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Differential Cross-section Measurements for Deuteron Elastic Scattering on ^{11}B

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Abstract. The implementation of boron in several fields, such as in the creation of p-type semiconductors in electronics, has created the need for the accurate quantitative determination of its depth profile concentrations in near surface layers of various matrices. In the framework of IBA techniques, a combination of Elastic Backscattering Spectroscopy (EBS), along with Nuclear Reaction Analysis (NRA), has been proposed in order to address the current needs for boron depth profiling, based on the use of a proton beam. Deuterons offer superior mass resolution with respect to protons, having similar stopping power values, but, unfortunately, the lack of experimental datasets concerning the deuteron elastic scattering on boron impedes their use. Thus, in the present work, the first set of measurements for the ^{11}B(d,d$_0$) differential cross sections covering the E$_{d,lab}$=1300-1860 keV energy range for the backscattering angles of 150°, 160° and 170° was carried out. The study was conducted at the 5.5 MV Tandem Accelerator of the Institute of Nuclear and Particle Physics, in the National Center of Scientific Research "Demokritos", Athens, Greece. The target was a thin, self-supporting aluminum foil, upon which a thin ^{nat}B (isotopic ratio: ^{11}B 80.1%, ^{10}B 19.9%) layer was deposited using the sputtering technique at RBI, Zagreb, Croatia, followed by the evaporation of an ultra-thin layer of ^{197}Au on top for wear protection and normalization purposes. The outgoing particles were detected using 6 Silicon Surface Barrier (S.S.B.) detectors and the differential cross sections for the elastic scattering were determined from the resulting spectra via the relative measurement technique.

1. Motivation

Boron is composed of two stable isotopes, ${}^{10}_{5}B(19.9\%)$ and ${}^{11}_{5}B(80.1\%)$ and is an element which is becoming increasingly important due to the large variety of its applications in several different industries. More specifically, it constitutes one of the most common dopants for the creation of p-type silicon semiconductors, covering the majority of the electronics industry. It also appears as a dopant in the field of metallurgy due to its beneficial effect in the mechanical properties of specific alloys [1]. Furthermore, in recent studies [2], boron's use in biocompatible thin films has been confirmed, creating possibilities for more advanced implants in medicine. Thus, the accurate quantitative determination of its depth profile concentrations in near surface layers of various matrices is of the utmost importance.

Ion beam analysis techniques offer least-destructive, precise boron depth profiling - with proton beams being usually implemented. In particular, the proton Nuclear Reaction Analysis (p-NRA) technique, based on the reaction ${}^{11}_{5}B\left(p,a_0\right){}^{8}_{4}Be$, along with the proton Elastic Backscattering Spectroscopy (p-EBS) one, based on the elastic scattering ${}^{11}_{5}B\left(p,p_0\right){}^{11}_{5}B$ have been proposed to cover applications over a wide energy range ([3],[4]). However, the deuteron beam offers a greater mass resolution compared to the proton one, with relatively similar stopping power values, while also being able to simultaneously excite most of the light isotopes in a single measurement, if the need arises. Thus, a combination of d-NRA and d-EBS could prove to be a viable alternative to boron depth profiling in matrices that are rich in light elements. Unfortunately, the current lack of experimental datasets concerning the deuteron elastic scattering on boron for backscattering angles suitable for EBS impedes their potential use. Therefore, the aim of the present work is to enrich the literature and the online library IBANDL (Ion Beam Analysis Nuclear Data Library, https://www-nds.iaea.org/exfor/ibandl.htm) with new, corresponding differential cross-section data.

