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A Bragg curve counter with an internal production target for the measurement of the double-differential cross-section of fragment production induced by neutrons at energies of tens of MeV

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ABSTRACT

A Bragg curve counter equipped with an internal production target was developed for the measurements of double-differential cross-sections of fragment production induced by neutrons at energies of tens of MeV. The internal target permitted a large detection solid angle and thus the registration of processes at low production rates. In this specific geometry, the detection solid angle depends on the emission angle and the range of the particle. Therefore the energy, atomic number, and angle of trajectory of the particle have to be taken into account for the determination of the solid angle. For the selection of events with tracks confined within a defined cylindrical volume around the detector axis, a segmented anode was applied. The double-differential cross-sections for neutron-induced production of lithium, beryllium, and boron fragments from a carbon target were measured at 0° for 65 MeV neutrons. The results are in good agreement with theoretical calculation using PHITS code with GEM and ISOBAR model.

1. Introduction

The cross-section of charged particle production induced by neutrons at energies of tens of MeV is an important parameter in the estimation of energy transferred to matter by neutrons. In this energy range, neutrons generate not only light charged particles (p, d, t, ^{3}He, α) but also charged particles heavier than lithium (e.g., lithium, beryllium, and boron, referred to as fragments hereafter) through nuclear reactions with materials since the projectile energy is sufficient to induce fragmentation. In the estimation of the contribution of the fragments to the deposited energy, we require data set of energy and angular distributions, that is, the double-differential cross-section (DDX). The DDX is used in dosimetry and cancer radiotherapy to estimate the effects of exposure considering the particle species, absorbed energy, and spatial distribution. The DDX is also useful for simulating the rate of error in a silicon device due to electrons along the ionization track of charged particles generated from a reaction in the device material induced by neutrons originated from cosmic-ray [1–3].

Several experiments have been carried out for neutron-induced charged-particle production with light target nuclei at energies below 100 MeV to obtain DDX data. DDX data have been reported for a carbon target and the production of light charged particles (p, d, t, ^{3}He and α) by Kellogg [4], Subranabian et al. [5], Nauchi et al. [6], Slypen et al. [7], Dufauquez et al. [8] and Bergenwall et al. [9]. The Los Alamos National Laboratory Evaluated Nuclear Data Library LA-150 [10] and the Japanese Evaluated Nuclear Data Library High-Energy File [11] are available for consideration of the contribution to the deposited energy in these reactions. In contrast, for fragment production, there are few experimental data in this energy range. Currently, no evaluated nuclear data are available. The effect of fragment production has been neglected until now.

An alternative path for obtaining DDX data is the theoretical prediction using reaction models and parameters. In prediction, the validation of the models and parameters must be assessed using experimental data. DDX data for proton-induced reactions are suitable for this purpose since the data can be obtained more easily than data for neutron-induced reactions due to the availability of the monochromatic, intense, and focused primary beam in research [12,13]. The scheme provides reasonable DDXs

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for the higher energy region; however, for the lower energy region close to the reaction threshold and for the reaction on light target nuclei, the prediction of the neutron DDX is difficult. Thus, experimental data for neutrons are required at least for this condition (i.e., for light target nuclei around the reaction threshold energy, tens of MeV) to assess the applicability of the reaction models and their parameters, and to assure validity of the results.

There is a lack of data for the DDX of neutron-induced fragment production because there has been no appropriate detector for measuring fragments in this energy range. The detector should have a large solid angle of detection, particle identification capability, low stopping power, insensitivity to neutrons and light charged particles, and be suitable for low production rates and strong background signals. The conventional counter telescope used for the DDX measurement of light charged particle production is not applicable since no suitable transmission-type silicon detector is available with a wide area, a thickness of several microns, and good energy resolution.

A Bragg curve counter (BCC) is a good candidate for fragment measurement because of its large solid angle of detection, particle identification capability, small pulse-height defects, and insensitivity to protons, neutrons, and photons [12–15]. In this study, we develop a BCC for the DDX measurement of fragments from neutron-induced reactions at energies of tens of MeV. To enhance the solid angle of fragment counting, the production target is placed in the BCC. Fragments are contained in a cylindrical volume defined by a segmented anode to avoid events escaping the BCC. The solid angle of detection under this condition, which depends on particle species and their ranges, was obtained by both calculation and experiment. The DDXs of lithium, beryllium, and boron productions at 0° for neutron-induced reactions on carbon at 65 MeV are obtained using the BCC.

