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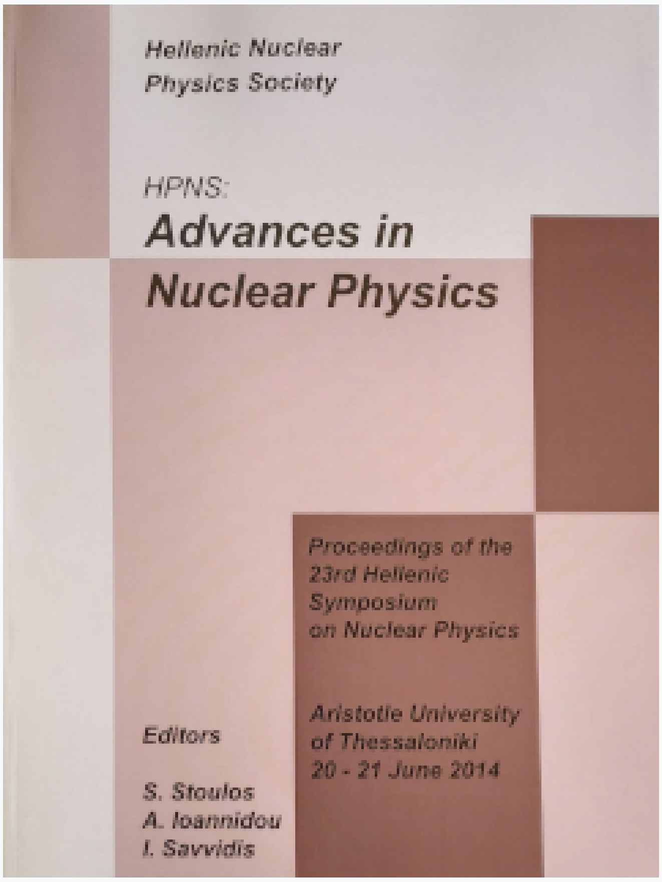

Study of the 10B(p,αγ)7Be and 10B(p,p’γ)10B reactions for PIGE purposes

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Study of the $^{10}B(p,\alpha\gamma)^{7}Be$ and $^{10}B(p,p'\gamma)^{10}B$ reactions for PIGE purposes *

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1. Introduction

NRA, and especially Particle-Induced Gamma ray Emission (PIGE) is a well-known and widely used method, usually in conjunction with PIXE, due to its enhanced detection sensitivity for many nuclides as well as its high isotopic selectivity. While a lot of effort has recently been devoted to the precise determination of reliable cross sections for use with charged particle NRA [1-2], there is a lack of data in the literature regarding PIGE. The use of differential cross section data for PIGE analysis along with a suitable code, instead of thin or thick target yields, will greatly enhance the use of the technique as it will lead to samples quantification without utilizing reference materials
In the case of ^{10}B, the majority of the existing data are from studies performed for spectroscopic purposes [3-10], and only few of them are suitable for PIGE analysis. This situation is further complicated by the fact that among these few datasets there are big discrepancies, which in certain cases can reach up to a factor of 5. The aim of the present work was to disentangle these discrepancies and to provide reliable differential cross section data for the PIGE ^{10}B quantification. For this reason, the characteristic γ-rays 429 and 718 keV, originating from the $^{10}B(p,\alpha\gamma)^{7}Be$ and $^{10}B(p,p'\gamma)^{10}B$ reactions respectively, have been studied at 8 different angles for the proton beam energy range between 2000 and 5000 keV with a variable energy step of 20 to 40 keV.

2. Experimental Setup

The measurements were carried out at the Tandem Accelerator Laboratory of the Institute of Nuclear and Particle Physics, National Centre of Scientific Research (N.C.S.R.) "Demokritos", using the installed 5.5 MV TN11 Tandem Accelerator. The energy of the protons ranged from E_{lab} = 2000 - 5000 keV with a variable step of 20 - 40 keV. Before and after the cross section measurements the accelerator was calibrated using the well-known resonances of $^{27}Al(p,\gamma)^{28}Si$ and $^{13}C(p,\gamma)^{14}N$ at E_p = 991.9 and 1746.9 keV respectively. The offset of the analyzing magnet was found to be 2 keV while the ripple was estimated to be ~ 1.5 ‰. The beam was lead through a 2 mm tantalum collimator, approximately 1 m before the target placed into a cylindrical reaction chamber. The air cooled target was placed in the center of the chamber and was perpendicular to the beam. The whole chamber acted as a Faraday cup, while a suppression voltage of +300 V was applied to the collimator in order to ensure a reliable beam charge collection. The beam current did not exceed 600 nA on target in order to keep a low counting rate and to avoid any possible thermal damage.
The detection setup consisted of three HPGe detectors of 100% relative efficiency and a fourth one of 70%. They were mounted on a motorized turntable at initial angles of 0^o, 55^o, 90^o and 165^o with respect to the beam direction, and at a distance of ~ 25 cm from the target. The angular acceptance of each detector was $\pm10^o$ and covered a solid angle of

