Differential cross sections of reactions of the beryllium with deuteron, at energies and angles suitable for nuclear reaction analysis

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Abstract

The cross sections of the $^{9}Be(d,p_0)^{10}Be$, $^{9}Be(d,p_1)^{10}Be$, $^{9}Be(d,a_0)^{7}Li$ and $^{9}Be(d,a_1)^{7}Li$ with the deuteron energy in the range 1.0 – 2.2 MeV and at detection angles of 120°, 140°, 150°, 160° and 170° were measured. These cross sections are appropriate for nuclear reaction analysis, a non-destructive technique to detect and quantify light elements. The determination of the cross sections was performed using the elastic scattering cross sections of the natural silicon. The results were validated with a bulk beryllium target and the difference between the simulation and the experimental spectra does not exceed 10%.

Keywords

Beryllium, Deuteron, NRA, Differential Cross Section

Introduction

Beryllium (Be) is a light weight metal with atomic number 4 and density 1.85 g/cm^3 at room temperature. It has a melting-point of 1560 K, high specific heat capacity of 1.825 J/(g·K) and a thermal conductivity of 2.01 W/(cm·K). Its electrical resistivity is 36 nΩ·m at 293 K. It has a low neutron absorption and high neutron-scattering cross sections. Due to these unique characteristics, the beryllium has found wide use in plenty different applications.

Beryllium metal is used in nuclear weapons, aircraft brake parts, spacecraft structures, navigation systems, X-ray windows, mirrors, and audio components. Beryllium alloys represent the largest use of beryllium. Copper–beryllium alloys typically have 0.15–2.0% beryllium content and are used for applications such as coaxial connectors in cell phones, computers, aircraft bushings, non-sparking tools, automotive switches and sensors, and plastic injection molds. Aluminium–beryllium alloys are used as optical substrates for night

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vision systems and avionics applications. Nickel–beryllium alloys have good spring characteristics and are used in applications such as thermostats and bellows [1,2].

Beryllium is also a candidate material for the plasma facing material of the future fusion devices [3,4]. Due to its low atomic number it prevents the dilution of plasma, its relatively high melting point makes it appropriate for high temperature environment and the low fuel retention beryllium presents is crucial for the lifetime of the wall and the conservation of the fuel. Beryllium is also an oxygen getter which reducing the oxygen impurities of the plasma [5]. The main chamber of the JET tokamak is equipped with a beryllium first wall and acts as test bed for ITER [6,7,8].

On the other hand the determination of beryllium amount in a sample is very important. One widespread technique to measure concentration of light elements with accuracy of a few percent and the depth profile of them is Nuclear Reaction Analysis (NRA). Proper quantification using the NRA technique requires the prior knowledge of the cross sections of the reactions that take place. 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} = 1.0 – 2.2 MeV with an energy step of 20 keV and at the detection angles of 120°, 140°, 150°, 160° and 170°. The determination of these cross sections is imperative for the NRA analysis using a deuteron beam of beryllium Tiles from the main wall of the JET Tokamak [9].

Experimental Setup

The measurements were carried out using the 5.5 MV TN11 HV Tandem Accelerator at NCSR "Demokritos". The detection system consisted of five silicon surface barrier detectors with thicknesses of 500 μm which were placed at angles of 120°, 140°, 150°, 160° and 170° with respect to the beam direction, in a cylindrical scattering chamber with radius of 40 cm, equipped with a high precision goniometer (0.1°). The detectors were equipped with orthogonal slits in front of them and were placed at a distance of ∼ 10 cm from the target resulting at an angular uncertainty of ±∼ 1°. During the measurements, the vacuum was kept at around 1 × 10^{-6} Torr. A set of two collimators was placed at a distance of 40 and 90 cm before the target forming a cyclic beam spot with radius of around 0.5 mm. The energy of the deuterons varied in the range E_{lab} = 1.0 – 2.2 MeV using a constant beam energy step of 20 keV. The beam energy was measured constantly using a nuclear magnetic resonance probe at the 90° magnet of the accelerator. The beam energy was calibrated, using the 991.89 keV resonance of the $^{27}Al(p,\gamma)^{28}Si$ reaction employing a 18% HPGe detector. The offset was found to be 1.18 ± 0.36 keV. The sample consisted of a beryllium layer having nominal thickness of 77 nm deposited on a Si_3N_4 (50 nm) membrane using the thermionic vacuum arc method (TVA) [10].

For the determination of the beryllium thickness, proton beam measurements were performed at energies, 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 [11,12,13]. Additionally, transmission Elastic Recoil Detection Analysis (ERDA) measurements with an oxygen beam were carried out in the energy range 11.75 – 12.5 MeV and at the detection angle of 30°. In these measurements, the Rutherford cross sections were used for the calculation of the thickness and confirmation of the value acquired from the proton beam.

A benchmarking experiment was also carried out in order to confirm the energy dependence and the absolute values of the measured cross sections. This procedure was performed, measuring a sample of bulk beryllium with a thin gold (Au) layer of known thickness, deposited on its surface. The measured cross sections were used as an input in the simulation and the simulated spectra were compared against the experimental ones in order to check the validity of the cross sections.

