Study of secondary charged-particle production by proton-induced reactions at several tens of MeV

M. Harada[a)], A. Yamamoto, Y. Tanaka, Y. Watanabe, K. Shin[*],
S. Meigo[**], O. Iwamoto[**], H. Nakashima[**], H. Takada[**],
S. Chiba[**], T. Fukahori[**], T. Sasa[**] and Su. Tanaka[***]
Department of Energy Conversion Engineering, Kyushu University, Kasuga,Fukuoka 816-8580, Japan
[*]*Department of Nuclear Engineering, Kyoto University, Kyoto, 606-8501, Japan*
[**]*Tokai Establishment, JAERI, Tokai-mura, Ibaraki 319-1195, Japan*
[***] *Takasaki Establishment, JAERI, Takasaki, Gunma 370-1292, Japan*
[a)]e-mail : harada@aees.kyushu-u.ac.jp

Double differential cross sections (DDXs) of charged particles emitted from proton-induced reactions on ^{12}C and ^{27}Al were measured at E_p=42 and 68 MeV. Experimental DDXs of protons were in fairly good agreement with LA150 evaluation, except for very forward angles. Coupled-channels calculation with the soft-rotator model reproduced well experimental angular distributions of elastic and inelastic proton scattering. Experimental angular distributions of continuum proton spectra showed overall good agreement with the Kalbach systematics.

1. Introduction

Proton and neutron nuclear data in the intermediate-energy region are requested in various applications, e.g. evaluation of radiation dose in proton radiotherapy and LSI damage estimation in cosmic space. Some of the authors[1)] have recently evaluated the neutron nuclear data and kerma factor of ^{12}C for energies up to 80 MeV. As the second step, we have started the evaluation of proton nuclear data of ^{12}C in the energy region up to 200 MeV.

Double-differential cross sections (DDXs) are needed for calculations of particle transport in matter. There are currently some available experimental DDXs data of proton-induced reactions, but few systematic measurements in the energy region ranging from a few tens of MeV to 200 MeV. Thus, we have started the experiments to measure DDXs of secondary charged-particles emitted from proton-induced reactions on several targets.

In the present work, we have measured DDXs of all emitted light-charged particles from ^{12}C and ^{27}Al with 42 and 68 MeV proton beams at the AVF cyclotron facility, TIARA. In this paper, preliminary results of the measurements and analyses are reported.

2.Measurement

The experiments were carried out with 42 and 68 MeV proton beams delivered to the HB-1 beam line at the AVF cyclotron facility. Detailed information on each experiment is summarized in Table 1. A 60 cmϕ scattering chamber was installed in the beam line as illustrated in Fig. 1. To reduce γ-ray backgrounds, a beam dump made of graphite was placed at a distance of 3 m from the chamber. Targets, which were self-supporting natural carbon foil (0.5 mg/cm^2 in thickness) and aluminum foil (0.9 mg/cm^2 in thickness), were located at the center of the chamber.

In order to measure the energy spectra of emitted charged particles, we have used a counter telescope consisting of three detectors: two thin silicon-semiconductor ΔE-detectors (30 μm and 500 μm in thickness, respectively), and a CsI(Tl) E-detector (18 mmϕ x 30 mm) with photo-diode readout. Fig. 2 shows a schematic side-view of the counter telescope. Those thickness and size were optimized using a Monte Carlo simulation of energy deposit in the detectors in which the effect of energy straggling was taken into account. The counter telescope was placed at a distance of 14.5 cm from the target in the scattering chamber and detected light-charged particles over the outgoing energy range from 1.5 MeV to 90 MeV for protons.

Energy signals from each detector were converted to digital data by using conventional NIM and CAMAC modules, and those data were stored event by event on an MO disk with SDAQ system[2)]. Off-line data processing was made with the PAW system in CERNLIB[3)].

3. Experimental results and analyses

In Fig. 3, experimental differential cross sections of proton elastic and inelastic scattering from ^{12}C at 42 and 68 MeV are compared with the coupled-channels calculations based on the soft-rotator model (SRM)[4)]. The optical potential parameters used in the calculation were the same as in Ref.[4)]. The SRM prediction is in good agreement with the experimental data.