approximately 17.6 msr. At every energy step the table was turned by 15° enabling the acquisition of data at four additional angles, namely 15°, 40°, 105° and 150°. The energy, as well as the efficiency calibration of the detectors was performed using a calibrated ^{152}Eu source both at the beginning and at the end of the experiment in order to ensure proper functionality of the detectors. The data acquisition was accomplished using standard NIM electronics. The ADC's dead time did not exceed 5% throughout the whole experiment.

A thin ^{nat}B target and an enriched ^{10}B one were used for the cross section measurements. Both targets were prepared by electron gun evaporation on thick tantalum backings. The thin ^{10}B enriched target was characterized by applying the Elastic Backscattering Spectrometry (EBS) method. Protons were accelerated at an energy of E_p = 2500 keV and were led in the goniometric chamber, where they were detected with the use of a 1000 μm thick surface barrier detector (SSB) placed at an angle of 170°. For the thickness measurement of the ^{nat}B target, the energy of the impinging protons was set to E_p = 2600 keV and a combination of the EBS and NRA techniques was used. In order to minimize pile up effects the beam current was kept as low as 1 nA. The backscattered protons from ^{11}B and the α particles emitted due to the $^{11}B(p,\alpha)^{8}Be$ reaction were simultaneously detected by a SSB detector placed at 150°. Having measured the thickness of ^{11}B, which has a natural abundance of 80.1%, the thickness of ^{10}B can be easily derived. The analysis of the acquired spectra was made using the SIMNRA code [11]. For the ^{nat}B target two analyses were performed using the different datasets [1], [12] available for downloading through the IBANDL nuclear database from IAEA [www-nds.iaea.org/ibandl/]. The difference in the results of both analyses did not exceed 2% and was included in the final uncertainty. The experimental spectra along with the simulation curves are presented in Fig. 1. The thicknesses of the enriched ^{10}B and of the ^{nat}B targets were found to be 1750 and 577 x 10^{15} at/cm^2 respectively. The uncertainty in the thickness measurement of the ^{nat}B target was 5% while for the enriched one was ~ 25%, mainly due to the low cross section of the $^{10}B(p,p)^{10}B$ reaction, to the discrepancies between the available elastic datasets used for the analysis and to the high background originating from the tantalum backing.

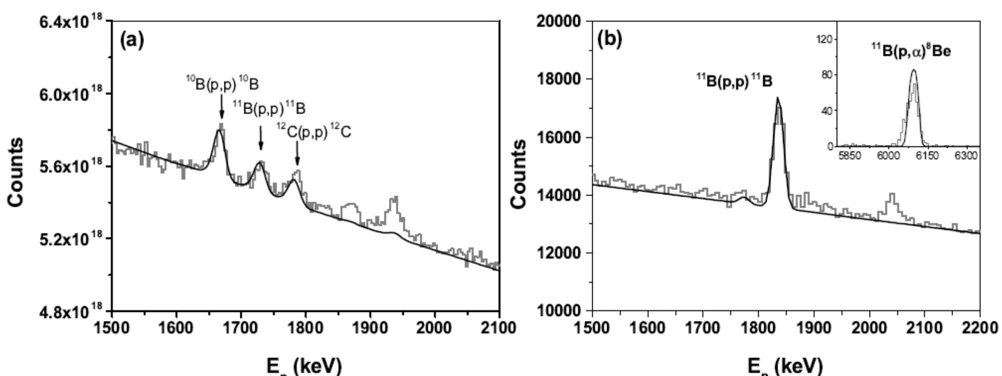

Fig 1: (a) The EBS spectrum of the ^{10}B enriched target along with the simulation of SIMNRA [11]. The highly induced background from the Tantalum backing results at a high uncertainty in the determination of the target's thickness. (b) The backscattered elastic peak from ^{11}B was analyzed simultaneously with the $^{11}B(p,\alpha)^{8}Be$ peak (insert).

