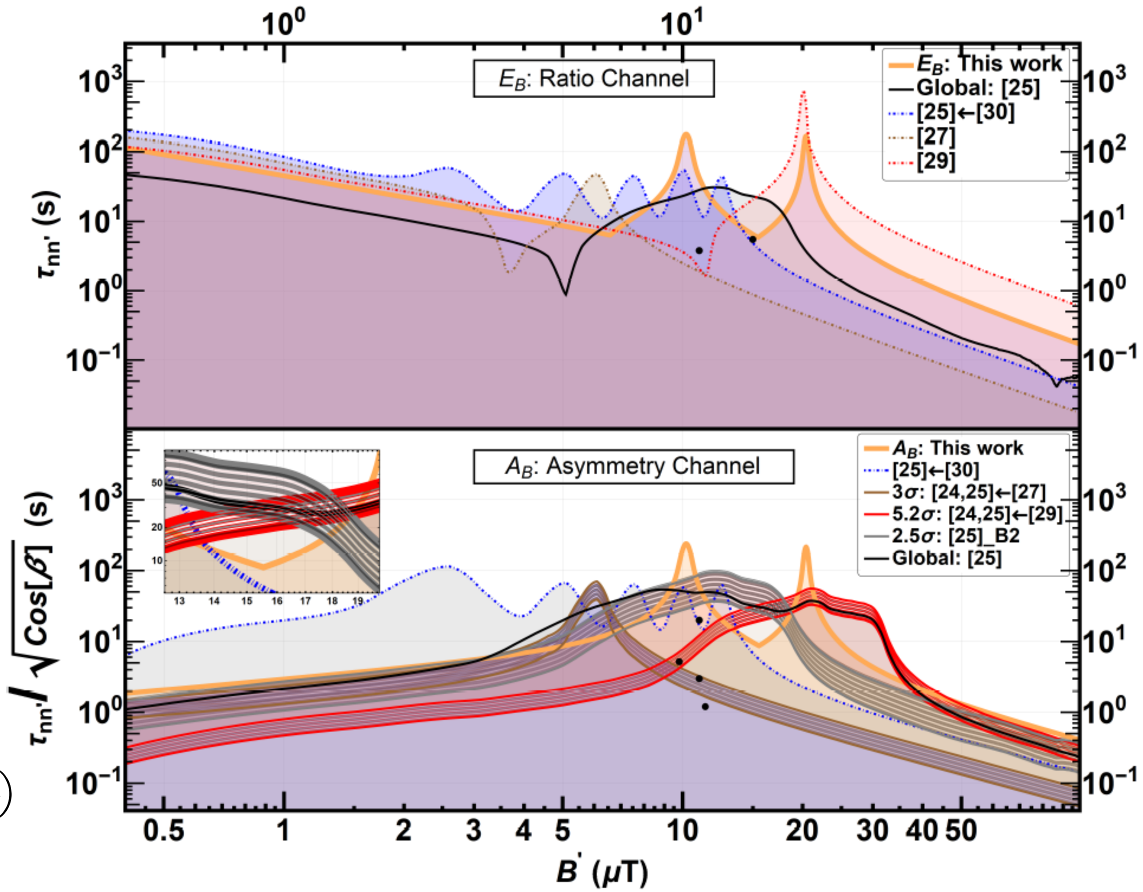
Prior searches

- First searches for $n \rightarrow n'$ used UCN to place strong limits assuming $B' = 0$: (E_B channel)
  - $\tau_{nn'} > 448$ s (90% CL) NIMA **611** (2008) 137-140
  - Reanalysis with $B' \neq 0$ found anomalies in A_B channel EPJC **72** (2012) 1974 (with update EPJC 78 (2018) 717)
- Dedicated search with $B' \neq 0$ PRD 80 (2009) 032003
  - $\tau_{nn'} > 12$ s for 0.4μT < B'<12.5 μT (95% CL)
- PSI nEDM (arXiv:2009.11046) refutes anomalous signals reported in EPJC **72** (2012) 1974, excludes some (not all) regions where anomalous "bands" overlap EPJC 78 (2018) 717
- Recent limits on another concept – "hidden neutrons" arXiv:2007.11335
  - Neutron "swapping" prob. $p < 4.0 \times 10^{-10}$ (95% CL)

$$E_B^{(t_s)} + 1 = \frac{2n_0^{(t_s)}}{n_B^{(t_s)} + n_{-B}^{(t_s)}}$$

$$A_B^{(t_s)} = \frac{n_B^{(t_s)} - n_{-B}^{(t_s)}}{n_B^{(t_s)} + n_{-B}^{(t_s)}}$$

"Ratio" E_B and "asymmetry" A_B channels

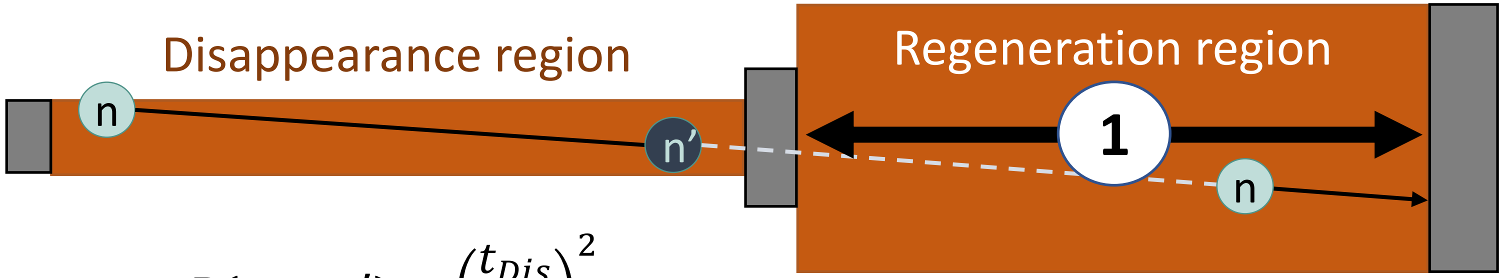


Complementary approach: cold neutrons

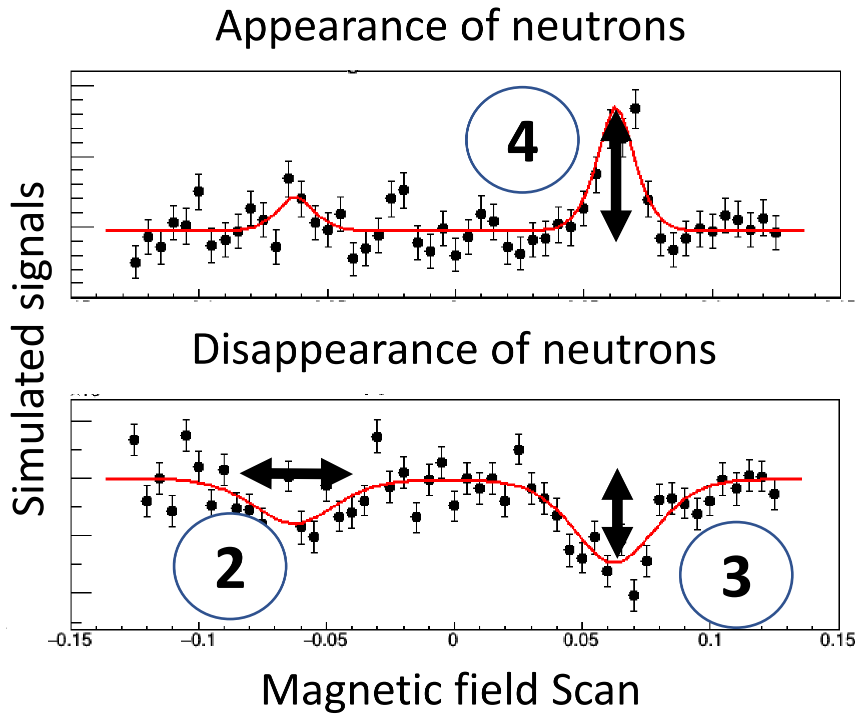
- UCN fluxes much lower than CN but can have 1000's bounces/UCN.
- CN beams provide much higher intensities; however, long free flight time required
  - CN experiments need long, large area beamguides, in contrast to smaller UCN bottles
- CN offer robust approach to searches
  - Regeneration = unambiguous signal; less dependent on changing intensity/spectrum
  - Avoids ambiguity with wall losses
  - Rapid B variations possible
- First regeneration search attempt with 6m flight path: $\tau_{nn'} > 2.7$ s Schmidt 2007
- Detailed requirements for regeneration method described PRD 96 (2017) 035039
- Sensitive searches can be performed using existing neutron scattering instruments at ORNL arXiv:1710.00767, EPJWebConf 219 (2019) 07002

