A measurement of the time profile of scintillation induced by low energy gamma-rays in liquid xenon with the XMASS-I detector


Kamioka Observatory, Institute for Cosmic Ray Research, The University of Tokyo, Higashi-Mozumi, Kamioka, Hida, Gifu 506-1205, Japan
Center of Underground Physics, Institute for Basic Science, 70 Yuseong-daero 1689-gil, Yuseong-gu, Daejeon 305-811, South Korea
Institute for Space-Earth Environmental Research, Nagoya University, Nagoya, Aichi 464-8601, Japan
Institute of Socio-Arts and Sciences, The University of Tokushima, I-1 Minamijosanjimacho Tokushima city, Tokushima 770-8502, Japan
Kavli Institute for the Physics and Mathematics of the Universe (WPI), the University of Tokyo, Kashiwa, Chiba 277-8582, Japan
Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8602, Japan
Department of Physics, Kobe University, Kobe, Hyogo 657-8501, Japan
Korea Research Institute of Standards and Science, Daejeon 305-340, South Korea
Department of Physics, Miyagi University of Education, Sendai, Miyagi 980-0845, Japan
Department of Physics, Tokai University, Hiratsuka, Kanagawa 259-1292, Japan
Department of Physics, Faculty of Engineering, Yokohama National University, Yokohama, Kanagawa 240-8501, Japan

XMASS Collaboration

A R T I C L E  I N F O

Article history:
Received 12 April 2016
Received in revised form 5 August 2016
Accepted 5 August 2016
Available online 6 August 2016

Keywords: Decay time constant Liquid xenon Scintillator

A B S T R A C T

We report the measurement of the emission time profile of scintillation from gamma-ray induced events in the XMASS-I 832 kg liquid xenon scintillation detector. Decay time constant was derived from a comparison of scintillation photon timing distributions between the observed data and simulated samples in order to take into account optical processes such as absorption and scattering in liquid xenon. Calibration data of radioactive sources, $^{55}$Fe, $^{241}$Am, and $^{57}$Co were used to obtain the decay time constant. Assuming two decay components, $\tau_1$ and $\tau_2$, the decay time constant $\tau_2$ increased from 27.9 ns to 37.0 ns as the gamma-ray energy increased from 5.9 keV to 122 keV. The accuracy of the measurement was better than 1.5 ns at all energy levels. A fast decay component with $\tau \sim 2$ ns was necessary to reproduce data. Energy dependencies of $\tau_2$ and the fraction of the fast decay component were studied as a function of the kinetic energy of electrons induced by gamma-rays. The obtained data almost reproduced previously reported results and extended them to the lower energy region relevant to direct dark matter searches.

© 2016 Elsevier B.V. All rights reserved.

1. Introduction

Liquid xenon (LXe) has been used in many experiments for dark matter searches [1–4], double beta decay searches [5] and lepton flavor violation searches [6]. The time profile of LXe scintillation is important information for these experiments. It could potentially be used for particle identification [7] and vertex reconstruction [8,9].

Basic characteristics of scintillation emission in LXe have been intensively studied elsewhere in order to understand the detector response. There are two scintillation processes in LXe, the direct scintillation and the recombination processes. The direct scintillation process proceeds through two states, singlet excitation $\Sigma^+$ and triplet excitation $\Sigma^+$. The decay time constants of singlet and triplet states are a few ns and $\sim$20 ns, respectively [10,11]. The recombination process has a longer decay time constant of $\sim$30 ns or more [10,11]. The scintillation time profile can be used to
discriminate between nuclear recoil events and electron events since the ratio of singlet to triplet excitations as well as the recombination time depend on ionization density [11,12].

Existing time profile measurements have been conducted with a small amount of LXe [10,11,13–18]. This method minimizes the scattering and absorption of scintillation photons by xenon itself. Some prior research, however, reported that decay time constants do not agree with each other, as reviewed in [18,19]. The disagreements might be caused by differences in the experimental setups, conditions of the LXe, or analysis methods. Furthermore, the fast decay component and the energy dependence of the decay time constant must be considered [10,14]. Moreover, most of the previous measurements were performed with relatively small photoelectron yield making it difficult to measure events induced by low energy particles. Therefore, detailed measurements with larger photoelectron yield are necessary.