Figure 4 shows measured DDXs of proton, deuteron, triton, ^{3}He and α-particle from 42 MeV proton-induced reactions on ^{12}C and 68 MeV proton-induced reactions on ^{27}Al at 30° in the laboratory system. Similar results were obtained for other angles. There is the energy region where no data were taken in Fig. 4 (a), because of higher discrimination level that was set to eliminate the electric noise in the signals from CsI detector. Since we failed to take low pulse signals from the ΔE1 detector in the 42 MeV proton-induced experiment, the threshold energies of proton, deuteron and triton in the experiment were rather high as shown in Fig. 4 (b). Also, continuum proton spectra measured at angles smaller than 45° may include a background component due to edge-penetration of elastic protons in the defining collimator. The background components are now under detailed investigation.

To check the reliability of the present data, the DDXs are compared with other experimental data[5,6)] and LA150 evaluation[7)] in Fig. 5. Our data show overall agreement with other experimental data, although they are slightly smaller than the data of Bertrand and Peelle[5)] at lower outgoing energies. The LA150 evaluation underestimates the measured DDXs in the continuous region between 15 and 50 MeV at 30°, while it shows fairly good agreement with the experimental data for the other angles.

Angular distributions of continuum proton spectra are compared with the Kalbach systematics[8)] in Fig. 6. A parameter " f_{msd} " which stands for the ratio of MSD component, were the same as used in LA150 evaluation[7)]. The calculations of the Kalbach systematics are in good agreement with the experimental angular distribution, except for underestimation seen at backward angles and overestimation at intermediate angles.

4. Summary

We have carried out the proton-induced experiments for ^{12}C and ^{27}Al at E_p=42 and 68 MeV at TIARA facility and measured the DDXs of secondary charged-particles (p, d, t, ^{3}He and α) emitted from these reactions. The experimental angular distributions of elastic and inelastic proton scattering from ^{12}C were in quite good agreement with the coupled-channels calculation based on SRM. Comparisons with other experiments and LA150 evaluation showed good agreement for ^{12}C(p,xp) and ^{27}Al(p,xp) reactions. The shape of continuum (p,p') angular distributions were reproduced well by the Kalbach systematics. The detector system developed in the present work was found to be reliable and useful in DDXs measurements, although there was a difficulty on the elimination of electric noise in the signal from the CsI-detector. The obtained data will be useful for intermediate-energy proton nuclear data evaluation.

In the future, we plan further measurements of DDXs for some different incident energies and supplementary experiments to measure deficient region of the energy spectra.

Acknowledgments

This work was undertaken as the Universities-JAERI Collaboration Research Project. We wish to thank the staff of AVF cyclotron team for their cyclotron operation during our experiment. This work is partly supported by Grand-in-Aid Scientific Research of the Ministry of Education, Science and Culture (No. 09558059).

Reference

[1] M. Harada *et al.*: *J. of Nucl. & Technol.* **34**, 116 (1997).
[2] K. Sato: Master thesis, Kyushu Univ., (1993) (unpublished).
[3] PAW-Physics Analysis Workstation CERN Program Library entry Q121 (1993).
[4] E.S. Sukhovitskii, *et al.*: *Nucl. Phys.*, **A640**, 147 (1998).
[5] F.E. Bertrand and R.W. Peelle: *Phys. Rev. C*, **8**, 1045(1973); ORNL report *ORNL*-4799, (1973).
[6] H. Sakai *et al.*: *Nucl. Phys.* **A344**, 41 (1980).
[7] M.B. Chadwick *et al.*: *LA-UR*-98-1825 (1998); to be published in *Nucl. Sci. Eng.* (1998).
[8] C. Kalbach: *Phys. Rev. C*, **37**, 2350 (1988).

Table 1: Details of the proton-induced experiments at TIARA.

