Measurement Cell and Light Collection System Simulations at nEDM@SNS

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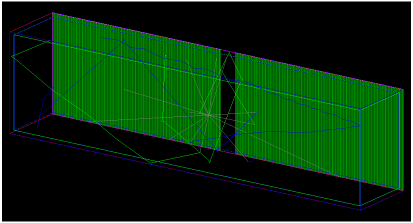
Light Collection System Simulation

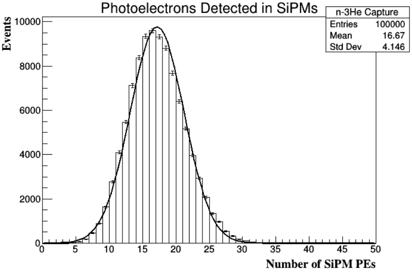
- Geant4 used to simulate transport of scintillated light in measurement cell to wavelength-shifting fibers
- Wavelength-shifting coating (dTPB + dPS) on surface of measurement cell
  - Wavelength-shifting with G4MaterialPropertiesTable (V M Gehman et al 2013 JINST 8 P04024)
- Thin reflector (Vikuiti$^{\mathrm{TM}}$) on cell walls increases collection efficiency
  - 96% reflective G4OpticalSurface with specular lobe reflection about micro-facets
- Losses in fiber transport to the silicon photomultipliers accounted for by scaling the number of initial scintillated photons in the measurement cell
- Photoelectrons are weighted by SiPM photon detection efficiency and photon counting technique limits one photoelectron per SiPM per event



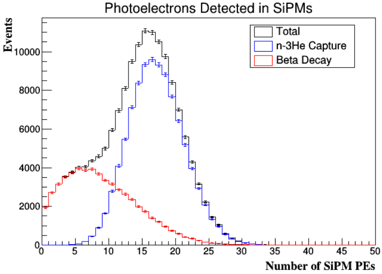
Efficiencies in Fiber Transport	
Fiber trapping	11%[1]
WLS Fiber transmission	53%[2]
Clear Fiber transmission	74%[3]
WLS/clear fiber interface	90%[4]
Fiber/SiPM interface	90%[4]
Fiber bends	95%[1]

[1] Kuraray datasheet
[2] NOνA TDR
[3] Eska datasheet
[4] A. Kriplani *et. al.* 2003 IEEE Nuclear Science Symposium.3036-3040 Vol.5

Capture Signal + β-Decay Background



n-$^{3}\mathrm{He}$ Capture Signal



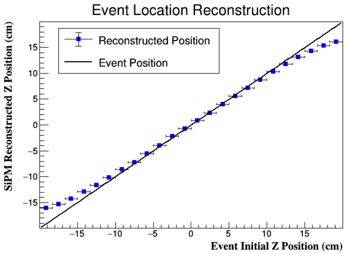
β-Decay

- We expect $\sim$ 5000 EUV photons to be produced from n-$^{3}\mathrm{He}$ capture process (T. M. Ito et al., Phys. Rev. A85, 042718 (2012))
- Loss mechanisms in fiber transport: 3.25% of photons shifted in fibers will make it to SIPM for detection
- 163 ± 12.8 EUV photons are emitted in Geant4 from event position
- β are selected from neutron β decay spectrum and undergo scintillation in superfluid $^{4}\mathrm{He}$ with native Geant4 scintillation process (Adams et. al., Journal of Low Temperature Physics 113, 1121–1128 (1998))
- Photoelectrons detected in SiPMs are normalized by the ratio of the β decay rate to the capture signal rate

Location Reconstruction + Detection Efficiency

Location Reconstruction

- Weighted mean of hit readout channel (group of 16 SiPMs across 3.2 cm range in beam direction) positions can be used to reconstruct event position along beam axis
  - Potential for diagnosing some systematics
  - Position-dependent cuts on number of photoelectrons to reduce background

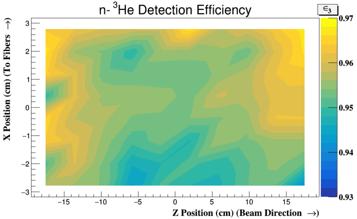


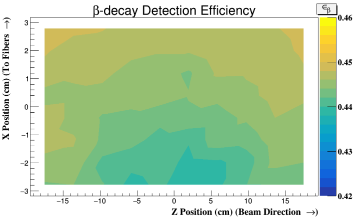
Detection Efficiency

- Design goals for signal and β detection efficiency (M.W. Ahmed et al 2019 JINST 14 P11017)

ε_3	Detection efficiency for UCN-^{3}He capture	0.93
ε_β	Detection efficiency for β-decay	0.5

  - With optimal position-dependent NPE cuts: efficiencies satisfy design goals and are uniform (δ_{ϵ_3}, $\delta_{\epsilon_\beta} < 2\%$) across cell





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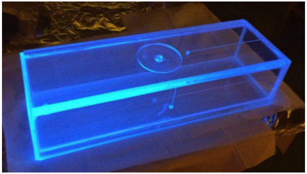
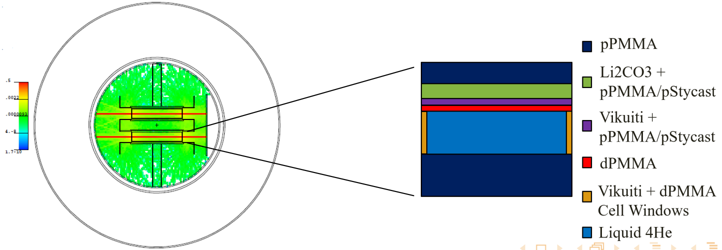
Measurement Cell Design

