New Limits on Mirror Neutron Oscillations

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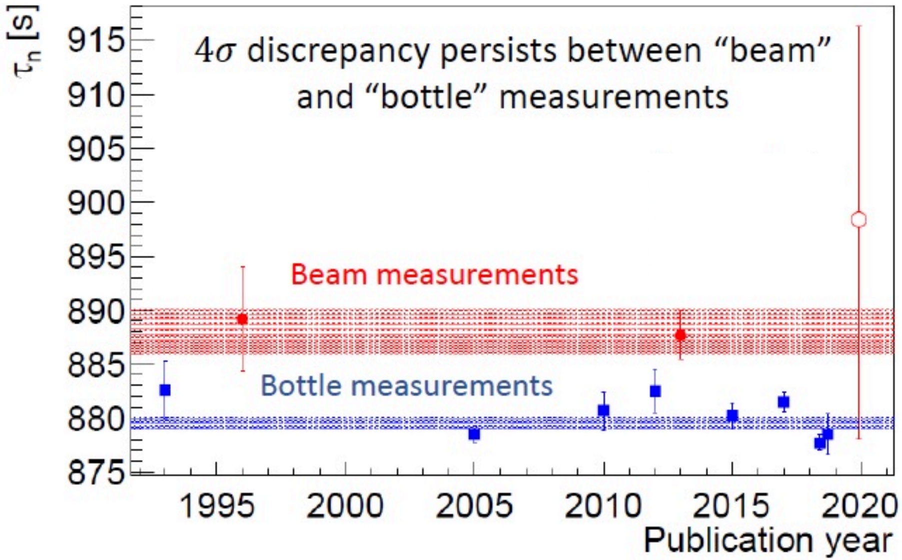
The Neutron Lifetime Discrepancy

- An unexplained 4σ discrepancy persists between "beam" and "bottle" measurements of the neutron lifetime
- Bottle experiments measure the rate of disappearance of ultracold neutrons in a magnetic or gravitational trap
- Cold neutron beam experiments detect the appearance of either protons or electrons from neutron β-decay



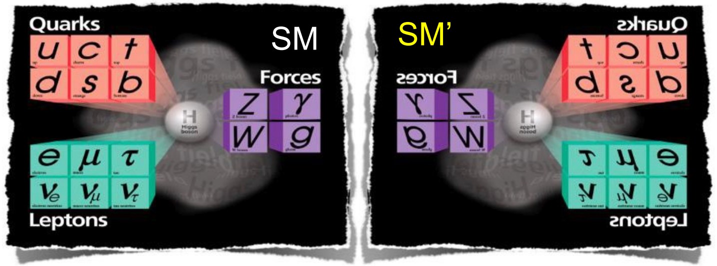
Sterile “Mirror” Neutrons

- Hidden, mirror sectors proposed as dark matter candidate: predicts phenomenon of neutron oscillations into “mirror” neutrons $n \rightarrow n'$ PRL **96** 081801 (2006), EPJC **64** 421 (2009)

- New theoretical model of non-degenerate mirror matter could explain the neutron lifetime anomaly EPJC **79**, 484 (2019)

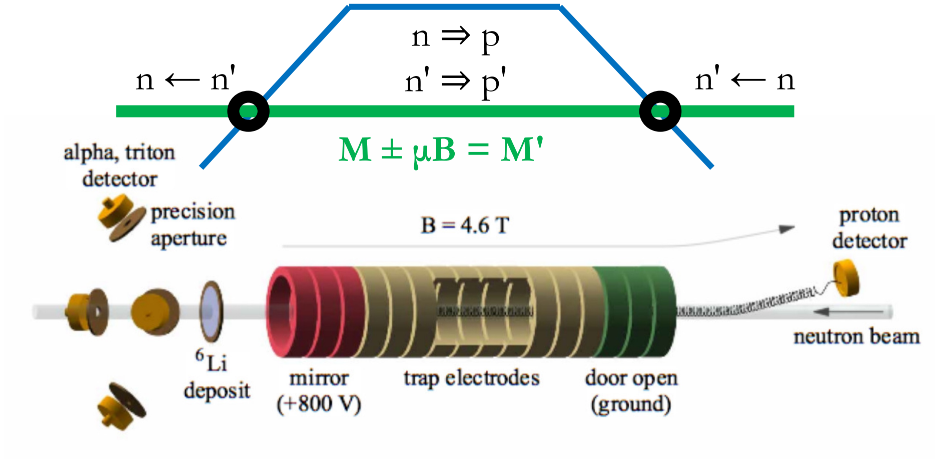
- In this model, the neutron n mixes with a sterile “mirror” neutron n' with a non-degenerate mass $m_{n'} = m_n \pm \Delta m$ via an oscillation described by a mixing angle θ_0