All simulations were performed using the SIMNRA software [14].

Data analysis results and discussion

The beryllium layer deposited on a thin silicon nitride membrane was measured with three different kinds of beam. The proton and the oxygen beams measurements were carried out in order to assess the silicon to beryllium ratio N_{Si}/N_{Be} , while the deuteron beam was used to determine the cross section.

In a nuclear reaction, the number of products Y in a specific energy, E, and at detection angle, θ, is given by:

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

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 beryllium - deuteron reactions were determined using the corresponding formula of the relative measurement technique [15]. Using the cross sections of silicon - deuteron elastic scattering, the cross sections of the beryllium can be obtained by:

$$\frac{d\sigma_{Be}}{d\Omega} = \frac{Y_{Be}}{Y_{Si}}\,\frac{N_{Si}}{N_{Be}}\,\frac{d\sigma_{Si}}{d\Omega} \tag{2}$$

where the Y_{Be} and Y_{si} are determined experimentally simultaneously from the measured spectra as the sample consists of beryllium and silicon (in the substrate), $(d\sigma_{Si})/d\Omega$ has been measured recently [16] and the ratio N_{Si}/N_{Be} is determined employing the proton and the oxygen beam using the known cross sections, either analytically or from the literature, as it is described below. The use of this method rules out systematic errors from the direct measurement of the beam charge and solid angle. On the other hand, as this is a relative method based on the recently measured silicon –deuteron elastic scattering, the error of the cross sections (~1.5%) and of the ratio N_{Si}/N_{Be} (5.5%) contribute to the systematic error of the measurements.

Using eq.1 for the proton and oxygen beam, the calculation of the ratio N_{Si}/N_{Be} (Eq. 3) is feasible as the cross section for both elements is known either from the literature in case of the proton beam or from the Rutherford cross section for the oxygen beam:

$$\frac{N_{Si}}{N_{Be}} = \frac{Y_{Si}}{Y_{Be}} \frac{\frac{d\sigma_{Be}}{d\Omega}}{\frac{d\sigma_{Si}}{d\Omega}} \tag{3}$$

Fig. 1 presents representative experimental and simulated spectra of the proton beam measurements, the energy is 1.5 MeV and the detection angle 170°. The integrals of the peaks of the $^{9}Be(p,p_0)^{9}Be$ and the $^{28}Si(p,p_0)^{28}Si$ reactions constitute the values of the Y_{Be} and Y_{Si}, respectively. Using eq. 3 and the literature cross sections [11,12,13], the ratio N_{Si}/N_{Be} was calculated for different energies and detection angles (Table 1).

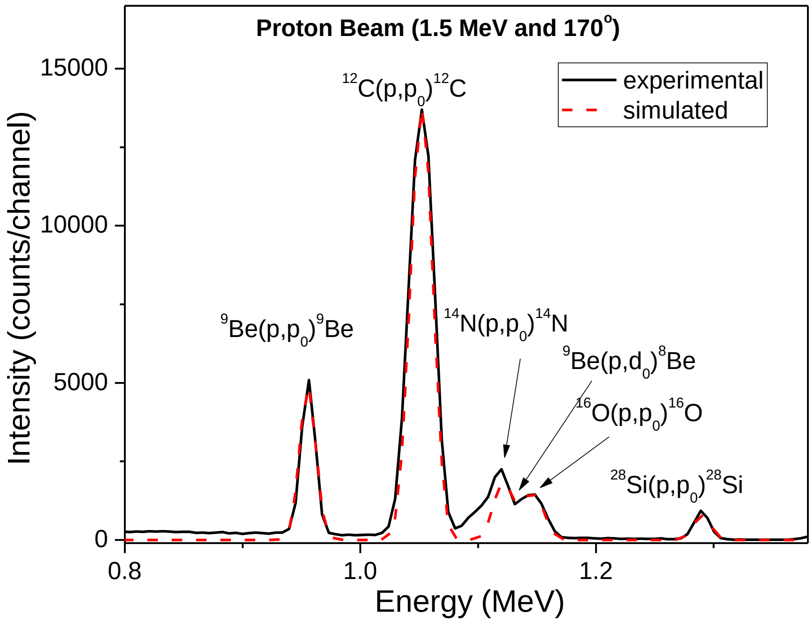

Figure 1: *Experimental (solid line) and simulated (dash line) spectra from the proton beam measurements. The beam energy was 1.5 MeV and the detection angle was 170°.*

Table 1: *The values of the cross sections at specific energies and angles from the literature data and the calculated ratio* N_{Si}/N_{Be}.

