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The Proton Energy Response of a LYSO Crystal

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We measured the energy response of a LYSO ($Lu_{2(1-x)}Y_{2x}SiO_5$) crystal by using a proton beam. The LYSO crystal has good performances, such as a fast decay time, a high light output and radiation hardness and it is widely used for nuclear physics and medical imaging. The experiment was carried out in the MC-50 cyclotron at the Korea Institute of Radiological and Medical Sciences (KIRAMS) by using 35 and 45 MeV proton beams. Different thicknesses of Al degraders were used with the 35 and the 45 MeV proton incident energies to measure the light output response function of the LYSO crystal. The results were calibrated with a ^{137}Cs γ-ray source for the different energy response of the LYSO and were compared with the proton energy calibrated by using the SRIM code, which is a well-known stopping-range calculation code. This is the first time for measuring the response function of the LYSO crystal with a proton beam.

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I. INTRODUCTION

The BGO ($Bi_4Ge_3O_{12}$) crystal is a good scintillator for proton energy monitoring. It has high-Z materials, such as bismuth and high density. For these reasons, BGO has high stopping power. However it has a crucial defect, low light yield. The LYSO crystal has many advantages over the BGO crystal. It has a higher light output, a faster decay time and stronger radiation hardness. While the HPGe or the Si(Li) detector has better energy resolution than scintillators, they have lower stopping power and longer shaping time and are weaker against radiation. Also, an indirect method is available for measuring the proton energy [1]. Table 1 compares the scintillator properties of the LYSO crystal with those of other high-Z scintillation crystals [2].

$$\frac{dL}{dx} = \frac{A\frac{dE}{dx}}{1 + kB\frac{dE}{dx}} \quad : \text{Birk's formula}$$

The response light output per unit length, dL/dx, related to the specific ionization by Birk's formula. A is the absolute scintillation efficiency and kB is a parameter relating the density of ionization centers to dE/dx [3]. The experimental information is usually presented as an energy versus light output response plot on arbitrary channels, with both scales expressed in non-calibrated values (ADC channels). The energy calibration of the light output can be made in a fairly simple way in the scintillator by using the monochromatic energy of a radioactive γ-ray source or by measuring the energy deposited in the semiconductor detector by some specific mono-energetic

Table 1. Scintillators properties of scintillation crystals.

	LYSO	GSO	BGO
Decay time (ns)	53	60	300
Light output (PMT)	75	20	15
Peak emission (nm)	420	430	480
Density (g/cm^3)	5.37	6.71	7.13
Effective Z	54	58	73

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Fig. 1. The LYSO crystal detector system on the beam line.

ions. The pulse height (or light output) exhibits, for all types of scintillators, a dependence on energy E, charge Z and atomic mass number A of the registered particle. Therefore, the validity of the spectroscopic information depends strongly on the precision of the calibration of the response function L(Z, A, E). Many different empirical and semi-empirical response functions have been proposed, in particular, for CsI(Tl) crystals [4]. Also, the response function of the GSO crystal for proton has been measured [5].

No response function for charged particle for the LYSO crystal has been published yet. We present the response function of the LYSO crystal, which were obtained by using a radioactive γ-ray source and a proton beam. Proton beams with energies of the 35 and the 45 MeV were used for the measurements of the light output and the energy resolution of the LYSO scintillator. We measured the light responses of the LYSO crystal for various energies by Al using degraders with different thicknesses.

II. EXPERIMENTS

1. MC-50 Cyclotron of KIRAMS

The 50 MeV proton-beam test facility at the MC-50 cyclotron of KIRAMS (Korea Institute of Radiological & Medical Science) was established by the PEFP (Proton Beam Engineering Frontier Project) of KAERI (Korea Atomic Energy Research Institute) [1]. This beam line has been used for the pilot studies of the PEFP, especially, for studies using low flux proton beams, $10^4 \sim 10^{10}$ proton/sec.

We had the 35 MeV and the 45 MeV proton beams to test various detector systems. The 35 MeV incoming proton beam passed through a 0.2-cm-thick aluminum window capping the beam pipe and lost energy down to 27.5 MeV. Then, the 27.5 MeV proton beam was collimated to a 1-mm-diameter beam spot by using an 1-mm aluminum collimator. Finally, the proton energy became 25.2 MeV after passing through 114.5 cm of air to reach the LYSO crystal. The 45 MeV proton beam became 37.5 MeV for same reason. Both energies were simulated with the SRIM code [5]. Figure 1 shows the LYSO crystal detector system on the proton beam line.

