Light output response of GSO(Ce) and NaI(Tl) to protons up to 160 MeV

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Abstract

An experimental study on GSO(Ce) scintillation crystals was made in terms of the light output response to proton in an energy range up to 161 MeV. The experiment was carried out for cubic crystals of 43 mm edge length by using a 392 MeV proton beam. A good linearity was observed between 30 and 161 MeV, and a slight non-linearity below 30 MeV. A relation of dL/dE versus E was determined with stopping protons. A calculation using the relation has agreed with measured pulse heights of protons penetrating the crystal, as well as those of stopping protons. Similar measurements were made for NaI(Tl) crystals of 2 in. cubic. Rather large non-linearity was observed in the proton energy range 0–122 MeV. © 1998 Elsevier Science B.V. All rights reserved.

1. Introduction

Counter telescopes consisting of scintillators make practical spectrometers for intermediate energy experiments. Compared with more conventional magnet-wire chamber spectrometers they offer low cost, compact design and easy data analysis. To stop energetic charged particles the crystal is required to be long enough. In this case one may make spectrometers with several scintillators put in-line to the direction of charged particles. Such stacked spectrometers are known to provide good particle identification. Moreover, energy calibration of each element can be made easily by referring to maximum energy which is uniquely determined by the range of protons.

The light output response of inorganic scintillators such as NaI(Tl) and CsI(Tl) to various charged particles has been investigated extensively. Several inorganic scintillation crystals were developed in the past few years. A scintillator cerium-doped gadolinium orthosilicate, Gd2SiO5–GSO(Ce), is one of the new crystals. Optical performances of the GSO(Ce) were studied and found to be excellent [1–7]: high light output about 20% of that of NaI(Tl), a short scintillation decay constant 50–60 ns, and remarkably high radiation hardness.
The effective atomic number of the GSO crystal is large, and this is another advantage for detecting highly energetic charged particles. These characteristics suggest that the GSO(Ce) is a powerful candidate to construct a spectrometer of stacked scintillators for intermediate energy experiments.

So far, the light output response to protons was studied by Avdeichikov et al. up to 30 MeV [5,6]. It is valuable to extend the investigated energy range up to several hundreds of MeV. Furthermore, in measurements of proton energy by stacked spectrometers, one must pay attention to the pulse height difference between the stopping and the penetrating protons even if they would deposit the same energies in the crystal. Such pulse height correction is possible by the differential light output $dL/dE$. The proton range–energy relation is also necessary. It is, however, unknown in this energy range, and hence must be investigated.

In this paper, we describe an experimental study of light output response of GSO(Ce) to protons up to 161 MeV. Similar experiments are carried out for NaI(Tl) crystals. The linearity of light output is discussed for each crystal. The proton range–energy relation in the GSO is also presented.

2. Experimental

2.1. Apparatus

The stacked GSO(Ce) scintillators spectrometer is sketched in Fig. 1. It consisted of three cubic crystals having edge length of 43 mm and a cylindrical one of 62 mm in diameter and 120 mm long. Three thin plastic scintillator plates were located in front of the GSO(Ce) array to produce trigger signals. One of the plastic plates had a hole of 15 mm diameter and played as an active slit for the
spectrometer. All the scintillation signals were read out through photo-multiplier tubes. In the present experiments, the large cylindrical crystal played to identify the proton range whether it could reach the crystal or not.

The stacked NaI(Tl) spectrometer had a similar construction to that depicted in Fig. 1, and consisted of four 2-inch cubes and a cylinder of 80 mm diameter by 180 mm long. Two silicon semiconductor detectors having thickness 150 and 300 μm were used instead of plastic scintillator plates of the GSO(Ce) spectrometer. Their active area was 450 mm².

2.2. Procedure

The experiments were carried out at the Research Center for Nuclear Physics (RCNP), Osaka university. The ring-cyclotron provides a proton beam of 200–400 MeV. The proton beam energy was 392 MeV for the GSO(Ce), and 350 MeV for the NaI(Tl) experiments. The proton beam bombarded a target of 1.2 mm thick polyethylene plate to produce quasi-monoenergetic protons from H(p,2p) scattering. The measurements for GSO(Ce) were carried out at three laboratory angles, 30°, 40°, and 50°. The energies of recoiled protons at these angles are 279.3, 211.7 and 144.2 MeV, respectively. The measurements for NaI(Tl) were made with two angles 30° and 45° corresponding to 248.7 and 158.2 MeV, respectively. Protons of continuum energy spectrum were also measured. A coincidence detector was used to discriminate events of H(p,2p) from those of 12C(p, p'x).

