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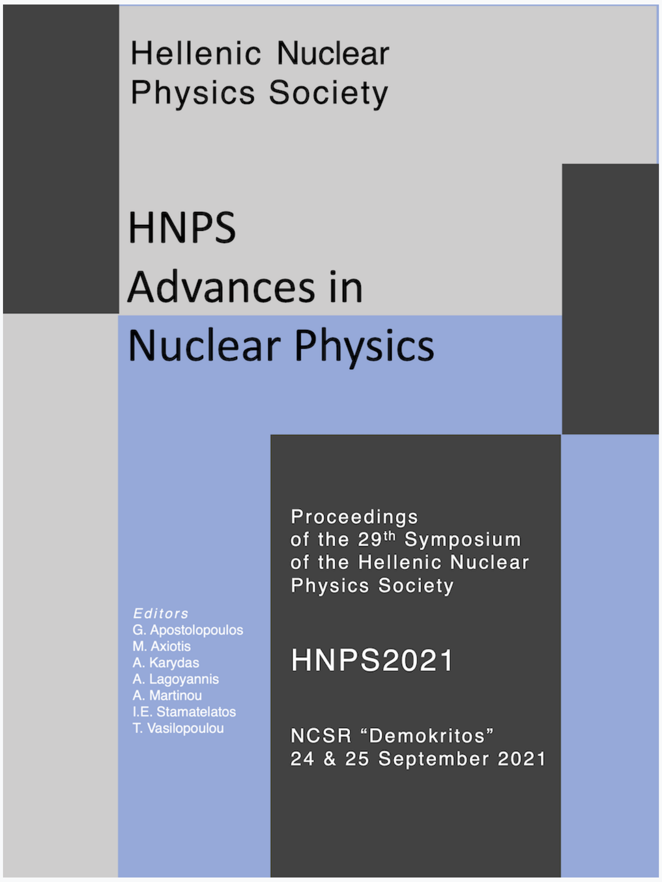

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Study of the Elastic Scattering in the d + ^{11}B system for EBS purposes

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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, along with Nuclear Reaction Analysis, has been proposed in order to address the current needs for boron depth profiling, focusing on the use of proton beams. Deuteron beams however offer superior mass resolution with similar stopping power values and simultaneous excitation of most light elements. 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 section covering the $E_{d,lab}$=1300-1860 keV energy range for the backscattering angles of 150°, 160° and 170° were 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 normalization and wear protection purposes. The outgoing particles were detected using silicon surface barrier (S.S.B.) detectors and the differential cross sections for elastic scattering were determined from the resulting spectra via the relative technique.

Keywords EBS, Cross Section, Boron

INTRODUCTION

Boron is composed of 2 stable isotopes: $^{10}_{5}B(19.9\%)$ & $^{11}_{5}B(80.1\%)$ and is an element presenting a large variety of applications in different industries. More specifically, it appears as a common dopant in the p-type silicon semiconductors as well as a dopant in the field of metallurgy on account of its beneficial effect in the mechanical properties of specific alloys [1]. For this reason, the accurate quantitative determination of its depth profile concentrations in near surface layers of various matrices is of utmost importance. Ion beam analysis techniques offer precise, least-destructive depth profiling with the proton Nuclear Reaction Analysis (p-NRA) technique based on the reaction $^{11}_{5}B(p,a_0)^{8}_{4}Be$ along with the proton Elastic Backscattering Spectroscopy (p-EBS) mainly being proposed to cover applications in a wide energy range ([2], [3]). Deuterons, however, offer greater mass resolution compared to protons, with similar stopping power values and the ability to simultaneously excite most light isotopes, if the need arises. Thus, the combination of d-NRA and d-EBS could prove to be an alternative for boron depth profiling in complex light matrices. Unfortunately, the current lack of

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experimental datasets concerning the ${}^{11}_{5}B(d,d_0)$ cross section for backscattering angles impedes their use. Therefore, the aim of the present work is to enrich the literature and the online library IBANDL (https://www-nds.iaea.org/exfor/ibandl.htm) with new data concerning the differential cross-section values of ${}^{11}_{5}B(d,d_0)$.

