Search for double electron capture on ^{124}Xe with the XMASS-I detector

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Abstract. The XMASS project is a multi-purpose experiment using highly-purified liquid xenon scintillator located underground at the Kamioka Observatory in Japan. A search for two-neutrino double electron capture on ^{124}Xe is performed using 165.9 days of data collected with the XMASS-I detector. No significant excess above background was observed and we set a lower limit on the half-life as 4.7×10^{21} years at 90% confidence level.

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 2νECEC so far: a geochemical measurement for ^{130}Ba with a half-life of $(2.2 \pm 0.5) \times 10^{21}$ years [1] and a direct measurement for ^{78}Kr with a half-life of $(9.2^{+5.5}_{-2.6}(stat) \pm 1.3(sys)) \times 10^{21}$ years [2].

A previous experiment used enriched xenon. A gas proportional counter containing 58.6 g of ^{124}Xe (enriched to 23%) was looking for the simultaneous capture of two K-shell electrons on that isotope, and published the latest lower bound on the half-life $T^{2\nu 2K}_{1/2}$ as 2.0×10^{21} years [3, 4]. Recently, it has been pointed out that large volume dark matter detectors with natural xenon as targets have the potential to measure the 2νECEC on ^{124}Xe [5, 6].

In this paper, we present the result from a search for 2νECEC on ^{124}Xe using the XMASS-I liquid xenon detector.

2. XMASS-I detector

The XMASS project is designed to detect dark matter, neutrinoless double beta decay, and ^{7}Be/pp solar neutrinos using highly-purified liquid xenon scintillator in an ultra-low radioactivity environment.

The XMASS-I detector is a single phase liquid xenon scintillator detector located underground (2700 m water equivalent) at the Kamioka Observatory in Japan. It contains 832 kg of liquid xenon in an active region. The volume is viewed by 630 hexagonal and 12 cylindrical Hamamatsu R10789 photomultiplier tubes (PMTs) arranged on an 80 cm diameter pentakis-dodecahedron support structure. A total photocathode coverage of more than 62% is achieved. The spherical arrays of PMTs are arranged in a double wall vessel made of oxygen free high conductivity (OFHC) copper. In order to shield the liquid xenon detector from external gammas, neutrons, and muon-induced backgrounds, the copper vessel was placed at the center of a ϕ10 m× 10.5 m cylindrical tank filled with pure water. The water tank is equipped with 72 Hamamatsu R3600 20-inch PMTs to provide both an active muon veto and passive shielding against these backgrounds. XMASS-I is the first direct detection dark matter experiment equipped with such an active water Cherenkov shield. The liquid xenon and water Cherenkov detectors are hence called an Inner Detector (ID) and an Outer Detector (OD), respectively. Data acquisition is triggered if four or more PMTs have more than 0.2 photoelectron (PE) within 200 ns. More details are described in Ref. [7].

3. Expected Signal

The process of 2νECEC on ^{124}Xe is

$$^{124}\mathrm{Xe} + 2e^- \rightarrow ^{124}\mathrm{Te} + 2\nu_e \qquad (1)$$

with a Q-value of 2864 keV. In the case that two K-shell electrons in the ^{124}Xe atom are captured simultaneously, 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 in the detector is $2K_b = 63.6$ keV, where K_b is the binding energy of a K-shell electron in a tellurium atom. The energy deposition from the recoil of the daughter nucleus is ∼30 eV at most, which is negligible. Although ^{126}Xe can also undergo 2νECEC, this reaction is expected to be much slower than that on ^{124}Xe since its Q-value of 896 keV is smaller.

4. Data sample and event selection

The data used in the present analysis were collected between December 24, 2010 and May 10, 2012. After removing periods of operation with excessive PMT noise, unstable pedestal levels, or abnormal trigger rates, the total livetime becomes 165.9 days. Event selection proceeds in four stages: pre-selection, fiducial volume cut, timing balance cut, and band-like pattern cut.

