Light Output Response of LYSO(Ce) Crystal to Relativistic Helium and Carbon Ions

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Abstract– **The light output response of LYSO(Ce) crystals was investigated using helium and carbon beams of 720 MeV and 3.48 GeV, respectively. Experimental results showed good agreement with the calculated curves by the Birks equation but the values of the parameters in the equation were different between helium and carbon ions.**

I. Introduction

The medical application of relativistic heavy ions is significantly growing in the field of radiotherapy. A lot of treatments have already been carried out, especially for deep-seated tumors. For highly accurate treatments, a precise simulation of the interactions between incident heavy ions and nuclei in a human body is important, therefore experimental nuclear reaction data on such interactions are urgently needed. In the measurement of nuclear reaction data, an inorganic crystal is often used as a charged particle spectrometer due to its high stopping power. Recently, celium doped lutenium-yttrium oxyorthosilicate [$Lu_{1.8}Y_{0.2}SiO_5$(Ce); LYSO(Ce)] has been developed and is expected as one of the promising scintillation materials used in future nuclear data measurements, because it has excellent characteristics such as high scintillation efficiency, high stopping power, non-hygroscopicity and fast decay time. In order to apply LYSO(Ce) for nuclear data measurements using heavy ions, the light output response to heavy ions needs to be investigated. However, the existing experimental data are very limited and confined to gamma ray measurements for applications in the medical industry such as PET detectors [1].

In this report, the light output response of a LYSO(Ce) crystal to helium and carbon ions of energies up to 720 MeV and 3.34 GeV is reported, respectively.

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II. LYSO(Ce) Crystal Properties

In high energy experiments, various scintillators have been developed strenuously with the increase of energy and beam intensity of accelerators. Table I shows the basic characteristics of representative scintillators used in high energy experiments. The performance requested for these scintillators is heavier, faster and more tolerant to radiation damage. LYSO(Ce) is one of the scintillators which have been developed for these requests.

A. Basic Characteristics

The effective atomic number of LYSO(Ce) is 66 and density is 7.1 g/cm^3 and these values are big compared to other crystals. The light output of LYSO(Ce) is higher than GSO(Ce) or BGO and it is twice as high as that of GSO(Ce). Decay time is 45 ns, so LYSO(Ce) is well-suited for high counting rate experiments. Emission length is 420 nm, so we can use a photomultiplier tube with bialkali photoelectron surface.

However, LYSO(Ce) contains a radioisotope ^{176}Lu as its component and it disintegrates into ^{176}Hf. Fig. 1 shows the decay scheme of ^{176}Lu. In the disintegration of ^{176}Lu, one beta ray and three gamma rays are emitted.

TABLE I
BASIC CHARACTERISTICS OF REPRESENTATIVE INORGANIC SCINTILLATORS IN HIGH ENERGY EXPERIMENTS

Scintillator	LYSO(Ce)	GSO(Ce)	BGO	NaI(Tl)	CsI(Tl)
Composition	$Lu_{1.8}Y_{0.2}SiO_5$	Gd_2SiO_5	$Bi_4Ge_3O_{12}$	NaI:Tl	CsI:Tl
Effective Z	66	59	74	51	54
Density [g/cm^3]	7.1	6.71	7.13	3.67	4.51
Light output (relative) fast/slow	40	18/2	7	100	145
Decay time [ns] fast/slow	45	60/600	300	230	1000
Emission WL [nm] fast/slow	420	430/430	505	415	540
Radioactivity	yes	no	no	no	no
Hygroscopicity	no	no	no	yes	yes

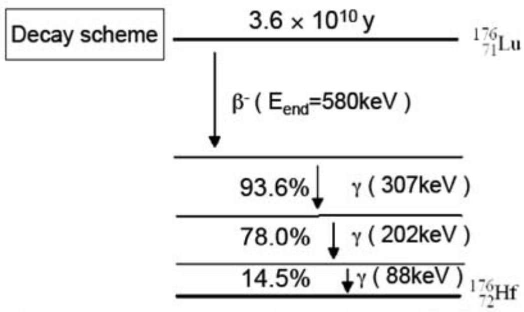

Fig. 1. Decay scheme of [176]Lu. One beta ray and three gamma rays are emitted in the disintegration.

