Measurement of charged-particle emission DDX for carbon with 14-MeV incident neutrons

Keitaro Kondo[1], Isao Murata[1], Kentaro Ochiai[2], Hiroyuki Miyamaru[1], Naoyoshi Kubota[2†], Chikara Konno[2] and Takeo Nishitani[2]

[1] *Division of Electrical, Electronic and Information Engineering, Graduate School of Engineering, Osaka University, Yamada-oka 2-1, Suita, Osaka 565-0871, Japan*

[2] *Japan Atomic Energy Agency,*
Shirakata Shirane 2-4, Tokai-mura, Naka-gun, Ibaraki, 319-1195, Japan

[†] *Present address: Materials Characterization Laboratory, Nippon Steel Corporation*

e-mail: ktaro@ef.eie.eng.osaka-u.ac.jp

A preliminary measurement of charged-particle emission double differential cross-section (DDX) for carbon with 14-MeV incident neutrons was carried out. In the measurement, a superior S/N ratio, fine energy and angular resolution were realized with a pencil-beam neutron source and a counter telescope consisting of a pair of silicon surface barrier detectors, ΔE and E. Minimum detection energy of 1.0 MeV for α-particles was achieved by utilizing an anticoincidence spectrum of the ΔE detector. The agreement of our measurement with a previous data measured by Haight et al. was fairly well in the higher energy part of DDX, while a discrepancy was observed below 3 MeV. In order to investigate the mechanism of the $^{12}C(n,n'+3\alpha)$ reaction, we tried to calculate energy distributions of emitted particles by the Monte Carlo method considering reaction kinematics of a lot of channels which contribute to the reaction. As a results, the contribution of the $^{9}Be^{*}_{(4.7\,MeV)}$ channel was suggested and the estimated branching ratio for the $^{12}C(n,\alpha)^{9}Be^{*}_{(\geq 2.43 MeV)}$ channels was more than 30%.

1. Introduction

In fusion reactor development, double-differential cross-section (DDX) for charged-particle emission reaction induced with 14-MeV neutrons is needed to calculate nuclear heating and fundamental values to evaluate material damages, i.e. primary knock-on atom (PKA) spectra, amount of gas production and displacement per atom (DPA) cross-sections. The particularly important charged-particle emission DDX is of nuclides contained in the first wall and blanket materials highly exposed to 14-MeV incident neutrons. We recently developed an improved measurement system for secondary emitted charged particles using a pencil-beam neutron source furnished in the Fusion Neutronics Source (FNS) in Japan Atomic Energy Agency (JAEA) [1]. Systematic measurements are being carried out for light nuclei of which the measurement has not yet been performed sufficiently so far [2]. In this paper, a preliminary result of measurement for carbon is presented. Carbon is one of the important nuclides for organic materials. Regarding the fusion reactor development, carbon is proposed for an alternative first wall and contained in SiC, which would be an advanced material for various devices. Detailed measurement is also important from an aspect of nuclear physics because of the complex mechanism of the $^{12}C(n,n'+3\alpha)$ reaction. We tried to reproduce energy spectra of emitted particles from the reaction by Monte Carlo calculations considering reaction kinematics. The reaction mechanism was investigated through the calculation and analysis.

2. Experimental

2.1 Charged-particle spectrometer using a pencil-beam neutron source

All the present measurements of DDX were carried out with the pencil-beam DT neutron source available at FNS/JAEA. A schematic view of the facility and the experimental setup is shown in **Figure 1**. In the facility, a deuteron beam of 350 keV and 20mA at the maximum bombards a large tritium target. Generated DT neutrons are collimated by a 2 m thick shielding structure with a narrow hole of 2 cm in diameter. The mean neutron energy is 14.2 MeV. A vacuum chamber was set at the outlet of the neutron beam, and a sample material was fixed at the center of the chamber. The sample material used in the present study is a self-supported carbon foil of 5 μm thickness (1033 $\mu g/cm^2$). A counter-telescope system with a pair of silicon surface barrier detectors, one for ΔE (thickness of 9.6 μm) and the other for E (thickness of 760 μm), was employed in order to distinguish kinds of emitted charged particles. The minimum detectable energy of the telescope, which depends on the thickness of the ΔE detector, is 2.5 MeV for α-particles. In order to extend the detectable energy range for α-particles as much as possible, we attempted to use an anticoincidence spectrum of the ΔE detector. When the ΔE detector of 9.6 μm thickness is used, the threshold energy beyond which the ΔE detector can be penetrated is around 700 keV for protons and around 1.0 MeV for tritons. The anticoincidence spectrum above those threshold energies for protons and tritons hence originates only from α-particles or particles heavier than α-particles. In the present measurement, recoiling carbon and ^{9}Be particles emitted via the $^{12}C(n,\alpha_0)^{9}Be$ reaction cannot be negligible and their contributions were calculated and subtracted. As a result, the measurement of α-particles with a minimum energy of around 1 MeV was successfully realized.

