A Proposal to Use Neutron Capture as a Source of Low Energy NRs with MiX

Chami Amarasinghe
Work done with R. Coronel, D.Q. Huang, M. Arthurs, and W. Lorenzon

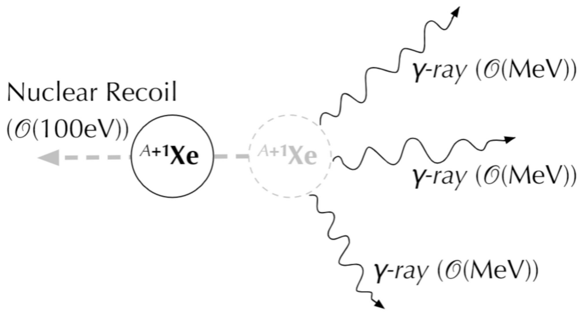
LIDINE
16th September 2021

Introduction

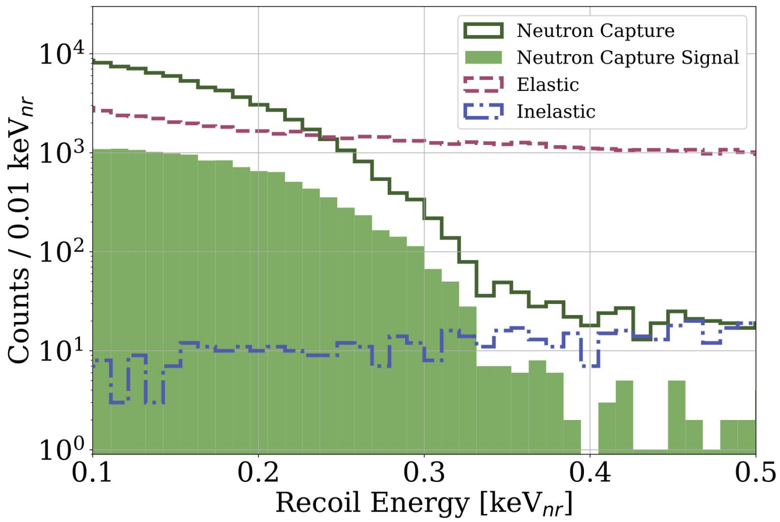
Goal: A measurement of the NR scintillation and ionization yields in LXe below around 0.3 keV_{nr}.

Apparatus: The Michigan Xenon (MiX) detector and a *pulsed neutron generator*.

NR source: Neutron captures on xenon where the emission of prompt **γ** rays recoil the xenon nuclei [1-4].



- Several **γ** rays are emitted following capture.
- Events where all **γ** rays escape the active volume of the detector will have pure NR signature [4].



Simulated recoils of neutron interactions in the MiX detector

MiX Detector and Simulations

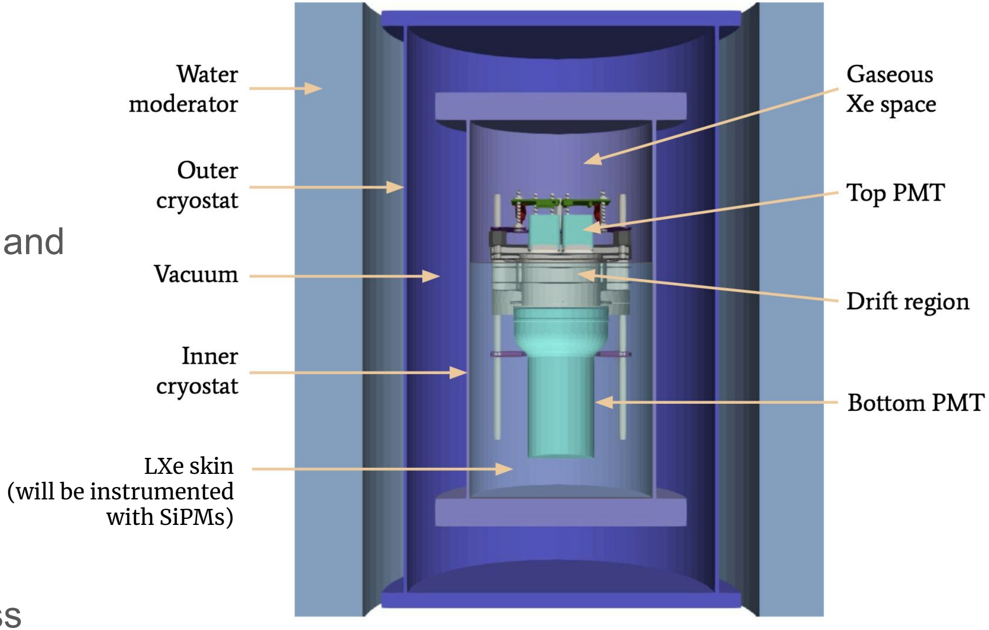
MiX is a small, dual-phase, LXe TPC designed to have high signal collection [5]:

