Sensitive search for double electron capture on $^{124}$Xe in XMASS-I

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Abstract. Double electron capture is a rare nuclear decay process in which two orbital electrons are captured simultaneously in the same nucleus. We have conducted an improved search for two-neutrino double electron capture on $^{124}$Xe and $^{126}$Xe using 800.0 days of the XMASS-I data. As a result of fitting the observed energy spectra with the expected signal and background, no significant signal is found. Therefore, we set the most stringent lower limits on their half-lives at $2 \times 10^{22}$ years for $^{124}$Xe and $1.9 \times 10^{22}$ years for $^{126}$Xe at 90% confidence level. The limits get improved by a factor of 4.5 compared to the previous result.

1. Introduction

Double electron capture (ECEC) is a rare nuclear decay process in which two orbital electrons are captured simultaneously in the same nucleus. Measurement of its two-neutrino mode would provide a new reference for the calculation of nuclear matrix elements whereas observation of its neutrinoless mode would demonstrate lepton number violation. There exist only a few positive experimental results for 2ν-ECEC so far: geochemical measurements for $^{130}$Ba [1, 2] and a direct measurement for $^{78}$Kr [3] with half-lives in the order of $10^{21} - 10^{22}$ years.

Natural xenon contains the double electron capture nuclei $^{124}$Xe (abundance 0.095%) and $^{126}$Xe (0.089%). In the case that two $K$-shell electrons in the $^{124}$Xe atom are captured simultaneously (2ν2K), a daughter atom of $^{124}$Te is formed with two vacancies in the $K$-shell and de-excites by emitting atomic X-rays and/or Auger electrons. The total energy deposition is $\sim 64$ keV, which is twice of the $K$-shell binding energy of tellurium. $^{126}$Xe can also undergo 2ν-ECEC, however, this reaction is expected to be much slower than that on $^{124}$Xe since its $Q$-value is smaller.

Previous experimental searches for 2ν2K on $^{124}$Xe have been conducted using a gas proportional counter with enriched xenon [4, 5] and large-volume liquid xenon (LXe) detectors with natural xenon as targets [6, 7]. The current best experimental constraint on the $^{124}$Xe 2ν2K half-life, $T_{1/2} > 4.7 \times 10^{21}$ years at 90% confidence level (CL), is set by the XMASS experiment using 132.0 live days of data with a fiducial xenon mass of 41 kg (containing 39 g of $^{124}$Xe). In addition, XMASS also set the first experimental lower limit on the $^{126}$Xe 2ν2K half-life as $T_{1/2} > 4.3 \times 10^{21}$ years at 90% CL.
In this paper, we present the result of an improved search for $2\nu2K$ on $^{124}$Xe and $^{126}$Xe using 800.0 live days of the XMASS data with a fiducial xenon mass of 327 kg (containing 311 g of $^{124}$Xe and 291 g of $^{126}$Xe).

2. XMASS-I detector

XMASS-I is a large single phase liquid xenon detector located underground (2700 m water equivalent) at the Kamioka Observatory in Japan [8]. An active target of 832 kg of liquid xenon is held inside of a pentakis-dodecahedral copper structure that holds 642 inward-looking 2-inch Hamamatsu R10789 photomultiplier tubes (PMTs) on its approximately spherical inner surface at radius of about 40 cm. The photocathode coverage of the inner surface is 62.4%. The signals from each PMT are recorded with the CAEN V1751 waveform digitizers with a sampling rate of 1 GHz and a 10 bit resolution. The liquid xenon detector is placed at the center of a cylindrical water Cherenkov detector, which is 11 m high with a 10 m diameter. The outer detector is equipped with 72 20-inch Hamamatsu H3600 PMTs. It acts as an active veto counter for cosmic-ray muons as well as a passive shield against neutrons and $\gamma$-rays from the surrounding rock.

The non-linear response in scintillation light yield for electron-mediated events in the detector was calibrated in the energy range between 5.9 keV and 662 keV using various gamma-ray calibration sources: $^{55}$Fe, $^{241}$Am, $^{109}$Cd, $^{57}$Co, and $^{137}$Cs. The calibrated energy is called the electron equivalent energy, $\text{keV}_{ee}$, hereafter.

3. Data set and event selection

The data used in this analysis were collected between November 20, 2013 and July 20, 2016. The total livetime is 800.0 days. The data set was divided into four periods depending on the detector condition. The period 1 started two weeks after introduction of LXe in the detector inside the water shield and we observed the neutron-activated peaks, $^{131m}$Xe and $^{129m}$Xe, at the beginning. We also performed the $^{252}$Cf calibration data taking twice in the period. Runs within 10 days after each calibration were excluded from the data set. The period 1 ended 60 days after the second $^{252}$Cf calibration since the neutron-activated peaks caused by the $^{252}$Cf disappeared. Then, the period 2 was defined as the period until gas circulation with a getter purifier was started. The period 3 was ended for xenon purification. During the purification work, LXe was extracted from the detector, and therefore xenon was exposed to thermal neutron outside the water shield and activated.

The event reduction consists of four steps: pre-selection, the fiducial volume selection, the $^{214}$Bi identification, and particle identification.

- The pre-selection requires that no outer detector trigger is associated with the event, that the time difference to the previous inner detector event is larger than 10 ms, and that the standard deviation of the inner detector hit timings of the event is less than 100 ns. The last two cuts remove events caused by the PMT afterpulses following bright events.