2. BCC for neutron-induced reactions

2.1. Internal production target and segmented anode

We employed an internal production-target setup that was similar to the gridded ionization chamber used in our previous studies [16,17] to measure the DDX with compensation of the low-intensity neutron flux and small production cross-section. Fig. 1 shows schematic diagrams of BCC setups with (a) external and (b) internal production targets. The BCC is a parallel-plate gas ionization chamber with a Frisch grid [14,15]. Normally, the BCC is used in an external production-target configuration with the target placed a certain distance from the BCC (Fig. 1(a)) [18,19]. In this configuration, the projectile beam irradiates the target. The BCC has a thin entrance window that enables the fragment to penetrate. The solid angle of detection Ω for this setup is

$$\Omega=\frac{\omega^2}{4}\left\{1-\frac{3}{4}(\phi^2+\omega^2)+\frac{15}{8}\left(\frac{\phi^4+\omega^4}{3}+\phi^2\omega^2\right)\right.$$
$$\left.-\frac{35}{16}\left[\frac{\phi^6+\omega^6}{4}+\frac{3}{2}\phi^2\omega^2(\phi^2+\omega^2)\right]\right\}\phi=R_s/d\omega=R_d/d \qquad (1)$$

where R_s is the radius of the production target, d the distance from the production target to the entrance window, and R_d the radius of the detector, which is equal to the radius of the window in this configuration [20]. As shown in Fig. 1(b), once the production target is set on the cathode plate, a shorter d and larger R_d give a larger solid angle.

Unfortunately, besides increasing the detection solid angle, the internal production-target setup introduces difficulty in the determination of the solid angle for fragments from the target.

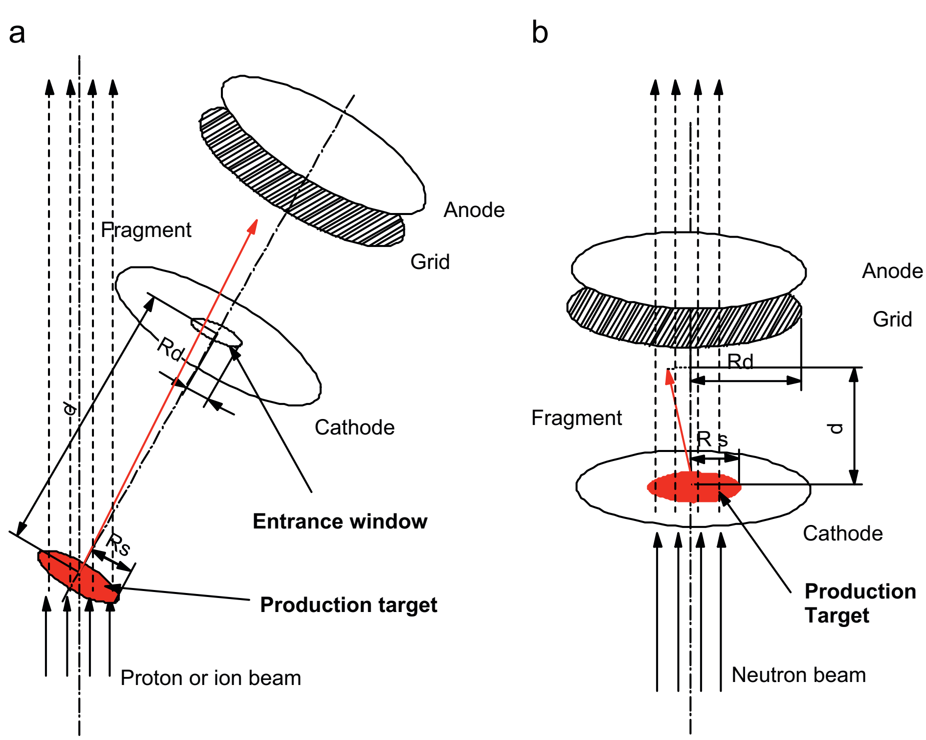

Fig. 1. Schematic diagrams of BCC configurations with (a) external and (b) internal production targets. BCCs are depicted as three electrodes: cathode, grid, and anode. In the external production-target layout, the target (radius *Rs*) is placed at a distance *d* from the BCC. The BCC has a thin entrance window (radius *Rd*). In the internal production-target setup, the target (radius *Rs*) is placed on the cathode. The solid angle of a fragment from the target is measured in terms of *Rs*, *d*, and *Rd* for both detection geometries. Since for fragment measurement with the use of BCC and the internal target setup *d* is not fixed, for the determination of detection solid angle the trajectories and ranges of the particles must be taken into account (for more details see text).