

Separating Double-Beta Decay Events from Solar Neutrino Interactions in a Kiloton-Scale Liquid Scintillator Detector By Fast Timing

Andrey Elagin^{a,*}, Henry J. Frisch^a, Brian Naranjo^b, Jonathan Ouellet^c, Lindley Winslow^c, Taritree Wongjirad^c

^a Enrico Fermi Institute, University of Chicago, Chicago, IL, 60637

^b University of California, Los Angeles, CA, 90024

^c Massachusetts Institute of Technology, Cambridge, MA 02139

Abstract

We present a technique for separating nuclear double beta decay ($\beta\beta$ -decay) events from background neutrino interactions due to ${}^8\text{B}$ decays in the sun. This background becomes dominant in a kiloton-scale liquid-scintillator detector deep underground and is usually considered as irreducible due to an overlap in deposited energy with the signal. However, electrons from $0\nu\beta\beta$ -decay often exceed the Cherenkov threshold in liquid scintillator, producing photons that are prompt and correlated in direction with the initial electron direction. The use of large-area fast photodetectors allows some separation of these prompt photons from delayed isotropic scintillation light and, thus, the possibility of reconstructing the event topology. Using a simulation of a 6.5 m radius liquid scintillator detector with 100 ps resolution photodetectors, we show that a spherical harmonics analysis of early-arrival light can discriminate between $0\nu\beta\beta$ -decay signal and ${}^8\text{B}$ solar neutrino background events on a statistical basis. Good separation will require the development of a slow scintillator with a 5 nsec risetime.

1. Introduction

The electron, muon, and tau neutrinos are unique among the standard model fermions in being electrically neutral and orders-of-magnitude less massive than their standard model charged partners [1]. These two properties motivate the possibility that these neutrinos are ‘Majorana’ rather than ‘Dirac’ particles, i.e. different from their respective charged partner leptons by being their own anti-particle [1, 2]. In 1939 W. Furry pointed out that a Majorana nature of the electron neutrino would allow neutrinoless double-beta decay, in which a nucleus undergoes a second order β -decay without producing any neutrinos, $(Z, A) \rightarrow (Z + 2, A) + 2\beta^-$ [3]. This is in contrast to the Goepfert-Mayer two-neutrino double beta ($2\nu\beta\beta$) decay, the second order standard model (SM) β -decay channel in which lepton number is conserved by the production of two anti-neutrinos, $(Z, A) \rightarrow (Z, A + 2) + 2\beta + 2\bar{\nu}_e$ [4].

The standard mechanism of $0\nu\beta\beta$ -decay is parametrized by the effective Majorana mass, defined as $m_{\beta\beta} \equiv \left| \sum_i U_{ei}^2 m_i \right|$, where U_{ei} are the elements of the PMNS matrix and m_i are the neutrino masses [1]. Current half-life limit translate to a limit on $m_{\beta\beta} \lesssim 61 - 165$ meV [5]. The next generation of $0\nu\beta\beta$ -decay experiments [6] seek to be sensitive enough to detect or rule out $0\nu\beta\beta$ -decay

*Corresponding Author: elagin@hep.uchicago.edu

16 down to $m_{\beta\beta} \lesssim 10$ meV. This will require a detector to instrument roughly a ton of active isotope
17 with good energy resolution and a near zero background.

18 Liquid scintillator-based detectors have proven to be a competitive technology [7] and offer
19 the advantage of scalability to larger instrumented masses by dissolving larger amounts of the
20 isotope of interest into the liquid scintillator (LS). This may allow scaling to 1 ton or more of
21 isotope using detectors already in operation [8]. In a large LS detector, most backgrounds can be
22 strongly suppressed through a combination of filtration of the LS to remove internal contaminants,
23 self-shielding to minimize the effects of external contaminants, and vetoes to reduce muon spal-
24 lation backgrounds. The dominant backgrounds are the standard model $2\nu\beta\beta$ -decay and electron
25 scattering of neutrinos from ${}^8\text{B}$ decays in the sun.

26 In a previous work [9] we have shown that large-area photo-detectors with timing resolution of
27 ~ 100 ps can be used to resolve prompt Cherenkov photons from the slower scintillation signal in
28 a large LS detector and that the resulting distributions can be fit for the directions and origin of
29 \sim MeV electrons. Here we present a study of applying this technique to the topological separation
30 of $0\nu\beta\beta$ -decay signal and ${}^8\text{B}$ background using a spherical harmonic decomposition to analyze
31 the distribution of early (and hence weighted toward Cherenkov photons) photoelectrons (PEs) as
32 a topological discriminant.

33 The organization of the paper is as follows. Section 2 describes the detector model. Details on
34 event kinematics and PE timing for signal and background are given in Section 3. In Section 4,
35 we introduce the spherical harmonic decomposition and discuss the performance of this analysis
36 in Section 5. The conclusions are summarized in Section 6.

37 2. Detector Model

38 We use the Geant4-based simulation of Ref. [9] to model a sphere of 6.5 m radius filled with
39 liquid scintillator. We consequently limit the discussion of the simulation to a summary of the
40 most relevant parameters.

41 The scintillator composition has been chosen to match a KamLAND-like scintillator[10]. The
42 composition is 80% n-dodecane, 20% pseudocumene and 1.52 g/l PPO with a density of $\rho =$
43 0.78 g/ml). We use the Geant4 default liquid scintillator optical model, in which optical pho-
44 tons are assigned the group velocity in the wavelength region of normal dispersion. The attenua-
45 tion length[11], scintillation emission spectrum[11], and refractive index[12] include wavelength-
46 dependence. The scintillator light yield is assumed to be 9030 photons/MeV) with Birks quench-
47 ing ($kB \approx 0.1$ mm/MeV)[13]. However, we deviate from the baseline KamLAND case in that the
48 re-emission of absorbed photons in the scintillator bulk volume and optical scattering, specifically
49 Rayleigh scattering, have not yet been included. A test simulation shows that the effect of optical
50 scattering is negligible [9].

51 The technique of using Cherenkov light for topological ${}^8\text{B}$ background rejection depends on
52 the inherent time constants that (on average) slow scintillation light relative to the Cherenkov light
53 for wavelengths longer than the scintillator absorption cutoff (between 360-370 nm [14]). The first
54 step in the scintillation process is the transfer of energy deposited by the primary particles from
55 the scintillator's solvent to the solute. The time constant of this energy transfer accounts for a rise
56 time in scintillation light emission. Because past neutrino experiments were not highly sensitive
57 to the effect of the scintillation rise time, there is a lack of accurate measurements of this property.

We assume a rise time of 1.0 ns from a re-analysis of the data in Ref. [14] but more detailed studies are needed.

The decay time constants are determined by the vibrational energy levels of the solute and are measured to be $\tau_{d1} = 6.9$ ns and $\tau_{d2} = 8.8$ ns with relative weights of 0.87 and 0.13 for the KamLAND scintillator [15]. In a detector of this size, chromatic dispersion, wherein red light traveling faster than blue due to the wavelength-dependent index of refraction, enhances the separation.

