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

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ABSTRACT

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, τ_1 and τ_2, the decay time constant τ_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 $\tau_1 \sim 2$ ns was necessary to reproduce data. Energy dependencies of τ_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.

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 $^1\Sigma_\mu^+$ and triplet excitation $^3\Sigma_\mu^+$. The decay time constants of singlet and triplet states are a few ns and ~20 ns, respectively [10,11]. The recombination process has a longer decay time constant of ~30 ns or more [10,11]. The scintillation time profile can be used to

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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

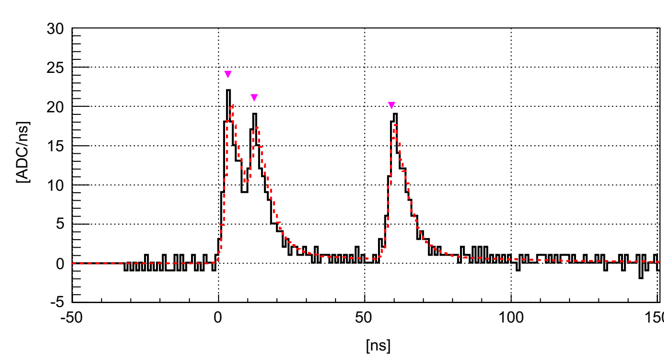

Fig. 1. A typical raw waveform in a PMT (solid line) overlaid with the reconstructed waveform as the sum of 1 PE pulses (dashed curve) for the 122 keV gamma-ray from the ^{57}Co source placed at $Z=0$ cm. The triangle markers indicate timings of the decoupled 1 PE pulses.