Energy (MeV)	Angle	Work Author	Be (p,p_0) C. S. (mb/sr)	$\frac{N_{Si}}{N_{Be}}$
1.2	120°	Tsan Mo [11]	92 ± 6	0.227 ± 0.025
	150°	N. Catarino [12]	93 ± 6	0.226 ± 0.016
	170°	Z. Liu [13]	98.00 ± 0.03	0.210 ± 0.005
1.5	120°	Tsan Mo [11]	117± 8	0.200 ± 0.013
	150°	N. Catarino [12]	97 ± 8	0.211 ± 0.017
	170°	Z. Liu [13]	103.00 ± 0.04	0.231 ± 0.004
Average				**0.218 ± 0.012**

The results for the ratio $N_{Si}/N_{Be}$from the proton beam measurements depend on the validity of the cross section used and they are reported in Table 1. In order to cross – check these results a second experiment was performed employing oxygen beam.

Fig. 2 shows representative experimental and simulated spectra of the oxygen beam with energy of 11.75 MeV and at detection angle of 30°. The yields of the beryllium, Y_{Be} and the silicon, Y_{si} are determined by the integration of their peaks. Applying eq. 3 for the oxygen beam measurements, the ratio N_{Si}/N_{Be} was calculated using the Rutherford cross section. Table 2 summarizes this ratio for all the different energies.

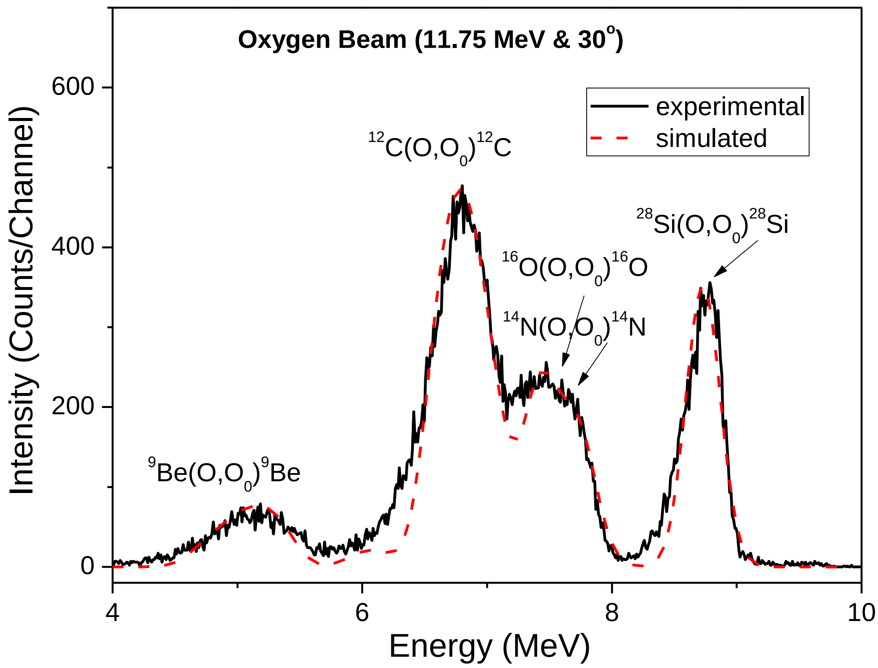

Figure 2: *Experimental (black solid line) and simulated (red dash line) spectra from the oxygen beam measurement. The beam energy was 11.75 MeV and detection angle was 30°.*

Table 2: Oxygen beam energy and the calculated ratio N_{Si}/N_{Be}.

Energy (MeV)	$\frac{N_{Si}}{N_{Be}}$
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**

The resulting ratio N_{Si}/N_{Be} from the proton and oxygen beam experiments is the same within error bars, namely 0.218 ± 0.012 for the proton beam and 0.219 ± 0.007 for the oxygen beam. The value of the proton beam was used for the calculation of the differential cross sections of the beryllium – deuteron reactions.

Below we discuss the determination of the differential cross section of ^{9}Be(d,p$_0$)^{10}Be, ^{9}Be(d,p$_1$)^{10}Be, ^{9}Be(d,a$_0$)^{7}Li and ^{9}Be(d,a$_1$)^{7}Li reactions. Fig. 3 presents a representative deuteron beam spectrum with E_{lab} = 2.2 MeV and at the detection angle of 170^{o}. A number of nitrogen peaks are observed in the spectrum, some of which overlap with the beryllium peaks for specific energy ranges where the cross sections cannot be calculated and were excluded from the final results. The statistical error of the cross sections came from the error of the integration of the beryllium and the silicon peaks. Moreover, the uncertainty of the ratioN_{Si}/N_{Be} (5.5%) and the systematic error of the cross sections of ^{nat}Si(d,d$_0$)^{nat}Si ($\pm$~1.5%) constitute the systematic error of the measurements (~7%).