- This $n \leftrightarrow n'$ mixing is amplified when the mass splitting Δm compensates the magnetic potential $\mu_n B$



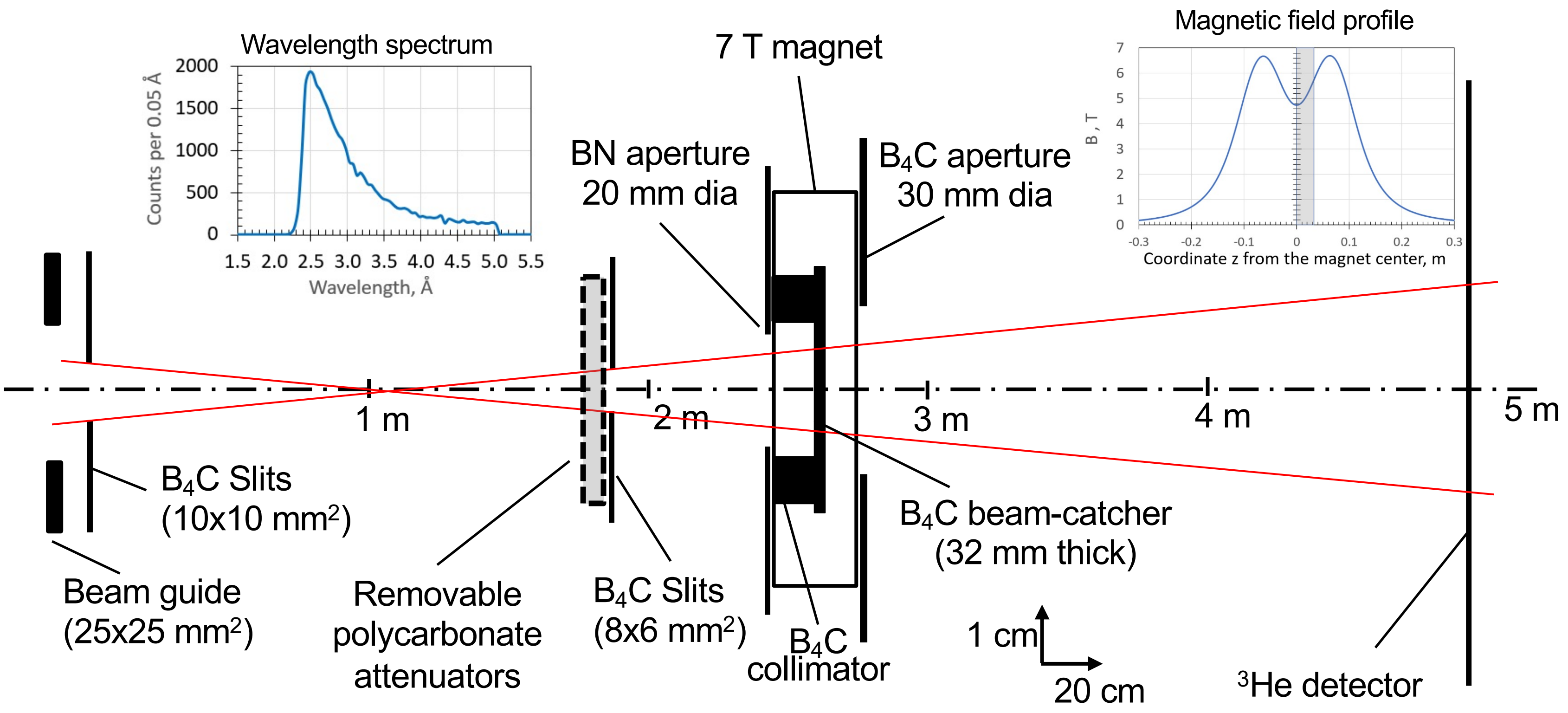
$$H_{osc} = \begin{pmatrix} m_n - |\mu_n B| & 0 & \epsilon & 0 \\ 0 & m_n + |\mu_n B| & 0 & \epsilon \\ \epsilon & 0 & m_{n'} & 0 \\ 0 & \epsilon & 0 & m_{n'} \end{pmatrix}$$

