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Differential cross section measurement of the $^{nat}O(d,d_0)$ reaction at energies and angles relevant to EBS

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ABSTRACT

In the present work, differential cross section values of the $^{16}O(d,d_0)$ reaction were obtained for $E_{d,lab}$ = 900–2000 keV, at four scattering angles, namely at 90°, 135°, 150° and 165° using a thin SiO target having a thickness of (910 ± 36) × 10^{15} at/cm^2. The cross section values were determined with an energy step of ~10 keV while, the detailed measurements were carried out with an energy step of ~5 keV around the resonance peaks. The results were compared with those of the previous studies.

1. Introduction

Oxygen is a highly reactive nonmetallic element and oxidizing agent that readily forms compounds (notably oxides) with most elements. It is the most abundant element in the Earth's crust and living matter and is present in almost all Ion Beam Analysis (IBA) samples. Thus, the determination of absolute concentrations and depth profiling of oxygen in the near-surface layers of different samples is important from the IBA point of view. The analytical study of natural oxygen is practically equivalent to the study of the main isotope, ^{16}O (99.762% natural abundance).

It has been generally established that the deuteron Nuclear Reaction Analysis (d-NRA) is a suitable technique to analyze the oxygen especially on heavy substrates [1]. The $^{16}O(d,p)^{17}O$ and $^{16}O(d,a)^{14}N$ reactions are most frequently used for natural oxygen analysis because of their large cross section even at low energy deuteron beam, readily accessible in IBA labs. Moreover, according to the high positive Q-values of these reactions, the products appear far from the backscattering edge of the matrix [2,3]. When the oxygen concentration is not very low and there is no signal interference from other light elements, deuteron Elastic Backscattering Spectroscopy (EBS) and particularly simultaneous analysis of d-NRA/EBS are preferred. In this situation, precise information of the $^{16}O(d,d_0)^{16}O$ reaction cross section is required. Unfortunately, no practical method exists at present for accurate calculation of the deuteron induced reaction (at low energy and light targets) cross sections and they can be obtained from experimental procedures with some limited margin of error and confidence [4]. Moreover, the experimental differential cross section data for the $^{16}O(d,d_0)^{16}O$ reaction, suitable for accurate oxygen detection and depth profiling, are inadequate and discrepant in many cases. The evaluated differential cross section data for this reaction were made available through the on-line calculator (http://sigmacalc.iate.obninsk.ru/) and through IBANDL (http://www-nds.iaea.org/ibandl/). However, it should be noted that the differential cross section evaluation is a dynamical process and strongly depends on the quality and availability of the experimental data over a wide range of energies and scattering angles [5].

In this research work, the differential cross section data for the $^{16}O(d,d_0)^{16}O$ reaction in the deuteron beam energy range $E_{d,lab}$ = 900–2000 keV and at the scattering angles of 90°, 135°, 150° and 165° suitable for EBS have been studied. The results were compared with the ones of reported in the literature, as well as recently evaluated data of SigmaCalc. The similarities and differences have been discussed in detail.

2. Experimental setup and procedure

The deuteron beam from the 3 MV Van de Graaff accelerator of NSTRI was employed with an energy resolution of ±1 keV. The energy calibration of the accelerator was done using the $^7Li(p,n)$ threshold reaction at 1880.4 keV. The deuteron beam with a spot size of 1.5 × 1.5 mm^2 impinged on the target with a current of 40–50 nA, resulting in a small dead-time, less than 10%, during

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data acquisition. The accumulated charge for each spectrum corresponded to ~10 μC. The differential cross section values were obtained with an energy step of ~10 keV. However, detailed measurements were carried out with an energy step of ~5 keV around the resonance peaks. The vacuum of the reaction chamber was kept less than $\sim 1 \times 10^{-6}$ mbar during the measurements. The details of the experimental chamber have been discussed in Ref. [6].

The solid ^{16}O target used for the measurements was made by evaporating high purity SiO on a thin silver backing. The same chemical was evaporated after being heated in a tantalum boat under a pressure of about 2×10^{-6} mbar. The heating rate of the boat was kept slow to prevent SiO from jumping overboard. The silver backing was prepared in a similar way, by evaporating a piece of pure silver wire in vacuum onto a microscope slide previously dipped in a detergent solution. A self-supporting film was obtained by floating the silver film on water and fishing it onto an appropriate target holder [7,8].

The target characterization was accomplished by averaging the simulation results of two different proton elastic scattering spectra (E_p = 2000 and 2500 keV) at the detection angles of 150° and 165°. Simulations were performed with the SIMNRA 6.06 code [9]. Ziegler/Biersack stopping power data and Chu and Yang straggling model were adopted, as implemented in the code. A typical measured spectrum is shown in Fig. 1, for $E_{p,lab}$ = 2500 keV at the detection angle of 165°. The target was tilted by 45° with respect to the beam. As it is shown in Fig. 1, there is some carbon contamination on the surface of the target. The evaluated differential cross section data were obtained from online the R-matrix calculator SigmaCalc for proton elastic scattering on C, O and Si. These, along with the Rutherford values for protons on Ag, were used in the simulations. The thickness of the SiO and Ag layers were estimated to be $(910 \pm 36) \times 10^{15}$ at/cm^2 and $(580 \pm 23) \times 10^{15}$ at/cm^2, respectively. The energy correction of the target thickness and the energy loss in the carbon layer were calculated for each incoming deuteron beam using SRIM 2013 [10]. It should be noted that the target thickness which was directly calculated, was used only for the determination of the deuteron beam energy loss inside the target. As it will be discussed in the next section, for the determination of the differential cross section values, the target was characterized by means of the areal density ratio $\frac{N_{Ag}}{N_O}$ treated as a free parameter.