- *g1 = 0.239 ± 0.012 PE/photon **
- *g2 = 16.1 ± 0.6 PE/electron*

BACCARAT was used to simulate the passage and interactions of neutrons in MiX [6,7]:

- Pulsed beams of 2.45 MeV D-D neutrons were shot at the detector.
- A 5 cm thick water tank surrounds the detector to moderate neutron energies

Pulse width, frequency, and moderator thickness were optimized using simulations.



Model of the MiX detector with a water tank around it

* Large TPCs employed in dark matter searches have a g1 of around 0.1 PE/photon.

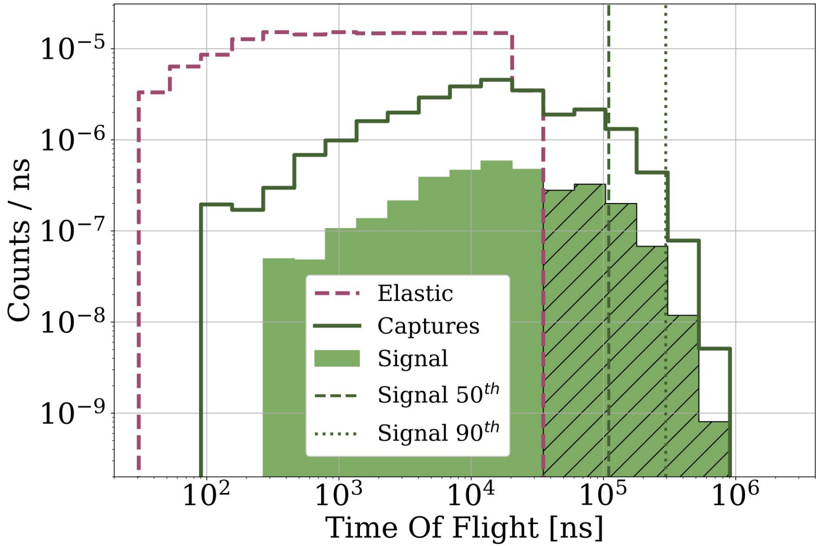
Timing Effects

In each beam pulse...

- The water tank moderates neutrons and filters them by speed.
- Since the capture cross section scales inversely with neutron speed, capture events occur much later than scatters.
- There is a window of time (~ 500μs) where the only NRs are due to neutron capture.

Optimal timing parameters:

- *Pulse width = 30 μs*
- *Pulse frequency = 60 Hz*



Simulated time (from the start of the pulse) at which neutron interactions occurred in the MiX TPC.

