Study of the p+^{12}C reaction at energies up to 30 MeV

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Double differential cross sections of charged-particles emitted in the p+^{12}C reaction were measured in the energy region from 14 to 26 MeV. The observed continuous components of emitted protons and α-particles were analyzed by assuming sequential decay of intermediate reaction products and/or simultaneous breakup process. It was found that the three body simultaneous decay, p+α+^{8}Be, and the sequential decay via p+$^{12}C^*_{3-}$ and α+$^{9}B_{g.s.}$ are most important in the proton-induced breakup of ^{12}C for energies up to 30 MeV.

1. Introduction

Intermediate energy nuclear data of neutron- and proton-induced reactions on ^{12}C are required for various applications, e.g., dose evaluation in proton radiotherapy. Some of the authors have recently evaluated the neutron nuclear data of ^{12}C for energies up to 80 MeV[1]. In the work, it was found that α-particle production cross sections for the n+^{12}C reaction become large at energies around 20 MeV. They assumed that α-particle emission occurs mainly via the sequential and simultaneous breakup of intermediate excited nuclei such as ^{12}C and ^{9}B and evaluated double-differential cross sections (DDXs) for neutron and α-particle emission. To understand the detail of such many-body breakup processes, measurements of DDXs for all particles emitted at the same incident energy and simultaneous analysis are helpful. However, there is few experimental data not only for the n+^{12}C reactions, but also for the p+^{12}C reaction in the energy region of interest. Thus, we have started to study the nucleon-induced breakup processes for ^{12}C through proton experiments which can provide the data with better statistics than neutron experiments. The result is expected to be useful for intermediate energy proton and neutron nuclear data evaluation.

In the present work, we have measured the DDXs of protons and α-particles emitted in the p+^{12}C reaction at energies of 14, 18 and 26 MeV by using two type of ΔE-E counter telescopes and analyzed the continuum components observed in proton and α-particle emission spectra. In this report, preliminary results of our analyses are reported.

2. Measurement

2.1.Counter telescopes

We have developed two counter telescopes for the present experiments. One was a ΔE-E counter telescope having three stacked Si-SSD detectors as ΔE-E detector and an NE102A plastic scintillator as active collimator (AC). The details have been reported in Refs. [2,3,4,5]. A schematic side-view of the counter telescope is illustrated in Fig. 1 and their thickness are also tabulated. The AC played a role of a veto detector to reduce the continuum background component due to the edge-penetration which makes it difficult to measure continuum (p,p') spectra at very forward angles.

The other was a ΔE-E counter telescope with a gas proportional counter as ΔE-detector and a Si-SSD as E-counter. A side-view of the counter telescope is shown with the specification in Fig. 2. The details have been described in Ref.[6]. We chose the gas proportional counter as the ΔE-detector because we make the detectable threshold energy as low as possible. Note that the threshold energy obtained in the present measurement was 1 MeV for α-particles and 0.5 MeV for protons.

2.2.Outline of the experiments

Two experiments have been carried out using (i) the Kyushu University Tandem accelerator for 14 and 18 MeV and (ii) the JAERI Tandem accelerator for 26 MeV. The above-mentioned two counter telescopes were used in the experiment (i), however only the ΔE-E counter telescope with the AC was used in the experiment (ii). A natural carbon foil of 100 $\mu g/cm^2$ thick was used for both measurements. Signals from each detector were processed using commercially available NIM modules and were stored as even-by-event data using PC-based multi-parameter data acquisition system. Proton and α-particle emission spectra were measured at angles from 20° to 150° in step of 10° in the laboratory system for the 14 MeV and 26 MeV and at 20°, 30°, 40°, 60°, 90°, 120° and 150° in the laboratory system for 18 MeV.

3. Analysis

3.1. Simulation code for breakup processes

The SCINFUL/DDX code[1] developed for the neutron nuclear data evaluation for ^{12}C was revised partly for the analysis of continuous spectra of emitted protons and α-particles. In the revised code, we took account of ten sequential decay processes and one three-body simultaneous break-up (3BSB) as listed in Table I. This code calculates DDXs of particles emitted via these many-body breakup processes by using a Monte Carlo method. The cross sections and angular distributions necessary as the input data are summarized in Table II. The angular distributions of particles emitted at the second stage and afterwards were assumed to be isotropic in the c.m. system. In the addition, the finite lifetime for levels of excited states of ^{12}C, ^{9}B, ^{8}Be were considered by using the decay width of a Lorentzian or Gaussian shape. Finally, the calculated results were smoothed using a Gaussian distribution with the experimental energy resolution (200 keV FWHM) for comparisons with the experiments.