The inner sphere surface is used as the photodetector. It is treated as fully absorbing with no reflections and with 100% photocathode coverage. As in the case of optical scattering, reflections at the sphere are a small effect that would create a small tail at longer times and, hence, does not affect the identification of the early Cherenkov light. The assumed quantum efficiency (QE) is that of a typical bi-alkali photocathode (Hamamatsu R7081 PMT [16], see also Ref. [17]), which is 12% for Cherenkov light and 23% for scintillation light. We note that the KamLAND 17-inch PMTs use the same photocathode type with similar quantum efficiency; photocathodes with higher efficiencies are now starting to become better understood theoretically and may become commercially available [18–20]. In order to neglect the effect of the transit-time-spread (TTS) of the photodetectors, we use a TTS of 100 ps (σ), which, for example, can be achieved with large area picosecond photodetectors (LAPPDs) [21]. We neglect the (small) threshold effects in the photodetector readout electronics, spatial resolution of the photoelectron hit positions, and contributions to time resolution other than the photodetector TTS.

3. Kinematics and Timing of Signal and Background events

3.1. Kinematics of the $0\nu\beta\beta$ -decay signal

We simulate the kinematics of $0\nu\beta\beta$ -decay events using a custom Monte Carlo with momentum and angle-dependent phase space factors for $0\nu\beta\beta$ -decay [22]. The spectrum in kinetic energy of one electron in $0\nu\beta\beta$ -decays of ^{130}Te is shown in Figure 1.

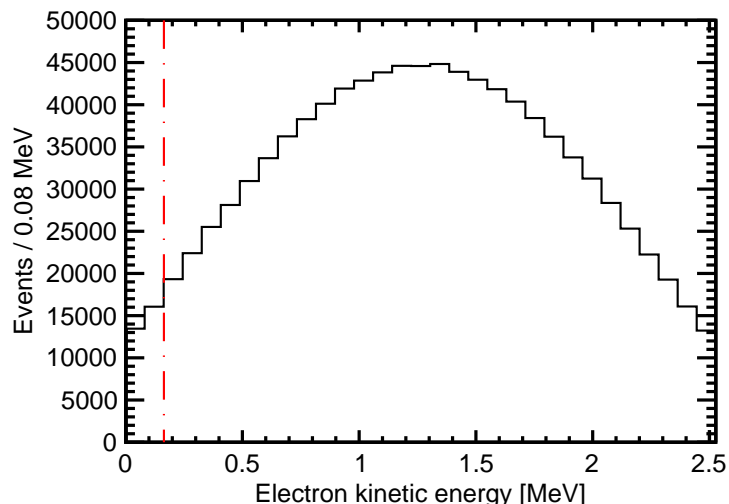


Figure 1: The spectrum in kinetic energy of one of the electrons in $0\nu\beta\beta$ -decays of ^{130}Te (endpoint 2.53 MeV). The vertical dashed line indicates the Cherenkov threshold in the liquid scintillator of the detector model. Single electrons from ^8B solar neutrinos that are potential background to the $0\nu\beta\beta$ -decay search are close in energy to the endpoint and will be above the Cherenkov threshold.

82 The distribution in $\cos(\theta)$ between the two electrons is presented in the left-hand panel of Fig. 2
 83 (solid line), showing the preference towards a back-to-back topology. The energy sharing between
 84 the electrons peaks at an equal split, as shown in the right-hand panel of Fig. 2 (solid line).

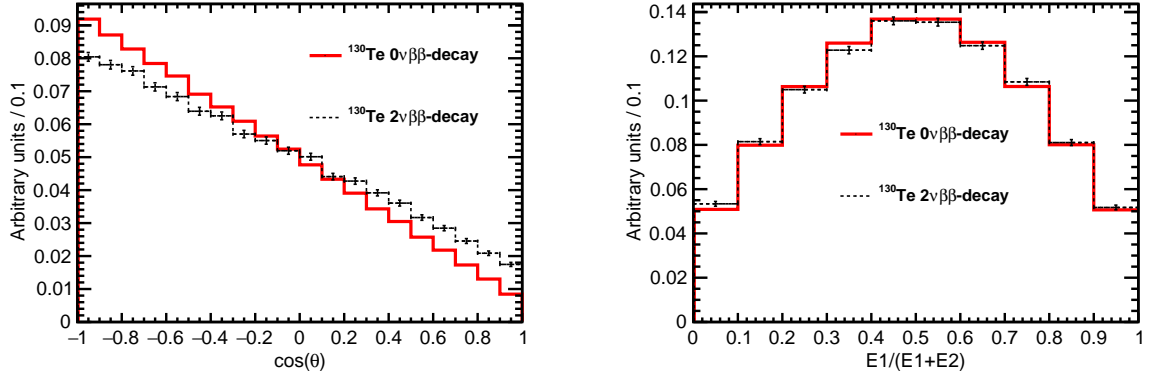


Figure 2: *Left*: The distribution in the cosine of the angle between the two electrons for $0\nu\beta\beta$ -decays (solid red line). *Right*: The fraction of the total energy carried by one of the two electrons in $0\nu\beta\beta$ -decays (solid red line). In both panels the dashed black line is the corresponding distribution for SM $2\nu\beta\beta$ -decay events with the total kinetic energy of the electrons above 95% of the Q-value.

85 3.2. Comparison to SM $2\nu\beta\beta$ -decay

86 Figure 2 also shows the angular separation and energy sharing of the two electrons in SM $2\nu\beta\beta$ -
 87 decay events with the total kinetic energy of the electrons above 95% of the Q-value, found using
 88 the same Monte Carlo generator but with SM phase space factors [22]. As seen from the plot, the
 89 electron angular correlations for $0\nu\beta\beta$ -decay are slightly more back-to-back than those from $2\nu\beta\beta$ -
 90 decay due to a contribution from the neutrino wave-functions even at vanishingly small energies
 91 of the neutrinos [22]. The energy sharing is essentially identical.

92 3.3. Production and Selection of Cherenkov light by electrons from $^{130}\text{Te } 0\nu\beta\beta$ -decays

93 Figure 1 also shows the threshold for the production of Cherenkov light. Examining the kine-
 94 matics for one of the electrons from $^{130}\text{Te } 0\nu\beta\beta$ -decay with an equal energy split, the 1.26 MeV
 95 electron travels on average a total path length of 7.1 ± 0.9 mm, has a distance from the origin of
 96 5.6 ± 1.0 mm in 26 ± 4 ps, and takes 24 ± 3 ps to drop below Cherenkov threshold. We note that due
 97 to scattering of the electron, the final direction of the electron before it stops does not match the
 98 initial direction; however, the scattering angle is small at the time that the majority of Cherenkov
 99 light is produced.

100 Figure 3 shows distributions from the detector simulation for 1000 $^{130}\text{Te } 0\nu\beta\beta$ -decay events at
 101 the center of the detector. The left-hand panel compares the time of PE arrival at a photodetector
 102 anode for Cherenkov and scintillation light, assuming a TTS in the photodetector of 100 ps. A
 103 selection of the PEs with relatively early arrival time creates a sample with a high fraction of
 104 directional Cherenkov light, designated as the ‘early PE’ sample.

105 The right-hand panel shows the composition of the early PE sample, selected with a time cut
 106 of 33.5 ns (vertical line on plot). On average each $^{130}\text{Te } 0\nu\beta\beta$ -decay produces 62.8 ± 0.3 PEs in the
 107 early PE sample, with an RMS width of 8.9 PEs from event-by-event fluctuations. On average the
 108 early PE sample consists of 28.6 ± 0.2 scintillation PEs and 34.2 ± 0.2 Cherenkov PEs, with RMS
 109 distribution widths of 5.2 and 7.3 PEs respectively.