A measurement of the time profile of scintillation in LXe using the XMASS-I detector was conducted. The XMASS experiment is for direct dark matter search using the 832 kg of LXe scintillator [1]. The XMASS-I detector has a large photo-coverage of more than 62%. Owing to the large amount of LXe and large photo-coverage, it is possible to obtain the time profile measurements. In this paper, radioactive sources, $^{55}$Fe, $^{241}$Am and $^{57}$Co, were used to measure the time profile for a wide energy range, between 5.9 keV and 122 keV as gamma-ray energy.

2. The XMASS experiment

The XMASS detector consists of a copper vessel surrounded by a large water tank for shielding [1]. The LXe in the inner vessel is viewed by 642 photomultiplier tubes (PMTs). The PMTs are implemented into PMT holders made of oxygen free high conductivity copper. The holders are assembled into a pentakis dodecahedron surrounding LXe for maximizing the collection efficiency of the scintillation photons. Xenon was purified by two SAES PS4-MT15 getters before filling into the detector. As a result, the light yield is quite high, approximately 14 photoelectrons (PE)/keV.

A radioactive source can be inserted into the detector for the purpose of calibration. The source position is movable only along the Z (vertical) axis. The detector center is at Z=0 cm. The sources can be divided into two groups according to their structure. All of them are mounted in the needle-shaped containers with different diameters. The 2π sources, $^{55}$Fe and $^{241}$Am (2π), have a 10 mm diameter. The 4π sources, $^{241}$Am (4π) and $^{57}$Co, have a 0.21 mm diameter [1,20]. The two types of sources were developed to better handle the shadow effect from the source itself. A thin source structure is preferred because it is better at avoiding the shadow effect by source itself. However, in the case of low energy radiation, interactions occur close to the source due to the short attenuation length. Therefore, the shadow effect can be observed even for a thin structure. The uncertainties caused by roughness of the source surface must be considered. While it is difficult to polish a thin structure, 2π sources make handling the uncertainties easier due to their well polished flat surfaces. $^{55}$Fe decays into $^{55}$Mn via electron capture and 5.9 keV characteristic X-rays are emitted. $^{241}$Am decays into its daughter nuclei $^{237}$Np. $^{237}$Np emits 59.5 keV gamma-rays and 17.8 keV X-rays. While both of the 59.5 keV gamma-rays and 17.8 keV X-rays are observable in the case of $^{241}$Am (4π), 17.8 keV X-rays are not observable in the case of $^{241}$Am (2π) due to the thick structure. When a 59.5 keV gamma-ray is absorbed in LXe, a 25.0 keV electron is emitted from the K-shell due to the photoelectric effect, and an approximately 30 keV characteristic X-ray and low energy Auger electrons are emitted. In the case of the $^{241}$Am (2π) source, the X-rays often escape from LXe back into the source itself due to the large solid angle of the source, and therefore an “escape peak” can be observed at the deposited energy of ∼30 keV. $^{57}$Co emits 122 keV gamma-rays and 59.3 keV X-rays from tungsten contained in the source.

The signals from the PMTs pass through ∼20 m coaxial cables to CAEN V1751 waveform digitizers. The waveforms in each PMT are recorded with 1 GHz sampling rate and 10 bit resolution. The threshold for a PMT is set to −5 mV and it corresponds to 0.2 PE. A trigger is issued when at least four PMTs detect signals exceeding the threshold within 200 ns. A detailed explanation is provided in [1].

Timing calibration with $^{57}$Co is regularly carried out to adjust the timing offset of each PMT channel due to the differences in their cable lengths (at most 2 m) and responses of the electronics. The $^{57}$Co source is placed at Z=0 cm where the distance to each PMT is nearly equal. With approximately 10,000 events in the 122 keV gamma-ray peak, the distribution of the threshold crossing time for each channel is fitted with a combination of two exponential functions convoluted with a Gaussian to get the timing offset of each channel so that the rising edges of the distributions are aligned. The precision of the calibration is better than 0.3 ns, estimated from the uncertainty in the fitting. PMT gain stability is monitored using signals generated by a blue LED implemented on the inner surface of the detector.

