Neutrino-less double-β decay of ^{48}Ca studied by CaF_2(Eu) scintillators

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We searched for the neutrino-less double-β decay($0\nu\beta\beta$) of ^{48}Ca by using CaF_2(Eu) scintillators. Analysis of their pulse shapes was effective to reduce backgrounds. No events are observed in the $Q_{\beta\beta}$ value region for the data of 3394 kg · day. It gives a lower limit (90% confidence level) of $T_{1/2}^{0\nu\beta\beta} > 2.7 \times 10^{22}$ year for the half-life of $0\nu\beta\beta$ of ^{48}Ca. Combined with our previous data for 1553 kg · day [I. Ogawa *et al.*, Nucl. Phys. **A730**, 215 (2004)], we obtained a more stringent limit of $T_{1/2}^{0\nu\beta\beta} > 5.8 \times 10^{22}$ year.

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$0\nu\beta\beta$ is acquiring great interest after the confirmation of neutrino oscillation [1–3] which demonstrated nonzero neutrino mass. Measurement of $0\nu\beta\beta$ provides a test for the Majorana nature of neutrinos and gives an absolute scale of the effective neutrino mass. Many experiments have been carried out so far and many projects have been proposed. A recent review of $0\nu\beta\beta$ experiments is presented elsewhere [4].

Among double-β-decay nuclei, ^{48}Ca has an advantage of the highest $Q_{\beta\beta}$ value (4.27 MeV). This large $Q_{\beta\beta}$ value gives a large phase-space factor to enhance the $0\nu\beta\beta$ rate and the least contribution from natural background radiations in the energy region of the $Q_{\beta\beta}$ value. Therefore, a good signal to background ratio is ensured in the measurement of $0\nu\beta\beta$. However, not many studies have been carried out [5–9], because the natural abundance of ^{48}Ca is only 0.187%.

We carried out the measurements of $0\nu\beta\beta$ with CaF_2(Eu) scintillators. We previously reported a lower limit (90% confidence level) of 1.4×10^{22} year for the half-life of $0\nu\beta\beta$ of ^{48}Ca [10]. The measurement employed the ELEGANT VI system at the Oto Cosmo Observatory. We observed 0 events in the $Q_{\beta\beta}$-value region, although the expected background exceeded 1 event, which limits our experimental sensitivity. In what follows we describe characteristics of our measurement to achieve further background reduction.

The ELEGANT VI system consists of three kinds of scintillation detectors. A CaF_2(Eu) scintillator (45 mm cube) works as an active source-detector. We employed 23 CaF_2(Eu) scintillators, which contained 7.6 g of ^{48}Ca. CaF_2(pure) and CsI(Tl) scintillators worked as veto counters for CaF_2(Eu). Further details of the detector can be found in Ref. [10].

A charge sensitive ADC (CSADC) and a flash ADC (FADC) recorded energy and pulse shape of CaF_2(Eu) signals, respectively. The energy was obtained by summing the signals from two photomultiplier tubes (PMTs) for each CaF_2(Eu). The two signals were used for effective background reduction.

Each CaF_2(Eu) scintillator was calibrated by γ rays from ^{137}Cs and β rays and α rays from ^{214}Bi and ^{216}Po as internal contaminations. A standard γ-ray source of ^{137}Cs was also used. Linearity was confirmed in an energy range from 662 keV to 3.27 MeV and assumed to hold to up to the $Q_{\beta\beta}$ value. An energy resolution was measured by a peak width of the α rays from ^{216}Po. The peak was clearly observed at 1.3 MeVee (electron equivalent energy). The energy resolution was assumed to be inversely proportional to the square root of deposited energy in an energy region up to the $Q_{\beta\beta}$ value. This dependence has been confirmed up to 2.33 MeV by using a $0^+ \to 0^+$ transition in ^{40}Ca for a CaF_2(Eu) scintillator [10]. The extrapolated resolution was evaluated to be 4–6% in FWHM depending on each CaF_2(Eu) scintillator.

The ELEGANT VI system is able to strongly suppress backgrounds by the 4π active shield and the large $Q_{\beta\beta}$ value of ^{48}Ca. Only a few processes are conceivable as backgrounds [10]. The main background processes are due to pileup events from Bi and Po nuclei, which are radioactive contaminations in the CaF_2(Eu) scintillators.

