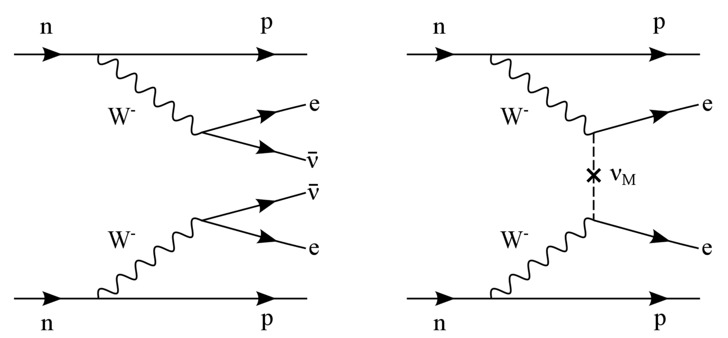
Directional Liquid Scintillator Detector for Neutrinoless Double-Beta Decay

A. Elagin (UChicago), H. Frisch (UChicago), B. Naranjo (UCLA), J. Ouellet (MIT), L. Winslow (MIT), T. Wongjirad (MIT)

Abstract

In a liquid scintillator detector electrons from double-beta decay often exceed Cherenkov threshold. Selection of early photons using fast photo-detectors separates prompt directional Cherenkov light from delayed isotropic scintillation light. This leads to the possibility of reconstructing the event topology of $0\nu\beta\beta$-decay candidate events by analyzing spatial and timing distribution of early photons. Using a simulation of a 6.5 m radius liquid scintillator detector with 100 ps resolution photo-detectors, we present a technique for separating $0\nu\beta\beta$-decay events from background due to ^{8}B solar neutrino interactions and ^{10}C decays. These represent key backgrounds at deep and shallow detector sites. We separate $0\nu\beta\beta$-decay and ^{8}B events by comparing the event topologies using a spherical harmonics analysis of the early light emitted in each candidate event. ^{10}C events can be identified by comparing photons arrival time distributions. In particular, we focus on suppression of ^{8}B background which is traditionally viewed as an irreducible background to $0\nu\beta\beta$-decay searches.

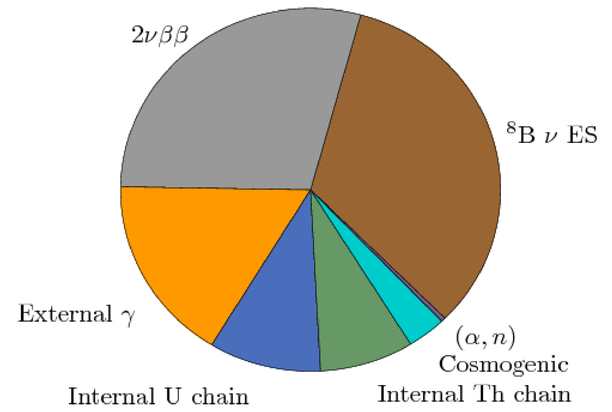
Signal and Backgrounds



$2\nu\beta\beta$- and $0\nu\beta\beta$-decay diagrams

$0\nu\beta\beta$-decay

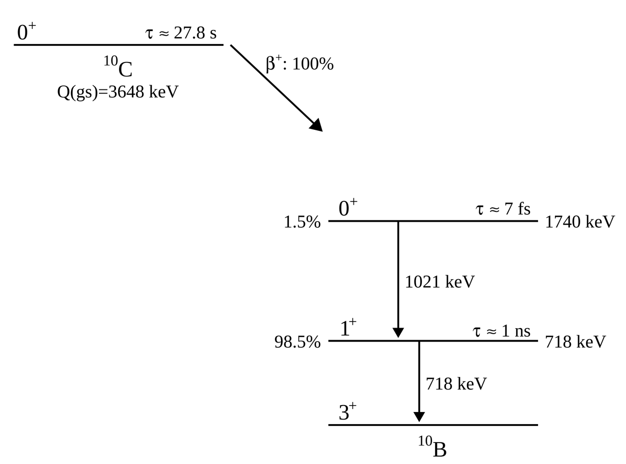
- Very large detector mass is required to search for $0\nu\beta\beta$-decay
- Liquid scintillator detectors offer good scalability
- Efficient background suppression is critical
- Event topology: two electrons



Example of background budget (SNO+)

^{8}B background

- Becomes dominant at large detector masses
- ^{8}B background is traditionally viewed as irreducible
- Event topology: single electron