Mirror Neutrons in Beam Lifetime Experiments

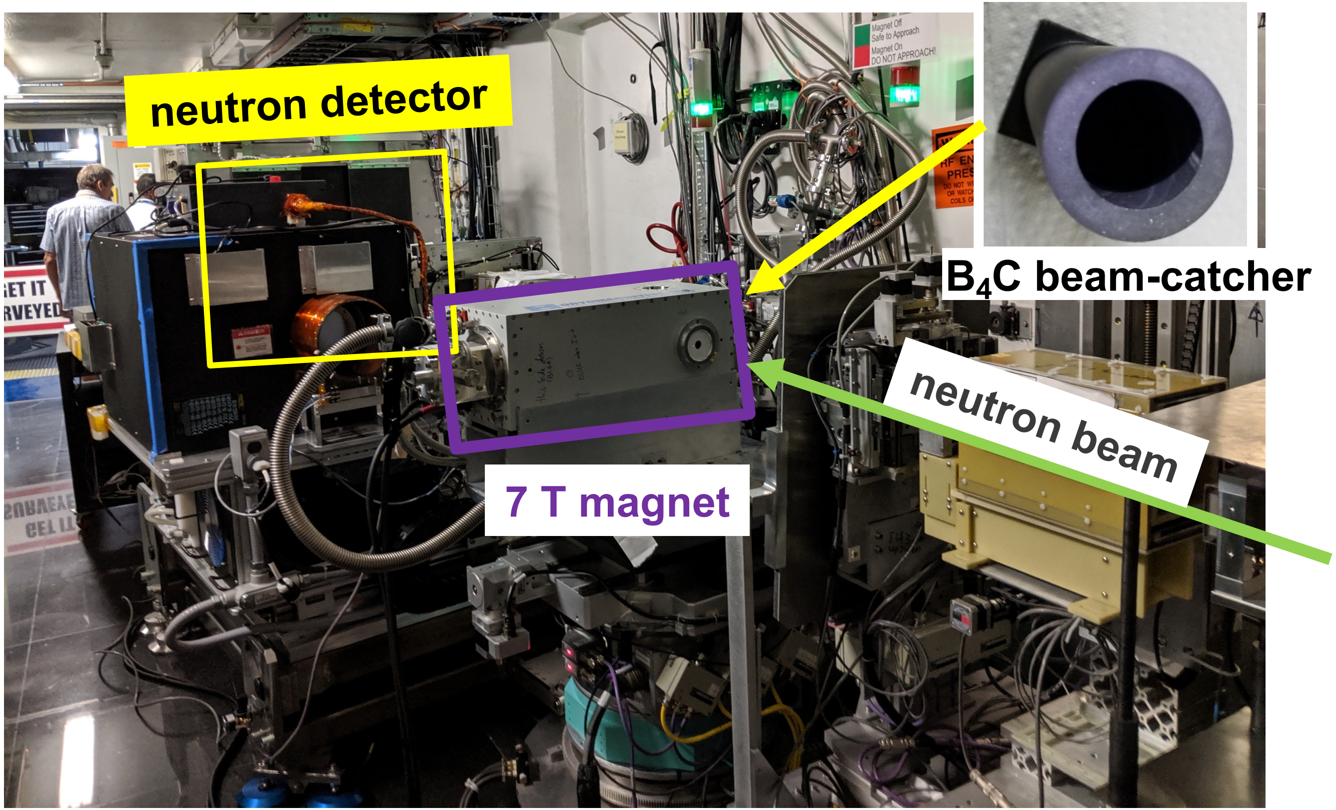


- In beam lifetime experiments, neutrons that oscillate into mirror neutrons would decay into mirror protons and would not be counted
- Mirror neutrons that don't decay will regenerate and not affect the measured neutron flux
- The lower proton appearance rate would lead to a longer lifetime measurement

