A Cryogenic Witness Detector for Low-Energy Neutron Backgrounds

A.N. Villano

University of Colorado Denver
Neutrons are (still) DM Backgrounds

- Thermal neutrons (which predominately create captures) have been traditionally not important b/c their backgrounds are very low energy. Now, they are because of the low-energy reach of new detectors.

Also: neutrons in the energy range 1 keV – 1 MeV will quickly create thermal fluxes and have their own impact in this energy range via elastic scattering.

K. Harris; A. Gevorgian; A.J Biffl, A.N. Villano ; Physical Review D (PRD) 107 076026 (2023)
Neutron Backgrounds Underground: SNOLAB

- One of the lowest-flux environments for neutrons is the SNOLAB underground lab.
- Only the thermal neutron flux and “fast” neutron flux (> 1 MeV) are measured.

Villano, A.N.; Journal of Low Temperature Physics (LTD20); under review
Gaseous $^3$He detectors have been used for many years to detect neutrons for two main reasons:

- The process $^3$He(n,p) has a high cross section and;
- Displays a mono-energetic peak that maps directly to the incoming neutron energy.

Sharbaugh, A.E., Jones, L., Villano, A.N.; Journal of Undergraduate Reports in Physics (JURP); in press

https://arxiv.org/abs/2305.00145
3He Detectors: Liquid Design

- SPICE/HeRALD collaboration demonstrated phototube readout (see: Phys. Rev. D 105 092005 (2022))

- Density boost of 3He is between a factor of 64 – 107x compared to gas detectors of 4—10 atm partial pressure

- Hermetic design with copper vessel shown at right; copper is important for background mitigation (see later slides)

Sharbaugh, A.E., Jones, L., Villano, A.N.; Journal of Undergraduate Reports in Physics (JURP); in press

https://arxiv.org/abs/2305.00145
Gaseous $^3$He Performance: HALO @ SNOLAB

- Compare to HALO detector at SNOLAB: 0.75 m$^3$ of $^3$He gas at 2.5 atm partial pressure

- Very low neutron flux environment.

- In 1 year of running will reach 11,000 neutron counts in the 1 keV and above region but will also have around 140,000 alpha background events from surfaces

- These tubes are probably the lowest background available with 1 ppt thorium contamination (see NIMA 449(1) p 172 (2000))

Villano, A.N.; Journal of Low Temperature Physics (LTD20); under review
Liquid $^3$He: 8 cm$^3$ @ SNOLAB

- Same very low neutron flux environment as HALO
- Only 30 total neutron events over 1 yr of running in the region 1 keV—1 MeV compared to 11,000 …BUT…
- Small volume can be integrated into or near other detectors; including deep cryogenic ones as a witness
- Expect ~ 100 bknd alpha events dominated by PMT (might be able to remove)

Sharbaugh, A.E., Jones, L., Villano, A.N.; Journal of Undergraduate Reports in Physics (JURP); in press
https://arxiv.org/abs/2305.00145
Liquid $^3$He Performance: Background Budget

- Alpha backgrounds from surface are dominant, other ambient gammas or ($\alpha,n$) from detector less important
- Use low-background copper
- If modifications can be done to remove PMT readout (maybe with TES or MKID detector coupled to silicon substrate inside the hermetic volume), then we can have signal-to-noise of around 217 for this detector

<table>
<thead>
<tr>
<th>Component</th>
<th>Contamination Level (ppt)</th>
<th>Background ($\alpha$/yr)</th>
<th>Best signal-to-noise$^1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>standard copper$^2$</td>
<td>39</td>
<td>179</td>
<td>0.10</td>
</tr>
<tr>
<td>ultra clean copper$^3$</td>
<td>0.03</td>
<td>0.138</td>
<td>0.26</td>
</tr>
<tr>
<td>quartz window$^4$</td>
<td>2</td>
<td>1.9</td>
<td>0.26</td>
</tr>
<tr>
<td>TPB coating</td>
<td>120</td>
<td>112</td>
<td>0.26</td>
</tr>
</tbody>
</table>

$^1$assuming all other components optimized for low background with photomultiplier readout
$^2$Copper wire used in the Majorana project [13]
$^3$as demonstrated by the Majorana project [13] using electroformed copper
$^4$as demonstrated by the EXO project [14]

Villano, A.N.; Journal of Low Temperature Physics (LTD20); under review
Prototype Design:

1. Build a low-cost L$^4$He prototype on a 2” KF-50 dipstick and put into LHe Dewar
2. Test for scintillation yield with neutrons and gammas—
3. Design a ³He system to keep detector volume on a closed cycle; can pump on Dewar volume to reach lower temperatures for ³He liquefication
4. Test with neutrons of reasonable between 10 keV and 1 MeV; can use neutron beam such as at Notre Dame
5. Re-design the detector volume with clean copper for deployment as a low-flux detector
6. Possible re-design without PMT
Initial $^4$He Design and Costs

- Simple initial design for liquid $^4$He using mostly off-the-shelf parts and a capillary tube to a small LHe volume.
- Read out with a Hamamatsu 2 cm x 2 cm square PMT through a quartz window.
- TPB coating as a LHe wavelength shifter.
- About $30k$ including 1 extra PMT and electronics and ~ $11k$ of LHe.
- $11k$ of LHe is for 10 60L Dewars which last around 10—15 days of running each (unless include boiloff mitigation).

Cold End: Design by Weijun Yao @ ORNL

Warm End: Design by Weijun Yao @ ORNL
Summary

- Backgrounds from neutron energies that have traditionally been overlooked are important now! All the way from 1 MeV to thermal energies

- It’s hard to get a precise measurement of flux there; best bet is to use the $^3\text{He}(n,p)$ process

- Liquid $^3\text{He}$ detectors can offer advantages in compactness, and radiopurity

- Prototyping is underway

- See QR code for talk slides