2. Experimental Setup

The study was conducted at the 5.5 MV T11/25 Tandem Accelerator of the Institute of Nuclear and Particle Physics (INPP), at the National Centre of Scientific Research (NCSR) “Demokritos”, Athens, Greece. During the experiment deuterons were accelerated in the energy range $E_{d,lab}$ = 1000–1860 keV, with a chosen variable energy step of 5–10 keV, based on the lack of any superfine structure in the resulting compound nucleus (${}^{13}_{6}C$) energy levels [9]. The deuteron beam was led, through a tantalum collimator/antiscatterer set, to a high-precision goniometer ($\sim 0.1^o$) inside a cylindrical scattering chamber. The targets were fixed in the center of the chamber and six silicon surface barrier (SSB) detectors (thickness: 500 μm) were mounted at 120°, 130°, 140°, 150°, 160° and 170° (with respect to the beam direction) and at a distance of 10-15 cm from the targets. In front of each detector window an orthogonal slit of ~2 mm in width was placed in order to reduce the angular uncertainty below 1°. Small cylindrical tubes were also used to shield each detector from possible multiple scattering events occurring in the chamber walls. For the data acquisition, standard NIM electronics were utilized and the spectra from all six detectors were simultaneously recorded for every deuteron beam energy step. All the ADC units were calibrated using the position of the ${}^{197}_{79}Au\left(d,d_0\right)$ peak in a considerable number of spectra, thus ensuring and verifying the linear response of the whole experimental setup.

The target used for the cross-section measurements was constructed at Ruđer Bošković Institute, Zagreb, Croatia. Initially, an aluminum foil was created via the evaporation technique in order to act as the backing of the target. On top of it a thin layer of ${}^{nat}B$ was deposited with the use of magnetron sputtering and subsequently, an ultra-thin ^{197}Au layer was evaporated on its surface for wear protection and normalization purposes. In the surface and backing layers that were created via the evaporation, there was a low but inevitable carbon contamination, which will be further discussed in the following sections. Complementary measurements using a proton beam ($E_{p,lab} = 2750, 2920$ keV) were carried out in order to properly estimate the target thickness. Since no available evaluated cross section datasets concerning nuclear reactions or elastic scattering with boron exist, it was decided to carry out the target thickness measurements in an energy range where at least 2 different datasets, in good agreement with one another, existed ([3], [5]), thus increasing the credibility of the obtained results. Finally, the energy calibration of the experiment was tuned to the elastic scattering region, thus limiting our ability to detect particles with energy values higher than 3.5 MeV and consequently forbidding the use of the

${}^{11}_{5}B\left(p,a_0\right){}^{8}_{4}Be$ reaction for the target thickness determination.

3. Data Analysis

For the calculation of the differential cross section at energy E and at scattering angle θ, the corresponding formula of the relative technique was used: $\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)^{\mathrm{E},\theta}_{11_\mathrm{B}} = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)^{\mathrm{E}',\theta}_{Au} \frac{\mathrm{Y}_{11_\mathrm{B}}}{\mathrm{Y}_\mathrm{Au}} \frac{\mathrm{N}_{\mathrm{t,Au}}}{\mathrm{N}_{\mathrm{t},11_\mathrm{B}}}$ (1). In the formula, E represents the energy in the middle of the target thickness, while E′ represents the real energy of the beam reaching the target surface. The accelerator calibration was considered to be well-known from previous experiments in the same setup and equal to a -3 keV offset from the nominal energy determined via NMR. The ripple of the energy beam was also estimated based on previous works in the same setup as equal to $\sim$ 3 keV. The term $\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)^{\mathrm{E}',\theta}_{Au}$ represents the Rutherford differential cross section calculated for the energy range under study (with the accelerator calibration having been taken into account) and corrected by the screening factor by L' Ecuyer et al. [6]. Additionally, the terms $\mathrm{Y}_{11_\mathrm{B}}$ and Y_{Au} refer to the integrated yields of the elastic ${}^{11}_{5}B\left(d,d_0\right){}^{11}_{5}B$ and ${}^{197}_{79}Au\left(d,d_0\right){}^{197}_{79}Au$ peaks respectively. Peak integration or fitting and background subtraction was carried out using the SPECTRW [7] code. A part of a typical deuteron spectrum in the elastic region is shown in Fig 1 for the nominal deuteron energy of 1625 keV and the backscattering angle of 160°. Due to the superior mass resolution of deuterons as compared to protons, the elastic scattering, along with protons from the (d,p$_0$) reaction on ^{12}C appeared (Fig 1) in 2 distinct peaks, revealing the presence of carbon not only inside the target, but also in its back. Unfortunately, the elastic peak from the backside carbon often presents a partial or even a complete overlap with the under study ${}^{11}_{5}B\left(d,d_0\right){}^{11}_{5}B$ peak. Most of these cases, occurred (because of kinematics) at the backscattering angles of 120°, 130°, 140°, but also in the lower energy region, namely for $E_{d,lab}$ < 1500 keV, concerning the detector angle of 150° and for $E_{d,lab}$ < 1300 keV concerning the detector angles of 160° and 170°. Therefore, it was judged that no reliable, high-accuracy results could be obtained in the aforementioned cases.