3.2.Results and discussion

Figures 3 to 5 show comparisons of the measured DDXs of $^{12}C(p,xp)$ and $^{12}C(p,x\alpha)$ with the calculated ones for 14, 18 and 26 MeV, respectively. Open circles and open triangles stand for the experimental data taken using the counter telescope with AC and those taken using of the counter telescope with the gas counter. The calculated spectra show overall good agreement with the experimental data.

From the analysis, it was found that the continuous spectra observed in the lower emission energy region are formed mainly via the sequential decay processes denoted by (1) to (10) in Table I. It should be remarked that the present detector system succeeded in observing low energy protons emitted via the sequential decay processes (3) in Table I for 14 and 18 MeV. The component of sequential proton decay of $^{9}B_{g.s.}$ deduced from the experimental cross section of $^{12}C(p,\alpha)^{9}B_{g.s.}$ reproduces satisfactorily the bump structure observed in the low energy part of the proton spectra measured at small angles for 14 and 18 MeV. Also, α-particles decaying chain via $^{9}B_{g.s.}$((3) in Table I) form the small bump observed in the experimental data for 14 and 18 MeV as shown in Figs. 3 and 4. Discrepancies seen in Fig. 4 is attributable to ignoring (p,np) reaction and $(p,\alpha)^{9}B^{*}_{7MeV}$ reaction in the present version of our simulation code.

On the other hand, the 3BSB process becomes predominant with increasing emission energy. The ratios of the 3BSB to the total continuum component extracted from the present analysis amount to 23 % for 14 MeV, 50 % for 18 MeV and 71 % for 26 MeV. This indicates that the 3BSB process has the most dominant contribution to the many-body breakup process of ^{12}C induced by proton with 14 to 26 MeV. However, the 3BSB components near the threshold energy underestimate both the experimental (p,xp) and (p,xα) spectra for any incident energies. It is expected that a possible reason is why the $p+\alpha+^{8}Be_{g.s.}$ process was neglected in the calculation. According to Antolkovic et al., the fraction of the total cross section of the $n+^{12}C\rightarrow n+3\alpha$ amounts to 12.5% for 18 MeV[7]. Our preliminary calculation for the $p+^{12}C$ reaction at 18 MeV with this value showed that the agreement was improved at small angles, but the calculated cross sections overestimated the experimental ones at large angles. This might be due to some differences between the n+^{12}C and p+^{12}C reactions at the same energy. Further study the 3BSB process in nucleon-induced breakup reactions on ^{12}C will be necessary to know the detail of the mechanism.

4.Conclusion

The DDXs of emitted charged particles in the p+^{12}C reaction were measured at three incident energies of 14, 18 and 26 MeV. The continuum components in proton and α-particle emission spectra were analyzed by assuming the many-body breakup processes. It was found that the sequential decay via p+$^{12}C^*_{3-}$ and α+$^{9}B_{g.s.}$ are dominant in the low emission energy region component and the 3BSB process becomes large with increasing emission energy. There appear some discrepancies between the calculated and measured continuous spectra. Further detailed analysis will be necessary to resolve them and to enhance the understanding of nucleon-induced breakup of ^{12}C over the wide incident energy region.

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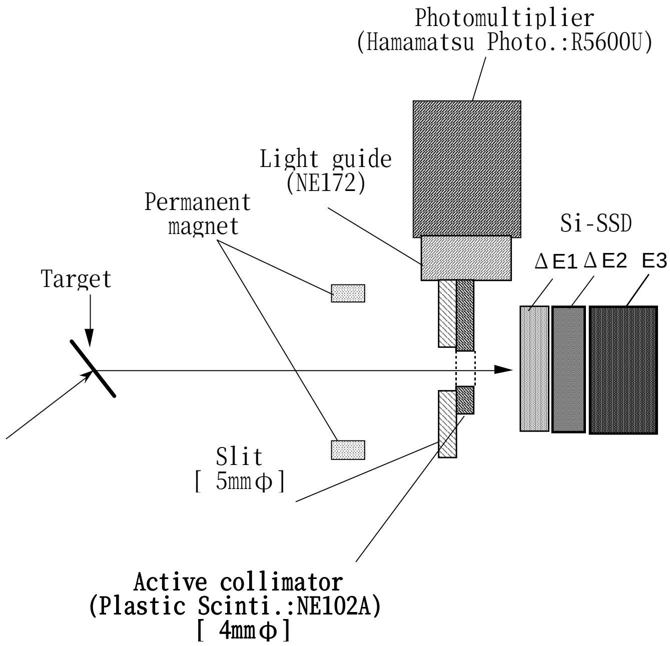
Table I : Reaction processes considered in the present analysis