- **Pre-selection**
  The pre-selection requires that no outer detector trigger is associated with the event, that the event is separated in time from the nearest event by at least 10 ms, and that the RMS spread of the inner detector hit timings of the event is less than 100 ns. This pre-selection reduces the total effective lifetime to 132.0 days in the final sample.
- **Fiducial volume cut**
  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 [7]. We select events satisfying that the radial distance of their reconstructed vertex from the center of the detector is smaller than 15 cm. The fiducial mass of natural xenon in that volume is 41 kg, containing 39 g of ^{124}Xe.
- **Timing balance cut**
  The remaining two cuts deal with mis-reconstructed events. The timing balance cut uses the time difference between the first hit in an event and the mean of the timings of the second half of all the time-ordered hits in the event. Events with smaller time difference are less likely to be events from the detector's inner surface that were wrongly reconstructed and are kept.
- **Band-like pattern cut**
  The band-like pattern cut eliminates events that reflect their origin within grooves or

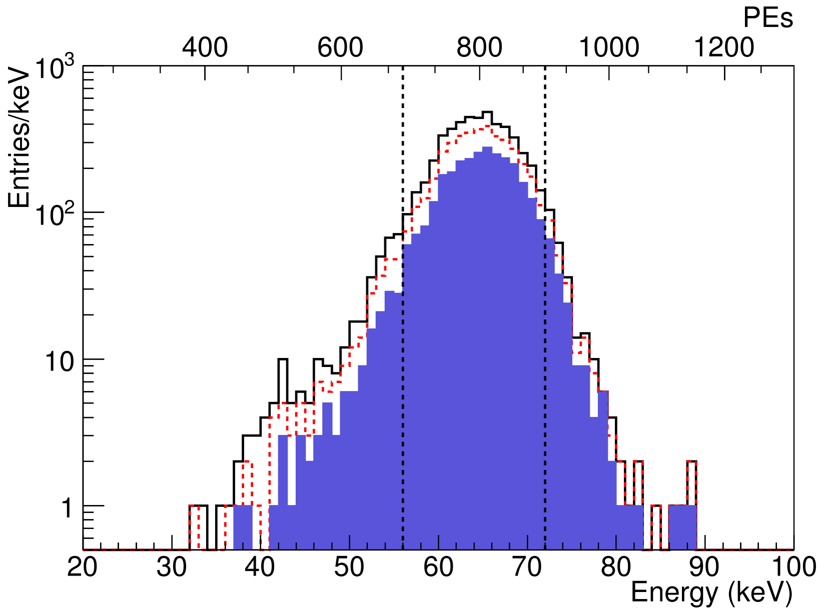

Figure 1. Energy spectra of the simulated events after each reduction step. From top to bottom, the simulated energy spectrum after pre-selection and radius cut (black solid), timing balance cut (red dashed), and band-like pattern cut (blue filled) are shown. The vertical dashed lines indicate the 56-72 keV signal window.

crevices in the inner detector surface through a particular illumination pattern: The rims of the groove or crevice act as an aperture that is projected as a "band" of higher photon counts onto the inner detector surface. This band is characterized by the ratio of the maximum PEs in the band of width 15 cm to the total PEs in the event [8]. Events with smaller ratio are less likely to originate from crevices and are selected.

In the present analysis, the total energy deposition of events is reconstructed from the observed number of photoelectrons correcting for the non-linear response of scintillation light yield. The correction is performed assuming the light originates from two X-rays with equal energy. Finally, the signal window is defined such that it contains 90% of the simulated signal with equal 5% tails to either side after all the above were applied, which results in a 56−72 keV window. Fig. 1 shows energy spectra of the simulated events after each reduction step. From the simulation, signal detection efficiency is estimated to be 59.7%.

5. Results and discussion

Energy distributions of data events remaining after each reduction step is shown in Figure 2. After all cuts, 5 events are left in the signal region but no significant peak is seen. The main contribution to the remaining background in this energy regime is the ^{222}Rn daughter ^{214}Pb in the detector. The amount of ^{222}Rn was estimated to be 8.2 ± 0.5 mBq from the observed rate of ^{214}Bi-^{214}Po consecutive decays. The concentration of krypton in the xenon was measured to be <2.7 ppt [7], and thus background from ^{85}Kr is negligible in this analysis. The background from $2\nu\beta^-\beta^-$ of ^{136}Xe ($T_{1/2} = 2 \times 10^{21}$ years [9]) is also negligible compared with the ^{214}Pb background. The energy spectrum after cuts in data is consistent with the expected ^{214}Pb background spectrum, and given the measured decay rate the expected number of background events in the signal region from this decay alone is estimated to be 5.3 ± 0.5 events.