The pileup events come from the following sequential decays:

(i) $^{212}\text{Bi}\ (Q_\beta = 2.25\ \text{MeV}) \xrightarrow[\beta]{} {}^{212}\text{Po}\ (Q_\alpha = 8.95\ \text{MeV},\ T_{1/2} = 0.299\ \mu s) \xrightarrow[\alpha]{} {}^{208}\text{Pb}$ (Th chain),

(ii) $^{214}\text{Bi}\ (Q_\beta = 3.27\ \text{MeV}) \xrightarrow[\beta]{} {}^{214}\text{Po}\ (Q_\alpha = 7.83\ \text{MeV},\ T_{1/2} = 164\ \mu s) \xrightarrow[\alpha]{} {}^{210}\text{Pb}$ (U chain).

A typical pulse shape of the pileup event is shown in Fig. 1. In particular, the sequential decay (i) is serious because ^{212}Po has the half-life of 0.3 μs, which is much shorter than the CSADC gate width of 4 μs for the 1 μs decay constant of the CaF_2(Eu) signal. As a consequence, the sequential decay (i) frequently becomes a pileup event in the CSADC gate. The CSADC gives the sum energy of β and α rays, which is occasionally close to the $Q_{\beta\beta}$ value.

The pileup events can be rejected by using pulse shape information. The 100 MHz FADC recorded the pulse shape in a time window of 10 μs, which is long enough for the CaF_2(Eu) signal. To reduce data size, only a sum of 46 signals from 23 CaF_2(Eu) scintillators was recorded. The energy threshold for the FADC was 500 keV.

The criteria used to select candidate events for $0\nu\beta\beta$ are as follows:

(i) Single CaF_2(Eu) scintillator fires
(ii) No CsI(Tl) scintillators fire

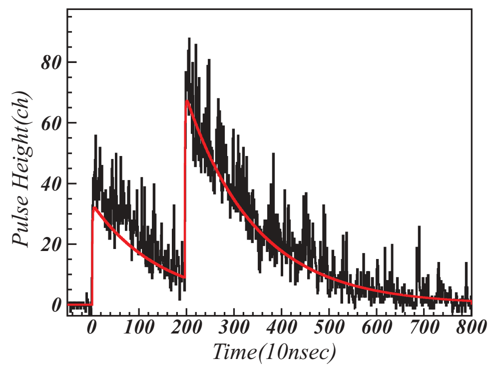

FIG. 1. (Color online) A pulse shape of a typical β-α sequential event observed by the FADC. A solid (thin) line represents pulse shape from the FADC (fitted pileup event shape).

(iii) Pulse shape analysis (PSA) tells that the events are not the pileup events.

The criteria (i) and (ii) are the same as those in the previous analysis [10]. The new criterion (iii) is to realize further background reduction in this analysis.

PSA can identify the pileup event when the time difference of the two pulses is longer than a certain value. Rejection of the pileup events is carried out by the following three procedures:

(i) Preparation of reference pulse shape $f_{\mathrm{ref}}(t)$
(ii) Identification of the pileup events
(iii) Estimation of a rejection efficiency.

Next, we describe each step:

(i) Reference pulse shape, $f^i_{\mathrm{ref}}(t)$, was obtained for each CaF_2(Eu) scintillator; i stands for the scintillator number. Equation (1) represents the pulse shape where both decay and rise are represented by exponential functions with the time constants τ^i_d and τ^i_r, respectively.

$$\begin{aligned} f^i_{\mathrm{ref}}(t) &= A \times \left(\exp\left(-t/\tau^i_d\right) - \exp\left(-t/\tau^i_r\right)\right) && (t \geqslant 0), \\ &= 0 && (t < 0). \end{aligned} \quad (1)$$

Here A is a normalization parameter corresponding to energy. We fitted the shapes generated by summing up pulse shapes of events in an energy region from 1 to 2 MeV where we can safely assume that almost all of the events are due to single-pulse events. Obtained τ^i_d ranged from 1230 to 1480 ns for each scintillator. After fixing τ^i_d, τ^i_r was obtained by averaging that for each event, because time jitter between events deteriorated sharp rise time. τ^i_r was obtained as 6–8 ns for each scintillator.

(ii) A fitting function $f(t)$ for the pileup event has a delayed component represented by $f_{\mathrm{ref}}(t-\Delta t)$,

$$\begin{aligned} f(t) &= A_1 \times f_{\mathrm{ref}}(t) + A_2 \times f_{\mathrm{ref}}(t-\Delta t) && (t \geqslant \Delta t), \\ &= A_1 \times f_{\mathrm{ref}}(t) && (\Delta t \geqslant t \geqslant 0), \\ &= 0 && (0 > t). \end{aligned} \quad (2)$$

Here A_1 and A_2 correspond to energies of prompt and delayed components, respectively. We measured pulse shapes of β and α components and found that their difference is negligibly small for the present analysis. We evaluate χ^2 for a certain Δt by fitting $f(t)$ to events above 3 MeV. We took Δt that gave the least χ^2.