The detection system included four 300 μm-thick surface barrier detectors located at 90°, 135°, 150° and 165° with relative to the incident beam. The target was tilted by 45° with respect to the beam in order to facilitate the measurement at the detection angle of 90°. A typical measured spectrum is shown in Fig. 2, for $E_{d,lab}$ = 1870 keV for the detection angle of 150°.

3. Data analysis, results and discussion

The differential cross section values of the $^{16}O(d,d_0)$ reaction were obtained from Eq. (1) for relative measurements, compared to the differential cross section values of the $^{nat}Ag(d,d_0)$ reaction, which do not deviate from the Rutherford formula over the entire energy range covered by the measurements [11].

$$\left(\frac{d\sigma}{d\Omega}\right)^{O}_{\theta,E_{SiO}} = \left(\frac{d\sigma}{d\Omega}\right)^{Ag}_{\theta,E_{Ag},Ruth} \times \frac{Y_O}{Y_{Ag}} \times \frac{N_{Ag}}{N_O} \quad (1)$$

where Y corresponds to the experimental yield (net area under the elastic scattering peak), and N to the areal density of the target. Mean deuteron energies $E_{SiO} = E_0 - \Delta E_{SiO}/2$ and $E_{Ag} = E_0 - (\Delta E_{SiO} + \Delta E_{Ag}/2)$ in the target layers were calculated taking into account the energy loss of deuterons with the incident energy E_0 in the SiO and Ag thin layers, using SRIM 2013 [10]. Moreover, as mentioned above, the energy loss for each deuteron incident beam in the carbon contamination on the target was also taken into account.

To reduce the uncertainty, the target was characterized by means of the $\frac{N_{Ag}}{N_O}$ ratio treated as a free parameter [11]. This ratio was measured by the proton elastic scattering spectra (E_p = 2000 and 2500 keV) at the detection angles of 150° and 165° assuming the Rutherford formula for the $^{nat}Ag(p,p_0)$ elastic scattering and considering evaluated cross section data for the $^{16}O(p,p_0)$ reaction. The average value of the results was adopted as the $\frac{N_{Ag}}{N_O}$ ratio for the calculation of the $^{16}O(d,d_0)$ reaction cross section values.

Because of the adopted relative measurement, the results were free of any uncertainty due to the dead time, solid angle and charge measurement. The statistical error of the $\frac{N_{Ag}}{N_O}$ ratio was estimated to be less than 3%. The uncertainty from the yield ratio $\frac{Y_O}{Y_{Ag}}$ due to peak integration and background subtraction was kept <4% in all cases. The combined experimental errors (at ±1σ accuracy) were calculated according to the standard error propagation formulas [15] and estimated to be less than 5%.

The measured differential cross sections are presented in Figs. 3a–3d, along with the available experimental data from literature [12–14] and the SigmaCalc evaluated cross section data for

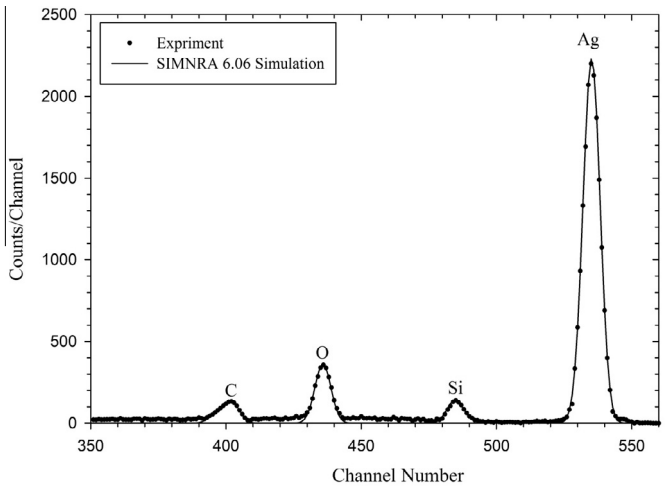

Fig. 1. A typical proton spectrum taken at 165° and $E_{p,lab}$ = 2500 keV which was used for the target characterization. The target was tilted by 45° with respect to the beam.

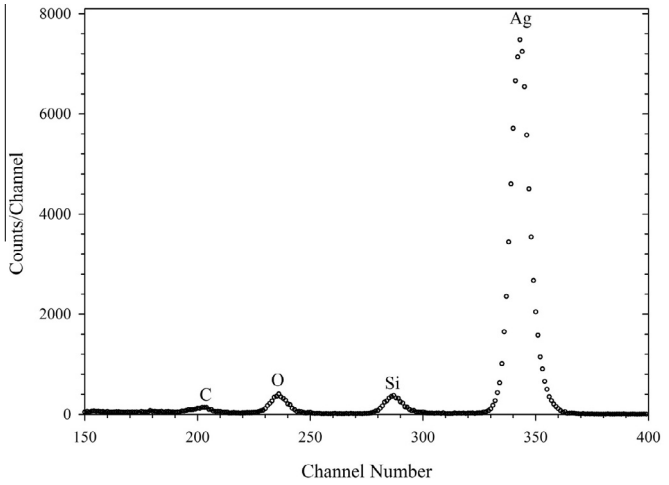

Fig. 2. A typical deuteron elastic scattering spectrum taken at 150° and $E_{d,lab}$ = 1870 keV.