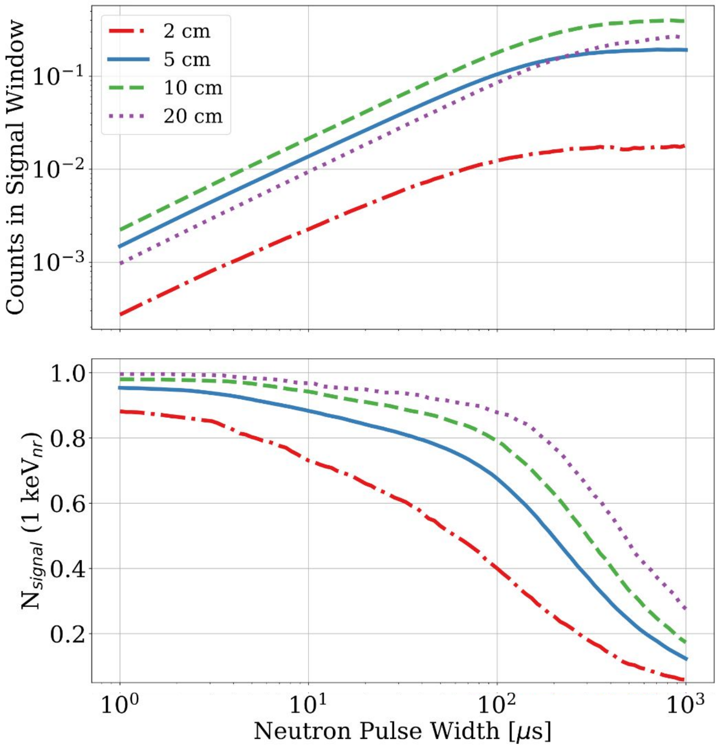
Neutron Pulse Width

Neutron pulse width affects the timing of neutron scatters more than neutron captures.

Increase in neutron pulse width causes number of signals to increase, until the elastic scatters overlap with captures (decreasing signal window length).

$$\mathrm{N}_{\mathrm{signal}}(E_{\downarrow}, w_n) = \frac{\text{Number of capture signals after the last scatter}}{\text{Total number of capture signals}}$$

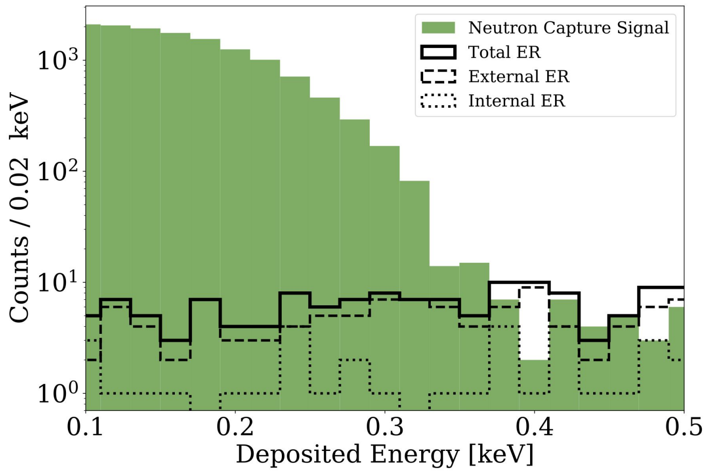
First hint of constraints of the neutron pulse width.



Signal counts per pulse and fraction of signals in the acquisition window as a function of neutron pulse width

Backgrounds

Estimate of the low energy ER background shows it not to be a concern.



Simulated low energy deposits from ERs, along with the neutron capture signal deposits

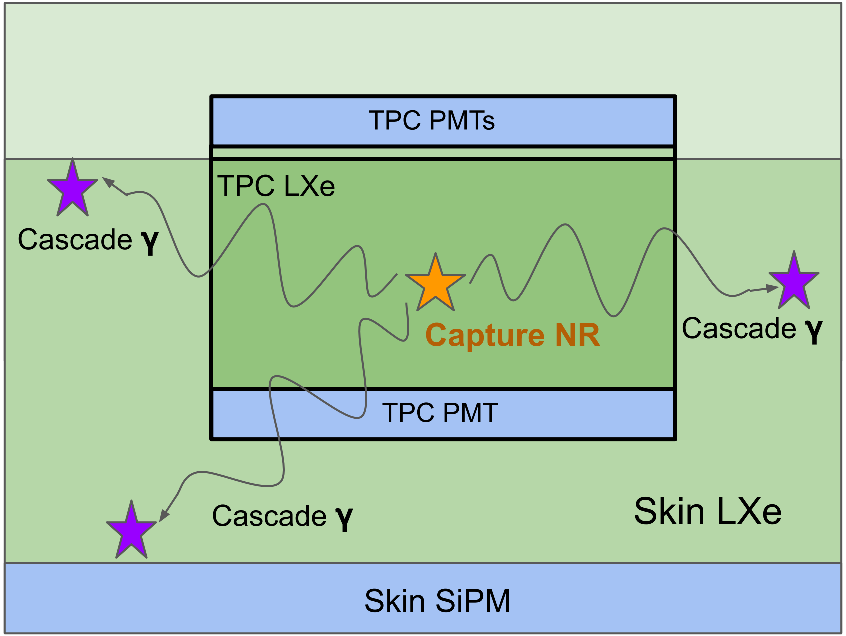
Single electron backgrounds (i.e. e-train) typically following large S2s from > O(100) keV_{ee} energy deposition in LXe are obstacles for the ionization measurement.

