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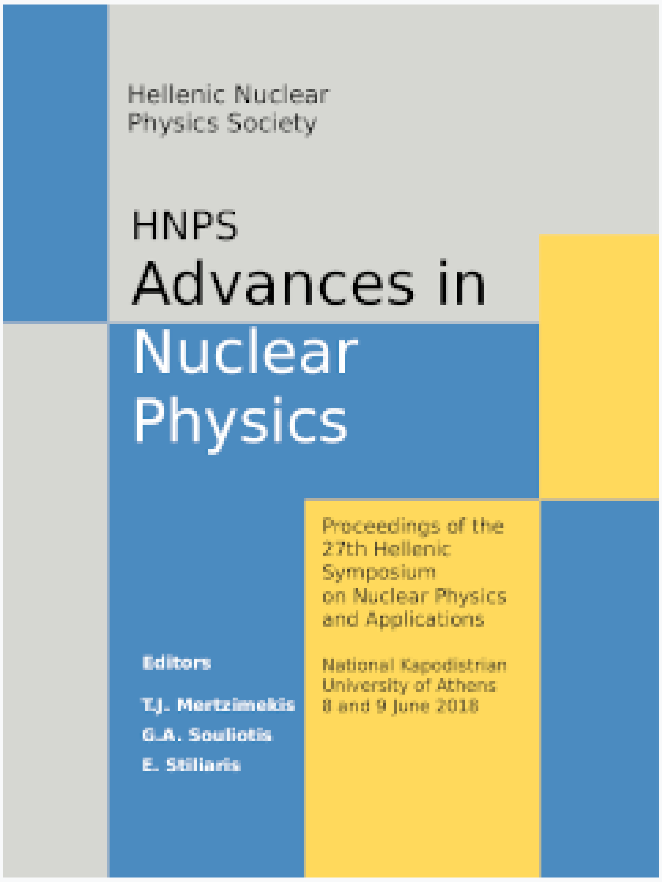

Differential Cross Sections of 9Be(d,p0)10Be, 9Be(d,p1)10Be, 9Be(d,α0)7Li and 9Be(d,α1)7Li reactions

P. Tsavalas, A. Lagoyannis, K. Mergia, E. Ntemou, C. P. Lungu

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Differential Cross Sections of $^{9}Be(d,p_0)^{10}Be$, $^{9}Be(d,p_1)^{10}Be$, $^{9}Be(d,\alpha_0)^{7}Li$ and $^{9}Be(d,\alpha_1)^{7}Li$ reactions

P. Tsavalas[1,2,*], A. Lagoyannis[3], K. Mergia[1], E. Ntemou[2,3], C. P. Lungu[4]

[1]*National Centre for Scientific Research "Demokritos", Institute of Nuclear and Radiological Science and Technology, Energy and Safety, 15310 Aghia Paraskevi, Athens, Greece*
[2]*National Technical University of Athens, Department of Physics, Zografou Campus, Athens, Greece*
[3]*National Centre for Scientific Research "Demokritos", Institute of Nuclear and Particle Physics, 15310 Aghia Paraskevi, Athens, Greece*
[4]*National Institute for Laser, Plasma and Radiation Physics, 077125 Magurele, Bucharest, Romania*

Abstract In the present work, the cross sections of the $^{9}Be(d,p_0)^{10}Be$, $^{9}Be(d,p_1)^{10}Be$, $^{9}Be(d,\alpha_0)^{7}Li$ and $^{9}Be(d,\alpha_1)^{7}Li$ in the deuteron energy range E_{lab} = 1 – 2.2 MeV with an energy step of 20 keV and at detection angles between 120° and 170° were measured, suitable for nuclear reaction analysis. A Si_3N_4 film coated with a thin Be layer was used and the cross sections are determined relatively to the cross section of the $^{nat}Si(d,d)^{nat}Si$ elastic scattering. Additionally, proton and oxygen beam measurements were carried out in order to determine the atomic areal density which is required to determine the cross sections.

