Ultra-Cold Neutron measurement of Proton branching ratio in neutron Beta decay (UCNProBe)

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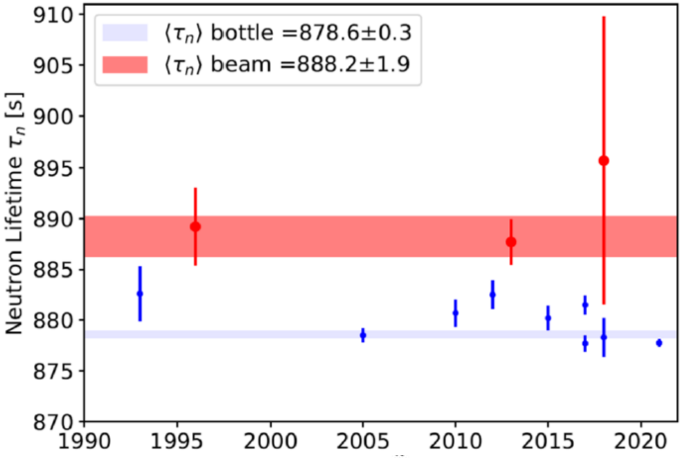
- Neutron lifetime
    - Why are we interested in it?
    - How to measure it?
    - How ultracold neutrons can help?
- Our new method for measuring neutron lifetime.
- Discussion of systematic effects

Neutron lifetime puzzle may hint at new physics

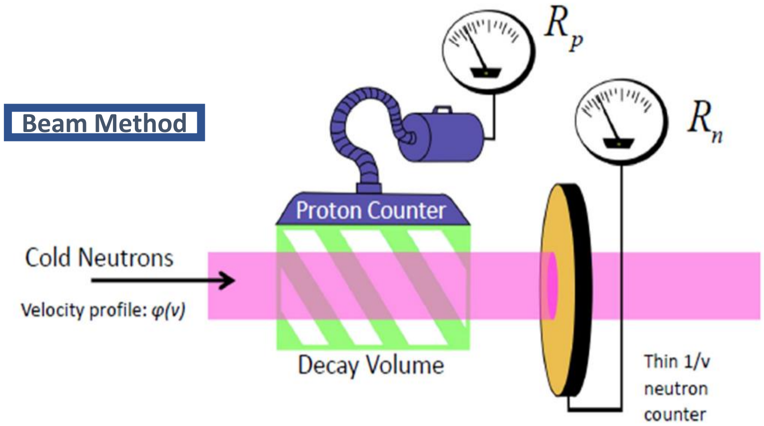


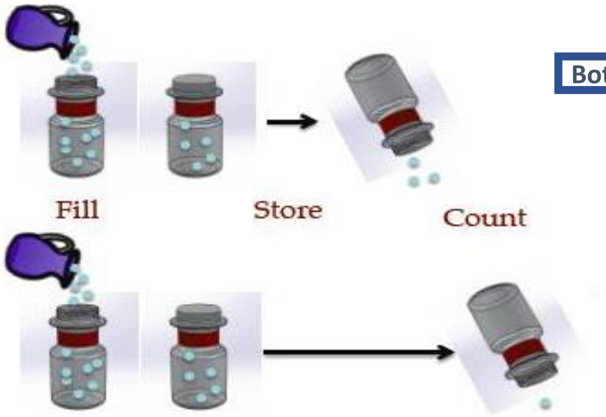
- Implication for CKM unitarity (V_{ud}) and primordial He abundance
- Two different methods
  1. Beam method (CN), measures τ_β
  2. Bottle method (UCN), measures τ_n
- 10 seconds or 5σ discrepancy (unknown systematics or new physics?)

$$\frac{1}{\tau_n}=\frac{1}{\tau_\beta}+\frac{1}{\tau_{new\ physics??}}$$

- Potential new physics/explanation
  - Mirror neutrons
  - Dark matter channels
  - Self-interacting dark matter clumps
- Ultimately, the τ_n puzzle needs to be addressed with experiments

