New Search for Mirror Neutrons at HFIR

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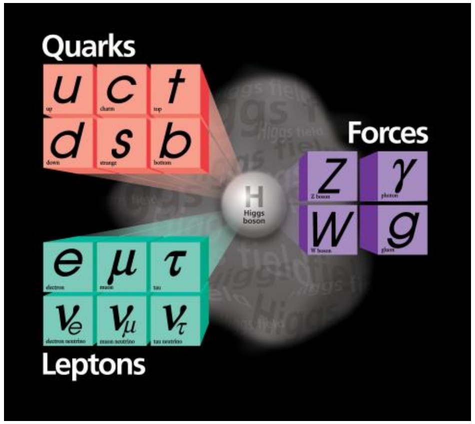
October 24, 2017

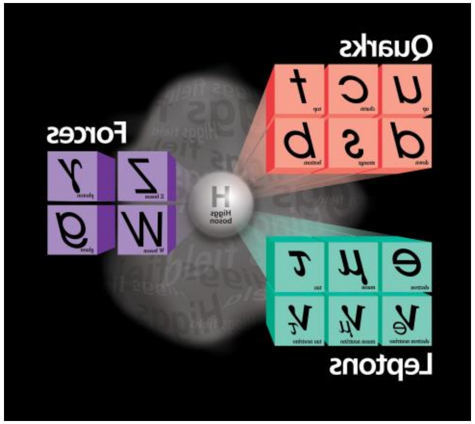
Neutron-Antineutron Oscillations: Appearance, Disappearance, and Baryogenesis (October 23 - 27, 2017)

Primer on Mirror Matter

SM



SM′



- Identical copy of SM with opposite parity
- No new parameters
- Long considered a ‘hidden sector’ DM candidate

Phys. Usp. **50** 380 (2007)

Neutron Oscillations

- Small B’ possible due to accumulated MM captured by earth

$$\hat{H} = \begin{pmatrix} m - i\Gamma / 2 + \mu(\vec{B}\cdot\vec{\sigma}) & \varepsilon \\ \varepsilon & m' - i\Gamma' / 2 + \mu'(\vec{B}'\cdot\vec{\sigma}) \end{pmatrix}$$

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

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

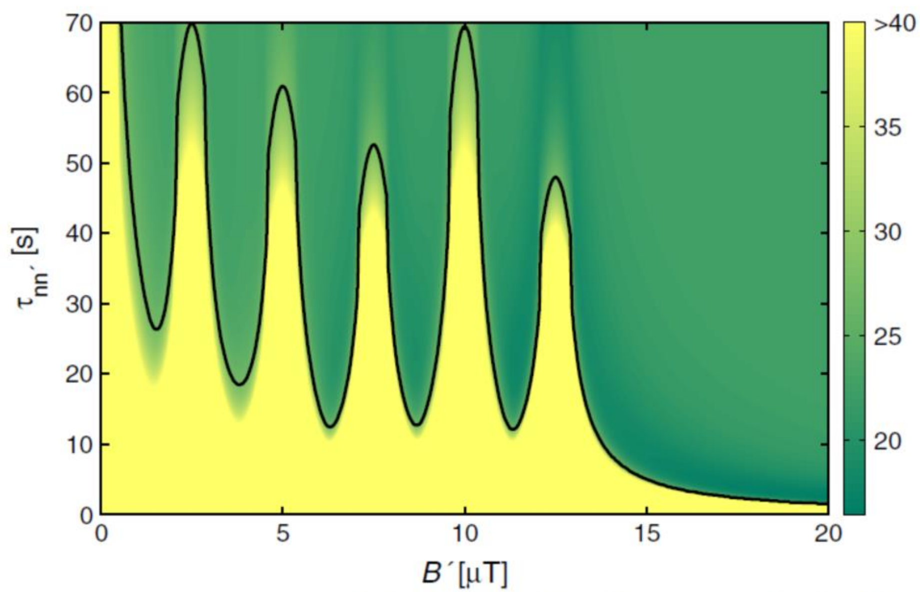
$\omega = \frac{1}{2}|\mu B|$, $\omega' = \frac{1}{2}|\mu' B'|$, $\mu = \mu'$ and $\tau = \frac{1}{\varepsilon}$

- Scales as t^2/τ^2
- Resonance condition
- **B**-**B’** direction

Berezhiani and Bento PRL **96** (2006) 081801

Previous UCN searches for n → n’

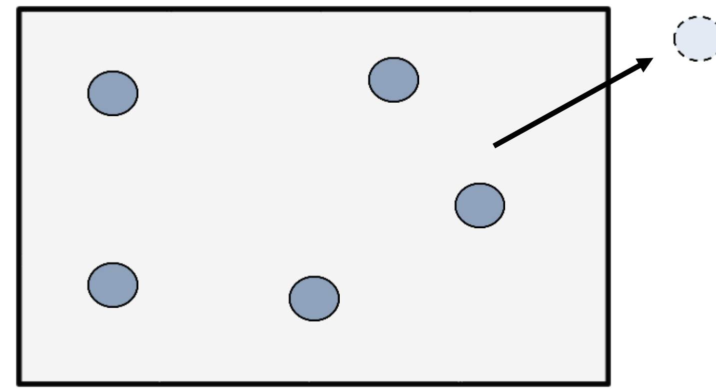
- Strong limits from Serebrov[1] if B’= 0 ($\tau > 448$ s)
  - Compare to neutron β decay lifetime ~ 15 minutes
  - Reanalysis[2] with B’≠ 0, anomaly at B’ ~ 100 mG, τ ~ 10 s
- Altarev et al[3] scanned for B’ up to ±125 mG
  - Sensitivity limited by large 25 mG step size
  - Limit: $\tau > 12$ s (95% C.L.)



