Directional Reconstruction of Reactor Antineutrinos via Electron Scattering in Gd-doped Water Cherenkov Detectors

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Introduction

Large scale Gd-doped water Cherenkov antineutrino detectors (WCDs) are being investigated for remote (> 10 km) monitoring of nuclear reactors [1-3]. Measurements of the flux and energy spectrum of reactor antineutrinos via the inverse beta decay (IBD) ($\bar{\nu}_e + p \rightarrow e^+ + n$) interaction enable the calculation of important reactor characteristics such as the operational status (on/off) and relative power output. Directional information from the antineutrinos would allow for a reduction in backgrounds from known nearby reactors and may facilitate search abilities for unknown reactors. Liquid scintillator detectors [4] have demonstrated antineutrino pointing over time using IBD, but this method is currently not feasible in WCDs due to the lower sensitivity and spatial resolution. In this work, we investigate an alternative and highly directional interaction channel, elastic antineutrino electron scattering (ES) ($\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$), and determine the experimental conditions required for 3σ directional reconstruction of antineutrinos in WCDs.

Detection and Reconstruction

ES is a threshold-less reaction and the cross section is ~6 times smaller than IBD for a single water molecule (Fig. 1a). The interaction is highly directional (Fig. 1b) [5].

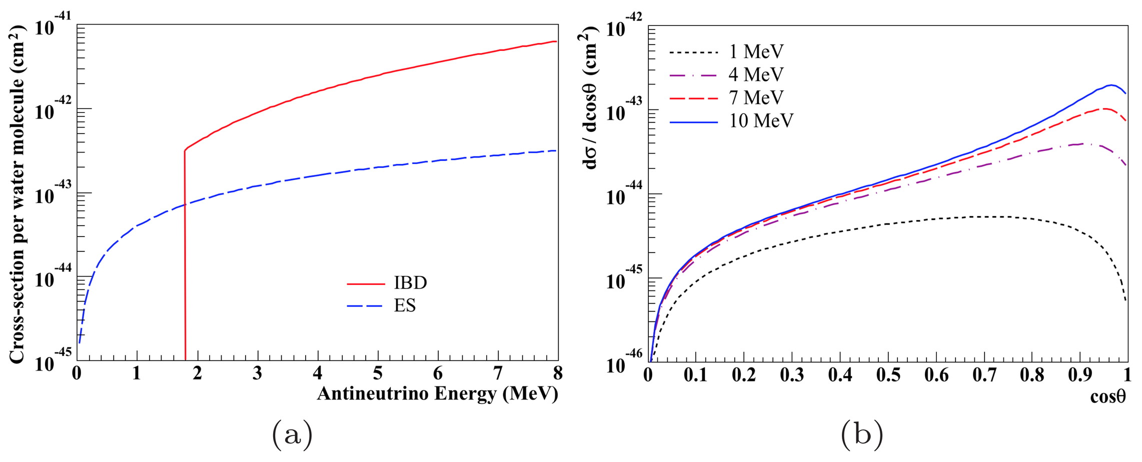


Fig. 1. (a) Cross sections of IBD and ES interactions per water molecule (2 p, 10 e^-) . (b) Differential scattering cross section.

Scattered e^- can produce a Cherenkov cone (Fig. 2) which is detected by photomultiplier tubes (PMTs). Positional and directional reconstruction is done by analyzing the PMT detection pattern.

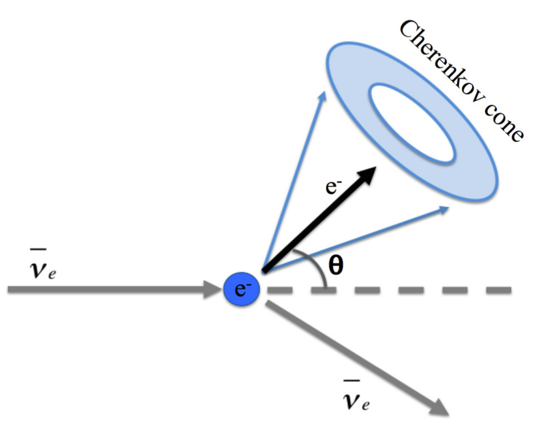


Fig. 2. Schematic of ES.