Ingredients for a Resonance Search

$$P(n \rightarrow n' \rightarrow n) \propto \left(\frac{t_{Dis}}{\tau}\right)^2 \left(\frac{t_{Reg}}{\tau}\right)^2$$



$$P(n \rightarrow n') \propto \left(\frac{t_{Dis}}{\tau}\right)^2$$

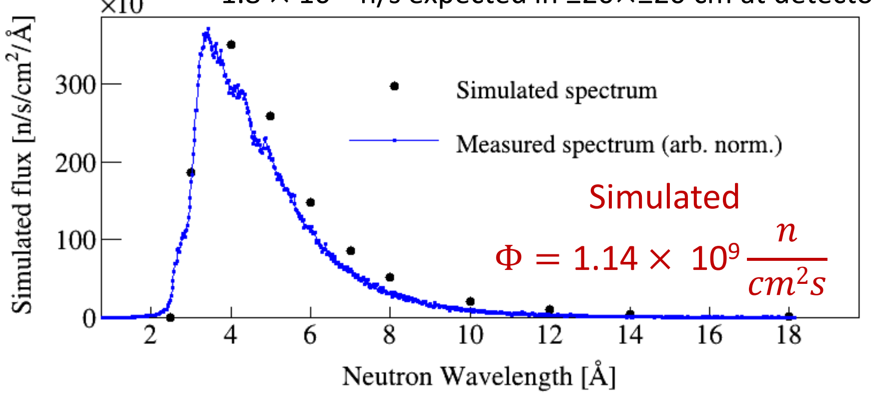


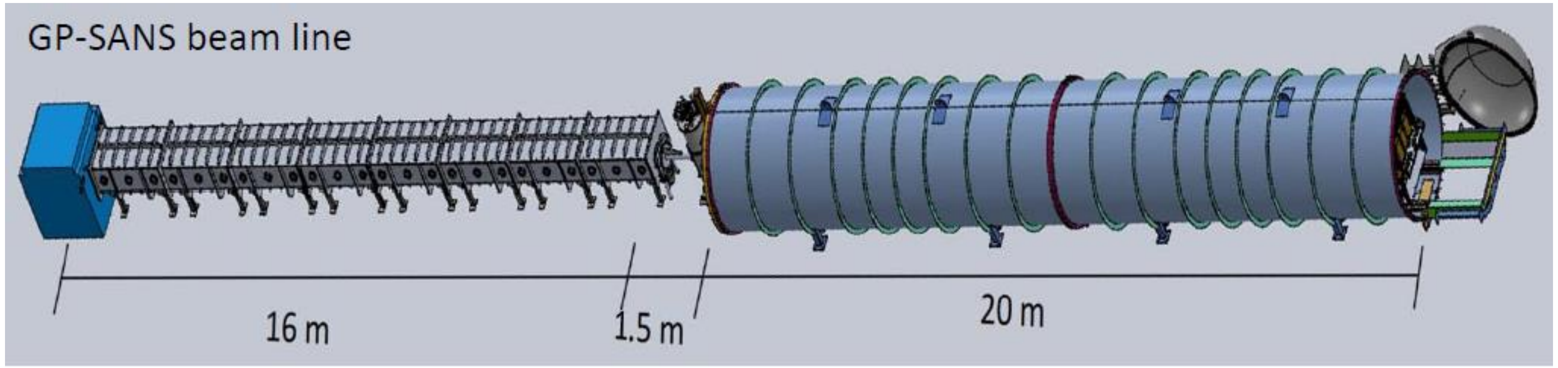
1. High neutron flux + long, large area guides
2. Magnetic field uniformity and control
3. Precise monitoring of changes in transmission
4. Regeneration: large area, low bkgd detector

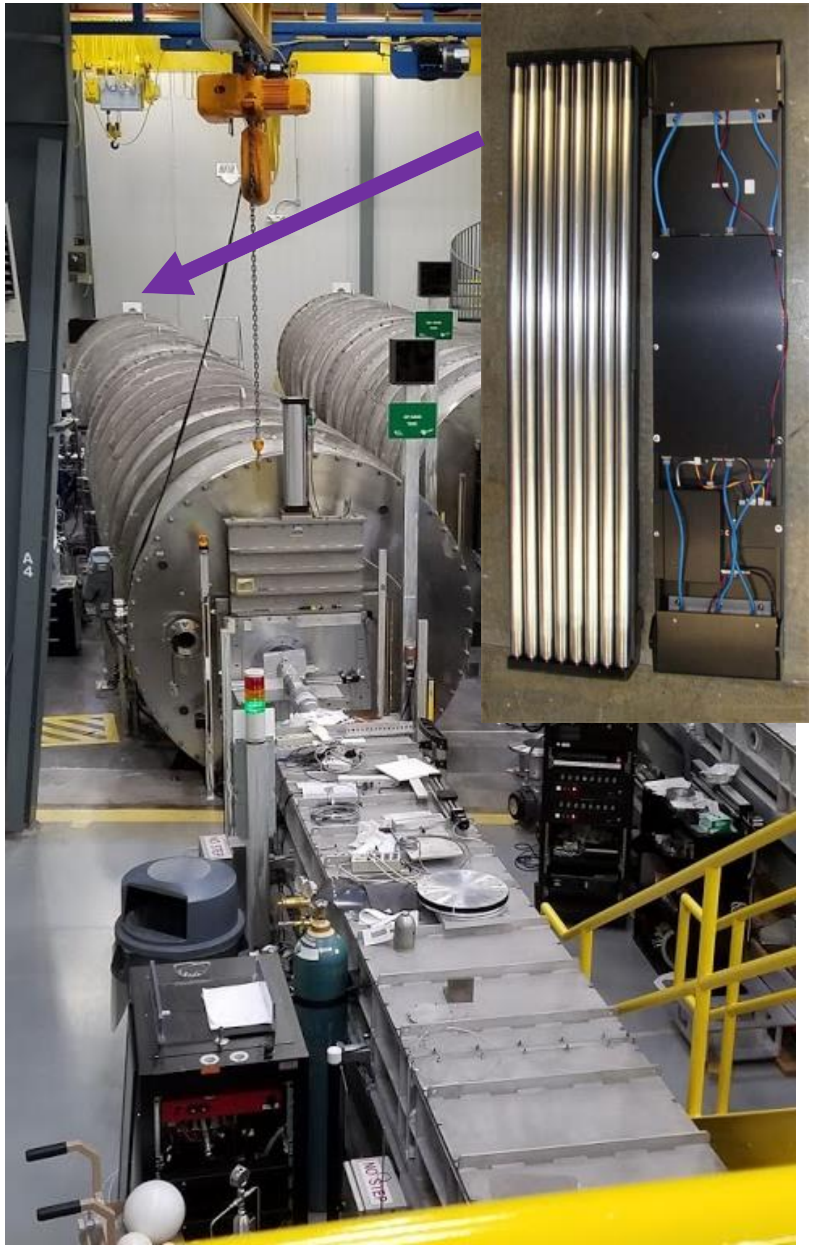
Search at ORNL

- High Flux Isotope Reactor - 85 MW: highest reactor-based source of neutrons for research in US
- Existing instrument: General-Purpose Small Angle Neutron Scattering
  - Long, large area beamguides for both disappearance and regeneration
  - 1 m x 1 m ^{3}He neutron detector in Cd shielded tank