PHYSICAL REVIEW D **80**, 032003 (2009)

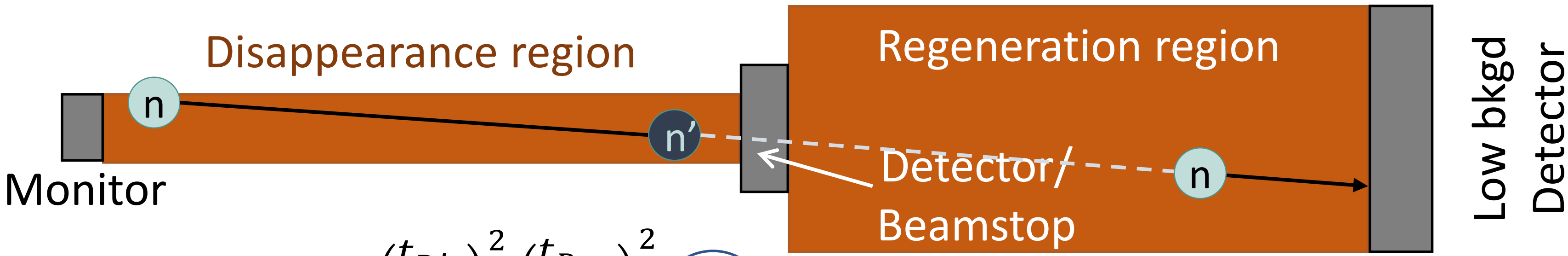
Serebrov, NIMA **611** 137 (2009)
Berezhiani and Nesti, Eur. Phys. J C **72** 1974 (2012)
Altarev, PRD **80** 032003 (2009)

UCN searches



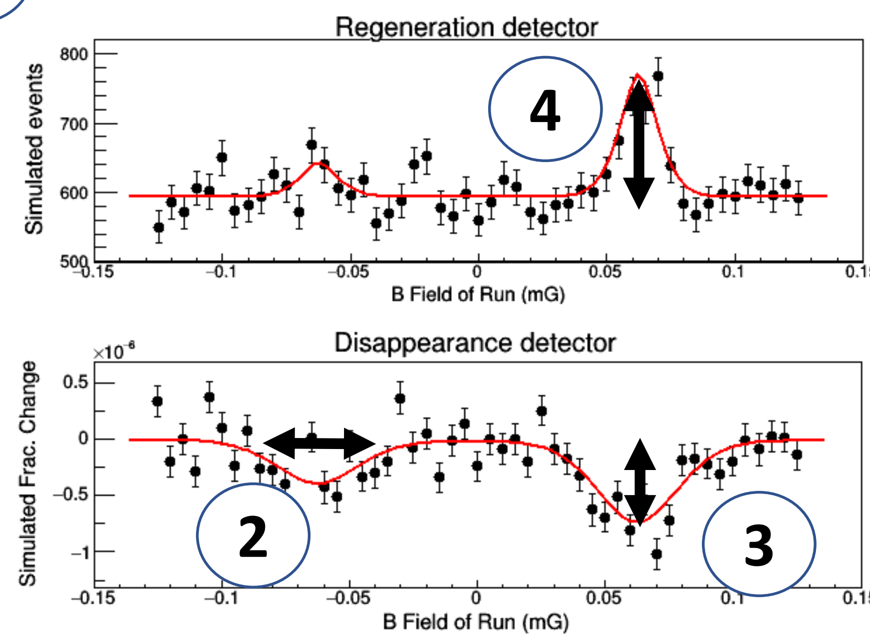
- Disappearance only: study storage time
- $\tau_{st}^{-1} = \tau_{\beta}^{-1} + \mu_{loss}\upsilon + \frac{\langle \tau_f^2 \rangle}{\tau_{osc}^2}\upsilon$
- Goals: Large volume, small μ, high UCN densities
- Considerations: constant μ with B? unmonitored spectral variations? field uniformity? transport in/out of trap?
  - Good to have independent approach

Search for n → n′ with CN



$$P(n \rightarrow n' \rightarrow n) \propto \left(\frac{t_{Dis}}{\tau}\right)^2 \left(\frac{t_{Reg}}{\tau}\right)^2$$ 1

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



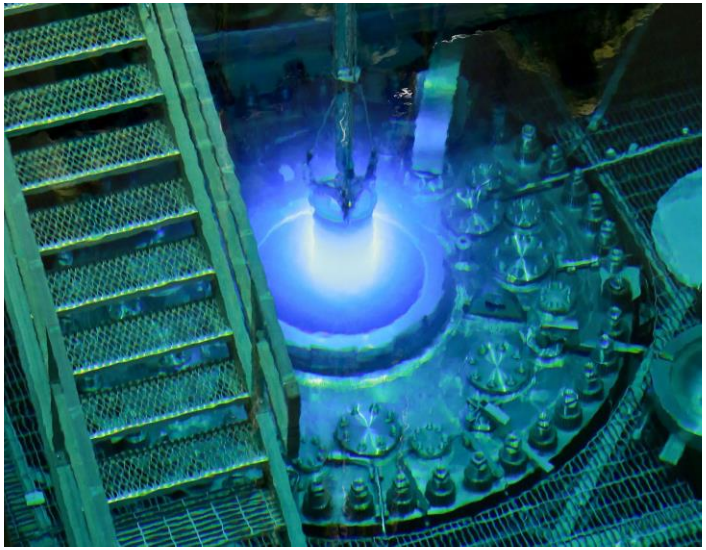
U. Schmidt, Search for Baryon and Lepton number Violations Int’l Workshop (2007)
Z. Berezhiani *et al*, *PRD* ***96*** *035039 (2017)*

