

Scintillation Efficiency of Inorganic Scintillators for Intermediate-Energy Charged Particles

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We carried out experiments to investigate the light output response of NaI(Tl), CsI(Tl), GSO(Ce) and LYSO(Ce) crystals for intermediate-energy ⁴He, ¹²C and ⁴⁰Ar beams from HIMAC at National Institute of Radiological Sciences. And we investigate the light output of these crystals for several-energy gamma-ray for comparison. From these light output responses, we obtained the relationships between the scintillation efficiency (dL/dx) and the specific energy loss (dE/dx) for each crystal. The scintillation efficiency curves of NaI(Tl) and CsI(Tl) crystal have the peak in a particular dE/dx. On the other hand, the scintillation efficiency curves of GSO(Ce) and LYSO(Ce) crystal decrease with increasing dE/dx. The light output curves of these crystals were systematically reproduced using obtained scintillation efficiencies.

KEYWORDS: *inorganic scintillator, scintillation efficiency, specific energy loss, NaI(Tl), CsI(Tl), GSO(Ce), LYSO(Ce)*

I. Introduction

It is well known that the light output response of inorganic scintillator bear a nonlinear relationship with the deposited energy. In order to improve the energy identification performance, it is necessary for this nonlinearity to be investigated enough.

In high energy experiments, various scintillators have been developed strenuously with the advancement of energy and beam intensity of accelerators. The performance requested for these scintillators is heavier, faster and more tolerant to radiation damage. GSO(Ce) and LYSO(Ce) are one of the scintillators which have been developed for these requests. In order to use them as high precision calorimeters, it is necessary to investigate the light output characteristics of these scintillators. Especially, it is very important to define a light output curve which is the relationship between the energy deposited in crystals and the amount of the luminescence.

We carried out experiments on the light output characteristics of several scintillators for intermediate-energy (several hundred MeV/u) charged particles in order to investigate these nonlinear relationships in wide energy range¹⁾. Focusing attention on the relationship between the scintillation efficiency (dL/dE) which is the amount of the luminescence per unit energy, and the specific energy loss (dE/dx), we investigated the light output response of four kinds of crystals, NaI(Tl), CsI(Tl), GSO(Ce), and LYSO(Ce). And we investigate the light output of these crystals for several-energy gamma-ray for comparison. The light output curves of these crystals were systematically reproduced.

II. Experiment

Measurements were performed at the PH1 course of HIMAC (Heavy Ion Medical Accelerator in Chiba) in the National Institute of Radiological Sciences. Monochromatic ⁴He, ¹²C and ⁴⁰Ar particles accelerated up to 180 MeV/u, 290 MeV/u and 650 MeV/u were used in the experiments. And Monochromatic proton (80 MeV) was used in the LYSO(Ce) experiment. **Figure 1** shows the schematic view of present measurement system. It was composed of, from upstream, a degrader changer, an active collimator, a thin plastic scintillator with the thickness of 2 mm, and two inorganic scintillators. The active collimator has an aperture of 5 mm diameter as an active slit to determine the solid angle of the spectrometer. The thin plastic scintillator generated the trigger signals by the coincidence method with the signal of the inorganic crystal. The dimensions of inorganic scintillators are NaI(Tl) : 50.8 mm, CsI(Tl) : 43 mm, GSO(Ce) : 43 mm, and LYSO(Ce) : 20 mm cube. Each crystal was coupled to a photomultiplier tube (Hamamatsu R329: NaI(Tl), R580: CsI(Tl) and GSO(Ce), R7415: LYSO(Ce)). In order to change incident energy to the inorganic scintillators we used some degraders made of aluminum or copper. The measured energy region was 150~700 MeV for ⁴He, 500~3,400 MeV for ¹²C, 4,000~14,000 MeV for ⁴⁰Ar. The light output of scintillators was normalized with a LED and ¹³⁷Cs radiation sources. The unit of each light output is [1/L(¹³⁷Cs)], where L(¹³⁷Cs) is the light output of each crystal for 0.662 MeV gamma.

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

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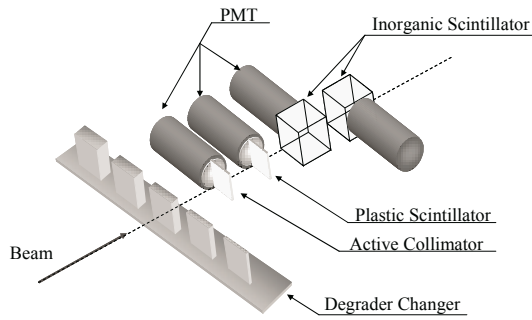


Fig.1 The schematic view of present measurement system. Each scintillator was attached a photomultiplier tube.

