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Determination of ^{9}Be(p,p$_0$)^{9}Be, ^{9}Be(p,d$_0$)^{8}Be and ^{9}Be(p,α_0)^{6}Li cross sections at 150° in the energy range 0.5–2.35 MeV

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ABSTRACT

Beryllium and Tungsten have been chosen as the new “plasma facing materials” for fusion reactors. Understanding plasma wall interactions and their effects such as erosion and redeposition leading to the formation of alloys from the different materials present in the reactor chamber, is critical to model the retention of hydrogen isotopes by the wall materials. Determining the amount and the depth profile of Be and other elements deposited in the walls is a mandatory requirement in fusion reactors, making the knowledge of the relevant cross sections essential for IBA analysis. In this work we measured the ^{9}Be(p,p$_0$)^{9}Be, ^{9}Be(p,d$_0$)^{8}Be and ^{9}Be(p,α_0)^{6}Li cross sections in the energy range 0.5–2.35 MeV, at an angle of 150°.

1. Introduction

Due to its low nuclear charge, relatively high melting point, and its ability to getter oxygen, Beryllium is used as plasma-facing component of the ITER tokamak (with a Be first wall and a W divertor), which is currently being built in Cadarache, France [1].

In order to investigate Beryllium migration, which connects the lifetime of first-wall components under erosion with tokamak safety, the elastic backscattering (EBS) technique is often employed for depth profiling. However, for light elements Rutherford backscattering with protons does not follow the Rutherford regime of elastic scattering. In fusion related materials, the signal of heavy elements such as W or Mo is superimposed to the signal from Be, reducing the sensitivity as well as the accuracy of the measurements. Elastic backscattering, often with a proton beam [2,3], takes advantage of enhanced non Rutherford cross sections. So the precise knowledge of the cross sections is fundamental for accurate quantitative measurements.

The International Atomic Energy Agency compiled from the literature a vast collection of experimental cross sections for diverse reactions in the database IBANDL [4] and EXFOR [5]. Another reference data base is provided by Gurbich [6–8], who has analytically reviewed and evaluated cross section data. The evaluations were made accessible through the program SigmaCalc [9], but so far no evaluation has been presented for Be.

There are only a few data sets available for the ^{9}Be(p,p$_0$)^{9}Be backscattering cross-section [10–14], with three data sets close to a scattering angle around 150°, but each covering only a limited energy range. The most complete set was published recently by Krat et al. [13] covering the whole energy range from 0.4 to 4.1 MeV at a scattering angle of 165°. Besides elastic scattering, there are two nuclear reactions of protons with ^{9}Be that we should consider: ^{9}Be(p,d$_0$)^{8}Be and ^{9}Be(p,α_0)^{6}Li. In the case of nuclear reactions the data available [13,15–18] is more limited than for backscattering. The ^{9}Be(p,d$_0$)^{8}Be reaction has a relatively large cross-section in the energy range 1–2.5 MeV and must be considered for accurate measurement. In the case of ^{9}Be(p,α_0)^{6}Li at angles closes of 150°, no data has been published at energies higher than 1.3 MeV.

Therefore, we decided to measure the ^{9}Be(p,p$_0$)^{9}Be, ^{9}Be(p,d$_0$)^{8}Be and ^{9}Be(p,α_0)^{6}Li at 150°, which is the angle used at Instituto Superior Técnico for fusion materials research with IBA, in order to extend the values available in the data bases.

2. Experimental

The samples were analyzed at the 2.5 MV Van de Graaff accelerator of Laboratório de Aceleradores e Tecnologias da Radiação of Instituto Superior Técnico in the chamber dedicated to fusion

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research, where samples contaminated with e.g. T and Be can be measured.

The backscattering spectrum and nuclear reaction products were recorded using a solid state detector at a scattering angle of 150° with an accuracy better than ±1°, and a solid angle of 4.22 ± 0.15 msr. A simple method, based on the $^{19}F(p,\alpha\gamma)^{16}O$ resonance excitation of gamma-rays at 872, 935, 1375 and 1691 keV [19] from lead fluoride (PbF_2) when bombarded with protons in the energy range from 0.8 to 2.4 MeV, was used for accelerator energy calibration. The accuracy of the incident beam energy is about ±3 keV. The incident beam energy spread is below 1 keV.

The samples consisted of polished Beryllium foils. On top of the Beryllium a thin Au layer with a thickness of 3.9×10^{15} at/cm^2 was evaporated. The thicknesses of the Au layers and the amount of other impurities were checked with RBS using a ^{4}He beam. The data was analyzed with the NDF code [20]. The accuracy of the thicknesses is about 0.15×10^{15} at/cm^2. The Be samples were carefully cleaned to distinguish the peaks of other elements, such as oxygen, carbon or aluminum, from the evaporation process, observed in the EBS spectra (Fig. 1).

Measurements with proton beam energies in the range of 500–2350 keV, with steps 50 keV in plateaus and 10 keV in the vicinity of resonances were performed. The beam current was 2 nA and a charge of 5 μC per measurement, with 2% precision, was accumulated in most points. In selected points higher beam fluences were used.