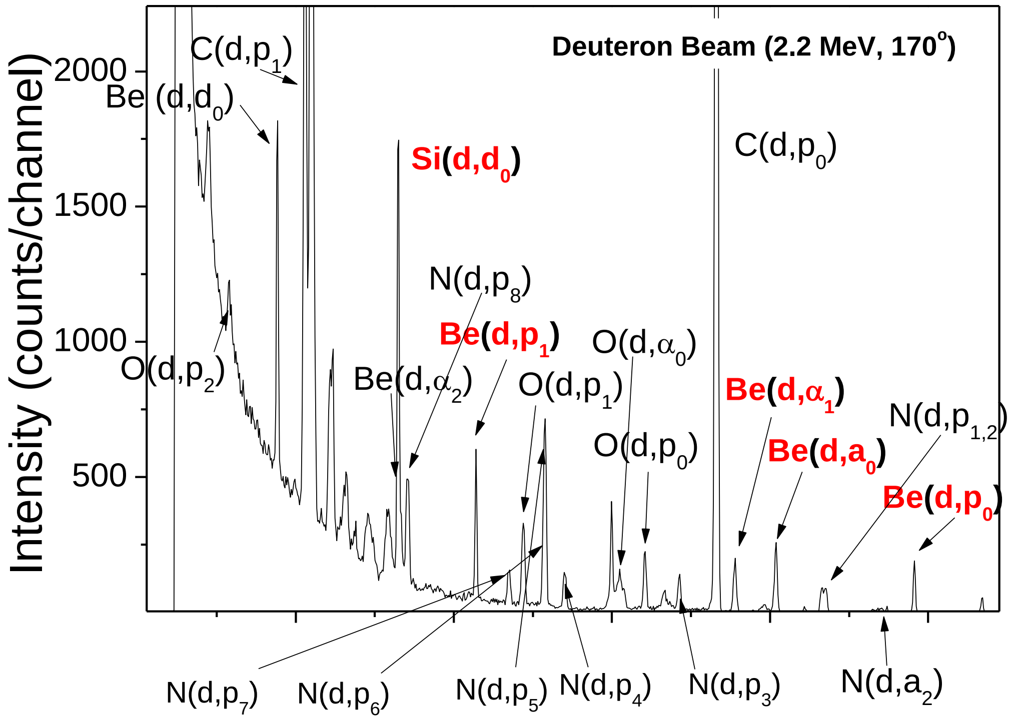

Figure 3: *A typical spectrum of deuteron beam with energy 2.2 MeV and at detection angle of 170^{o}. The peaks noted with red-bold were used for the analysis.*

In the following figures, the cross section of three of the detection angles is presented for clarity, while the conclusions have been drawn from all angles.

A. The ^{9}Be(d,p$_0$)^{10}Be Reaction

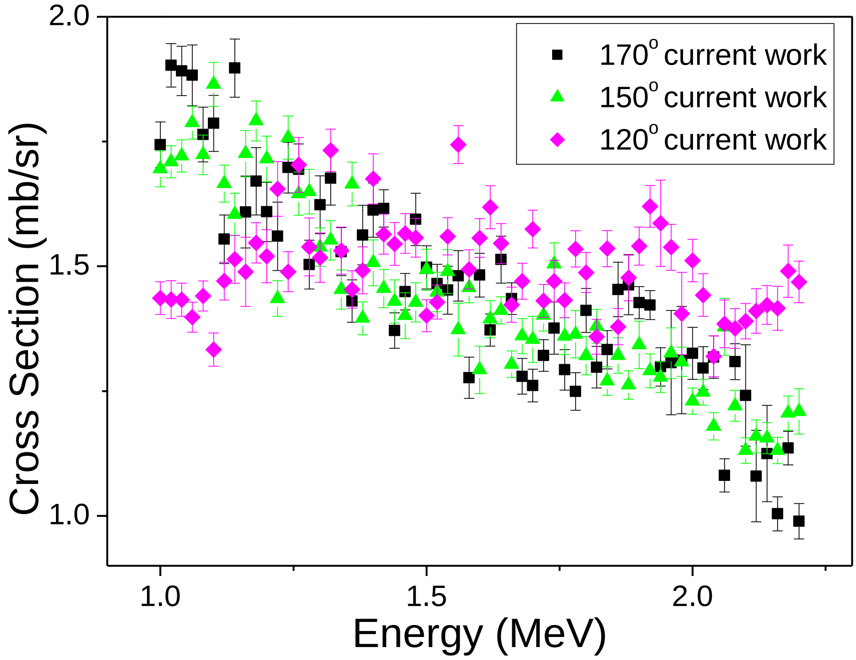

Figure 4: *Measured cross section of the $^{10}Be(d,p_0)^{9}Be$ at detection angles of 120°, 150° and 170°.*

