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Study of a new crystal array detector to measure double differential cross sections of proton-actinide reactions in 600-MeV region

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Abstract. A new crystal array detector is proposed to conduct charged particle cross section measuremets with actinide targets for a study of accelerator transmutation of waste. The detector enables both the Time-of-Flight and the Pulse-Height measurements in an energy range around 600 MeV. From the simulation designs, it was revealed that the detector has great potential to realize a moderate energy resolution and a wide energy acceptance. Characteristics of GSO(Ce) and LYSO(Ce) crystals were also investigated through charged particle bombardment in view of consideration of the candidate crystal for this detector.

1 Introduction

The accelerator driven system (ADS) has been recognized as one of most attractive options for the nuclear transmutation of high level nuclear waste. One may expect ADS to reduce a hazard level of the waste dramatically, and to operate as an energy generator. To realize ADS, it is necessary to conduct various areas of fundamental researches and technical developments. Double differential cross section (DDX) data of nucleon-actinide reactions are of highly importance for the nuclear waste transmutation facilitated by ADS. Since charged particle emission data are strongly required as well as neutron data up to 1500 MeV, we plan to conduct charged particle measurements with typical actinide targets at the cyclotron facility, the Joint Institute for Nuclear Research, Dubna, in the energy range 200 to 700 MeV.

In order to obtain high-quality nuclear data of DDX, one needs to use a detector that offers a moderate energy resolution of a few percent and a wide energy acceptance covering from almost zero up to the maximum emission energy. Moreover, detection efficiency should be high enough for the usage of a thin target. A crystal array detector is the most suitable one to these conditions, and the only solution above 100 MeV. However, there are some crucial problems when one uses it at energies of around/above 600 MeV.

In the present article are described a design study of a new crystal array detector that combines the Time-of-Flight (TOF) and the Pulse-Height (PH) measurement. In addition we reports characteristics of scintillation crystals of GSO(Ce) and LYSO(Ce), which are considered to be the best candidate as the detector element, because of its relatively high light output and very short scintillation decay constant, investigated through experiments using charged particle beams.

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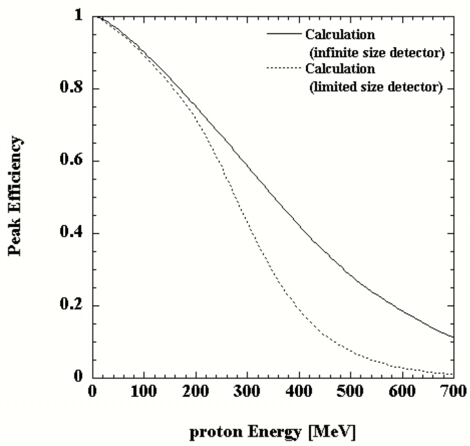

Fig. 1. The calculated peak efficiency of GSO(Ce) crystal to protons. See text for more details.

2 Crystal array detector for charged particles

2.1 Difficulties of present methods

When one applies a crystal detector to measure charged particle energies of several hundreds MeV, the particle identification (PI) analysis is most useful to deduce DDXs. However, the PI analysis is recognized to become insufficient in a high energy range. This is because the peak efficiency, the ratio of the number of full energy peak events to the total events, decreases to a level where the PI analysis is no longer applicable.

In figure 1 are shown typical examples of the peak efficiency curves of GSO(Ce) crystal to protons as a function proton energy. They were calculated by the simple Monte Carlo procedure [1,2]. The dotted line is the calculated efficiency for a crystal having a cross section of 43 mm × 43 mm, which is the largest possible presently. It is found that the curve drops rapidly above 200 MeV and approaches to zero at around 600 MeV. The solid line is that for infinite size crystal, of which the efficiency is determined solely by the nuclear

