Characterizing the Neutron Tagging Efficiency Rate of the Lux-Zeplin Detector Using an AmBe Radioisotope

Anh Ramirez, David Woodward

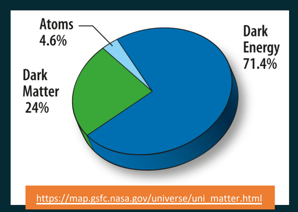
Black Hills State University, Pennsylvania State University

Abstract

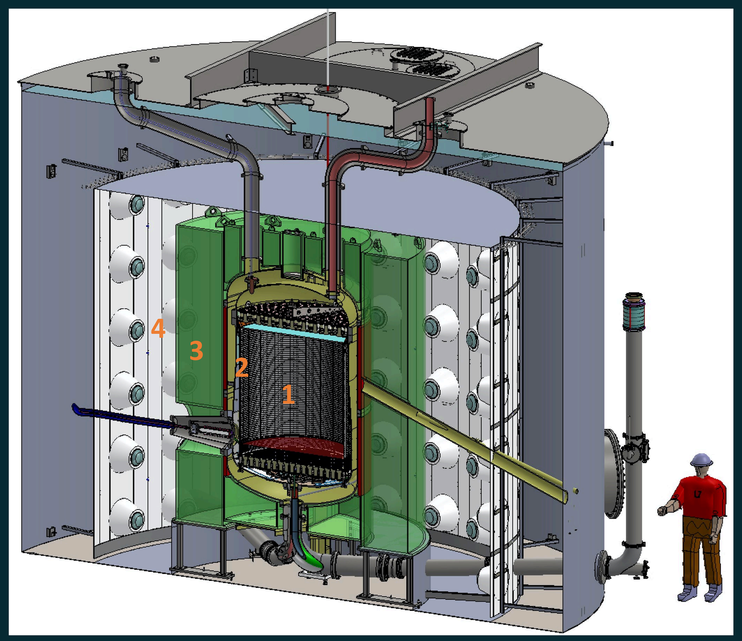
The universe is dominated by a non-baryonic, low-luminosity substance known as dark matter. Detecting it has been the central goal of the Lux-Zeplin(LZ) experiment at Sanford Lab in Lead, South Dakota since 2014. At present, the leading candidate for dark matter takes form in Weakly Interacting Massive Particles(WIMPs). The ten ton liquid xenon detector housed a mile underground at Sanford lab is designed to record electrons and photons generated from a collision between a WIMP and a xenon atom. To detect such small signals requires extensive calibration and background characterization of the detector. Using specially made deployment apparatus located above the detector, radioactive samples can be lowered between detector walls to expose the time projection chamber(TPC) to various radioisotopes. In the case of neutron emitting sources, detector behavior is especially important to establish as incident neutrons deposit a similar amount of energy upon interaction with the xenon medium relative to the amount predicted for that of WIMPs. Using ROOT data analysis software in combination with applied statistics, the neutron tagging efficiency of the TPC can be calculated. This rate is crucial in profiling the behavior of the TPC in response to background neutron radiation and in distinguishing neutron signals from candidate WIMP signals.

Introduction

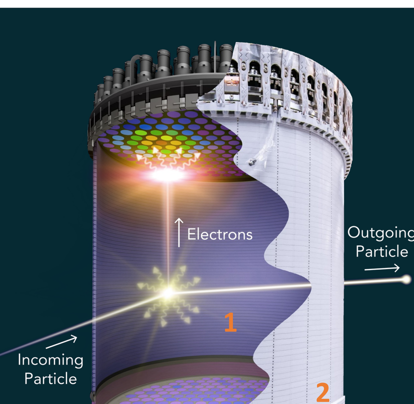
- Dark matter
  - Universe composition dominated by dark matter and dark energy
- WIMPs are a popular candidate
  - Would match the currently observed density of dark matter
  - Appealing spin independent nucleon cross section and energy range
  - Motivated by cosmology and particle physics