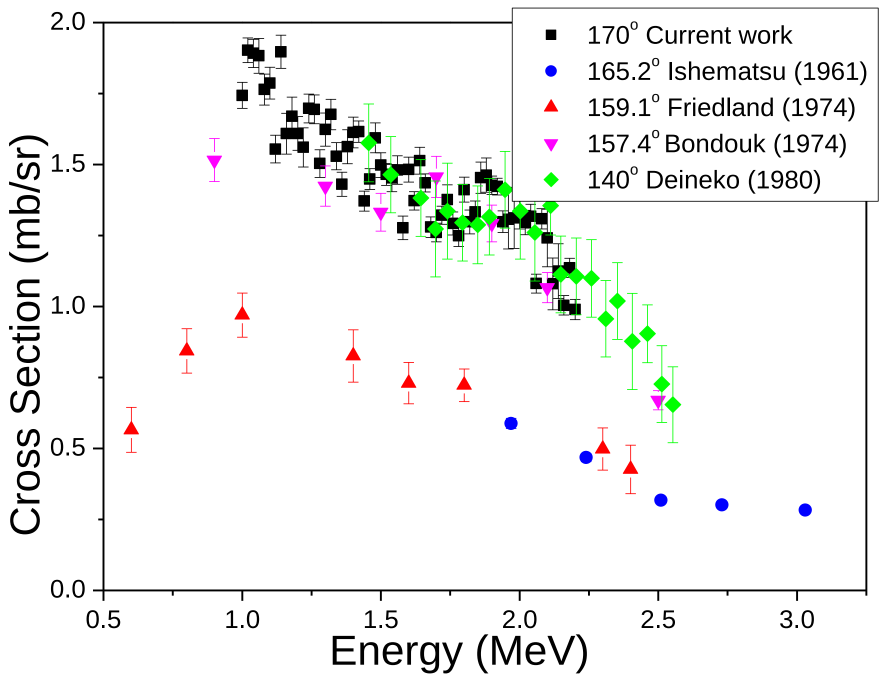

Figure 5: *Comparison of the cross section of the $^{9}Be(d,p_0)^{10}Be$ reaction of the current work with that of T. Ishematsu et al [17], E. Friedland et al [18], I. I. Bondouk et al [19] and A. S Deineko et al [20].*

Overall the cross section of the $^{9}Be(d,p_0)^{10}Be$ reaction shows an almost linear decrease with the incease of the energy and as the detection angle decrease the slope decreases. For the detection angle of 170°, the cross section is 1.9 mbarn at 1.0 MeV and decreases to 1 mbarn at 2.2 MeV. On the other hand, the cross section of 120° presents different behaviour as it is almost constant around the value of 1.5 mb/sr (with fluctuations) for the whole energy range (Fig.4).

In Fig. 5, the data of the current work with previous works are compared. As there is no angle dependence for energies higher than 1.3 MeV and lower than 2.2 MeV, the comparison of cross sections from different angles is valid. The present results agree with those of I. I. Bondouk et al [19] and A. S. Deineko et al [20], while we have disagreement in absolute values, but not in the energy dependence, with E. Friedland et al [18] and T. Ishematsu et al [17], which are 45% lower than the present values.

B. $^{9}Be(d,p_{1})^{10}Be$ Reaction

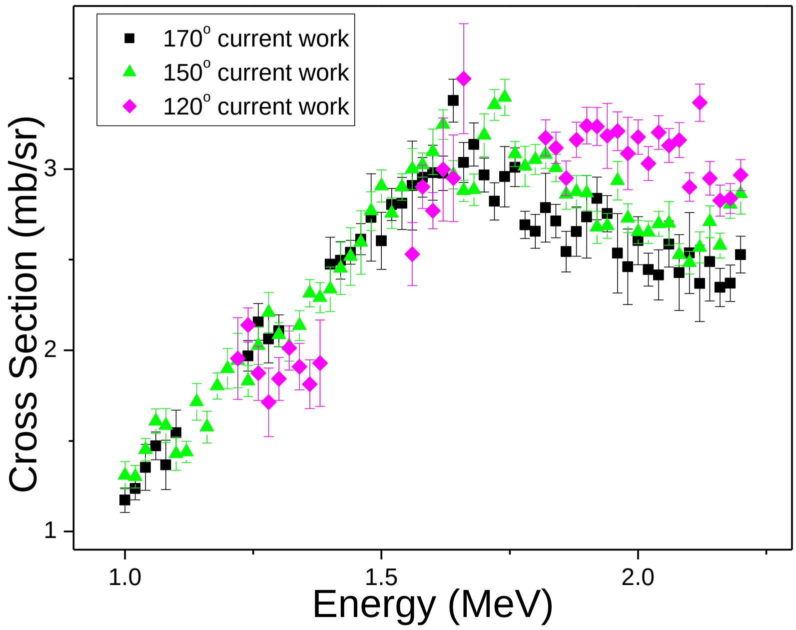

Figure 6: *a) Cross Section of the $^{9}Be(d,p_{1})^{10}Be$ reaction at detection angles of 170°, 150° and 120°.*