1, p + ^{12}C → p' + ^{12}C* (0^+, ex.=7.65MeV)	5, p + ^{12}C → p' + ^{12}C* (1^-, ex.=10.8MeV)
2, p + ^{12}C → p' + ^{12}C* (3^-, ex.=9.64MeV)	6, p + ^{12}C → p' + ^{12}C* (2^-, ex.=11.8MeV)
→ α + $^{8}Be_{g.s.}$	7, p + ^{12}C → p' + ^{12}C* (1^+, ex.=12.7MeV)
→ α + α	8, p + ^{12}C → p' + ^{12}C* (4^+, ex.=14.1MeV)
3, p + ^{12}C → α + $^{9}B_{g.s.}$	9, p + ^{12}C → p' + ^{12}C* (1^+, ex.=15.1MeV)
→ p + $^{8}Be_{g.s.}$	10, p + ^{12}C → p' + ^{12}C* (2^+, ex.=16.1MeV)
→ α + α	→ α + ^{8}Be* (2^+, ex.=2.94MeV)
4, p + ^{12}C → α + ^{9}B*(5/2^-, ex.=2.36MeV)	→ α + α
→ α + ^{5}Li	11, p + ^{12}C → p + α + ^{8}Be* (2^+, ex.=2.94MeV)
→ p + α	→ α + α [3BSB]

Table II : Input data used in the simulation code

Reaction	Cross Section	Angular distribution
1, 2	14MeV : Hane (1992)[8] 18MeV : Peelle(1957)[9] 26MeV : Kashimoto(1993)[10]	14MeV : Hane (1992) 18MeV : Peelle(1957) 26MeV : Kashimoto(1993)
3, 4	14MeV&18MeV : *Present work* 26MeV : Kashimoto(1993)	14MeV&18MeV : *Present work* 26MeV : Kashimoto(1993)
5 - 10	14MeV&18MeV : *Present work* 26MeV : Kashimoto(1993)	14MeV&18MeV : *Present work* 26MeV : Kashimoto(1993)
11	14MeV&18MeV : $\sigma_{reac.}$[a)] - σ_{2+}[b)] - $\Sigma_{1\text{-}10}\sigma_n$ 26MeV : $\sigma_{p+3\alpha}$[c)] - $\Sigma_{1\text{-}10}\sigma_n$	isotropic

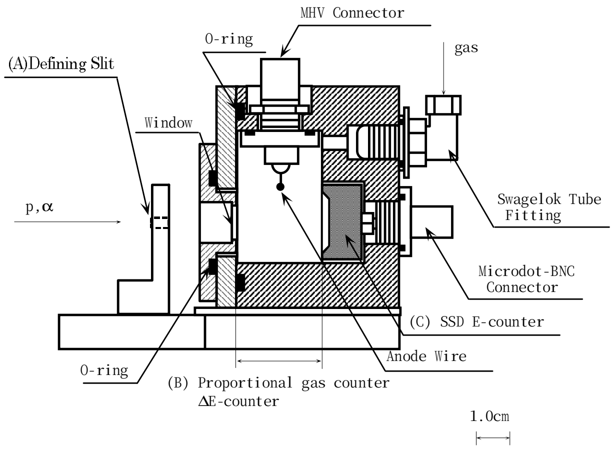
[a)] Total reaction cross section : Makino(1965)[11]
[b)] Inelastic 2^+ cross section : Peelle(1957)
[c)] p+3α reaction cross section : Kashimoto(1993)



[Thickness of each detector]

	Kyushu-Univ. Exp.	JAERI Exp.
AC	0.5 mm	2 mm
ΔE1	25 μm	30 μm
ΔE2	100 μm	200 μm
E3	2000 μm	5000 μm

Fig. 1 : Side view of counter telescope with active collimator



[Detail of defining slit and each detector]

defining silt	3mmϕ	
ΔE-detector	proportional gas counter	
	anode wire	nichrome, 20μmϕ
	window	mylar foil, 1.6μm
	gas	P-10 gas
E-detector	300μm Si-SSD	