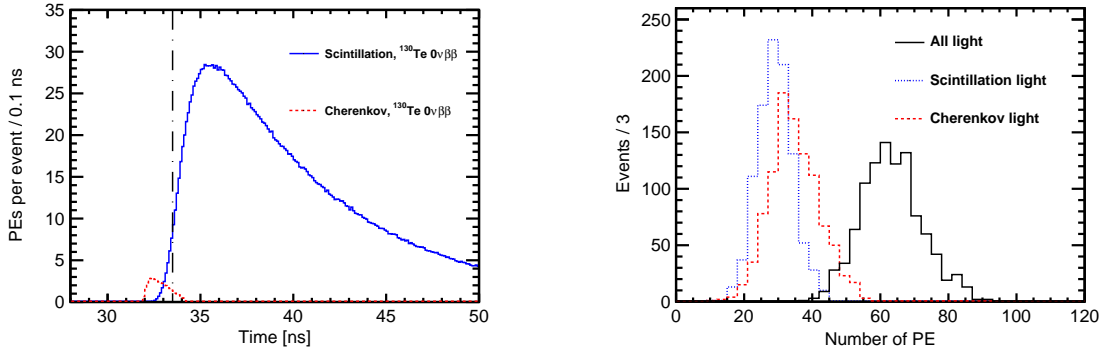


Figure 3: *Left*: PE arrival times after application of the photo-detector TTS of 100 ps for the default simulation of ^{130}Te $0\nu\beta\beta$ -decay produced at the center of the detector. Scintillation PEs (blue solid line) are compared to Cherenkov PEs (red dotted line). The vertical line at 33.5 ns indicates the time cut for the selection of the early PE sample. *Right*: Composition of the early PE sample (to the left of the vertical line in the left-hand panel): the number of Cherenkov (dashed red line), scintillation (dotted blue line), and total (solid black line) PEs per event.

110 3.4. ^8B solar neutrino background

111 For a detector similar to our model, the ^8B solar neutrino background is significant due to the
 112 large total mass of the liquid scintillator in the active region. Electrons from elastic scattering
 113 of ^8B solar neutrinos have nearly a flat energy spectrum around the Q-value [23]. We simulate
 114 ^8B background as a single monochromatic electron with energy of 2.53 MeV (Q-value of ^{130}Te).
 115 A 2.53 MeV electron travels a total path length of 15.5 ± 2.0 mm, has a distance from the origin of
 116 12.6 ± 2.2 mm in 55 ± 7 ps, and takes 49 ± 2 ps to drop below Cherenkov threshold.

117 The shape of scintillation and Cherenkov PE timing distributions in ^8B events match very
 118 closely the shape of corresponding distributions for $0\nu\beta\beta$ -decay events shown in Fig. 3. The elec-
 119 tron path length is too short compared to the detector size to introduce any noticeable difference
 120 in the shape of PE timing distributions between a single electron from ^8B events and two electrons
 121 from $0\nu\beta\beta$ -events.

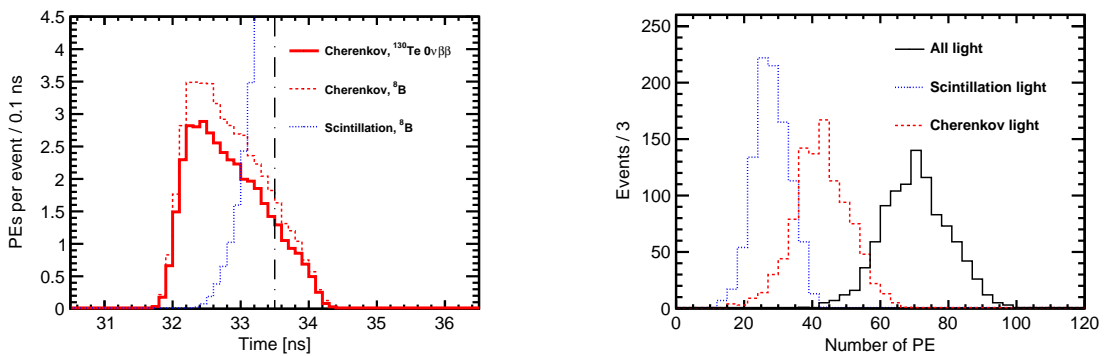


Figure 4: *Left*: A ‘zoomed-in’ view of the PEs arrival times of signal and background events produced at the center of the detector. The distribution in time for Cherenkov PEs from ^{130}Te $0\nu\beta\beta$ -decay is shown in solid black; Cherenkov PEs from ^8B solar neutrino background are shown in dashed red. PEs from scintillation are shown as the blue solid line. The line at 33.5 ns indicates the cut for the early PE sample selection. *Right*: Composition of the early PE sample: the number of Cherenkov PEs (dashed red line), scintillation PEs (dotted blue line), and total (solid black line) PEs per event.

122 On average each ^8B neutrino event produces 69.9 ± 0.3 PEs in the early PE sample, with an

123 RMS distribution width of 9.7 PEs due to event-by-event fluctuations. On average the early PE
124 sample consists of 27.6 ± 0.2 scintillation and 42.3 ± 0.3 Cherenkov PEs, with event-by-event fluc-
125 tuations contributing an RMS width of 5.2 and 8.2 PEs, respectively. The total energy deposited
126 in the detector in ${}^8\text{B}$ solar neutrino and $0\nu\beta\beta$ -decay events is the same. This leads to nearly the
127 same amount of scintillation light produced in the detector.

128 The number of Cherenkov photons is $\sim 10\%$ higher for ${}^8\text{B}$ neutrino events compared to $0\nu\beta\beta$ -
129 decay events. This is because Cherenkov light in ${}^8\text{B}$ neutrino interactions is being produced
130 by a single electron, while the same kinetic energy is split between two electrons in $0\nu\beta\beta$ -decay
131 events ¹.

132 4. Event Topology and the Spherical Harmonics Analysis

133 We have developed a method based on a spherical harmonics decomposition to discriminate the
134 topologies of $0\nu\beta\beta$ -decay two-electron events and ${}^8\text{B}$ -neutrino single-electron events. The identi-
135 fication of the Cherenkov photon clusters is challenging due to the smearing of the characteristic
136 ring pattern by multiple scattering of the electrons and by the smallness of the Cherenkov signal
137 relative to the large amount of uniformly-distributed scintillation light. We find that performing
138 the spherical harmonics analysis on the smaller early PE sample, which has a relatively high frac-
139 tion of Cherenkov PEs, can discriminate $0\nu\beta\beta$ -decay signal events from backgrounds, although a
140 high rejection factor will require a slower scintillator than in the model.

141 4.1. Topology of $0\nu\beta\beta$ -decay and ${}^8\text{B}$ Events

142 With ${}^{130}\text{Te}$ as the active isotope, all background from ${}^8\text{B}$ solar neutrinos will have the single
143 electron above Cherenkov threshold in the liquid scintillator. Also, a large fraction of $0\nu\beta\beta$ -decay
144 signal events will have both electrons above Cherenkov threshold.