Detecting Mirror Neutrons



Detecting Mirror Neutrons



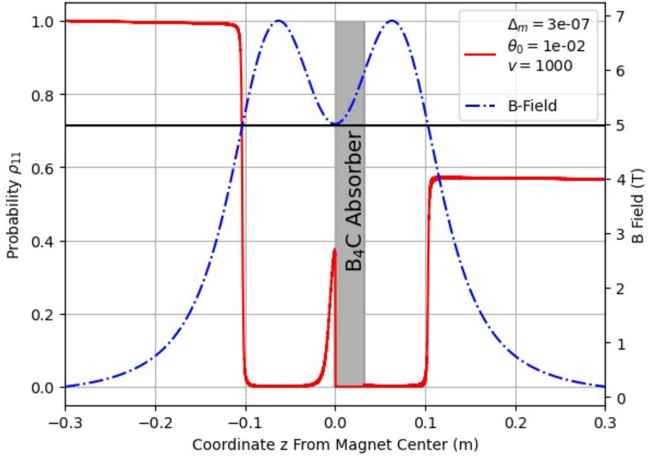
Simulation

- We want to calculate the probability of detecting neutrons behind the absorber
- We do this by numerically integrating the Liouville-von Neumann equation to calculate the evolution of the density matrix
  - This is very computationally intensive!
- GPU parallelization using CUDA and the Julia language allows us to calculate tens of millions of parameter combinations simultaneously

$$\hat{\rho} = \begin{pmatrix} \langle\psi_n|\psi_n\rangle & \langle\psi_n|\psi_{n'}\rangle \\ \langle\psi_{n'}|\psi_n\rangle & \langle\psi_{n'}|\psi_{n'}\rangle \end{pmatrix}$$

$$i\hbar\frac{\partial\hat{\rho}}{\partial t} = H\hat{\rho} - \hat{\rho}H^{\dagger}$$

$$H = \begin{pmatrix} V - iW - \Delta m \pm \mu_n B(z) & \epsilon \\ \epsilon & 0 \end{pmatrix}$$

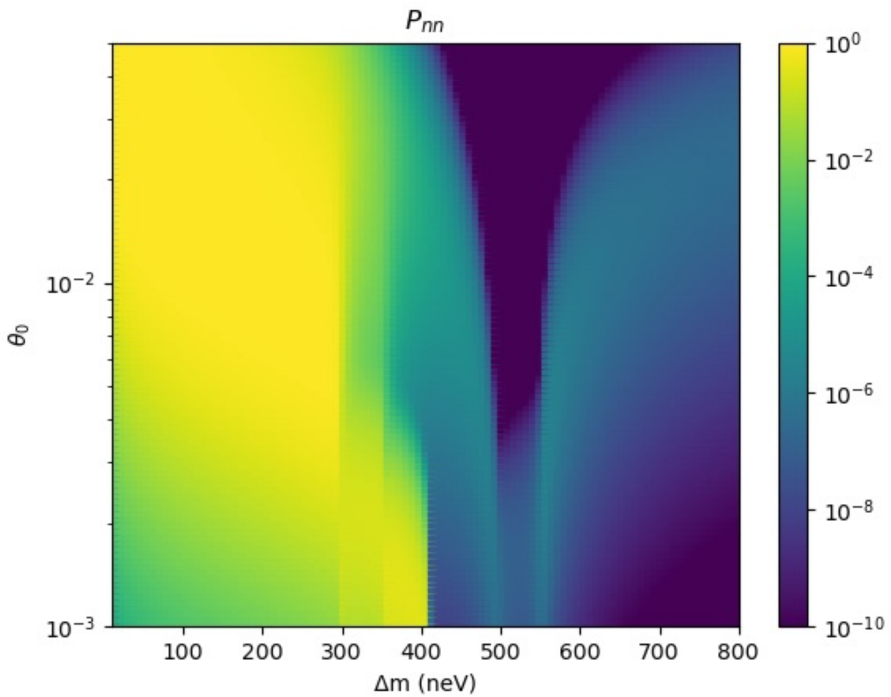


- We average the final probabilities over the velocities present in the neutron beam and over both neutron polarizations $(\pm\mu_n B)$