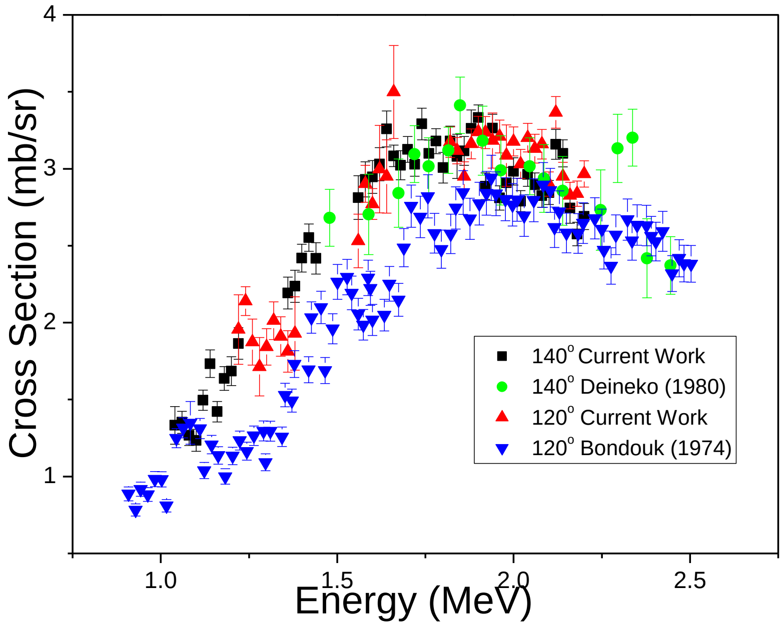

Figure 7: *Comparison of the $^{9}Be(d,p_1)^{10}Be$ reaction of the current work with A. S. Deineko et al [20] and the I. I. Bondouk et al [19] for the detection angles of 120° and 140°.*

The cross section of the $^{9}Be(d,p_1)^{10}Be$ reaction starts 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. For higher energy the cross section decreases with the energy, while the slope of the cross section depends on the angle, as the slope becomes steeper with the increase of the detection angle (Fig. 6).

The results of the current work agree with those of A. S. Deineko et al [20], while the data of I. I Bondouk et al [19] exhibit 15 – 20% lower values, but the same energy dependence (Fig. 7).

C. The $^{9}Be(d,\alpha_0)^{7}Li$ reaction

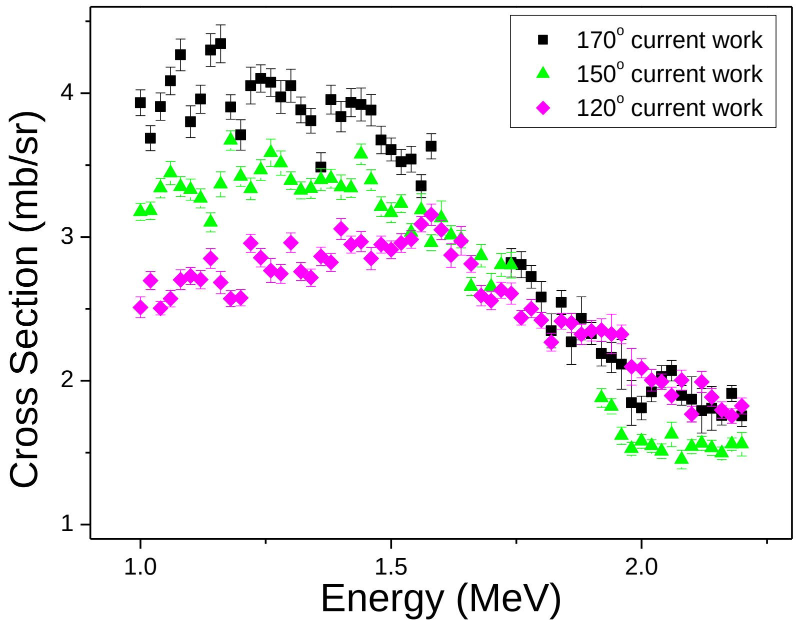

Figure 8: *Measured cross section of the $^{9}Be(d,\alpha_0)^{7}Li$ reaction at the detection angles of 170°, 150° and 120°.*

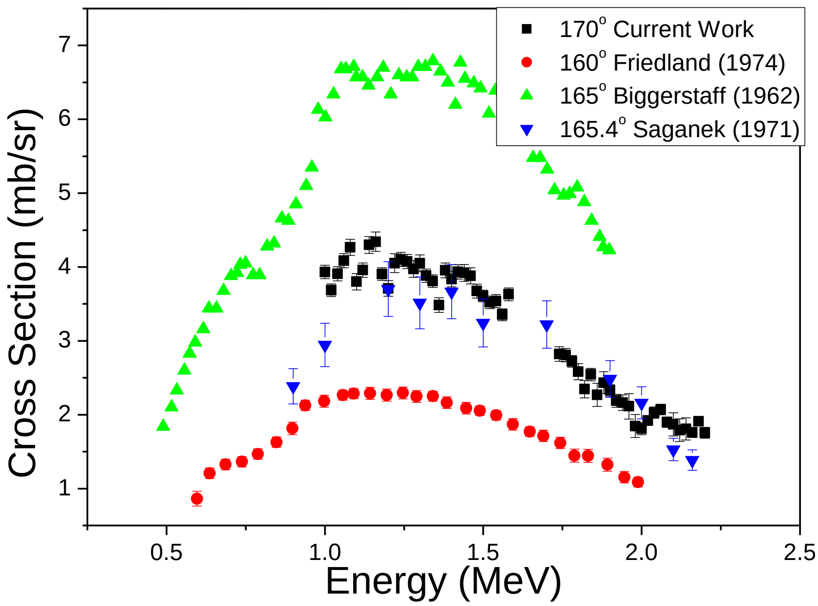

Figure 9: *Cross section comparison for the $^{9}Be(d,\alpha_0)^{7}Li$ reaction between the current work and the E. Fredland et al [18], J. A. Biggerstaff et al [21] and A. Saganek et al [22] for the detection angle range between 160°-170°.*

