PROCEEDINGS OF SCIENCE

A New Method for Detecting Charged-Current Neutrino Interactions on ^{136}Xe in KamLAND-Zen: Implications for Solar Neutrino Measurements and Fermionic Dark Matter Searches

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A ^{136}Xe nuclei capture electron neutrinos through charged-current (CC) interaction. This lead to an excited state of ^{136}Cs : $\nu_e + {}^{136}\mathrm{Xe} \rightarrow \mathrm{e}^- + {}^{136}\mathrm{Cs}\ (1^+)$. This reaction can be used for low energy solar neutrino measurements and MeV scale mass fermionic dark matter searches. The recent observation of low-lying isomeric states in ^{136}Cs with lifetimes on the order of 100 ns implies that the CC interaction can be identified by a delayed-coincidence measurement in liquid scintillator detector. This technique involves detecting a prompt signal conposed of the electron and most of the de-excitation γ-rays, followed by a delayed signal consisting of the remaining de-excitation γ-rays with energies below 140 keV. KamLAND-Zen is an experiment designed to search for neutrinoless double-beta decay of ^{136}Xe. KamLAND-Zen uses organic liquid scintillators dissolving 750 kg of xenon (91% enriched in ^{136}Xe) and has the world's largest exposure to the CC reaction. We conducted a feasibility study of identifying the CC interaction in KamLAND-Zen.

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1. Introduction

ν_e(or dark matter : χ) $+^{136}$ Xe $\rightarrow$ e$^-$ $+^{136}$ Cs*(XeCC) is an available reaction channel at xenon-based experiments whose observables are recoil electrons and de-excitation γ-rays from the excited state of ^{136}Cs [1]. Recentry, the low-lying isomeric states in ^{136}Cs* with lifetimes on the order of 100 ns were observed [2, 3]. Therefore, one can conduct delayed-coincidence tagging of multiple time-correlated de-excitation γ-rays using a ns-response detector like liquid scintillator. The sizable Gamow-Teller transition strengths result in a relatively large cross section connecting the 0^+ ground state of ^{136}Xe and the lowest-lying 1^+ excited states of ^{136}Cs near 588.8 and 850 keV. Therefore the XeCC interaction has low energy threshold of 79 keV (Q-value [4]) + 588.8 keV = 667.8 keV. There are three main de-excitation modes with time scales that we can observe,

- Mode-1 (branch 58%): 588.8 keV $\rightarrow$ 140.3 keV (90 ns) $\rightarrow$ 73.7 keV (157 ns) $\rightarrow$ $G.S.$
- Mode-2 (branch 14%): 588.8 keV $\rightarrow$ 140.3 keV (90 ns) $\rightarrow$ 105.0 keV $\rightarrow$ $G.S.$
- Mode-3 (branch 27%): 588.8 keV $\rightarrow$ 422.1 keV $\rightarrow$ 313.6 keV $\rightarrow$ 73.7 keV (157 ns) $\rightarrow$ $G.S.$

2. Physics targets

The low interaction energy threshold of XeCC is useful for low energy solar neutrino measurements [1]. Unlike the electron scattering channel, XeCC allows one-to-one neutrino energy reconstruction by detecting e^- and all de-excitation γ-rays. Figure 1 shows the expected energy spectrum of XeCC events caused by solar neutrinos, where $\Delta m^2_{21} = 7.51 \times 10^{-5}$ eV^2, $\sin^2\theta_{12} = 0.306$, $\sin^2\theta_{13} = 0.0219$ [5] and BP16-GS98 SSM [6] were assumed. The ^{7}Be-ν rate, 5.9 ton^{-1} yr^{-1}, may be within reach of KamLAND-Zen 800 (see Section 3). Future detectors with an energy resolution of a few percent at 1 MeV can measure CNO-ν's mitigating ^{7}Be-ν and pep-ν backgrounds (BG). Moreover, each of the CNO components, ^{13}N and ^{15}O, can be determined separately.

Fermionic dark matter (FDM) interacts with Standard Model particles via right-handed gauge boson W', which are particles beyond the Standard Model framework. One can use the XeCC interaction to search for dark matter in the mass range of a few MeV to several tens of MeV. EXO-200 performed a FDM search through the interaction using "single event" datasets. The ^{136}Xe double-beta decay ($2\nu\beta\beta$) BG is dominant in the low mass region. If delayed coincidence tagging is available, sensitivity can be improved in this mass region.

3. KamLAND-Zen 800

3.1 Detector

The KamLAND-Zen (KLZ) [7] is a neutrinoless double-beta decay ($0\nu\beta\beta$) search experiment using ^{136}Xe-dissolved organic liquid scintillator (XeLS). The XeLS is housed in a nylon film balloon which is located at the center of the 1-kton liquid scintillator (LS) detector, KamLAND. Scintillation photons are detected by 1879 PMTs surrounding the LS. The current phase of KLZ, KLZ-800, has been running for more than 4 years of live time holding 0.68 ton of ^{136}Xe. Assuming 100% detection efficiency, more than 16 of ^{7}Be-ν XeCC events are expected in KLZ-800. The scintillation decay time and the number of PMT hits per MeV of XeLS are ~6 ns and ~250 hits, respectively. The

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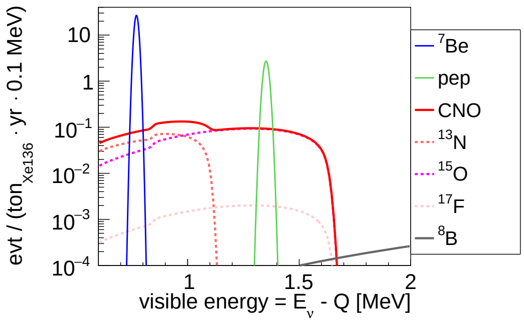

Figure 1: The expected energy spectrum of XeCC events caused by solar neutrinos. $\Delta E/E = 1\%/\sqrt{E\ [\mathrm{MeV}]}$ is assumed.

