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Fusion Engineering and Design 81 (2006) 1527–1533

Fusion Engineering and Design

www.elsevier.com/locate/fusengdes

New approach to measure double-differential charged-particle emission cross sections of several materials for a fusion reactor

K. Kondo[a,*], S. Takagi[a], I. Murata[a], H. Miyamaru[a],
A. Takahashi[a], N. Kubota[b], K. Ochiai[b], T. Nishitani[b]

[a] *Department of Electronic, Information Systems and Energy Engineering, Osaka University,*
Yamada-oka 2-1, Suita, Osaka 565-0871, Japan
[b] *Japan Atomic Energy Research Institute, Tokai-mura, Naka-gun, Ibaraki-ken 319-1195, Japan*

Received 7 February 2005; received in revised form 31 August 2005; accepted 31 August 2005
Available online 20 December 2005

Abstract

Double-differential charged-particle emission cross section (DDXc) is a fundamental value to estimate nuclear heating and material damages in fusion reactor development. In the present study, measurements of DDXc for several light elements have been carried out with a newly developed spectrometer. In the spectrometer, a good signal-to-noise ratio and very low minimum measurable energy were realized by using a pencil-beam DT neutron source of FNS in JAERI and a counter-telescope system with very thin silicon surface barrier detectors of appropriate thicknesses. The detailed DDXc data in a wide emission energy range were obtained for ^{27}Al, ^{9}Be, $^{\mathrm{nat}}$C and ^{19}F. For ^{27}Al(n,$x\alpha$) reactions, the measured total cross section agreed well with the evaluated data. For ^{9}Be(n,$x\alpha$) reactions, there were differences in the α-particle emission DDX between measurement and the evaluated data in the detail of energy structure. For $^{\mathrm{nat}}$C(n,$x\alpha$) reaction, a large discrepancy between the present result and the previous experimental data appeared. For ^{19}F(n, charged-particle) reactions, some peaks corresponding to excited states of the residual nuclei were observed in the energy spectrum of emitted proton, deuteron, and triton particles.

Keywords: Neutrons; Charged particles; Double-differential cross section; Nuclear reaction; Nuclear data

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1. Introduction

In fusion reactor development, it is important to estimate nuclear heating and material damages of candidate materials irradiated with DT neutrons. Double-differential charged-particle emission cross section (DDXc) is needed, because they are indispensable to calculate primary knock-on atom (PKA) spectra, gas production per atom (GPA) and displacement per atom (DPA) cross-sections. In particular, several light nuclei such as beryllium, carbon and lithium would be used in large quantities in the blanket region of a fusion

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* Corresponding author. Tel.: +81 6 6879 7894;
fax: +81 6 6879 7899.
E-mail address: ktaro@ef.eie.eng.osaka-u.ac.jp (K. Kondo).

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doi:10.1016/j.fusengdes.2005.08.070

reactor. Charged-particle emission nuclear reactions from these materials are complex due to contributions from sequential decays and multi-body break-up. For this reason, it is known that theoretical calculations of energy spectra of emitted particles are difficult, and therefore precise measurement of DDXc is quite important.

Measurement of DDXc is difficult since charged-particle emission reaction has a small cross section and generally speaking a background count rate is high. In 1960s–80s, several early studies of charged-particle emission reactions induced by DT neutrons were carried out. Since these studies were from a standpoint of nuclear physics to investigate mainly details of the direct nuclear reaction process, spectra of emitted charged particle in whole energy range were not obtained [1–3]. In the author's group, an E-TOF method was developed at OKTAVIAN facility in Osaka University [4] and measurements of DDXc for several medium heavy elements for a fusion reactor were successfully carried out [5]. However, the method was a little hard to apply for precise measurements of lighter elements, DDXc for these elements were not obtained with an acceptable accuracy.

Recently, we developed a unique spectrometer for detailed measurement of DDXc using a pencil-beam DT neutron source of the Fusion Neutronics Source (FNS) in Japan Atomic Energy Research Institute (JAERI) [6]. The spectrometer realized a good signal-to-noise (S/N) ratio, good energy resolution and very low minimum measurable energy. In the present report, measurements of DDXc for ^{27}Al, ^{9}Be, ^{nat}C and ^{19}F with the spectrometer are described. Aluminum was chosen as a standard sample in order to confirm the validity of the present spectrometer. Beryllium is regarded as one of the most important materials in a fusion blanket. Carbon is contained in SiC, which would become an alternative first wall material. Fluorine is contained in FLiBe (Li_2BeF_4), which is regarded as a promising liquid blanket material.

2. Experimental

There are two distinctive features of the present spectrometer. One is the significantly good S/N ratio, and the other is that the minimum measurable energy is lower than those of previous methods. The details are described in this section.

Table 1
The specification of sample materials

Sample	Condition	Thickness	Diameter (cm)
^{9}Be	Metal foil	20 μm	3
^{nat}C	Carbon foil	9.59 mg/cm^2 (75 μm)	1.8
^{19}F	Teflon (($CF_2)_n$) foil	10.7 mg/cm^2 (50 μm)	1.8
^{27}Al	Metal foil	50 μm	3

The good S/N ratio of the spectrometer was realized by using a pencil-beam DT neutron source of FNS in JAERI. In the neutron source, generated DT-neutrons are collimated with a 2 m thick shielding structure consisting of Fe, Pb, Cd and polyethylene with a narrow hole of 2 cm in diameter to extract a neutron beam of 2 cm-Ø. Characteristics of the beam, such as intensity, profile and neutron background, were well investigated [7]. The neutron energy calculated according to the reaction kinematics is 14.2 MeV. The maximum neutron flux at the outlet of the beam is 1×10^6 cm^{-2} s^{-1} and the background neutron flux outside the beam is lower than 5×10^2 cm^{-2} s^{-1}. We can therefore arrange a detector very close to a sample material without any radiation shield and the high S/N ratio is achieved. A sample and detectors were located in an experimental vacuum chamber of 40 cm-Ø by 30 cm in height, which was set at the outlet of neutron beam. The specifications of the sample materials are shown in Table 1. The experimental arrangement is shown in Fig. 1.

To distinguish kinds of charged particles, we employed a counter-telescope system with a pair of silicon surface barrier detectors of ΔE and E, and a two-dimensional multi-channel analyzer. Fig. 2 shows a typical two-dimensional spectrum obtained with the spectrometer. To distinguish proton, deuteron and triton emitted in wide energy range separately, appropriate thickness of ΔE detector should be chosen although minimum measurable energy becomes high as increasing of the thickness of ΔE detector. The details of the ΔE detectors and E detectors used in the present study are shown in Table 2. Energy resolutions were derived from FWHM of the peak in the energy spectra obtained by summing energies deposited in the ΔE and E detectors.