Measurement of Fragment Production Cross-section on Nucleon-induced Reaction

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We introduce our activities on measurements of fragment which are secondary particles heavier than alpha-particles produced by nucleon-induced reaction and have been recognized to be a cause of serious problem to semiconductor devices and human in a space environment by using a Bragg curve spectrometer (BCS) and energy-time-of-flight method (E-TOF), together with the activities in other facilities. For these studies and estimation, it is important to know the fragment production yield including the energy and angular distribution (double-differential cross-section (DDX) data) of fragments emission.

We have resulted in success to obtain light fragments on proton- and neutron-induced reactions by using a BCS developed for neutron specially and E-TOF method. Double-differential fragment production cross-sections obtained will be applied for the analysis of SEU and dose contributions.

1. INTRODUCTION

The radiation effects such as a single event effect (SEE) by terrestrial cosmic ray neutrons on microelectronics as well as on board aircrafts, have recently become serious problem and attracted much attention [1]. Among SEEs, single event upsets (SEU) or soft errors are presently considered the most important effects for the electronics. The particle with strongest effects is thought to be spallation neutrons created in the atmosphere by cosmic-ray protons and heavy particles because of much higher flux than other terrestrial cosmic-rays. When a circuit is exposed to a single particle such as proton or neutron, almost all these particles pass through the device with only little effect due to its low LET (liner energy transfer), but some particles induce nuclear reaction with the component materials of the device and produce secondary charged particles. Secondary particles heavier than alpha-particle that are called ‘’fragment” will be important on the SEE phenomena. Production rate of fragments is lower than one of lighter particles, but fragment cause a large local ionization and can make large energy deposition in μm order region because of significantly large LET. The charge released by ionization in a sensitive device region can cause a flip of the memory content in a bit, which is called a single-event upset (SEU). Unlike radiation with large dosage, an SEU event usually does not cause a permanent damage in the circuit, but it may cause serious reliability and performance problems that must be addressed in advanced technologies.

As mentioned above, for study and estimation of SEU, it is important to know the fragment production yield with the energy and angular distribution (doubly differential cross-section (DDX) data) of fragments emission induced by neutrons and protons. The energy information of fragment is required to know the energy deposition on the sensitive area of semiconductor devices. The angular information is also important because the energy spectrum of fragment has strong angular dependence. Moreover, data are required especially in intermediate energy region (ten’s of MeV – several 100 MeV) by considering the neutron flux energy distribution and the energy dependence of SEE probability [1].

The fragment data will also be important for the dosimetry for human in space and particle beam radiotherapy (proton, carbon and so on.). Usually the estimation of dosimetry does not include the effect of the fragment production. The conventional treatment of proton beam dosimetry is based only on the ionization loss according to the Bragg curve. However, from the calculation considering the nuclear spallation reactions, the dosimetry due to the spallation products (protons, light ions and heavy recoils) is found to be larger than usually believed [2]. Therefore the contribution of secondary particles including fragments produced by spallation reaction must be checked for the precise estimation of dosimetry in space environment and radiotherapy treatment.

2. PRESENT STATUS OF FRAGMENT PRODUCTION DATA

For light charged particles such as p, d, t and α, several experimental data have been reported. However for the fragments heavier than alpha-particle, the spectrum data is very few, because of such difficulties in the fragments measurement as low count rate, much short range and so on. Then the most of past fragment production data were obtained by activation method which provides no information on energy and angular distributions.

For proton-induced reaction, there are several data above 1 GeV energy region by nuclear physics group, but in intermediate energy region only two experimental data has been reported for carbon (45-100 MeV protons) by C. T. Roche et al. [3] and aluminum (180 MeV protons) by K. Kwiatkowski et al. [4] using Eergy-TOF (E-TOF) method (combination of energy and time-of-flight).