2.2 Data analysis

In order to obtain an actual energy spectrum of emitted charged particles, the measured spectrum must be corrected for energy loss in the sample. A relationship between the actual spectrum and the measured spectrum was calculated by the Monte Carlo code SRIM-2003 [3] combined with the processing codes we made. Then the spectrum unfolding was carried out with our original code based on the spectrum type Bayes estimation method [4] to obtain the actual spectrum. For a standard cross section, 122.0 mb for the $^{27}Al(n,\alpha)$ reaction evaluated in JENDL-3.3 [5] was used.

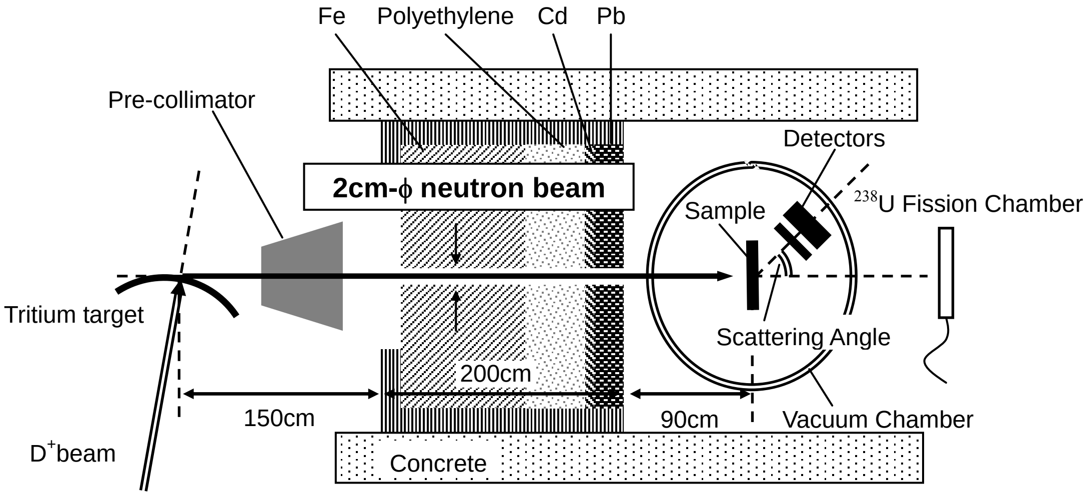

Figure 1　Experimental arrangement.

3. Results and discussion

3.1 Measured double-differential cross-section for α-particles

Up to now, DDX for α-particles has been obtained for only 30 degrees of emission angle in our measurement and further measurements are still in progress. **Figure 2** shows the obtained DDX and the previously measured DDX by R. C. Haight *et al.* [6] at the emission angle of 30 deg.. In our DDX, the contribution from the $^{12}C(n,\alpha)^{9}Be$ was clearly identified. The obvious structures according to $^{9}Be_{(Ground\ State)}$ and $^{9}Be^{*}_{(2.43\ MeV)}$ appeared. Also the contribution of $^{9}Be^{*}_{(4.7\ MeV)}$ might exist. Between the both measurements, the agreement of the higher energy part of DDX is fairly well, while a slight discrepancy was observed below 3 MeV.

