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Tagging long-lived radioactive isotopes produced through cosmic-ray muon spallation in KamLAND

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Summary. — The most stringent limit on the neutrinoless double beta decay half-life of ^{136}Xe is set by KamLAND-Zen at $T_{1/2} > 2.3 \times 10^{26}$ yr. The experiment's sensitivity is limited by long-lived radioactive isotopes produced from muon spallation of xenon nuclei in the xenon-doped liquid scintillator. The long lifetimes of the isotopes, typically up to several days, challenge the creation of an efficient tagging method, currently achieving only $42 \pm 8.8\%$. We summarise the tagging techniques for both light and heavy spallation isotopes employed in KamLAND-Zen, and highlight the critical role of FLUKA simulations in developing new veto strategies.

1. – Introduction

Neutrinoless double beta decay ($0\nu\beta\beta$) of a nucleus offers a practical approach for testing the Majorana nature of neutrinos. The decay's half-life provides insight into the effective Majorana mass under standard assumptions [1], connecting the potential discovery to a statement about the absolute neutrino mass scale. However, to date, $0\nu\beta\beta$ decay has not been observed. The leading experiment, KamLAND-Zen, has set a lower bound on the half-life of ^{136}Xe $0\nu\beta\beta$ decay at $T_{1/2} > 2.3 \times 10^{26}$ yr [2]. The experiment's dominant background is constituted by β-decays of long-lived radioactive isotopes, produced through muon spallation of xenon [3]. Our work focuses on simulating and identifying muon spallation products in KamLAND-Zen and discussing the challenges posed by long-lived isotopes for current and future $0\nu\beta\beta$ detectors.

2. – KamLAND-Zen

The Kamioka Liquid Scintillator Anti-Neutrino Detector (KamLAND) is a general purpose neutrino detector situated about 1000 m underground in an old mine below Mt. Ikenoyama in Japan [3]. The detector consists of an outer Cherenkov detector (OD) and an inner scintillation detector (ID). The OD is a cylindrical cave structure of 20 m diameter by 20 m height, filled with 3.2 kton pure water, to shield from γ-rays

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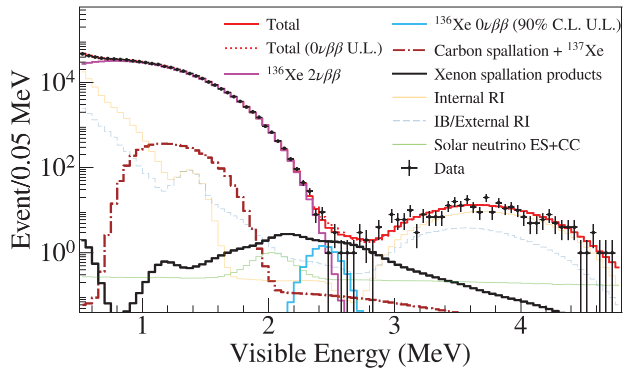

Fig. 1. – The energy spectra of double beta candidates from a 970 kg yr exposure of KamLAND-Zen, adapted from [2]. The best-fit backgrounds are included, with the spallation backgrounds and the upper limit for $0\nu\beta\beta$ at 90% C.L. in bold. The $2\nu\beta\beta$ decay spectrum and muon spallation of xenon dominate the background in the $0\nu\beta\beta$ region of interest.

and fast neutrons from the surrounding rock. In addition, it enables cosmic-ray muon tagging through Cherenkov light, captured by the 20-inch photomultiplier tubes (PMTs) mounted on the inside of the cavern. The ID, located inside the OD, has a 18 m spherical stainless steel tank with 1325 17-inch and 554 20-inch PMTs mounted on the inner surface of the tank. In the center of the tank, a 13 m diameter nylon spherical outer balloon (OB) contains 1 kton of liquid scintillator (LS). The LS is a mixture of dodecane, serving as the solvent, pseudocumene (PC) and PPO. Scintillation light is generated through interactions of particles. The light output of the primary scintillating agent, PC, is enhanced by the fluor PPO, enabling its detection by the surrounding PMTs. To shield against PMT material radioactivity, the gap between the balloon and steel tank is filled with non-scintillating buffer oil.