- Protonated poly(methyl methacrylate) (pPMMA) cell walls
  - High purity $\rightarrow$ Minimize neutron activation backgrounds
  - Transparent for blue photons
- Inner surface of cell walls coated with dTPB + dPS
  - High Fermi potential $\rightarrow$ prevent UCN wall loss
  - Long $^{3}\mathrm{He}$ depolarization times
- 96% reflective thin dielectric mirror (Vikuiti)
- dPMMA cell entrance and exit windows
  - Transmission of 8.9 Å neutrons
- Lithium neutron absorber
  - Reduce activation background and cell charging



K.K.H Leung

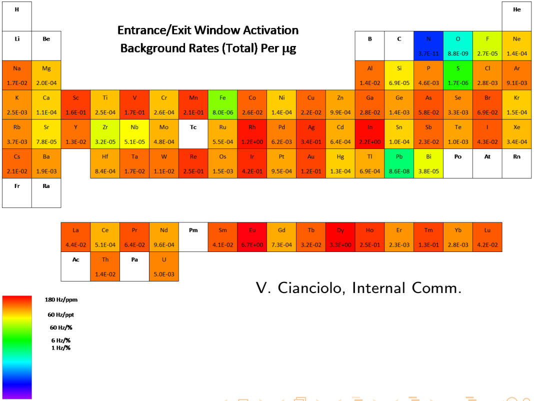


Neutron Activation Backgrounds

- Neutrons scattered from beam can be captured in materials near the measurement cells and activate, causing delayed β and γ radiation to travel into measurement cell and mimic signal
  - Sensitive to small amounts of material impurities
- Activation background rate is calculated with MCNP neutron flux tallies using previously determined background rate per gram data for relevant isotopes

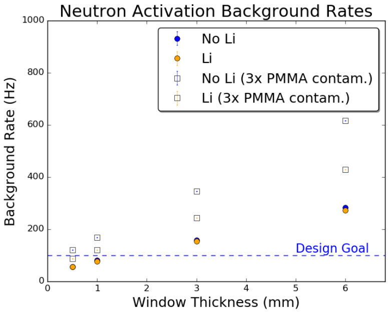
$$R = [\frac{\beta_i^{\gamma,\beta}}{\Omega_0 \varphi_0}] \Omega M_i \int \varphi(E) \sqrt{(^{1meV}/_E)} dE$$

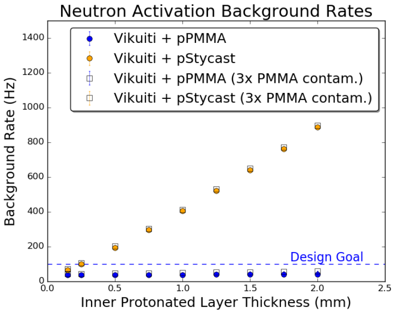
  - $\frac{\beta_i^{\gamma,\beta}}{\Omega_0 \varphi_0}$: background rate per gram per unit solid angle per unit flux
  - Ω: solid angle subtended by the measurement cell from activated volume
  - M_i: effective mass of activated volume



V. Cianciolo, Internal Comm.

Neutron Activation Backgrounds



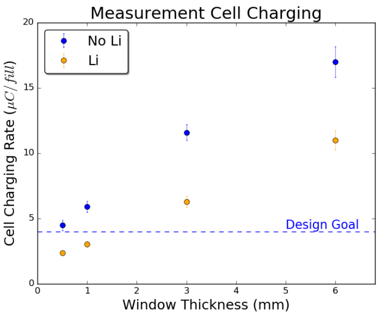


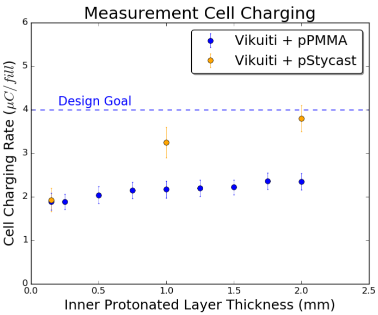
- Push to thin measurement cell entrance and exit windows
- High chlorine content in pStycast epoxy is harmful to activation background
- With reasonable design constraints (Lithium neutron absorber casted in pPMMA, cell windows $\lesssim$ 1 mm thick and Vikuiti + pStycast $\lesssim 250\ \mu m$), R $\sim$ 100 Hz

Measurement Cell Charging

- Neutrons captured in materials in the central volume can also excite nuclei, which promptly decay, releasing ionizing radiation
  - Can deposit its energy in the measurement cell helium, creating electron-ion pairs that collect on cell walls
- Energy deposition tally from MCNP is converted to charge collected in measurement cell:

$$Q = M_{He}\left(\frac{1-f_{recomb}}{I}\right)\varphi \int D(E)dE$$





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Conclusions/Outlook

- These simulations suggest:
  - Light collection system detects a sufficient number of photoelectons per n-$^3\mathrm{He}$ capture event, can reconstruct event position along beam axis to $\sim$ 3 cm
    - Position-dependent cuts on the number of detected photoelectrons can lead to a uniform event detection efficiency above design goal of 93% while reducing β-decay background by factor of two
  - Measurement cell design choices can reduce neutron activation background rates and measurement cell charging to levels reasonable for the experiment
- More complete light collection analysis in near future? – including additional backgrounds (activation,cosmic,wall loss)
- Development of the light collection system underway, SiPM boards successfully tested (V. Cianciolo's talk)
- Good progress in R&D for measurement cell construction (K. Leung's talk)

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