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

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, I is the mean excitation potential. In the measured energy range Eq. (1) calculates the specific energy loss with satisfactory accuracy.

III. RESULT

Figure 2 shows the light output of scintillators as a function of deposit energy for several charged particles and gamma ray. In **Figure 2** error bar shows the standard deviation of total absorption peaks. The larger the atomic number of incident particle is, the smaller the light output of the same deposited energy is.

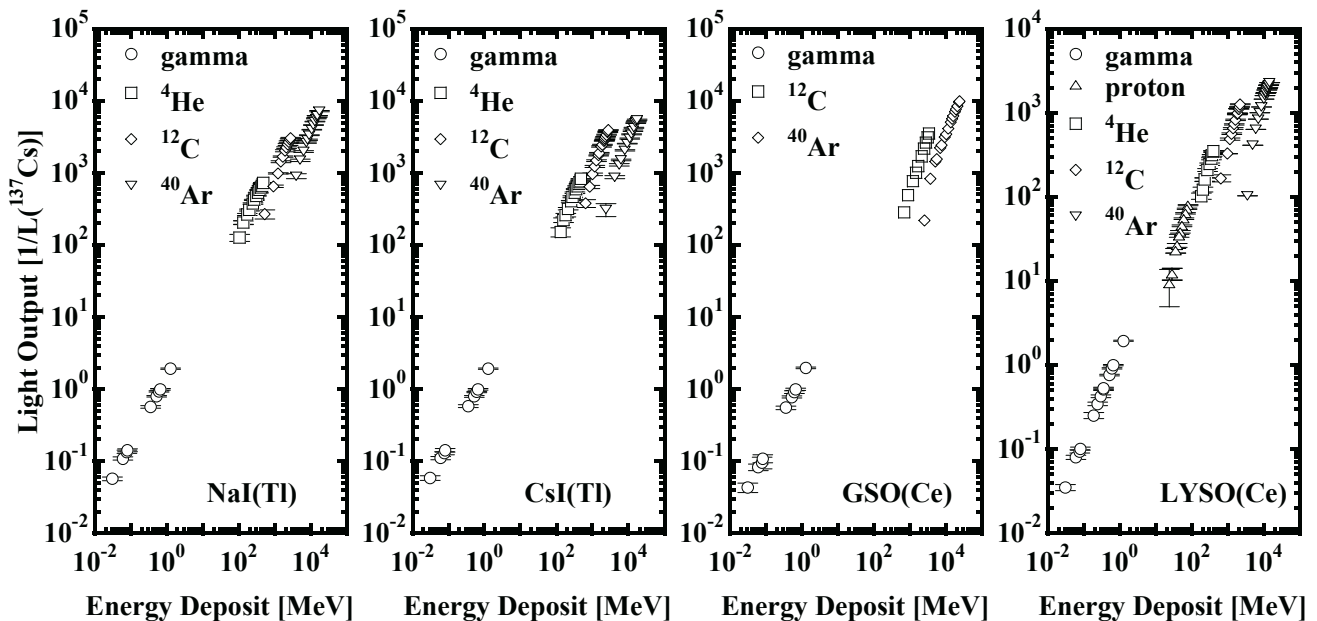


Fig.2 The light output of NaI(Tl), CsI(Tl), GSO(Ce) and LYSO(Ce) crystal as a function of deposit energy to gamma and several charged particles.

As described above, the light output curves considerably change its shape with the measured particle. Therefore it is difficult that the light output (L) is represented by the unified equation with the deposited energy (E). So we focused attention on the relationship between the scintillation efficiency (dL/dE) and the specific energy loss (dE/dx). At first, the scintillation efficiency was defined approximate slope of the light output curve on each measurement. The specific energy loss on incident particles without electrons was calculated with Eq. (1). In low dE/dx field, the electrons were generated by converting the gamma rays to the energetic electrons through photoelectric effect in crystals. The specific energy loss of electrons was referred to ESTAR²⁾. **Figures 3~6** show the relationship between the scintillation efficiency and the specific energy loss of crystals^{3,4)}. In all region of the specific energy loss, the scintillation efficiency of GSO(Ce) and LYSO(Ce) decreases monotonically, but that of NaI(Tl) and CsI(Tl) become lowering in the region of the low specific energy loss.