- In order to select events occurring in the fiducial volume, an event vertex is reconstructed based on a maximum likelihood evaluation of the observed light distribution in the detector. We select events satisfying that the radial distance of their reconstructed vertex from the center of the detector is smaller than 30 cm.

- In order to remove the $^{214}$Bi events, events whose time difference to the subsequent event is less than 1 ms are rejected. Its counterpart sample, events with $0.015 \text{ ms} < dT_{\text{post}} < 1 \text{ ms}$, is called as the $^{214}$Bi sample and used to constrain the $^{214}$Bi and $^{214}$Pb backgrounds.

- Scintillation time profile of LXe can be used for particle identification. In this analysis, it is used to eliminate the $\alpha$-ray backgrounds and also to discriminate the $2\nu2K$ signal from the $\beta$-ray backgrounds. The particle identification parameter $\beta$CL is constructed from timings.
Figure 1. Energy spectra after each event reduction step for the observed data. From top to bottom, energy distributions after the pre-selection (black solid), fiducial volume selection (red solid), the $^{214}$Bi rejection (blue dashed) and the $\beta$-like event rejection (magenta points) are shown.

of 1 photoelectron pulses in the event. While the $\beta$-ray events distribute widely between 0 and 1, the $\gamma$-ray or $2\nu 2K$ events has a peak at $\beta CL = 0$. Events with $\beta CL$ less than 0.05 are classified as the non-$\beta$ enriched sample, and the rest is named as the $\beta$ enriched sample.

Figure 1 shows energy spectra after each event reduction step for the observed data and the simulated $2\nu 2K$ sample.

4. Results and discussion

In order to extract the $2\nu 2K$ signal from the observed data, the energy spectra for the non-$\beta$ enriched samples, the $\beta$ enriched samples, and the $^{214}$Bi samples are fitted with the expected signal and background spectra simultaneously. The energy range between 30 keV$_{ee}$ and 200 keV$_{ee}$ is used in the fitting.

The close-up energy spectra between 30 keV$_{ee}$ and 100 keV$_{ee}$ for the non-$\beta$ enriched samples are shown in Figure 2. A peak found at 67.5 keV$_{ee}$ is due to the $^{125}$I decay. $^{125}$I decays by 100% electron capture via an excited state of $^{125}$Te into the ground state of $^{125}$Te. Although the LXe detector is shielded against environmental neutrons by water, a part of the detector components such as the cable feed-through box, the calibration system, and the cryogenic system exists outside the water shield, which is filled with gas xenon. The xenon is activated by thermal neutron capture and mixed with the LXe in the detector. The $^{125}$I is produced from $^{125}$Xe and $^{125m}$Xe created by this thermal neutron capture on $^{124}$Xe. The event rate of the $^{125}$I decay is constrained by the thermal neutron flux in the mine, which is measured independently.

Figure 3 shows the normalized profile likelihood $L/L_{max}$ as a function of the inverse of the $^{124}$Xe $2\nu 2K$ half-life, where $L_{max}$ is the maximum value of the likelihood. No significant excess over the expected background is found in the signal region, and hence we calculate the 90%
Figure 2. Energy spectra between 30 keV\textsubscript{ee} and 100 keV\textsubscript{ee} for the non-\(\beta\) enriched samples. The observed data spectra (points) are overlaid with the best-fit \(2\nu 2\K\) signal and background spectra (colored stacked histograms). Colored histograms are the \(2\nu 2\K\) signal (red filled), \(^{125}\text{I}\) (green hatched), \(^{133}\text{Xe}\) (blue hatched), \(^{14}\text{C}\) (orange filled), \(^{39}\text{Ar}\) (magenta filled), \(^{85}\text{Kr}\) (blue filled), \(^{214}\text{Pb}\) (cyan filled), \(^{136}\text{Xe} 2\nu\beta\beta\) (brown filled), and the external backgrounds (gray filled).

Confidence level (CL) limit from the relation

\[
\frac{\int_{0}^{\xi_{\text{limit}}} L(\xi) d\xi}{\int_{0}^{\infty} L(\xi) d\xi} = 0.9
\]

where \(\xi = 1/T_{1/2}^{2\nu 2\K}\). This leads to

\[T_{1/2}^{2\nu 2\K} \left(^{124}\text{Xe}\right) > \frac{1}{\xi_{\text{limit}}} = 2.1 \times 10^{22} \text{ years}.\]  

In addition, the fact that we do not observe significant excess above background allows us to give a constraint on \(2\nu 2\K\) on \(^{126}\text{Xe}\) in the same manner.

\[T_{1/2}^{2\nu 2\K} \left(^{126}\text{Xe}\right) > 1.9 \times 10^{22} \text{ years}\]  

at 90\% CL.

5. Conclusions

We have conducted an improved search for \(2\nu 2\K\) on \(^{124}\text{Xe}\) and \(^{126}\text{Xe}\) using 800.0 days of the XMASS-I data. As a result of fitting the observed energy spectra with the signal and background spectra, no significant \(2\nu 2\K\) signal over the expected background is found. Therefore we set the most stringent lower limits on their half-lives at \(2.1 \times 10^{22}\) years for \(^{124}\text{Xe}\) and \(1.9 \times 10^{22}\) years for \(^{126}\text{Xe}\) at 90\% CL. The limits get improved by a factor of 4.5 compared to the previous result.
Figure 3. Normalized profile likelihood $L/L_{\text{max}}$ as a function of the inverse of the $^{124}\text{Xe}$ $2\nu2\text{K}$ half-life. The vertical line indicates the 90% quantile from which the lower limit on the half-life is derived.

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