Nuclear Instruments and Methods in Physics Research A 457 (2001) 471–475

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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# Test of CsI (Tℓ) crystals for the dark matter search

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Received 24 November 1999; received in revised form 16 June 2000; accepted 6 July 2000

## 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 a few keV are detected with CsI(Tℓ) crystal detector. A clear peak at 6 keV is observed using an X-ray source. Good energy resolution and linearity have been achieved down to the 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. © 2001 Elsevier Science B.V. All rights reserved.

*PACS:* 95.35. + d; 29.40.Mc

*Keywords:* Dark matter; CsI(Tℓ); PSD; Linearity; Resolution

## 1. Introduction

Several evidence from a variety of sources indicates that the universe contains a large amount of dark matter [1]. The strongest evidence for the existence of dark matter comes from the studies of 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 is weakly interacting massive particles (WIMP). The leading candidates for WIMPs include the neutralino, the lightest super-symmetric particles such as photinos, Higgsinos, and Z-inos [3,4]. 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 by target nuclei could be detected by measuring the recoil energy of the nucleus, which is up to several tens of keV [5]. Recently, a great deal of attention has been drawn to crystal detectors since the detection technique is already developed and the radioactive background from the crystal is under control. In particular, the most stringent limit for the direct detection of

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PII: S0168-9002(00)00796-8

WIMP has been established using the NaI(T1) crystal detector [6,7]. A threshold as low as 6 keV and relatively good separation between the recoiling events and the ionizing events by background γ's using the difference of the scintillation decay time have been achieved.

Recently, a positive signal of annual modulation has been reported by the DAMA group [8,9]. Looking at similar sensitivity regions employed in other experiments involving different systematics is absolutely necessary to confirm their results. It has been noted by several authors that the CsI(Tℓ) crystal may give better performance for the separation between recoiling events and ionizing events by background γ [10]. Although, the light yield of CsI(Tℓ) crystal is slightly lower than that of NaI(T1) crystal, better particle separation can be more advantageous for WIMP search. Also CsI(Tℓ) has much less hygroscopicity than NaI(T1), and has a higher density (see Table 1). The spin independent cross-section of WIMP is larger for CsI(Tℓ) than NaI(T1) because CsI(Tℓ) is a compound with two similar heavy mass nuclei, while the 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 [11,12]. Thus, fabricating large amounts of crystals is quite feasible. In this report, we have studied the characteristics of CsI(Tℓ) crystal for the possible use in dark matter search experiments [13,14].

## 2. Experimental setup

We prepared a 3 cm × 3 cm × 3 cm CsI(Tℓ) crystal with all surfaces polished. Photo-multiplier tubes of 2 in diameter (Hamamtsu H1161) are directly 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 μm 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 so 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 α energy. Signals from both PMTs are then amplified using a home-made AMP( × 8) with low-noise and high-slew rate. Other signals are amplified by the ORTEC AMP ( × 200) to generate the trigger logic. Discriminator thresholds are set at the level of a 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 form a self coincidence for each PMT signal, which require that at least two photoelectrons occur within 200 ns. Then the coincidence of both PMT signals is used for the final trigger decision. In this way, the triggers caused by accidental noise are strongly suppressed. With this condition, the effective threshold is four photoelectrons, which roughly corresponds to 40 photons produced. Using the widely accepted light yield of CsI(Tℓ), ~ 50,000 photons/MeV, our threshold can be interpreted as 2 keV. The crystal and PMTs are located inside the 5 cm thick lead blocks in order to stop the environmental background. A digital oscilloscope is used for the data taking with a GPIB interface to a PC with a LINUX operating system. We developed a DAQ system with GPIB and CAMAC interface based on the ROOT package [15] and the entire analysis was performed with the ROOT package too. The schematics of the experimental setup and the trigger elements are shown in Fig. 1(a) and (b). Testing was performed at room temperature (20°C). The digital oscilloscope we used for our experiment samples the signal at 1 Gs/s with 8 bit pulse height information and two channels are read out simultaneously. Full pulse shape informations are saved for further analysis.

Table 1
Comparison of CsI(Tℓ) and NaI(T1) characteristics

| Property | CsI(Tℓ) | NaI(Tℓ) |
|---|---|---|
| Density ($g/cm^3$) | 4.53 | 3.67 |
| Decay constant (ns) | ~ 1000 | ~ 250 |
| Peak emission (nm) | 550 | 415 |
| Light yield (relative) | 85 | 100 |
| Hygroscopicity | Slight | Strong |

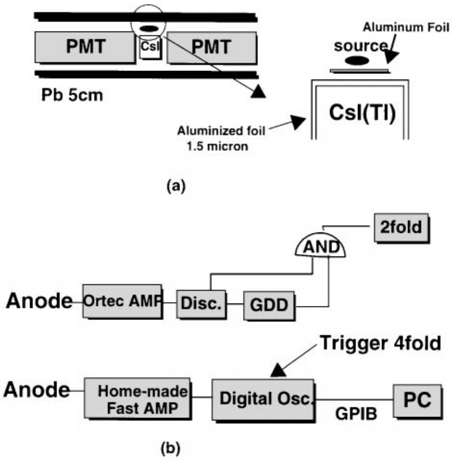


Fig. 1. (a) Schematic drawing of the experimental setup and (b) the trigger logic.

