Elastic Recoil Detection Method using DT Neutrons for Hydrogen Isotope Analysis in Fusion Materials

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Abstract

The Fusion Neutronics Source of Japan Atomic Energy Research Institute has started the study on the hydrogen isotope analysis for fusion components since 2002 on the basis of the techniques such as nuclear activation method, ion beam method and imaging plate method. In this study, we propose the elastic recoil detection analysis (NERDA) method using 14.1 MeV neutron beam to extend the analyzable depth of hydrogen isotopes analysis up to several hundreds micrometers. An experimental setup for NERDA was constructed and a proof-of-principle experiment was then made using a standard sample of deuterated polyethylene film containing a known concentration of deuterium with thickness of 100 μm. The depth resolution of the present condition was estimated to be 158 μm for the sample.

1. Introduction

Hydrogen isotopes show complicated behavior on the surface of plasma facing components (PFC) in fusion devices, and the study is important for the design of the fuel recycling, the plasma control *etc*. In case that carbon based materials are used as PFC, co-deposited layers of carbon compounds are formed with the thickness of several tens of micrometers on PFC surfaces due to plasma-wall interactions [1-2]. Since these layers retain a lot of hydrogen isotopes more than the bulk in PFC, it is necessary to reveal hydrogen isotope distributions beyond co-deposited layer. However, conventional non-distractive analyses for hydrogen isotopes on the surface, *e.g.* Elastic Recoil Detection Analysis, Rutherford Backscattering Spectroscopy and Nuclear Reaction Analysis (NRA), were not appropriate in such depth region because of their shallow probing depth.

A powerful and unique method with monochromatic neutrons instead of ion beam, namely, Neutron Elastic Recoil Detection Analysis (NERDA) has been developed. This method was applied to measure hydrogen isotopes in divertor tiles of the DIII-D reactor and palladium-hydrogen system [3-4]. The advantages of neutron usages for the material analysis are to probe the deeper depth and to obtain the same sensitivity as the conventional ion beam

analysis due to large scattering cross sections for hydrogen isotopes. In addition, beam-irradiation induced degradation of hydrogen isotopes distribution could be minimized.

The Fusion Neutronics Source (FNS) of Japan Atomic Energy Research Institute (JAERI) has started the study on the hydrogen isotope analysis for fusion components since 2002 on the basis of the techniques such as the nuclear activation method, the ion beam method and the imaging plate method. So far, deuterium and tritium distributions as regards the depth from the surface of the JT-60U plasma facing components up to the range of a few micrometers were obtained by means of the deuteron induced NRA. In this study, we propose NERDA using the 14.1 MeV neutron beam produced by T(d,n)a reactions to extend the analyzing depth of hydrogen isotopes up to several hundreds micrometers. A proof-of-principle experiment was made using a standard sample of deuterated polyethylene film containing a known concentration of deuterium.

2. Experimental

Depth distributions are estimated with energy and yield of recoil particle from the sample by NERDA method. The detection energy E_{d} is expressed as,

$$E_{\mathrm{d}} = E_{\mathrm{r}} - \mathrm{d}E_2(x), \tag{1}$$

where Er and $\mathrm{d}E_2(x)$ are the recoil energy of the target atom and the energy loss of the recoil particle before reaching the sample surface. The energy E_{r} is led by the energy and momentum conservation laws:

$$E_{\mathrm{r}} = \left(\frac{4M_1M_2}{(M_1+M_2)^2} \cos^2\phi \right) E_1 . \tag{2}$$

where M_1, M_2, are the mass of the probe neutron and that of the target atom, ϕ is the recoil angle, E_1 is the incident energy of the probe neutron. The energy loss of $\mathrm{d}E_2$ is expressed using stopping power $\mathrm{d}E/\mathrm{d}x$ for recoil particles in the sample;

$$\mathrm{d}E_2 = \int_0^{x/\sin(\phi-\theta_0)} \left(-\frac{\mathrm{d}E}{\mathrm{d}x} \right) \mathrm{d}x \tag{3}$$

where x is the depth in the target, θ_0 is the incident angle of the probe neutron.