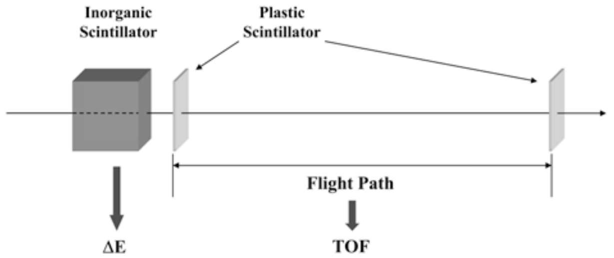

Fig. 2. Sketch of the detector concept. The system consists of dE and TOF measurement parts. See text for more details.

reactions and remains to be about 20% at 600 MeV. However, the crystal dimension must be unreasonably large. In addition to this low efficiency, the 2D PI plot which is necessary for the PI analysis is known to scatter widely and obscure at these energies. Thus, it will be concluded that the conventional PI analysis is not very useful in this energy range.

Although there are some alternative options such as the unfolding analysis and the TOF technique, they have also serious difficulties. The unfolding analysis suffers from a large ambiguity when it is applied to continuum energy spectra. Although TOF is effective to detect high energy protons, its efficiency becomes very low due to a long flight path length that leads to an extremely small solid angle and a large portion of beam bunch thinning-out in cyclotrons. Moreover, it is impossible to realize a wide energy acceptance with a long flight path in charged particle measurements under atmosphere.

2.2 Proposal of new detector system used in 600-MeV range

In order to meet the criteria discussed above, we propose a new detector system which enables nuclear data measurement in a 600-MeV range. It utilizes both the pulse height and TOF in proton measurements. As the concept is illustrated briefly in figure 2, it consists from two sections; one is a crystal detector based on the ordinal dE-E method, and the other the TOF section following the crystal.

The crystal detector works as an E detector for low energy protons and an energy degrader for high energy protons. Since low energy protons stop in the crystal, one needs not the beam bunch thinning-out in cyclotron operations. The shorter flight path length, which is realized by the degrader, offers great advantages: the larger solid angle and easy preparation of a vaccum duct to cover the flight section which is essential for charged particle measurements. The detector proposed presently is expected to offer the best characteristics to fulfill required specifications, such as energy resolution and energy acceptance.

3 Design study of new detector system

3.1 Specifications

Since we have a lot of experiences in this kind of experiment, we decided to determine the specifications by following the parameters optimized in the previous experiments [3–5]. The detector we used had a solid angle of about 1 msr. The energy resolution of GSO(Ce), which was operated for the dE-E method, was 5 to 10%. Furthermore, the peak efficiency of at least 50% was found to be preferable to perform the most reliable PI analysis. Although the deeper crystal results in more loss of particles, the following TOF section benefits from a smaller number of particles. It seems reasonable to determine the crystal depth as to be equivalent with 50% of the peak efficiency.

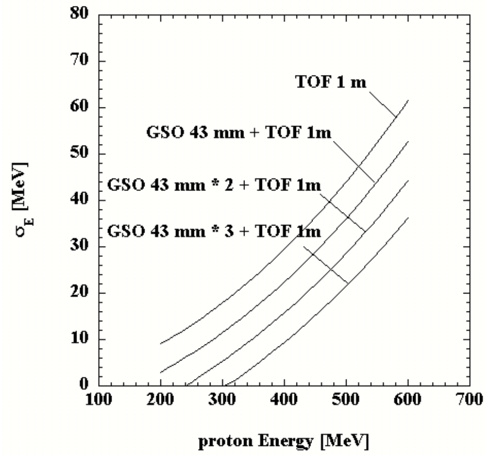

Fig. 3. Estimated energy resolutions for TOF as a function of proton energy and degrader (crystal detector) thickness.

The basic criteria for the TOF section should come from difficulties in manufacturing and placing a long vacuum line. A one-meter long duct should be reasonable, and an enough area to be installed is available in the planned experimental hall of JINR. Moreover, the spread in time measurement appears also to be reasonable as discussed in the following section.

The specifications targeted in this study are summarized as below:

- energy resolution is 10%,
- solid angle is 1 msr,
- peak efficiency of crystals is at least 50%,
- the fight path is one meter.