2. DAQ System Setup

The LYSO crystal scintillatior ($7 \times 7 \times 30$ mm^3) was used for the proton energy measurements. The LYSO crystal was wrapped with Teflon, followed by Al foil. A metal package E5780 PMT of 8 mm in diameter (Hamamatsu Co.) was attached to the long side of the LYSO crystal. A high voltage of –600 V was applied to the PMT. A 25-MHz USB2-based flash analog-to-digital converter (FADC) board was used to digitize the analog signal. The analog signal from the PMT was fed to an ORTEC 570 shaping amplifier. Since the decay time of the LYSO is as short as 50 ns, a shaping time of 0.5 μs was used for the test. This amplified signal was fed to the 25-MHz FADC. A software threshold setting was applied to trigger an event by using a self-trigger algorithm on the field programmable gate array (FPGA) chip of the FADC board. The FADC output was recorded into a personal computer by using a USB2 connection and the recorded data were analyzed with a C++ data analysis program [6]. Also, a 4-channel digital oscilloscope (LeCroy Waverunner 6100A) was used for the pulse-shape monitoring during the data taking. Figure 2 shows a schematic of the experimental setup for measuring the energy response of the LYSO to a proton beam.

III. RESULTS

1. Light Responses of the LYSO crystal Scintillators

For the electron-equivalent energy calibration, a ^{137}Cs γ-ray source with a 661 keV energy was used. We observed a clear full peak with an energy resolution of 29.7 % FWHM for the 661 keV γ energy. The full energy peak determination had a ±2.0 % uncertainty base on a Gaussian fit. The calibration constant was determined to be 0.172 ± 0.003 channel/keV, where the error was determined by using the uncertainty of fitting. Figure 3 shows the energy response of LYSO for a ^{137}Cs γ-ray source, which was measured the coarse gain with 1000 on 570 ORTEC amplifier. The pedestal was measured to be 30 channel with random trigger logic.

The proton beam energy responses of the LYSO crystal were measured with 25.2 MeV and 37.5 MeV proton beams. We set the gain conditions of the 570 ORTEC amplifier with the 25.2 MeV energy of proton beam such

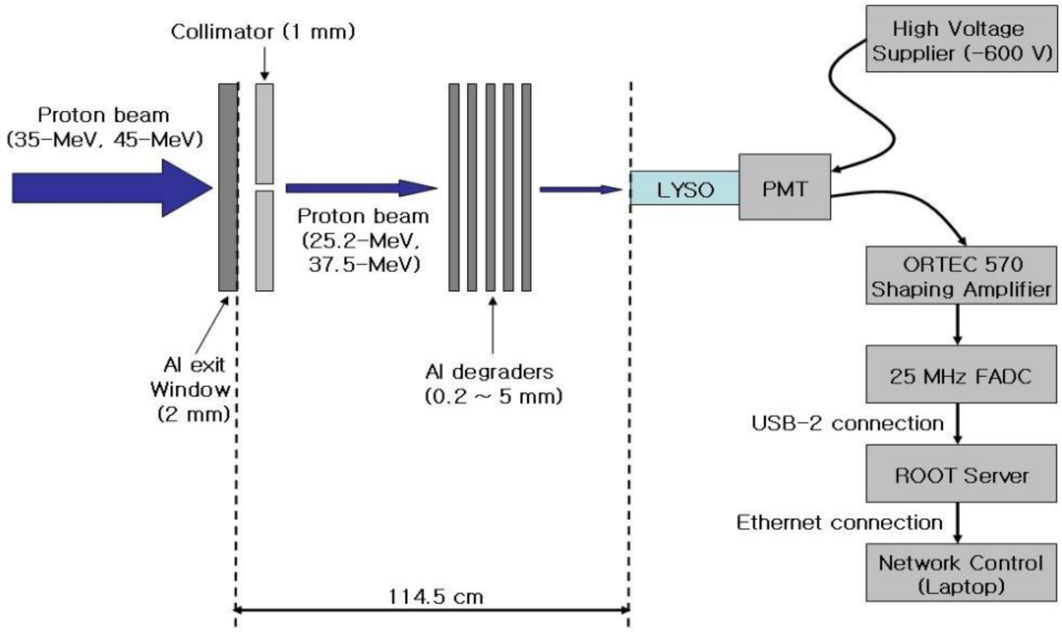

Fig. 2. Schematic of the experimental setup for measuring the energy response of the LYSO with a proton beam.