On the other hand, the yield $\mathrm{d}Y$ of the recoil particles originating in the region between

a depth x and x + dx is expressed by;

$$\mathrm{d}Y = Q\frac{\mathrm{d}\sigma_{\mathrm{r}}(E)}{\mathrm{d}\Omega}N\mathrm{d}x\Delta\Omega\,, \tag{4}$$

where Q is the number of incident neutrons, $\mathrm{d}\sigma_{\mathrm{r}}(E)/\mathrm{d}\Omega$ is the angular differential recoil cross section in laboratory system, N is a density of the target atom, $\Delta\Omega$ is a solid angle. Thus, the distribution of the target atoms is deduced from the detection energy and yield of the recoil particle.

Experimental setup is shown in Fig. 1. The 14.1 MeV neutrons produced by T(d,n)^{4}He reactions with 350 keV deuterons at the target of the 0° beam line of FNS were collimated with a hole of 20 mm in diameter. The collimated neutrons, *i.e.* neutron beam, were incident on the sample from the direction at an angle of 0°. Emitted particles from the sample were measured using a ΔE-E telescope system with the solid angle of 1.8×10^{-2} sr. A pair of solid state detectors (SSDs) with the depletion layer thickness of 75 and 1500 μm was positioned at the detection angle of 25°. Output signals from each SSD were analyzed with a multi-parameter analyzer to estimate the particle mass and its energy. The energy calibration of SSDs was corrected based on an ^{241}Am alpha source (5.486MeV). Typical fluence of incident neutrons was 4.0×10^9 neutrons/cm^2, which was monitored with a ^{238}U fission chamber located behind the target chamber.

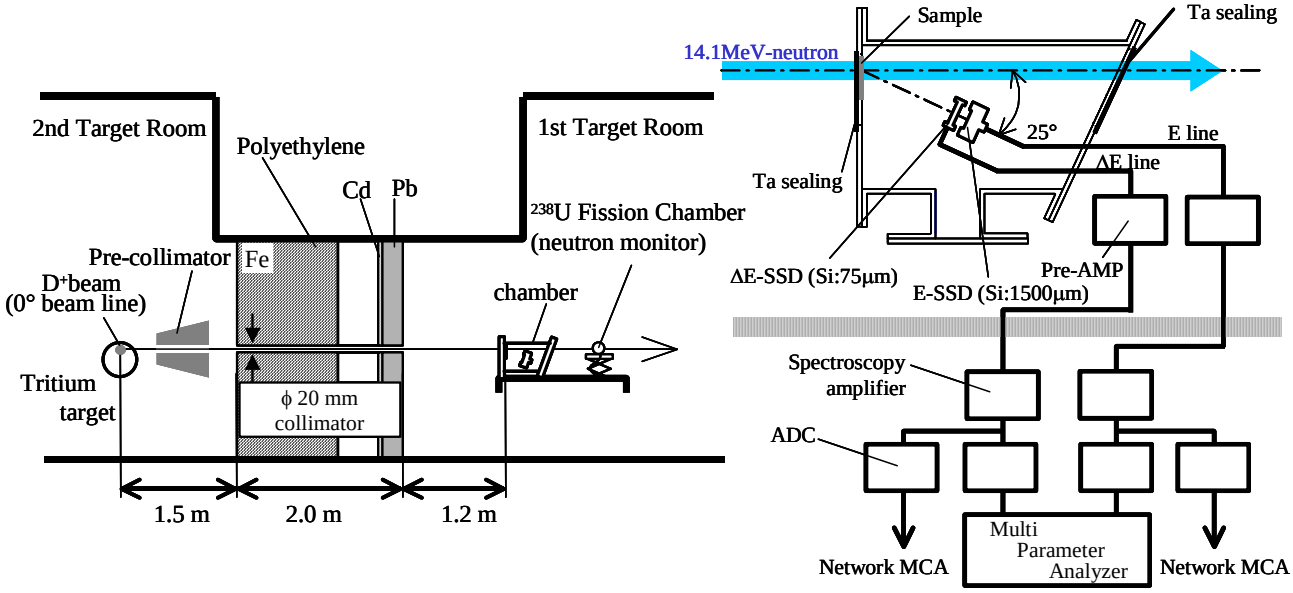

Fig. 1. The neutron beam system in FNS (left hand side) and the experimental setup of NERDA (right hand side).

