III. 5. Measurement of Secondary Heavy Charged Particle Spectrum by Tens of MeV Nucleons

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We have continued the development of experimental techniques for fragment detection. Spectrum data of fragments (charged particles heavier than helium) induced by tens of MeV nucleon are important in the field of the space technology and radiation dosimetry because of the high LET. The data of the fragment production, however, are very scarce except for the integral data by activation method because of the experimental difficulties for direct fragment detection, i.e., low yield, large energy loss in samples. Therefore, it is important to develop an experimental method suitable for the fragment measurement and to accumulate reliable experimental data.

For detection of fragment, we adopted 1) a Bragg curve spectrometer (BCS)\(^1,2\) providing almost all information on the fragment with a single counter and 2) an energy-time of flight (E-TOF) method\(^3\) having the capability of mass identification in almost whole energy region for fragments.

For proton induced reaction, BCS was improved at the part of entrance window to decrease the lower limit of the detection energy. We use an aluminized Mylar film (2.5 \(\mu\)m thick) supported by tungsten wire to act as not only entrance window but also as a cathode electrode simultaneously. With the BCS developed, the new measurements of proton-induced reaction were performed using 70 MeV protons at 31-1 course of CYRIC. For samples, foils of aluminum 2 \(\mu\)m thick and polypropylene 4 \(\mu\)m thick were employed. Figures 1 and 2 show the measured two-dimensional spectra on the energy vs. Bragg peak of fragments from 4 \(\mu\)m thick polypropylene and 2 \(\mu\)m thick aluminum, respectively. Excellent separation of each fragment and S/N ratio are confirmed up to \(Z = 6\) (Carbon), 9 (Fluorine) for polypropylene and aluminum sample, respectively. In the method 2), the energy and TOF of the fragment is measured by SSD (silicon solid state detector) and Ultra
thin plastic scintillator (5 μm thick), respectively, and the mass number is derived by combing the energy, TOF and the energy loss information. The energy spectra of fragment heavier than alpha particle were obtained by both methods of BCS and E-TOF. Figure 3 shows the energy spectra of α-particle emitted to 30 degree from carbon and aluminum which were obtained with the BCS and E-TOF method. As shown in Fig.3, the data obtained with BCS and E-TOF method are consistent with each other in the overlapping region. The result of α-particle shows good agreements with LA150$^4$ except for the case of aluminum above 10 MeV. Figure 4 shows the energy spectra of fragments with mass number 6 obtained with E-TOF method. The present data for the mass number 6 agree with PHITS code$^5$, but not with LA150. Figure 5 and 6 show the energy spectra of beryllium from carbon and aluminum, respectively, at 30, 60 and 90 degree obtained with BCS. The present data show high angular dependence.

For neutron induced reaction, we designed a BCS$^6$ with special care to apply to neutron beam in the previous study and resulted in success first in the world to identify the fragments by neutron-induced reactions. Neutron data, however, was inferior to proton data because of mixing of particles with different directions from the sample on the cathode. In this study, an anode electrode with a segment pattern was newly adopted to the BCS as shown in Fig 7 to overcome the problem for inferior separation limit and uncertainty of the detector solid angle. The BCS was tested using a mixed α-source and fragments produced by 65 MeV quasi-monoenergite neutron source$^7$ at 32-1 course of CYRIC. Besides, the solid angle obtained with the segmented anode was compared with calculation based on energy-range relationship. Using a calibrated α-source, good agreement among experimental and calculation for the detector efficiency was confirmed in Fig. 9. The signal selection with the segmented anode improves particle separation in lower energy region as shown in Fig.8 and Fig. 10.

References

7) Okamura H. et al., this annual report.
Fig. 1. energy vs Bragg peak two-dimensional spectra for polypropylene 4 μm thick sample.

Fig. 2. energy vs Bragg peak two-dimensional spectra for aluminum 2 μm thick sample.

Fig. 3. DDX (alpha) at 30 degree compared with BCS and E-TOF method.

Fig. 4. DDX (mass 6) of p-C reaction at 30 degree compared with calculations.

Fig. 5. C(p,x)Be DDX at 30, 60 90 degree compared with calculations.

Fig. 6. Al(p,x)Be DDX at 30, 60 90 degree obtained with BCS.
Fig. 7. Schematic view of Bragg curve spectrometer, segment anode electrode and sample changer.

Fig. 8. Scatter plot of signals from center and around electrodes, and energy spectrum with and without rejection for mixed $\alpha$-source.

Fig. 9. Results of solid angle as a function of fragment range.

Fig. 10. Demonstration of improvement for secondary fragment identification by event rejection with segmented electrode.