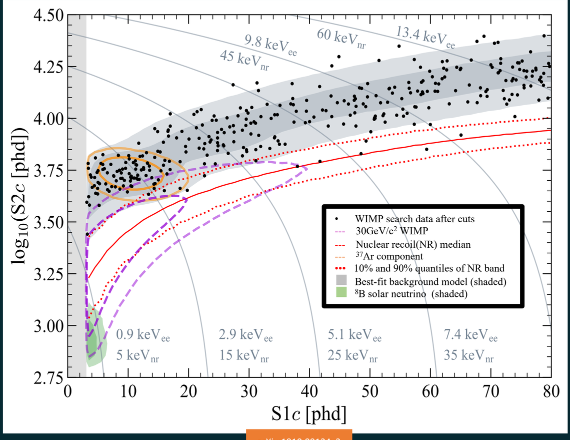
- Large Underground Xenon(LUX) – ZonEd Proportional scintillation in LIquid Noble gases(ZEPLIN)



- Cavern on 4850 level of Sanford Lab in Lead, South Dakota
- Approximately a mile underground to reduce cosmogenic background
- Detector components
  1. Time projection chamber(TPC) sits in a vacuum insulated titanium cryostat vessel
  2. Field cage applies a vertical electric field between cathode grid at the bottom and an anode and gate grid at the top
  3. Acrylic vessels filled with Gadolinium Liquid Scintillator(GdLS) for background radiation detection and vetoing
  4. Ultra pure water for shielding from cavern radioactivity



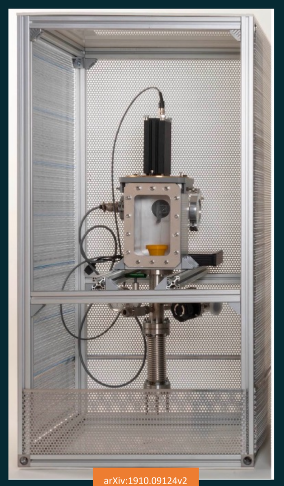
- Detector requires calibrations to characterize background radiation and its own behavior
  - Allows for profiling detector behavior and feedback on detector functioning efficiency
- WIMP signals resemble neutrons in the TPC
- Assuming spin-independent scattering from a 30GeV/c^2 WIMP



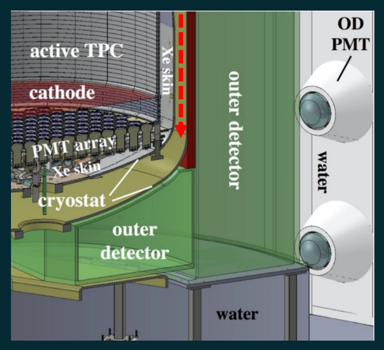
- Calibration of the detector and added sensory instruments working together allows for added sensitivity
- Able to distinguish background radiation from WIMP interactions

Materials & Apparatus

- A controlled exposure of the TPC to radioactive sources requires sophisticated apparatus
- Calibration Source Deployment(CSD)
  - Three situated around the top of the detector
  - Lower samples into the inner vacuum space of the cryostat vessel
    - Nylon filament
    - Nitrogen filled chamber
    - Laser readout to position source with ±5mm accuracy



- A popular neutron source: AmBe
  - Americium-241 supplies alpha particles to be absorbed by Beryllium-9 which emits neutrons and gamma rays
  - Source no.3
    - 293 n/s
    - Am-241 activity: 0.13mCi
    - Gamma ray energies: 4.4 or 3.3 MeV occurring with 70% of emitted neutrons