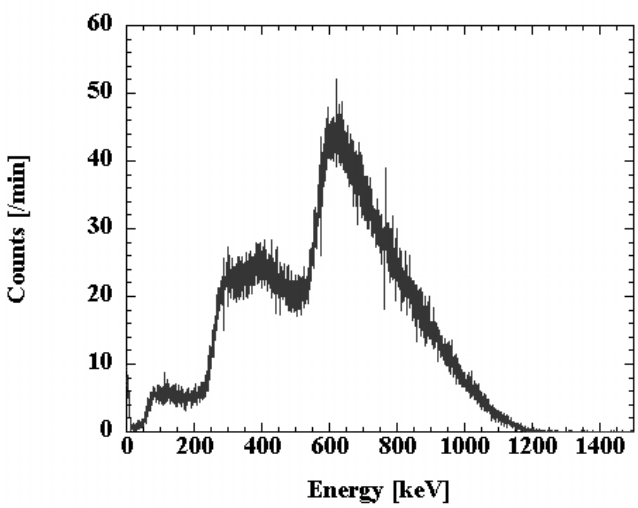

Fig. 2. The measured background spectrum of LYSO(Ce). The dimension of the crystal is a cube 20 mm on a side.

Fig. 2 shows the measured energy spectrum of the background. We used LYSO(Ce) crystals made by Saint Gobain Crystals (PreLude[TM] 420 crystal). According to their catalog the total rate of background activity is about 40 cps/g [2].

B. Timing Property

We measured the timing property of two LYSO(Ce) crystals using annihilation gamma rays from ^{22}Na. Fig. 3 shows the obtained experimental spectrum. Considering the spread of electron transit time of photomultiplier-tubes and the fluctuations due to electronic devices, the timing resolution of LYSO(Ce) for a 511 keV annihilation gamma ray is shown by following equations,

$$\begin{aligned}\sigma_{\Delta t}^{2} &= \sigma_{stop}^{2} + \sigma_{start}^{2} \\ &= (\sigma_{LYSO2}^{2} + \sigma_{device}^{2} + \sigma_{PMT}^{2}) \\ &\quad + (\sigma_{LYSO1}^{2} + \sigma_{device}^{2} + \sigma_{PMT}^{2}).\end{aligned} \quad (1)$$

$$\sigma_{LYSO}^{2} = \frac{\sigma_{\Delta t}^{2}}{2} - \sigma_{device}^{2} - \sigma_{PMT}^{2}. \quad (2)$$

where $\sigma_{\Delta t}$ is the obtained experimental timing resolution, σ_{start} , σ_{stop} are the resolution of start and stop timing, $\sigma_{LYSO}(=\sigma_{LYSO1}=\sigma_{LYSO2})$ is the timing resolution of an LYSO(Ce) crystal, σ_{device} is the fluctuations due to electronic devices and σ_{PMT} is the electron transit time spread of photomultiplier tubes. According to the previously performed experiment, σ_{device} is 91 psec. We used Hamamatsu H7415 photomultiplier tube at 1000 V in our measurements. Under this condition, the electron transit time spread is about 650 psec [3]. The timing resolution of LYSO(Ce) crystal for 511 keV gamma ray was found to be about 820 psec.

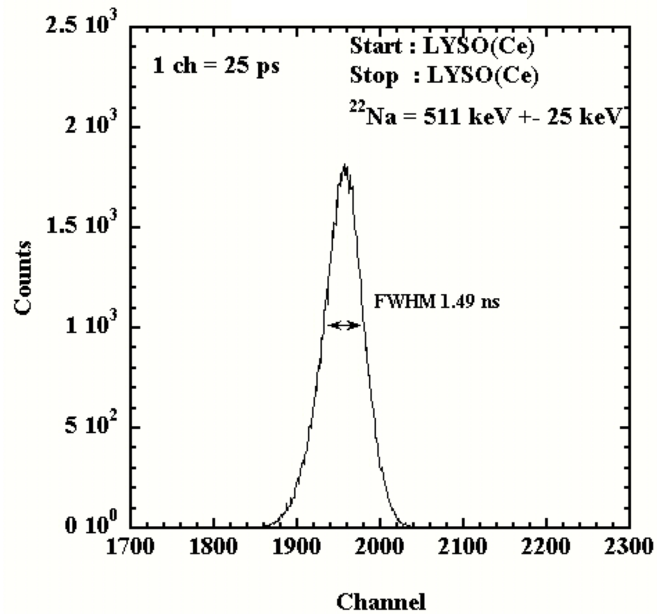

Fig. 3. The obtained experimental timing spectrum of LYSO(Ce).