- SE emission time scales (O(10 ms) [8]) can be longer than acquisition windows, constraining the neutron pulsing frequency:
    - *f = 60 Hz*
    - *Require e-trains to decay away from previous* **γ** *(following capture) TPC deposits to mitigate SE BG rates.*

Mitigating SE Background

In addition to neutron pulsing, the SE BG rate can also be much further suppressed

- Tagging TPC capture NR signals with coinciding cascade γ rays that escape the TPC but deposit energy in the skin
    - Once the MiX skin is instrumented with SiPM (in plan)



Cartoon of how capture-induced NRs might be tagged using an instrumented skin

ER Contamination

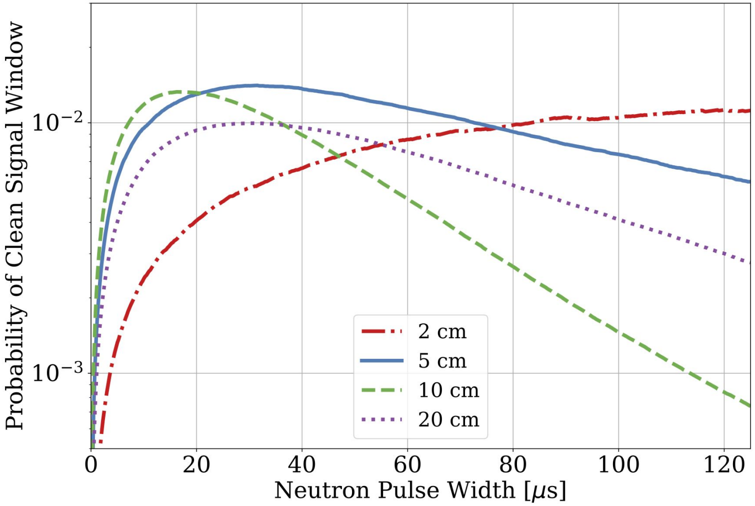
Large ERs from **γ** rays due to captures on nuclei outside the TPC often contaminate the capture-NRs in the signal window.

There is a tradeoff between number of neutron capture signals, and mitigating ER contamination.

For example, in larger water tanks

- More neutron thermalization and captures in the TPC.
- But, also more captures on nuclei outside TPC, whose **γ** rays interact in the TPC.

Compromise is reached for water tank sizes and neutron pulse width.



Probability of obtaining a signal window with no ER deposits, as a function of pulse width