Beam Method

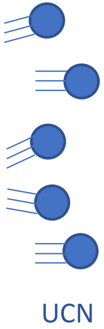


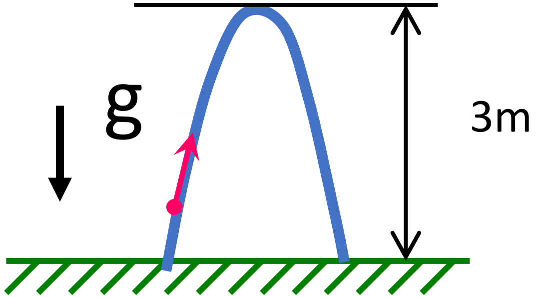


Bottle Method

Ultracold neutrons provide a sensitive tool for precision experiments

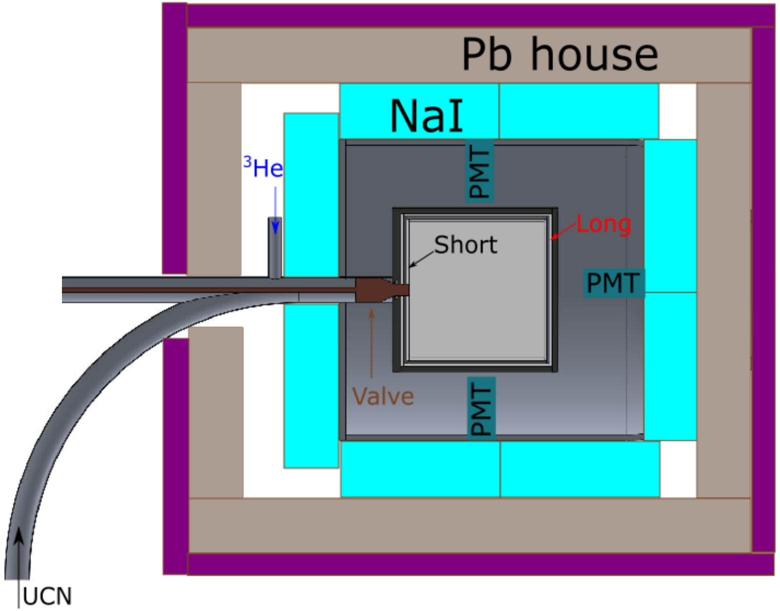
- Can be confined in material and magnetic bottles
  - Longer observational time → precision measurements
  - Serve as a unique probe for both basic and applied research
- Kinetic energy ~ gravitational energy ~ magnetic energy
  - Gravitational potential: 100 neV/m
  - Magnetic potential: 60 neV/T
- Typically:
  - Velocity < 8 m/s
  - Kinetic energy < 300 neV
  - Temperature < 4 mK
  - Wavelength > 50 nm





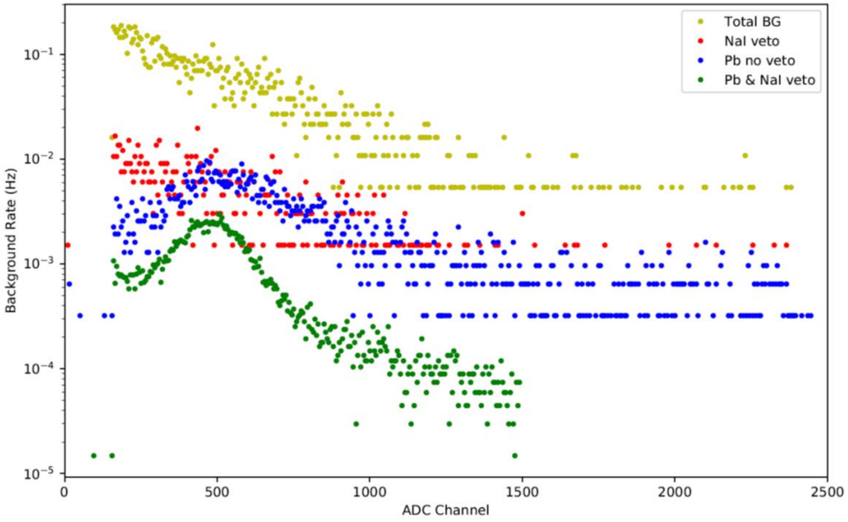
Our new experiment will provide check on the "beam" method

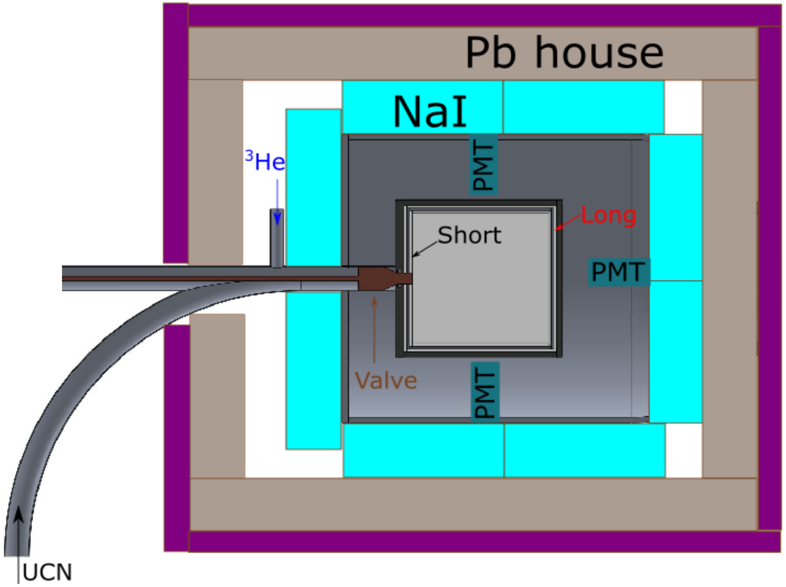
- Statistics for the beam experiments are dominated by a single experiment.
- **Our goal is to measure τ_β using UCN with a total error of 1-2 seconds with totally different systematic effects compared to past "beam" experiments.**
    - $\tau_\beta > \tau_n$, then possible new physics
    - if $\tau_\beta = \tau_n$(from Bottle), then unaccounted systematic error in beam method
- **Requires absolute measurements of two quantities to 0.1%**
    - Number of neutrons in the trap
    - Number of neutrons that decayed (measurement of charged particles)