An obtained Δt distribution is shown in Fig. 2(a). The Δt distribution is well represented by an exponential decay. An obtained half-life of 296 ± 10 ns is consistent with the half-life of 299 ns of ^{212}Bi. The energy spectra of prompt and delayed components are shown in Figs 2(b) and 2(c). One can see an end point of 2.2 MeV, which is consistent with ^{212}Bi β decay in the spectrum of the prompt component [Fig. 2(b)]. A peak of α rays from ^{212}Po is observed at 2.0 MeVee in Fig. 2(c). These facts show that events above 3 MeV are due to the sequential decay (a).

(iii) We evaluated the rejection efficiency of the events from the sequential decay (a). The rejection efficiency depends on where a cut point on Δt is set. We set the cut point at 30 ns. The rejection efficiency was obtained to be 90% by analyzing software-generated

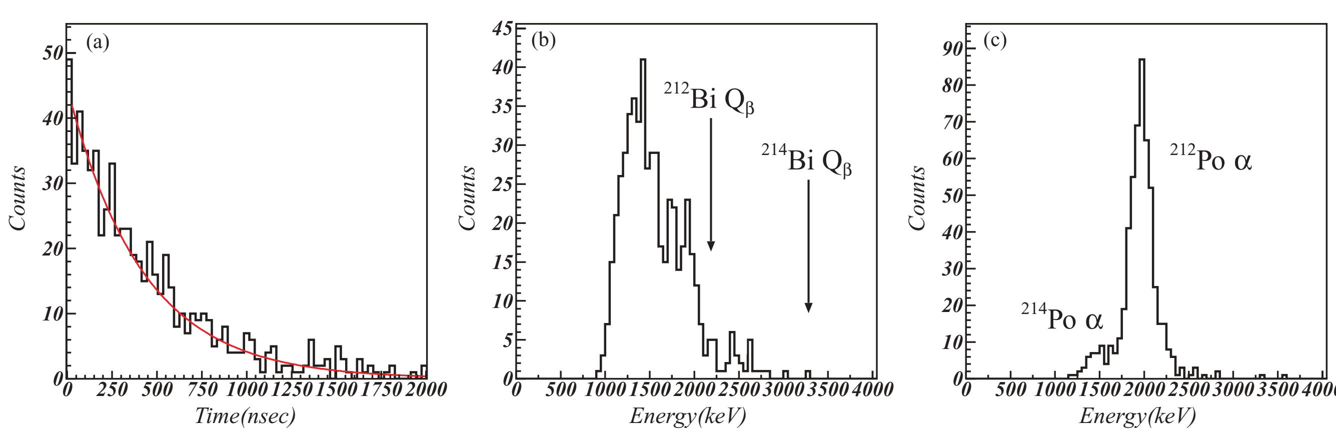

FIG. 2. (Color online) (a) A typical Δt distribution obtained by applying PSA for events from 3 to 4.5 MeV. A solid line corresponds to the best fit with a half-life of $T_{1/2} = 296 \pm 10$ ns. (b) An energy distribution of the prompt component for the events $\Delta t >$ 30 ns in Panel (a). Q_β values of β decays of ^{212}Bi and ^{214}Bi are indicated by arrows. (c) An energy distribution of the delayed component for the events $\Delta t > 30$ ns in Panel (a). The electron equivalent energies of α rays from ^{212}Po and ^{214}Po are 2.0 and 1.6 MeVee, respectively.

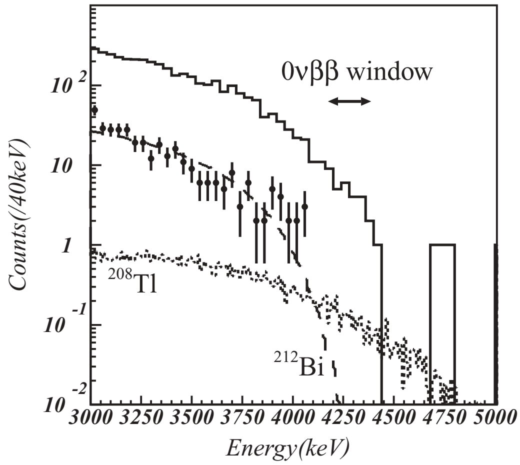

FIG. 3. Energy spectra are shown together with the expected background spectra. Solid circles represent experimental data with PSA. No events are seen in the $0\nu\beta\beta$ window. A solid line represents a spectrum without PSA. A dashed line and a dotted line correspond to the expected backgrounds after PSA from ^{212}Bi and ^{208}Tl, respectively. Backgrounds from ^{214}Bi are negligible in this measurement, because the pileup events from ^{214}Bi were effectively rejected by PSA.

events from the sequential decay (a). The rejection may introduce inefficiency for the single-pulse events due to misidentification. It is found to be negligible for the present cut point.

