Study of the $^{11}B(p, p'\gamma)^{11}B$ reaction for PIGE applications

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The differential cross sections of the 2125 keV $\gamma$-ray, emitted by the $^{11}B(p, p'\gamma)^{11}B$ reaction were measured at six (6) angles and at proton energies from 2.5 to 5.0 MeV. The experimental setup consisted of three (3) 100% relative efficiency HPGe detectors placed on a motorized turntable. The comparison between the present measurements, which have an overall uncertainty of ~8%, and previous ones from literature gives contradictory results. While there are large differences with previous differential cross-section measurements from literature, there is good agreement with previous thick-target yield ones. Additional thick-target measurements were performed in an effort to explain the observed discrepancies.

1. Introduction

The wide use of boron in many industrial and technological applications poses an important challenge for most of the Ion Beam Analysis (IBA) techniques. Widely used techniques such as Elastic Backscattering Spectroscopy (EBS) and Proton Induced X-ray Emission (PIXE) are problematic in most of the cases where boron coexists in matrices with other light elements. An alternative approach to the problem of boron's quantification in various matrices, that has been used successfully in the past, is Nuclear Reaction Analysis (NRA) and more specifically Particle Induced Gamma ray Emission (PIGE) [1–5]. PIGE has certain advantages over charged particle NRA, with the enhanced detection sensitivity being the most important one. The main drawback in the applicability of PIGE in the quantification of light elements, is the need for reference materials similar in composition to the one under study, because of the important role of the energy loss in the calculations. On the other hand, the use of differential cross sections as inputs in appropriate simulation codes, such as ERYA code described by Mateus et al. [6,7], Fonseca et al. [8] and Barradas et al. [9], could overcome this difficulty. The only published study about the cross section of the $^{11}B(p, p'\gamma)^{11}B$ reaction is the one by Boni et al. [10]. However, the serious discrepancies observed between that work and the work by Lagoyannis et al. [11] for the case of the $^{10}B(p, p'\gamma)^{10}Be$ reaction motivated the study of the characteristic $\gamma$-ray of 2125 keV, originating from the $^{11}B(p, p'\gamma)^{11}B$ reaction, has been studied at 6 different angles for the proton beam energy range between 2580 and 5000 keV with a variable energy step of 10–20 keV.

2. Experimental setup

The proton beam was delivered by the 5.5 MV TN11 Tandem Accelerator installed at the Tandem Accelerator Laboratory of the Institute of Nuclear and Particle Physics, National Centre of Scientific Research (N.C.S.R.) “Demokritos”. The beam energy range was $E_{\text{lab}} = 2580–5000$ keV with a variable step of 10–20 keV and an accuracy of 0.1% as it was measured using the narrow resonances of $^{27}$Al$(p, \gamma)^{28}$Si and $^{12}$C$(p, \gamma)^{13}$N at $E_p = 991.9$ [12] and 1746.9 keV [13], respectively. The air-cooled target was placed perpendicularly to the beam axis at the center, in the center of an electrically isolated, cylindrical chamber which also acted as a Faraday cup. The beam spot on the target had a diameter of ~2 mm as a result of a set of tantalum collimators placed approximately 1 m before the chamber. A voltage of ~300 V was applied to the collimator set in order to suppress the emission of secondary electrons. The intensity of the beam was kept below 100 nA to keep the ADC dead time below 5% and avoid pile-up effects. The detection setup consisted of three (3) HPGe detectors of 100% relative efficiency. They were mounted on a motorized turntable at initial angles of 0°, 90° and 165° with respect to the beam direction. A more detailed description of the detection system can be found in [11]. Due to

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the highly energetic $\gamma$-ray emitted (2125 keV), a calibrated point source of $^{226}$Ra was used for the energy, as well as for the efficiency calibration of the detectors. The data acquisition was accomplished using standard NIM electronics.