Keywords Beryllium, Deuteron, NRA, Differential Cross Section

INTRODUCTION

Beryllium is one of the candidate elements for the plasma-facing material of the future fusion devices due to its low atomic number and low fuel retention. Nowadays, the main chamber of the ITER-like wall Joint European Torus (JET) tokamak consists of beryllium and different D – D campaigns were carried out in order to investigate the plasma – first wall interaction. In order to understand material migration and erosion phenomena of the plasma-facing components, the tiles of the JET tokamak are analysed with different nuclear analytical techniques. Nuclear reaction analysis (NRA) employing a deuteron beam is widely used in order to determine the depth profile of light elements of plasma facing materials. For the evaluation of the NRA spectra, it is crucial to have reliable cross sections of the beryllium – deuteron reactions.

The aim of the current work is to measure the cross sections of the $^{9}Be(d,p_0)^{10}Be$, $^{9}Be(d,p_1)^{10}Be$, $^{9}Be(d,\alpha_0)^{7}Li$ and $^{9}Be(d,\alpha_1)^{7}Li$ reactions in the energy range E_{lab} = 1 – 2.2 MeV with energy step of 20 keV and at the detection angles of 120°, 140°, 150°, 160° and 170°.

EXPERIMENTAL DETAILS

The measurements were carried out using the 5.5 MV TN11 HV Tandem Accelerator at NCSR “Demokritos”. The detection system consisted of five Si surface barrier detectors with thicknesses of 500 μm which were placed in a cylindrical scattering chamber with radius of 40 cm, equipped with a high precision goniometer (0.1°) at angles of 120°, 140°, 150°, 160° and 170° with respect to the beam direction. During the measurements, the vacuum was kept at around 1×10^{-6} Torr. Additionally, a 2 mm collimator was used forming a cyclic beam spot with radius of around 0.5 mm. The energy range of deuterons was E_{lab} = 1 – 2.2 MeV using a constant beam energy step of 20 keV. The sample was a Si_3N_4 (50 nm) membrane coated with Be (77 nm) using thermionic vacuum arc method (TVA) [1].

For the determination of the atomic areal density, proton beam measurements were performed with E_{lab} = 1.2 MeV and E_{lab} = 1.5 MeV, where the cross sections present a plateau, at the detection angles of 120°, 150° and 170°, where literature data exist. Additionally, measurements with oxygen beam were curried in the energy range 11.75 – 12.5 MeV and at the detection angle of 30°. In these measurements, we use the Rutherford cross sections to calculate the atomic areal density.

METHODOLOGY

The number of products Y at a specific energy, E, and detection angle, θ, is given by:

$$Y(E,\theta) = Q\,\Omega\,N\,\frac{d\sigma(E,\theta)}{d\Omega} \quad (1)$$

where Q is the number of incident particles, Ω is the solid angle, N is the atomic areal density of the target and $\frac{d\sigma}{d\Omega}$ is the differential cross section of the reaction to be measured.

In the current work, the cross sections of the Be - deuteron reactions are determined using the corresponding formula of the relative measurement technique [2]. Using the cross sections of Si - deuteron elastic scattering, the cross sections of the Be can be obtained by:

$$\frac{d\sigma_{Be}}{d\Omega} = \frac{Y_{Be}}{Y_{Si}}\,\frac{N_{Si}}{N_{Be}}\,\frac{d\sigma_{Si}}{d\Omega} \quad (2)$$

where the Y_{Be} and Y_{si} are measured simultaneously as the sample consists of Be and Si, the $\frac{d\sigma_{Si}}{d\Omega}$ have been measured recently [3] and the ratio $\frac{N_{Si}}{N_{Be}}$ is determined from the proton and oxygen beam.

Using the eq.1 for the proton and oxygen beam we can calculate the ratio $\frac{N_{Si}}{N_{Be}}$ (eq. 3) as the cross sections are known, from literature for the proton beam and from the Rutherford for the oxygen beam:

$$\frac{N_{Si}}{N_{Be}} = \frac{Y_{Si}}{Y_{Be}}\,\frac{\frac{d\sigma_{Be}}{d\Omega}}{\frac{d\sigma_{Si}}{d\Omega}} \quad (3)$$

ATOMIC AREAL DENSITY DETERMINATION

Proton Beam Measurements

The energies of the proton beam were 1.2 MeV and 1.5 MeV and the detection angles were 120°, 150° and 170°. Using eq. 3 and the literature cross sections, the ratio $\frac{N_{Si}}{N_{Be}}$ was calculated for different energies and detection angles (Table 1).