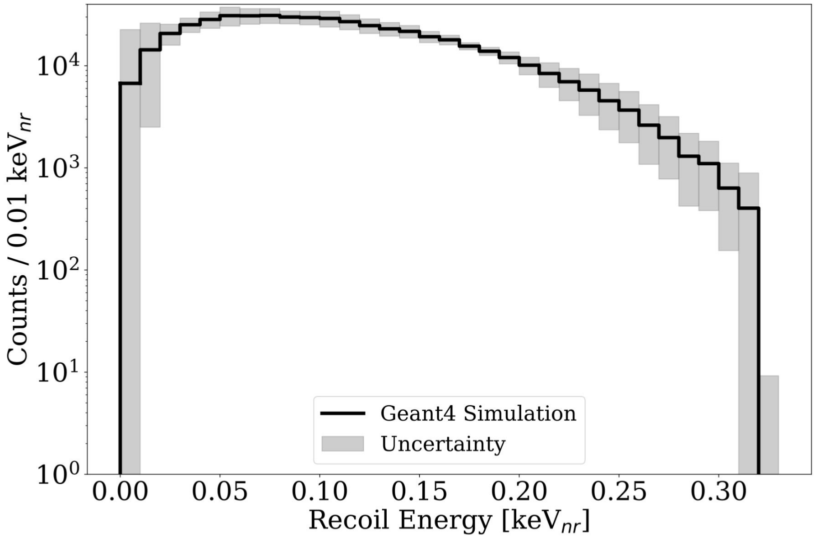
NR Spectrum Uncertainty

Since this is a **model-dependent** measurement, we have calculated the uncertainty of the NR spectrum.

Sources of uncertainty:

- Imperfect knowledge of **γ** spectra per isotope:
    - Deviations among two databases (GEANT4 and EGAF) were used.
- No knowledge of multiplicity distributions from data:
    - Used the difference between broad and narrow distributions.

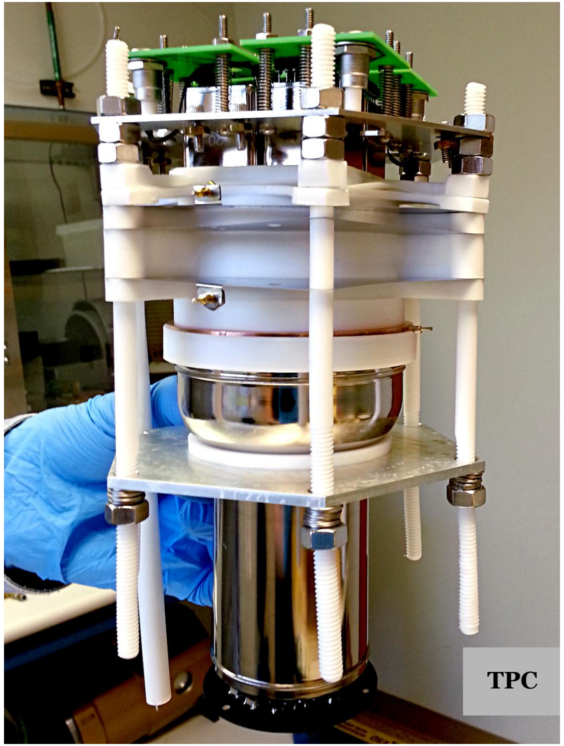
*Random emission directions of **γ** rays make the NR spectrum robust to these sources of error.*