145 In some cases only one Cherenkov cluster is produced in $0\nu\beta\beta$ -decay signal events. This hap-
146 pens either when the angle between the two $0\nu\beta\beta$ -decay electrons is small and Cherenkov clusters
147 overlap or when the energy split between electrons is not balanced, causing one electron to be
148 below Cherenkov threshold. Such signal events cannot be separated from background based on
149 the topology of the distribution of Cherenkov photons on the detector surface. However, the di-
150 rectionality of the electron that is above Cherenkov threshold can still be reconstructed. This
151 directionality information may allow for suppression of ${}^8\text{B}$ events based on the position of the
152 sun [24].

153 For the purpose of illustrating the spherical harmonics analysis concept, we first consider two
154 distinct topologies: a) two electrons produced back-to-back at an 180° angle; and b) a single
155 electron. Figure 5 shows an idealized simulation of these two topologies for a total electron energy
156 of 2.53 MeV. In order to emphasize ring patterns formed by Cherenkov photons, the electron
157 multiple scattering process is turned off in this idealized simulation and a photocathode QE of 30%
158 is used for both Cherenkov and scintillation photons. Here the single-electron event represents an
159 idealized ${}^8\text{B}$ event topology and the two-electron events represent two special cases of an idealized
160 $0\nu\beta\beta$ -decay topology.

¹We do not use the small difference in the total number of PEs in the early PE sample due to the Cherenkov PE contribution to separate $0\nu\beta\beta$ -decay signal from ${}^8\text{B}$ background. However, it may provide an extra handle on signal-background separation in a multivariate analysis when combined with directional and topographical information.

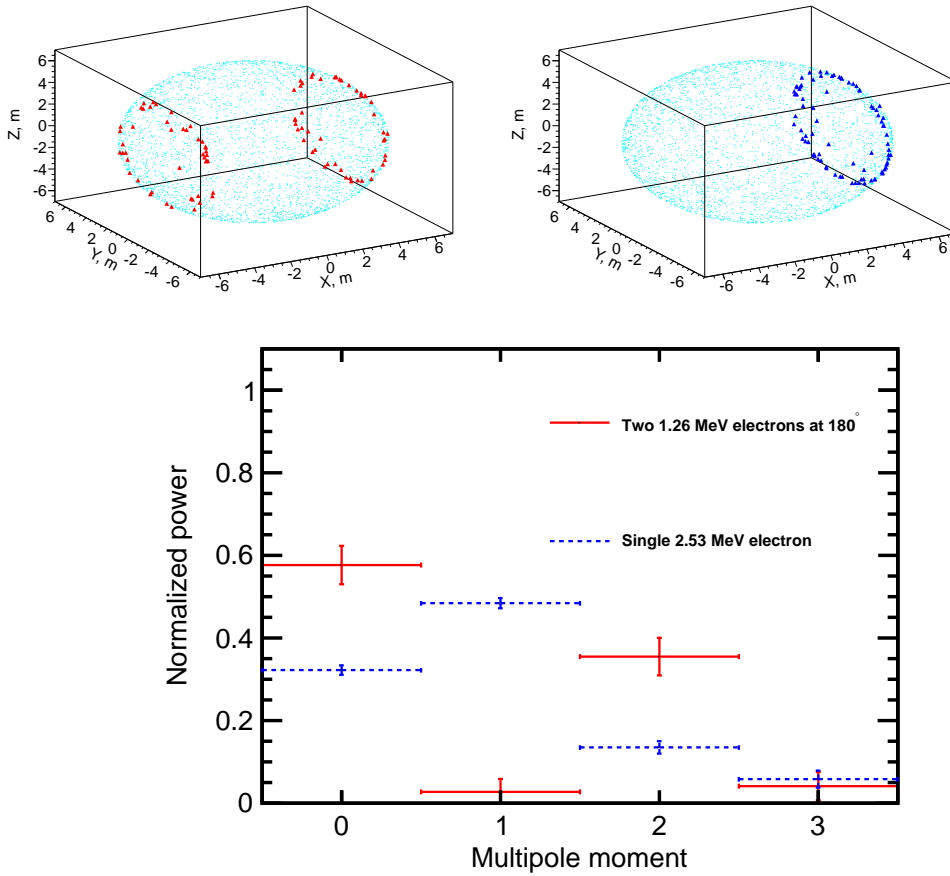


Figure 5: *Top panels*: Idealized event displays, with multiple scattering turned off and at the center of the detector, of: (*top left*) a signal event with two 1.26 MeV back-to-back electrons; and (*top right*) a ${}^8\text{B}$ neutrino background event with single 2.53 MeV electron. A 30% QE is assumed for both Cherenkov PEs (*triangles*) and scintillation PEs (*dots*). *Bottom panel*: The normalized power spectrum S_ℓ for the Cherenkov PEs only, calculated event-by-event for 100 events for the two above topologies. The heights of the vertical bars correspond to event by event variation ($\pm 1\sigma$).

161 4.2. Description of the Spherical Harmonics Analysis

162 The central strategy of the spherical harmonics analysis is to construct rotationally invariant
 163 variables that can be used to separate different event topologies. To account for the fluctuation of
 164 the number of PEs from event to event, we use a normalized power, S_ℓ , defined in Appendix A.

165 The bottom panel in Fig. 5 compares the normalized power spectra for the two representative
 166 event topologies in the idealized case of no multiple scattering and with a 30% quantum efficiency
 167 for both Cherenkov and scintillation photons. In this case, the method gives a good separation
 168 between the two event topologies.

169 At energies relevant to $0\nu\beta\beta$ -decay, multiple scattering makes the Cherenkov rings fuzzy. In
 170 most cases, ~ 1 MeV electrons produce randomly shaped clusters of Cherenkov photons around
 171 the direction of the electron track. Examples of ${}^{130}\text{Te}$ $0\nu\beta\beta$ -decay and ${}^8\text{B}$ events simulated with
 172 multiple scattering, but still at the center of the detector, are shown in Fig. 6. ${}^{130}\text{Te}$ events are gen-
 173 erated based on the phase factors described in [22]. ${}^8\text{B}$ events are implemented as monochromatic
 174 electrons with the initial direction along the x -axis. The default QEs of 12% for Cherenkov light

175 and 23% for scintillation light have been applied. Figure 6 shows early PEs that pass the 33.5 ns
 176 time cut.

177 In this more realistic example, the uniformly distributed scintillation light makes it difficult to
 178 visually distinguish the event topology. The power spectra shown in the bottom panel of Fig. 6 are
 179 different only at $\ell=0$ and $\ell=1$. We use this difference to separate $0\nu\beta\beta$ -decay signal from ${}^8\text{B}$ back-
 180 ground events.