Fig. 2 : Side view of low threshold energy counter telescope

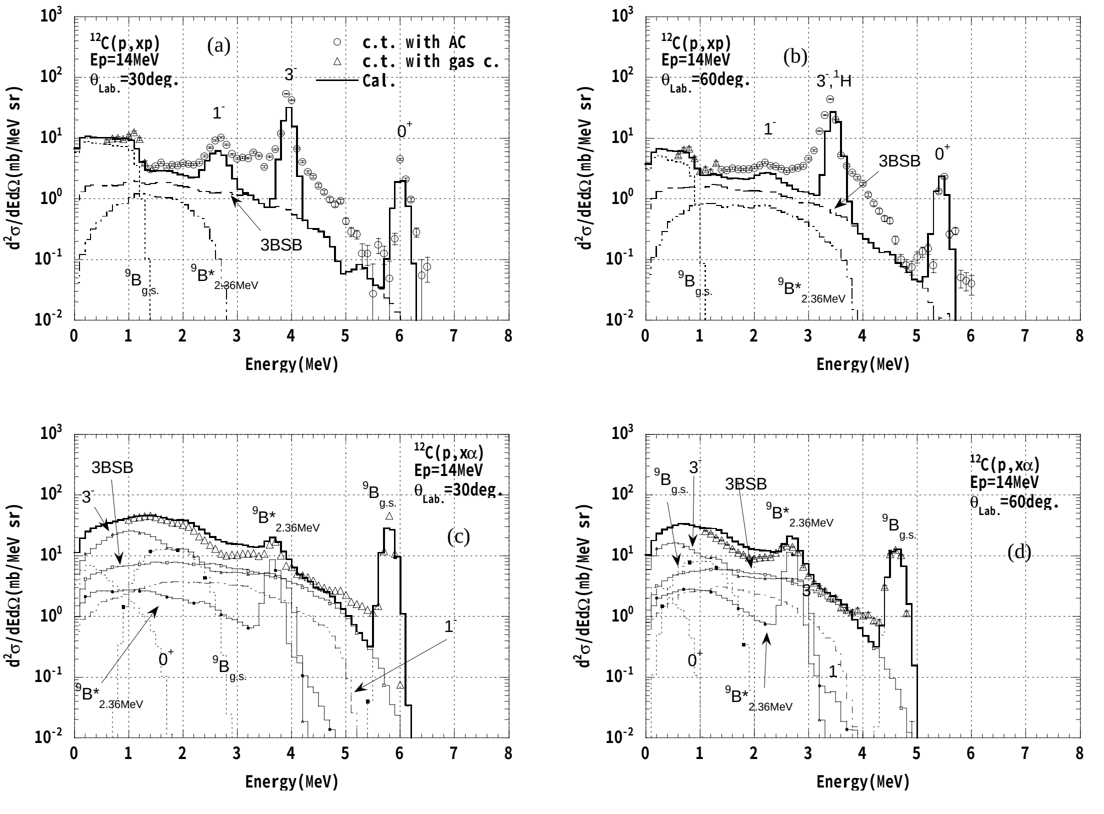


Fig. 3 : Measured and calculated DDXs for 14 MeV (p,xp) and (p,xα) for laboratory angles of 30° and 60°

The peak of the contamination (Hydrogen-1) is denoted by the symbol ^{1}H.