III. Experiment

Measurements were performed at the PH1 course of the Heavy Ion Medical Accelerator in Chiba (HIMAC) in the National Institute of Radiological Sciences. Monochromatic beams of helium and carbon ions accelerated up to 720 MeV and 3.48 GeV were used in the experiments. Fig. 4 shows the schematic view of the present measurement system. It was composed of a degrader changer, an active collimator, a thin plastic scintillator 2 mm thick and two LYSO(Ce) crystals. The active collimator has an aperture of 5 mm diameter as an active slit to determine the solid angle of the spectrometer. Trigger signals were generated by the coincidence of the thin plastic scintillator and the upstream LYSO(Ce). The dimension of LYSO(Ce) is 20mm cube. In order to change the incident energy to LYSO(Ce), we used degraders made of aluminum and/or copper. The incident energy region was 150 to 700 MeV for helium and 500 to 3400 MeV for carbon. The light output of crystals was normalized by using a LED and standard radiation sources.

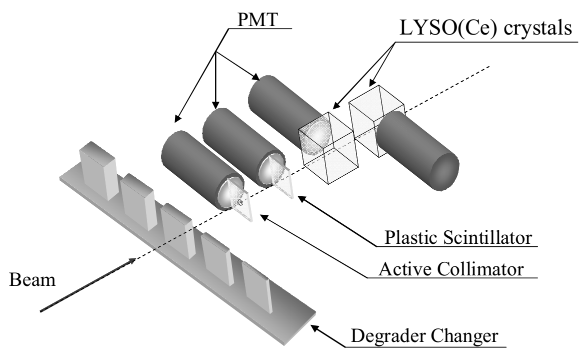

Fig. 4. The schematic view of the present measurement system. Each scintillator was optically coupled to a photomultiplier-tube.

IV. Calculation

The deposited energy in crystals or degraders was calculated by the following equation,

$$-\frac{dE}{dx} = 4\pi r_0^2 z^2 \frac{m_e c^2}{\beta^2} NZ \left[\ln\left(\frac{2m_e c^2}{I}\right) - \ln\left(1-\beta^2\right) - \beta^2 \right] \quad (3)$$

where r_0 is the classical electron radius, z is charge of incident particles, $m_e c^2$ is the rest mass energy of electron, Z is atomic number of material, N is atomic density of material and I is the mean excitation potential.

In order to reproduce the light output of LYSO(Ce), we applied the Birks equation. In general, the light output curves of scintillators are nonlinear. This is one of the undesirable problems when we use scintillators as calorimeters. In order to represent the light output curve of organic scintillators, Birks introduced the following equation on the assumption that the amount of the luminescence per unit length is described by a function of its stopping power,

$$\frac{dL}{dx} = \frac{S(dE/dx)}{1 + kB(dE/dx)}, \quad (4)$$

where S is the absolute scintillation efficiency and kB is the Birks parameter, which shows the magnitude of quenching effect [4]. Equation (4) shows that the amount of the luminescence per unit length is decreased by quenching effects in high dE/dx region. Equation (4) reproduces the light output curves of organic scintillators appropriately. This equation was also applied to inorganic crystals and was found to reproduce their light output curve relatively.

V. Result

Fig. 5 and 6 show the results of the experiment for helium and carbon ions, respectively.

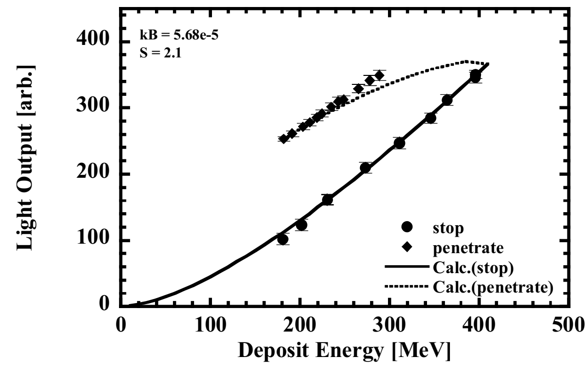

Fig. 5. The light output of LYSO(Ce) for helium as a function of the deposited energy in crystal.