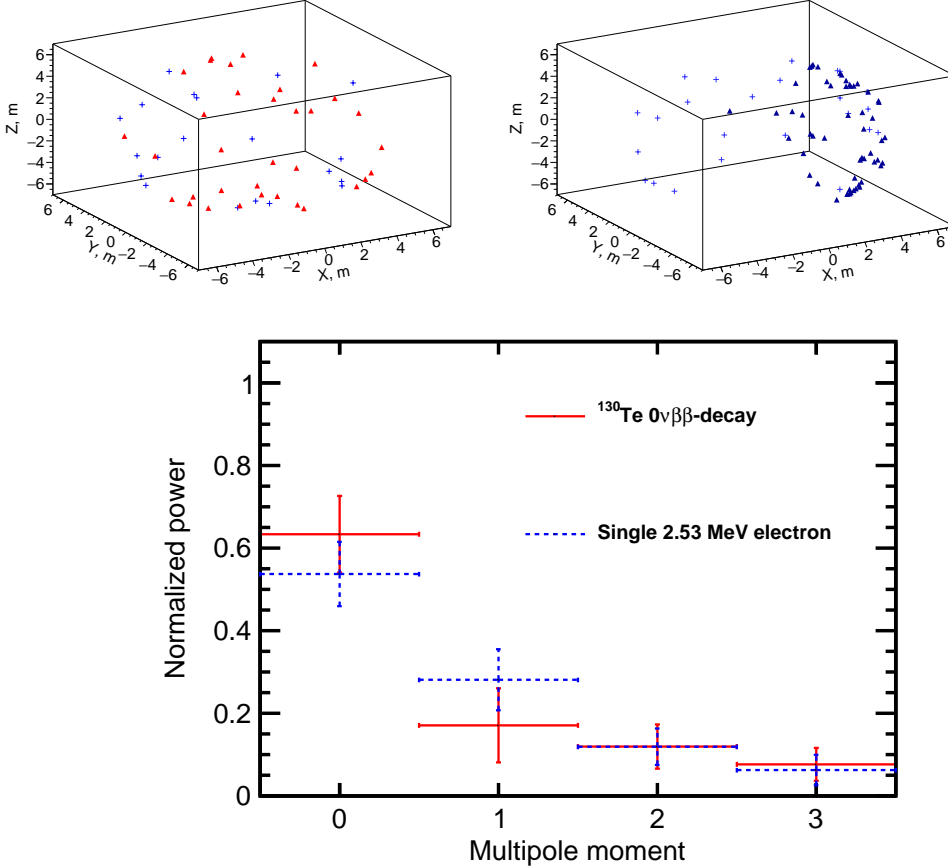


Figure 6: *Top panels:* Event displays with multiple scattering and at the center of the detector for: (*top left*) a signal event with two 1.26 MeV back-to-back electrons; and (*top right*) a ${}^8\text{B}$ neutrino background event with a single 2.53 MeV electron. Only early PEs are shown. The model QEs are assumed for both Cherenkov PEs (*triangles*) and scintillation PEs (*crosses*). *Bottom panel:* The normalized power spectrum S_ℓ for all early PEs, calculated event-by-event for 1000 events of $0\nu\beta\beta$ -decay signal and ${}^8\text{B}$ neutrino events. The heights of the vertical bars correspond to event by event variation ($\pm 1 \sigma$).

181 As expected, we find that $0\nu\beta\beta$ -decay events become indistinguishable from single-track events
 182 when the angle between the two electrons is small and two Cherenkov clusters overlap. Event
 183 topologies of $0\nu\beta\beta$ -decay and ${}^8\text{B}$ events are also very similar when only one electron from $0\nu\beta\beta$ -
 184 decay is above the Cherenkov threshold. The spherical harmonics analysis is most efficient for
 185 events with large angular separation between the two electrons and when both electrons are above
 186 Cherenkov threshold [25].

5. Performance of the Spherical Harmonics Analysis in Separating $0\nu\beta\beta$ -decay from ${}^8\text{B}$ Background.

The separation of signal and background comes almost entirely from the first two multipole moments, $\ell=0$ and $\ell=0$. However, higher multipole moments are needed for the event-by-event normalization of the power spectrum S_ℓ (Eq. A.6). In the following, we choose to calculate the power spectrum s_ℓ up to $\ell=3$ and use only the normalized variables S_0 and S_1 , where the normalization is given by

$$S_{0,1} = \frac{s_{0,1}}{\sum_{\ell=0}^3 s_\ell}. \quad (1)$$

As discussed below, a linear combination of S_0 and S_1 can be used to separate $0\nu\beta\beta$ -decay and ${}^8\text{B}$ events.

5.1. Central events with no uncertainty on the vertex position

To illustrate the technique, we initially evaluate the performance of the spherical harmonics analysis in the idealized case of events at the center of the detector with perfect reconstruction of the event vertex position.

Comparisons of S_0 and S_1 distributions for ${}^{82}\text{Se}$ and ${}^{130}\text{Te}$ $0\nu\beta\beta$ -decay signal and corresponding ${}^8\text{B}$ background events are shown in Fig. 7. Both variables, S_0 and S_1 , provide a noticeable separation between signal and background. ${}^{82}\text{Se}$ $0\nu\beta\beta$ -decay events are shown to demonstrate that in the energy range of interest, the S_ℓ do not strongly depend on the energy deposited in the detector, i.e. information contained in the normalized power spectrum is complimentary to the energy measurements.

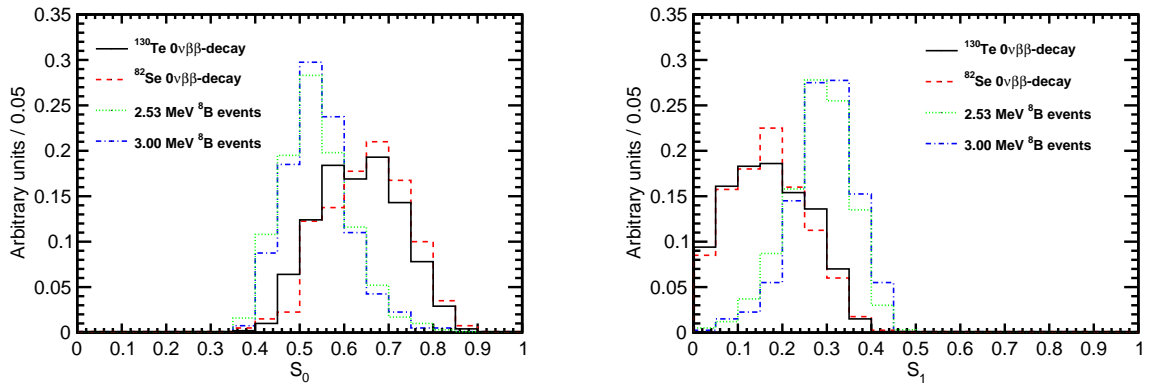


Figure 7: Results from the idealized case of central events at the detector origin(i.e. perfect vertex reconstruction); a time cut of 33.5 ns on the PE arrival time is applied. The default QE and 100% photo-coverage are used in the simulation. (Left) S_0 and S_1 (right) distributions for 1000 simulated $0\nu\beta\beta$ -decay signal and ${}^8\text{B}$ background events. Two different isotopes are compared, ${}^{130}\text{Te}$ and ${}^{82}\text{Se}$. The corresponding kinetic energies of background ${}^8\text{B}$ neutrino single electrons are 2.53 MeV and 3.00 MeV.

The left-hand panel in Fig. 8 compares scatter plots of the first two components of the power spectrum, S_0 and S_1 , for signal and background. In order to illustrate the separation between ${}^{130}\text{Te}$ and ${}^8\text{B}$ events, a linear combination of variables S_0 and S_1 is constructed as follows ².

²A multi-variate event-by-event analysis will have more discriminatory power than this simple 1-dimensional separation, but in the absence of a real detector is a waste of time [26].