A selection of candidate events was made for 3394 kg · day of data as described above. The energy spectrum is shown in Fig. 3. One finds that the event rate is reduced by one order of magnitude by requiring PSA. As a result, we observe no events in a $0\nu\beta\beta$ window of 4.17–4.37 MeV.

Estimation of a background rate is needed to derive the half-life of $0\nu\beta\beta$. We know a contribution from the radioactive contaminations in the scintillators gives dominant background, which is estimated by a Monte Carlo simulation [11]. Radioactivities in the CaF_2(Eu) scintillators were 0.11 and 1.20 mBq/kg on average for ^{220}Rn (Th chain) and ^{214}Bi (U chain), respectively. The radioactivities in each CaF_2(Eu) are listed in Ref. [10]. From the simulation using the measured radioactivities and the background rejection efficiency, we estimated the background rate in the $0\nu\beta\beta$ window to be 0.70 events/3394 kg · day as given in Table I. A contribution from two neutrino double-β decay ($2\nu\beta\beta$) is found to be negligible from the lifetime published elsewhere [8,9,12].

TABLE I. A summary of measurements.

	Present measurement	Previous measurement [10]
Pulse shape information	Yes	No
Observed events (counts)	0	0
Expected background events (counts)	0.70	1.30
Statistics (kg · day)	3394	1553
Half-life ($\times 10^{22}$ year)	2.7	1.4

The detection efficiency, which includes the acceptance efficiency of PSA, was evaluated by a Monte Carlo simulation. The efficiency was estimated to be 53% for the $0\nu\beta\beta$ window. It is dominantly determined by the probability that two electrons from $0\nu\beta\beta$ are fully contained in a single CaF_2(Eu).

Here we discuss systematic errors. They are mainly from the uncertainties in the estimation of following three items. (1) Uncertainty on absolute energy calibration and gain stability may obscure the $0\nu\beta\beta$ window. We found it to be less than 1%. (2) Uncertainty on PSA efficiencies was estimated to be 3%. (3) Uncertainty on radioactivities in the CaF_2(Eu) scintillators may change the estimation of backgrounds. It was estimated to be 3%. Uncertainty (1) has no effect, becuase we still have no event even though we have the energy calibration off by 1%. Uncertainties (2) and (3) are much smaller than statistical error. We thus do not take them into account in deriving the half-life.

Following a procedure in Ref. [13], we derive a lower limit at the 90% confidence level (C.L.) on the half-life to be $T_{1/2}^{0\nu\beta\beta} > 2.7 \times 10^{22}$ year. The previous measurement employed essentially the same apparatus except for the FADC and observed no events in the $0\nu\beta\beta$ window for 1553 kg · day [10] as given in Table I. We combined these results to give more stringent limits. Taking into consideration 2.0 events of expected backgrounds, a combined lower limit with the 90% C.L. is $T_{1/2}^{0\nu\beta\beta} > 5.8 \times 10^{22}$ year, which is the most stringent limit of $0\nu\beta\beta$ of ^{48}Ca. The half-life leads to an upper limit on the effective Majorana neutrino mass $\langle m_\nu \rangle < (3.5–22)$ eV (90% C.L.), using the nuclear matrix elements given in Refs. [14] and [15]. We present an experimental sensitivity because the number of observed events is fewer than that of the expected backgrounds. The sensitivity with the 90% C.L. is 1.8×10^{22} year for the combined measurement.

We have studied $0\nu\beta\beta$ of ^{48}Ca by using the ELEGANT VI system, which realized an effective background reduction of radiations from outside the system. The FADC achieved a reduction of the backgrounds inside the system. The lower limit for the half-life of $0\nu\beta\beta$ of ^{48}Ca was obtained as $T_{1/2}^{0\nu\beta\beta} > 2.7 \times 10^{22}$ year (90% C.L.). The further stringent lower limit of 5.8×10^{22} year (90% C.L.) was obtained by combining with the previous measurement.

One has to prepare a large amount of source material to sense the mass region suggested by the oscillation experiments. Although the 4π active shield and the pulse shape analysis are shown to be effective to realize the background-free measurement, the ELEGANT VI system is not suitable to scale up. These techniques are applied to the detector system CANDLES [16–22], which realizes large scalability of the detector size.

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