The cross section of the $^{9}Be(d,\alpha_0)^{7}Li$ reaction present angular dependence for energies lower than about 1.5 MeV with its value increasing with the increase of the detection angle. For energies higher than 1.5 MeV, the cross section decreases with the energy from 3 mb/sr at E_{lab} = 1.6 MeV to 1.5 mb/sr at E_{lab} =2.2 MeV, for all detection angles (Fig. 8).

In Fig. 9, the results of the current work are compared with the literature data for similar detection angles. The results of the current work agree with A. Saganek et al [22] data within errors bars, while the datasets of E. Freidland et al [18] and J A Biggerstaff et al [21] have the same energy dependence but considerably different absolute values. Specifically, the cross section of E Freidland et al [18] is 45% lower, while that of J. A. Biggerstaff et al [21] is 1.6 - 1.8 times higher than the present data.

D. The $^{9}Be(d,\alpha_1)^{7}$Li reaction

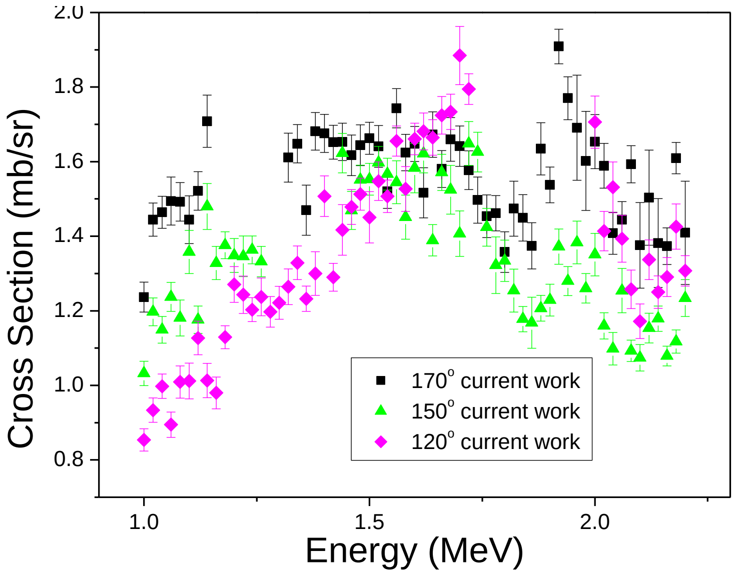

Figure 10: *The measured cross sections of the $^{9}Be(d,\alpha_1)^{7}Li$ reaction at the detection angles of 120°, 150° and 170°.*

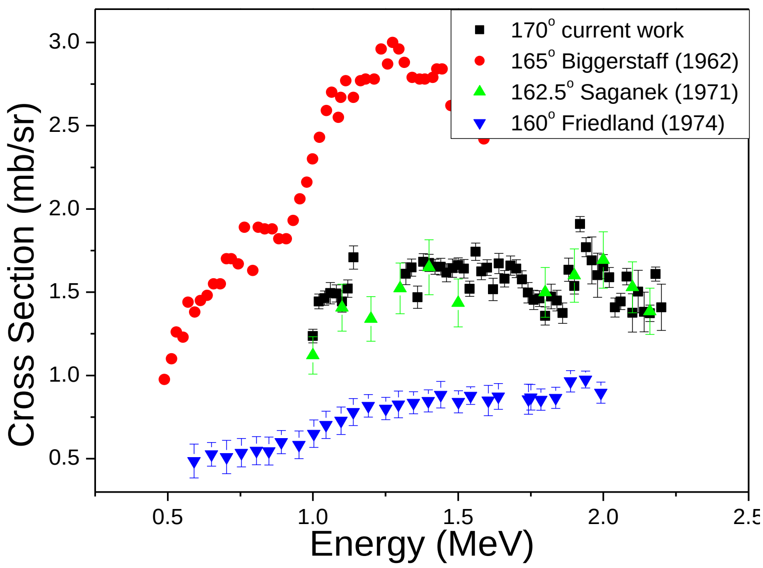

Figure 11: *Comparison of the cross section for the $^{9}Be(d,\alpha_1)^{7}Li$ reaction between the current work and that of J. A. Biggerstaff et al [21], A. Saganek et al [22] and E. Friedland [18].*

The cross section of the $^{9}Be(d,\alpha_1)^{7}Li$ reaction presents angle dependence in the whole energy range and its value increases as the detection angle increases, with the exception of the cross section for 120° detection angle and energy larger than 1.5 MeV. A peak in the energy range of 1.75 - 2 MeV is also observed (Fig. 10).

