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Application of gamma Transition-Edge-Sensor (TES) to ^{112}Sn two-neutrino double electron capture search

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Double electron capture (DEC) is a rare nuclear decay process in which two orbital electrons are simultaneously captured in the same nucleus. The measurement of its two-neutrino emitting mode (2νDEC) provides a new reference for the calculation of nuclear matrix elements, while the zero-neutrino emitting mode (0νDEC) would demonstrate a violation of lepton number conservation. For ^{112}Sn, the search for DEC to the excited state in ^{112}Cd has been carried out using a High-Purity Germanium detector and a ^{112}Sn enriched tin sample, but no significant signal has been observed so far. 2νDEC to the ground state in ^{112}Cd has not been performed due to the self-absorption of X-rays and Auger electrons in the tin sample.

We propose a novel approach to search for the 2νDEC mode to the ground state in ^{112}Cd using a γ-ray Transition Edge Sensors (γ-TESs) with tin absorbers. The calorimetric approach in which the signal would be generated in the detector allows us to detect two X-ray or Auger electrons resulting from the ^{112}Sn DEC with high energy resolution. The future multi-pixel γ-TESs increase the target mass and thus the sensitivity. In this proceedings, we demonstrate the 2νDEC search with this approach. The preliminary results of our search for the ^{112}Sn 2νDEC to the ground state in ^{112}Cd with 90 hours, four γ-TESs data, and the future prospects are presented.

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1. Introduction

Two-neutrino double electron capture (2νDEC) is a rare nuclear decay process allowed by the Standard Model. In this process, two orbital electrons are captured simultaneously in the same nucleus and two neutrinos are emitted ($(A, Z) + 2e^- \rightarrow (A, Z-2) + 2\nu_e$). On the other hand, neutrinoless DEC (0νDEC) is not allowed in the Standard Model and would demonstrate the lepton number violation and the Majorana nature of the neutrino. So far, only 2νDEC of ^{124}Xe has been observed [1, 2]. The observation of 2νDEC would provide a new reference for the calculation of nuclear matrix element which may contribute to the theoretical calculation for 0νDEC. The observation of 2νDEC requires the detection of two X-rays or Auger electrons, which deposit an energy of the order of a few tens of keV.

^{112}Sn is one of the nuclei which undergoes the $2\nu(0\nu)$DEC:

$$^{112}\mathrm{Sn}\ (\mathrm{g.s.}, 0^+) + 2\mathrm{e}^- \rightarrow ^{112}\mathrm{Cd}\ (\mathrm{g.s.}, 0^+) + (2\nu_\mathrm{e}) + 1.919\ \mathrm{MeV}.$$

Since Q-value is larger than twice of the electron mass, ^{112}Sn can also undergo one β^+ and one electron capture (β^+EC) mode. The search for $2\nu(0\nu)$DEC to the excited state and for β^+EC to the ground state and the excited state has been carried out with the ^{112}Sn enriched tin (Sn) sample and High-Purity Germanium (HPGe) detector by detecting the deexcitation γ and the annihilation γ [3, 4]. This HPGe measurement method is hard to obtain signal that the 2νDEC mode goes to the ground state, due to self-absorption of X-rays and Auger electrons in the sample. We propose a novel approach to search for the 2νDEC mode to the ground state in ^{112}Cd using γ-ray Transition Edge Sensors (γ-TESs) with tin absorbers. In this proceedings, the configuration of the γ-TES, signal simulation, preliminary analysis result and future prospects are shown in the following sections.

2. Gamma-ray Transition-Edge-Sensor

TESs are thermal detectors using the steep resistance transition of superconducting materials as thermometers [5]. TESs widely use tin absorbers in order to stop γ-rays and convert their energy into heat. Since energy resolution of TESs is much better than that of HPGe, they are used for nuclear materials for safeguards and fuel cycle applications [6, 7] and dark matter searches. Contrary to HPGe detectors, the ^{112}Sn 2νDEC signals would be naturally produced in the tin absorber. Owing to high energy resolution and the calorimetric approach, sensitivity for X-rays or Auger electrons resulting from 2νDEC is unprecedantly high. In this proceedings, data obtained from the four γ-TESs developed by National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan have been used. Each of the four γ-TESs is equipped with a cubic tin absorber with 0.5 mm sides supported by four gold bumps. The ^{237}Np γ-ray source is located 8 mm from the γ-TESs. Platinum (Pt) is used to encase and protect the radiative part of the source. This data can be used to demonstrate the high energy resolution and to search for the ^{112}Sn 2νDEC mode to the ground state. More details on the detector setup, including the calibration source, can be found in Ref. [7].

3. Expected signal

When two K-shell electrons are simultaneously captured in the ^{112}Sn atoms ($2\nu2$K, one of the decay modes of 2νDEC), a ^{112}Cd with two holes in the K-shell is formed and this atom relaxes by emitting X-rays and/or Auger electrons. The ratio of $2\nu 2K$ to 2νDEC is estimated to be 70.9% (considering K and L1 shells) or 73.4% (considering up to N5 shells, following to Ref. [2]). In this analysis, the Monte Carlo simulations of atomic relaxation are based on the Geant4 simulation tools (Geant4-11.0.4) [8]. Following Ref. [9], we assume that the X-rays and Auger electrons emitted in the $2\nu 2K$ event are similar to those produced by two nuclei that have a single K-shell hole. Under this assumption, the total deposition energy is given by the twice the binding energy of the Cd K-shell (53.4 keV). Taking into account the energies of the other orbitals, total deposition energy of 53.7 keV is expected [10]. The difference will be considered as a systematic uncertainty in the further analysis. In the simulation, two ^{112}Cd nuclei with a single hole in the K-shell were uniformly generated in a 0.5 mm tin cube and the deposition energy on the tin cube was recorded. Figure 1 shows the expected signal from $2\nu 2K$ with an energy resolution of 50 eV. The detection efficiency is estimated to be 45.4% when the signal region is defined as 51 - 54 keV.