Table 1: The values of the cross section at specific energies and angles from the literature data and the calculated ratio $\frac{N_{Si}}{N_{Be}}$.

Energy (MeV)	Angle	Work Author	Be (p,p$_0$) C. S. (mb/sr)	Ratio $\frac{N_{Si}}{N_{Be}}$
1.2	120°	Tsan Mo [4]	92 ± 6	0.227 ± 0.025
	150°	N. Catarino [5]	93 ± 6	0.226 ± 0.016
	170°	Z. Liu [6]	98.00 ± 0.03	0.210 ± 0.005
1.5	120°	Tsan Mo [4]	117± 8	0.200 ± 0.013
	150°	N. Catarino [5]	97 ± 8	0.211 ± 0.017
	170°	Z. Liu [6]	103.00 ± 0.04	0.231 ± 0.004
Average				**0.218 ± 0.012**

Oxygen Beam Measurements

The energies of the oxygen beam were 11.75 MeV, 12 MeV, 12.25 MeV and 12.5 MeV and the detection angle was 30°. Applying eq. 3 for the oxygen beam measurements, the ratio $\frac{N_{Si}}{N_{Be}}$ was calculated using the Rutherford cross section. The Table 2 shows this ratio for different energies.

Table 2: Energy of the beam and the calculated ratio $\frac{N_{Si}}{N_{Be}}$.

Energy (MeV)	Ratio $\frac{N_{Si}}{N_{Be}}$
11.75	0.216 $\pm$ 0.003
12.00	0.210 $\pm$ 0.003
12.25	0.226 $\pm$ 0.004
12.5	0.221 $\pm$ 0.003
Average	**0.219 ± 0.007**

Comparing the results from the proton and oxygen beam, we notice that the ratio $\frac{N_{Si}}{N_{Be}}$ is identical, namely 0.218 ± 0.012 for the p beam and 0.219 ± 0.007 for the O beam. This value was used for the calculation of the differential cross sections of the Be – deuteron reactions.

RESULTS AND DISCUSION

The energy range of the deuteron beam was 1 MeV – 2.2 MeV, the energy step was 20 keV and the detection angles were 120°, 140°, 150°, 160° and 170°. Fig. 1 presents a deuteron beam spectrum with E_{lab} = 2.2 MeV and at the detection angle of 170°. As we observe, there are a lot of nitrogen peaks, some of which overlap with the Be peaks for specific energy ranges where the cross sections cannot be estimated.

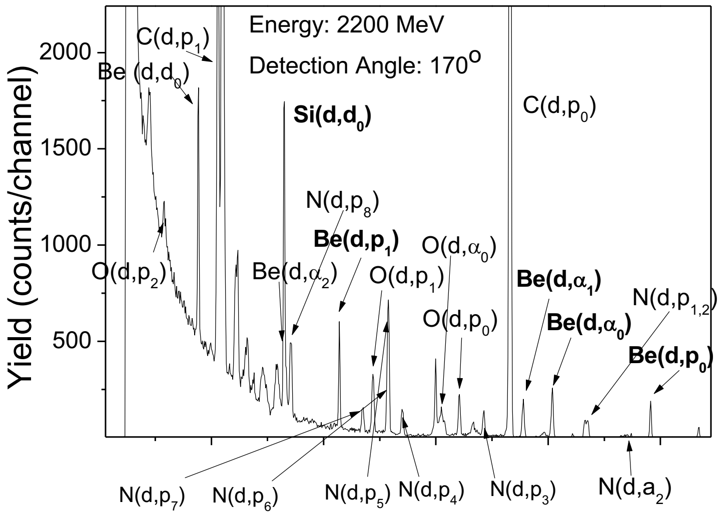

Figure 1: A typical spectrum of d beam. The peaks noted with bold were used for the analysis.

In the presentation of the current results, we show the cross sections of three of the detection for clarity, while the conclusions have been drawn from all angles.