In fig 1 an overlap between the less abundant ${}^{10}_{5}B\left(d,d_0\right)$ and ${}^{12}_{6}C\left(d,p_1\right){}^{13}_{6}C$ reaction peaks is also observed, with the latter exhibiting several times higher counts. For deuteron beam energies exceeding 1800 keV a similar problematic overlap between the under study ${}^{11}_{5}B\left(d,d_0\right)$ peak and the ${}^{12}_{6}C\left(d,p_1\right){}^{13}_{6}C$ reaction one began to occur and intensified at an alarming rate, leading to the termination of the measurement process at the 1860 keV nominal deuteron beam energy value.

The quantities $\mathrm{N}_{\mathrm{t,Au}}$ and $\mathrm{N}_{\mathrm{t},11_\mathrm{B}}$ refer to the total thickness in at/cm^2 of ^{197}Au and ^{11}B nuclei present in the target respectively. The ratio of these quantities was determined with the use of the SIMNRA code [8], version 7.03 with the following procedure: At first, the QxΩ product was determined based on the ${}^{197}_{79}Au\left(d,d_0\right)$ peak counts and the keV/channel & energy offset were used as obtained by the relevant accelerator calibration process. Afterwards, a virtual target with characteristics described in section 2 was created and slowly altered until an agreement of the experimental and simulated counts was achieved for the ${}^{11}_{5}B\left(d,d_0\right)$ peak, for the nominal proton beam energies of 2750 and 2920 keV and the backscattering angles of 140° and 160°. An example is presented in fig 2 for the nominal beam energy of 2920 keV at 160°. The process was repeated twice, each time utilizing a different cross section dataset among [3] and [5] and the final result was obtained by averaging the 8 acquired values, adopting as statistical uncertainty the standard deviation of the results. The obtained ratio ^{197}Au/^{11}B was thus equal to 0.0615±0.0022 and was considered constant for the remaining analysis. Finally, the realistic virtual target created in SIMNRA, provided an estimation for the energy loss, as well as, the energy straggling of the beam from the surface to the middle of the target thickness, equal to ~3 keV and ~2.5 keV respectively.