IV. DISCUSSION

In order to represent the light output curves of organic scintillators, Birks showed the following equation on the assumption that the amount of the luminescence per unit length is described by a function of its stopping power,

$$\frac{dL}{dx} = \frac{S(dE/dx)}{1 + kB(dE/dx)}, \quad (2)$$

where S is the absolute scintillation efficiency and kB is the Birks parameter. Eq. (2) shows that the amount of the luminescence per unit length decreases by the quenching

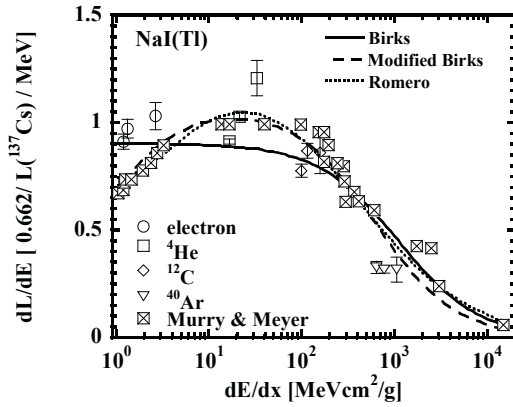


Fig.3 Scintillation Efficiency of NaI(Tl).

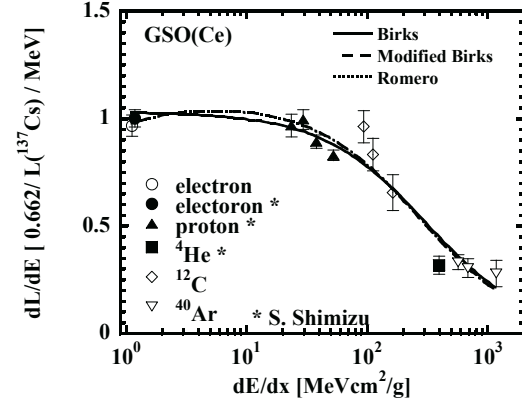


Fig.5 Scintillation Efficiency of GSO(Ce).

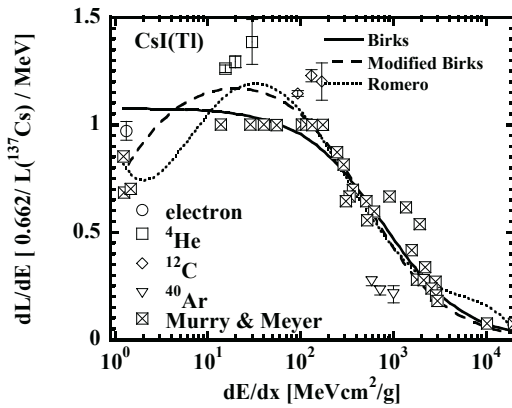


Fig.4 Scintillation Efficiency of CsI(Tl).

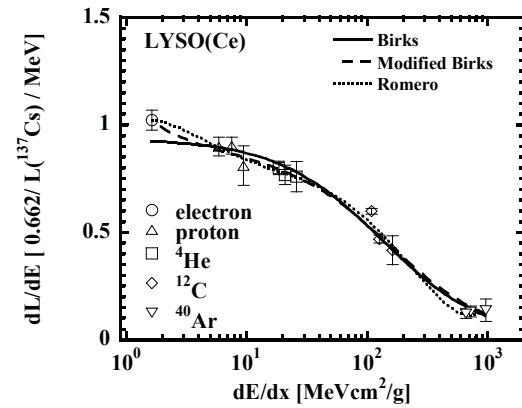


Fig.6 Scintillation Efficiency of LYSO(Ce).

effect in high dE/dx region. Eq. (2) reproduced light output curves of organic scintillators appropriately.

The equation of scintillation efficiency (dL/dE) is derived by Eq. (2),

$$\frac{dL}{dE} = \frac{a}{1+b(dE/dx)}. \quad (3)$$

And in order to reproduce quenching in low specific energy loss range, we modify Eq. (3) as,

$$\frac{dL}{dE} = \frac{a}{1+b(dE/dx)+c(dE/dx)^{-1}}. \quad (4)$$

The scintillation efficiency of NaI(Tl) for several charged particles was reported by Romero *et al.*⁵⁾. Romero *et al.* parameterized dL/dE as a function of dE/dx in the following way,

$$\frac{dL}{dE} = \sum_{i=0}^5 a_i \left(\ln \frac{dE}{dx} \right)^i. \quad (5)$$

In order to represent the scintillation efficiency of these crystals, we applied the above equations. **Table 1** shows parameters for equations obtained with best fit. Because the scintillation efficiency curves of NaI(Tl) and CsI(Tl) have quenching in the region of low specific energy loss, these curves are not represent well by Birks equation, which shows monotonically decreasing function. **Figure 7** shows the light output curves calculated using Eq. (1) or ESTAR

and Eq. (4) with parameters of Table 1. These calculation curves reproduced the light output response of each crystal roughly using simple equation, despite the kinds of the particle are different.