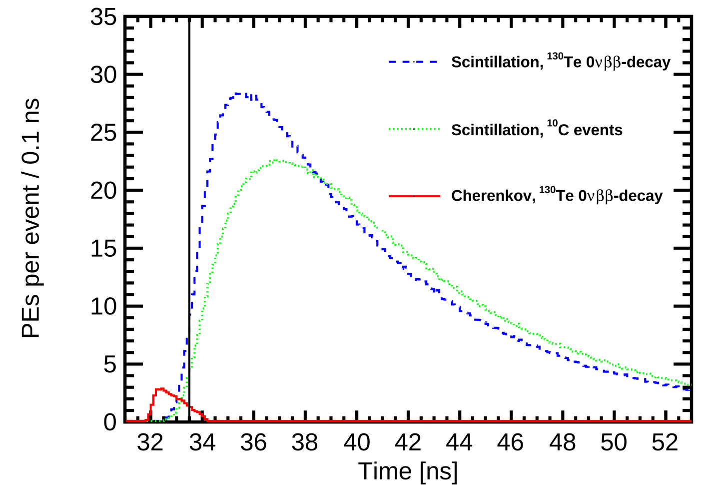


^{10}C decay scheme

^{10}C background

- May become significant at a shallow detector depth
- Event topology: positron accompanied by gamma(s)
- 98% of ^{10}C decays through a long-lived (~1 ns) excited state
- e^{+} has ~50% chance to form ortho-positronium with a life-time of ~3 ns

Cherenkov/Scintillation Light Separation



PE arrival times (R=6.5 m, TTS=100 ps)

- Fast timing enables new background suppresion techniques
- Cherenkov light arrives first
- Early light contains directionality and event topology information
- Cherenkov light is a handle on ^{8}B
- Time profile of the scintillation light provides an extra handle on ^{10}C

Spherical Harmonics Analysis

$$f(\theta,\phi)=\sum_{l=0}^{\infty}\sum_{m=-l}^{l} f_{lm}Y_{lm}(\theta,\phi), \qquad (1)$$

where Y_{lm} are Laplace's spherical harmonics defined in a real-value basis using Legendre polynomials P_l:

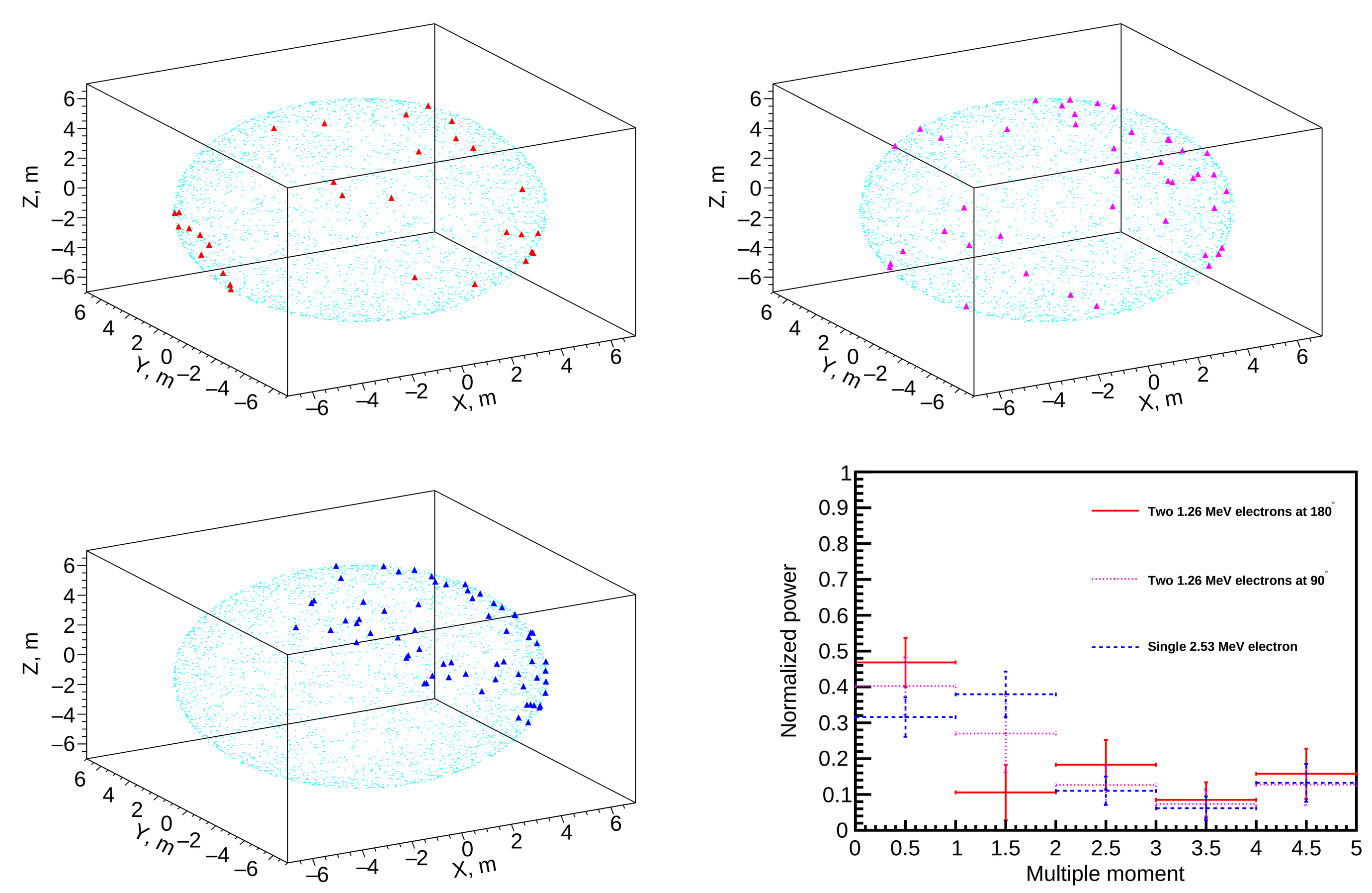
$$Y_{lm}=\begin{cases}\sqrt{2}N_{lm}P_l^m(cos\theta)cos\, m\phi, & \text{if } m>0\\ N_{lm}=\sqrt{\frac{(2l+1)}{4\pi}\frac{(l-m)!}{(l+m)!}}, & \text{if } m=0\\ \sqrt{2}N_{l|m|}P_l^{|m|}(cos\theta)sin\,|m|\phi, & \text{if } m<0\end{cases} \qquad (2)$$

