Test of CsI(Tℓ) crystals for the Dark Matter Search

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Abstract

Searches for weakly interacting massive particles (WIMP) can be based on the detection of nuclear recoil energy in CsI(Tℓ) crystals. We demonstrate that low energy gamma rays down to few keV is detected with CsI(Tℓ) crystal detector. A clear peak at 6 keV is observed using X-ray source. Good energy resolution and linearity have been achieved down to X-ray region. In addition, we also show that alpha particles and gamma rays can be clearly separated using the different time characteristics of the crystal.

Key words: Dark Matter, CsI(Tℓ), PSD, Linearity, Resolution

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Several evidences from a variety of sources indicate that the universe contains a large amount of dark matter [1]. The most strong evidence for the existence of dark matter comes from the galactic dynamics. There is simply not enough luminous matter observed in spiral galaxies to account for the observed rotational curves [2]. Among several dark matter candidates, one of the most prominent candidate is the weakly-interacting massive particles (WIMP). The leading WIMP candidate is perhaps the neutralino, the lightest supersymmetric particles such as photinos, Higgsinos and Z-inos [3]. These particles typically have masses between 10 GeV and a few TeV and couple to ordinary matter only with weak interactions. The elastic scattering of WIMP with target nuclei could be detected by measuring the recoil energy of the nucleus, which is up to several tens of keV [4]. Recently, a great deal of attention has been drawn to crystal detectors since the detection technique is already developed and radioactive background from the crystal is under control. Especially, the most stringent limit for the direct detection of WIMP has been established using the NaI(Tl) crystal detector [5]. They achieved as low threshold as 6 keV and relatively good separation between the recoiling events and the ionizing events by background $\gamma$'s using the difference of the scintillation decay time.

Recently, positive signal of annual modulation has been reported by DAMA group [6]. Looking at the similar sensitivity region with other experiments which involves different systematics is absolutely necessary to confirm their results. It has been noted by several authors that CsI(Tℓ) crystal may give better performance for the separation between recoiling events and the ionizing events by background $\gamma$ [7]. Although the light yield of CsI(Tℓ) crystal is slightly lower than NaI(Tl) crystal, better particle separation can be more advantageous for WIMP search. Also CsI(Tℓ) has much less hygroscopicity than NaI(Tl), and has higher density (see Table I). The spin-independent cross section of WIMP is larger for CsI(Tℓ) than NaI(Tl) because CsI(Tℓ) has a compound with two similar heavy mass nuclei while spin-dependent cross section will be comparable. Moreover hundreds of tons of CsI(Tℓ) crystals are already being used for several detectors in high energy experiment [8]. Thus fabricating large amount of crystals is quite feasible. In this report, we have studied the characteristics of CsI(Tℓ) crystal for the possibility of dark matter search experiment [9].

2 Experimental Setup

We prepared a 3cm×3cm×3cm CsI(Tℓ) crystal with all surfaces polished. Photo-multiplier tubes of 2 inch diameter (Hamamatsu H1161) are directly at-
attached on two opposite end surfaces. The cathode planes of PMT cover all the area of the crystal surfaces attached. The other sides are wrapped with 1.5 $\mu$m thick aluminized foil window or Teflon tapes followed by black tapes. It is necessary to use only very thin foil for the side where X-ray sources are attached that low energy X-rays are not blocked. For the alpha source, additional aluminum foil is located between the aluminized foil and the source to reduce the $\alpha$ energy. Signals from both PMTs are then amplified using a home-made AMP($\times 8$) with low noise and high slew rate. Another signals are amplified with ORTEC AMP($\times 200$) to make the trigger logic. Discriminator thresholds are set at the level of single photoelectron signal. By using LED, we confirmed that the single photoelectron signal is well above the electronic noise. In order to suppress the accidental triggers from dark currents, we delay the signal by 100 ns and then formed a self coincidence for each PMT signal, which require that at least two photoelectrons occur within 200 ns. Then coincidence of both PMT signals are made for the final trigger decision. In this way the trigger caused by the accidental noises are suppressed by a great amount. With this condition the effective threshold is four photoelectrons, which roughly corresponds to 40 photons produced. Using the widely accepted light yield of CsI(T$_\ell$), $\sim$50,000 photons/MeV, our threshold can be interpreted as 2 keV. The crystal and PMTs are located inside the of 5 cm thick lead blocks in order to stop the environmental background. A digital oscilloscope is used for the data taking with GPIB interface to a PC with LINUX system. We developed DAQ system with GPIB and CAMAC interface based on the ROOT package [10] and entire analysis was performed with the ROOT package too. The schematics of the experimental setup and the trigger elements are shown in Figure 1 a) and b). The digital oscilloscope we used for our experiment samples the signal at 1 Gs/sec with 8 bit pulse height information and two channels are read out simultaneously. Full pulse shape informations are saved for the further analysis.

3 Calibration

We have performed measurements of X-rays, $\gamma$-rays, and alpha particles using various radioactive sources with the setup described in the previous section. The energy spectra of X-rays and $\gamma$ rays from the $^{57}$Co source is given in Fig. 2. The highest peak is from the gamma ray of 122 keV. Shown in left side of broad distribution of pulses are the Compton edge. The energy resolution at 122 keV is about 7%. Also, the X-ray peak at 6.4 and 14.4 keV are clearly seen with energy resolution of 30 and 20%, respectively. This resolution is not much worse than that of NaI(Tl) crystal [5]. Many calibration sources such as $^{57}$Co, $^{109}$Cd, $^{137}$Cs, $^{54}$Mn and $^{60}$Co are used for the determination of linearity and resolution. Fig. 3 shows the energy resolution of CsI(T$_\ell$) crystal with PMT on
The best fit of the resolution with following the parameterization is

\[
\frac{\sigma}{E(\text{MeV})} = \frac{0.03}{\sqrt{E(\text{MeV})}} \oplus 0.01, \quad (1)
\]

and it becomes

\[
\frac{\sigma}{E(\text{MeV})} = \frac{0.02}{\sqrt{E(\text{MeV})}} \oplus 0.01 \quad (2)
\]

, when we add PMT signals from both sides.