Utilizing a combination of passive and active shielding to reduce background

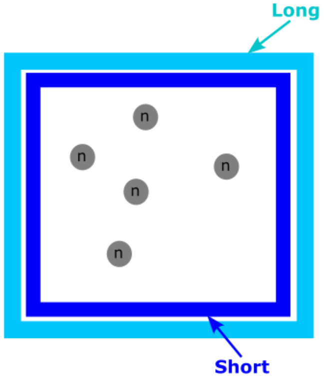
- The nature of the spallation source and UCN storage time allows us to eliminate prompt background.
- Outer layer of borated polyethylene to reduce neutron activation of inner layers
- Pb layer to reduce delayed gamma sources
- Active NaI array allows us to veto muons and further reduce gamma backgrounds.
- Outer polystyrene scintillator measures background from capture of upscattered UCN

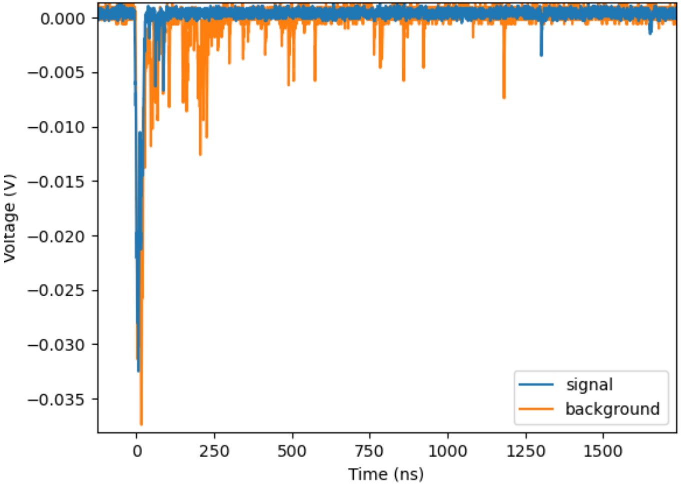


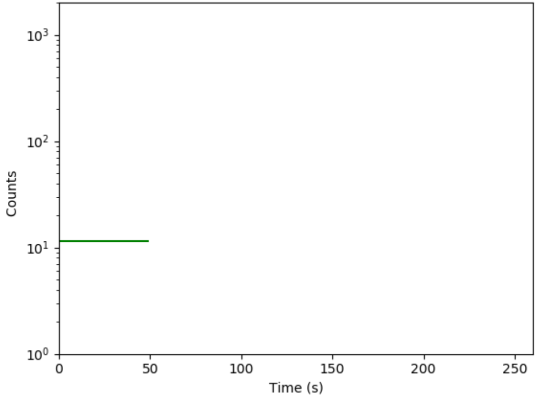


Two-layer scintillator box allows for further reduction in background

- Using deuterated polystyrene as both a UCN trap and as the in-situ detector.
- Light collection
  - Using a few PMT to collect light from scintillator boxes
  - Vacuum chamber lined with Teflon for diffusive light reflection (~96%)
  - Outer layer of scintillator has a long decay time so that background and data can be collected separately (Phoswich)

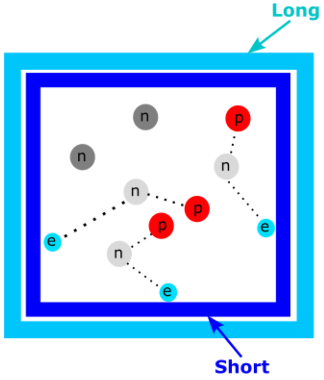


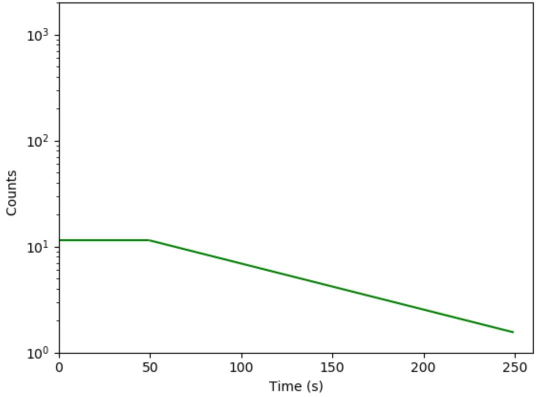




Two-layer scintillator box allows for further reduction in background

- Using deuterated polystyrene as both a UCN trap and as the in-situ detector, Fermi potential measured at 168 neV.
- Light collection
  - Using 4 PMTs to collect light from scintillator boxes
  - Vacuum chamber lined with Teflon for diffusive light reflection (>95%)
  - Outer layer of PS scintillator has a long decay time so that background and data can be collected separately
- Using electrons for charged particle detection.





