Pulse-Shape Discrimination of CaF$_2$(Eu)

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Abstract

We measured the decay time of the scintillation pulses produced by electron and nuclear recoils in CaF$_2$(Eu) by a new fitting method. In the recoil energy region 5–30 keVee, we found differences of the decay time between electron and nuclear recoil events. In the recoil energy region above 20 keVee, we found that the decay time is independent of the recoil energy.

Keywords: Dark matter, WIMP, CaF$_2$(Eu), Scintillator, PSD

1. Introduction

There is convincing evidence that most of the matter in our Galaxy must be dark matter. One of the most popular candidates for dark matter is Weakly Interacting Massive Particles (WIMPs). WIMPs are thought to be non-baryonic particles, and the most plausible candidates for them are the Lightest Supersymmetric Particles (LSPs) and the Lightest Kaluza-Klein Particles (LKPs)[1].

WIMPs can be searched for directly, as they interact with atomic nuclei in detectors. Direct detection relies on one of two modes of interaction with target nuclei. The first mode is called spin-independent (SI) coupling. It describes coherent interaction with the entire nuclear mass. Therefore the SI part of the WIMP-nucleus cross section is large, if the target nuclei have the large mass number. For example, xenon and iodine are the favorable nuclei to detect
WIMPs for the SI interaction. The second mode is called spin-dependent (SD) coupling. It describes interaction of WIMP with the spin-content of the nucleus. Hence the SD part of the WIMP-nucleus cross section is large, if the spin-content of the target nuclei is large. For example, $^{19}$F is one of the most favorable nuclei to detect WIMPs for the SD interaction because of its large nuclear spin.

Several direct WIMP searches using $^{19}$F-based detectors, such as bolometers, a bubble chamber, scintillators, a superheated droplet detector and so on, have already been performed. In our group, a WIMP search experiment using a CaF$_2$(Eu) scintillator is carried out at Kamioka observatory in 2005. CaF$_2$(Eu) is one of the most suitable material among $^{19}$F-based scintillator because of its high light-output.

In other direct WIMP searches, pulse shape discrimination (PSD) technique is used in order to statistically discriminate nuclear recoil signal events from electron recoil background events. A nuclear recoil event is different from an electron recoil event in decay time of their pulse shapes. In the PSD technique, a distribution of the decay time constant is utilized for the statistical discrimination. The PSD feature in CaF$_2$(Eu) was reported in the MeV region. The pulse shape of CaF$_2$(Eu) scintillator in lower energy region relevant to the dark matter WIMP search was measured previously by Tovey et al. They reported that CaF$_2$(Eu) has no PSD capability in the 10–30 keVee region. However, we recently measured the pulse shape of CaF$_2$(Eu) and analysed our data by a more careful statistical method. In this paper, we report on the new measurement of CaF$_2$(Eu) pulse shape and the analysis. We found a difference in the pulse shape of CaF$_2$(Eu) between nuclear and electron recoil events.

2. Experimental methods

2.1. Measurement system

The scintillator sample consisted of an unencapsulated, double-ended, 20-mm-diameter, 20-mm-long crystal of CaF$_2$(Eu) with europium doping content.
of 0.5%. The crystal was glued on two 2-inch photomultiplier tubes (Hamamatsu R329-02).

$^{252}\text{Cf}$ was used as a neutron source together with three detectors as shown in Fig. 1. Nuclear recoil candidates were selected by looking for coincidences between events in three detectors. The first one was the target $\text{CaF}_2(\text{Eu})$. The second was a plastic scintillator, which detected prompt $\gamma$ rays from fission decays of $^{252}\text{Cf}$. The last was a liquid scintillator (Saint-Gobain, BC-501A), which caught scattered neutrons from the target $\text{CaF}_2(\text{Eu})$.

For the latter two detectors, Hamamatsu R329-02 photomultiplier tubes were also used. Signals from all the photomultiplier tubes were sent to fast discriminators with sufficiently low thresholds. A special care was taken to the two output signals of the $\text{CaF}_2(\text{Eu})$ scintillator so as to suppress multiple trailing pulses due to its long decay time constant. A coincidence of these two discriminator outputs were taken to define the $\text{CaF}_2(\text{Eu})$ scintillator hit with a coincidence width of 160 ns. Coincidence widths of the plastic scintillator and $\text{CaF}_2(\text{Eu})$ scintillator, and the plastic scintillator and the liquid scintillator were set to 195 ns and 400 ns, respectively.
The photomultiplier outputs of the CaF$_2$(Eu) and the liquid scintillators and the discriminator output of the plastic scintillator were recorded with a Tectronix TDS3034B digital oscilloscope with sampling frequency of 2.5 GHz and 300 MHz bandwidth by a trigger of the coincidence of three detectors. The pulse shape of the CaF$_2$(Eu) scintillator and the timing of all the detectors are thus recorded and sent to a computer.