3. Results and discussion

3.1. Proton range–energy relation in GSO

The range–energy relation can be found roughly by the observation of pulse height spectra of each crystal of the stacked spectrometer. The range of protons was estimated from the measured pulse heights for the crystal in which the protons were expected to be stopped. By assuming an almost linear light output also, one could know whether the stopped position is in the first-half or the second-half of the crystal. The proton range in a material is also theoretically estimated by energy loss calculation using the Bethe equation as a function of proton energy. For a composite material, the proton energy loss is expressed by

$$\frac{1}{\rho} \left( \frac{dE}{dx} \right)_{\text{GSO}} = \sum_i \omega_i \frac{1}{\rho_i} \left( \frac{dE}{dx} \right)_i,$$

where ω is the weight ratio of each constituent to the crystal, and ρ the density of the material. The subscript i represents the component, Gd, Si, and O of the GSO crystal. Table 1 summarizes the range–energy relation for the experiment and the calculation. The ambiguities in Table 1 correspond to the half-depth of the GSO crystal.

The pulse height spectra measured at 35° are shown in Fig. 2 for each crystal. The large peak comes from the pp scattering events for which the energy of outgoing protons is 246 MeV. The total amount of energy deposited in the GSO crystals was calculated to be 241 MeV by taking the energy loss in the air and the plastic scintillators into account. In the spectrum of the second GSO, most events are observed as a peak with a very large pulse height. In contrast, the third GSO has a small number of events having a very small pulse height. It is obvious that most protons stop at the end of the second GSO crystal. Due to energy loss straggling and energy spread, a part of protons could reach the third crystal. Thus, the range of 241 MeV proton is expected to be almost the total depth of two crystals of 8.6 cm. The calculated range was 8.5 cm, and hence the validity was ascertained.
The largest pulse height is produced by protons of which the range is the same as the crystal depth. Hence, the maximum energy deposited in the 43 mm cubic GSO(Ce) is calculated to be 161 MeV. As is shown in Fig. 3, the maximum energy is clearly observed as a shoulder in the highest pulse height region, when one measures a continuum energy spectrum. It is a good measure to normalize the pulse heights of each crystal. In the following sections, this normalization procedure was used to study the light output response.

3.2. Light output response of GSO(Ce)

The light output response of GSO(Ce) to stopping protons is determined by using pp scattering data at three angles and the maximum pulse height corresponding to 161 MeV produced by p + $^{12}$C inelastic scatterings. The result is shown in Fig. 4, where the dots are the measured data, the diamonds are of Avdeichikov et al. [5,6]. The error bars of the present data correspond to FWHM of the peaks in measured energy spectra.

The pedestal was adjusted by means of a pulse generator.

It appears reasonable to give a linear relation in the energy range 30–160 MeV. Then a line was fitted to the present data above 30 MeV. A polynomial fitting was made below 30 MeV. The curve should come into contact with the line smoothly. Therefore, we made the fitting very carefully such that the line and the curve would have the same values of $dL/dE$ as well as the light output $L$ at $E = 30$ MeV. As the result, the response is written by

$$L(E) = -57.3 + 6.68, \quad E \geq 30 \text{ MeV}, \quad (2)$$

$$L(E) = -0.2 + 1.596E + 0.1341E^2 - 1.279 \times 10^{-3}E^3 + 3.917 \times 10^{-6}E^4, \quad E \leq 30 \text{ MeV}. \quad (3)$$

The present results are found to be consistent with the result in Refs. [5,6] below 30 MeV. From Eqs. (2) and (3), we determined $dL/dE$ as a function of proton energy $E$. As seen in Fig. 5, the
The present result of $dL/dE$ has a constant value above 30 MeV, and a curve below 30 MeV.

The response to penetrating protons is calculated by the use of this relation. Fig. 6 shows the response to penetrating protons as well as stopping protons that are the same as in Fig. 4. The measured data are well described by using the relation $dL/dE$ versus $E$ determined presently.
3.3. Light output response of NaI(Tl)

Romero et al. [8] have summarized the light output response of NaI(Tl) to $Z = 1$ particles in a wide $dE/dx$ range. By referring to their results, the response to stopping and penetrating protons is calculated as a function of deposited energy in the NaI(Tl) crystal. The calculated light outputs are shown in Fig. 7, and compared with the results of the present measurements. The maximum
energy deposited in this NaI(Tl) crystal was 122 MeV. A slight non-linearity is observed in the calculation for stopping protons in the whole measured range from zero to 122 MeV. The maximum energy difference is about 3 MeV at proton energy of 70 MeV. The calculation is in reasonable agreement with the experiment. The pulse heights for penetrating protons appear to be smaller than that for stopping protons. This feature is in the opposite tendency against that of GSO(Ce), and is described reasonably by the relationship between $dL/dE$ and $dE/dX$ in Ref. [8].

4. Conclusions

The light output response of GSO(Ce) to protons up to 161 MeV was investigated by using pp scattering at a lab. energy of 392 MeV. The linear relation was observed in the energy range 30–160 MeV, though a slight non-linearity was observed at energies below 30 MeV. The light output difference between the stopping and the penetrating protons has been reasonably described by the $dL/dE$ versus $E$ relation determined in this work. Similar experiments were carried out with NaI(Tl) crystals. The light output non-linearity was observed in the energy range 0–122 MeV.

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References