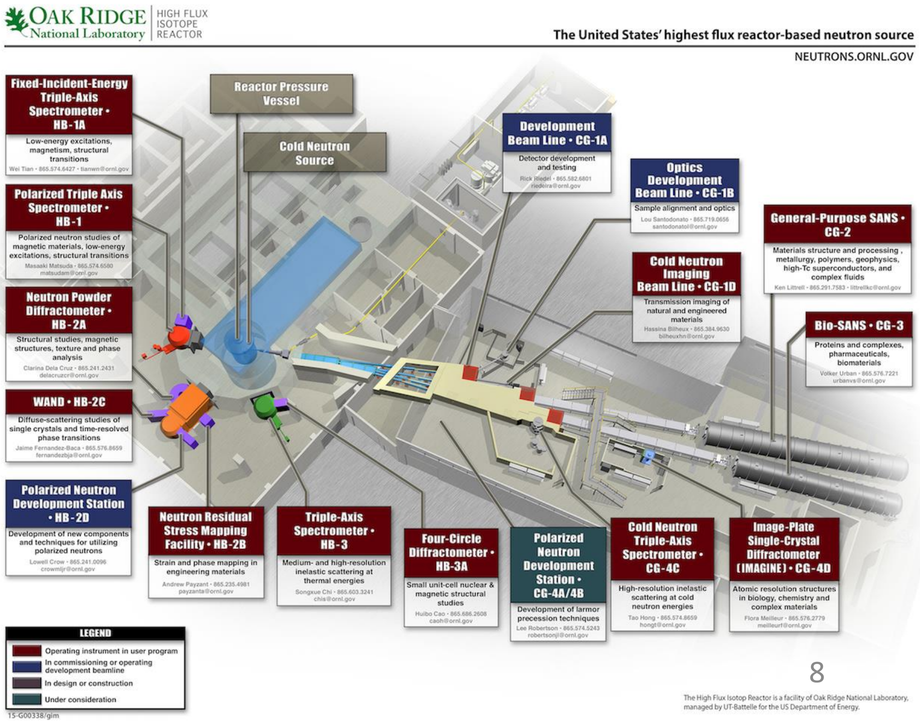
Contrast: CN vs UCN

- UCN
  - Compact!
  - Very low flux, 10k’s of bounces
  - Measurement cycle ~ minutes, but less sensitive to normalization
- CN
  - Long beamline required ($$$)
  - High flux, few bounces
  - Measurement cycle ~ < 1s, but more sensitive to beam intensity, detection efficiency
  - Back pocket: regeneration for unambiguous signal

High Flux Isotope Reactor

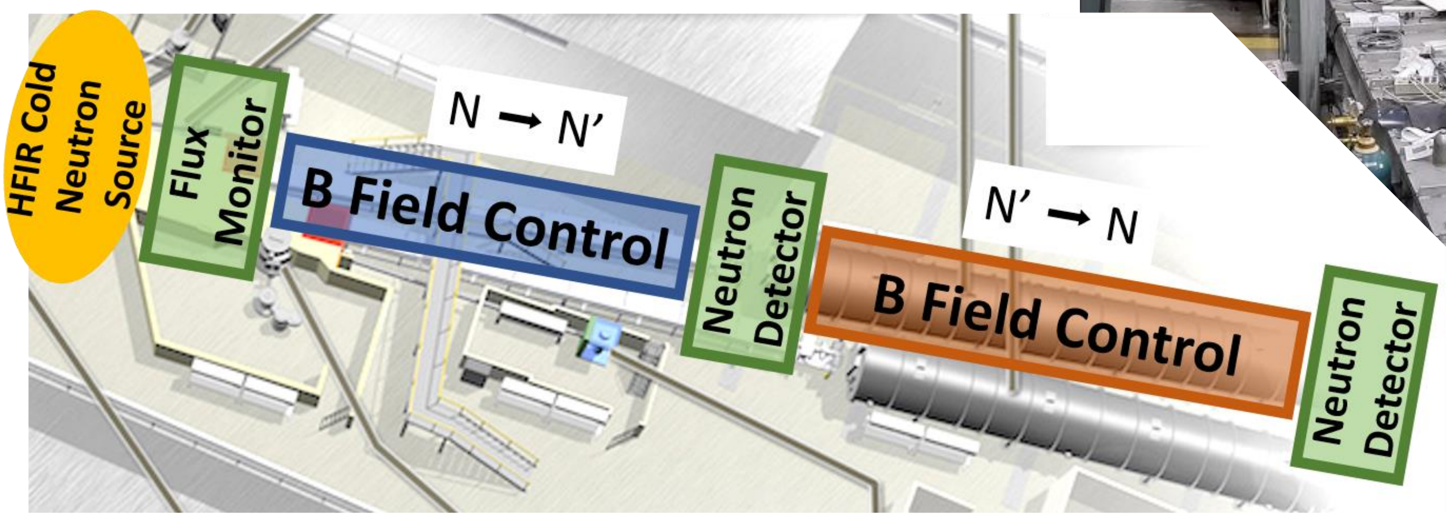
- 85 MW reactor: highest reactor based source of neutrons for research in US