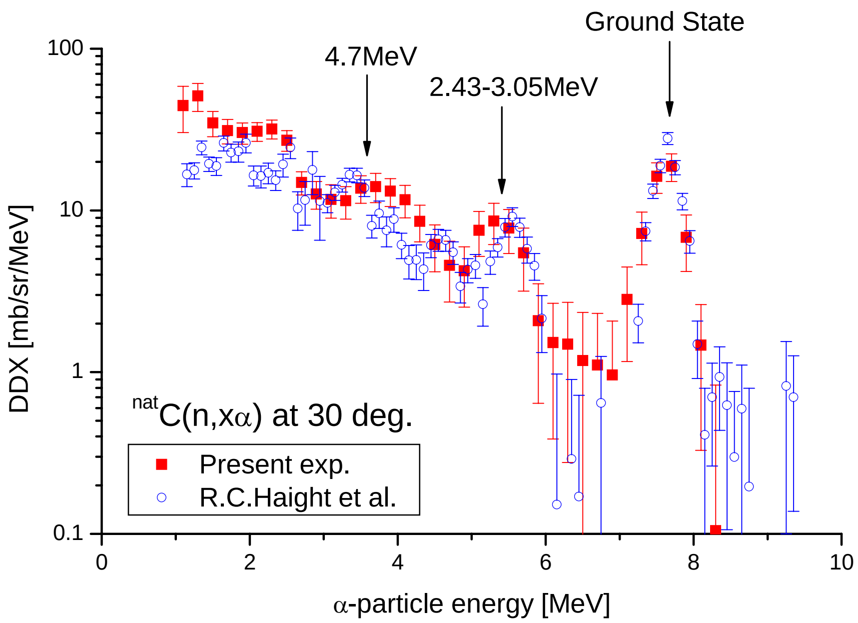

Figure 2　Our obtained DDX and previously measured DDX at the emission angle of 30 deg.

3.2 Monte Carlo calculation and analysis

The mechanism of the $^{12}C(n,n'+3\alpha)$ reaction is complex, because a lot of reaction channels can contribute to formation of 4-body final state of n'+3α. In order to investigate the reaction mechanism, we tried to calculate energy distribution of emitted particles for each channel which contributes to the reaction and determine the branching ratio to the channels so as to reproduce the experimental result well. This analysis is also useful to examine the cause of the large discrepancy in Fig. 2 in the lower energy part of DDX, which would make a large impact on the evaluation of the total α-particle production cross-section. The emitted energy distributions both for α-particles and neutrons were calculated by the Monte Carlo method based on reaction kinematics. The calculation scheme was entirely adopted from Ref. [7]. The contributed channels for the $^{12}C(n, n'+3\alpha)$ reaction were considerably identified by Antolković *et al.*, who carried out a kinematical analysis for the reaction using nuclear emulsions [8]. In the present calculation, simply 2-body sequential decays, which reach to the final states of n'+3α, via excited states of ^{12}C and ^{9}Be were considered based on their analysis. The decay schemes are as follows:

$$n + {}^{12}C \rightarrow n' + {}^{12}C^* \rightarrow n' + [\alpha + {}^{8}Be^*_{(GS\ or\ 3MeV)}] \rightarrow n' + [\alpha + (2\alpha)] \quad (1)$$
$$n + {}^{12}C \rightarrow \alpha + {}^{9}Be^* \rightarrow \alpha + [n' + {}^{8}Be^*_{(GS\ or\ 3MeV)}] \rightarrow \alpha + [n' + (2\alpha)] \quad (2)$$
$$n + {}^{12}C \rightarrow \alpha + {}^{9}Be^* \rightarrow \alpha + [\alpha + {}^{5}He^*] \rightarrow \alpha + [\alpha + (n' + \alpha)] \quad (3)$$

Decay modes of the intermediate nuclei, $^{8}Be^*$ and $^{5}He^*$, were adopted according to literatures [8, 9, 10]. For all the intermediate states, the density-of-states function was given by a Breit-Wigner distribution with constant level widths [9, 10]. The angular distributions for the inelastic scattering of neutrons were extracted from the neutron emission DDX measured by Takahashi *et al.* [11] for the excited states of ^{12}C at 7.65 and 9.64 MeV. For the other excited states of ^{12}C, the isotropic distribution in center-of-mass system was assumed. In other 2-body decays, also the isotropic distribution in center-of-mass system was assumed.

The calculated spectra were fitted into our obtained DDX for α-particles and DDX for neutrons measured by Takahashi et al. [11], and the branching ratio for the contributed channels was estimated. **Figure 3** shows the best fitted result of the DDX both for emitted α-particles and neutrons at the emission angle of 30 deg.. The continuum in lower energy of the neutron DDX is reproduced fairly well. In the present estimation, a large contribution of the $^{9}Be^*_{(4.7\ MeV)}$ channel plays an important role, although its validity should be confirmed by some theoretical analyses. The estimated branching ratio for the $^{12}C(n,\alpha)^{9}Be^*_{(\geq 2.43MeV)}$ channels was more than 30%. Such a large contribution of the $^{9}Be^*$ channels might suggest importance of the α-particle knock-on or stripping process. This supposition will be confirmed by further detailed measurement of the angular distribution of emitted α-particles. The measurement is also needed in order to estimate the total α-production cross-section.