4 cm × 4 cm aperture, 0.3° divergence
1.8×10^{10} n/s expected in ±20×±20 cm at detector





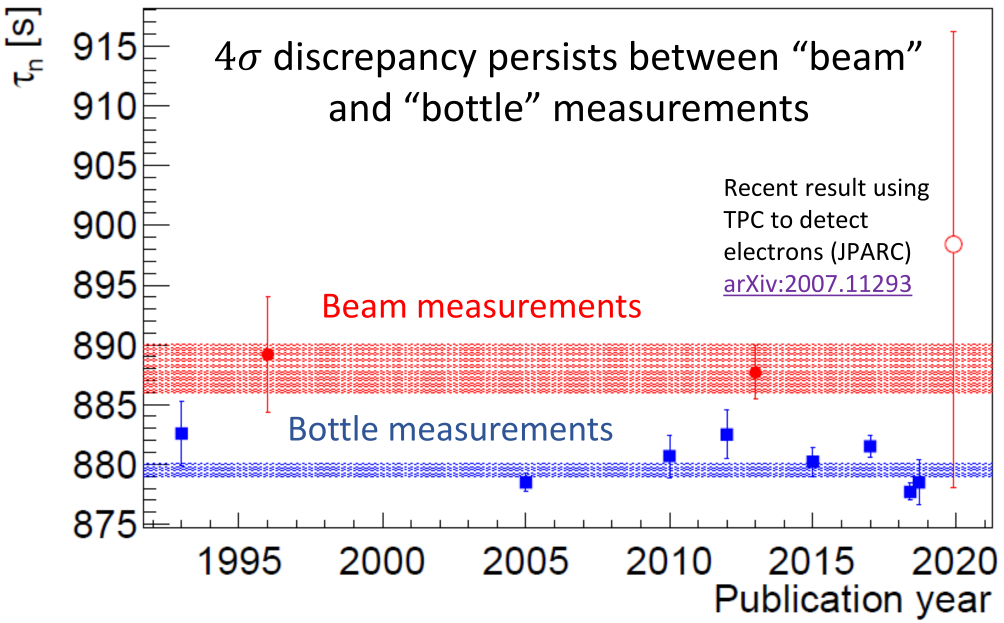


Planned searches at ORNL

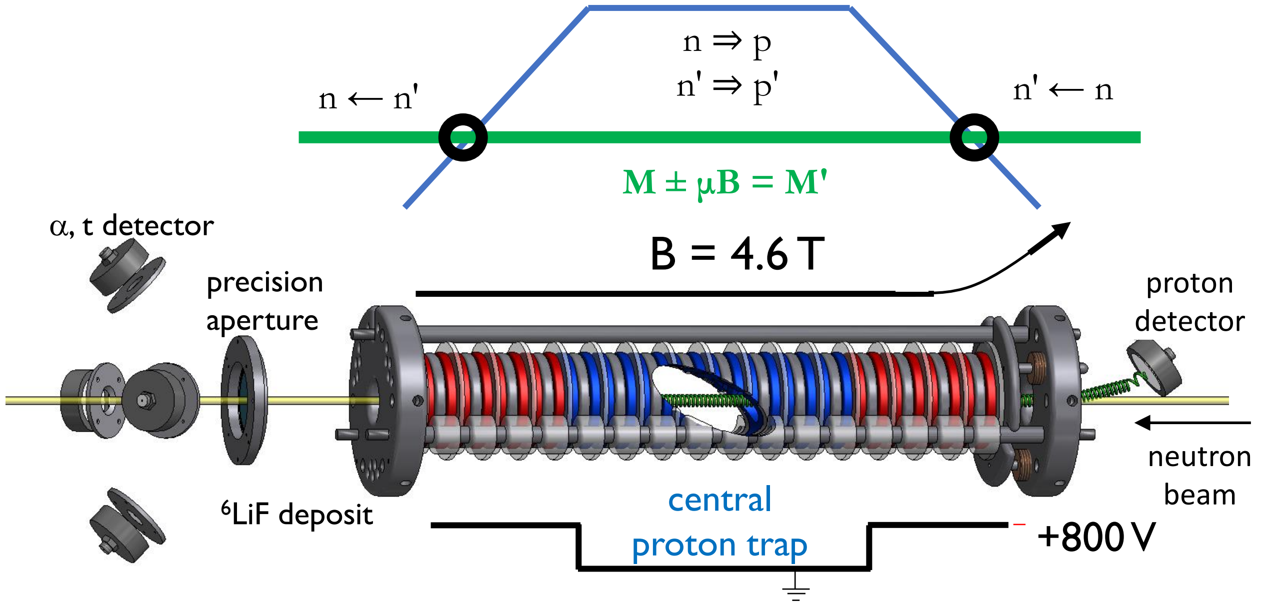
- GP-SANS is heavily subscribed, beamtime awarded by User Program -- experiments must have minimal impact on instrument
    - Experiments designed in collaboration with instrument scientists
- Staged program of small-scale experiments (increasing complexity/impact) to search for variations in nn' hypothesis over next several years
    - Search for small mass splitting
    - Search for TMM
    - Search for disappearance resonance
    - Search for neutron regeneration resonance
    - Search for antineutron regeneration resonance

Can *nn′* mass splitting explain CN lifetime?

- Neutron lifetime anomaly persists Atoms 6 (2018) 4
- Small mass splitting (100's neV) suggested to explain cold neutron lifetime EPJC **79**, 484 (2019)
- Neutron mixing with dark sector: relatively unexplored experimentally

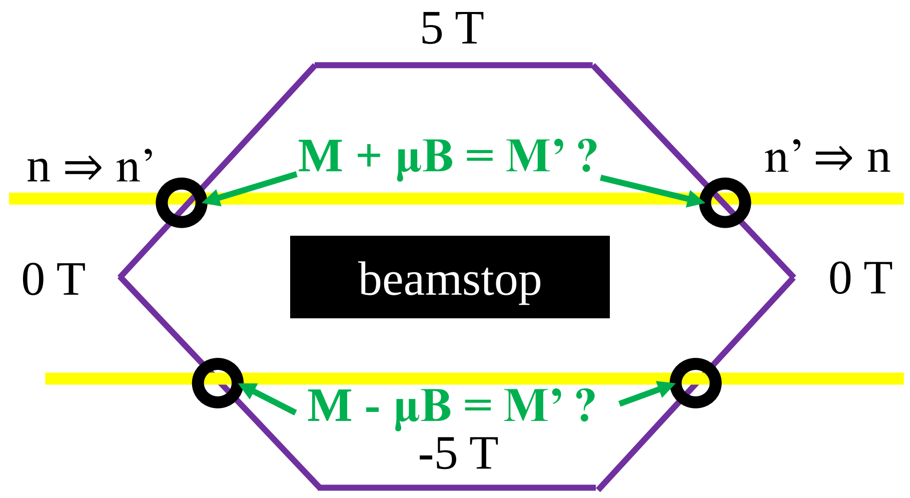


- Mass splitting: $n \rightarrow n'$ probability enhanced inside high B region
  - e.g. 1% chance n' decays into p', missed detection
  - n' probability reduces outside high B region = no impact on flux measured