EXPERIMENTAL DETAILS

The experiment was conducted at the 5.5 MV Tandem Accelerator of the National Centre of Scientific Research (NCSR) "Demokritos" in Athens, Greece. In the study, deuterons were accelerated in the energy range $E_{d,lab}$= 1000–1860 keV, with a chosen variable step of 5–10 keV. The targets were fixed in the center of a scattering chamber equipped with a high precision goniometer (~0.1°) and six silicon surface barrier (SSB) detectors were mounted at 120°-170° (step: 10°) and at a distance of 10-15 cm from the targets. 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. Each ADC unit was calibrated using the position of the ${}^{197}_{79}Au(d,d_0)$ peak in more than 30 spectra, ensuring solid knowledge of the keV/channel correspondence and verifying the linear energy-channel relationship for the entire duration of the experiment.

The target used for the cross-section measurements was constructed at Ruđer Bošković Institute, Zagreb, Croatia. At first, an aluminum foil was created via evaporation in order to act as the backing of the target. On top of it a layer of ${}^{nat}B$ was deposited with the use of magnetron sputtering and afterwards, 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 evaporation there was a low inevitable carbon contamination. Complementary measurements using a proton beam ($E_{p,lab} = 2750,\ 2920 keV$) were carried out in order to assess the target thickness. Unfortunately, for boron's case, no available evaluated cross section datasets exist, so it was decided to carry out the target thickness measurements using the ${}^{11}_{5}B(p,p_0){}^{11}_{5}B$ elastic scattering in an energy range where at least 2 different datasets [2,4], in good agreement with each other, were available, thus increasing the credibility of the obtained results.

RESULTS AND DISCUSSION

For the calculation of the differential cross sections the corresponding formula of the relative technique was used: $\left(\frac{d\sigma}{d\Omega}\right)^{E,\theta}_{^{11}B(d,d_0)} = \left(\frac{d\sigma}{d\Omega}\right)^{E',\theta}_{Au} \frac{Y_{^{11}B}}{Y_{Au}} \frac{N_{t,Au}}{N_{t,^{11}B}}$ (1). The term $\left(\frac{d\sigma}{d\Omega}\right)^{E',\theta}_{Au}$ represents the Rutherford differential cross section calculated for the under-study energy range (accelerator calibration taken into account) and corrected by the screening factor by L'Ecuyer et al. [5]. In the formula, E represents the energy at the middle of the target thickness and θ the scattering angle, while E' represents the real energy of the beam reaching the target surface. The accelerator calibration is considered 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 considered equal to ~3 keV. Additionally, $Y_{^{11}B}$ & Y_{Au} refer to the integrated yields of the elastic ${}^{11}_{5}B(d,d_0)$ and ${}^{197}_{79}Au(d,d_0)$ peaks respectively. Peak integration or fitting and background subtraction was carried out with the SPECTRW [6] 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 that deuterons offer compared to protons, the elastic scattering, along with protons from (d,p_1) reaction on ${}^{12}C$, appeared (Fig.1) in 2 distinct peaks, revealing an additional carbon presence in the backside of the target. The under study ${}^{11}_{5}B(d,d_0){}^{11}_{5}B$ peak often overlapped partially or even completely with the elastic peak of the backside carbon. These cases occurred (because of kinematics) at the backscattering angles of 120°, 130°& 140°, but also in the lower energy region $E_{d,lab} < 1500\ keV$ concerning 150° and $E_{d,lab} < 1300\ keV$ concerning 160° & 170°. Unfortunately, no high accuracy results could be obtained there.