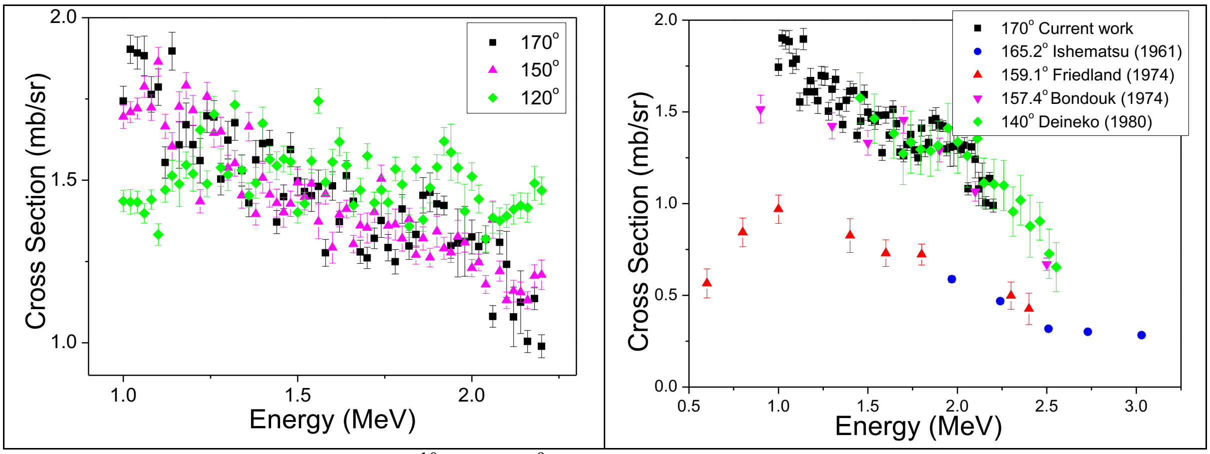

Figure 2: a) Cross section of the ^{10}Be(d,p$_0$)^{9}Be at 120^o, 150^o and 170^o b) Comparison between the current work and previous ones of the ^{9}Be(d,p$_0$)^{10}Be reaction

The cross sections of the ^{10}Be(d,p$_0$)^{9}Be reaction for most of the angles (all except for 120^o) and for energies higher than 1.3 MeV decrease as the energy increases from 1.6 mb/sr at 1.3 MeV to 1 mb/rs at 2.2 MeV. Additionally, a peak in the energy range of 1.75 – 2 Mev is observed, which probably corresponds to a level of the compound nucleus of the reaction between Be and deuteron, namely the ^{11}B. There is, also, an angle dependence for energies lower than 1.3 MeV, where the cross sections increase as the detection angle increases. On the other hand, the cross section of 120^o presents different behaviour as it is almost constant around the value of 1.5 mb/sr (with fluctuations) for the whole energy range, but the resonance in 1.75–2 MeV is also observed (Fig. 2a).

In Fig. 2b, we compare the data of the current work with previous works. As there is no angle dependence for energies higher than 1.3 MeV, we can compare cross sections from different angles. The present results agree with those of Bondouk [7] and Deineko [8], while we have disagreement in absolute values, but not in the energy dependence, with Friedland [9] and Ishematsu [10], which are 45% lower than the present values.