- For $\Delta m < 300$ neV, there is one Landau-Zener transition before and after the absorber, there are two for $300 < \Delta m < 400$ neV and none for $\Delta m > 400$ neV

- The Landau-Zener transition leads to a very large probability of detecting regenerated neutrons

Simulation

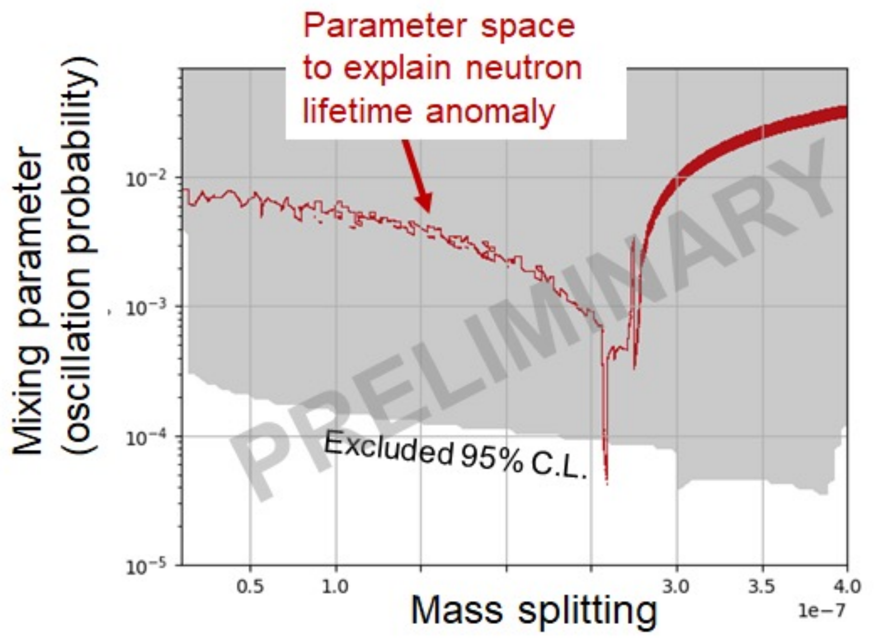


Experiment

- The beam intensity was determined by measuring the intensity with varying numbers of polycarbonate attenuators and was extrapolated to 0 attenuators. We found $I_0 = (1.05 \pm 0.24) \times 10^9$ n/C
- Performed measurements with beam-catcher in different positions and with magnetic field values
- No evidence of transmission through the B_4C beam-catcher was observed

B Field at B4C	B4C Position	Total Cts in ROI	Charge	Cts / 5C
+4.8 T	center	7748 ± 88	13.8 C	2805 ± 32
-4.8 T	center	4976 ± 70	8.8 C	2823 ± 40
0 T	center	6631 ± 81	11.9 C	2791 ± 34
3.33 T	center	1017 ± 32	1.8 C	2817 ± 88
+6.6 T	peak B	1010 ± 32	1.8 C	2804 ± 88
-6.6 T	peak B	1120 ± 33	2.0 C	2863 ± 86
0 T	peak B	4916 ± 70	8.7 C	2815 ± 40

Results



Gray – Excluded region from our experiment (95% CL)
Red – 1% ± 0.2% difference in neutron lifetime

- Calculation of effect consistent with lifetime anomaly was extended to Δm < 277 neV based on EPJC **79**, 484 (2019)
- We used the Feldman-Cousins method to calculate an anomalous transmission of < 3.4 x 10^{-7} (95% C.L.)
- We can exclude the non-degenerate mirror matter model as an explanation for the neutron lifetime anomaly for mass splittings from 10 neV to 400 neV, except for a narrow region around 277 neV

Acknowledgements

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