3. **Analysis and Results**

In every spectrum the 429 and 718 keV γ - rays, emitted from the de-excitation of the first level of the ^{7}Be and ^{10}B nuclei respectively, were clearly visible. In order to avoid any systematic errors due to computer integration programs, the peak was analyzed using two different codes, namely TV [13] and SPECTRW [14]. The difference of the integrals between the two codes was less than 1%. The reported energy values correspond to the mean proton beam energy at half of the target's thickness according to SRIM 2003 [15] calculations. The differential cross sections were derived using the formula:

$$\frac{d\sigma}{d\Omega} = \frac{N}{4 \cdot \pi \cdot Q \cdot \varepsilon_{abs} \cdot \xi}$$

where N corresponds to the integrated area of the peak, Q to the accumulated beam charge, ε_{abs} to the detector's absolute efficiency and ξ to the target's thickness. The systematic uncertainty for the measurement of the beam charge was estimated to be ~ 3.5% and for the target's thickness ~ 7%. Combining the error in the activity of the ^{152}Eu source, as it was given by the manufacturer, with the uncertainty of the branching ratios of the emitted γ-rays, the calculated systematic uncertainty of the detectors' efficiency was 1.5%. Applying the usual error propagation formula, this yields a total uncertainty budget of 8% for the differential cross-section measurements. On the other hand, the statistical errors coming from the integration of the peaks ranged between 3 - 5%. The differential cross sections of the ^{10}B(p,αγ)^{7}Be and ^{10}B(p,p'γ)^{10}B reactions are presented in Fig. 2.

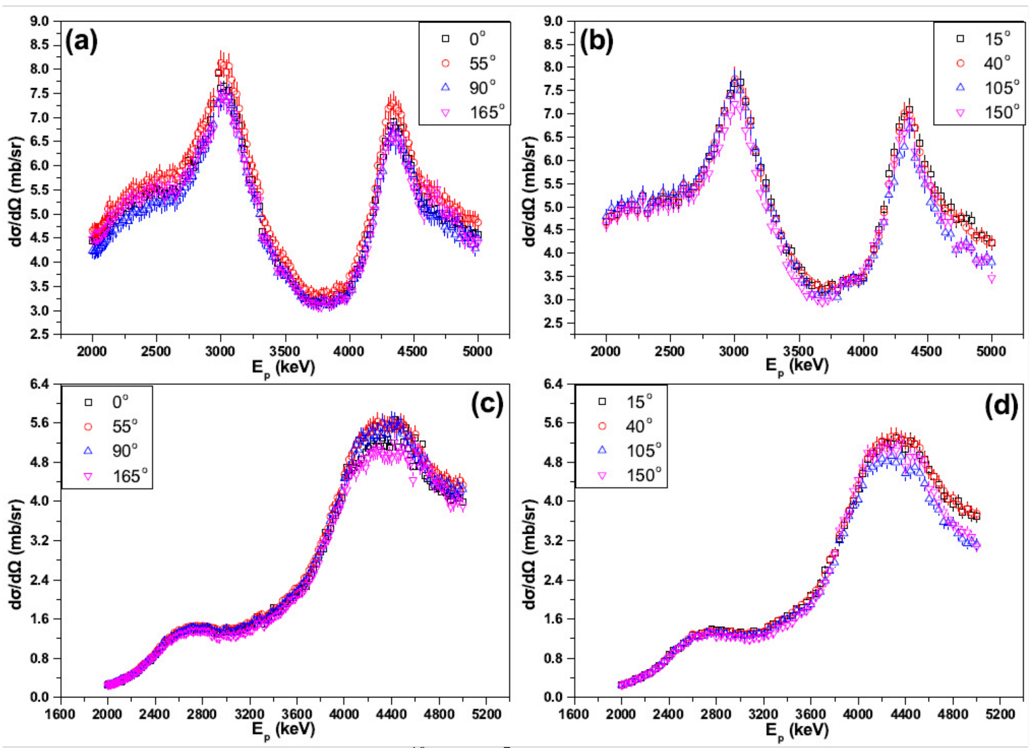

Fig 2: Differential cross sections of the ^{10}B(p,αγ)^{7}Be reaction at (a) 0°, 55°, 90°, 165° and (b) 15°, 40°, 105° and 150°. The differential cross sections for the same angle sets but for the ^{10}B(p,p'γ)^{10}B are presented at (c) and (d). Two broad resonances are evident for both the reactions at E_p= 3020 and 4355 keV.