A proof-of-principle experiment was performed using a standard sample of deuterated polyethylene film containing a known concentration of deuterium with the thickness of 100 μm. The deuterated polyethylene film was fabricated using a solvent-cast method. Spongelike pieces of deuterated polyethylene were solved with a toluene solution, which were controlled to become the density of 10 wt% or less. The solution was vaporized to form a film of deuterated polyethylene in air-drying at room temperature during two weeks.

3. Results and discussion

Typical ΔE-E contour map during the 14.1 MeV NERDA for the $(C_2D_4)_n$ sample with the thickness of 100 μm are shown in Fig. 2. The horizontal and vertical axes show the energy measured at the ΔE-SSD and the E-SSD, respectively. The D(n,d)n recoil deuterons appearing around (E, ΔE) = (180, 550) ch were recorded in the contour map. Protons originating in X(n,p) reactions with hydrogen, deuterium and other impurity on/in the target were also distinguishable. For example, D(n,p)2n reaction formed a continuum spectrum from (100, 700) ch to (400, 0) ch. Figure 3(a) and (b) show energy spectra measured with the (a) ΔE-SSD and (b) E-SSD, respectively, during the 14.1 MeV NERDA for the $(C_2D_4)_n$ sample. In each projected MPA spectrum only the recoil deuterons survived as a result of coincidence filtering.

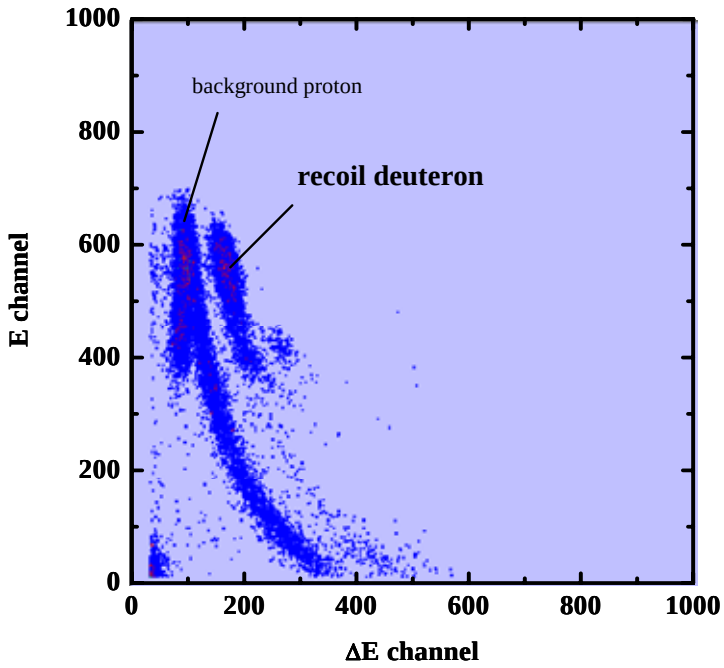

Fig. 2. The ΔE-E contour map measured with multi parameter analyzer during the 14.1 MeV NERDA for the $(C_2D_4)_n$ sample with the thickness of 100 μm.