As the natural abundance of $^{11}$B is 80.1%, a thin $^{nat}$B target on a tantalum backing was used for the cross-section measurements. For benchmarking purposes, two thick pellets were prepared by pressing amorphous powder; namely, a $^{nat}$B and a MgB$_2$ one. As boron is an insulator, an ultra thin layer of Au was evaporated on the surface of the thick $^{nat}$B target, as to avoid electrical sparks during the irradiations. The thickness of the thin $^{nat}$B target was measured by applying simultaneously the EBS (Elastic Backscattering Spectrometry) and NRA techniques. Details of the experimental setup used can be found in [14]. For this measurement, a proton beam with an energy of $E_p = 2600$ keV and an intensity of $\sim 1$ nA, in order to minimize pile-up effects, was used. A 1000 $\mu$m thick SSB detector placed at 150° served for the detection of both the elastically backscattered protons from the $^{11}$B(p,p)$^{11}$B reaction and the $\alpha$ particles from the $^{11}$B(p,$\alpha$)Be reaction. The acquired spectrum was analyzed using the SIMNRA code [15] and two different cross-section datasets from [16,17] available for downloading through the IBANDL nuclear database from IAEA [www-nds.iaea.org/ibandl/]. The two independent analyses gave no significant differences in the target thickness (2%). The experimental spectra along with the simulation curves are presented in Fig. 1.

The thickness of the $^{nat}$B target was found to be $577 \times 10^{-12}$ at/cm$^2$, with a statistical uncertainty of $\sim 5\%$.

Following the thin–target measurements, a benchmarking experiment for the $^{11}$B(p,p’)$^{11}$B reaction was performed. Two thick targets, namely a $^{nat}$B and a MgB$_2$ pellet, were mounted in the reaction chamber and their $\gamma$-ray spectra were detected for the beam energy range between 2000 and 2750 keV with a step of 250 keV.

### 3. Analysis and results

Due to the Doppler effect the short-lived first excited state of $^{11}$B ($T_{1/2} = 3.8$ fs) leads to a shift at the energy and a broadening of the observed 2125 keV $\gamma$-ray peak. Moreover, the $^{11}$B(p,p’)$^{11}$B reaction has a double kinematic solution, so, there are two different energies (two different velocities) for the recoil nucleus at the same laboratory angle, which results in two different Doppler-shifted peaks. The shape of these $\gamma$-ray peaks strongly depends on the angular distribution of the ejectile particles, as it was suggested by Tryti et al. [18] and Kiss et al. [19]. The combination of these effects at the experimental spectra is shown in Fig. 2 for the detector at 0° and at the energies of $E_p = 3000, 4000$ and 5000 keV. Because of its shape, the peak cannot be fitted by applying the usual Gaussian fit. Instead, the peak was integrated using two different algorithms incorporated in two different computer programs, namely TV [20] and SPECTRW [21], in order to avoid any systematic uncertainties. The proton beam energy was corrected, due to energy loss effects, according to SRIM 2013 calculations [22] by applying the usual convention of the reaction occurring at the middle of the thin target. The well known formula:

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

was used for the derivation of the differential cross sections. In the above relation $N$ corresponds to the integrated area of the peak, $Q$ to the accumulated beam charge. $\epsilon_{abs}$ to the detector absolute efficiency and $\xi$ to the target thickness. For the calculation of the detectors efficiency the yields from the $\gamma$-rays emitted from the $^{226}$Ra source, which are in the vicinity of the energy of the 2125 keV $\gamma$-ray, were fitted with the polynomial equation:

$$\epsilon_{abs} = \frac{1}{E_1^2} + \frac{1}{E_2^2} + \frac{1}{E_3^2}$$

The resulting differential cross sections of the $^{11}$B(p,p’)$^{11}$B reaction are presented in Fig. 3. All known sources of systematic errors along with the resulting total uncertainty of the experiment, using the usual error propagation formula, are included in Table 1.