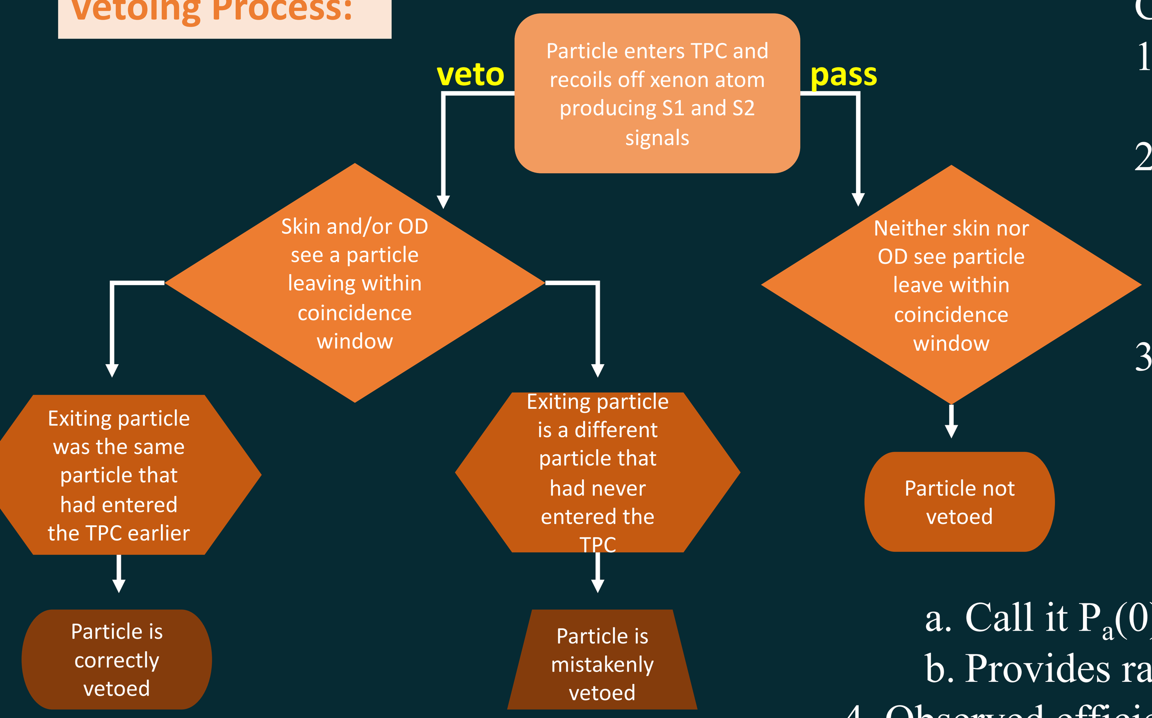
$$^{241}\text{Am} \rightarrow {}^{237}\text{Np} + \alpha$$

$$^{9}\text{Be} + \alpha \rightarrow {}^{13}\text{C}^{*} \rightarrow {}^{12}\text{C} + n + \gamma$$

Methods

- Suspend AmBe sources in intra-cryostat space at three different heights: 1300mm, 700mm and 100mm
  - Approximately the top, middle and bottom detector regions, respectively

Vetoing Process:



Coincidence Criterion			
Detector and Time Interval	Coincidence Window	PMT Coincidence Requirement	Pulse Area Threshold Requirement (phe)
Skin Prompt	±300ns	>2	>2.5
Skin Delayed	+1200μs	0	>50
OD Prompt	±300ns	>5	0
OD Delayed	+1200μs	>5	>37.5