Reactor $\bar{\nu}_e$ Spectrum

Fission product decays produce $\bar{\nu}_e$ with a continuum of energies. While still an active area of research, models [6] have been developed to describe the energy spectra of reactor $\bar{\nu}_e$ (Fig. 3).

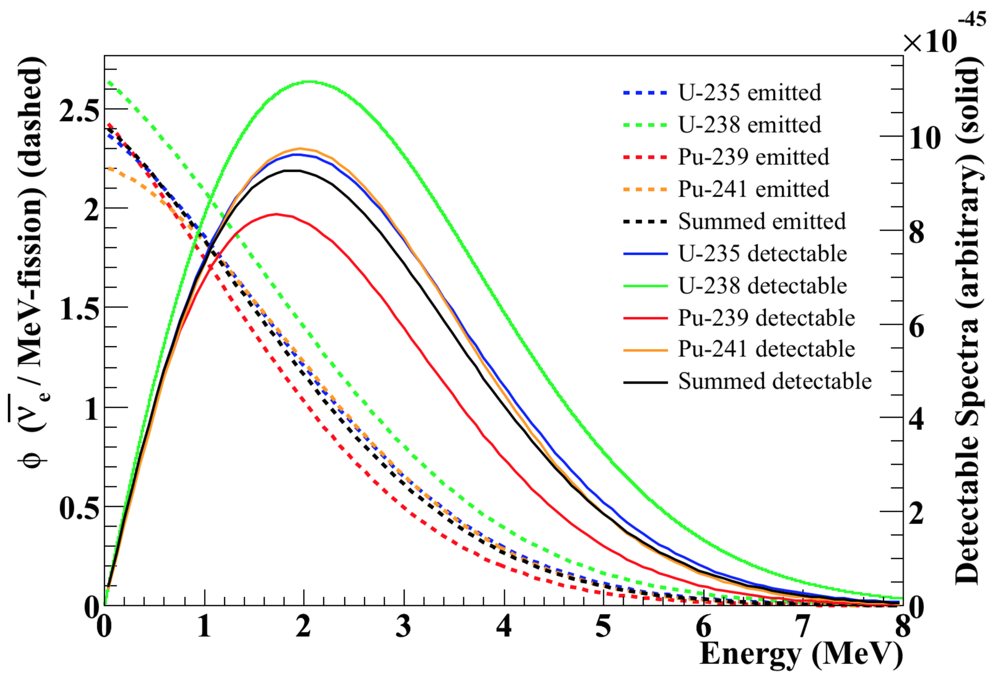


Fig. 3. Emitted and detectable $\bar{\nu}_e$ energy spectra per fission. Black lines represent the summation of the four isotopes weighted by typical fission fractions of a mid-cycle PWR.

Fission concentrations of a typical mid-cycle pressurized light water reactor (PWR) were used (49.6% ^{235}U, 35.1% ^{239}Pu, 8.7% ^{238}U, and 6.6% ^{241}Pu) [7].

Detector Model

The detector is modeled after the proposed WATCHMAN detector (Fig. 4a). There are ~4300 12-inch PMTs facing the target (2.1 kilotons) (~40% photocathode coverage) and 480 PMTs facing the veto (1 kiloton).