where the coefficients f_{lm} are defined as

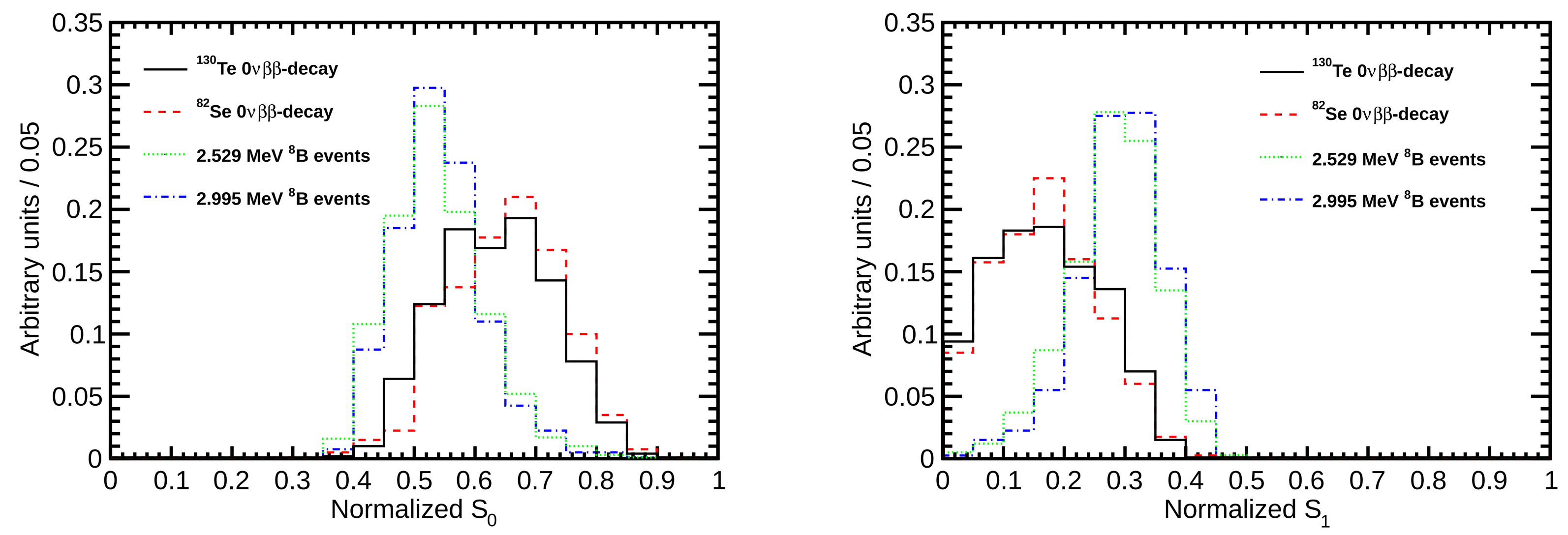
$$f_{lm}=\int_0^{2\pi}d\phi\int_0^{\pi}d\theta sin\theta f(\theta,\phi)Y_{lm}(\theta,\phi). \qquad (3)$$

Power spectrum, $s_l=\sum_{m=-l}^{m=l}|f_{lm}|^2$, is invariant under rotation. Normalized power spectrum is defined by event topology.