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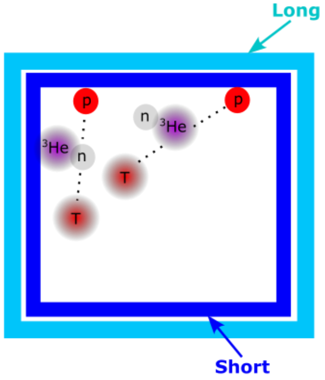
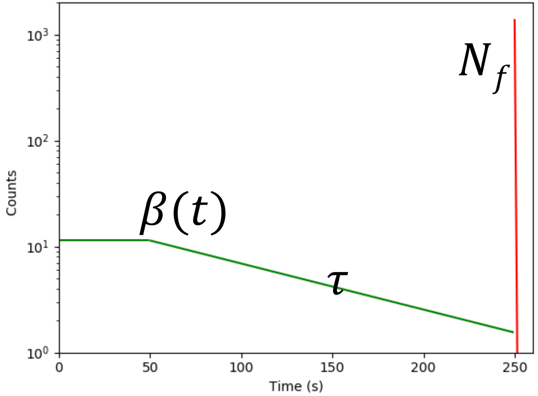
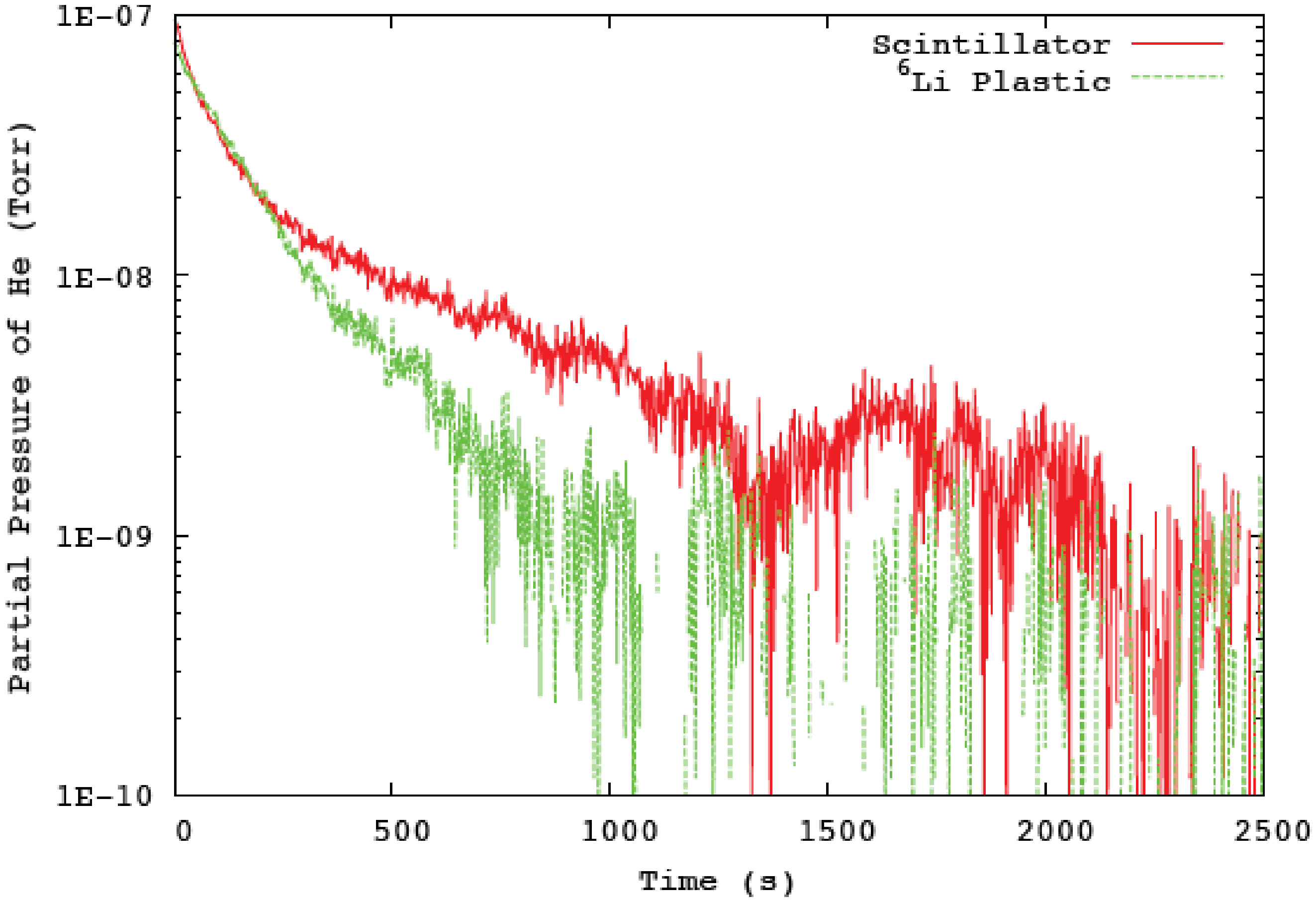
- Using electrons for charged particle detection.
- Neutron detection using ^{3}He gas, n + ^{3}He = p + T+ 764 keV.
- Detector efficiencies will be determined using gamma tagged sources
- Extraction of $\frac{1}{\tau_\beta} = \frac{\beta(t)}{N(t)}$ using $N(t) = N_f e^{(t_f - t)/\tau}$





Test shows ^{3}He can be pumped out



5x10^{-8} Torr of ^{3}He ⇒ 1 s effect on lifetime

Neutron reflectometry shows dPS V_F= 168.7 neV

- Measurement taken at LANSCE (Asterix beamline)
- Surface roughness of the scintillator produced off-specular reflection backgrounds
- Multiple incident angle measurements were taken to reduce the error in BG subtraction
- Fermi Potential measured to be 168.7+/-1.6 neV, compared to theoretical of 170 neV.