Incident energy	42 MeV		68 MeV
Accelerator	JAERI TIARA AVF cyclotron Accelerator		
Target	Self-supporting natural Carbon foil 0.5 mg/cm^2 Self-supporting Aluminum foil 0.9 mg/cm^2		
Configuration of counter telescope (applied bias voltage)	ΔE1 : Si-SSD 30 μm, 13 V ΔE2 : Si-SSD 500 μm, 135 V E3 : CsI(Tl) 3 cm, 80 V, Photo-diode readout		
Measured particles	p, d, t, ^{3}He, α-particle		
Measured angles (lab.)	^{12}C 25, 30, 35, 40, 45, 60, 75, 90, 105, 120, 130, 140, 150°	^{27}Al 25, 30, 35, 40, 45, 60, 75, 90, 105, 150°	^{12}C & ^{27}Al 25, 30, 35, 45, 60, 75, 90, 120, 150°
Beam current	2 ~ 23 nA*		2 ~ 16 nA*

*Beam currents depend on target and angle.

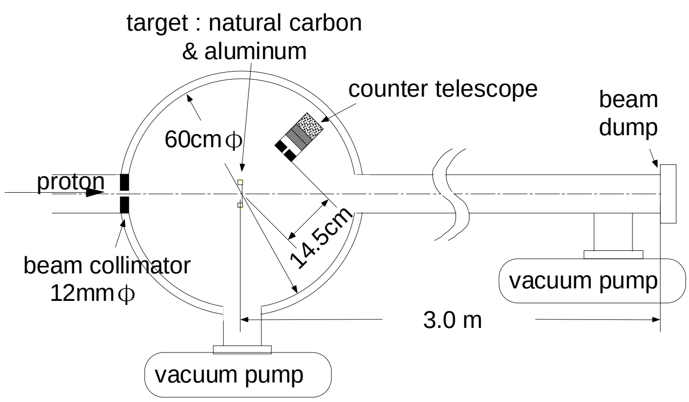

Fig. 1: Experimental setup of the HB-1 beam line at TIARA.

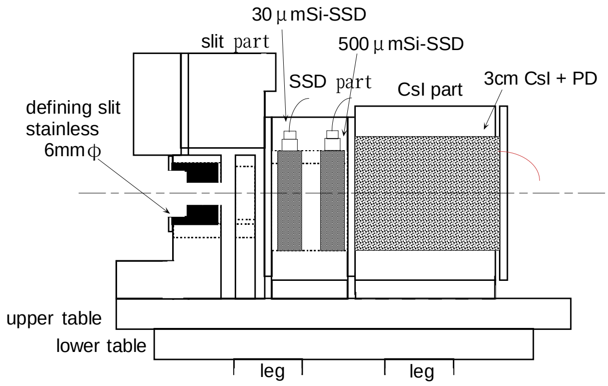

Fig. 2: Schematic side-view of ΔE-E counter telescope.

