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Differential cross sections for the $^{11}B(p,\alpha_o)^8Be$ and $^{11}B(p,p_0)^{11}B$ reactions, suitable for ion beam analysis

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ABSTRACT

Boron depth profiling presents strong analytical challenges for all Ion Beam Analysis (IBA) techniques. In the past, both the $^{11}B(p,\alpha_o)^8Be$ (NRA) and the $^{11}B(p,p_0)^{11}B$ (EBS) reactions have been proposed and they seem to be quite suitable for analytical purposes. Nonetheless, both reactions have not been adequately studied in literature (as far as data suitable for material analysis in the backscattering geometry are concerned). Moreover, the existing datasets are relatively discrepant. In an attempt to clarify the situation, both reactions were studied in the present work between 135° and 160°, in steps of 5°, for the proton beam energy range between 2.2 and 4.2 MeV, in steps of 50 keV. An attempt to explain the occurring results in the framework of the resonance mechanism is also presented, along with a comparison with previously published data.

1. Introduction

Boron is a highly regarded technological element and has numerous applications in various fields. It is widely used in the semiconductor industry as a dopant for Si and Ge substrates, and it is also an essential ingredient of hard coatings on the walls of thermonuclear plants. Thus, the accurate quantitative determination of boron depth profiles in heavy and light matrices or substrates is of great importance. However, the determination of the boron distribution, especially on heavy substrates and/or in the presence of other light elements, presents a strong analytical challenge for all Ion Beam Analysis (IBA) techniques. In the past, both the $^{11}B(p,\alpha_o)^8Be$ (NRA) and the $^{11}B(p,p)^{11}B$ (EBS) reactions have been proposed, and they seem to be quite suitable for analytical purposes.

EBS (Elastic Backscattering Spectroscopy) is well established as one of the principal IBA methods nowadays. General EBS characteristics involve high analytical power for the accurate quantitative determination of light element concentrations (owing mainly to the high cross sections involved), and capability of least destructive depth profiling. Thus, EBS is the most widely used IBA method for light element depth profiling. In the case of boron, however, the implementation of EBS is seriously impeded by the lack of adequate and/or reliable cross section data in literature over a wide range of energies and detection angles. The same problem also affects Nuclear Reaction Analysis (NRA), which is alternatively used for boron depth profiling, due to its high isotopic selectivity, enhanced sensitivity for many elements, capability of least destructive depth profiling, and the possibility of simultaneous analysis of several light elements in near-surface layers of materials.

Natural boron is comprised of 81.1% ^{11}B and 19.9% ^{10}B. Thus, as far as EBS and NRA are concerned, the analytical study of both isotopes is imperative. In the case of ^{11}B, only a few pioneer works have been presented in the field of charged particle spectroscopy in the past, suitable for ion beam analysis, investigating the $(^3He,x)$ [1–3], $(d,p/\alpha)$ [4,5], and (α,p) [6,7] reactions. However, the (p,p_0) and the (p,α_0) reactions are generally considered as the most suitable ones [8,9] for ^{11}B depth profiling, mainly due to the relatively high differential cross sections involved, and to the possibility of probing greater depths inside the targets with the use of a proton beam. Nevertheless, to the authors' best knowledge, there exist only a few, and relatively discrepant reports [8–13], concerning these reactions in literature, for the energy and angular range covered in the present work (suitable for IBA), with the situation being more problematic in the case of NRA.

In an attempt to clarify the situation, both the (p,p_0) and the (p,α_0) reactions were studied in the present work between 135° and 160°, in steps of 5°, for the proton beam energy range between 2.2 and 4.2 MeV, in steps of 50 keV. An attempt to explain the occurring results in the framework of the resonance mechanism is also presented, along with a comparison with previously pub-

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lished data. The results from the present work could be directly incorporated in widely used NRA algorithms (e.g. SIMNRA [14], WINDF [15]) and are already available to the scientific community through IBANDL (Ion Beam Analysis Nuclear Data Library, http://www-nds.iaea.org/ibandl/).

2. Experimental setup and procedure

The experiments were performed using the proton beam of the 5.5 MV TN11 Tandem Accelerator of N.C.S.R. "Demokritos", Athens, Greece. The protons, accelerated to $E_{p,lab}$ = 2200–4200 keV in steps of 50 keV, were led to a cylindrical scattering chamber of large dimensions ($R \sim 30$ cm). The final ion energy of the proton beam (energy offset ~3 keV) was determined by nuclear magnetic resonance measurements (NMR) with an estimated ripple of ~0.1–0.15%, as verified by the 991.89 keV resonance of the $^{27}Al(p,\gamma)$ reaction at the beginning and at the end of the experiment, using a HPGe detector. Possible significant non-linear deviations of the magnet at higher proton beam energies were not examined in the present work, but in principle they cannot be excluded, although they have not been observed in the past. For this reason the highest value of the ripple was adopted.

The detection system consisted of three Si surface barrier detectors (Thickness: 1000 μm; set at 10° intervals) along with the corresponding electronics. The spectra from all three detectors were simultaneously recorded, then they were all turned by 5°, recorded again, and the procedure was repeated for every $E_{p,lab}$. The beam spot size was 2.5×2.5 mm^2, while the current on target did not exceed 10 nA during all measurements. Two liquid nitrogen traps were set on both ends of the goniometer in order to reduce the carbon build-up on the target, while the vacuum was kept constant, as low as $\sim 5 \times 10^{-7}$ Torr. After every ~20 steps in beam energy, the beam spot position was slightly changed in order to avoid excessive carbon buildup and/or target deterioration (mainly through heating). The target was placed at a distance of ~9 cm from the detectors. Orthogonal slits ($\sim 4 \times 8$ mm^2) were placed in front of the detectors in order to reduce the angular uncertainty ($\sim \pm 1.5°$), while allowing an adequate effective solid angle to be subtended by the detectors.