GP-SANS at HFIR

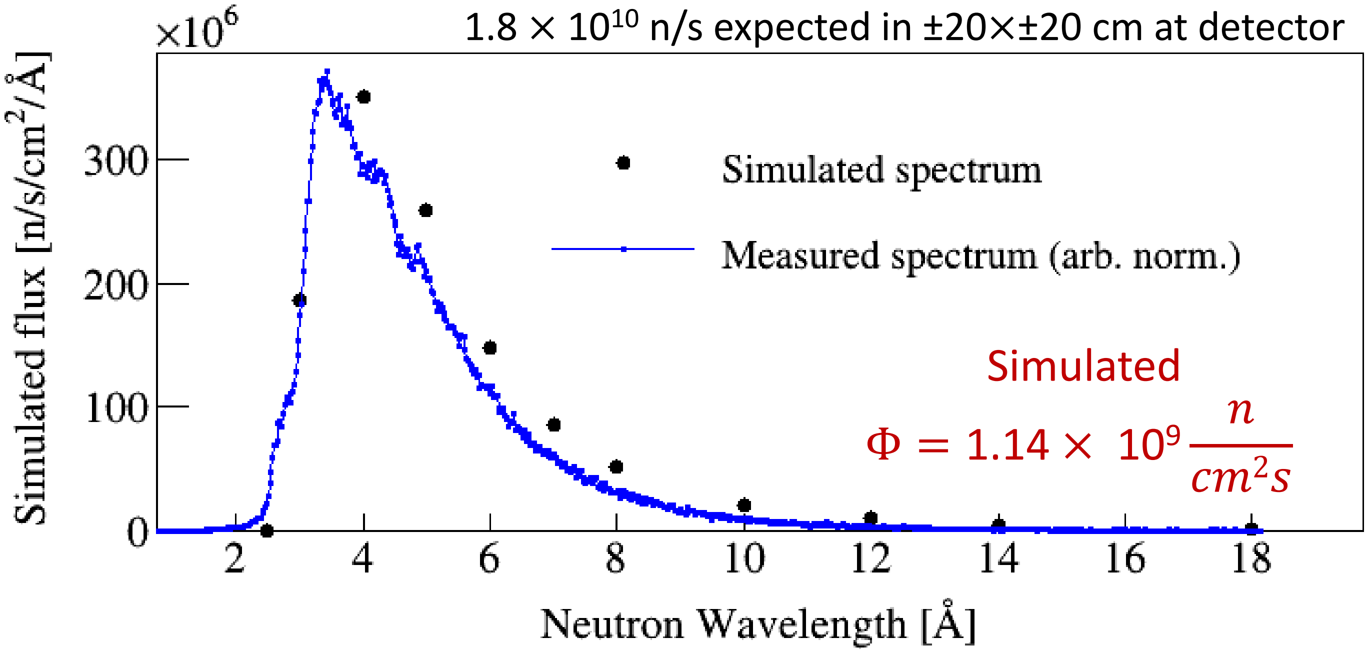
- Existing instrument: General-Purpose Small Angle Neutron Scattering
- Existing beamlines and regeneration detector
- Room for B control coils, monitors



GP-SANS neutron flux

- GP-SANS beamline: 1.8×10^{10} n/s, peaked at 4 Å
- At τ = 15 s expect: 10^4 n→n'/s; 0.05 n→n'→n/s

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



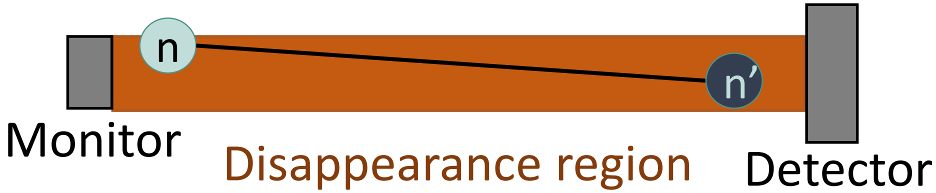
Simulated

$$\Phi = 1.14 \times 10^9 \frac{n}{cm^2 s}$$

Stage 1: Disappearance

- Considerations
  - Magnetic field control
  - Monitoring and detection
  - Nonstatistical neutron flux/spectral variations

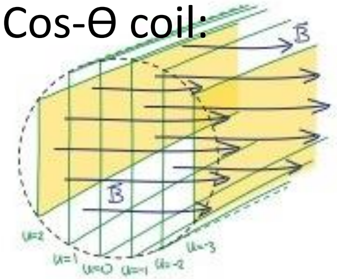
$$P(n \rightarrow n') \propto \left(\frac{t_{Dis}}{\tau}\right)^2$$

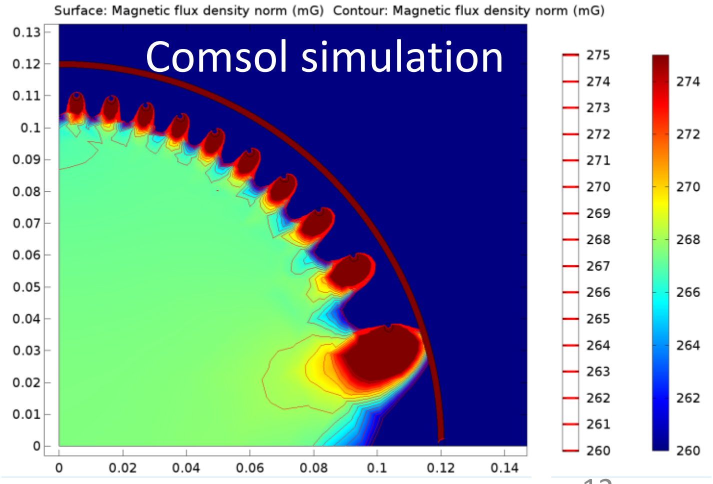


Magnetic field control

- Sensitive to other beamlines, some use ~10T magnets
  - 10 mG temporal, 100 mG spatial variations; ~1 G spikes
- Single layer Mu-metal + solenoid (z) and Cos-Θ coils (x-y)
  - ~mG level uniformity for 20 cm diameter guide

Cos-Θ coil:

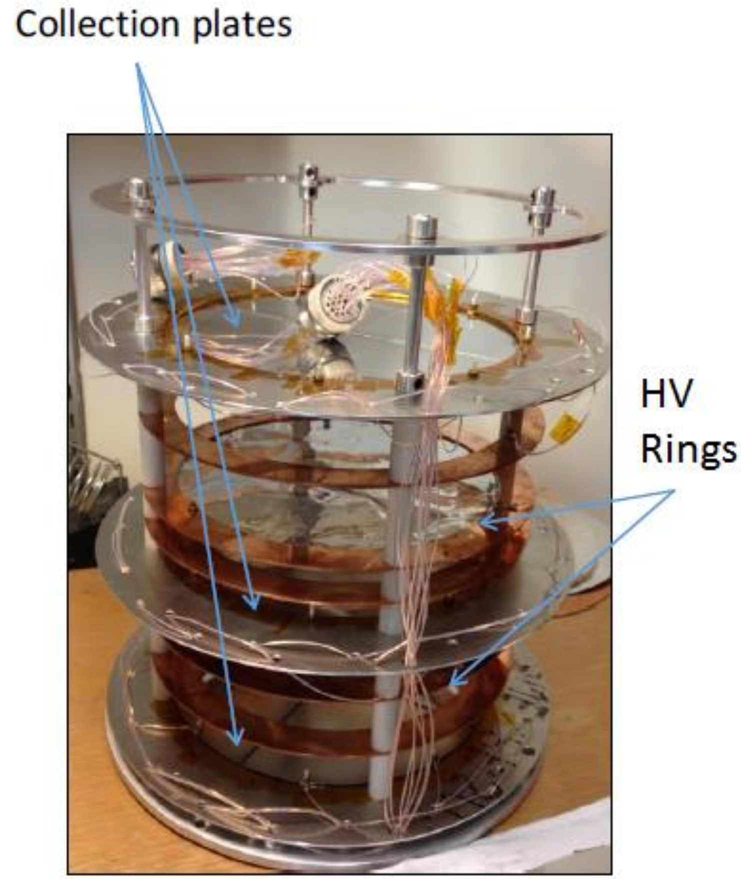




With J. Barrow, B. Chance, B. Rybolt, S. Vavra UTK; C. Crawford, UKy

Neutron flux monitoring

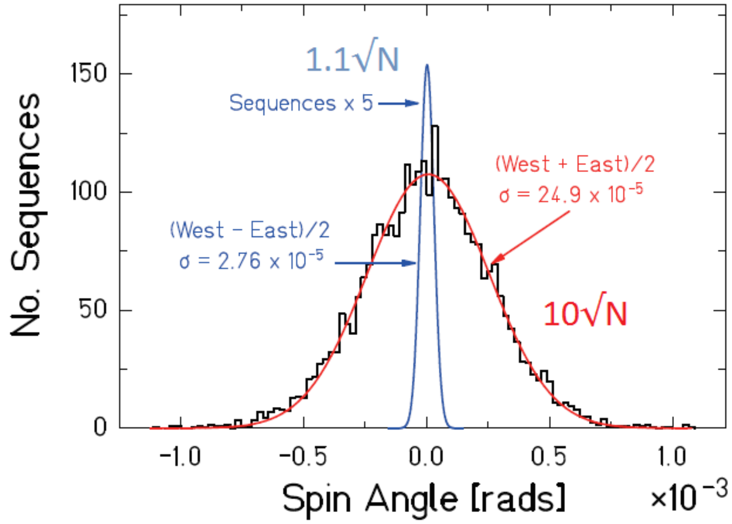
- Detector designed for n-^{3}He spin rotation experiment (Indiana U.)
  - Implemented for 10^{-8} level asymmetry measurements
- ^{3}He ion chamber[1]
  - *n+^{3}He→t+p*
  - Large signal, well defined amplitude, insensitive to gamma radiation
  - Current-mode detector: high flux
- Detailed characterizations required



[1]S. D. Penn *et al*, *NIMA* **457** (2001) 332

Nonstatistical flux variations

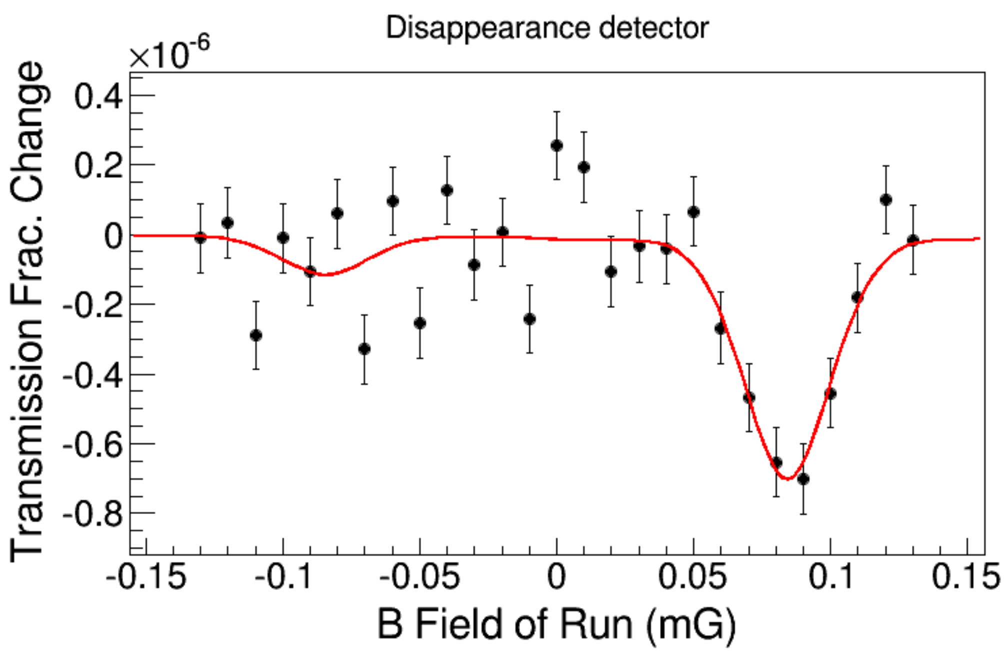
- 10^{-7} level monitoring of transmission goal
  - Lots of 2^{nd} order effects become important…
- First trick: run sequence cancels drift (+ - - + - + + -)
  - Goal: sub-second B-field switching
  - Obviate monitoring reqs?
- Second trick: Detector segmentation[1]
  - Spatial systematics
  - 1/f beam noise cancellation
  - Sensitivity 10% above stat limit!