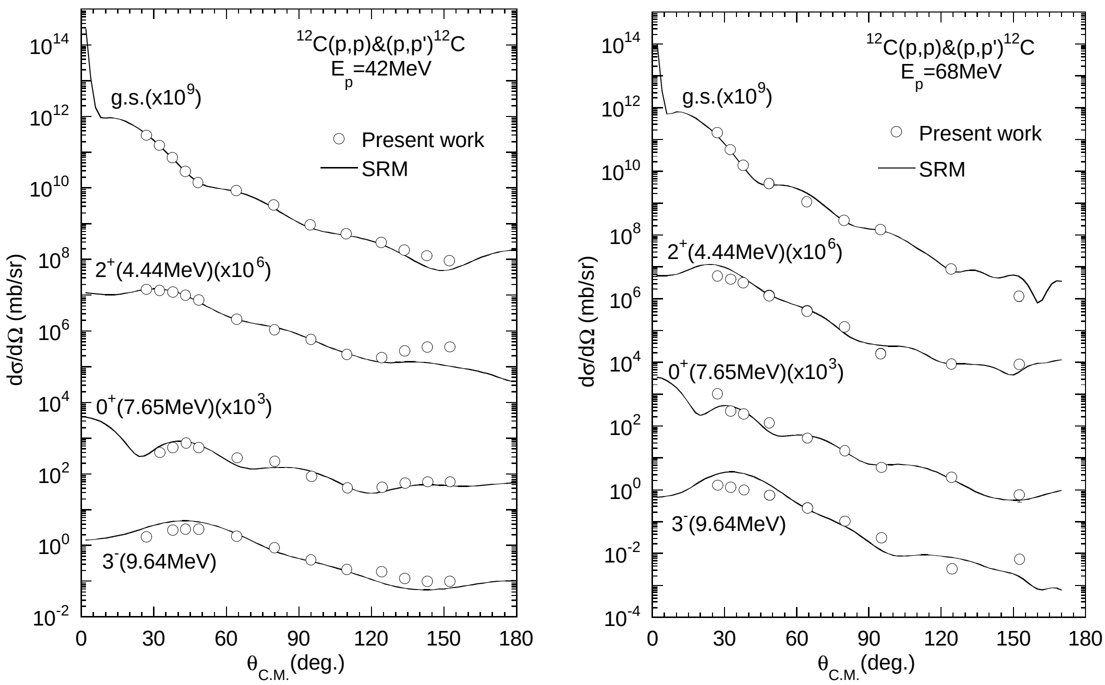

Fig. 3: Comparison of experimental angular differential cross sections of ^{12}C(p,p) and ^{12}C(p,p') scattering with coupled-channels calculation based on the soft-rotator model at 42 MeV (left-panel) and 68 MeV (right-panel).

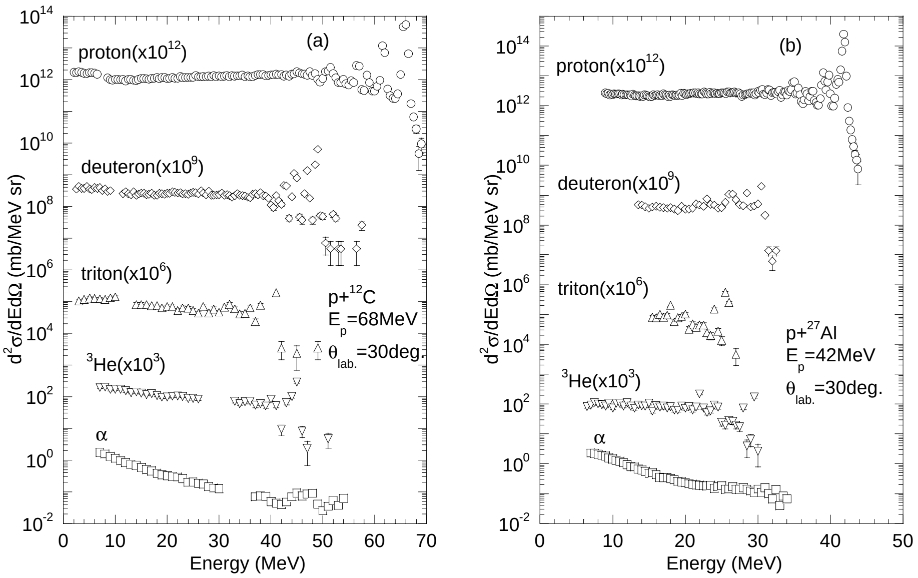

Fig. 4: Measured DDXs of proton, deuteron, triton, ^{3}He and α-particles: (a) 68 MeV p+^{12}C reaction and (b) 42 MeV p+^{27}Al reaction at 30° in the laboratory system.