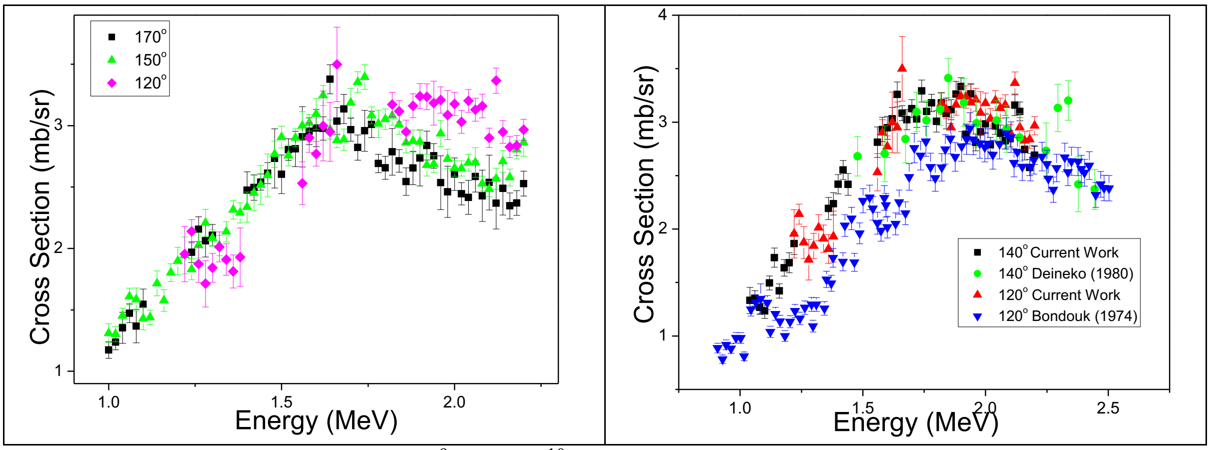

Figure 3: a) Cross Sections of the $^{9}Be(d,p_{1})^{10}Be$. b) Comparison between the current work and the previous ones for the detection angles of 120° and 140° of the $^{9}Be(d,p_{1})^{10}Be$ reaction.

The cross sections of the $^{9}Be(d,p_{1})^{10}Be$ reaction start from 1.2 mb/sr and increases up to 3.1 mb/sr at the energy E_{lab} = 1.7 MeV for all detection angles. An angular dependence is observed for higher energies, where the values of the cross sections decrease as the detection angle increases (Fig. 3a).

The results of the current work agree with those of Deineko [8], while the Bondouk [7] dataset exhibits 15 – 20% lower values, but the same energy dependence (Fig. 3b).

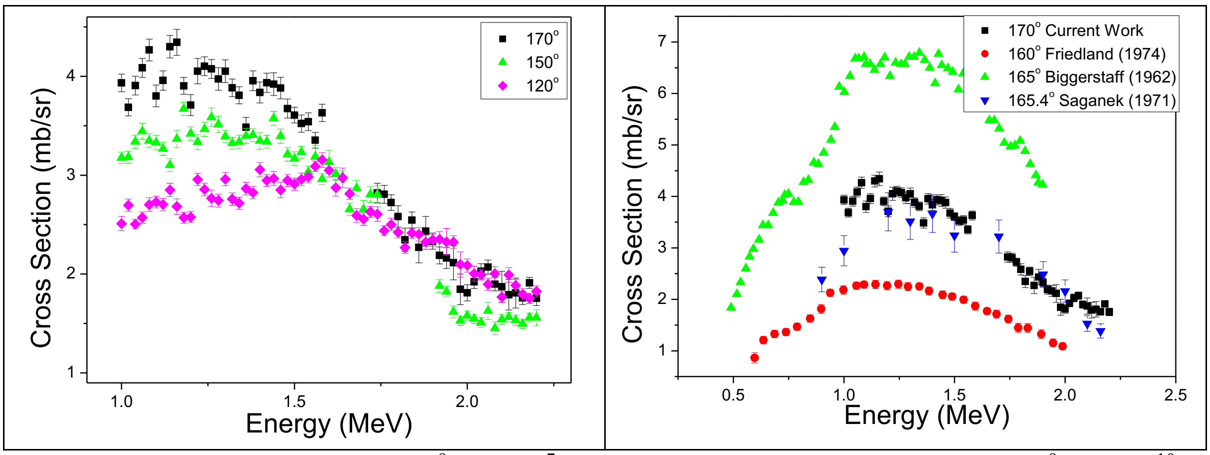

Figure 4: a) Cross Sections of the $^{9}Be(d,\alpha_{0})^{7}Li$. b) Cross section comparison for the $^{9}Be(d,\alpha_{0})^{10}Be$ reaction between the current work and the literature data

The cross sections of the $^{9}Be(d,\alpha_{0})^{7}Li$ reaction present angular dependence for energies lower than 1.5 MeV, where their values increase with the detection angle. For energies higher than 1.5 MeV, the cross sections decrease with the energy from 3 mb/sr at E_{lab} = 1.6 MeV to 1.5 mb/sr at E_{lab} =2.2 MeV (Fig. 4a).

In Fig. 4b we compare the results of the current work with the literature data for similar detection angles. The results of the current work agree with Saganek's [11] data within their errors, while Freidland [9] and Biggerstaff [12] data have the same energy dependence but different absolute values. Specifically, Freidland [9] cross section is 45% lower, while Biggerstaff's [12] cross sections are 1.6 - 1.8 times higher than the present data.