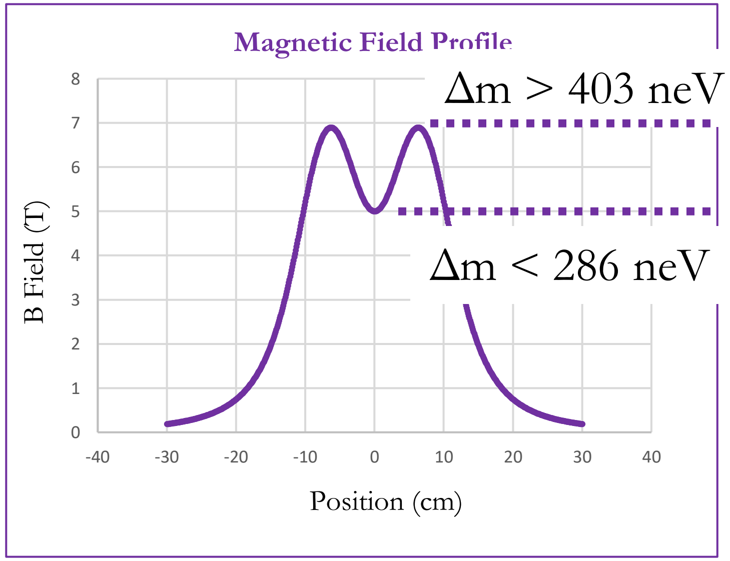


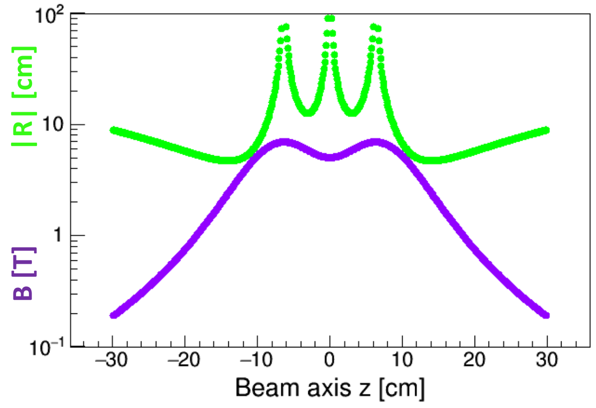
NIST neutron Beam Lifetime experiment (BL2)

Search for mass splitting



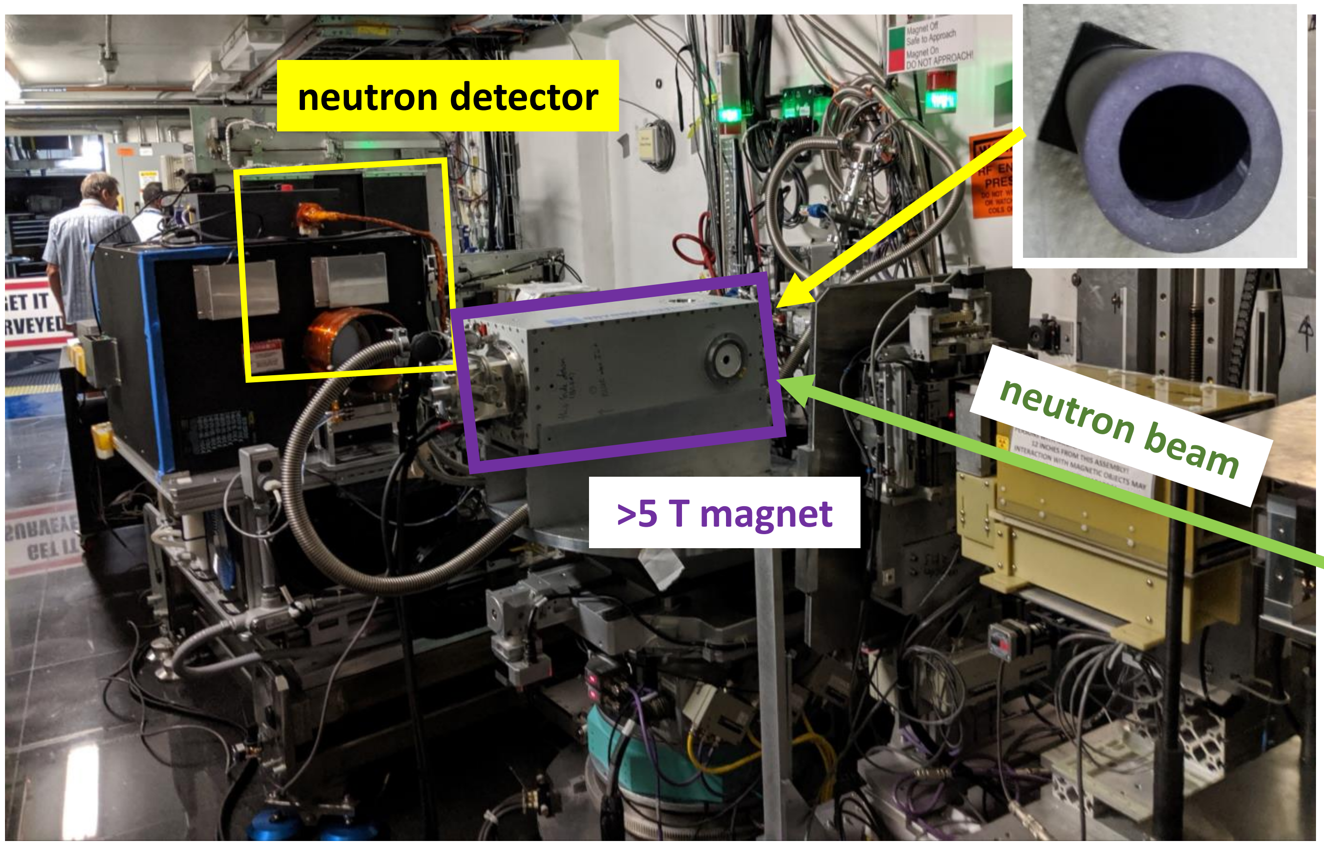
- In NIST BL experiment, neutron beta decay performs “measurement” – very small fraction of flux
- ORNL approach – use beamstop to “measure” neutron state in similar magnetic field profile.
- Landau-Zener transition: non-adiabatic probability of state crossing at resonance (B compensates δm)
- $P_{nn'} \approx \xi \approx \frac{\Delta E \cdot \Delta t}{\hbar} = \delta m \ \sin 2\theta_0 \frac{R(z)}{\hbar v}$
- Resonance length scale $R(z) = \frac{d(\ln B(z))}{dz}$
- Available at ORNL: split coil magnet, max field 7 T
  - Install beamstop at 5 T region





$n \rightarrow n'$ experimental approach

- Performed at ORNL's Spallation Neutron Source Magnetism Reflectometer (Beamline-4A)
  - Superconducting magnet > 5 T
  - Thick ^{10}B beam-catcher = n blocked, n' pass
- Spectral intensity calibration using attenuators
  - Total intensity $\sim 10^6\, n/s$ at 3.75 Å
- Measurement sequence: alternate magnetic field on/off (background)/opposite polarity
  - Ambient background in ROI $\sim 1\, n/s$
  - Position- and time-dependence used for S:B separation
- Multiple beam-catcher positions inside magnet and multiple magnetic field values
- Collimation study: beam profile in magnet



$n \rightarrow n'$ sensitivity (preliminary)