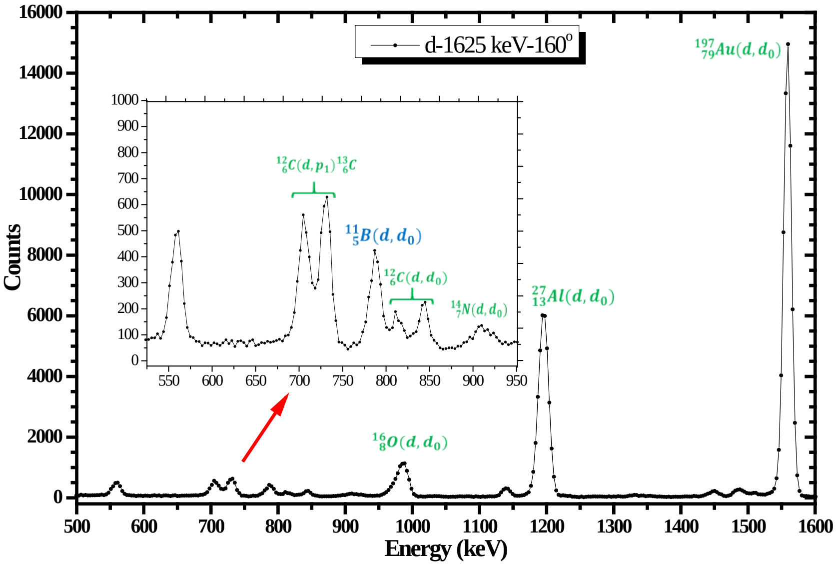

Fig. 1. Experimental deuteron spectrum along with the corresponding peak identification taken at $E_{d,lab} = 1625$ keV, 160°

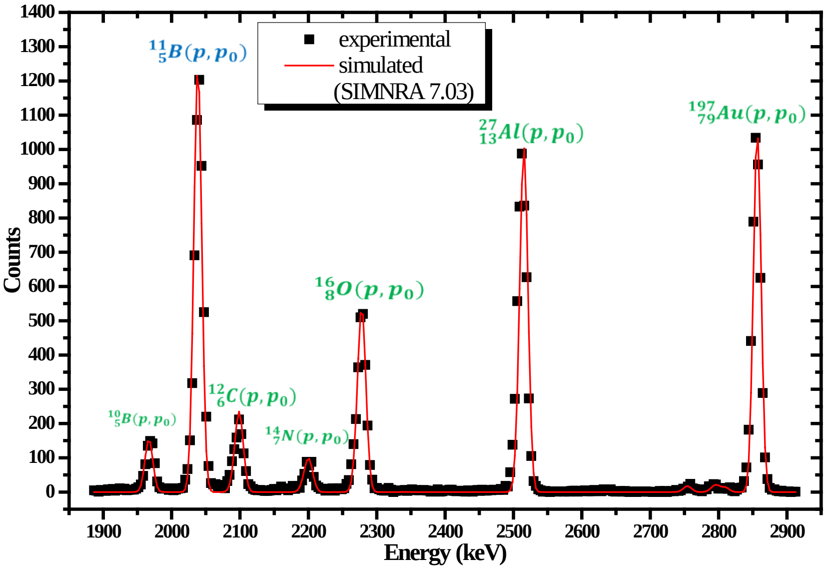

Fig. 2 Experimental and simulated proton spectra along with the corresponding peak identification taken at $E_{p,lab} = 2920$ keV, 160°

4. Results and Conclusions

The results from the calculations using the formula (1) are presented in fig 3 for the backscattering angles of 150°, 160° and 170°. The differential cross section values obtained correspond to the energy in the middle of the target thickness with the plotted statistical error being derived from the standard error propagation formula. The non-plotted systematic uncertainty (<5%) mainly concerned stopping power issues.