The estimated solid angles of the CaF$_2$(Eu) scintillator as seen from the $^{252}$Cf source and of the liquid scintillator from the CaF$_2$(Eu) scintillator are $1.2 \times 10^{-3}$ sr and $1.1 \times 10^{-1}$ sr, respectively. The scattering angle spanned by the three detectors was about 90 degrees. Between the plastic and liquid scintillators, polyethylene (PE) blocks (35 cm long) and Pb blocks (20 cm long) are placed in order to shield the liquid scintillator from neutrons coming directly from $^{252}$Cf.

2.2. Selection of nuclear recoils

We distinguished nuclear recoil events from electron recoil events using the time-of-flight (TOF) of the particle. The time-of-flight of the neutron from the $^{252}$Cf source to the liquid scintillator is

$$t_{SL} = t_{ST} + t_{TL} = \frac{L_{ST}}{\sqrt{2E_1/m_n}} + \frac{L_{TL}}{\sqrt{2E_2/m_n}}$$

(1)

Here $t_{ST}$ and $t_{TL}$ are the times-of-flight of the neutron from the $^{252}$Cf source to the target scintillator and from the target scintillator to the liquid scintillator, and $L_{ST}$ and $L_{TL}$ are the respective lengths. In this measurement, $L_{ST}$ and $L_{TL}$ are 70 cm and 15 cm. $E_1$ and $E_2$ are the neutron energies before and after the collision with the nucleus in the target, and $m_n$ is the neutron mass. Then, the energy of the recoil nucleus is

$$E_r = E_1 - E_2 = E_1 \times \frac{2m_n}{(M + m_n)^2} \times \left( M + m_n \sin^2 \theta - \cos \theta \sqrt{M^2 - m_n^2 \sin^2 \theta} \right)$$

(2)

when the scattering is elastic. Here $M$ is the recoil nucleus mass, and $\theta$ is the neutron scattering angle. In this measurement, since the recoil angle $\theta$ is around
90 degrees, the recoil energy is simply

$$E_r = E_1 - E_2 = E_1 \times \frac{2m_n}{M + m_n}. \quad (3)$$

Inelastic cross section is negligibly small in the neutron energy range relevant to the present measurement and therefore ignored in the analysis.

Density plots of the electron equivalent energy deposited in CaF$_2$(Eu) versus TOF $t_{SL}$ is shown in Fig. 2. Theoretical expectation curves are also show in the Fig. for the $^{19}$F and $^{40}$Ca with quenching factors of 0.05 and 0.15. On the other hand, Compton scattering events in the CaF$_2$(Eu) scintillator caused by gamma rays emitted by the $^{252}$Cf source are expected to gather in the region where TOF is 0 ns. Fig. 2 shows clear separation of the nuclear recoil events and the Compton scattering events.

To pickup the $^{19}$F and $^{40}$Ca recoil events, we put a rectangle where nuclear recoil events are expected. Consequently, we obtained enough pulse shapes for the PSD analysis.
2.3. New method of PSD

A pulse shape of scintillation is formed by a train of small single-photoelectron pulses. The arrival time relative to the pulse start time of each pulse follows an exponential distribution. Hence, the scintillation pulse shape has a characteristic time constant, which is different between electron and nuclear recoil events.

In many researches, integrated pulse is used for analysis, and an exponential rise function $A \times (1 - \exp[-(t - t_0)/\tau])$ is fitted to the data by the least-squares method\cite{14}. This analysis is statistically not strictly correct because integrated data points are not independent of each other. Therefore, the data themselves before integration must be used for the fitting analysis.

However, because the scintillation of CaF$_2$(Eu) is not bright enough and has large decay constant, it is difficult to fit an exponential fall function $A \times \exp[-(t - t_0)/\tau]$ to all the data points by the least-squares method. So we divided a train of data points of the oscilloscope into 40 ns bins, and fitted the estimate number of photoelectrons in each bin calculated by an exponential fall function to the data by the maximum-likelihood method via two parameters, the estimate value of the first bin and the decay time constant.

The number of photoelectrons in each bin follows a Poisson distribution. So the probability distribution function $f(x_i, \mu_i)$ of the observed charge $x_i$ in $i$-th bin is

$$f(x_i, \mu_i) = \sum_n \left[ \text{Poi}(n, \mu_i) \cdot \text{Gau}(x_i, Q_0 + nQ_1, \sigma_0^2 + n\sigma_1^2) \right],$$  \hspace{1cm} (4)