2-1. FRAGMENT EXPERIMENTS IN PROGRESS

Experiments for fragment production are mainly performed in the field of nuclear physics by using very high energy incident beam above 1 GeV/u. These experiments are classified into two parts generally by the experimental method.

One uses the “inverse kinematics method” and a large mass separator to overcome the problems of low count rate and very short range. By using the large detection system, many fragment production data have been obtained in GSI [5], MSU [6] and so on. In the “inverse kinematics method”, heavy ion is accelerated for projectile and bombard to light ion target like hydrogen. Due to the high energy of the center of mass, almost all products are transported to forward direction and the mass and charge information are obtained by using a magnetic field and ΔE, TOF measurement. The almost all data obtained by this method are limited in high energy region above 1 GeV/u. On the other hand, The Svedberg Laboratory in Uppsala has started using inverse kinematics method like GSI in the energy range of 100-470 MeV/u using a silicon projectile and a hydrogen target to study the fragment production reaction from silicon [7]. This method can perform very clear identification of isotopes over wide mass and charge range of fragments and enables to deduce production cross-section of the fragments simultaneously. This method is very effective to measure the production cross-section, but not effective to deduce the energy and angular distribution in proton-induced reaction.

Another method is recoil measurement and done at several facilities like KEK [10]. In this method, to overcome low count rate and the very short range, a Bragg curve spectrometer (BCS) [8, 9] which has flexibilities owing to be a gas counter is used for the main detector of fragments. Most experiments employing the technique are performed in very high energy region above 1 GeV/u., but below 1 GeV, PISA project [11] aims at double-differential cross-section measurement for proton induced reactions in 200 to 2,500 MeV region has been started recently.

2-2 CALCULATION

In the following we describe briefly the major reaction models which treat fragment production. The GNASH code developed by the Los Alamos National Laboratory [12] is constantly upgraded and has been very popular in radiation physics communities in recent years. However the code is limited to reactions of the energy below 150 MeV. For the data library, LA150 [13] which was evaluated with GNASH code is available below 150 MeV. This library is mainly used above 20 MeV regions in various fields. However, the fragment data for mass region above helium treat the angular distribution as isotropic.

As a nuclear model for application to high energy region, the JQMD code is recently developed by JAERI on the basis of quantum molecular dynamics [14]. Above 150 MeV, JQMD is recently used for SEU estimation. However these theoretical calculations treating fragment production are not validated well and uncertain due to very few experimental data. They should be examined by reliable experimental data.

3 PRESENT STUDIES

An important motivation of our group is to generate new data on energy and angular distribution of fragment produced from nucleon-nucleus reaction in ten's of MeV region. The fragment measurement has many difficulties such as low yields and large energy loss in sample and window and so on. In particular for neutron, which is very limited in flux compared with protons, the problem of low yield is critical for conventional counter telescope method (ΔE-E method). Therefore in the fragment measurement, large detection area, large solid angle and identification capability of fragments is required.

In this study, to overcome these problems, we adopted for the fragment measurements in ten's of MeV region 1) a Bragg curve spectrometer (BCS) [8, 9] providing various information with a single counter and 2) an energy-time of fight (E-TOF) method [3] having the capability of mass identification even in the energy region where BCS is not applicable, while the solid angle is very small. For 1), BCS was designed with special care to apply to a neutron beam as well as a charged particle beam, and resulted in success to obtain light fragments by proton- and neutron-induced reactions [15, 16]. For 2), the E-TOF method is restricted only to charged particle-induced reactions due to small detector solid angle. The dynamic range of fragment energy is higher than in BCS.

Table 1 shows the comparison to our group with other group introduced above. Our group aims to obtain energy-angular fragment production data in proton- and neutron-induced reaction with BCS and E-TOF method. The energy region is lower than in other facilities but this energy region is very important for SEU estimation and dosimetry for proton radiotherapy. For neutron, only our group has been challenging the measurements.