Fig. 11 presents the comparison between the cross section of the $^{9}Be(d,\alpha_1)^{7}Li$ reaction of the current work and previous ones for similar detection angles. The cross section of this study agrees with that of A. Saganek et al [22], while the data of E Freidland et al [18] and J A Biggerstaff et al [21] have similar energy dependence with the present results but different absolute values, 45% lower and 1.7 times higher than present ones, respectively. These differences are similar to 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. The results will soon be available to the scientific community via IBANDL (http://www-nds.iaea.org/ibandl/).

In order to validate the energy dependence and the absolute values of the determined cross sections, a bulk beryllium with a thin gold layer (9.42 nm) layer deposited on its surface was measured at different energies and angles. Specifically, the beam energy varied in the range 1.2 – 2.2 MeV with a step of 0.2 MeV and the detection angles were 120°, 140°, 150°, 160° and 170°. For the benchmarking of the cross sections, the $^{9}Be(d,p_0)^{10}Be$ reaction was used as it does not overlap with any other reactions. The thin gold layer was used in order to calculate the total charge through gold Rutherford backscattering. Using the value of the calculated charge, the $^{9}Be(d,p_0)^{10}Be$ reaction spectrum was simulated employing the measured cross sections. Fig. 12 shows representative experimental and simulated spectra of the thick sample measurements with deuteron beam energy of 2 MeV and at detection angle of 170° focused on the $^{9}Be(d,p_0)^{10}Be$ reaction energy area.

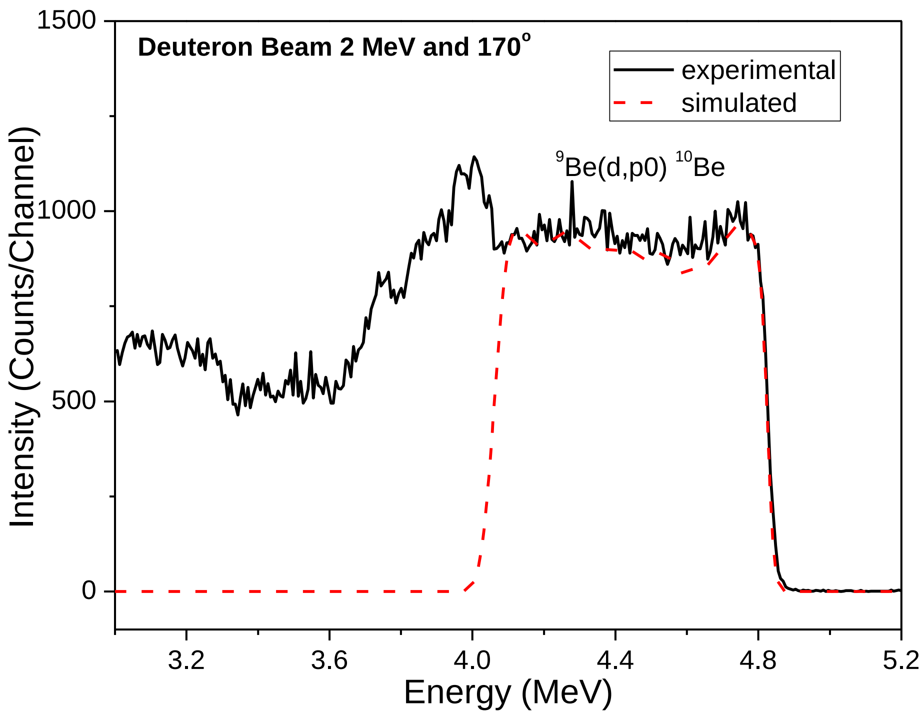

Figure 12: *Experimental (black line) and simulated (red dish line) spectrum of the sample consists of bulk beryllium with a thin gold layer*

As Fig. 12 shows, the energy dependence of the cross section agrees well with the experimental spectrum. This agreement applies to all beam energies and all detection angles. The simulated spectrum of Fig. 12 agrees within 3% with the experimental thick target spectrum, with the simulated one being systematically bellow the experimental spectrum. For all the thick target measurements, the difference between the experimental and the simulated spectra does not exceed 10%.

Conclusions

The cross section of the reactions between beryllium and deuteron reactions was measured in the energy range 1.0 – 2.2 MeV at the detection angles of 120°, 140°, 150°, 160° and 170° in order to be used for the NRA technique. The target used was a beryllium layer deposited on a Si_3N_4 membrane. The values of the cross sections were determined using the cross sections of the $^{nat}Si(d,d)^{nat}Si$ elastic scattering. Comparing the results with the previous data, the current cross sections of the $^{9}Be(d,p_{0,1})^{10}Be$ reactions agree with A. S. Deineko et al [20] and the cross sections of the $^{9}Be(d,\alpha_{0,1})^{7}Li$ reactions agree with A. Saganek et al [22]. The benchmarking shows that the energy dependence of the cross section is consisted with the acquired thick target spectra for all detection angles with the difference between the experimental and the simulated spectra not exceeding 10%. These new results are going to facilitate the ion beam analysis of beryllium based plasma facing materials to be used in the future fusion reactors.

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