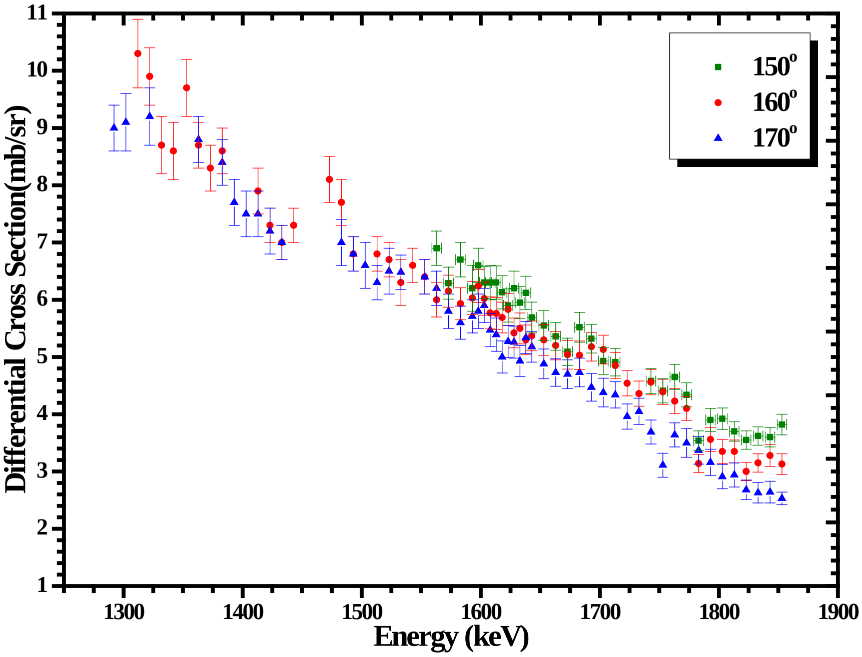

Fig. 3. Differential cross section values (mb/sr) of the elastic ${}^{11}_{5}B\left(d,d_0\right){}^{11}_{5}B$ scattering measured at $E_{d,lab}=$1300-1860 keV for the scattering angles of 150°, 160°, 170°

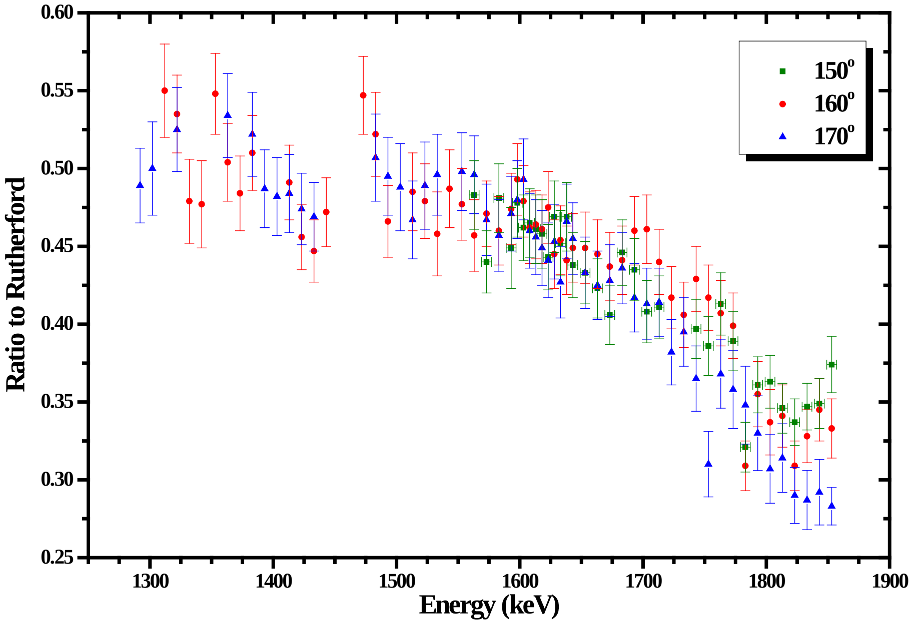

Fig. 4. Ratio to Rutherford of the elastic ${}^{11}_{5}B\left(d,d_0\right){}^{11}_{5}B$ scattering measured at $E_{d,lab}=$1300-1860 keV for the scattering angles of 150°, 160°, 170°

Additionally, values for the Rutherford differential cross section ${}^{11}_{5}B\left(d,d_0\right)$ were also calculated in order to determine the corresponding ratio of the values obtained in the present work. As shown in fig 4, the experimental values appear to be lower than the Rutherford ones by a factor of 2-3 depending on the energy region. For higher energy values the deviation from the Rutherford values seems to be intensifying. As seen in figs 3 and 4, there is a lack of any particular pronounced structure in the obtained results and this can be explained by the fact that the cross section is dominated by wide, overlapping resonances originating from the excited levels of the compound nucleus ${}^{13}_{6}C$ [9] over the whole scanned energy range. Finally, no pronounced angle distribution was observed for the backscattering angles studied in this experiment. This particular study complements a long, thorough research effort initiated by our group to accurately determine the differential cross sections for deuteron elastic scattering on practically all the most abundant stable, light isotopes in the energy region below the deuteron breakup energy.

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