3. Analysis method

The scintillation time profile is evaluated by comparing the reconstructed pulse timing distributions over all PMTs of data and simulated samples with various timing parameters. Pulse splitting method has been developed in the XMASS experiment which enabled the ability to obtain peak timing of each scintillation photon pulse.

Pulse splitting is executed using a peak search algorithm based on Savitzky–Golay filter [21]. The waveform data are fitted with a convolution of 1 PE pulse waveform obtained from LED calibration data. Waveform fitting using the 1 PE waveform template is done on a 1 ns grid. Fig. 1 shows a typical raw waveform in a PMT overlaid with the reconstructed waveform as the sum of the 1 PE pulses for the 122 keV gamma-ray from the $^{57}$Co source placed at Z=0 cm. It corresponds to 3 PE incident and the observed waveform can be clearly reconstructed as the sum of the three 1 PE pulses. Owing to a small fluctuation of the baseline, pulse splitting sometimes makes small artifact pulses in the data in the case of a large number of incident photons. These pulses clearly appear more than 60 ns after the primary and affect the apparent decay.

**Fig. 1.** A typical raw waveform in a PMT (solid line) overlaid with the reconstructed waveform as the sum of 1 PE pulses (dashed curve) for the 122 keV gamma-ray from the $^{57}$Co source placed at Z=0 cm. The triangle markers indicate timings of the decoupled 1 PE pulses.
time constant. These pulses can be rejected on the basis that the PE of a pulse is larger than 0.5 PE.

The XMASS Monte Carlo simulation is based on Geant4 [22]. The energy-dependent scintillation photon yield is taken into account using a non-linearity model from Doke et al. [23] with a further correction obtained from gamma-ray calibrations in the relevant energy range. A precise understanding of the optical characteristics inside the detector is needed to extract a time profile. Optical parameters of LXe and the inner surface material of the detector are also carefully tuned by source calibration data at various positions.

A scintillation photon observed time $T$ in the simulation is defined as follows:

$$T = t_{\text{edep}} + t_{\text{cont}} + t_{\text{f immediately after the source placed at the center of the detector, $Z=0$ cm. The induced gamma-ray energy $E_\gamma = 59.5$ keV corresponds to 750–770 PE. A simulated sample with $t_\Sigma = 32$ ns and $F_\Sigma = 0.05$ gives the minimum $\chi^2/\text{dof} = 153.0/118$. The pulse timing distribution of the observed data overlaid with those of the best fit simulated samples with and without a fast decay component is shown in Fig. 2 (middle). Simulated samples without a fast decay component gives $\chi^2 = 3094.6$ at the best with $t_\Sigma = 32$ ns due to the discrepancy for $t < 15$ ns. Therefore, a fast decay component is necessary to reproduce data. The more precise $t_\Sigma$ and $F_\Sigma$ values in between the two steps are estimated by interpolating $\chi^2$ values with a one-dimensional quadratic function, resulting in $t_\Sigma = 31.9$ ns and $F_\Sigma = 0.048$.