[1]W. M. Snow *et al, in prep*

Disappearance sensitivity

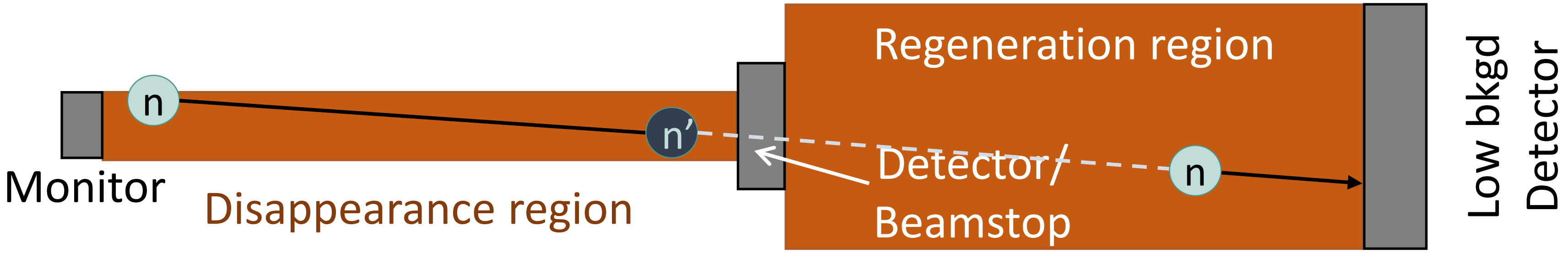
- B field step size of 10 mG is sufficient
- Assume 30% upstream monitor required
- Idealized: large guide = no bounces
- Sensitivity up to τ > 18 s (90% C.L)



Stage 2: Regeneration

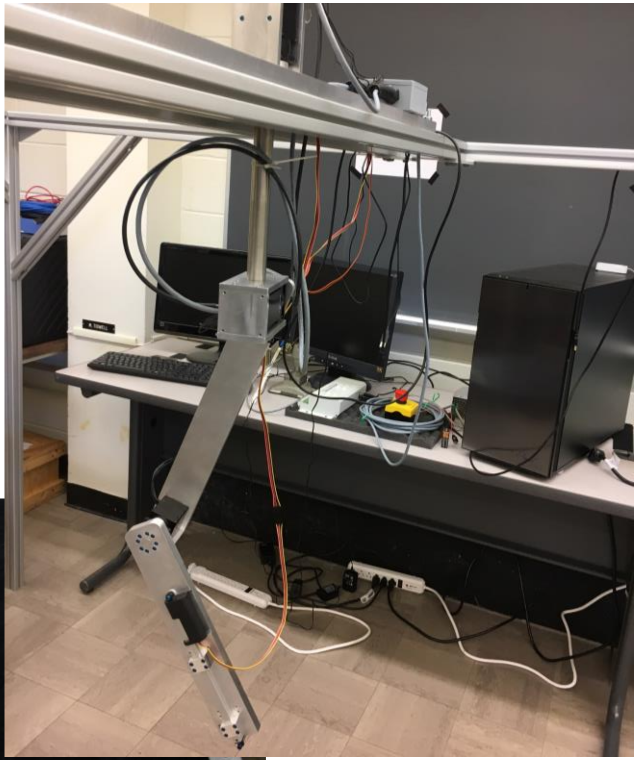
- Considerations:
  - Somewhat more awkward magnetic field control
  - Nominal flux monitoring needed
  - Primarily limited by detector backgrounds

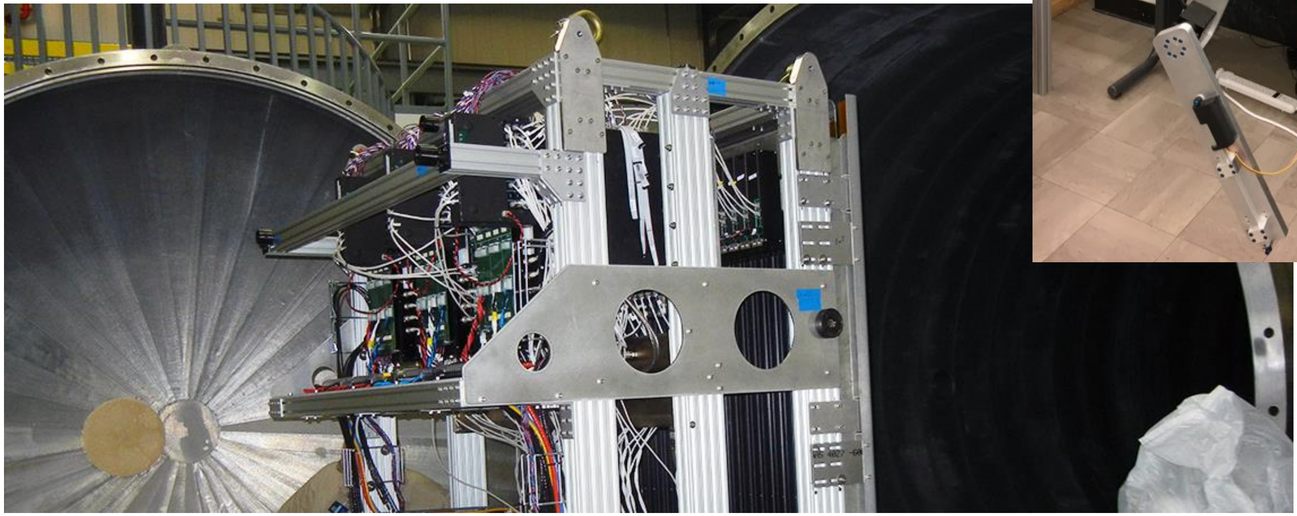
$$\mathrm{P}(\mathrm{n} \rightarrow \mathrm{n}' \rightarrow \mathrm{n}) \propto \left(\frac{t_{Dis}}{\tau}\right)^2 \left(\frac{t_{Reg}}{\tau}\right)^2$$