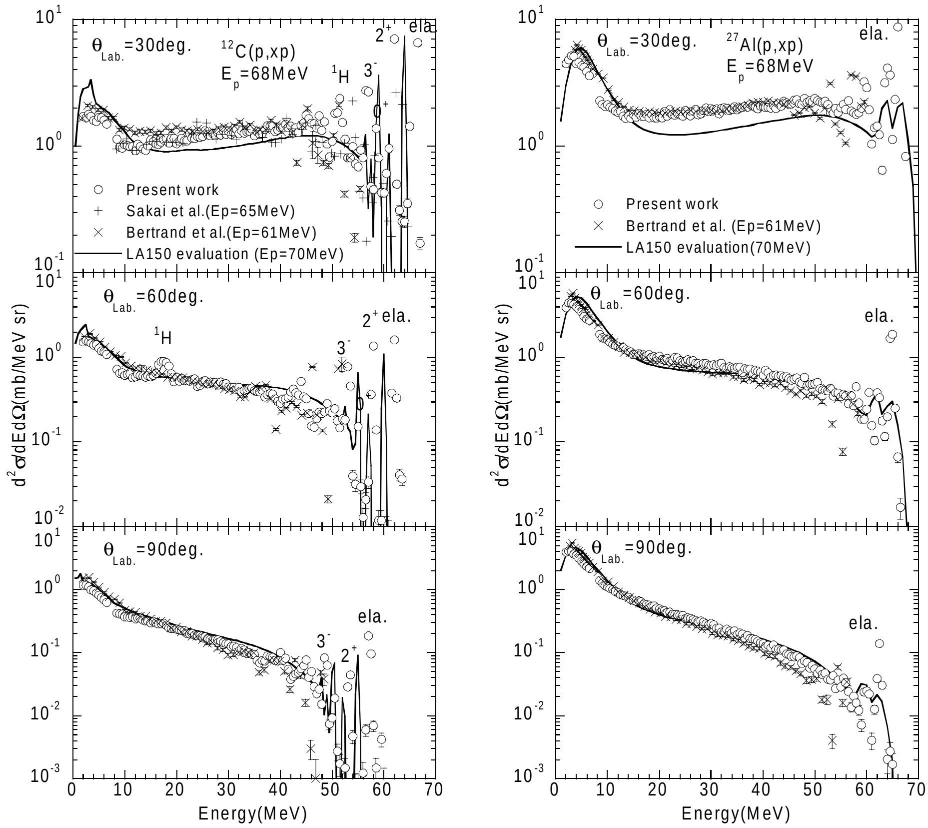

Fig. 5 : Comparison of experimental double differential cross sections of ^{12}C(p,xp) (left panel) and ^{27}Al(p,xp) (right panel) with other experimental data and evaluation of LA150 library for three angles and an incident energy of 68 MeV.

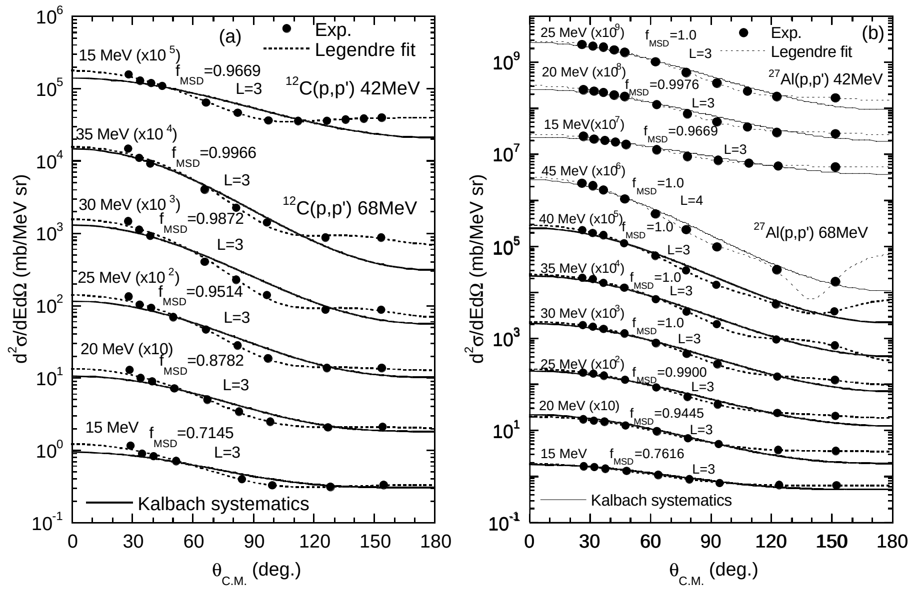

Fig. 6: Comparisons of experimental double differential cross sections with calculations using the Kalbach systematics at 42 and 68 MeV: (a) ^{12}C(p,p’) and (b) ^{27}Al (p,p’).