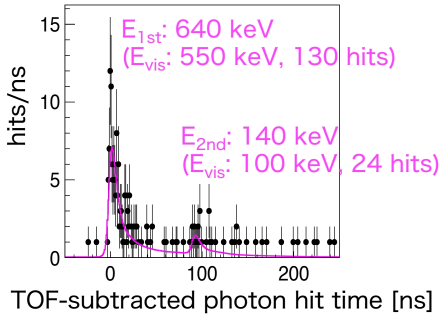

Figure 2: Toy-MC of ^{7}Be-ν XeCC event (Mode-2) in KamLAND-Zen.

current KLZ-800 event window is 200 ns, and the trigger threshold is approximately 300 keV. Therefore, only prompt pulses in XeCC exceed the threshold. Delayed pulses can be detected if they are in the event window of the prompt pulses. Figure 2 shows a Toy-Monte Carlo (Toy-MC) example of ^{7}Be-ν XeCC event (Mode-2).

The main challenges in the delayed coincidence analysis of XeCC are: (1) mis-identification of $2\nu\beta\beta$ as multi-pulse event due to statistical fluctuations that cause one waveform to be like two waveforms; and (2) pile up of accidental BG due to ^{14}C. The statistical fluctuations of the $2\nu\beta\beta$ signal were evaluated using Toy-MC as described in section 3.2. Given the rate of ^{14}C in the entire KamLAND detector (~5 kHz), the probability of accidentally including a ^{14}C event in a single event window is estimated to be around 10^{-3}. In the KLZ, the $2\nu\beta\beta$ signal is dominant up to a 2.5 MeV (visible energy). It is necessary to reduce the $2\nu\beta\beta$ BG by five orders of magnitude to observe the XeCC signal of solar neutrinos around 1 MeV in energy.

3.2 Toy-MC study

We generated about 10^5 single pulses each corresponding to several energies from the lowest reaction energy up to the $2\nu\beta\beta$ endpoint with the Toy-MC. Then, the generated pulses were fitted assuming multi-pulses (multi-pulse fit). The time difference ($\mathrm{d}t$) between the multi-pulses was obtained. Single pulses thickened by statistical fluctuations are fitted with a short $\mathrm{d}t$, so we set a threshold $\mathrm{d}t_{\mathrm{threshold}}$ to remove such things. The $\mathrm{d}t_{\mathrm{threshold}}$ and the corresponding signal acquisition efficiencies in the de-excitation Mode-2 are summarized in Table 1. The smaller the first pulse, the easier to find the second pulse. The efficiencies are several tens of percent around the 1 MeV energy region. Even near the $2\nu\beta\beta$ endpoint, it is still about 10%.

Table 1: Mode-2 efficiency of each E_ν and m_χ.

$E_{\nu_e}(m_\chi)$	[MeV]	0.67 (1.2)	0.86 (1.4)	1.3 (1.8)	1.9 (2.4)	2.2 (2.7)	2.5 (3.0)
$\mathrm{d}t_{\mathrm{threshold}}$	[ns]	66	70	97	106	125	140
Mode-2 efficiency	[%]	45.3	35.1	23.2	19.9	14.1	10.3

3.3 Evaluation of ^{214}Po data

We applied the multi-pulse fitter to ^{214}Po events obtained with >99% purity from ^{214}Bi-^{214}Po events tagged by delayed coincidence in the KLZ analysis. As a result, 10 events with longer dt than the d$t_{\rm threshold}$ out of a total of 80,000 events (>10^{-3}) were found. This almost agrees with the ^{14}C accidental BG expectation. For the purpose of BG removal of more than 5 orders, the removal of accidental BG is necessary.

4. Summary

We conducted a feasibility study of XeCC detection by multi-pulse tagging in KamLAND-Zen. When solar neutrinos with energies around 1 MeV are considered as signals, it is required to suppress the probability of misidentifying single pulses of $2\nu\beta\beta$ events as the signal to 10^{-5}. We evaluated the necessary time difference (d$t_{\rm threshold}$) between multiple pulses of the signals using Toy-MC to meet the requirement. Signal acquisition efficiencies corresponding to the d$t_{\rm threshold}$'s were several tens of percent. However, accidental BG from ^{14}C becomes a concern. To eliminate the BG, vertex reconstruction of delayed pulses is necessary. Our future project, KamLAND2-Zen, is expected to have more than 5 times the photons of the KLZ-800. This will result in a better pulse discrimination capability. Furthermore, if the event window is extended from the current 200 ns to 1000 ns in the new electronics for KamLAND2-Zen, it will benefit this research.

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