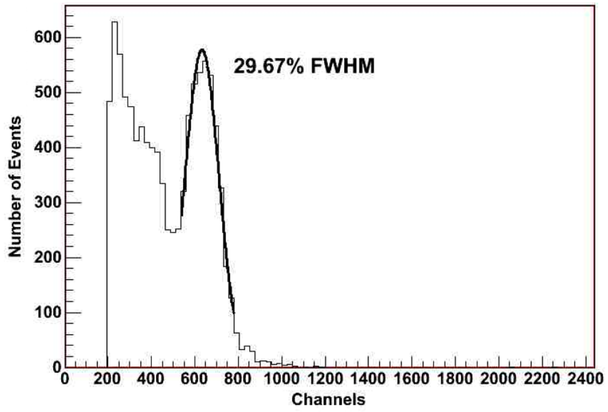

Fig. 3. Pulse height spectrum of LYSO with ^{137}Cs γ-rays.

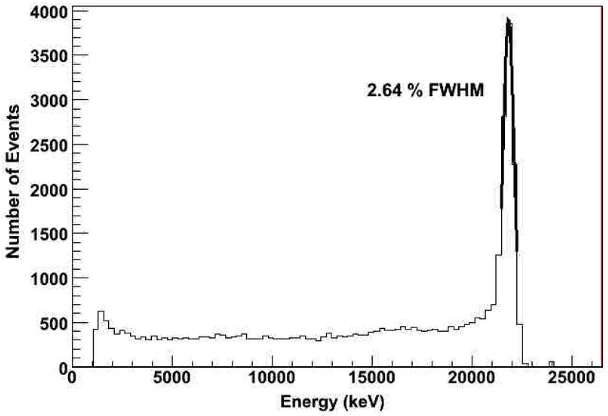

Fig. 4. Pulse height spectrum of the LYSO crystal with the 37.5 MeV proton beam.

that the fine gain (FG) was 0.75 and the coarse gain (CG) was 200, these gain conditions were used to measure the light responses of the LYSO crystal. The shaping time of the amplifier was set to 0.5 μs for the LYSO. The FWHM energy resolution was 6.34 % after Gaussian fitting. The energy response of the LYSO crystal was measured to be 13.5 ± 0.3 MeV electron-equivalent energy for the 25.2 MeV proton beam, which was calibrated with the 661-keV γ-ray from a ^{137}Cs source. Then, we used the 37.5 MeV proton beam to measure a higher energy response of the LYSO crystal. We changed the gain conditions on the 570 ORTEC amplifier so that the FG was set to be 0.9 and the CG was 100. Figure 4 shows a pulse height spectrum of the LYSO crystal for the 37.5 MeV proton beam. The FWHM energy resolution was 2.64 % after Gaussian fitting and the response energy of the LYSO crystal for the 37.5 MeV proton beam was 21.8 ± 0.4 MeV electron-equivalent energy, which was calibrated by using a ^{137}Cs γ-ray source. The error corresponds to the uncertainty in the gain calibration with the ^{137}Cs γ-ray source.

2. Light Responses of a LYSO Crystal with Degraders

We used Al degraders of different thicknesses to reduce the initial proton energy. Energy degraders were located in front of the LYSO crystal to measure the energy response of the LYSO scintillator. As shown in Figure 5, the pulse height decreased as the thickness of the energy

Table 2. Energy responses of the LYSO crystal with different degraders.