- No anomalous signal above background observed in initial experiment
- Reproduce Landau-Zener transition probability
  - Magnetic field profile and optical potential of beam-catcher material: impact oscillation probability
  - Numerically solve density matrix evolution

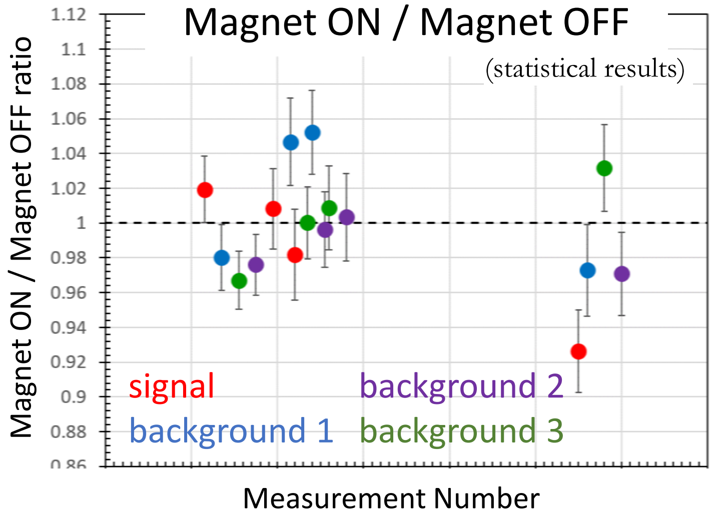
$$\frac{\partial}{\partial t}\hat{\rho} = -i[\hat{H}\cdot\hat{\rho}] = -i\hat{H}\hat{\rho} + i\hat{\rho}\hat{H}^{\dagger}$$

Liouville–von Neumann equation

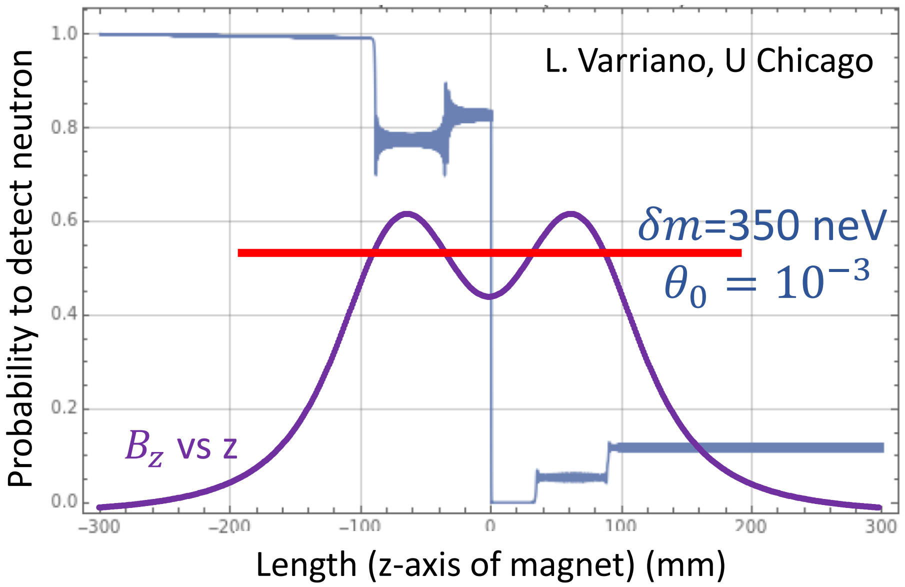
$$\hat{H} = \begin{pmatrix} m + V - iW + \mu B & \epsilon \\ \epsilon & m + \Delta m \end{pmatrix}$$

$$\hat{\rho}(0) = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} = n$$

- Can we rule out $n \rightarrow n'$ as explanation for lifetime anomaly?
  - Calculation of limit is computationally intensive, analysis ongoing
- Improved search at GP-SANS/HFIR
  - More beamtime, higher intensity, lower/more uniform backgrounds