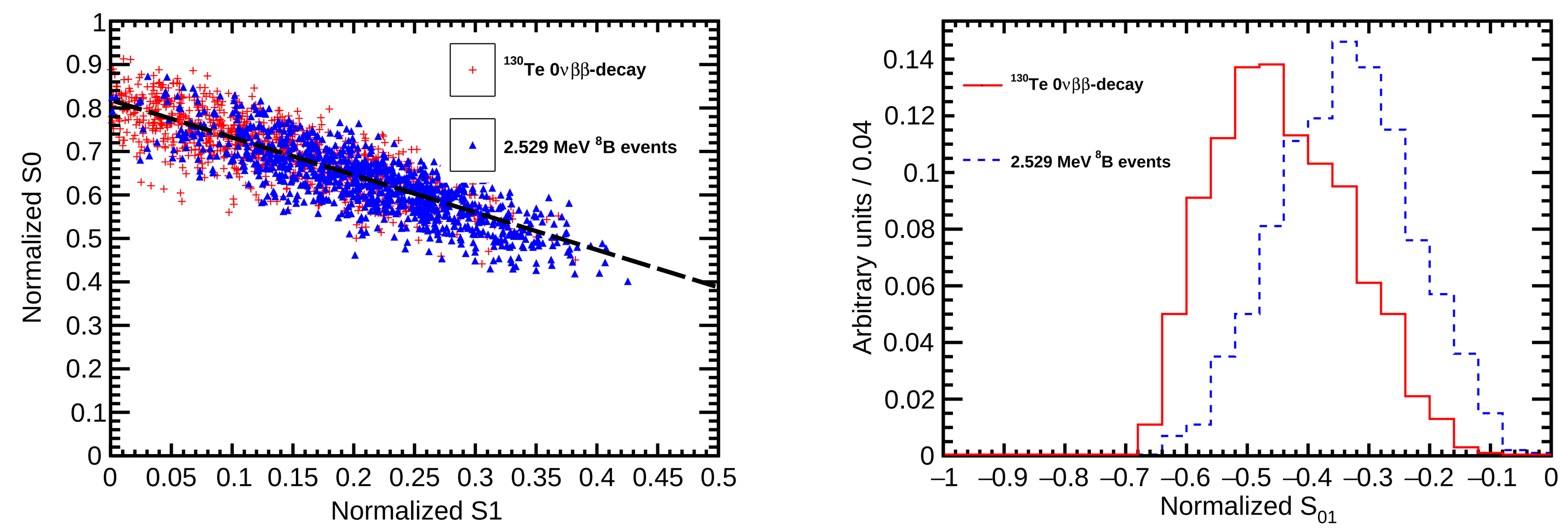
$$S_l=\frac{s_l}{\sum_{l=0}^{\infty}s_l}=\frac{s_l}{\int_{\Omega}|f(\theta,\phi)|^2 d\Omega}, \qquad (4)$$



Separation between $0\nu\beta\beta$-decay and ^{8}B Events



Spherical harmonics power spectrum components S_0 (*left*) and S_1 (*right*). Central events assuming perfect reconstruction of vertex position. Time cut of 33.5 ns on the PE arrival time is applied to select early light sample. QE$_{che}$=12%, QE$_{sci}$=23%. Photo-coverage is 100%. Scintillation rise time constant is τ_r =1 ns



Separation between $0\nu\beta\beta$-decay signal and ^{8}B background. Events are simulated within R <3 m. Verticies are smeared with 3 cm resolution Early light sample is selected by a time cut $\Delta t=t_{measured}^{phot}-t_{predicted}^{phot}$ <1 ns. QE$_{che}$=12%, QE$_{sci}$=23%. Photo-coverage is 100%. Scintillation rise time constant is increased to τ_r =5 ns.

Conclusions

There are handles on the "irreducible" ^{8}B background in liquid scintillator detectors for $0\nu\beta\beta$-decay searches. Detector requirements for signal/background separation using spherical harmonics analysis:

- Photo-detectors with TTS~100 ps
- Liquid scintillator with rise time constant τ_r ~5 ns

References and Acknowledgments

For details on Cherenkov/scintillation light separation and directionality reconstruction in a large liquid scintillator detector see:

C. Aberle, A. Elagin, H.J. Frisch, M. Wetstein, L. Winslow, "Measuring Directionality in Double-Beta Decay and Neutrino Interactions with Kiloton-Scale Scintillation Detectors", JINST 9 (2014) P06012.

Acknowledgements: C. Aberle (UCLA), M. Wetstein (Iowa State), E. Spieglan (UChicago), E. Angelico (UChicago), C. Pilcher (UChicago), M. Yeh (BNL), J. Flusser (IITA, CAS), G. Orebi Gann (UC Berkeley)