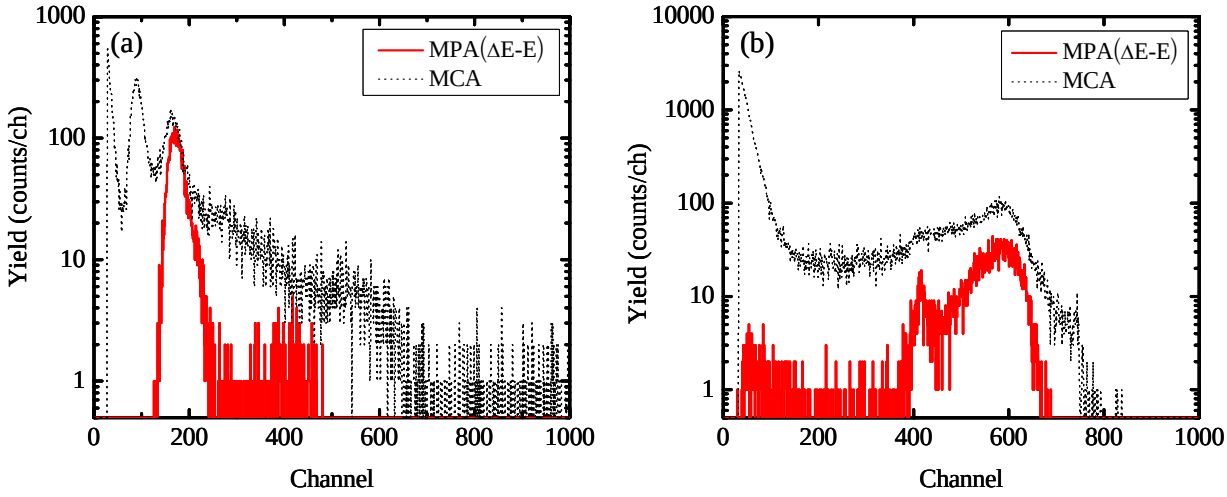

Fig. 3. Energy spectra measured with the (a) ΔE-SSD and (b) E-SSD during the 14.1 MeV NERDA for the $(C_2D_4)_n$ sample. In each MPA-spectrum only the recoil deuterons survive as a result of coincidence filtering.

A deuterium depth distribution estimated from the total energy spectrum of recoil deuterons is shown in fig. 4. In Eq. (4), the value of 53.6 mb/sr was used as the differential cross section of recoil deuterons [5]. The deuterium distribution like Gaussian was obtained for the standard sample with the homogeneous distribution of deuterium. The distribution was expressed as a Gaussian response function with a standard deviation of 67 μm. The depth resolution, which was defined as the value of a standard deviation multiplied by a factor of $2(2\ln 2)^{1/2}$ on the Gaussian response function, was then evaluated to be 158 μm corresponding to 16 % of the analyzable depth of 957 μm for the $(C_2D_4)_n$ sample.

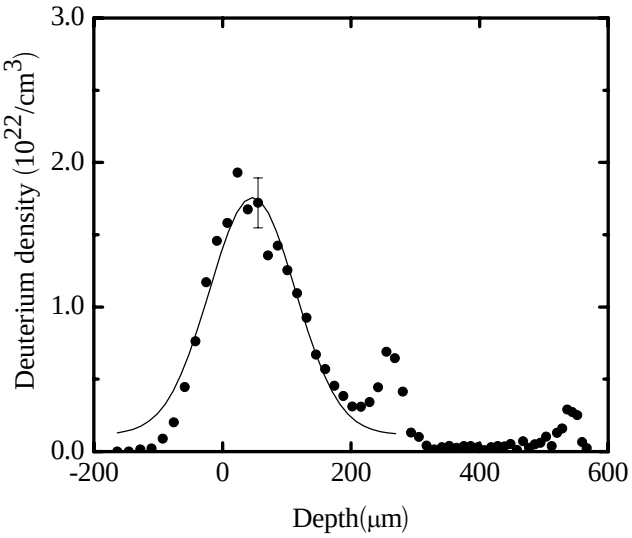

Fig. 4. Deuterium depth distribution of the $(C_2D_4)_n$ sample estimated using the total energy spectrum of deuterons. The solid line indicates the fitting curve using Gaussian.

4. Summary

The elastic recoil detection analysis using T(d,n) neutrons was proposed to extend the analyzing depth of hydrogen isotopes up to several hundreds micrometers. The proof-of-principle experiment was performed using the 14.1 MeV neutron beam and the standard sample of the deuterated polyethylene film containing a known concentration of deuterium. With uses of the ΔE-E system, recoil deuterons and proton spectra were obtained separately under the low background condition. The estimated depth resolution corresponded to 16 % of the analyzable depth for the standard sample, which is enough to analyze fusion materials.

References

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