Magnetic field control

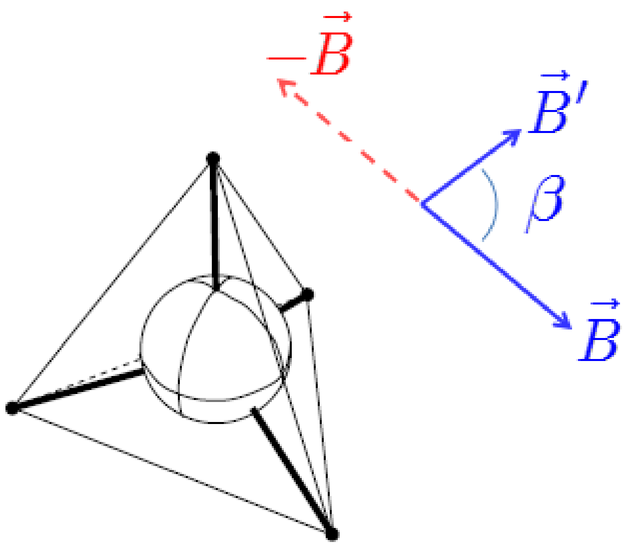
- Limited chamber access
- Ambient B field studies: attach robot arm to movable detector (developed for UCNτ)
- Maps 1.5m radius half-sphere, 1 mm^3 position resolution



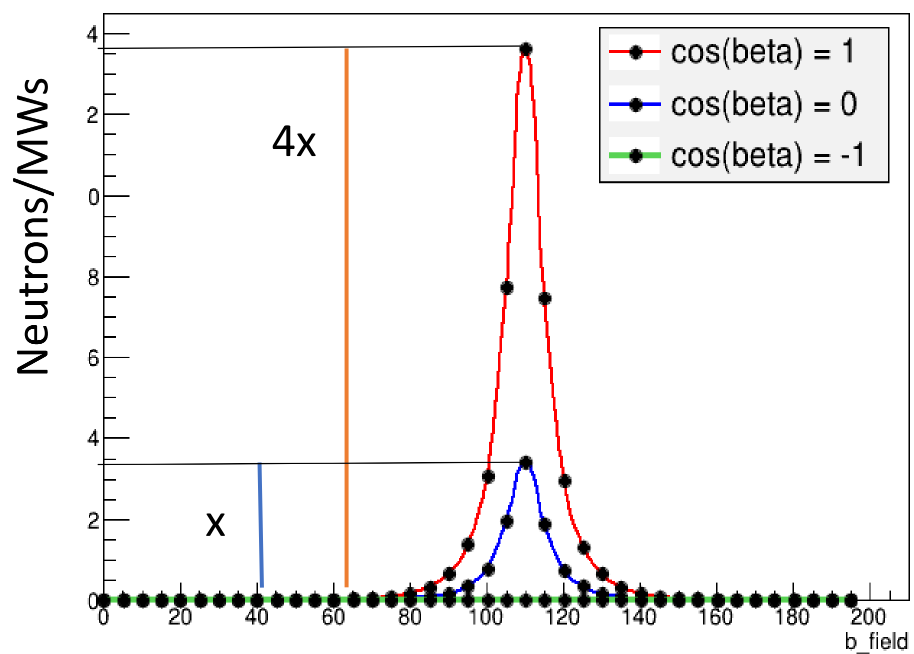


Magnetic field scan optimization

- Regeneration more sensitive to B-B’ misalignment
- Optimal sensitivity from 4 point 3D scan (worst case β=60°)