Table 1 Comparison with each facility in fragment measurement

	THO	TSL	PISA	GSI etc.
enery range (MeV)	30 - 90	100 - 470A	200 - 2500	>1A GeV
projectile	n,p	Si	p	Pb, U ….
method	BCS for n,p E-TOF for p	inverse kinematics	BCS and E-TOF coupled	inverse kinematics
data	DDX	reaction XS	DDX	reaction XS

3-1. BRAGG CURVE SPECTROMETER (BCS)

The details of Bragg curve spectrometer developed are described in the previous report [16]. Figure 1 shows a schematic diagram of BCS. It is a cylindrical gridded ionization chamber (GIC) [17] filled with an Ar + 10%CH_4 gas at a pressure of ~200 Torr. In the case of proton induced reaction, fragments produced from targets in the vacuum chamber enter the detector through a thin film window and ionize the gas in BCS. The free electrons drift to the anode by the electric field keeping a shape of Bragg curve. The time distribution of the anode signal corresponds to the reversal of the ionization distribution (Bragg curve) by the fragment. Therefore the fast part of anode signal is proportional to the Bragg peak value that is in proportion to the atomic number (Z) of the fragment. The integration of the whole anode signal represents the total charge that is proportional to the fragment energy. Therefore, BCS can provide information on the energy and the atomic number of fragments using only the anode signal.

To apply BCS to neutron-induced reactions, we put samples inside the chamber and irradiate the chamber by neutron directly to decrease the energy loss of fragments and enlarge the detection solid angle. We adopt tight neutron collimation, high-Z element (Ta) electrodes having small fragment production rate, and an additional shield electrode to reduce backgrounds due to neutron irradiation of the chamber body and counting gas.

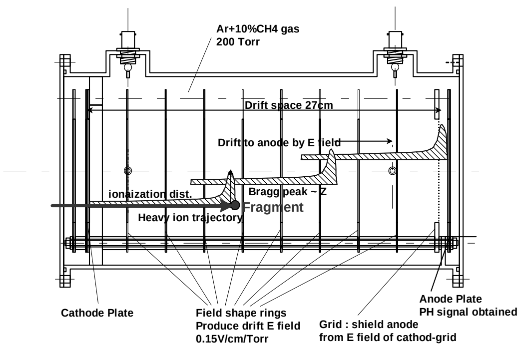

Fig. 1 Schematic diagram of the developed Bragg curve spectrometer (BCS)

Figures 2 and 3 show the measured two-dimensional spectra on the energy *vs.* Bragg peak of fragments from 4 μm thick polypropylene for 70 MeV proton and 75 MeV quasi-monoenergetic neutron [18], respectively. Excellent separation of each fragment and S/N ratio are confirmed up to Z = 6 (Carbon) for proton energy region where particles are separated by the difference of Bragg peak value. In case of neutron fragments heavier than α particle are separated distinctly, though the separation of Bragg peak is much inferior compared with proton-induced reaction due to the effects of the various emission angle. It is confirmed that we could obtain the yields of fragments with sufficient statistics using thin target (4 μm thick polypropylene) for sample and Au foil for background measurement.

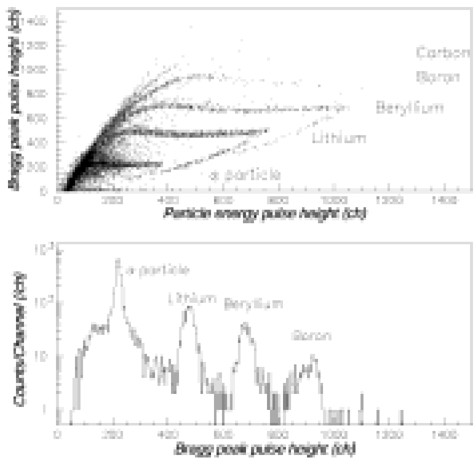

Fig.2 Energy vs. Bragg peak two-dimensional spectrum (top) and Bragg peak spectrum above separation limits (bottom) for polypropylene (4 μm) induced by 70 MeV protons.