As seen in Fig. 3, the differential cross section of the reaction above 2800 keV exhibits a smooth variation with the bombarding energy, originating from an overlap of broad resonances. The only narrow resonance is presented at $E_p = 2655$ keV (width $\sim 40$ keV), which corresponds to the excited state of the compound nucleus, $^{12}$C, at $\sim 18.39$ MeV which is in very good agreement with the broader reported value in literature ($18.35 \pm 0.05$ MeV, $\Gamma = 350$ keV) [23] which lies along with several others in this energy region. There are also some wider structures at $E_p \approx 3135, 3770$ and 4660 keV, which could be attributed to the excited levels at $18.80 \pm 0.04$ MeV ($\Gamma = 100$ keV), $19.40 \pm 0.03$ MeV ($\Gamma = 480$ keV) and $20.27 \pm 0.05$ MeV ($\Gamma = 140$ keV), respectively. Moreover, the

![Fig. 1. The backscattered elastic peak from $^{11}$B(p,p)$^{11}$B was analyzed simultaneously with the $^{11}$B(p,$\alpha$)Be peak (insert), using the SIMNRA code [15].](image)

![Fig. 2. Spectrum of the $^{11}$B(p,p’)$^{11}$B reaction, showing the combination of Doppler shift, angular distribution and double kinematic solutions of the 2125 keV $\gamma$-ray peak for the detector at 0° and at the energies of $E_p = 3000, 4000$ and 5000 keV.](image)
data from different angles revealed that there is no strong angular dependence throughout the energy range.

In order to check the validity of the measured differential cross sections, a homemade C++ code was developed and a thick-target experiment was performed. The code calculates the number of γ-rays produced by a certain reaction assuming a uniform thick target, taking into account the differential cross sections to be checked, the energy loss in the target, the integrated beam current and the detector efficiency. The output was then compared against experimentally acquired thick-target yields for proton energies between 2500 and 2750 keV. The differences between the calculated and the measured thick-target yields did not exceed 5% in all studied cases.

4. Discussion

The differential cross sections of the present work at 90° are plotted along with the only available data in the literature from Boni et al. [10] in Fig. 4. The large difference between the two data sets, despite the obvious qualitative agreement in shape, namely a factor of ~5, cannot be explained either by the systematic uncertainties of the present work or from the ones reported by C. Boni et al. (15%). It has to be noted that the same factor was also found in the case of the 10B(p, pγ)7Be reaction cross section as reported by A. Lagoyannis et al. [11]. The validity of the present results is supported not only by the benchmark procedure that was followed, but also by comparing the integrated differential cross sections with the previously reported thick target yields by Kiss et al. [24], Savidou et al. [25] and Chiari et al. [submitted to NIM B, already available in the IBANDL nuclear data library from IAEA (www-nds.iaea.org/ibandl/)] (Fig. 5). The data by C. Boni et al. were normalized at 2.4 MeV with the data by A.Z. Kiss as there are no measurements below 2.6 MeV. The two integrated datasets (black and red solid circles) exhibit different slopes, but only the present ones follow the thick-target yields trend. This fact further supports the validity of the obtained results of the present work.

5. Conclusions

The differential cross section of the 2125 keV γ-ray emitted by the 11B(p, pγ)11B reaction at six (6) angles for the proton beam energy range between 2.5 and 5.0 MeV was studied. The observed discrepancies between the present data and the previous ones were discussed. The high cross-section values (1.0–8.0 mb/sr) of

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Uncertainty (%)</th>
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<tr>
<td>Integrated beam current</td>
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</tr>
<tr>
<td>Target thickness</td>
<td>5</td>
</tr>
<tr>
<td>Detectors efficiency</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>7</strong></td>
</tr>
</tbody>
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Fig. 3. Differential cross sections of the 11B(p, pγ)11B reaction for the two angle sets. Up: first set (0°, 90° and 165°). Down: second set (15°, 105° and 150°).

Fig. 4. Comparison of the differential cross sections between present work and Boni et al. [10] multiplied by a factor of 5.

Fig. 5. Comparison of calculated thick-target yield obtained by using the differential cross section of present work (black solid circles) with measured ones from the literature (see text). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
the reaction, as well as, the highly energetic γ-ray it emits, makes it ideal for most of the PIGE experiments for boron quantification, especially for the ones with low resolution. Moreover, the lack of any evident angular dependence permits the use of experimental setups where the γ detector is placed close to the target. Four levels of the compound nucleus, 12C, seem to be reflected on the measured cross sections. Furthermore, a benchmark experiment was performed in order to validate the obtained differential cross-section datasets. Thick-target yields were accumulated from two thick-boron targets and compared with the calculated ones and those reported in literature.

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References