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Measurement of differential cross section of D(3He,p)4He from 0.8 MeV to 3.6 MeV

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ABSTRACT

Precise knowledge of the nuclear reaction cross-section is crucial for nuclear reaction analysis methods and its applications. In order to apply nuclear reaction analysis methods to Plasma Facing Materials studies on 4.5 MV electrostatic accelerator at Peking University, differential cross-section for d(^{3}He,p)α at several backward angles was measured with a relative error about $\pm$6.2%, gives detailed information at the laboratory angle of 135° from 800 keV to 3600 keV, as well as a rough angular distribution from 130° to 160°.

1. Introduction

Nuclear reaction analysis (NRA) based on d(^{3}He,p)α has been initially adopted and successfully applied in quantitative depth profiling of deuterium in the near-surface layers of solids for more than three decades [1]. Its applications ranges from isotopic tracer experiments, hydrogen embrittlement studies, to plasma facing materials (PFMs) analysis in fusion devices [2]. Comparing to Secondary Ion Mass spectroscopy (SIMS), accelerator-based ion beam analysis (IBA) presents distinct advantages in deuterium analysis, such as non-destructive, quantitative, matrix independent, and so on. Elastic Recoil Detecting Analysis (ERDA), one of the widely-used IBA method, requires grazing incident geometry and particle identification to maintain a good depth resolution in the limited detecting depth of hundreds of nm from the sample surface. By adopting several incident energies in depth profiling experiment, as well as by detecting protons and α particles simultaneously at backward angles, NRA methods has been improved by Mayer et al. [3] to fulfill the growing needs of deuterium analysis wih reasonable depth resolution throughout the whole analyzing depth up to tens of μm.

Precise knowledge of the nuclear reaction cross-section is crucial for NRA applications to retrieve accurate elemental concentration and distribution. The d(^{3}He, p)α nuclear reaction has been studied extensively since the 1950s. However, the motivation varies from the study of the ^{5}Li system to electron screening determination [4] in the nuclear physics domain, which makes these cross-section values far from being practically used in NRA. Moreover, previous reported data of ^{3}He-D cross-section differs by more than 30% at the maximum and its corresponding incident energy due to unidentified reasons. This ambiguity confuses the IBA community for choosing a proper data set. Additionally, only two sets of experimental data measured by V.Kh. Alimov et al. [5] and B.Wielunska et al. [6] are availabe in the nuclear data libraries, such as Ion Beam Analysis Nuclear Data Library (IBANDL) and Experimental Nuclear Reaction Data (EXFOR). Consequently, we carried out a new round of measurement of d(^{3}He, p)α cross-section in order to apply NRA methods to PFMs studies at Peking University (PKU).

2. Experimental

The deuterium target used for cross-section determination is a thin layer of amorphous deuterated hydrocarbon (a-C:D) deposited on top of optically flat Si⟨1 1 1⟩ plate prepared by radio frequency discharge from CD_4 at Max-Planck-Insitut für Plasmaphysik (IPP Garching) [7]. The amount of D was determined by NRA at the Garching tandem accelerator [5,6]. D density of this sample is 1.4×10^{18} D/cm^2 with a D/C ratio of 0.64 and the uncertainty is about 5%, mainly derived from the uncertainty of the cross-section data in [8], proton yields, and the solid angle.

The ^{3}He$^+$ beam for NRA was produced by 4.5 MV electrostatic accelerator at PKU with energy ranging from 800 kev to 3600 keV. The incident ions delivered from ion source was selected by a 90° bending magnet, and then passed through a rectangular aperture, which defined a beam spot area of 2 mm × 5 mm at

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normal incidence. Before formal experiments, ^{7}Li(p,n)^{7}Be was used to determine the linear dependence between the terminal voltage and the magnetic field intensity of the bending magnet system. The energy spread is below 0.07% at 2000 keV and ~0.1% at 800 keV. An analyzing dose of 3.6 μC was collected averagely for each data point.

The experimental geometry of NRA is represented in Fig. 1. There were two Au-Si surface barrier detectors positioned in the cylindrical experimental chamber for detecting projectile protons and Rutherford backscattering (RBS) ^{3}He particles. The samples were mounted in a rotatable octahedral copper target and the distances between target center and two detectors both were 77.1 mm. Protons emitted from d(^{3}He, p)α reaction were detected at a laboratory angle of 135° (in the measurement of angular distribution, the detected angle was changed from 130° to 160°). The depletion depth of the detector is 2000 μm for completely stopping high energy protons. In order to limit the solid angle and reduce the geometry straggling, a parabolic slit with a width of 3 mm and height of 17 mm [3] was put in front of the detector and resulted in a angular spread of ±7.2°. A 50 μm thick mylar foil was also used to prevent backscattering ^{3}He and ^{4}He produced by nuclear reaction from entering the window. RBS ^{3}He ions were detected by another detector at an angle of 153°. To reduce the effect of dead time and pile-up on backscattering signal, a 3 mm × 10 mm parabolic slit was mounted ahead of the RBS detector. Both the solid angles of two detectors were determined based on the mechanical distances, simply given by Eq. (1), where S is the size of the slit and d is the target-detector distance. The solid angle of the NRA detector is 8.5×10^{-3} sr with an uncertainty of 2.7% and the solid angle of the RBS detector is 5.0×10^{-3} sr with an uncertainty of 2.0%. During the experiment, the vacuum in the chamber was kept in 10^{-3} Pa.