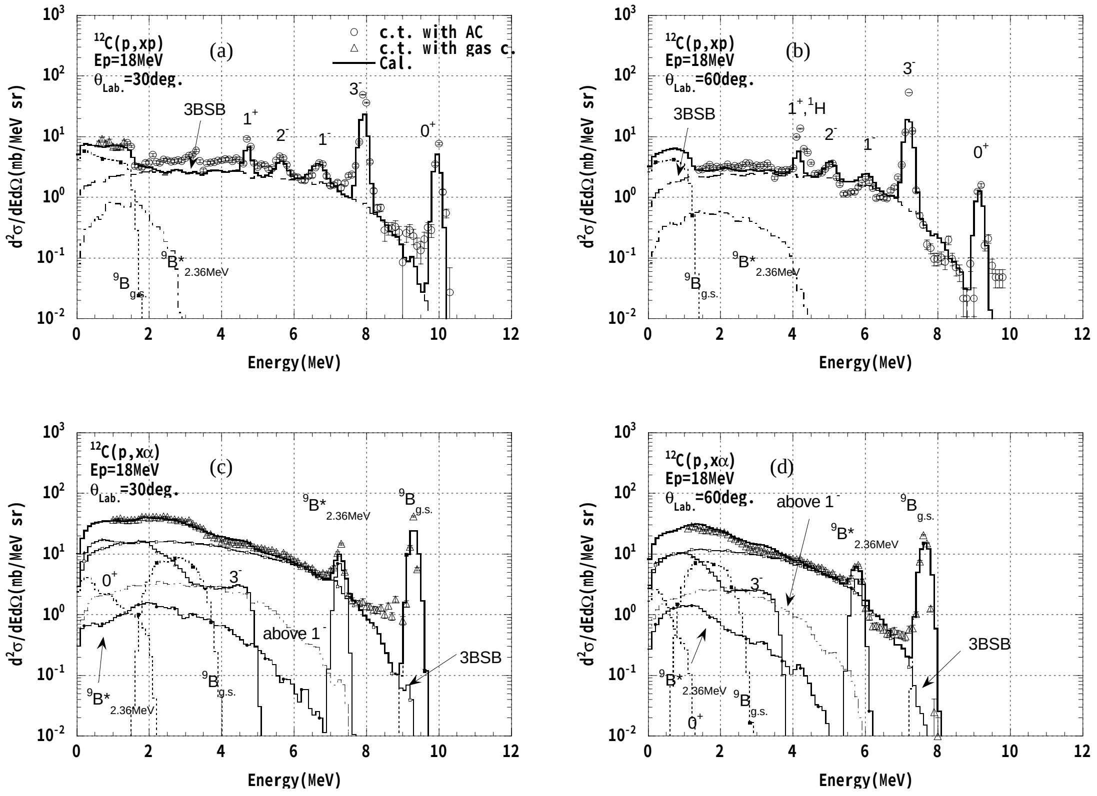


Fig. 4 : Same as in Fig. 3, but for 18 MeV

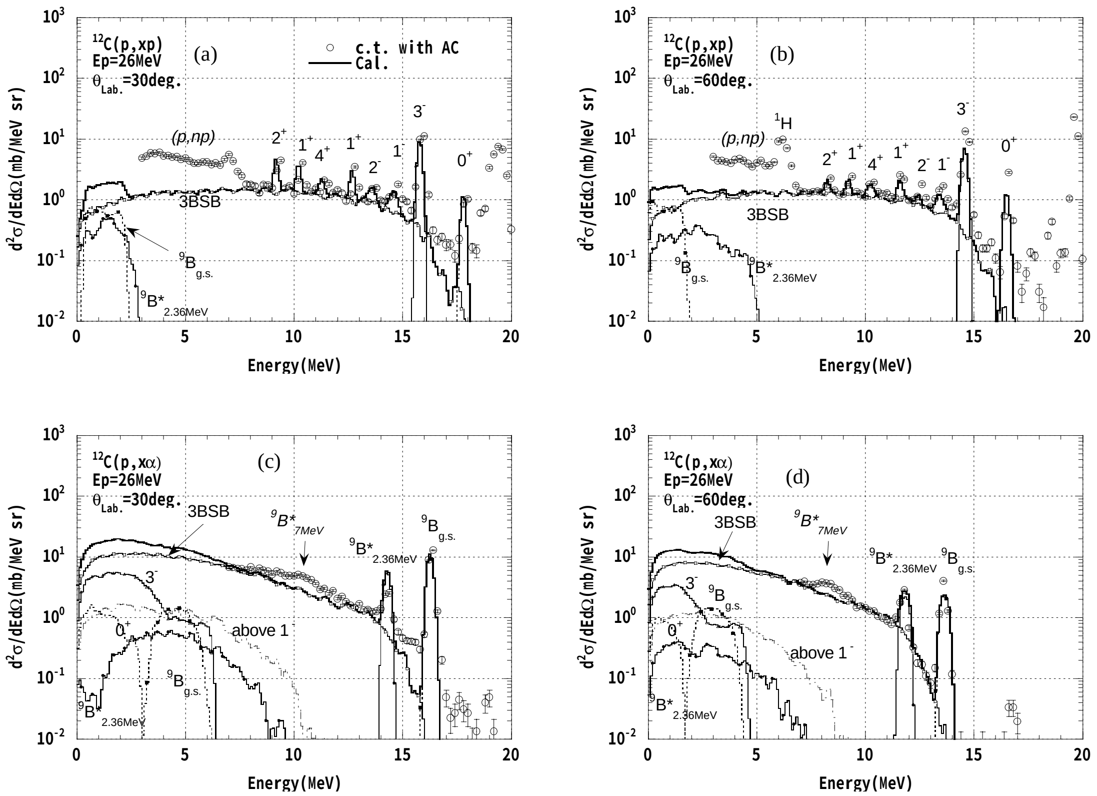


Fig. 5 : Same as in Fig. 3, but for 26 MeV