The KamLAND Zero Neutrino Double Beta (KamLAND-Zen) experiment, an upgrade of KamLAND [4], features a 3.8m diameter inner balloon (IB) at the center of the OB. This IB is filled with xenon-doped liquid scintillator (Xe-LS), composed of decane, PC, PPO and 745 kg of enriched xenon gas, approximately 91% of which is ^{136}Xe. The $0\nu\beta\beta$ decay search in KamLAND-Zen faces backgrounds from $2\nu\beta\beta$ decay, solar neutrino interactions, radioactive contaminants, and muon spallation products. The current phase of KamLAND-Zen has been running since January 2019, and the experiment's latest publication [2] has revealed that xenon spallation products predominantly contribute to the background in the energy spectra of $0\nu\beta\beta$ candidates, as shown in fig. 1.

3. – Muon spallation background

The 1000 m of rock overlying KamLAND-Zen act as a shield against cosmic-ray muons. Nevertheless, high-energy muons still pass through the detector, approximately once every 3 seconds. These muons produce radioactive isotopes through spallation on hydrogen, carbon, nitrogen, oxygen and xenon within the detector, posing a background for the $0\nu\beta\beta$ search. To address this, interactions of muons with the Xe-LS were simulated using FLUKA, leading to the development of effective veto techniques.

TABLE I. – *Production rate of the four dominant radioactive isotopes produced through muon spallation on xenon in the region of interest of* $0\nu\beta\beta$. *The muon interactions were simulated with FLUKA and the subsequent* β*-decay with GEANT4. The table is adapted from* [3].

Isotope	$\tau_{1/2}$ (s)	Q (MeV)	ROI $(\mathrm{kton}\times\mathrm{day})^{-1}$	Total $(\mathrm{kton}\times\mathrm{day})^{-1}$
^{88}Y	9.212×10^6	3.62 (EC/$\beta^+\gamma$)	0.110	0.136
^{118}Sb	2.160×10^2	3.66 (EC/$\beta^+\gamma$)	0.165	1.288
^{122}I	2.178×10^2	4.23 (EC/$\beta^+\gamma$)	0.289	1.965
^{124}I	3.608×10^5	3.16 (EC/$\beta^+\gamma$)	0.190	1.654

3˙1. *Muon spallation simulation.* – FLUKA is an extensive Monte Carlo (MC) code used for particle transport and interactions with matter [5]. It is broadly used to simulate hadronic interactions. The three main outputs that are important for developing a technique to veto radioactive spallation isotopes are the isotope yields, the spatial correlations between the isotopes and neutrons or other correlated events, and the energy deposition along the muon track to correlate possible muon showers with the spallation products. For the simulation of muon interactions in a Xe-LS volume, we injected 2×10^7 muons according to the charge ratio $\mu^+/\mu^- = 1.3$ and with energies following the muon energy spectrum at KamLAND [6], into a Xe-LS filled cylinder of 10 m radius and 40 m height. All muons were directed along the cylinder's central axis, aligned with the long-axis, disregarding those with an angular deviation from the vertical. Additionally, we omitted the edges of the cylinder to eliminate boundary effects. The simulation corresponds to a detector livetime of 9 yr. The MC code GEANT4 [7] was used for the subsequent decay of radioactive isotopes. The decay paths are especially important for xenon spallation, because its large mass number can lead to the formation of various unstable isotopes.