$$\Omega = \int \frac{1}{d^2}, \mathrm{d}S \tag{1}$$

According to ref [5,8], the loss of deuterium in target due to bombardment of incident ^{3}He should be taken into consideration. However, comparing to their experimental condition, lower beam and greater beam spot area caused inject ^{3}He ions per unit area in target to be 10% of that in [5], so the loss of deuterium during this experiment was considered to be negligible.

Rutherford backscattering and nuclear reaction signals were registered on two multi-channel analyzers simultaneously. To analyze and simulate recorded spectra, a Microsoft Windows program named SIMNRA [9] was used. Typical RBS and NRA spectra are shown in Fig. 2 and Fig. 3. Since backscattering of 3He from Si is Rutherford until 3.875 MeV [10], incident ^{3}He dose was determined by simulating the height of the front edge of Si signal in RBS spectrum.

The differential cross-section of d(^{3}He, p)α at a specific angle σ(E,φ), is given by Eq. (2). E is calculated by using mean energy approximation, half of the energy loss in the a-C:D layer was subtracted from incident ^{3}He energy. Y_p(E) is the yield of detected protons, which was presented in NRA spectrum as the proton peak area. Q is the analyzing beam dose on the target, determined by simulating of RBS spectrum. Ω is the solid angle of NRA-p detector, (Nt) is the areal density of deuterium in the sample.

$$\sigma(E, \varphi) = \frac{Y_p(E)}{Q\Omega(Nt)} \tag{2}$$

The measured differential cross section and corresponding uncertainty at a laboratory angle of 135° are shown in Table 1 and Fig. 4(together with the results of Alimov and Wielunska in [5,6]). Total relative uncertainty is about ±6.2%, derived from follows: (i) the uncertainty of the areal density of D in the deuterium target is about 5%; (ii) the statistical error of proton yields is <2.4%; (iii) the error induced by calculation of the incident ^{3}He dose is ~1.6%; (iv) the error induced by the mechanically measured solid angle is ~2.7%. In Fig. 4 one can see that our data is in good agreement with the results of Alimov and Wielunska (only slight

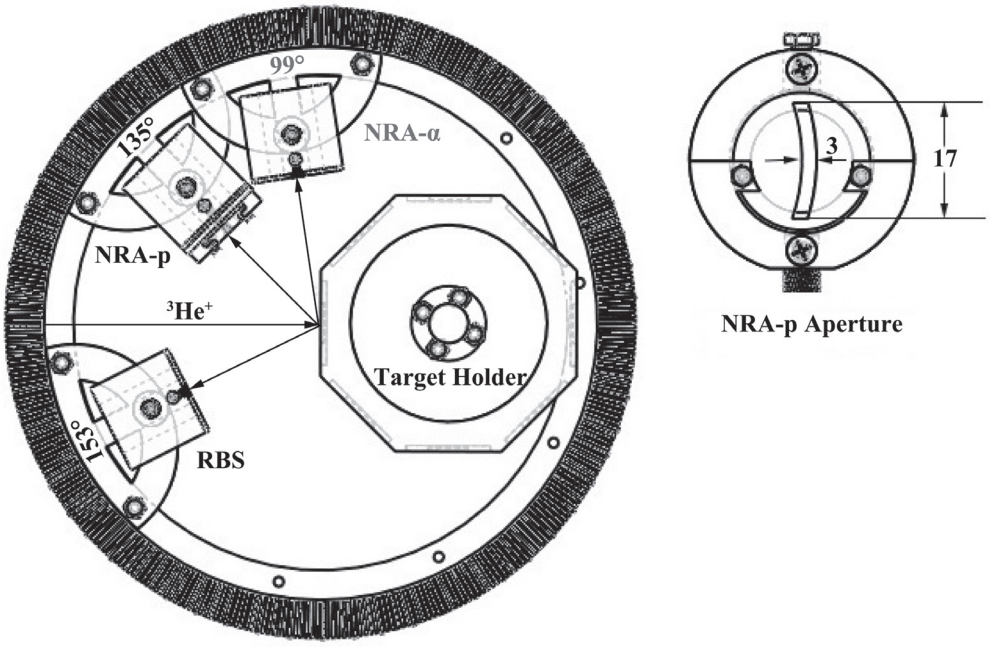

Fig. 1. Experimental geometry of d(^{3}He, p)α nuclear reaction.