The differential cross sections of both the reactions exhibit a smooth variation with the bombarding energy. The absence of strong narrow resonances throughout the whole energy range is evident. The high cross section values (3.0 - 8.0 mb/sr) of the ^{10}B(p,αγ)^{7}Be reaction, renders it more appropriate for most of the PIGE experiments. However, in PIGE systems with low resolution detectors, the ^{10}B(p,p'γ)^{10}B reaction is more appropriate as there are no other γ lines in the vicinity of the 718 keV line. In the case of the ^{10}B(p,αγ)^{7}Be reaction, two broad structures were observed at E_p = 3020 and 4355 keV. These resonance energies correspond to the excited levels at 11.44 and 12.65 MeV of the compound nucleus ^{11}C [16]. The fact that the observed structures in the excitation functions are broad could be attributed to the rather large width (Γ = 350 keV) of the ^{11}C excited levels. Both of these structures also appear in the case of $^{10}B(p,p'\gamma)^{10}B$, as both studied reactions produce the same compound nucleus. Moreover, the comparison between the eight different detection angles reveals no significant angular dependence of the cross section. This weak angular dependence can in principle facilitate PIGE studies, especially for experimental setups where the γ detector is placed close to the target, enhancing thus, its angular uncertainty.

4. **Discussion**

In Fig. 3 the cross section data at 55° obtained in the present work are compared with the ones previously reported [9-12]. The agreement of both the reactions with the data of Day et al. [9] is excellent, except for the case of the $^{10}B(p,\alpha\gamma)^{7}Be$ reaction at $E_p > 2500$ keV where slightly higher values were reported. This difference can be attributed, as stated by Day et al., to the contribution of the 718 keV line in their spectra. The values given by T. R. Ophel et al. [10] are ~ 3.5 times lower than the current measurements. The reported 20% error in the determination of the cross section could not justify the observed disagreement. However, they acknowledge that the main uncertainty in their measurement derives from the target's thickness which was taken as the nominal value given by the manufacturer. In addition, it appears from the plotted data that there is an energy shift of ~ 70 keV at the vicinity of the second resonance in both studied reactions. However, this shift appears only at the plotted data, while in the text the reported resonance energies agree with the ones of the present work. The measurements of Hunt et al. [8] and Segel et al. [4] produced cross sections approximately 2 times lower than these of the present work. While this disagreement in the case of Segel et al. could be attributed to their rather large dead time of the experiment (50%), there is no apparent reason for such a difference with Hunt et al. The same statement also stands for the data measured by C. Boni et al. [9]. Although there is a very good agreement in the form of the excitation function, the reported cross sections are underestimated by a factor of 5. The observed discrepancies could not be attributed either to the systematic uncertainties of this work, which do not exceed 8%, or to the ones reported by C. Boni et al. (15%).

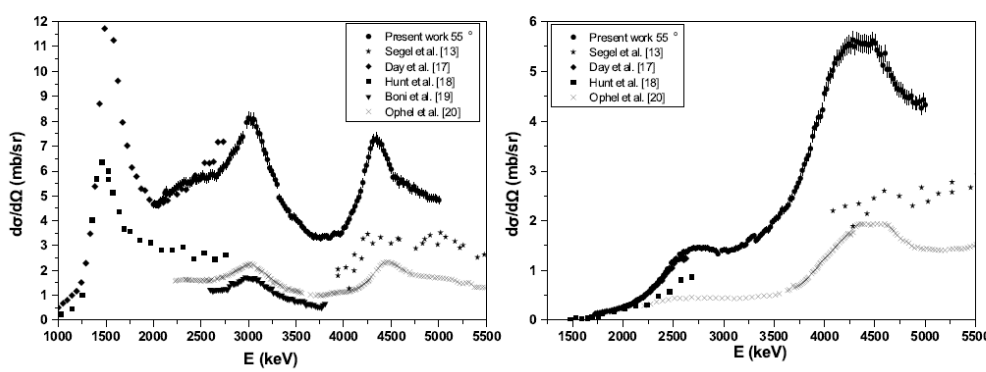

Fig 3: Comparison of the $^{10}B(p,\alpha\gamma)^{7}Be$ and $^{10}B(p,p'\gamma)^{10}B$ cross sections at 55° with the experimental data of previous works. The possible reasons for the observed differences are discussed in the text.

5. **Conclusions**

In the present work differential cross section data of the $^{10}B(p,\alpha\gamma)^{7}Be$ and $^{10}B(p,p'\gamma)^{10}B$ reactions have been derived at 8 angles for the proton beam energy range between 2.0 and 5.0 MeV. The additional data obtained highlighted the discrepancies found in previous works and possible explanations for them were suggested. In the case of the 429 keV γ - ray resulting from the $^{10}B(p,\alpha\gamma)^{7}Be$ reaction, two strong discrete broad resonances could be observed at ~ 3.0 and ~ 4.3 MeV. The data from different angles revealed that there is no strong angular dependence throughout the whole energy range.

Acknowledgements
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