All the systematic errors are itemized in Table 1. The position dependence is less than 1.3 ns and 0.017 for $t_\Sigma$ and $F_\Sigma$, respectively. It is evaluated from the standard deviation of the measured values in $^{241}\text{Am}$ ($4\pi$) data. The position dependence evaluated from 17.8 keV gamma-ray is applied for the gamma-ray energies of $E_\gamma = 17$ keV or less ($E_\gamma = 5.9, 17.8$ keV). On the other hand, position dependence evaluated from 59.5 keV gamma-ray is applied for mean kinetic electron energies of $E_{\text{electron}} \sim 22$ keV or more ($E_{\text{electron}} = 59.5, 59.3, 122$ keV and escape electron $E_{\text{electron}} \sim 22$ keV from $^{241}\text{Am}$ ($4\pi$)). Possible differences due to the source shape are evaluated from $Z=0$ cm data for $^{241}\text{Am}$ ($4\pi$) and $^{57}\text{Co}$. The uncertainty is $\pm 0.9$ ns and $\pm 0.004$ ns for $t_\Sigma$ and $F_\Sigma$, respectively. Timing jitter $t_{\text{jitter}}$ mainly affects the rising edge of the timing distributions. The error is evaluated by comparing the timing distributions of data and simulated samples with different assumptions for $t_{\text{jitter}}$. $t_{\text{jitter}}$ is changed to 0.0, 0.5, and 1.5 ns. The systematic error is less than 0.2 ns for $t_\Sigma$, and less than 0.009 for
The measured decay time constant values are summarized in Table 2. A clear energy dependence on the decay time constant $\tau_2$ is found. Such energy dependence at the energy range has already been reported by Akimov et al. [14] and Ueshima [16]. It would suggest that the fast decay component from the singlet state becomes visible because of a much shorter recombination time scale for the larger ionization density by a lower energy electron track. The fast decay component fraction $F_1$ decreases as the incident particle energy increases. Note that the fitting is performed in the tail region of $T \geq 30$ ns because of a bad $\chi^2$ calculation in $E_{\text{Electron}}$. No $F_1$ value is shown in $E_1 = 122$ keV of $^{57}$Co because the energy range for the $\chi^2$ calculation is changed.

$F_1$ The errors caused by the optical parameters in the Monte Carlo simulation are also evaluated as well as timing jitter. The scattering length is changed by $\pm 1$ cm. The absorption length is changed from 6 m to 4 m and 11 m. As a result, the errors caused by the optical parameters are less than 0.2 ns and 0.014 for $\tau_2$ and $F_1$, respectively. The detector stability including light yield change is evaluated by applying the same analysis method to other calibration data taken at different times. Nine other data sets of $^{57}$Co are used for the evaluation. The errors are found to be less than 0.9 ns and less than 0.009 for $\tau_2$ and $F_1$, respectively. The errors caused by step size of $\tau_2$ and $F_1$ values, 1.0 ns and 0.025, are evaluated from the differences between the parameters of the simulated samples which gives minimum $\chi^2$ and the values obtained by interpolation. The errors are $\pm 0.3$ ns for $\tau_2$ and $\pm 0.007$ for $F_1$. 

The errors caused by the optical parameters in the Monte Carlo simulation are also evaluated as well as timing jitter. The scattering length is changed by $\pm 1$ cm. The absorption length is changed from 6 m to 4 m and 11 m. As a result, the errors caused by the optical parameters are less than 0.2 ns and 0.014 for $\tau_2$ and $F_1$, respectively. The detector stability including light yield change is evaluated by applying the same analysis method to other calibration data taken at different times. Nine other data sets of $^{57}$Co are used for the evaluation. The errors are found to be less than 0.9 ns and less than 0.009 for $\tau_2$ and $F_1$, respectively. The errors caused by step size of $\tau_2$ and $F_1$ values, 1.0 ns and 0.025, are evaluated from the differences between the parameters of the simulated samples which gives minimum $\chi^2$ and the values obtained by interpolation. The errors are $\pm 0.3$ ns for $\tau_2$ and $\pm 0.007$ for $F_1$. 

The measured decay time constant values are summarized in Table 2. A clear energy dependence on the decay time constant $\tau_2$ is found. Such energy dependence at the energy range has already been reported by Akimov et al. [14] and Ueshima [16]. It would suggest that the fast decay component from the singlet state becomes visible because of a much shorter recombination time scale for the larger ionization density by a lower energy electron track. $F_1$ decreases as the incident particle energy increases. Note that the fitting is performed in the tail region of $T \geq 30$ ns for $122$ keV because of a bad $\chi^2$ for fitting in the entire time range. Therefore, $F_1$ is not shown here. This might imply that a single exponential decay with $\tau_1$ may not be the case for higher incident energy, possibly because the recombination process is more complex in this case. 