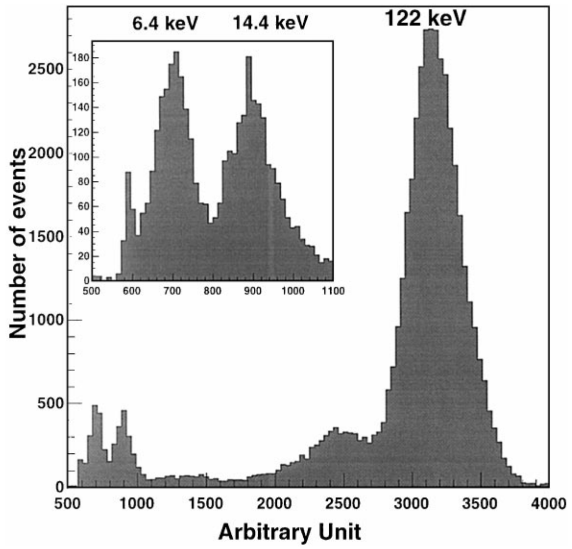


Fig. 2. Pulse height spectrum of CsI(T$\ell$) for $^{57}$Co source. The top left plot is a zoomed pulse height spectrum of the low energy X-ray.

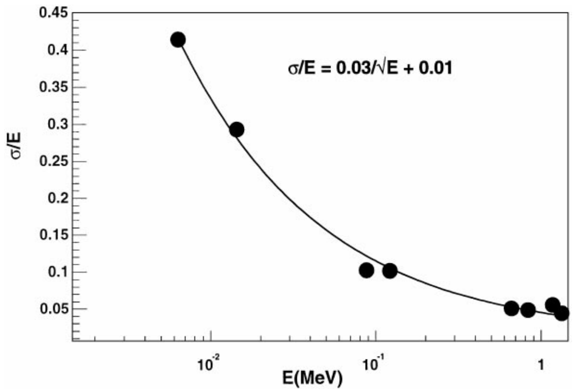


Fig. 3. The energy resolution of CsI(T$\ell$) with one-side PMT. The solid curve shows the best fit to data.

## 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 gamma rays of 122 keV. Shown to the left of the broad distribution of pulses are the Compton edge. The energy resolution at 122 keV is about 7%. Also, the X-ray peaks at 6.4 and 14.4 keV are clearly seen with an energy resolution of 30% and 20%, respectively. This resolution is not much worse than that of NaI(Tl) crystal [6,7]. Numerous calibration sources such as $^{57}$Co, $^{107}$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 each side. The best fit of the resolution by following the parameterization is

$$\frac{\sigma}{\mathrm{E\,(MeV)}} = \frac{0.03}{\sqrt{\mathrm{E\,(MeV)}}} + 0.01 \tag{1}$$

and it becomes

$$\frac{\sigma}{\mathrm{E\,(MeV)}} = \frac{0.02}{\sqrt{\mathrm{E\,(MeV)}}} + 0.01 \tag{2}$$

when we add PMT signals from both sides.

The pulse height 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 $\gamma$-ray line from $^{137}$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 in the X-ray region within 30% [16]. This is because photoelectrons ejected by incident $\gamma$-rays just above the K-shell

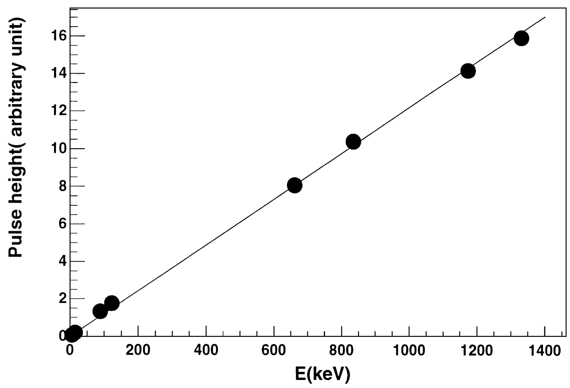


Fig. 4. Linearity distribution of CsI(Tℓ) crystal with several different photon sources. The solid line shows the linear fit to data.

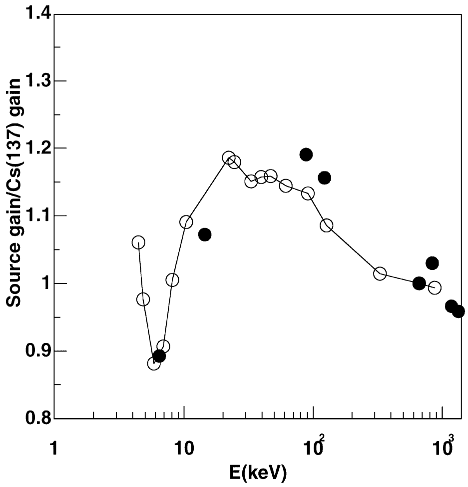


Fig. 5. Response of CsI(Tℓ) crystal relative to the pulse height of 662 keV $\gamma$-ray line from $^{137}$Cs. The filled circles are our data and the open circle with solid lines are the scanned data of 1/8 in crystal taken from Ref. [11].