The pulse shape is quite linear at high energy as shown in Fig. 4 but there is some deviation at low energy as shown in Fig. 5. The pulse height of the 662 keV γ-ray line from $^{137}\text{Cs}$ is defined as unity for the linearity plot. It turns out that the variation in the response function near the L-, K-shell of Cs and I causes nonlinearity at X-ray region within 30% [11]. This is because photoelectrons ejected by incident gamma rays just above the K-shell energy have very little kinetic energy so that the response drops. Just below this energy, however, K-shell ionization is not possible and L-shell ionization takes place. Since the binding energy is lower, the photoelectrons ejected at this point are more energetic which causes a rise in the response. The pulse shape is linear within 10% up to low energy X-ray region if these effects are corrected.

4 Pulse Shape Analysis

In many scintillating crystals, electrons and holes produced by ionization are captured to form certain meta-stable states and produce slow timing component. On the other hand, a larger stopping power from recoiling nucleus produces a higher density of free electrons and holes which favors their recombination into loosely bound systems and results in fast timing component. By using this characteristic, we may be able to separate X-ray backgrounds from the high ionization loss produced by WIMP. To demonstrate this difference, we measured signals produced by alpha particles using $^{241}\text{Am}$ source. Kinetic energy of the alpha particle is 5.5 MeV and the incident energy was controlled by the thickness of thin aluminum foil in front of the crystal. Although alpha particle at this energy stops in the crystal, the visible energy seen by the PMT is about 75% of the energy. This is due to the quenching factor for alpha particles and agrees with what were observed by the other experiments [12]. We show the two dimensional histogram of mean time vs. integrated charge
in Fig. 6. The mean time is the pulse height weighted time average, defined as

\[ < t > = \frac{\sum t_i \times q_i}{\sum q_i}, \]  

(3)

where \( q_i \) is the amplitude of the pulse at the channel time \( t_i \) up to 4 \( \mu \)s. It is practically the same as the decay time of the crystal. Two clear bands in the Fig. 6 indicate that we can make good separation between the alpha particle and X-ray. The low energy of X-ray from the \(^{241}\)Am source is 60 keV. In Fig. 7, we projected signals near 60 keV region to the mean time axis and it shows that the decay time for alpha particles is \( \sim 700 \) ns while for X-rays \( \sim 1100 \) ns. Two peaks are well separated by more than 3 sigma in this energy region.

5 Conclusion

We demonstrated that CsI(Tl) crystal can be used to measure low energy gamma rays down to few keV. Linearity within 10% and good energy resolution have been obtained down to 6 keV X-ray region. In addition, a good separation of alpha particles from gamma rays has been achieved by using mean time difference. If recoiled ions in the crystal behave similar to alpha particles, the mean time difference would be very useful to differentiate WIMP signals from backgrounds. The background study and neutron response on CsI(Tl) study are underway. If this study is successful, a pilot experiment with a large amount crystals will be launched in near future.

Acknowledgements

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References


Table 1
Comparison of CsI(Tℓ) and NaI(Tl) characteristics.

<table>
<thead>
<tr>
<th>Property</th>
<th>CsI(Tℓ)</th>
<th>NaI(Tl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density(g/cm³)</td>
<td>4.53</td>
<td>3.67</td>
</tr>
<tr>
<td>Decay constant(ns)</td>
<td>~1000</td>
<td>~250</td>
</tr>
<tr>
<td>Peak emission(nm)</td>
<td>550</td>
<td>415</td>
</tr>
<tr>
<td>Light yield(relative)</td>
<td>85</td>
<td>100</td>
</tr>
<tr>
<td>Hygroscopicity</td>
<td>slight</td>
<td>strong</td>
</tr>
</tbody>
</table>
Fig. 1. (a) Schematic drawing of the experimental setup and (b) the trigger logic.
Fig. 2. Pulse height spectrum of CsI(Tℓ) for $^{57}$Co source. The left top plot is zoomed pulse height spectrum of the low energy X-ray.
Fig. 3. The energy resolution of CsI(Tℓ) with one-side PMT. The solid curve shows the best fit to data.
Fig. 4. Linearity distribution of CsI(Tl) crystal with several different photon sources. The solid line shows the linear fit to data.
Fig. 5. Response of CsI(Tl) crystal relative to the pulse height of 662 keV gamma ray line from $^{137}$Cs. The filled circles are our data and the open circle with solid lines are the scanned data of 1/8 inch crystal taken from Ref. [11].
Fig. 6. Energy vs. mean time distribution of CsI(Tl) crystal with $^{241}$Am and $\gamma$ sources.
Fig. 7. Distribution of the decay time, $<t>$, of the CsI(Tl) crystal with $^{241}$Am sources when signals near 60 keV are projected. The solid curve shows double Gaussian fit. The dashed Gaussian curve is the decay time of the alpha particle and dotted-dash curve is the decay time of the gamma with the sample pulse height normalized as the alpha’s.