Ultracold neutron properties of the Eljen-299-02D deuterated scintillator

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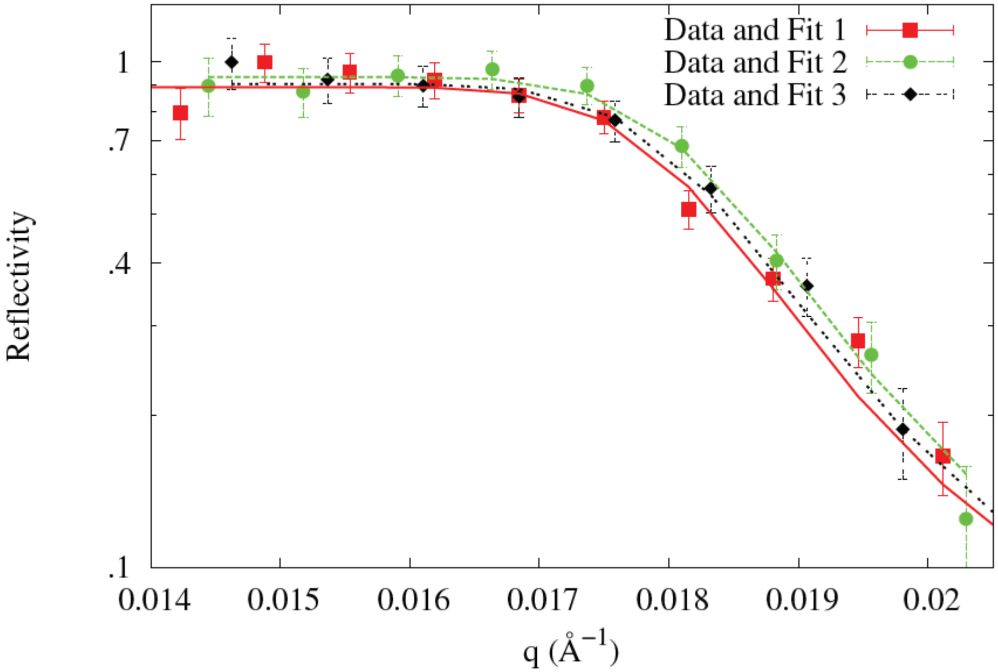
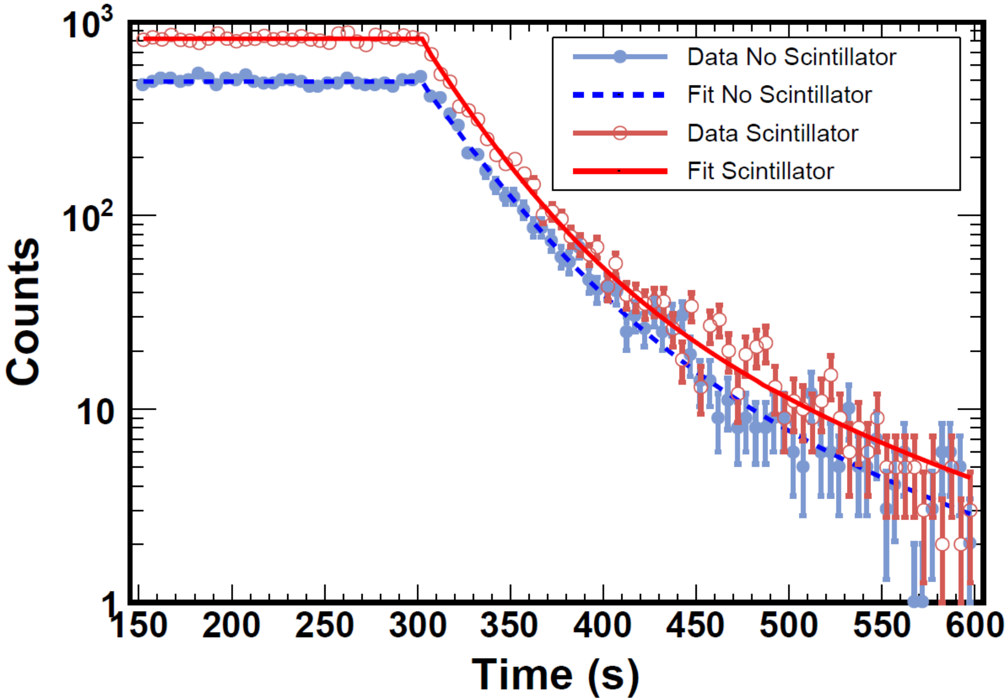
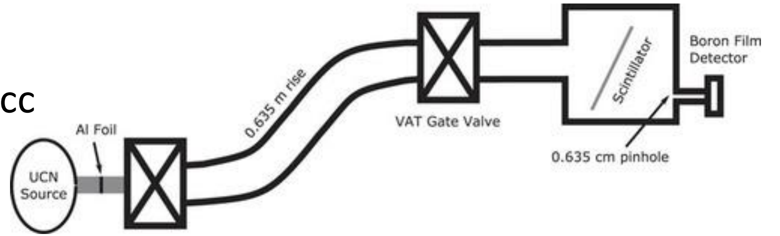
Z. Tang[1,a)], E. B. Watkins[1], S. M. Clayton[1], S. A. Currie[1], D. E. Fellers[1], Md. T. Hassan[1], D. E. Hooks[1], T. M. Ito[1], S. K. Lawrence[1], S. W. T. MacDonald[1], M. Makela[1], C. L. Morris[1], L. P. Neukirch[1], A. Saunders[1,b)], C. M. O'Shaughnessy[1], C. Cude-Woods[2,c)], J. H. Choi[2], A. R. Young[2], B. A. Zeck[2,c)], F. Gonzalez[3], C. Y. Liu[3], N. C. Floyd[4,c)], K. P. Hickerson[5], A. T. Holley[6], B. A. Johnson[7,c)], J. C. Lambert[7,c)], *and* R. W. Pattie[8]