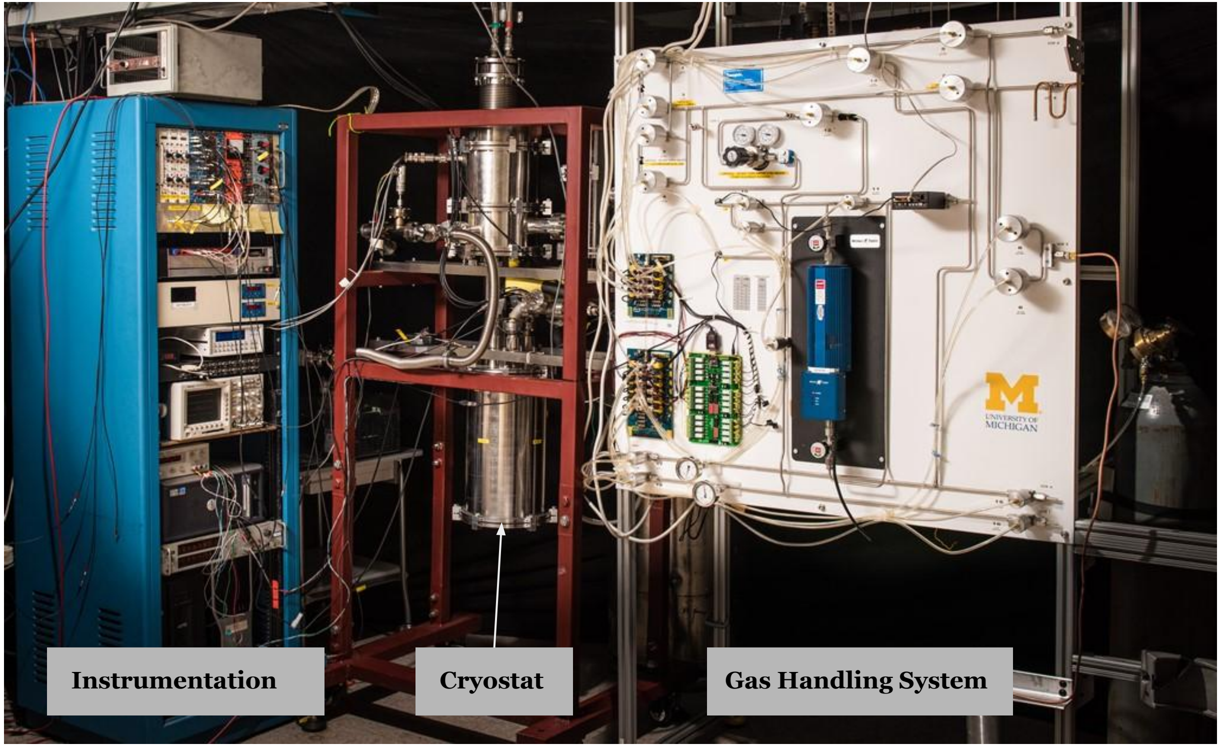


Recoil spectrum due to thermal neutron capture produced by a custom model, with the uncertainty band calculated using deviations in existing cascade data (GEANT4 & EGAF) and our ignorance of **γ** multiplicities [8-10]

Experimental Setup

This summer we have been preparing the MiX detector for operations.





Summary

Neutron transport simulations indicate a source of NRs below 0.3 keV_{nr} produced by neutron capture.

- A small TPC, pulsed neutron source, and a moderator allow these events to be isolated using a time cut.

A **simulation-dependent** measurement of NR yields can be carried out by fitting a yield model to measurements, assuming the NR energy spectrum is correct.

- Several uncertainties, primarily the deviations in measured **γ** cascades of xenon, contributing to the NR spectrum are identified and combined.

ER contamination and small electron backgrounds are the primary obstacles to the experiment. Ideas for mitigation are being investigated.

Preparations for this measurement are ongoing at the University of Michigan.

Write-up of the concept appearing on the arXiv soon.

References

Neutron capture in Ge:

1. K. Jones and H. Kraner, *Energy lost to ionization by 254-eV ^{73}Ge atoms stopping in Ge* - Phys. Rev. A **11**, 1347 (1975)
2. J. Collar, A. Kavner, and C. Lewis, *Germanium response to sub-keV nuclear recoils: A multipronged experimental characterization* - Phys. Rev. D **103**, 122003 (2021)

Neutron capture idea in LXe:

3. P. Sorensen and M. Szydagis, *Can LUX use thermal neutron capture for sub-keV nuclear recoil calibration?* - LUX internal note
4. D.Q. Huang, *Ultra-Low Energy Calibration of the LUX and LZ Dark Matter Detectors* - Brown University PhD thesis

MiX detector:

5. S. Stephenson, et. al., *MiX: A position sensitive dual-phase liquid xenon detector* - JINST **10** P10040 (2015)

Simulations (BACCARAT):

6. LUX Collaboration, *LUXSim* - NIM Physics **675**, 63 (2012)
7. LZ Collaboration, Simulations of events for the LZ dark matter experiment - Astroparticle Physics **125**, 102480 (2021)

Single electron:

8. LUX Collaboration, *Investigation of background electron emission in the LUX detector* - Phys. Rev. D **102**, 092004 (2020)

Prompt γ databases:

9. ENSDF (Used in GEANT4 photon evaporation) - Online database
10. IAEA, *Prompt gamma-ray neutron activation analysis* - Online database
11. Firestone, et. al., *The evaluated gamma-ray activation file (EGAF)* - AIP Conference Proceedings, Vol 769 (2005)