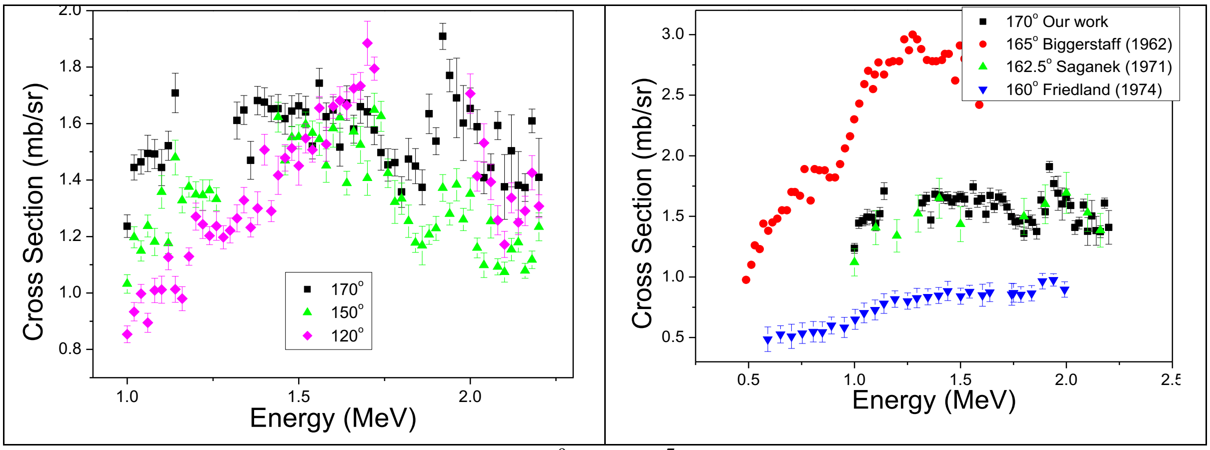

Figure 5: a) The cross section of the reaction $^{9}Be(d,\alpha_1)^{7}Li$. b) Comparison between the current work and the previous ones for the $^{9}Be(d,\alpha_1)^{10}Be$ reaction

The cross sections of the $^{9}Be(d,\alpha_1)^{7}Li$ reaction present angle dependence in the whole energy range and their values increase as the detection angle increases, with the exception of the cross section for 120° detection angle, where the cross section has different behaviour. The resonance in the energy range of 1.75-2 MeV is also observed (Fig.5a).

Fig. 5b presents the comparison between the cross sections of the $^{9}Be(d,\alpha_1)^{10}Be$ reaction of the current work and previous ones for similar detection angles. The current cross sections agree with Saganek's [11] data, while Freidland [9] and Biggerstaff [12] data have similar energy dependence with the present values but different absolute values, 45% lower and 1.7 times higher than ours, respectively. These differences are similar with the differences in the cross sections of the $^{9}Be(d,\alpha_0)^{7}Li$ reaction and can be attributed to the accuracy of their sample thickness measurements.

CONCLUSION

The cross sections of the reactions between beryllium and deuteron reactions were measured in the energy range 1 – 2.2 MeV at the detection angles of 120°, 140°, 150°, 160° and 170° in order to be used to NRA measurements. The sample was a Si_3N_4 membrane coated with Be. The values of the cross sections were determined using the cross sections of the $^{nat}Si(d,d)^{nat}Si$ elastic scattering, so the ratio $\frac{N_{Si}}{N_{Be}}$ is required, which was calculated with proton (0.218 ± 0.012) and oxygen (0.219 ± 0.007) beam. In the cross sections of the $^{9}Be(d,p0)^{10}Be$ and $^{9}Be(d,\alpha_1)^{7}Li$ reactions, a resonance in the energy range of 1.75 – 2 MeV was observed, which is probably due to a level of ^{11}B compound nucleus. Comparing the results with the previous data, the current cross sections of the $^{9}Be(d,p_{0,1})^{10}Be$ reactions agree with Deineko [8] and the cross sections of the $^{9}Be(d,\alpha_{0,1})^{7}Li$ reactions agree with Saganek [11]. These new results are going to facilitate the ion beam analysis of the facing materials to be used in the future nuclear reactors

ACKNOWLEGMENTS

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