Table 1 The parameters for each equation.

	NaI(Tl)	CsI(Tl)	GSO(Ce)	LSYO(Ce)
Birks				
a	0.905	1.08	1.03	0.938
b	9.10×10^{-4}	1.29×10^{-3}	3.22×10^{-3}	7.60×10^{-3}
Modified Birks				
a	1.08	1.26	1.08	0.883
b	1.65×10^{-3}	1.92×10^{-3}	3.66×10^{-3}	6.50×10^{-3}
c	0.594	0.747	0.110	-0.241
Romero				
a_0	0.765	0.912	0.897	0.975
a_1	2.76×10^{-2}	-0.535	0.707	0.219
a_2	0.104	0.514	-0.667	-30.7
a_3	-3.81×10^{-2}	-0.143	0.243	0.124
a_4	4.09×10^{-3}	1.52×10^{-3}	-3.89×10^{-2}	-2.19×10^{-2}
a_5	-1.42×10^{-4}	-5.59×10^{-4}	2.22×10^{-3}	1.35×10^{-3}

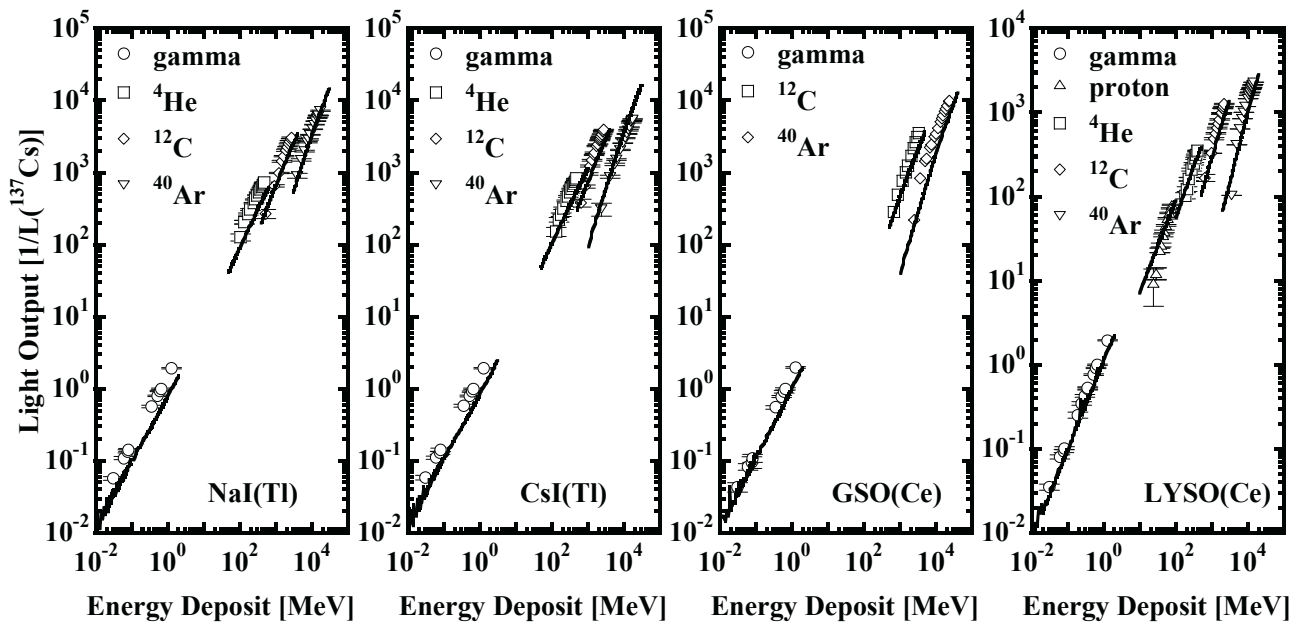


Fig.7 The calculation curves of the light output.

V. CONCLUSION

In order to investigate the light output response of inorganic scintillators, we carried out experiments at PH1 course of HIMAC (Heavy Ion Medical Accelerator in Chiba) in National Institute of Radiological Sciences.

By measurements of the wide range of intermediate energy, the scintillation efficiency for the wide range of the specific energy loss was measured. The scintillation efficiency of each crystal could be represented by some simple equation independent on the kind of particles. And the calculation curves using an equation could represent the light output of these crystals roughly. This study shows that the scintillation efficiency is a function of the specific energy loss. The more accurate scintillation efficiency is represented, the more strictly the light output curve may be represented. It is anticipated that the more refined researches of scintillation efficiency clear up the light output characteristics of inorganic scintillators.

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