3. Results and discussion

A typical EBS spectrum is shown in Fig. 1. The Au, O, C and Al peaks are well separated from the $^9Be(p,d_0)^8Be$ and $^9Be(p,\alpha_0)^6Li$ reaction and the $^9Be(p,p_0)^9Be$ backscattering plateaus. Since the height H_0 of the pulse-height spectrum at the surface does not depend on the atom density of the sample it can be used for the determination of the cross section. H_0 is directly proportional to [21]:

$$H_{Be} = \frac{d\sigma_{Be}}{d\Omega}(E - \Delta E_{Au}, \theta)Q\Omega\xi/\left[\varepsilon_{E-\Delta E_{Au}}\right] \quad (1)$$

where $d\sigma_{Be}/d\Omega$ is the differential scattering cross section evaluated at the incident energy $E - \Delta E_{Au}$, where E is the incident proton energy and ΔE_{Au} is the energy loss in Au layer. Since the energy loss of protons in the Au layer, calculated using SRIM-2013 stopping power data [22], varied from 0.1 to 0.05 keV for the 500 and 2350 keV projectile energy respectively, the correction ΔE_{Au} can be neglected. Ω is the detector solid angle, Q the number of incident H^+ ions, ξ the energy width of a channel (4.21 ± 0.06 keV/ch), determined by the electronic system and $[\varepsilon_{E-\Delta EAu}]$ is the nuclear stopping cross section factor for Be evaluated at the Be surface defined by:

$$[\varepsilon]_{nr} = \alpha_E \frac{\varepsilon_{In}}{\cos(\theta_{In})} + \frac{\varepsilon_{Out}}{\cos(\theta_{Out})} \quad (2)$$

The reaction factor α_E is the slope of the energy of the emitted particles and the energy of the incident protons, which in case of backscattered particles becomes the kinematics factor, K. Values of ε_{In} and ε_{Out} can be calculated using SRIM. The mean accuracy of SRIM, calculated by comparison to experimental data, is 5.4% for H/D, 6.1% for He and 7.5%, for H in Au, assuming the energy at surface and the energy of emitted/backscattered particles with 6% precision. $\cos(\theta_{In}) = 1 \pm 0.006$ is the cosine of the angle of incidence of the beam against the sample normal, and $\cos(\theta_{Out})$

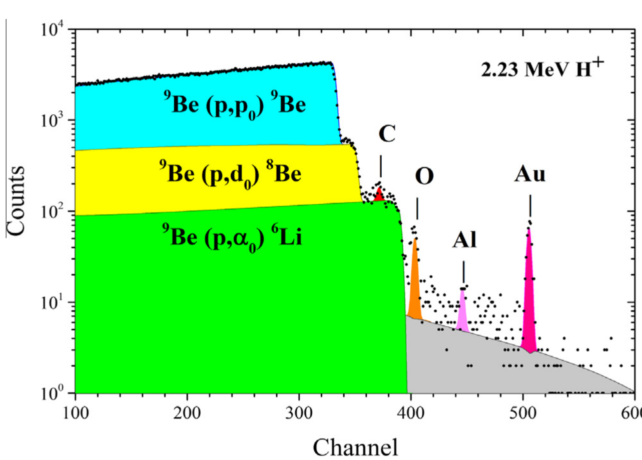

Fig. 1. Typical EBS and nuclear reaction spectrum for 2.23 MeV incident protons onto the Be target. Incident angle is 0°, scattering angle is 150°. The contribution of each particle that reaches the detector is labeled.

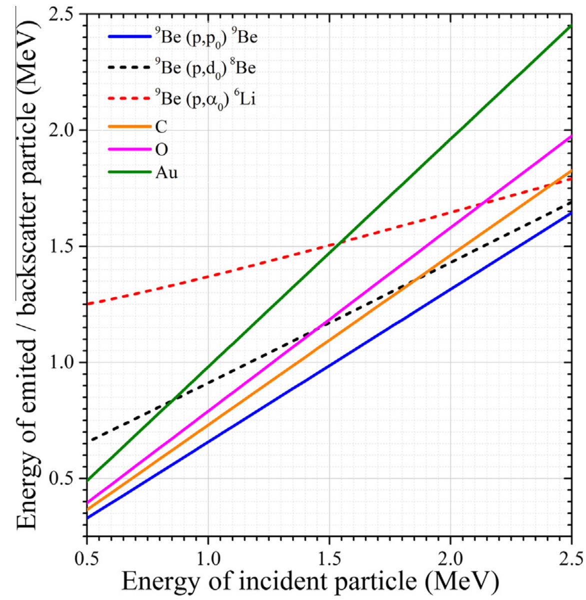

Fig. 2. Energies of backscattered particles (solid line) and nuclear reaction products (dashed line) vs. incident particle energy in the energy range 0.5–2.5 MeV.

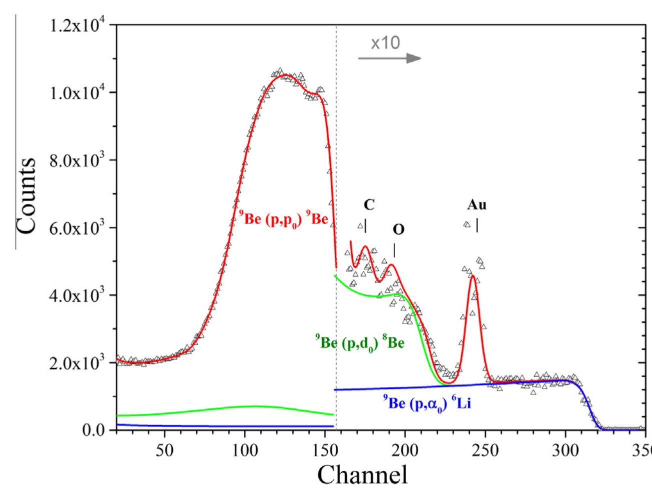

Fig. 3. Typical EBS and nuclear reaction spectrum for 1.10 MeV incident protons onto the Be target. The contribution of each particle that reaches the detector is labeled.