209 First, we perform a linear fit to $S_0 = A \cdot S_1 + B$, of all points on the scatter plot, as shown by
 210 the dashed line in the left-hand panel in Fig. 8. A 1-dimensional (1-D) variable S_{01} is defined
 211 as $S_{01} = S_1 \cdot \cos(\theta) + S_0 \cdot \sin(\theta)$, where $\tan(\theta)=A$. The right-hand panel in Fig. 8 compares
 212 distributions of S_{01} for $0\nu\beta\beta$ -decay signal and ${}^8\text{B}$ background. These 1-D histograms for S_{01}
 213 represent the projection of the points on the scatter plot onto the fitted line.

214 To quantify the separation between the signal and background we calculate the area of the
 215 overlap in the S_{01} distributions, $I_{overlap}$. There is no separation if $I_{overlap}=1$, and there is a 100%
 216 separation if $I_{overlap}=0$. Figure 8 shows the separation of this simple algorithm based on the shape
 217 of the early PE sample; the overlap between signal and background is $I_{overlap}=0.52$. At an efficiency
 218 for the signal of 70% we find a rejection factor of 4.6.

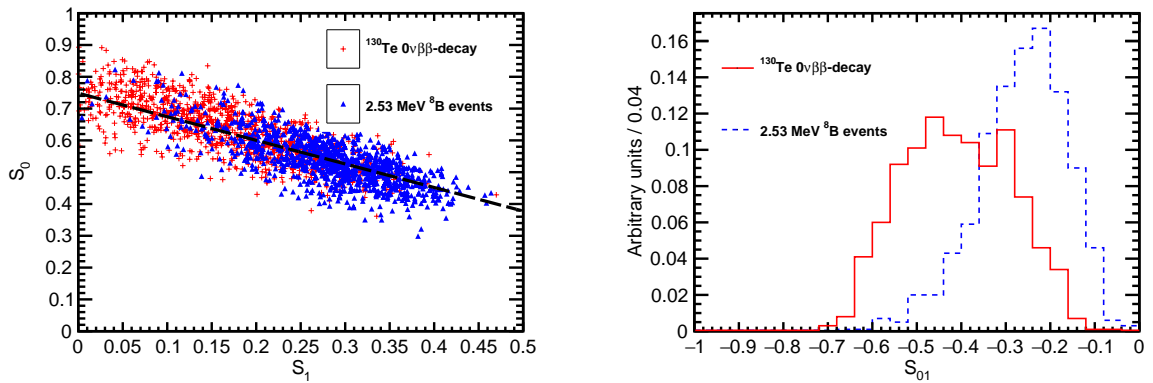


Figure 8: *Left*: Scatter plot of the moments S_0 versus S_1 for a simulation of 1000 signal (*red crosses*) and background (*blue triangles*), for the idealized case of central events assuming perfect reconstruction of the vertex position. A time cut of 33.5 ns on the PE arrival time is applied. The default QE and 100% photo-coverage is used in the simulation. The black dashed line corresponds to a linear fit for S_{01} . *Right*: Comparison of the S_{01} distribution between signal (*red solid line*) and background (*blue dashed line*). $I_{overlap}=0.52$.

219 5.2. Events in a fiducial volume with an uncertainty on the vertex position

220 We find that in the default detector model the separation power of the spherical harmonics
 221 analysis is significantly reduced when event vertex is not at the center of the detector and vertex
 222 resolution is taken into account.

223 For the general case, even significantly delayed scintillation photons can reach the side of the
 224 detector that is closer to the vertex much earlier than Cherenkov photons traveling to the opposite
 225 side of the detector. The time cut thus has to take into account the total distance traveled by
 226 each individual photon. In order to select early PE sample we use a differential cut of $\Delta t =$
 227 $t_{measured}^{phot} - t_{predicted}^{phot} < 1$ ns, where $t_{measured}^{phot}$ is the measured time of the photon hit and $t_{predicted}^{phot}$ is the
 228 predicted time based on the reconstructed vertex position.³

229 In general, the S_1 component of the spherical harmonics power spectrum is higher for asym-
 230 metric distributions and lower for symmetric distributions (e.g., compare the back-to-back and
 231 single electron topologies in Fig. 5). If a vertex is shifted in the direction opposite to the track
 232 of the electron, the differential time cut selects more scintillation photons that are emitted in the

³ $t_{predicted}^{phot} = L^{phot} / v^{phot}$, where the L^{phot} is the distance from the vertex to the photon hit on the detector sphere and v^{phot} is the photon group velocity. Chromatic dispersion thus reduces the efficiency of the time cut in selecting early PE sample with high fraction of Cherenkov PE.

233 direction of the electron track. Scintillation photons would enhance the forward asymmetry of
 234 the early PE sample, which in turn would move S_1 to higher values. Moreover, $S_1 = 0$ for a
 235 distribution with perfect symmetry with respect to the center of the sphere. If a vertex is shifted
 236 in the same direction as the direction of the electron, the differential time cut selects more scintil-
 237 lation photons that are emitted in the direction opposite to the electron track. The asymmetry of
 238 Cherenkov PEs would then be counter-balanced by scintillation PEs, which in turn, would move
 239 S_1 to lower values.

240 We simulated 1000 signal and background events that have their vertices uniformly distributed
 241 within a fiducial volume of $R < 3$ m, where R is the distance between the event vertex and the cen-
 242 ter of the detector, with a vertex resolution of 5.2 cm based on our earlier study of reconstruction[9].
 243 The uncertainty on the vertex reconstruction is implemented as smearing along x , y , and z direc-
 244 tions with three independent Gaussian distributions of the same width, $\sigma_x = \sigma_y = \sigma_z = 3$ cm.

245 Figure 9 shows the performance of the spherical harmonics analysis under these more realistic
 246 assumptions. The overlap between signal and background is $I_{overlap}=0.79$, which means that the
 247 separation is 52% worse than in an idealized scenario shown in Fig. 8. The spherical harmonics
 248 analysis brings little separation between signal and background in our default detector model after
 249 the chromatic dispersion and vertex resolution are taken into account. However, properties of the
 250 liquid scintillator can be adjusted to improve the performance of the spherical harmonics analysis.
 251 In the following we show that a single change in the scintillation rise time improves the separation.

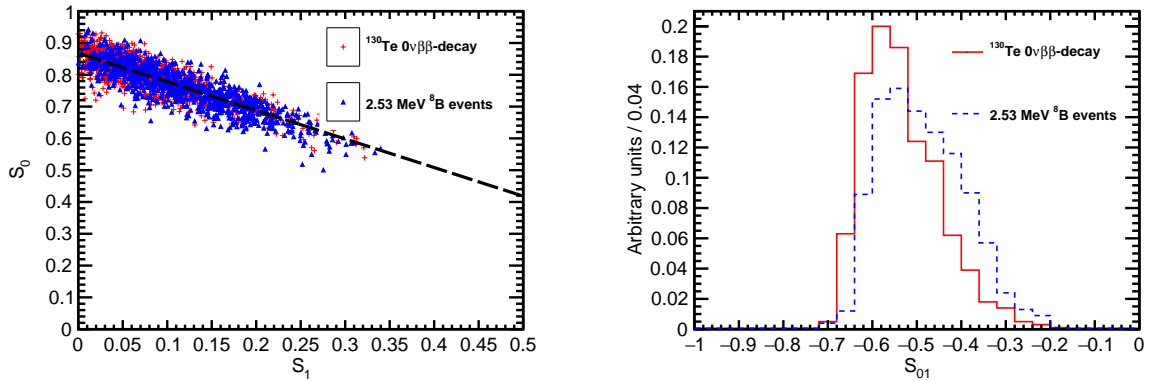


Figure 9: *Left*: Scatter plot of S_0 versus S_1 for a simulation of 1000 signal (red crosses) and background (blue triangles) events. Event vertices are uniformly distributed within the fiducial volume, $R < 3$ m. The vertex is smeared with 5.2 cm resolution. A differential cut of $\Delta t = t_{measured}^{phot} - t_{predicted}^{phot} < 1$ ns is applied to select the early PE sample. The default QE and 100% photo-coverage are used in the simulation. The black dashed line corresponds to a linear fit to define the 1-D variable S_{01} . *Right*: A comparison of the S_{01} distribution between signal (red solid line) and background (blue dashed line). $I_{overlap}=0.79$.