From the present analysis, it was found that the lower energy part of our measured DDX would be reasonable when the assumed reaction channels contribute to the reaction.

To examine the cause of the discrepancy with the Haight's result precisely, further measurements for other angles than 30 deg. are indispensable.

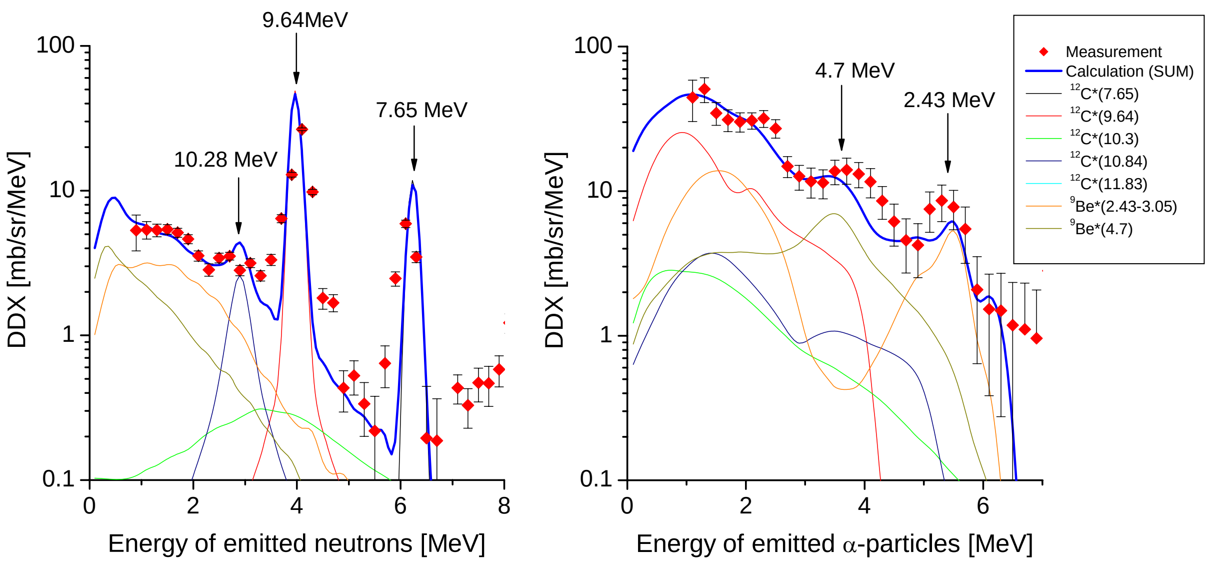

Figure 3 Best fitted result of the DDX calculation for both emitted α-particles and neutrons at the emission angles of 30 deg.

4. Conclusion

Measurement of the α-particle emission double differential cross-section (DDX) for carbon with 14-MeV incident neutrons is being carried out and a preliminary result was described in this paper. The agreement of our obtained DDX at the emission angle of 30 deg. with a previous data measured by Haight *et al.* was fairly well in the higher energy part, while a slight discrepancy was observed below 3 MeV. In order to investigate the mechanism of the $^{12}C(n,n'+3\alpha)$ reaction, we tried to calculate the energy spectra of emitted particles by the Monte Carlo method considering reaction kinematics of a lot of channels which contribute to the reaction. As a results, the contribution of $^{9}Be^{*}_{(4.7\ MeV)}$ was suggested and it was found that rather large contribution of the $^{12}C(n,\alpha)^{9}Be^{*}_{(\geq 2.43 MeV)}$ channels had to be assumed to reproduce the experimental results well. The assumed ratio to the total α-particle production was more than 30%. Such a large contribution of the $^{9}Be^{*}$ channels might suggest importance of the direct reaction process. More detailed measurement and analysis of the angular distribution of emitted α-particles are needed to reveal the mechanism of the $^{12}C(n,n'+3\alpha)$ reaction. Further measurement is also needed in order to estimate the total α-production cross-section.

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