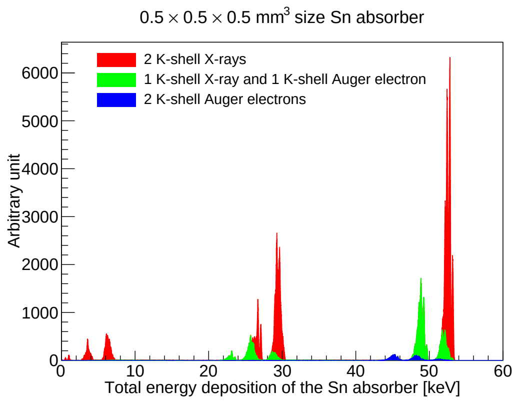

Figure 1: Total energy deposition of the tin absorber (0.5 mm cubic, density = 7.265 g/cm^3) for the simulated $2\nu 2K$ events (colored stacked histograms). Each color corresponds to 2 X-rays emission events (red), 1 X-ray and 1 Auger electron emission events (green), and 2 Auger electrons emission events (blue), respectively.

4. Result and discussion

In this analysis, we use data from four γ-TESs irradiated by a ^{237}Np γ-ray source for about 90 hours. Long-term time drift of γ-TESs output mentioned in Ref. [7] (Figure 2a, 2b and 2c) has been corrected by the cubic polynomial function using clear peaks from ^{237}Np γ-rays, Pt X-rays and Sn X-ray escape peaks. Figure 2 shows the energy spectrum of a single γ-TES. Some peaks are observed near the region of interest (ROI, 51 – 54 keV) due to Sn X-ray escape. In this analysis, there is no clear peaks in the ROI not only for this γ-TES but also all γ-TESs. To derive the limit of the 2νDEC half-life, count rate in the ROI subtracted by the count rate in the sideband region (54 - 56.5 keV) is used. By combining four γ-TESs data, we obtained the preliminary result of the lower limit of the half-life $T_{1/2}^{2\nu\mathrm{DEC\ (g.s.)}} > 9.0\times10^{12}$ years at a 90% confidence level, assuming that the tin absorber has a natural abundance of ^{112}Sn (0.97%), the absorber is a cube of 0.5 mm per side, and the density is 7.265 g/cm^3. The systematic uncertainties related to the detector and energy scale are ongoing. In order to increase the sensitivity to reach the predicted half-life of 1.7×10^{22} years [11], it is necessary to increase the number of γ-TESs, optimise the absorber size which affects the signal efficiency and energy resolution, and reduce the background. As a first

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step, we plan to take data with eight γ-TESs where the size of the tin absorber is 0.8 mm cubic, as described in Ref. [12]. The calibration source is located outside the cryostat so that data can be taken with and without the calibration source. The data would provide a more detailed understanding of the background in the ROI.

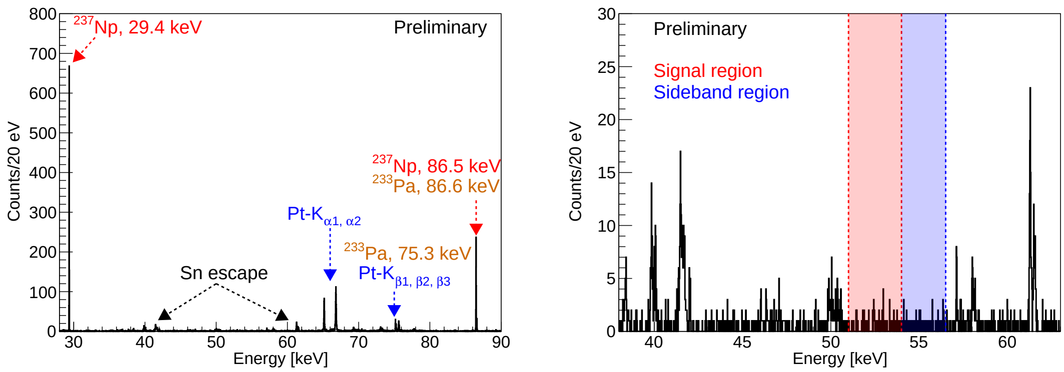

Figure 2: Energy spectra of a single γ-TES, integrated over 90 hours, in the energy range from 28 keV to 90 keV (left) and from 38 keV to 63 keV (right). In the left figure, candidate sources are listed for peaks due to the radiative source (^{237}Np; 29.4, 86.5 keV, ^{233}Pa, daugher nuclei of the ^{237}Np; 75.3, 86.6 keV), Pt X-rays and Sn X-ray escape. In the right figure, several peaks are observed mainly due to Sn X-ray escape. For example, peaks around 60 keV could be explained by ^{237}Np 86.5 keV photoelectric reaction. If Sn-K$_{\alpha 1}$ (K$_{\alpha 2}$, K$_{\beta 1}$) X-ray which has 25.3 (25.0, 28.5) keV is escaped, 61.2 (61.5, 58.0) keV peak could be appeared.

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