Energy dependencies of $\tau_2$ and $F_1$ are studied as a function of the kinetic energy of electrons induced by gamma-rays. In the case of $59.5$ keV gamma-rays, $25.0$ keV electrons are emitted from the K-shell, whose electron binding energy is $34.56$ keV, due to the photoelectric effect. Auger electrons, whose energy are $\sim 25$ keV or

### Table 1

<table>
<thead>
<tr>
<th>Error source</th>
<th>$\sigma_2$ (ns)</th>
<th>$\sigma_f$</th>
<th>Energy range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position dependence</td>
<td>$\pm 0.9$</td>
<td>$+0.017$</td>
<td>$E_1 \leq 17.8$ keV</td>
</tr>
<tr>
<td></td>
<td>$+0.3$</td>
<td>$+0.005$</td>
<td>$E_1 \geq 17.8$ keV</td>
</tr>
<tr>
<td></td>
<td>$-1.3$</td>
<td>$-0.004$</td>
<td>$E_1 \geq 17.8$ keV</td>
</tr>
<tr>
<td>Source difference</td>
<td>$\pm 0.6$</td>
<td>$\pm 0.002$</td>
<td>All</td>
</tr>
<tr>
<td>Timing jitter</td>
<td>$\pm 0.1$</td>
<td>$+0.009$</td>
<td>$E_1 \leq 17.8$ keV</td>
</tr>
<tr>
<td></td>
<td>$\pm 0.2$</td>
<td>$+0.001$</td>
<td>$E_1 \geq 17.8$ keV</td>
</tr>
<tr>
<td>Optical parameters</td>
<td>$\pm 0.2$</td>
<td>$+0.007$</td>
<td>$E_1 \leq 17.8$ keV</td>
</tr>
<tr>
<td></td>
<td>$\pm 0.1$</td>
<td>$+0.014$</td>
<td>$E_1 \geq 17.8$ keV</td>
</tr>
<tr>
<td>Detector stability</td>
<td>$+0.9$</td>
<td>$+0.005$</td>
<td>$E_1 \leq 17.8$ keV</td>
</tr>
<tr>
<td></td>
<td>$-0.0$</td>
<td>$-0.009$</td>
<td>$E_1 \geq 17.8$ keV</td>
</tr>
<tr>
<td></td>
<td>$+0.4$</td>
<td>$-0.009$</td>
<td>$E_1 \geq 17.8$ keV</td>
</tr>
<tr>
<td>Step size</td>
<td>$\pm 0.3$</td>
<td>$+0.007$</td>
<td>All</td>
</tr>
<tr>
<td>Total</td>
<td>$+1.5$</td>
<td>$+0.022$</td>
<td>$E_1 = 17.8$ keV</td>
</tr>
<tr>
<td></td>
<td>$-1.1$</td>
<td>$-0.02$</td>
<td>$E_1 = 17.8$ keV</td>
</tr>
<tr>
<td></td>
<td>$+1.2$</td>
<td>$+0.017$</td>
<td>$E_1 = 17.8$ keV</td>
</tr>
<tr>
<td></td>
<td>$-1.5$</td>
<td>$-0.019$</td>
<td>$E_1 = 17.8$ keV</td>
</tr>
<tr>
<td></td>
<td>$+0.9$</td>
<td>$-0.009$</td>
<td>$E_1 = 122$ keV</td>
</tr>
<tr>
<td></td>
<td>$-1.5$</td>
<td>$-0.019$</td>
<td>$E_1 = 122$ keV</td>
</tr>
</tbody>
</table>