3.2 Depth of crystal and peak efficiency

As found from figure 1, the proton energy range where the peak efficiency approaches 50% is around 300 MeV. The crystal depth needed to stop protons of 300 MeV is about 120 mm. Since the dimension of cubic GSO(Ce) crystals abailable presently is 43 mm in the edge length, two or three crystals must be placed in the front section.

When 600-MeV protons pass through a crystal with this thickness, 32% of protons will be lost due to nuclear reactions as a result of calculation. The survivors can enter the TOF section. It is preferable to decrease the number of particles in view of avoiding interfrences between two particles accidentally appear in the TOF simultaneously. The crystal depth of 86 mm will be the best to fulfill these requirements.

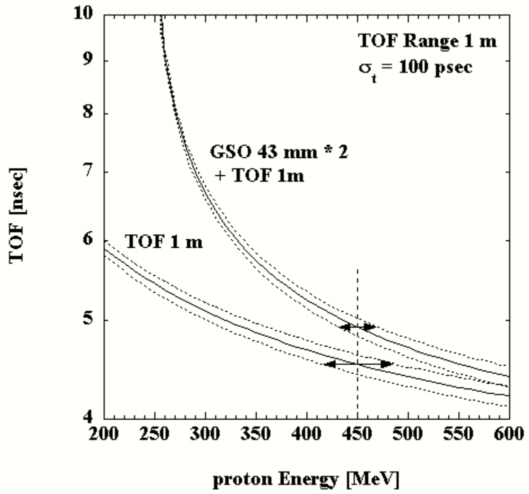

Fig. 4. Estimated energy resolution as a function of proton energy compared with/without crystal as energy degrader.

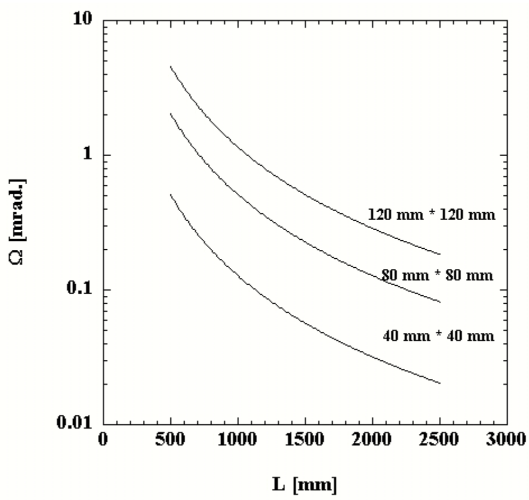

Fig. 5. The detector solid angle as function of the flight path length L and the dimension of TOF end detector.

3.3 Energy resolution

The estimated energy resolution in the sole TOF section after crystal is shown in figure 3, as a function of proton energy and the depth of crystal section of 0, 43, 86 and 129 mm. It is apparent that the TOF energy resolution improves as the crystal section becomes deeper. In this case, we have assumed the whole timing resolution to be 100 ps, which could be standard with fast plastic scintillator detectors. A resultant resolution was, for instance, about 30% at 600 MeV. However, we expect to have the better resolution by including additional information from crystal detector in actual measurements.

The advantage of this method is demonstrated in figure 4, which compares the time of flight with/without the degrader crystal under the flight path length of one meter. The effect of crystal degrader is significant, and helps to improve the energy resolution.

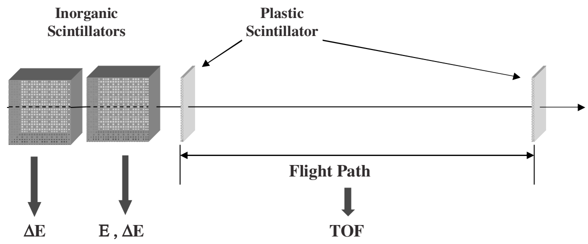

Fig. 6. The detector arrangement we decided.