252 5.3. Importance of the liquid scintillator properties

253 The strong dependence on the vertex resolution can be addressed by choosing a liquid scintil-
 254 lator mixture with a more delayed emission of scintillation light with respect to Cherenkov light.
 255 With a larger delay in scintillation light, a higher fraction of Cherenkov light can be maintained
 256 in the early PE sample even if the vertex position is mis-reconstructed. In addition, if the fraction
 257 of scintillation light is small compared to Cherenkov light, the distortions in the uniformity of
 258 the scintillation PE due to a shifted reconstructed vertex position does not significantly affect the

259 spherical harmonics power spectrum. Furthermore, the effects due to chromatic dispersion can
 260 be addressed by using liquid scintillators with a narrower emission spectrum [9], or red-enhanced
 261 photocathodes [9].

262 While the default detector model assumes a scintillation rise time of $\tau_r = 1$ ns, rise times up
 263 to $\tau_r = 7$ ns can be achieved (see Ref. [27]). As a test we increased the scintillation rise time
 264 parameter to $\tau_r = 5$ ns in the detector model, with all other parameters kept the same.⁴ Figure 10
 265 shows the overlap between signal and background is significantly decreased to $I_{overlap}=0.64$, i.e.
 266 the separation is 23% worse than in the idealized scenario shown in Fig. 8 and 23% better than in
 267 the default detector model shown in Fig. 9.

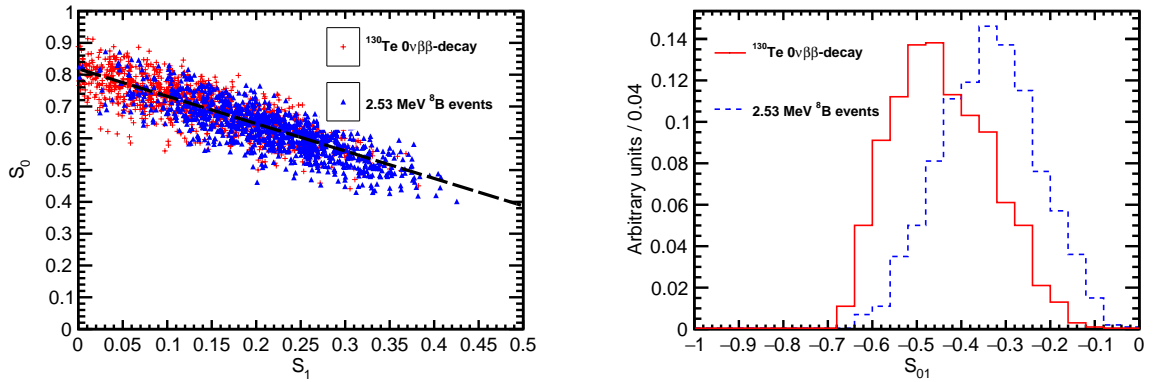


Figure 10: The scintillation rise time constant is increased to $\tau_r = 5$ ns compared to $\tau_r = 1$ ns in the default detector model. *Left:* Scatter plot of S_0 versus S_1 for a simulation of 1000 signal (*red crosses*) and background (*blue triangles*) events. Event vertices are uniformly distributed within the fiducial volume, $R < 3$ m. Vertex is smeared with 5.2 cm resolution. Differential cut of $\Delta t = t_{measured}^{phot} - t_{predicted}^{phot} < 1$ ns is applied to select early PE sample. The default QE and 100% photo-coverage is used in the simulation. Black dashed line corresponds to a linear fit to define 1-D variable S_{01} (see text for details). *Right:* Comparison of the S_{01} distribution between signal (*red solid line*) and background (*blue dashed line*). $I_{overlap}=0.64$.

⁴Usually, longer rise time implies lower light yeild. Here we keep exactly the same light yeild as in the default detector model, assuming future possible advances in liquid scintillator technology [28].

268 Figure 11 shows the efficiency for $0\nu\beta\beta$ -decay signal and the rejection factor for ${}^8\text{B}$ neutrino
 269 background for the default model (left-hand panel) and for the slower scintillator with a 5-ns
 270 risetime (right-hand panel) as a function of the S_{01} discriminant. We find a rejection factor of 2
 271 for the default case at 70% efficiency for signal. The rejection is increased to a factor of 3 for the
 272 5-nsec risetime scintillator.

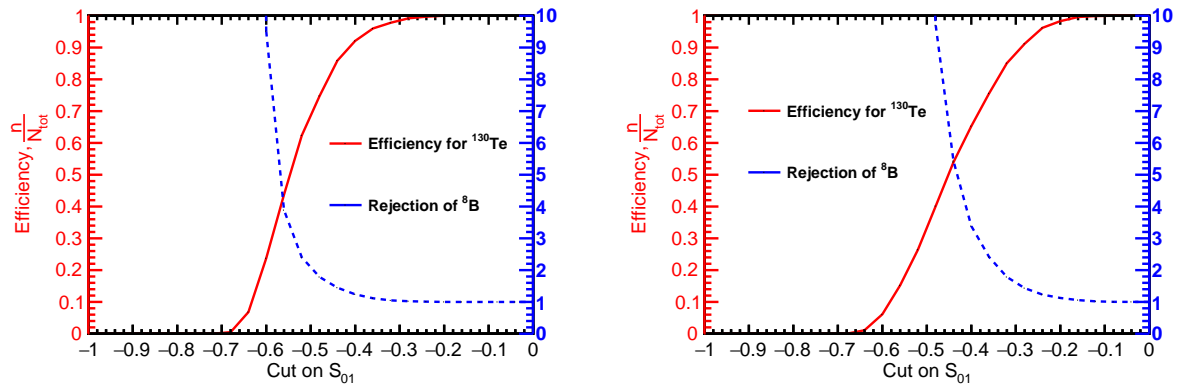


Figure 11: The efficiency for $0\nu\beta\beta$ -decay signal (red left-hand-scale) and the rejection factor for ${}^8\text{B}$ neutrino background (blue right-hand-scale) versus S_{01} for the default model (left panel) and a liquid scintillator with a 5-nsec risetime (right panel).