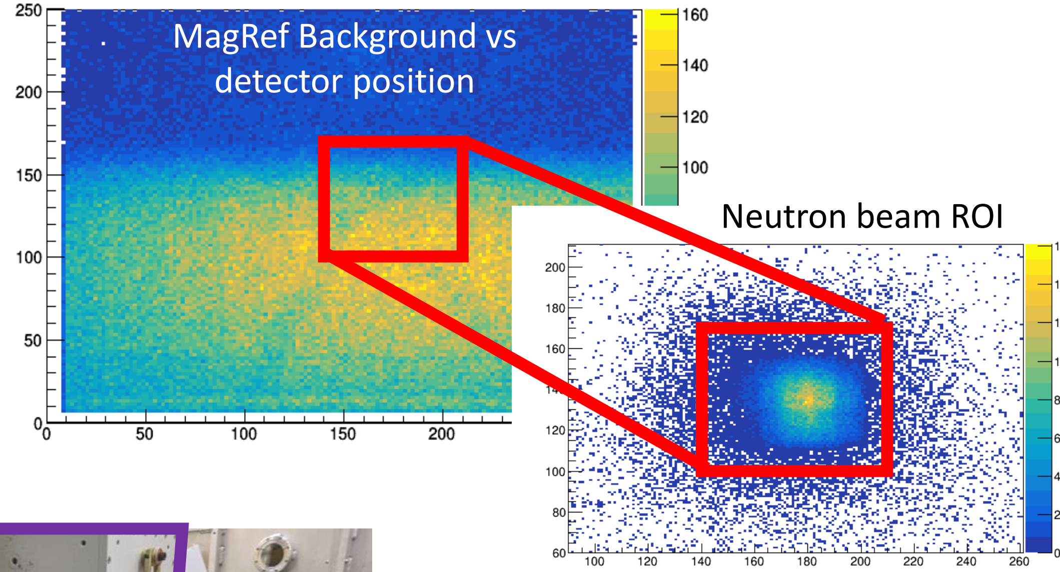


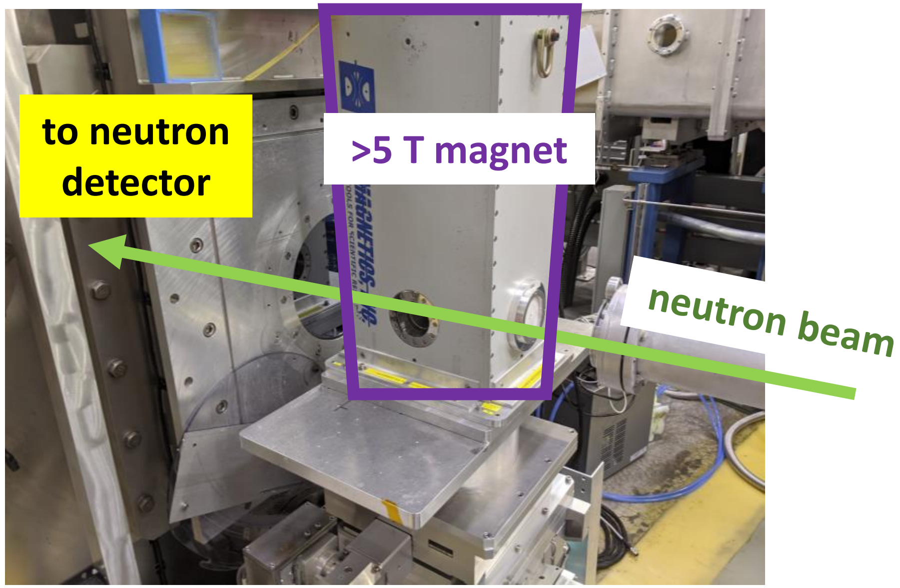
Example calculation L-Z transitions



Advantages of GP-SANS/HFIR vs Mag-Ref/SNS

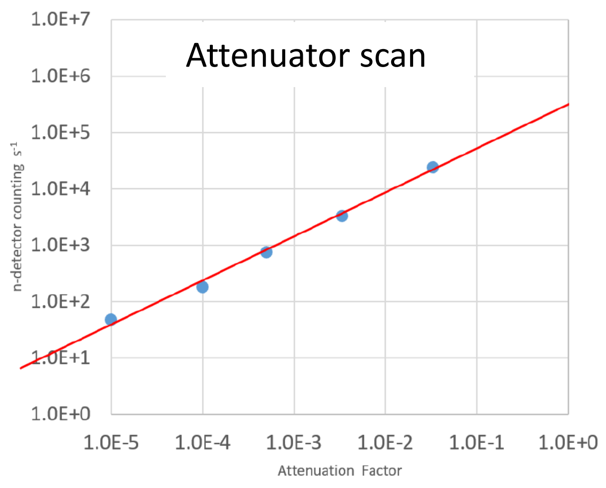
- SNS search = opportunistic experiment during HFIR outage
- Challenges at SNS
  - Larger nonuniform backgrounds
  - Lower intensity neutron beam; no simulation input
- Improve search at HFIR
  - Accept white beam at GP-SANS for higher intensity
  - Optimize beam-catcher material/ thickness with improved understanding of transition probability

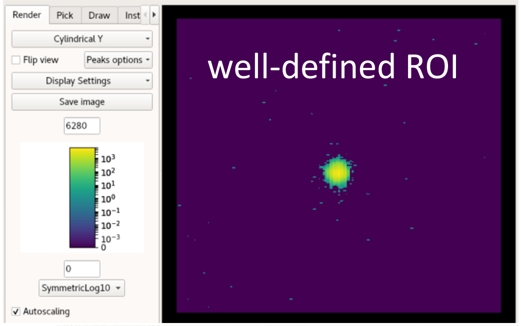


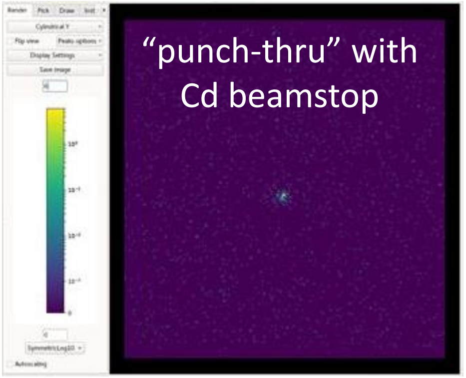


HFIR experiment status

- First beamtime to characterize GP-SANS recently completed
  - Characterized intensity with variable attenuation scans
  - Analysis in progress: spectral intensity, alignment, loss factors, detector efficiency & deadtime, bkgd subtraction etc
  - Low background rates in ROI: 0.2 – 0.5 cps
- Studied beamstop materials: BN, Cd, BC
  - Optimize to eliminate transmission without reducing sensitivity
- Beamtime awarded for next HFIR cycle to search for signal







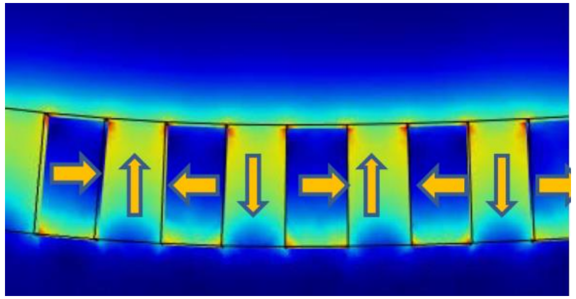
Next: can TMM explain UCN lifetime?

- Transformation possible without resonance
- B gradient specifies separation resulting in decoherence (uncertainty principle), performs "measurement"

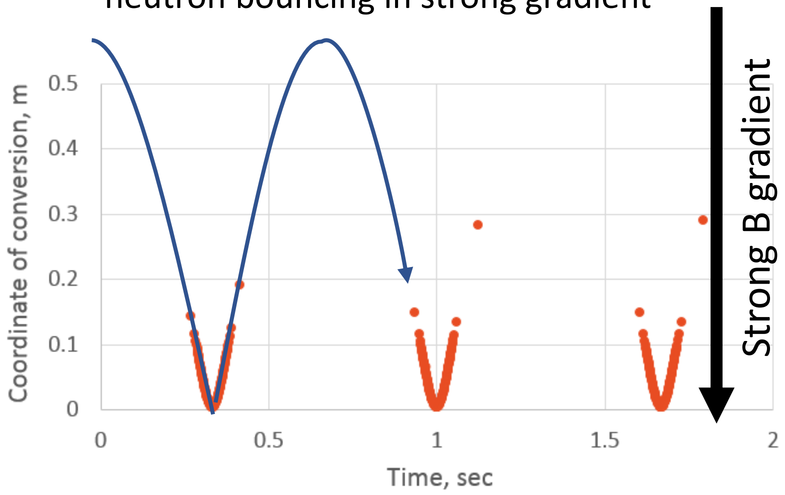
$$\mu\Delta B = \Delta E > \frac{\hbar}{\Delta t} = \frac{\hbar v}{\Delta x} \quad \rightarrow \quad \frac{dB}{dx} > \frac{\hbar v}{\mu \Delta x^2}$$

- Anomalous disappearance of UCN could explain lifetime puzzle [MDPI Phys **1** (2019) 271]
- Estimated limits from lifetime experiments
  - $P_{nn'} \approx \frac{2\eta^2}{\mu^2} \sim 10^{-7} - 10^{-9}$
  - $\frac{\eta}{\mu} \sim 10^{-4} - 10^{-5}$

UCNτ Halbach array



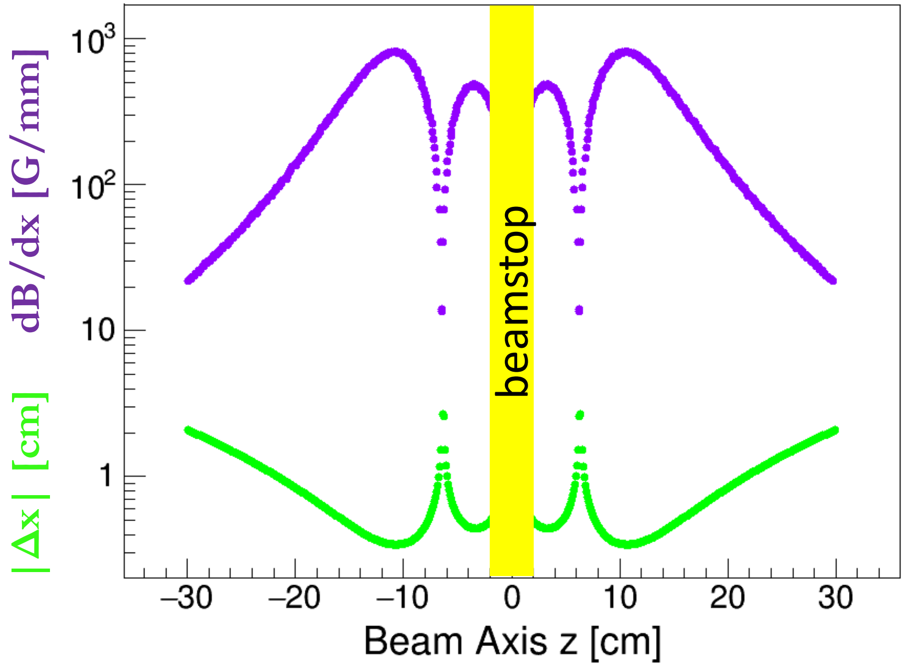
UCNτ simplified model
neutron bouncing in strong gradient