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 height is linear within 10% up to the 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 a slow timing component. On the other hand, a larger stopping power from the recoiling nucleus produces a higher density of free electrons and holes which favors their recombination into loosely bound systems and resulting in a 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 a $^{241}$Am source. Kinetic energy of the alpha particles is 5.5 MeV and the incident energy was controlled by the thickness of thin aluminum foil in front of the crystal. Although alpha particles at this energy stop 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 has been observed in the other experiments [17,18]. 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

$$\langle t \rangle = \frac{\sum t_i \times q_i}{\sum q_i} \tag{3}$$

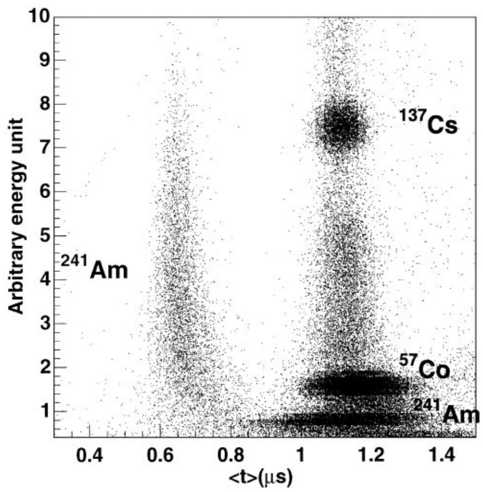


Fig. 6. Energy vs. mean time distribution of CsI(Tℓ) crystal with $^{241}$Am and $\gamma$ sources.

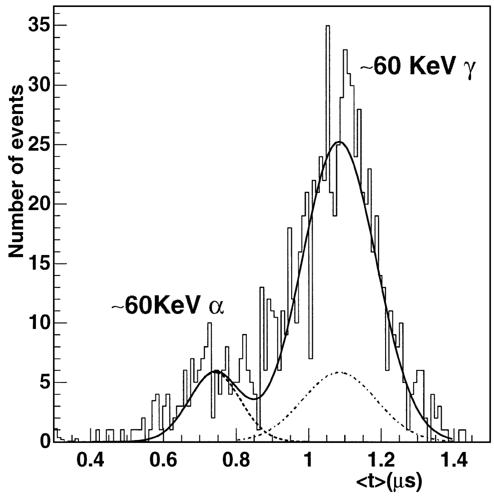


Fig. 7. Distribution of the decay time $\langle t \rangle$, of the CsI(T$\ell$) crystal with $^{241}$Am sources when signals near 60 keV are projected. The solid curve shows a double Gaussian fit. The dashed Gaussian curve is the decay time of the alpha particle and dotted-dash curve is the decay time of the gamma with the sample pulse height normalized to the alpha's.

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

## 5. Conclusion

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

## Acknowledgements

This work is supported by the Korean Ministry of Education under grant number BSRI 1998-015-D00078. Y.D. Kim wishes to acknowledge the financial support of the Korean Research Foundation made in the program year of 1998.

## References

[1] G.G. Raffelt, hep-ph/9712538, December 1997.
[2] K.G. Begeman, A.H. Broeils, R.H. Sanders, Mon. Not. R. Astron. Soc. 249 (1991) 523.
[3] H.P. Nilles, Phys. Rep. 110 (1984) 1.
[4] H.E. Haber, G.L. Kane, Phys. Rep. 117 (1985) 75.
[5] M.W. Goodman, E. Witten, Phys. Rev. D 31 (1985) 3059.
[6] P.F. Smith et al., Phys. Lett. B 379 (1996) 299.
[7] R. Bernabei et al., Phys. Lett. B 389 (1996) 757.
[8] R. Bernabei et al., Phys. Lett. B 424 (1998) 195.
[9] R. Bernabei et al., Phys. Lett. B 450 (1999) 448.
[10] J.B. Birks, Theory and Practice of Scintillation Counter, Pergamon Press, Oxford, 1964.
[11] E. Blucher et al. (CLEO), Nucl. Instr. and Meth. A 235 (1985) 319.
[12] M.T. Cheng et al., (BELLE), Technical Design Report, KEK Report 95-1, 1995.
[13] H.J. Kim et al., Proceeding of the 29th International Conference on High Energy Physics, Vancouver, 1998.
[14] E. Won et al., Nucl. Phys. B Proceedings Supplements, (1998), Submitted for publication.
[15] R. Brun, F. Rademakers, ROOT – An Object Oriented Data Analysis Framework, Proceedings AIHENP'96 Workshop, Lausanne, September 1996, Nucl. Instr. and Meth. A 389 (1997).
[16] D. Aitken, B.L. Leron, G. Yenicay, H.R. Zulliger, Trans. Nucl. Sci. NS-14 (2) (1967) 468.
[17] Y.K. Akimov, Phys. Part. Nucl. 25 (1994) 92.
[18] W.R. Leo, Techniques for Nuclear and Particle Physics Experiments, Springer, Berlin, 1993.