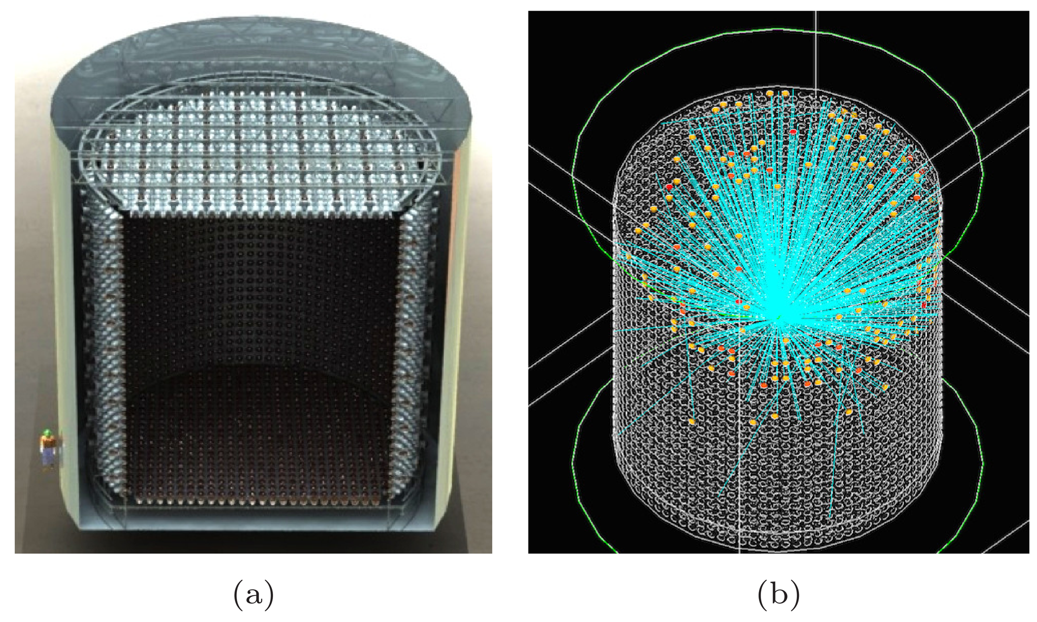


Fig. 4. (a) Basic design of WATCHMAN [3]. (b) Visualization of antineutrino electron scattering in Geant4 simulation.

Similar to the proposed WATCHMAN deployment, we assume a single-core 3.758-GWth PWR with 13-km standoff and 1500-m.w.e. depth. Geant4 was used to model detector response (Fig. 4b). Positional and directional reconstruction was done with the Super-K code, BONSAI [8].

Results

We determined the 1-year ES and background response in a kiloton fiducial volume by scaling from previous measurements (Fig. 5a) [9]. With sufficient fiducialization, we show that PMT backgrounds can be reduced to a subdominant level (Fig. 5b).