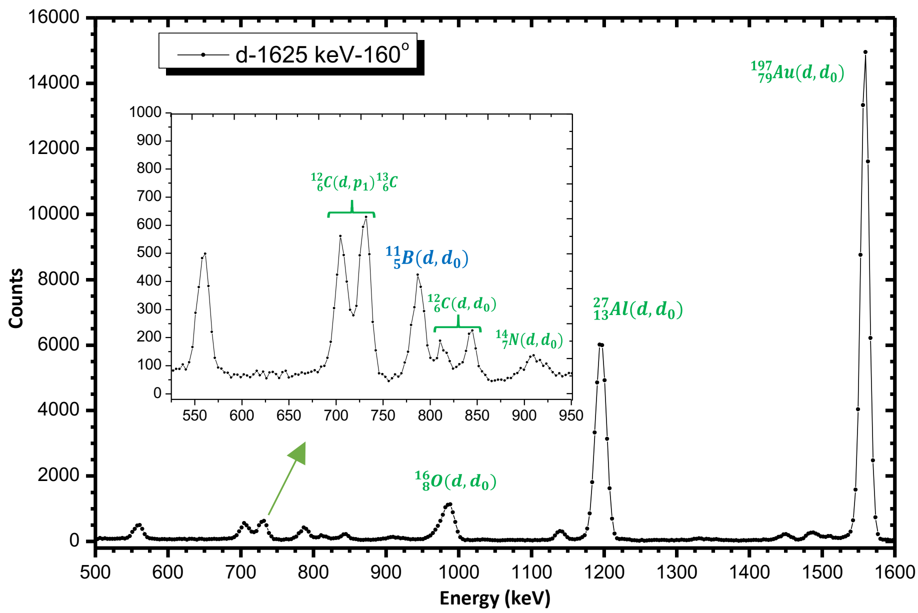

Fig. 1. *Experimental deuteron spectrum taken at $E_{d,lab}$ =1625 keV, 160°*

The quantities $N_{t,Au}$ & $N_{t,^{11}B}$ refer to the total thickness in at/cm^2 of ^{197}Au & ^{11}B nuclei present in the target respectively. The ^{197}Au/^{11}B ratio was determined with the use of the SIMNRA code [7], version 7.03. The stoichiometry of the virtual target was altered until an agreement of the experimental and simulated counts was achieved for the $^{11}_{5}B(d,d_0)$ peak for the nominal energies $2750, 2920\ keV$ and the backscattering angles of 140°, 160°. The process was repeated twice, each time utilizing a dataset between the [2],[4] and the final result was obtained by averaging the acquired values with the standard deviation being the error. The ratio obtained was: 0.0615±0.0022. The simulated target also yielded an energy straggling value ~ 2.5 keV. The error in energy was calculated based on the formula: $energy\ error = \sqrt{straggling^2 + ripple^2} \sim 4\ keV$.

The results from the calculations using formula (1) are presented in fig 2 for the backscattering angles of 150°, 160°, 170°. For the backscattering angles studied no pronounced angle distribution was observed. Finally, for the energy range scanned, the obvious lack of fine structure indicates that the cross section is dominated by overlapping resonances from the excited levels (https://www.nndc.bnl.gov/nudat2/getdataset.jsp?nucleus=13C) of the resulting compound nucleus $^{13}_{6}C$.

CONCLUSIONS

The first set of differential cross section values of the $^{11}_{5}B(d,d_0)^{11}_{5}B$ elastic scattering was obtained in the $E_{d,lab}$=1300-1860 keV energy range for the backscattering angles of 150°, 160° and 170°. This particular work complements a thorough research effort by our group to precisely determine the

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differential cross sections for deuteron elastic scattering on most of the light isotopes below the deuteron breakup energy.

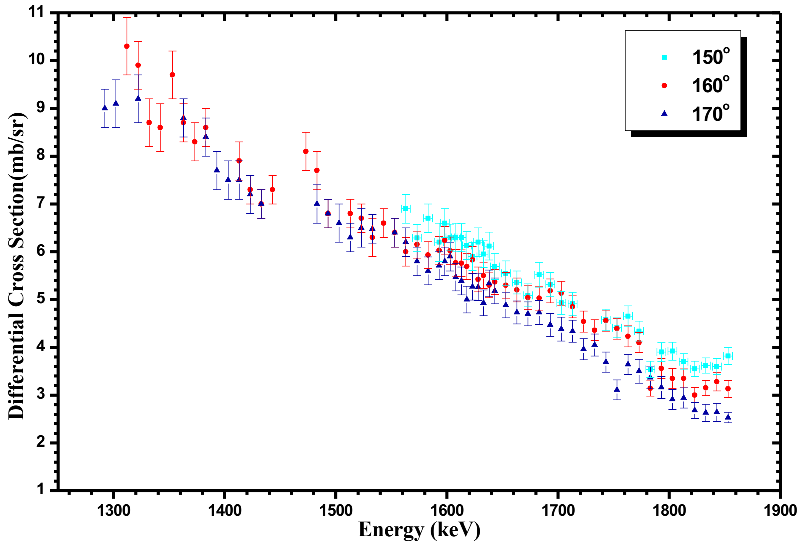

Fig. 2. *Differential cross section values at* $E_{d,lab}$ *=1300-1860 keV, 150°, 160°, 170°*

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