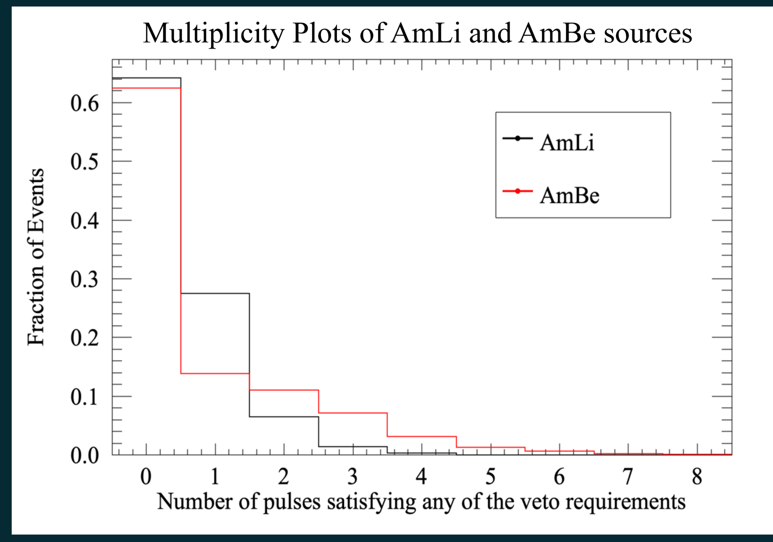
Calculations:

1. Record total number of events reviewed
2. Record number of accidental coincidences
   a. Provides number of populated windows
3. Calculate number of empty windows by taking total events and subtracting populated windows
   a. Call it $P_a(0)$
   b. Provides rate of empty windows
4. Observed efficiency is smaller by a factor of $P_a(0)$ than the true efficiency

$$\epsilon_{true} = \frac{\epsilon_{obs}}{P_a(0)}$$

5. The three different rates generated for the three different z positions are averaged to generate one neutron tagging rate for the AmBe source
6. The AmBe source rate will then be averaged again with another neutron source, AmLi, for a total combined tagging efficiency of the detector

Results & Discussion



AmBe:

Z Position (mm)	Correction Factor $P_a(0)$	Observed Efficiency (%)	Corrected Efficiency (%)
100	0.609	Analysis ongoing	Analysis ongoing
700	0.625	"	"
1300	0.617	"	"

AmLi:

Z Position (mm)	Correction Factor $P_a(0)$	Observed Efficiency (%)	Corrected Efficiency (%)
100	0.632	94.16	90.8
800	0.642	93.42	89.7
1500	0.737	90.16	86.6

- AmBe vs AmLi
  - AmBe emits a higher ratio of neutrons to gamma rays in radioactive decays relative to AmLi
  - Multiplicity plots reflect this difference
    - AmLi dominates in events experiencing fewer pulses passing veto criterion
      - Gamma rays are absorbed more readily so few survive to repeat as pulses in the OD and/or skin regions of the detector
    - AmBe dominates in higher pulse rates within the same event window
      - Neutrons tend to reflect and recoil more easily
      - More likely to be seen multiple times in an event window

Conclusion

- WIMPs offer a viable solution to the missing mass problem
  - Since 2014, LZ has been dedicated to its goal of directly detecting them
- Such small measurements require extensive instrument calibration
  - Conducted by exposing the TPC to external radioisotopes at varying positions
- Data is collected on detector reaction to profile its behavior in the face of incoming particles
  - Can quantify how well the detector is distinguishing signals from each other
- Future work will consist of applying the found correction factor to the observed efficiency after analysis is completed on more AmBe runs
  - Then the corrected rate will be combined with that of the AmLi source for a final neutron tagging efficiency rate

References

[1] Aalbers, J. *First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment*, https://doi.org/10.48550/arXiv.2207.03764.

[2] Akerib, D.S., et al. "The Lux-ZEPLIN (LZ) Experiment." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 953, 11 Feb. 2020, p. 163047, https://doi.org/10.1016/j.nima.2019.163047.

[3] Mount, B.J. *LUX-ZEPLIN (LZ) Technical Design Report*, https://doi.org/10.48550/arXiv.1703.09144.

[4] "Americium-241." *Wikipedia*, 11 May 2023, en.wikipedia.org/wiki/Americium-241#cite_note-8.

Acknowledgements

This project would not have been possible without the financial support of the NSF. Special thanks to BHSU for furthered support and to the collaborators at LZ for assisting and advising in this project.