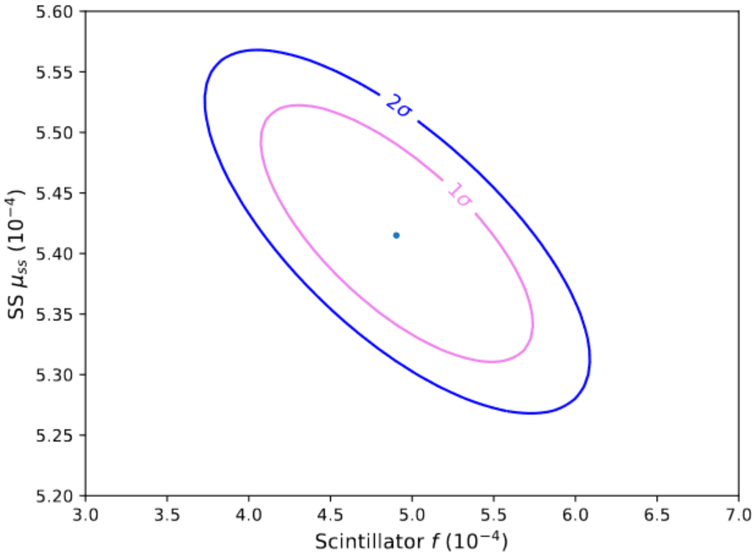


Test shows dPS scintillator exhibits good UCN reflectivity

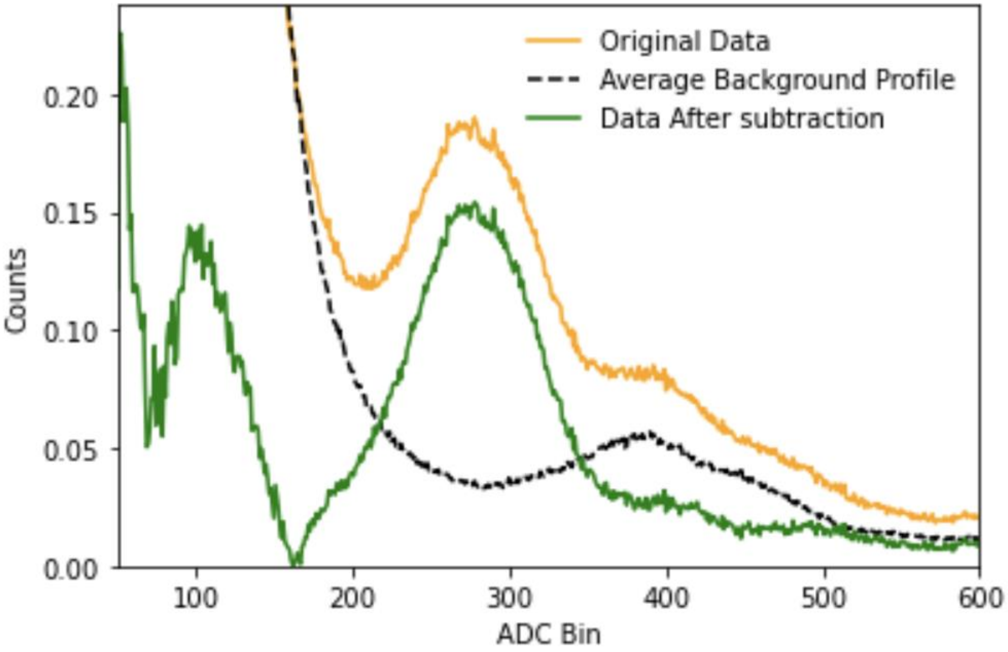
- Pinhole technique to measure the lifetime of bottle
    - Comparing scintillator in/out results
    - Loss parameter: 4.9 +/- 0.8 x 10^{-4}
    - Count rate of 2180-5640 decays per fill based on 39 UCN/cc