where $\mu_i$ is the estimate value of the number of photoelectrons in the $i$-th bin. $\text{Poi}(n, \mu)$ is a Poisson distribution function of $n$ with the mean value of $\mu$, and $\text{Gau}(x, Q, \sigma^2)$ is a Gaussian distribution of $x$ with the mean value of $Q$ and dispersion $\sigma^2$. $Q_0$, $\sigma_0$, $Q_1$ and $\sigma_1$ are the parameters for the conversion of the number of photoelectrons to the charge recorded by the oscilloscope. $Q_0$ and $\sigma_0$ are the pedestal and its width, and $Q_1$ and $\sigma_1$ are one photoelectron response and its standard deviation. These four parameters are characteristic of PMTs and they were measured by a single photoelectron spectra analysis.
independently\textsuperscript{13}. Tab.\textsuperscript{1} shows the typical values of $Q_0$, $\sigma_0$, $Q_1$ and $\sigma_1$ as measured in electron equivalent deposit energy. The $Q_1$, $\sigma_0$ and $\sigma_1$ values are stable within $\pm 4.5\%$, $\pm 16\%$ and $\pm 23\%$ in measurement after over a year, respectively.

| Parameter | PMT ch.1 [keV] | PMT ch.2 [keV] |
|-----------|----------------|----------------|
| $Q_0$     | $(1.1 \pm 0.3) \times 10^{-3}$ | $(2.2 \pm 0.3) \times 10^{-3}$ |
| $\sigma_0$ | $(1.56 \pm 0.04) \times 10^{-2}$ | $(1.83 \pm 0.04) \times 10^{-2}$ |
| $Q_1$     | $(3.15 \pm 0.07) \times 10^{-1}$ | $(3.06 \pm 0.07) \times 10^{-1}$ |
| $\sigma_1$ | $(1.70 \pm 0.08) \times 10^{-1}$ | $(1.69 \pm 0.08) \times 10^{-1}$ |

From this, the likelihood function $L(\mu_0, \tau)$ is

$$L(\mu_0, \tau) = \prod_{\text{PMT ch.1,2}} \prod_i f(x_i, \mu_0 \cdot \exp\left(-\frac{t \cdot (i-1)}{\tau}\right)), \quad (5)$$

where $t$ is the bin width. The two parameters, $\mu_0$ (the estimate value of the photoelectron number in the first bin) and $\tau$ (the decay time constant), are evaluated when they maximize the likelihood function $L(\mu_0, \tau)$.

### 3. Result and discussion

A sample of the result of the maximum likelihood fitting to the experimental data is shown in Fig.\textsuperscript{3} for $\gamma$ ray events with $^{241}$Am and $^{137}$Cs, and for selected neutron events with $^{252}$Cf. A difference is seen in the decay time distribution between electron and nuclear recoil events.

In order to see the difference more clearly, we divided the events into electron equivalent energy bins of 5 keV width, and evaluated the mean value of the decay constant in each bin. Exceptionally, we put regions of photoelectric absorption peaks, 13.9 keVee ($^{241}$Am), 59.5 keVee ($^{241}$Am) and 32.2–36.4 keVee ($^{137}$Cs), into wider single bins. The distribution of the decay time constant $\tau$ can be approximated by a Gaussian in $\ln(\tau)$:\textsuperscript{16}

$$\frac{dN}{d\tau} = \frac{N_0}{\tau \sqrt{2\pi \ln w}} \cdot \exp \left[-\frac{(\ln \tau - \ln \tau_0)^2}{2(\ln w)^2}\right]. \quad (6)$$
Figure 3: The scatter plot of the experimental data. The decay constant is evaluated by the maximum likelihood method. (Sec. 2.3)

Figure 4: The decay time constant versus the energy. The present result is shown by open circle, filled circle and open triangle signs. The results in Ref. [12] are open and filled squares.
We evaluate three parameters, $\tau_0$ (the mean value of the exponent), $N_0$ (the number of events) and $w$ (a width parameter), in each bin by the least-squares method. Fig. 4 shows the evaluated mean decay time constants $\tau_0$ as a function of energy. There are marked differences of the decay time between electron and nuclear recoil events.

The results in Ref. [12] are also shown in Fig. 4. In their results, the differences are not seen. Moreover, the decay constants rise rapidly with energy from $\sim 660 \text{ ns}$ to $\sim 850 \text{ ns}$. In the present work, a similar dependence exists in the low energy region, but it is weak.

Strictly speaking, because the pulse shape is not a single exponential curve, but the sum of a few exponential curves, the value of the decay time constant is dependent on the way of the analysis. So, the values of different measurements cannot be compared directly. However, these properties, the difference between the nuclear recoil and the electron recoil and the relation between the decay constant and the recoil energy, are independent of the way of the analysis.

4. Conclusion

We developed a new method to evaluate the decay time constant of scintillation and applied it to the CaF$_2$(Eu) scintillator. We found the difference in the scintillation decay constants between electron and nuclear recoil events (Fig. 4). We also concluded that the decay time constant of CaF$_2$(Eu) is constant in the recoil energy region above 20 keVee.

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