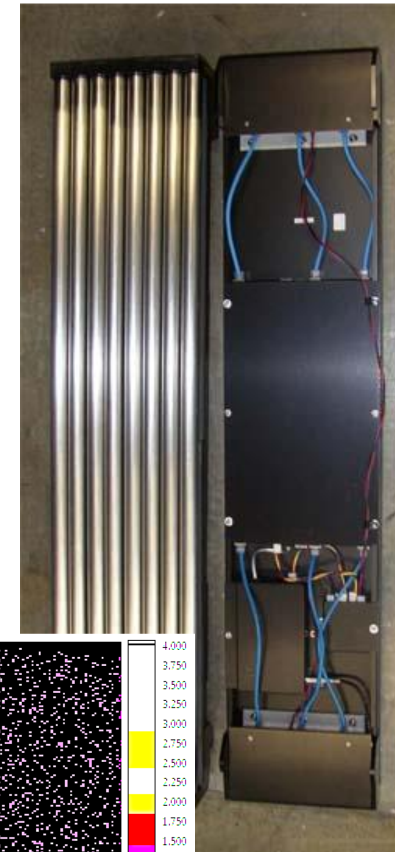


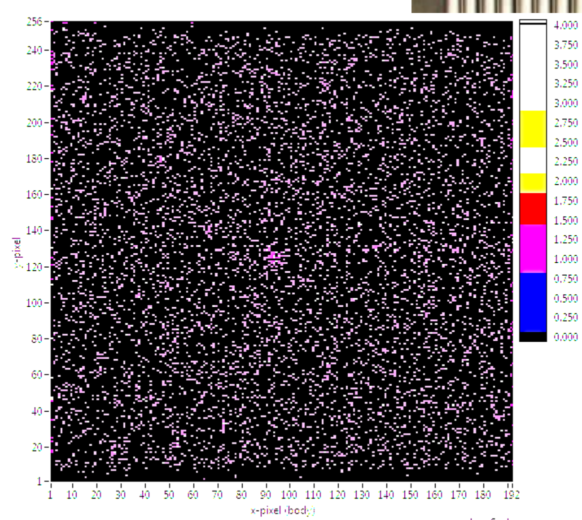
Example: $\tau = 3$, B’ = 110 mG



Regeneration detector

- 1 m x 1 m ^{3}He, position-sensitive detector[1]
  - $n+{}^3He \rightarrow t+p$
  - Large signal, well defined amplitude, insensitive to gamma radiation
  - 5 mm x 5 mm position resolution
- 2 x 10^{-4} cps/cm^2 background
  - Primarily from cosmogenic neutrons, moderated by concrete floor
  - Can use position cuts and additional shielding/veto
  - Goal: 0.05 cps total

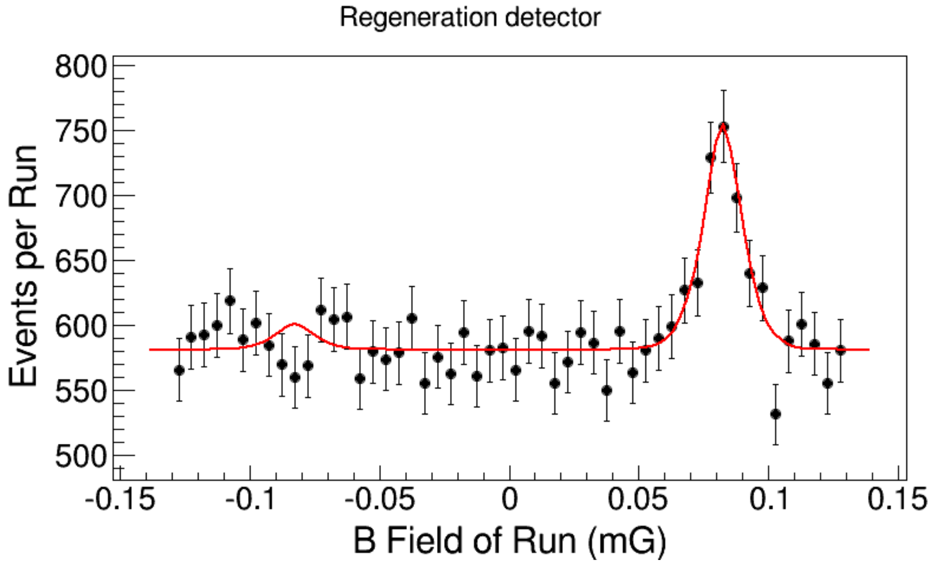




[1]K. D. Berry *et al*, *NIMA* **693** (2012) 179

Regeneration sensitivity

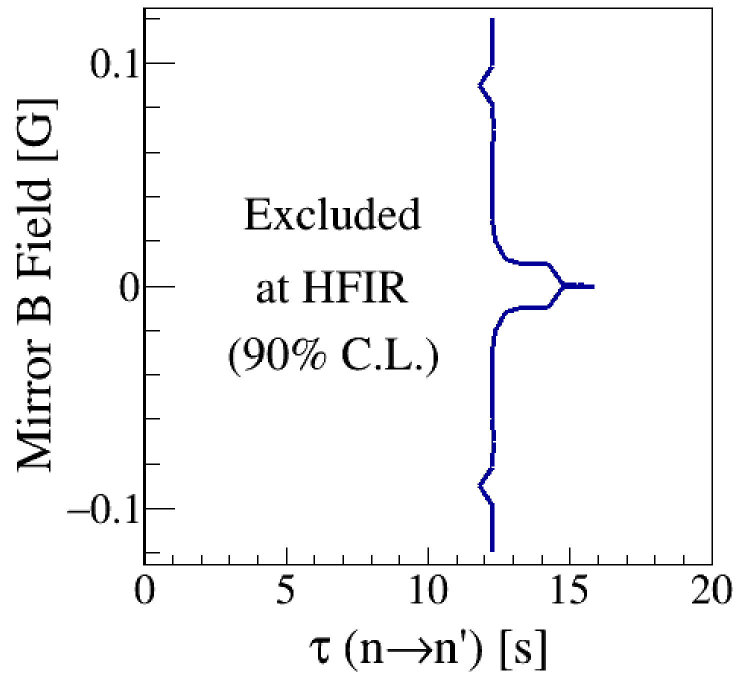
- B field step size of 5 mG required, 4 point 3D scan
- Assume 1% upstream monitor
- Total background 0.3 cps (1500 mm^2 area used)
- Sensitivity up to $\tau > 15$ s (90% C.L)



Simultaneous measurement

- Powerful systematic check to produce unambiguous signal
- Reduced statistical sensitivity
- 2 mG steps, 4 pt 3D search
- 30% upstream flux monitor
- Can reach τ < 12 s (90% C.L>) in 14 days beamtime

14 days beamtime



What's next?

- Demonstrate feasibility
  - Prototype short section of magnetic field control
  - Demonstrate flux monitoring techniques for disappearance
- Phase 1: Disappearance
  - Collimation upgrade in 2018 (reduce magnetic materials)
  - Flux monitor characterizations (10^{-7} level)
  - Implement mG-level magnetic field control
- Phase 2: Regeneration
  - Implement mG-level magnetic field control (limited access to chamber)
  - Implement additional background detectors, shielding, active veto system
- Expect to achieve interesting limits with very modest costs!

n → n′ Collaboration

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