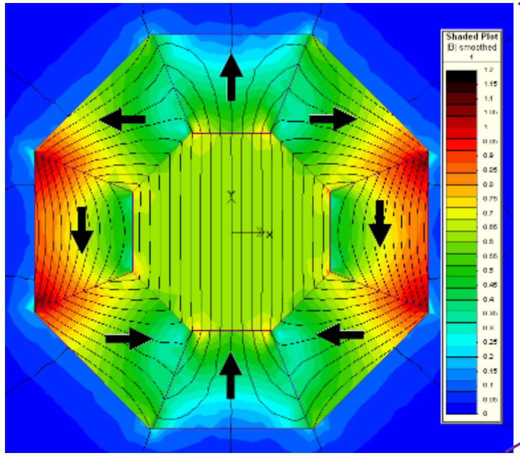


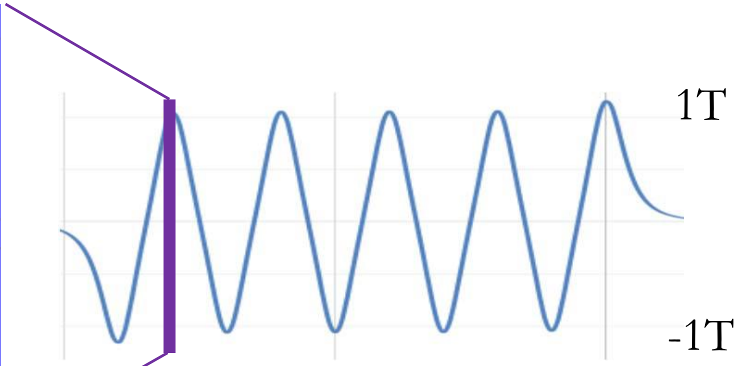
$1000's\ n \rightarrow n'$ "decoherences" per sec

Search for TMM at ORNL

- First search: use strong gradients in split-coil superconducting magnet
  - Upcoming beamtime. Sensitivity to $\frac{\eta}{\mu} < 10^{-3}$
- Improve sensitivity: oscillations enhanced in gas, if Fermi potential compensated by ~10 G field (e.g. for air)
  - Proposed for 2021. Approaching $\frac{\eta}{\mu} \sim 10^{-5}$
- Beyond $\frac{\eta}{\mu} \sim 10^{-5}$: strong gradients achievable with alternating sequence of Halbach array rings



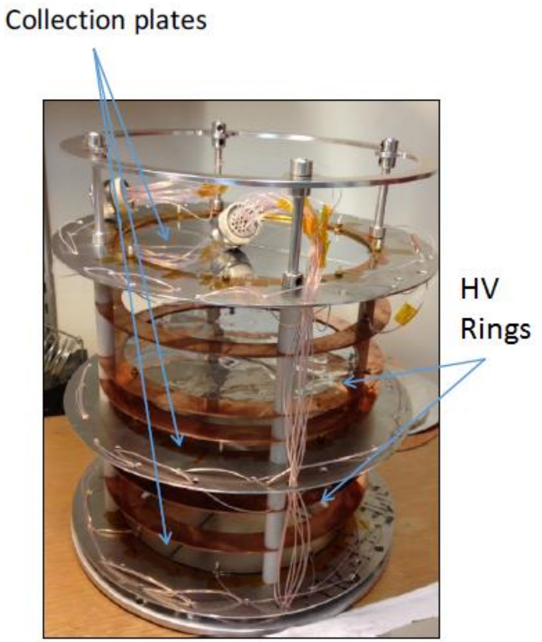


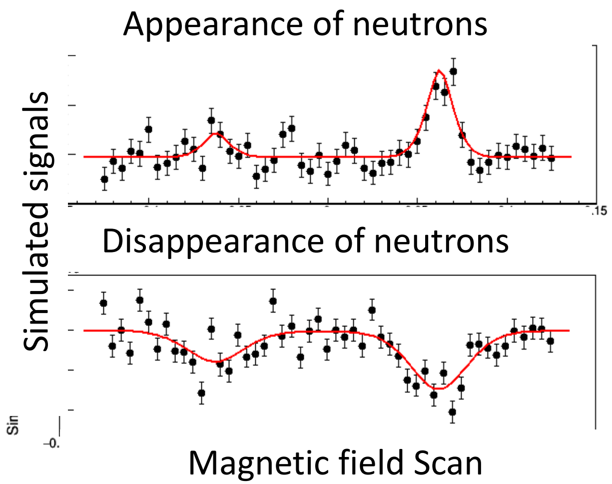


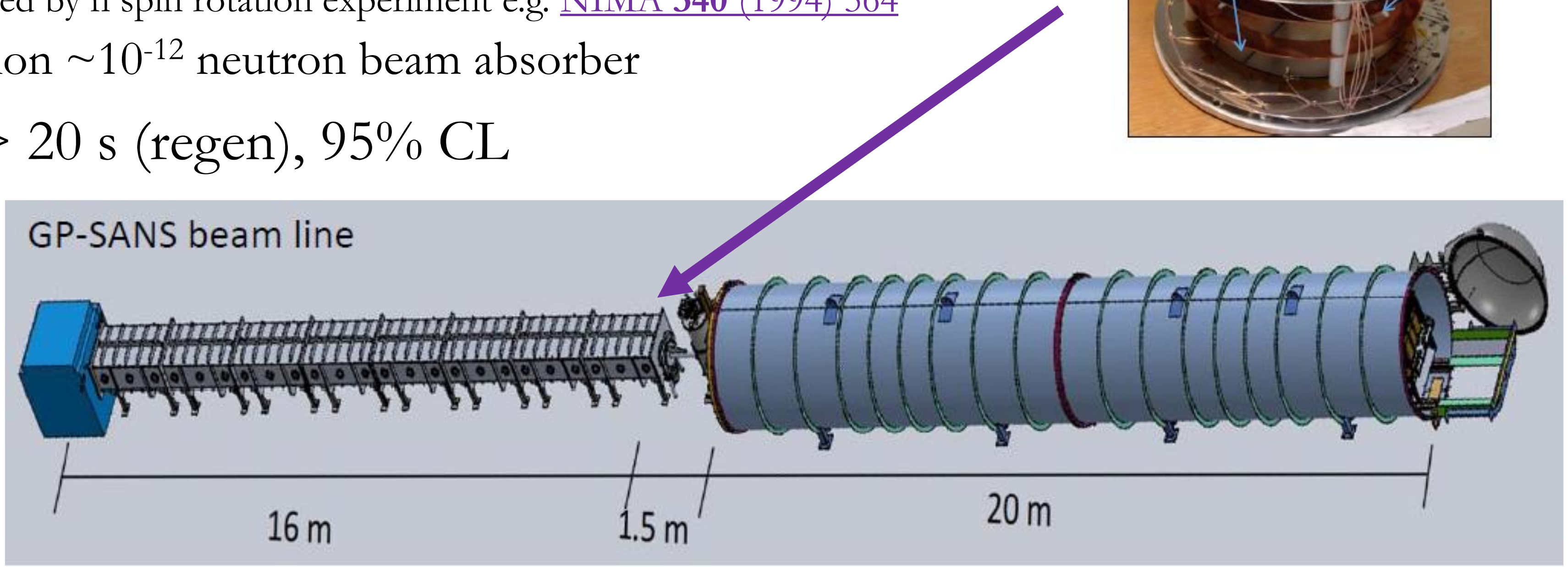
constant gradient > 10^5 G/m
$|\Delta x| < 1$ mm