273 6. Conclusions

274 We consider the use of large-area photodetectors with good time and space resolution in kiloton
 275 scale liquid scintillator detectors to suppress background coming from ${}^8\text{B}$ solar neutrino interac-
 276 tions. Using a default model detector with parameters derived from present practice, we show
 277 that a sample of detected photons enriched in Cherenkov light by a cut on time-of-arrival contains
 278 directional information that can be used to separate $0\nu\beta\beta$ -decay from ${}^8\text{B}$ solar neutrino interac-
 279 tions. The separation is based on a spherical harmonics analysis of the event topologies of the
 280 two electrons in signal events and the single electron in the background. The performance of the
 281 technique is constrained by chromatic dispersion, vertex reconstruction, and the time profile of
 282 the emission of scintillation light. The development of a scintillator with a rise time constant of
 283 at least 5 ns would allow a Cherenkov-scintillation light separation with a background rejection
 284 factor for ${}^8\text{B}$ solar neutrinos of 3 and an efficiency for $0\nu\beta\beta$ -decay signal of 70%.

285 Acknowledgements

286 The activities at the University of Chicago were supported by the Department of Energy under
 287 DE-SC-0008172, the National Science Foundation under grant PHY-1066014, and the Driskill
 288 Foundation, and at MIT by the National Science Foundation under grant 1554875.

289 We thank G. Orebi Gann for a discussion on expected backgrounds at the SNO+ experiment,
 290 and J. Kotilla for discussions on electron angular correlations in $0\nu\beta\beta$ -decay and for providing data
 291 with phase factors for generating $0\nu\beta\beta$ - and $2\nu\beta\beta$ -decay events. We are grateful to C. Aberle for
 292 initial development of the Geant-4 detector model used in this paper and for contributions to the
 293 development of the Cherenkov/scintillation light separation technique, and to M. Wetstein for help

294 with vertex reconstruction algorithms and productive discussions on Cherenkov/scintillation light
295 separation. We thank E. Spiegler for productive discussions on spherical harmonics analysis and
296 E. Angelico for estimating the effects of photo-detector position and time resolution on the vertex
297 reconstruction and verifying the effects of chromatic dispersion. We thank J. Flusser for helpful
298 discussions on image processing using moment invariants. Last but not least we thank M. Yeh for
299 discussions of the timing properties of liquid scintillators.

300 **A. Appendix A**

301 *A.1. Defining the Power Spectrum*

302 Let the function $f(\theta, \phi)$ represent the distribution of the photo-electrons (PE) on the detector
303 surface. The function $f(\theta, \phi)$ can be decomposed into a sum of spherical harmonics:

$$304 \quad f(\theta, \phi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} f_{\ell m} Y_{\ell m}(\theta, \phi), \quad (\text{A.1})$$

305 where $Y_{\ell m}$ are Laplace's spherical harmonics defined in a real-value basis using Legendre poly-
306 nomials P_{ℓ} [29]:

$$307 \quad Y_{\ell m} = \begin{cases} \sqrt{2} N_{\ell m} P_{\ell}^m(\cos \theta) \cos m\phi, & \text{if } m > 0 \\ N_{\ell m} = \sqrt{\frac{(2\ell+1)(\ell-m)!}{4\pi(\ell+m)!}}, & \text{if } m = 0 \\ \sqrt{2} N_{\ell |m|} P_{\ell}^{|m|}(\cos \theta) \sin |m|\phi, & \text{if } m < 0 \end{cases} \quad (\text{A.2})$$

308 where the coefficients $f_{\ell m}$ are defined as

$$309 \quad f_{\ell m} = \int_0^{2\pi} d\phi \int_0^{\pi} d\theta \sin \theta f(\theta, \phi) Y_{\ell m}(\theta, \phi). \quad (\text{A.3})$$

310 Equation A.4 defines the power spectrum of $f(\theta, \phi)$ in the spherical harmonics representation,
311 s_{ℓ} , where l is a multipole moment. The power spectrum, s_{ℓ} , is invariant under rotation.

$$312 \quad s_{\ell} = \sum_{m=-\ell}^{m=\ell} |f_{\ell m}|^2 \quad (\text{A.4})$$

313 The event topology in a spherical detector determines the distribution of the PE's on the detector
314 sphere, and, therefore, a set of s_{ℓ} 's. These values can serve as a quantitative figure of merit for
315 different event topologies. The rotation invariance of the s_{ℓ} 's ensures that this figure of merit does
316 not depend on the orientation of the event with respect to the chosen coordinate frame.

317 The sum of s_{ℓ} 's over all multipole moments equals to the L^2 norm of the function $f(\theta, \phi)$:

$$318 \quad \sum_{\ell=0}^{\infty} s_{\ell} = \int_{\Omega} |f(\theta, \phi)|^2 d\Omega. \quad (\text{A.5})$$

319 The normalized power spectrum is thus:

$$320 \quad \mathcal{S}_{\ell} = \frac{s_{\ell}}{\sum_{\ell=0}^{\infty} s_{\ell}} = \frac{s_{\ell}}{\int_{\Omega} |f(\theta, \phi)|^2 d\Omega}, \quad (\text{A.6})$$

321 and can be used to compare the shapes of various functions $f(\theta, \phi)$ with different normaliza-
 322 tions. As the total number of PEs detected on the detector sphere fluctuates from event to event
 323 we use the normalized power \mathcal{S}_ℓ .

324 A.2. Spherical Harmonics Analysis and Off-center Events

325 In general, events with the same event topology result in the same the power spectrum S_ℓ only if
 326 events originate in the center of the detector. In order to compare the spherical harmonics for events
 327 with verticies away from the center, a coordinate transformation for each photon hit is needed. The
 328 necessary transformation applied for each PE within an event is illustrated in Fig. A.12. The solid
 329 circle in Fig. A.12 has a radius R and shows the actual detector boundaries. The dotted circle
 330 shows a new sphere with the same radius R , which now has the event vertex in its center. The
 331 radius vector of each PE is stretched or shortened to its intersection with this new sphere using
 332 the transformation, $\vec{r}_{PE}^* = \frac{\vec{d}}{|\vec{d}|} \cdot R$, where \vec{r}_{PE}^* is a new radius vector of a PE and $\vec{d} = \vec{r}_{PE} - \vec{r}_{vtx}$ with \vec{r}_{PE}
 333 and \vec{r}_{vtx} being radius vectors of the PE and the vertex in the original coordinates, respectively.

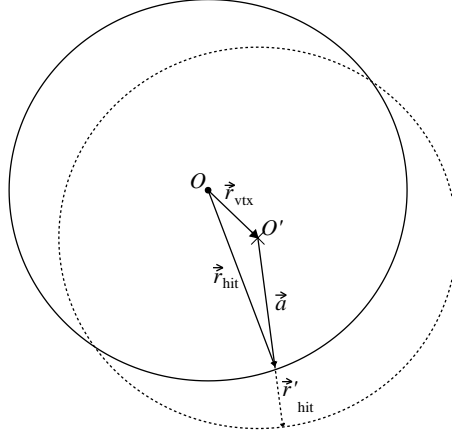


Figure A.12: The coordinate transformation which is applied to events that are off-center. The solid circle schematically shows the actual detector boundaries. The dotted circle shows a new sphere of radius $R=6.5$ m with the event vertex position in the center. The radius vector of each photon hit is stretched or shortened until the intersection with this new sphere using the transformation $\vec{r}_{hit}^* = \frac{\vec{d}}{|\vec{d}|} \cdot R$, where \vec{r}_{hit}^* is a new radius vector of the photon hit, R is detector sphere radius, and $\vec{d} = \vec{r}_{hit} - \vec{r}_{vtx}$ with \vec{r}_{hit} and \vec{r}_{vtx} being the radius vectors of the photon hit and vertex position in original coordinates, respectively.

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