### Table 2

<table>
<thead>
<tr>
<th>Source</th>
<th>$E_1$ (keV)</th>
<th>$E_{\text{Electron}}$ (keV)</th>
<th>$\tau_2$ (ns)</th>
<th>$F_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{54}$Fe</td>
<td>5.9</td>
<td>3.3 $\pm$ 1.3</td>
<td>27.8 $^{+1.5}_{-1.1}$</td>
<td>0.145 $^{+0.022}_{-0.020}$</td>
</tr>
<tr>
<td>$^{24}$Am</td>
<td>17.8</td>
<td>12.2 $\pm$ 4.6</td>
<td>27.9 $^{+1.5}_{-1.1}$</td>
<td>0.098 $^{+0.022}_{-0.020}$ (Escape electron from Xe(2 only))</td>
</tr>
<tr>
<td></td>
<td>59.5</td>
<td>59.5 $\pm$ 1.6</td>
<td>32.2 $^{+1.2}_{-1.1}$</td>
<td>0.063 $^{+0.017}_{-0.019}$</td>
</tr>
<tr>
<td>$^{57}$Co</td>
<td>59.3</td>
<td>59.3 $\pm$ 1.6</td>
<td>31.9 $^{+1.2}_{-1.1}$</td>
<td>0.045 $^{+0.017}_{-0.019}$</td>
</tr>
<tr>
<td>122</td>
<td>71.2 $\pm$ 32.0</td>
<td>37.0 $^{+0.9}_{-1.1}$</td>
<td>$\tau_2 \geq 30$ ns</td>
<td></td>
</tr>
</tbody>
</table>
les are also emitted. Thus, multiple electrons with various kinetic energies can be emitted from an incident gamma-ray. The mean kinetic energy of the electrons $E_{\text{electron}}$ is evaluated from a Monte Carlo simulation. The uncertainty for $E_{\text{electron}}$ is defined as the root mean square of released electron energy.

The energy dependence of the decay time constant in the $E_{\text{electron}} < 100 \text{ keV}$ region has already been reported in prior research [14,16,19]. The difference between $E_e$ and $E_{\text{electron}}$ for $\tau_2$ might be used for some experiments, such as specific dark matter searches [9,25], and two neutrino double electron capture searches [26], by discriminating the gamma-ray induced events and electron induced events.

Fig. 3 shows the decay time constant $\tau_2$ as a function of the electron kinetic energy $E_{\text{electron}}$. This analysis gave consistent results with Akimov et al. [14] and extended them to the lower energy region relevant to direct dark matter searches. Ueshima [16] reported a much longer decay time constant than this analysis. It was found that this previous result was not corrected for the detector response: the observed waveform, without accounting for the detailed detector response such as the 1 PE waveform shape, was fitted by a single exponential function. The present analysis, on the other hand, decomposed waveforms into 1 PE pulses and compared their timing distributions between data and simulation to account for the detector response.

5. Conclusions

The time profile of scintillation in liquid xenon has been measured with the XMASS-I detector. The measurement was conducted in a wide energy range, between 5.9 keV and 122 keV for gamma-ray energy, with various radioactive sources, $^{55}\text{Fe}$, $^{241}\text{Am}$, and $^{57}\text{Co}$. Energy dependence of the decay time constant was observed. The decay time constant increased from 27.8 ns to 37.0 ns, and the error was smaller than 1.5 ns. The obtained decay time constants are consistent with Akimov et al., but inconsistent with Ueshima. The discrepancy could be explained by the difference in the analysis methods. In addition, the 2.2 ns fast decay component, which corresponds to singlet excitation, was necessary to reproduce data. The number of photons that follow the fast decay component relatively decreased as incident particle energy increased. The ratio differed from 0.15 to 0.05 at the measured energy region.

The measurements in this study provided a time profile of LXe scintillation below 10 keV with induced gamma-ray energy and revealed an energy dependence of $\tau_2$ and $F_1$. They are important for pulse shape discrimination of nuclear recoil from the gamma-ray signal, and also for possible discrimination of electron incident from gamma-ray incident, or vertex reconstruction using the scintillation time profile in the experiments such as dark matter and rare decay searches.

Acknowledgments

We gratefully acknowledge the cooperation of Kamioka Mining and Smelting Company. This work was supported by the Japanese Ministry of Education, Culture, Sports, Science and Technology, Grant-in-Aid for Scientific Research, JSPS KAKENHI Grant Numbers, 19GS0204 and 26104004, and partially by the National Research Foundation of Korea Grant funded by the Korean Government (NRF-2011–220-C00006).

References