A highly pure (>99%), isotopically enriched (~99%) ^{11}B target deposited on a mirror polished thick tantalum backing was used for the experiments. The target was manufactured at Garching, Munich, had an active surface of 1×1 cm^2, and the nominal thickness was reported as 323 μg/cm^2, or 17.99E + 18 at/cm^2 (assuming nominal boron density) with a maximum uncertainty of 5%. The high lateral homogeneity, as well as the practically negligible oxygen and carbon content of the target were verified with the use of d-NRA at $E_{d,lab}$ = 1100 keV (via the $^{16}O(d,p_0,\alpha_0,p_1)$ and the $^{12}C(d,p_0)$ reactions [16]) The target thickness and its corresponding uncertainty were also verified in the present work using differential cross section data for the $^{11}B(d,\alpha_0)$ reaction [17], as well as low energy p-RBS spectra from both sides of the target (B on Ta and pure Ta respectively, via the energy difference of the Ta surface edge). Despite the many sources of uncertainty in this latter method (mainly due to the adopted stopping power values, as well as to the high penetrability of the proton beam), the obtained results differed by only 0.5% with one another, and corroborated with the manufacturer's analysis within error. Thus the final adopted value that was used in the determination of the differential cross sections was (17.4 ± 0.6)E + 18 at/cm^2 (with a relative error of approximately 3.5%).

The effective solid angle subtended by the detectors (along with their energy resolution) was determined via a 81.1 nCi triple α-source (^{241}Am/^{239}Pu/^{244}Cm, IAEA certified, at 4% accuracy), placed at the exact location of the beam spot (and being of approximately the same size). These values were also verified by fitting the thick tantalum background experimental spectra taken at the same beam energies (p-RBS), since $^{nat}Ta(p,p)$ does not deviate from Rutherford formula for the proton beam energies studied in the present work. SIMNRA (v. 6.05) was used for the analysis of the thick-target p-RBS spectra and Ziegler–Biersack-Littmark (ZBL, [18]) stopping power data for protons were implemented, as incorporated in the algorithm. The obtained simulated results for the $Q^*\Omega$ product involved a minimization window set relatively close to the surface (in order to exclude energy straggling effects) and verified the α-source results. Thus, the total estimated error for the product varied between ~3–4% (pending on the detector). The statistical error from peak integration also varied between ~1–5%.

Two different algorithms were implemented for peak fitting/integration and background subtraction, yielding results within 1–2%. For the charge measurements (charge collection and subsequent current integration) the whole chamber was electrically isolated from the beam line and voltage suppression of ~250 V was applied on both the collimator set and on target. A typical experimental spectrum taken at 145° and $E_{p,lab}$ = 3597 keV is presented in fig. 1, along with the corresponding peak identification. The broad background appearing between the Ta edge and the α_0 peak is related partly to the pileup due to the high-Z Ta backing, and partly due to the excited compound nucleus $^{12}C^* \rightarrow 3\alpha$ reaction, or to the resulting ^{8}Be nucleus breakup into two α-particles, which results in 3-body kinematics. This problem has been analyzed in several works in the past [9,17], concerning the highly excited compound nucleus $^{12}C^*$, and it constitutes one of the major drawbacks for the implementation of the $^{11}B(p,\alpha_1)$ reaction for IBA applications, as far as accurate boron depth profiling is required. The other major problem is the uncertainty in energy in the first excited state of the resulting nucleus ^{8}Be [17]. Thus, the present work, as far as NRA is concerned, was focused only on the analysis of the $^{11}B(p,\alpha_0)$ reaction, which is reliable for analytical purposes.

3. Analysis and discussion

The determination of the differential cross section values was carried out following the formula for absolute measurements:

$$\left(\frac{d\sigma}{d\Omega}\right)_\theta = \frac{Y}{Q * \Omega * Nt_i}$$

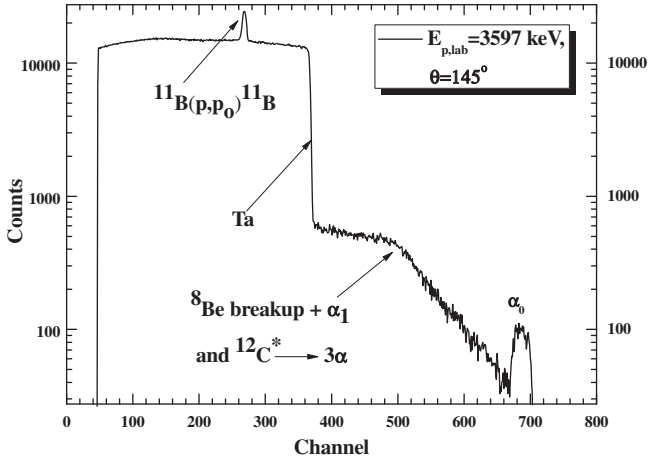

Fig. 1. Experimental spectrum taken at 145° and for $E_{p,lab}$ = 3597 keV, along with the corresponding peak identification. The broad background appearing between the Ta edge and the α_0 peak is related to both the pileup due to the high-Z Ta backing, and to the resulting 3-body kinematics, due to all the α-breakup induced reactions.