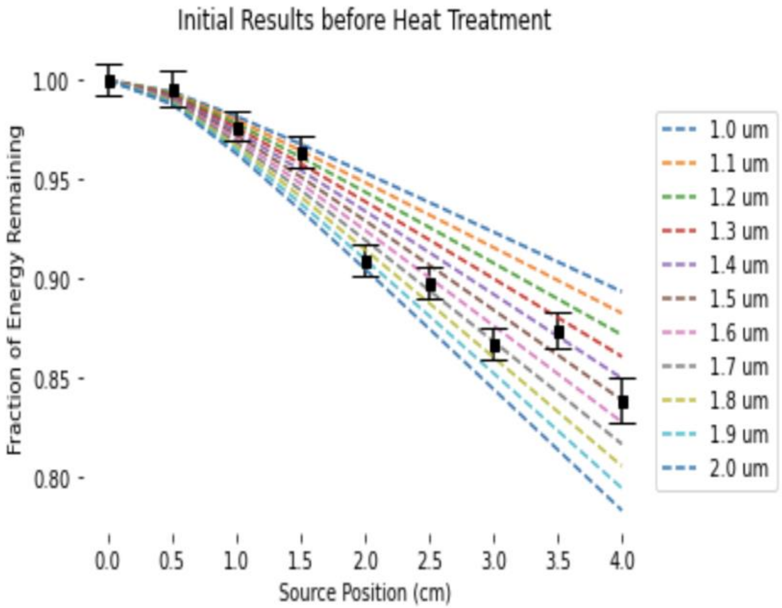


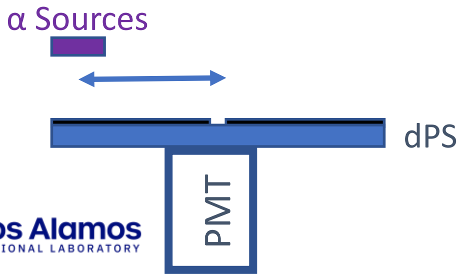




Scintillator deadlayer sufficient for proton detection







- Best fit => 1.55 +/- 0.2 um
- Using Birk's law $\frac{dL}{dx} = S\,\frac{dE/dx}{(1+kb\,dE/dx)}$, we expect protons will have a factor 4 reduction compare to Am-241
- Also heat treated scintillator with Ar and N (similar results)

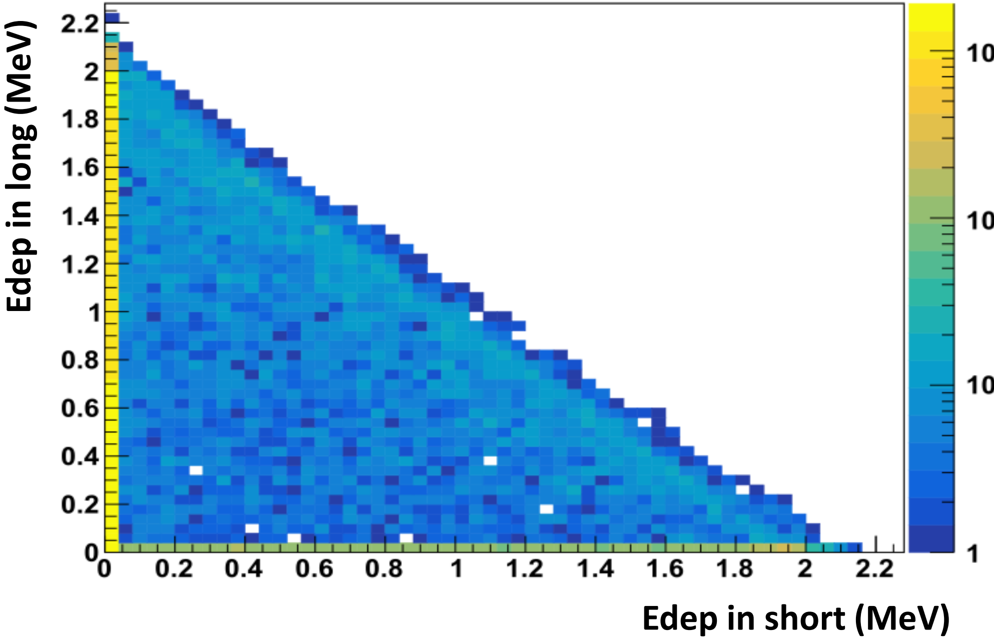
Optimization of scintillator thickness

- Need to eliminate electron punch through events to prevent rejection of beta signal by "long" decay time scintillator
- Varied the energy cut-off of the "long" scintillator and thickness of the "short" scintillator