Resonance searches

- 2022 – 2023 Search for resonance disappearance and regeneration with complementary approach to present UCN techniques
- ~mG control of magnetic field, addition of B control coils to both regions
- New equipment in "sample" region
  - Disappearance: high efficiency current-mode detectors,
    - Required stability ~10^{-7} exceeded by n spin rotation experiment e.g. NIMA **340** (1994) 564
  - Regeneration: high suppression ~10^{-12} neutron beam absorber
- Sensitivity: τ > 24 s (dis), τ > 20 s (regen), 95% CL

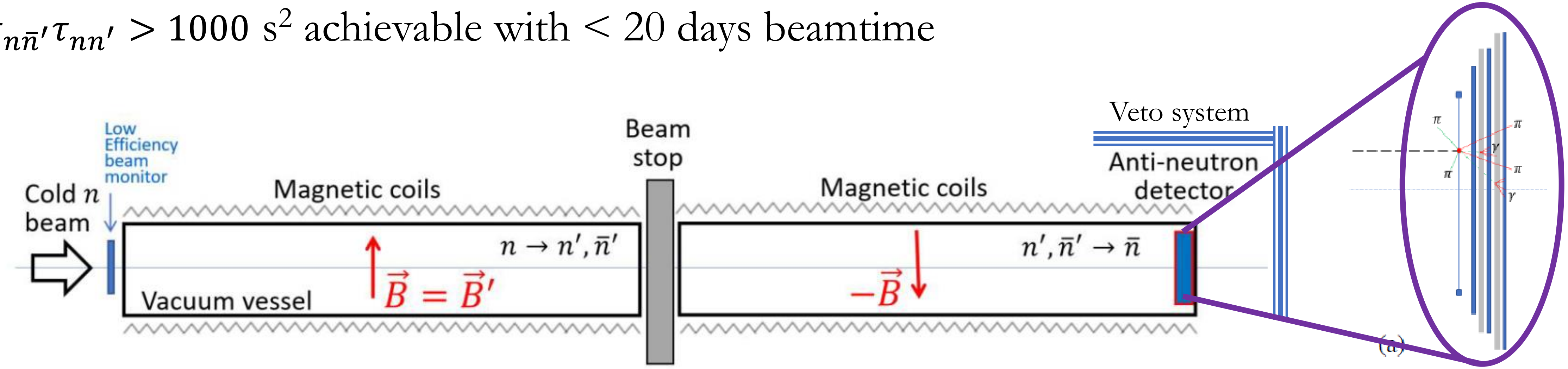






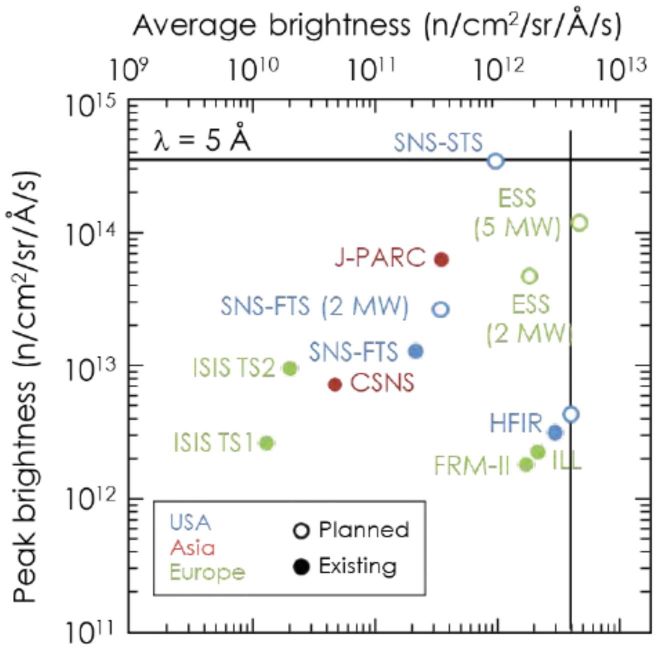
Search for $n \to n' \to \bar{n}$

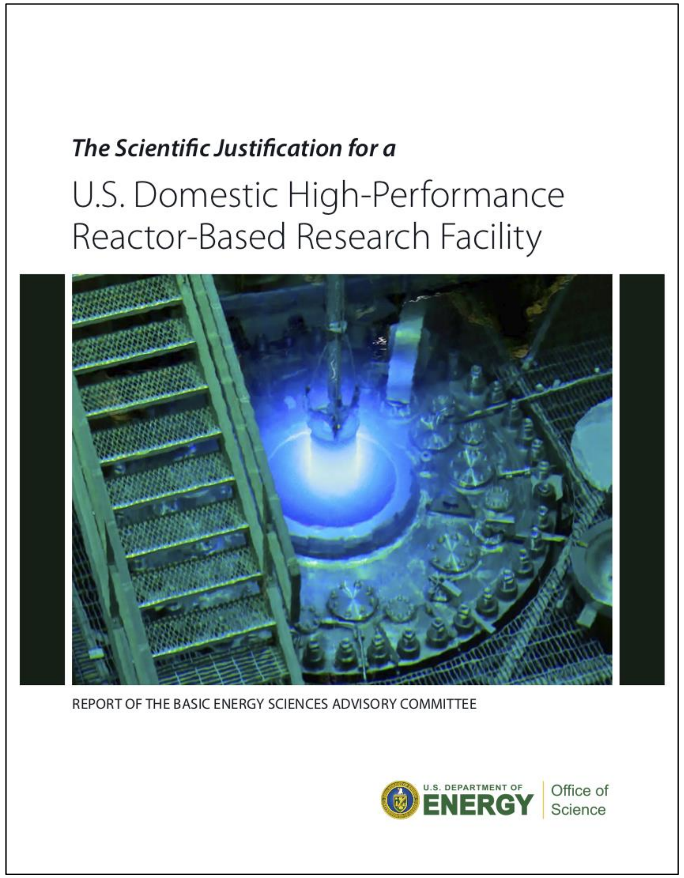
- Search for $n \to \bar{n}$ shortcut through general mixing of neutrons, antineutrons, and sterile sector
- Magnetic field scans with opposite fields to match magnetic field in sterile sectors
- Search for regenerated $\bar{n}$ == add $\bar{n}$ detector to GP-SANS
  - Early opportunity for NNBAR R&D!
  - Requires close coordination with GP-SANS instrument scientists
- $\tau_{n\bar{n}'}\tau_{nn'} > 1000\ \mathrm{s}^2$ achievable with < 20 days beamtime



HFIR Future

- Middle of decade: upgrade of upstream optics along with Be reflector changeout
  - Expect several times more neutrons
- Recent BESAC report: recommendation to coordinate pressure vessel replacement with LEU conversion and other upgrades
- ORNL now prioritizing study of HFIR upgrades
  - 100 MW operation, improved cold source, D_2O reflector, larger beam tubes, second guide hall, expanded guide hall
  - Possibly more opportunities for fundamental physics!





Summary

- $n \rightarrow n'$ oscillations are a testable consequence of a theory which could explain dark matter and baryogenesis
- Rich set of small-scale experimental possibilities can be tested, including some not yet explored
- First search for small mass splitting between n and n' which might explain the cold neutron lifetime completed at the SNS, with results in analysis
  - We're using what we've learned in an improved study at HFIR, with beamtime awarded
- Several searches for a transition magnetic moment are proposed, including possibility of first limits in parallel with search for mass splitting
- Search for magnetic field resonance using disappearance and regeneration can give a robust, unambiguous limit on $n \rightarrow n'$ oscillations
- Can look for shortcut to $n \rightarrow \bar{n}$ through mixing of $n, \bar{n}, n'$ by adding $\bar{n}$ detector = early NNBAR R&D

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