Proton with degrader	s Proton E (MeV)	Response E (MeV)	Peak Channels
37.5 MeV, Al 2.0 mm	30.1	16.8	2900
37.5 MeV, Al 3.0 mm	26.0	13.8	2376
25.2 MeV, Al 0.0 mm	25.0	13.5	2322
25.2 MeV, Al 0.2 mm	24.2	12.9	2231
25.2 MeV, Al 0.5 mm	22.7	11.9	2045
37.5 MeV, Al 4.0 mm	21.3	10.2	1757
25.2 MeV, Al 1.0 mm	20.0	9.8	1680
25.2 MeV, Al 1.5 mm	17.2	7.5	1284
37.5 MeV, Al 5.0 mm	15.9	5.5	941
25.2 MeV, Al 2.0 mm	13.8	4.5	771

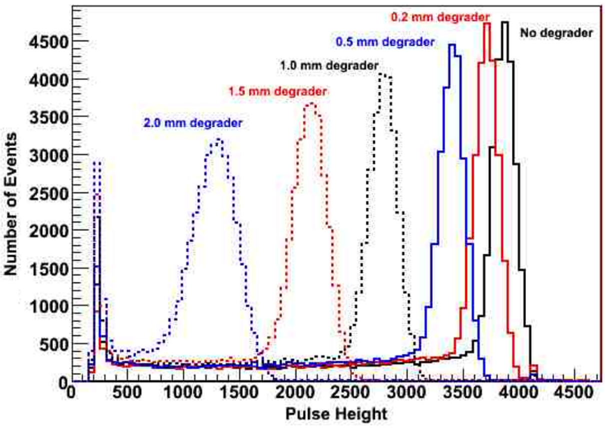

Fig. 5. Pulse height spectrum of the LYSO crystal with different degraders, as obtained by using a 25.2 MeV proton beam.

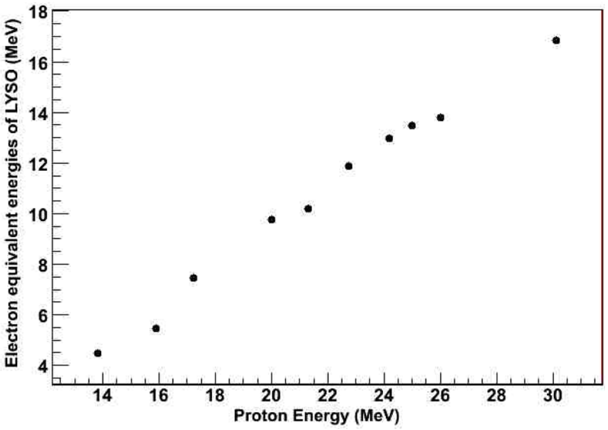

Fig. 6. Electron-equivalent energy versus proton energy of the LYSO crystal.

degrader increased. Degraders of 0.2, 0.5, 1.5, 1.0 and 2.0 mm in thickness were used for the 25.2 MeV proton beams and degraders of 1.0, 2.0, 3.0, 4.0 and 5.0 mm in thickness were used for the 37.5 MeV proton beam. The mean values of the energy response of the LYSO crystal for different thicknesses of the degraders were obtained with Gaussian fittings. Table 2 shows the detail results for the pulse heights of the 25.2 MeV and the 37.5 MeV data. The proton energies with different degraders were calculated using a well-known stopping-range calculation code (SRIM) [7].

These results were calibrated with a 661 keV γ-ray source (^{137}Cs) for calculating the response energy of the LYSO crystal. The high ionizing power of charged particles causes the thermal fraction to be larger than the luminescence fraction, where called quenching effect. Thus, a smaller fraction of the kinetic energy of proton is converted into fluorescent light in the scintillator, as explained by Birk's law. Figure 6 shows the proton energy versus the electron-equivalent energy of the LYSO crystal. For example, when the 28-MeV proton beam is incident on the LYSO crystal, the electron-equivalent energy will be 15.5 MeV.

IV. CONCLUSION

This is the first time for the response energy of the LYSO crystal to be measured with the 35 and the 45 MeV proton beams from the MC-50 cyclotron at the Korea Institute of Radiological and Medical Sciences, a 661-keV γ-ray (^{137}Cs) was used for electron-equivalent energy calculation. The best energy resolution of 2.64 % FWHM with a 37.5 MeV proton energy was obtained with the LYSO crystal. Moreover, we could measure the energy response function of the LYSO scintillator in the proton energy range from 13.8 MeV to 30.1 MeV. The results can be used for proton energy determination with a LYSO crystal in the energy range of 14 MeV to 30 MeV.

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