3˙2. *Carbon spallation.* – Muon-induced carbon spallation often involves the production of neutrons in the same interaction. These neutrons are predominantly captured by ^{1}H, with an average capture time of207μ s, subsequently emitting a 2.2 MeV γ-ray [3]. We distinguish the spallation background, mainly from ^{10}C ($T_{1/2} = 19.3$ s, Q = 3.65 MeV) and ^{6}He ($T_{1/2} = 0.81$ s, Q = 3.51 MeV), in the data with a three-fold coincidence method involving (1) a muon, (2) the neutron capture and (3) a β-decay that occurs within a time interval, ΔT, dependent on the half-life of the decay. Due to the non-zero vertex resolution in KamLAND-Zen, the distance between the β-decay and nearest neutron capture should not exceed $dR = 160$ cm.

β-decays exceeding the dR limit, along with non-neutron emitting isotopes, are identified in the data using a muon shower likelihood tag. This approach is based on the observation that most radioactive isotopes are produced in muon-induced showers [8]. We employ a likelihood probability density function based on three factors: (1) the energy deposition along the muon track, (2) the transverse distance from the muon track to the candidate signal and (3) the time interval between the muon event and the candidate signal. If a shower correlates with the candidate β-decay, it is classified as a spallation event. The rejection efficiencies of the two dominant background isotopes, ^{10}C and ^{6}He, are $> 99.3\%$ and $(97.6 \pm 1.7)\%$ respectively [2].

3˙3. *Xenon spallation.* – Muon-induced xenon spallation results in a list of radioactive isotopes comprising of over 200 candidates with individually small yields that are challenging to isolate and fit to the data [3]. The dominant isotopes within the $0\nu\beta\beta$

decay region of interest (ROI) are listed in table I. They have lifetimes ranging from seconds to multiple days. The long lifetimes of these isotopes cause the three-fold coincidence method used for carbon spallation to be less effective for xenon spallation given the KamLAND-Zen detector's livetime.

An additional parameter in the xenon spallation reactions is neutron multiplicity, which is especially relevant for daughter isotopes with a large mass difference from ^{136}Xe. Long-lived (LL) xenon spallation products are tagged using a likelihood function composed of (1) the time interval from a candidate event to the preceding muon, ΔT, (2) the spatial distance from the nearest neutron to the candidate, dR_{near}, and (3) the neutron multiplicity within $dR = 160\,\mathrm{cm}$ of a candidate event [3]. The likelihood's cut-off value is optimized via MC simulations based on the simulated isotope yields and KamLAND-Zen data. To balance detector dead-time with veto efficiency, events with $\Delta T < 4 \times 10^5$ s are vetoed, resulting in a dead-time of approximately 9% and LL-tagging selection efficiency of $42.0 \pm 8.8\%$.

The low efficiency of LL-tagging in KamLAND-Zen contributes to this background's dominance over other backgrounds, see fig. 1. Using FLUKA to simulate the creation processes of spallation isotopes could lead to new tagging strategies. One possibility is the correlation of light isotope bursts, initially observed for ^{11}C in ref. [9], and LL creation processes. Additionally, the connection between showers and LL-isotope production has not been considered in KamLAND-Zen data. Accurate FLUKA simulations are essential for both of these proposed methods.

4. – Conclusions

KamLAND-Zen holds the most stringent limit on the $0\nu\beta\beta$ decay half-life of ^{136}Xe. To date, the dominant background arises from cosmic-ray muon spallation of xenon nuclei inside the detector. Numerous unstable isotopes that β-decay in the $0\nu\beta\beta$ decay ROI are produced via xenon spallation, with lifetimes extending to several days. While ^{136}Xe's neutron-rich nature facilitates the use of neutron multiplicity in identifying spallation isotopes, the long lifetimes of the xenon spallation isotopes present a challenge for effective tagging. Exploring additional parameters for tagging, such as bursts of short-lived isotopes near the LL vertex or correlations with showers, is essential to improve the tagging efficiency. The outcome of this research is relevant for next-generation detectors, where the xenon spallation background must be reduced significantly either through the development of new tagging methods or via a reduced muon frequency that could be achieved by constructing the experiment deeper underground.

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