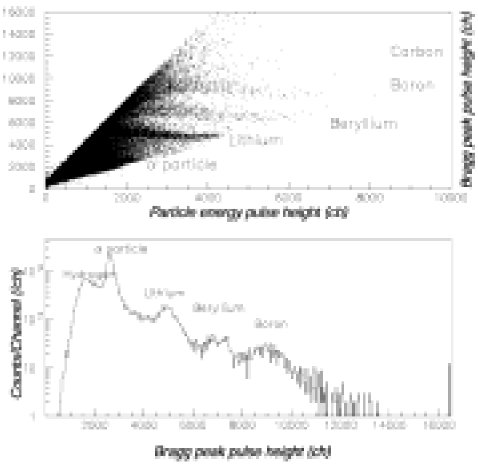

Fig.3 Energy vs. Bragg peak two-dimensional spectrum (top) and Bragg peak spectrum above separation limits (bottom) for carbon (200 μm) induced by 75 MeV quasi-monoenergetic neutron

3-2. ENERGY TIME-OF-FLIGHT (E-TOF METHOD)

For proton-induced reactions, we have applied an Energy-Time-Of-Flight (E-TOF) method which is used in heavy ion detection. In this method, the energy and TOF of the fragment is measured and mass number is derived by combing the energy and TOF. Therefore the dynamic range of fragment energy is higher than in BCS. These data will be useful to complement data obtained with BCS.

Up to now, we identified the fragments from polypropylene (4 μm thick) up to A=12 with the measurement system using an ultra-thin plastic scintillator and SSD with ~1 m flight path as shown in Fig.4. The energy spectra of fragments above mass of 6 were measured on the almost whole energy range. The fragments of mass number 5, 8, 9 were very few and the fragments above mass number 10 have small energy compared with lighter fragments. The time resolution of this setup was not so good because we use SSD for not only E detector but also a timing detector. We will develop the measuring system by using two timing detector for TOF measurement and E detector for energy measurement in the near future.

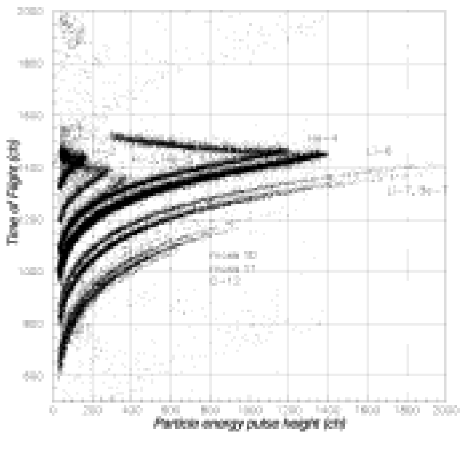

Fig.4 Energy *vs* TOF two-dimensional spectra for carbon 100 μm thick sample

5. SUMMARY

The present status of fragment experiment was reported for our group together with other facility. We are aiming at measurement of energy-angular spectrum of fragment induced by neutron and proton which is very important for SEU estimation and dosimetry for proton radiotherapy. For neutron, only our group has been challenging the measurements. To obtain the energy-angular spectrum of fragment by nucleon-induced reaction in ten's of MeV, we have developed a Bragg Curve Spectrometer (BCS) and E-TOF method. For BCS, excellent separation of each fragment are confirmed up to Z = 6 (carbon) for proton and neutron, respectively. Through the experiments, BCS proved to be applicable to not only proton-induced reactions but also neutron-induced reactions. We are also doing fragment production measurement for proton-induced reactions using the E-TOF technique to extend energy range and improve data quality and identified the fragments from polypropylene (4 μm thick) up to A=12 using an ultra-thin plastic scintillator for start detector and SSD for stop detector with ~1 m flight path. We intend to improve the measuring method with the refinement of data treatment and the data will be applied for the analysis of SEU and dose contributions.

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