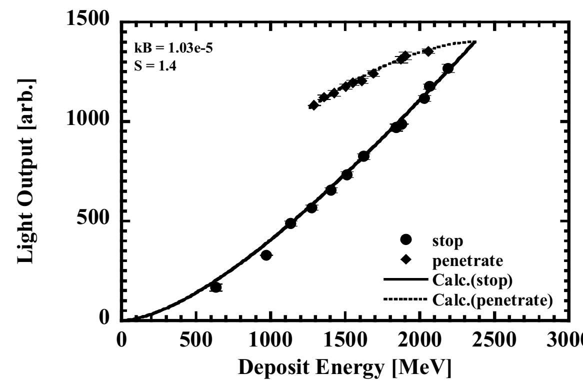

Fig. 6. The light output of LYSO(Ce) for carbon as a function of the deposited energy in crystal.

In both figures, closed circles are the light outputs from the ions that stop in a crystal and deposit all their energy. Rhombic points are the light outputs from the ions that penetrate a crystal and deposit a part of their energy. When the deposited energy is same, the light output of penetrating ions is higher than that of stopping ions. The curves in the figure are the calculated by the Birks equation. Solid line is for stopping ions and dashed line is for penetrating ions. In these calculation, the fitted values of Birks parameter were kB = 5.68×10^{-5} m/MeV for helium and kB = 1.03×10^{-5} m/MeV for carbon.

VI. Discussion

We carried out the experiment on GSO(Ce) crystals for intermediate energy charged particles, previously [5]-[8]. We found that the light output curve of GSO can be reproduced using the common Birks parameter for proton, deuteron, helium and carbon. In these experiments, the dimension of GSO(Ce) crystal is 43 mm cubic. Fig. 7 shows the light output curves of GSO(Ce).

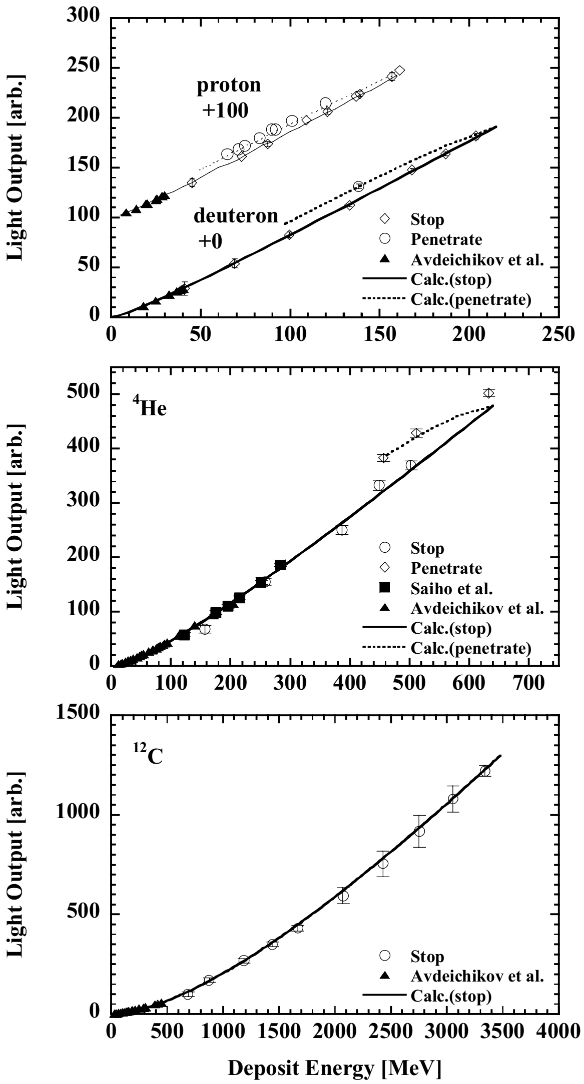

Fig. 7. The light output of GSO(Ce) as a function of the deposited energy in a crystal. The solid lines are the curves for stopping ions and the dotted lines are the curves of penetrating ions.

In these figures, calculated lines were made by common parameters, $kB = 1.7\times 10^{-5}$ MeV/m. Compared with this, the values of Birks parameter for LYSO(Ce) were different between two kinds of ions. We have the experimental data for only two kinds of ions now, so we need to carry out the experiments about another kind of ions for the better understanding of this difference.

VII. Conclusion

We have investigated the light output response of LYSO(Ce) crystals using helium and carbon beams of 720 MeV and 3.48 GeV, respectively. Experimental results showed good agreement with the calculated curves by Birks equation. But the parameters in the Birks equation were different between helium and carbon. On the other hand, the light output curves of GSO(Ce) are represented by the common value of Birks parameter. In order to use LYSO(Ce) for the measurement of heavy ions, it is necessary to investigate the light output responses for a different kind of charged particles.

Acknowledgment

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