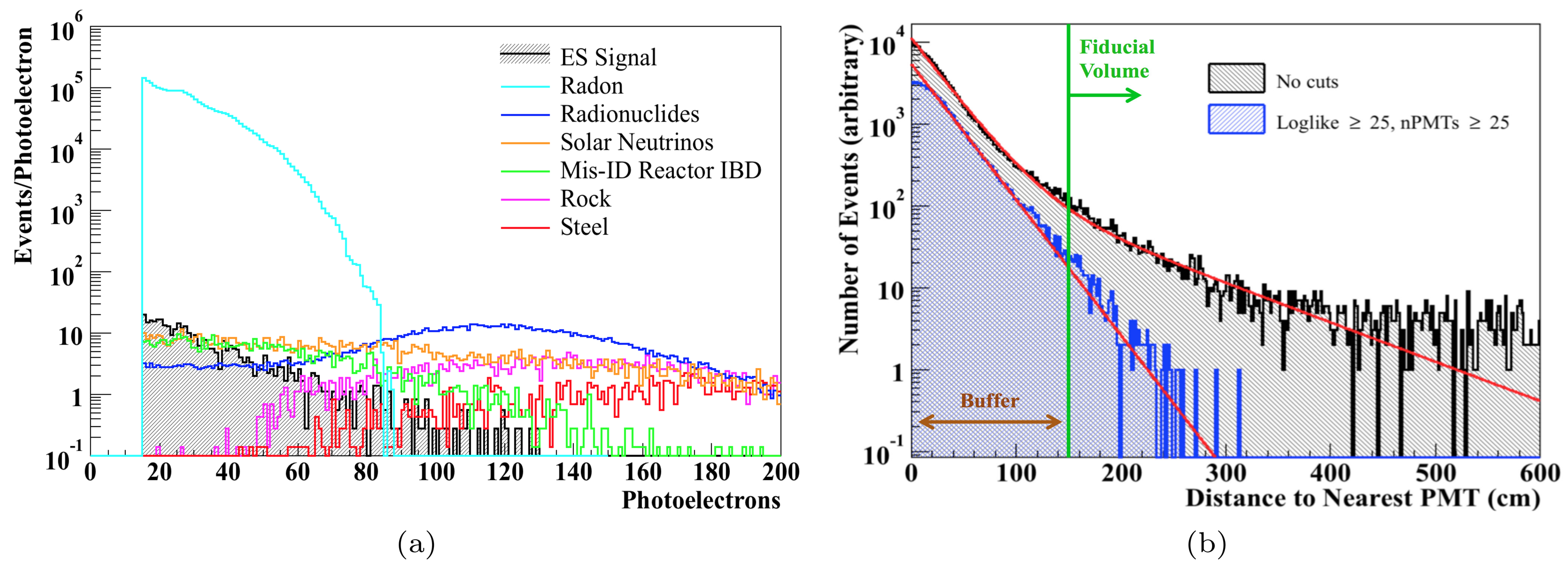
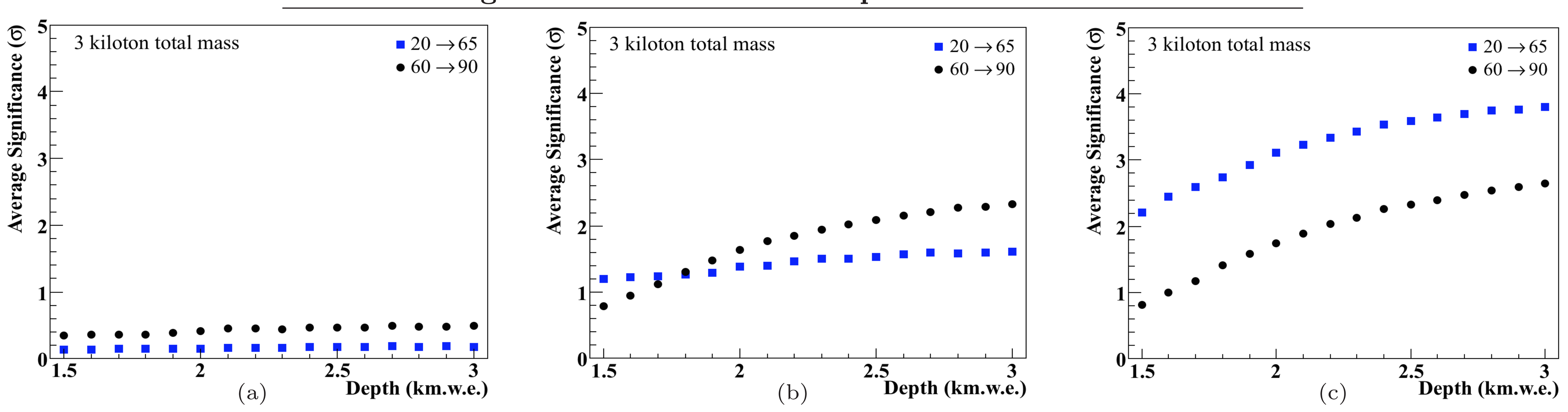


Fig. 5. (a) One-year signal and background (excluding PMTs) responses in a 1-kiloton WCD. (b) Spatial reconstruction of PMT background events - with specific cuts, the background can be significantly reduced.

We analyzed the sensitivity as a function of overburden and radon contamination (relative to the SNO detector [10]) using two different energy cuts (Figs. 6a-c). The radionuclide background was scaled with the showering and nonshowering muon rates as a function of depth [11-13]. We also determined the total detector volume required for 3σ significance at a given depth and radon contamination (Figs. 6d-f).

Directional Significance vs. Detector Depth and Radon Contamination



Required Detector Size for 3σ Significance vs. Detector Depth and Radon Contamination