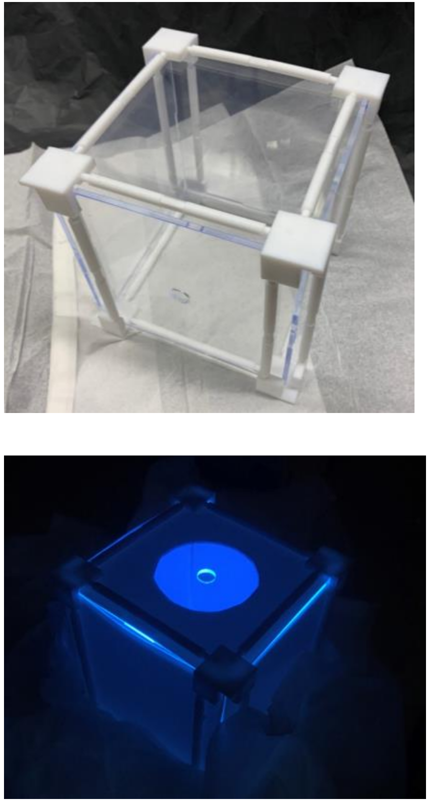
threshold (keV)	T @ 3.0 mm (%)	T @ 3.5 mm (%)	T @ 4.0 mm (%)
10	0.62	0.36	0.34
30	0.44	0.19	0.16
50	0.36	0.12	0.10
75	0.30	0.08	0.06
100	0.25	0.05	0.04

Background measurement and rejection

- In the phoswich setup, we cannot shield the “long” scintillator from upscattered UCN
- Simulation shows that “long” scintillator overestimates background
  - Different geometries
  - H and D have very different σ_n
  - H background at ~0.6%
- Need to use D“long” scintillator
- Background negligible at 3% H

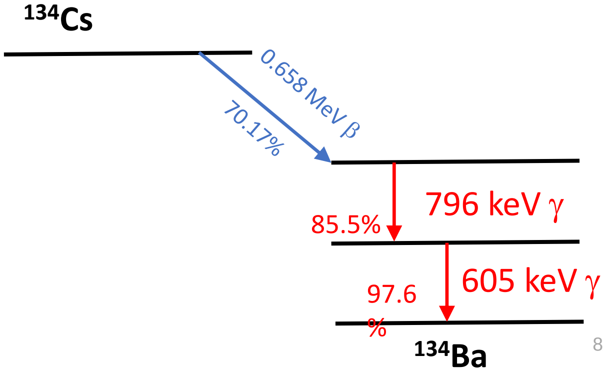


Prototype cell efficiency measurement



We plan to test the prototype cell using γ tagged βs from ^{134}Cs

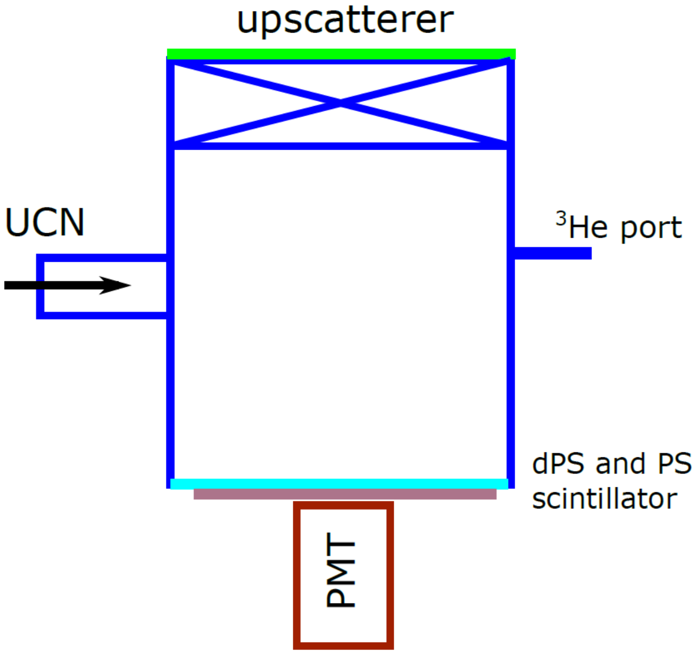
- The ^{134}Cs source has a clear gamma line at 605 keV, but we need to combine the multiple beta spectra, mainly from 89 keV (27.3%) and 650 keV (70.3%)
- The prototype cell is assembled all from hydrogen-based scintillators.
- The measurement will be performed with 2 PMTs and up to 2 HPGe detectors.



Upcoming experiment to study Helium diffusion into scintillator

- ^{3}He in the scintillator can capture upscattered UCN, which may mimic a beta signal.
- Measure spectra before and after saturating the scintillator with ^{3}He.
- Use large amount of ^{3}He and a long holding time to enhance the effect.

- We also plan to collect a pristine beta decay spectrum before injection of any ^{3}He.
- Final result will be a two-parameter fit of the beta spectrum and the (n,p)^{3}He signature.



Status

- Inputs from prototype cell measurements will influence final design
- Fabricated all “short” decay time deuterated scintillators

Timeline:
2023: Design and fabrication
2024: Assembly and calibration
2025: Commissioning run to study systematic effects
2026: Data taking (~400 hrs => 1s)

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