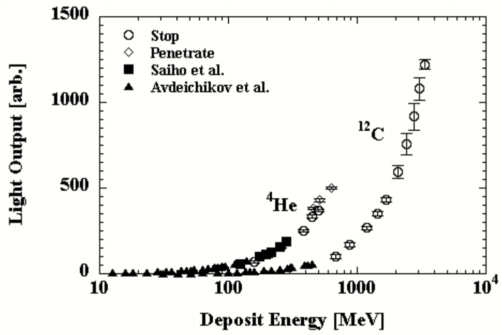

Fig. 7. Light output response of GSO(Ce) to ^{4}He and ^{12}C [8].

3.4 Solid angle and fight path

The detector solid angle is shown in figure 5 as a function of flight path length, and compared between three different dimensions of square plastic scintillators of 40, 80 and 120 mm on a side. At a flight path of one meter, the solid angle of 1 msr is realized with that of 80 mm.

This plastic cross section is reasonable from view points of manufacturing a vacuum duct and the time spread due to different flight path from the scintillation source to the photocathode in a photomultiplier.

3.5 Detector arrangement

As a result of the above discussion, we decided the detector arrangement as shown in figure 6. The low energy part consists of stacked crystal detectors where the conventional dE-E measurements are made up to 300 MeV.

Protons of energies higher than 300 MeV are measured by the TOF detector. It consists of two plastic scintillators with a one-meter flight path length. The end plastic is a square 80-mm on a side. The expected energy resolution is about 10% for 450 MeV protons.

4 Response characteristics of GSO(Ce) and LYSO(Ce) crystals

Characteristics of inorganic scintillators have been investigated extensively thanks to the development of a variety of crystals and the opening of new application fields. Among the crystals developed in recent days, some of them could be

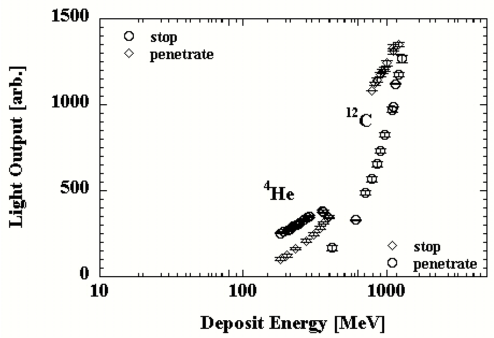

Fig. 8. Light output response of LYSO(Ce) to ^{4}He and ^{12}C.

Table 1. Basic characteristics of some typical crystals.

Scintillator	NaI(Tl)	GSO(Ce)	LYSO(Ce)	BGO
Composition	NaI:Tl	Gd_2SiO_5	$Lu_{1.8}Y_{0.2}SiO_5$	$Bi_4Ge_3O_{12}$
Effective Z	51	59	66	74
Density [g/cm^3]	3.67	6.71	7.1	7.13
Light Output (relative) fast/slow	100	18/2	40	7
Decay Time [ns] fast/slow	230	60/600	45	300
Emission WL [nm] fast/slow	415	430/430	420	505
Radioactivity	no	no	yes	no
Radiation Resistivity [rad]	103	109	>106	105-7
Hygroscopicity	yes	no	no	no

considered as a candidate of this detector. Basic characteristics of some typical crystals are listed in table 1.

In addition to these characteristics, we need to learn the response to charged particles. We chose GSO(Ce) and LYSO(Ce) from the table, and measured their response to relativistic heavy ions. In the experiments, each of cubic crystal, GSO(Ce) of 43 mm edge length and LYSO(Ce) of 20 mm was irradiated directly by 720 MeV ^{4}He and 3.48 GeV ^{12}C beams at NIRS-HIMAC. Figure 7 and figure 8 show the light output response to these particles which energy was changed by degraders. More details about experiments are described in refs. [6, 7].

5 Conclusion

A new type of detector system was studied to measure double differential cross sections of proton productions from proton-actinide reactions at around 600 MeV. The detector system is based on a combination of dE-E and TOF measurements to realize a moderate energy resolution and an extremely wide energy acceptance. On the base of simulation calculations, the detector arrangement has been optimized in terms of crystal dimensions, TOF path length, and more. The response of crystals to charged particles was also studied. Experimental results have appeared to be promising as for GSO(Ce) and LYSO(Ce).

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