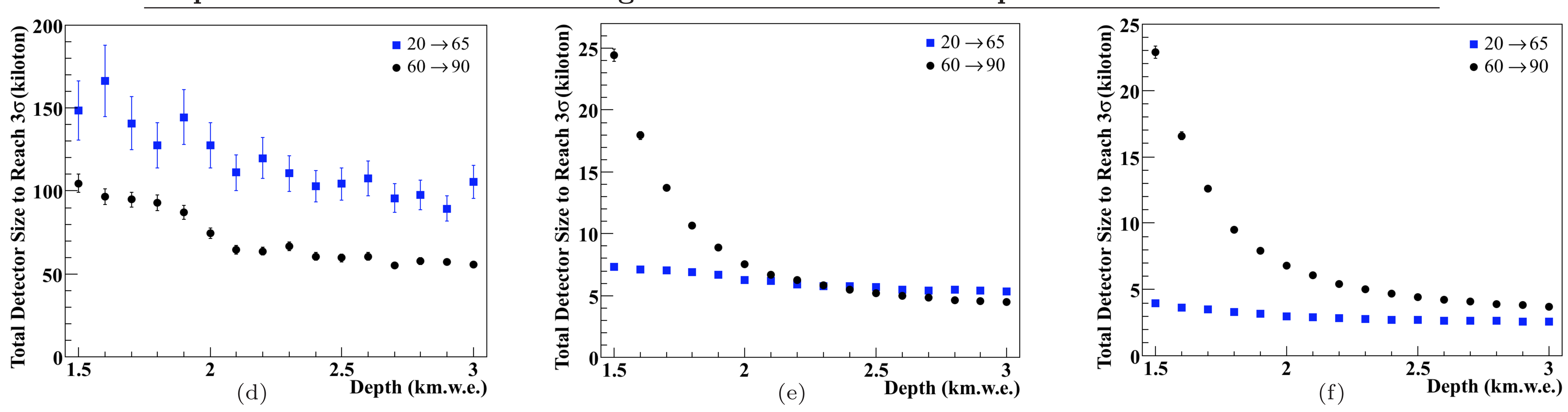


Fig. 6. Average statistical significance vs. depth using two energy ranges (25 → 65 and 60 → 90 hit PMTs), for radon levels of $1 \times$ SNO (a), $10^{-2} \times$ SNO (b), and $10^{-4} \times$ SNO (c). Total detector size required for 3σ significance vs. depth for radon levels of $1 \times$ SNO (d), $10^{-2} \times$ SNO (e), and $10^{-4} \times$ SNO (f).

Conclusions

Under certain conditions, directional reconstruction of nuclear reactors may be achievable via the antineutrino-electron scattering channel.

Flux scaling can approximate the directional sensitivity at greater distances and for smaller reactor power levels using even larger, megaton scale detectors (Table I). These detectors (i.e. Hyper-K [14]) represent the outer limit of possible field-able (anti)neutrino detectors.

Table I. Potential directionally sensitive scenarios for a 1-megaton WCD with 2500 m.w.e. overburden.

Radon ($\times$ SNO)	Reactor Power (MWth)	Standoff (km)
10^{-2}	3758	70
10^{-2}	125	13
10^{-4}	3758	105
10^{-4}	55	13

The dominant factor affecting sensitivity is radon contamination → further research is needed in the field of waterborne radon removal.

References

[1] A. Bernstein, et al., Science & Global Security 18 (3) (2010) 127-192.
[2] T. Lasserre, et al., arXiv:1011.3850 (2010).
[3] A. Bernstein, et al., arXiv:1502.01132 (2015).
[4] M. Apollonio, et al., Phys. Rev. D 61 (1999) 012001.
[5] C. Giunti, C.W. Kim, Fundamentals of Neutrino Physics and Astrophysics, Oxford University Press, Oxford, 2007.
[6] P. Vogel, J. Engel, Phys. Rev. D 39 (1989) 3378.
[7] G. Zacek, et al., Phys. Rev. D 34 (1986) 2621.
[8] M. Smy, in: Proceedings of the International Cosmic Ray Conference, Vol. 5 (HE part 2), Mexico City, Mexico, 2008, 1279-1282.
[9] D. Hellfeld, et al. NIM-A (2016), 10.1016/j.nima.2016.10.027
[10] I. Belvis, et al., NIM-A 517 (2004) 139D153.
[11] S. Abe, et al. (KamLAND Collab.), Phys. Rev. C 84 (2011) 035804.
[12] S. Abe, et al. (KamLAND Collab.), Phys. Rev. C 81 (2010) 025807.
[13] D.M. Mei, A. Hime, Phys. Rev. D 73 (2006) 053004.
[14] S. Abe, et al. (Hyper-K Working Group), arXiv:1109.3262 (2011).

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