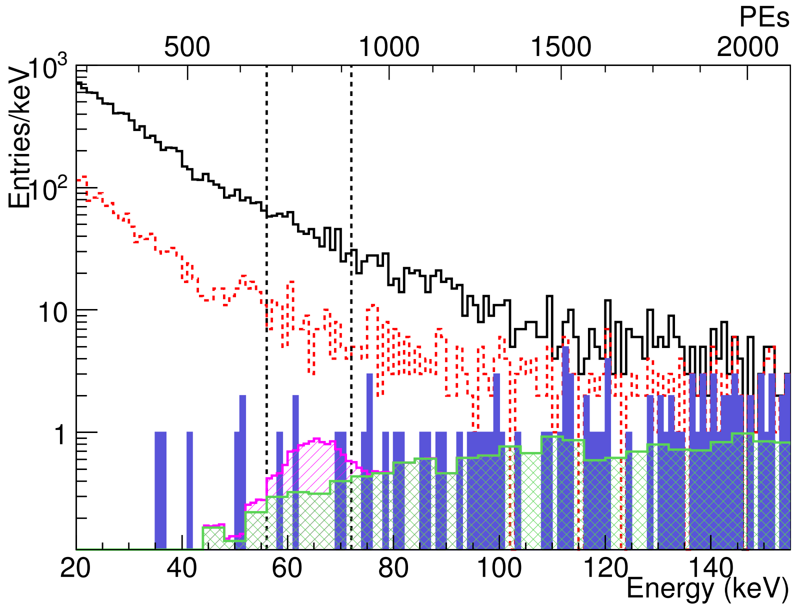

Figure 2. Energy spectra of the observed events after each reduction step for the 165.9 days of data. From top to bottom, the observed energy spectrum after pre-selection and radius cut (black solid), timing balance cut (red dashed), and band-like pattern cut (blue filled) are shown. The vertical dashed lines indicate the 56-72 keV signal window. The expected ^{214}Pb background (green hatched) together with the signal expectation for the 90% C.L. upper limit (magenta hatched) are also shown.

Since the observed data spectrum does not exceed the expected background in the signal region, a lower limit on the 2νECEC half-life is derived using the following Bayesian method that also accounts for systematic uncertainties to calculate the conditional probability distribution for the decay rate as follows:

$$P(\Gamma|n_{\rm obs}) = \iiiint \frac{e^{-(\Gamma\lambda\epsilon+b)(1+\delta)}((\Gamma\lambda\epsilon+b)(1+\delta))^{n_{\rm obs}}}{n_{\rm obs}!} P(\Gamma)P(\lambda)P(\epsilon)P(b)P(\delta)\mathrm{d}\lambda\mathrm{d}\epsilon\mathrm{d}b\mathrm{d}\delta \quad (2)$$

where Γ is the decay rate, $n_{\rm obs}$ is the observed number of events, λ is the detector exposure including the abundance of ^{124}Xe, ϵ is the detection efficiency, b is the expected number of background events, and δ is a parameter representing the systematic uncertainty in the event selection which affects both signal and background. The decay rate prior probability $P(\Gamma)$ is 1 for $\Gamma \geq 0$ and otherwise 0. The prior probability distributions incorporating systematic uncertainties in the detector exposure $P(\lambda)$, detection efficiency $P(\epsilon)$, background $P(b)$, and event selection $P(\delta)$ are assumed to be the split normal distribution centered at the nominal value with two standard deviations since some error sources are found to have a different impact on the positive versus the negative side of the distribution center.

Table 1 summarizes the systematic uncertainties in exposure, detection efficiency, and event selection.

Finally, we calculate the 90% confidence level (CL) limit using the relation

$$\frac{\int_0^{\Gamma_{\rm limit}} P(\Gamma|n_{obs})\mathrm{d}\Gamma}{\int_0^{\infty} P(\Gamma|n_{obs})\mathrm{d}\Gamma} = 0.9 \quad (3)$$

Table 1. Summary of systematic uncertainties in exposure, detection efficiency, and event selection.

Item	Error source	Fractional uncertainty (%)
Exposure	Abundance of ^{124}Xe	± 8.5
	Liquid xenon density	± 0.5
Efficiency	Energy scale	$\pm^{0}_{8.6}$
	Energy resolution	$\pm^{0}_{5.3}$
	Scintillation decay time	$\pm^{0}_{7.1}$
Event selection	Fiducial volume cut	$\pm^{0}_{6.7}$
	Timing balance cut	$\pm^{3.0}_{0}$
	Band-like pattern cut	± 5.0

to obtain

$$T_{1/2}^{2\nu 2K} > \frac{\ln 2}{\Gamma_{\text{limit}}} = 4.7 \times 10^{21} \text{ years.} \tag{4}$$

Details of the analysis can be found in Ref. [10].

6. Summary

We have searched for 2νECEC on ^{124}Xe using an effective live time of 132.0 days of XMASS-I data in a fiducial volume containing 39 g of ^{124}Xe. No significant excess over the expected background is found in the signal region, and we set a lower limit on its half-life of 4.7×10^{21} years at 90% CL.

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