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PIGE related differential cross-section measurements of the $^{25}Mg(p,p'\gamma)^{25}Mg$ reaction

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ABSTRACT

The differential cross sections of the $^{25}Mg(p,p'\gamma)^{25}Mg$ reaction, critical for the quantitative determination of magnesium in complex matrices using the PIGE technique, were measured at two (2) angles, 55° and 90°, and at proton energies from 2420 to 4550 keV, by detecting the 390, 585 and 975 keV γ-rays emitted. The experimental setup consisted of two 100% relative efficiency HPGe detectors. The results are compared to those already present in literature and an attempt is made to explain the existing discrepancies. The obtained results from the present work are validated via thick-target measurements.

1. Introduction

Magnesium is a light element found in many industrial, technological, medical, geological and environmental applications as well as in archaeological studies. Therefore, the quantitative determination of magnesium in various heavy element matrices is very important. The most common non-destructive techniques used for this purpose are the Ion Beam Analysis (IBA) ones, such as the Elastic Backscattering Spectroscopy (EBS) and the deuteron induced Nuclear Reaction Analysis (d-NRA) one. However, the EBS technique is in some cases inefficient, especially when magnesium coexists in matrices with other light elements, while a deuteron beam is not available in many laboratories. On the other hand, the Particle Induced Gamma ray Emission (PIGE) technique can generally yield more accurate results, although it has the drawback that the produced yield depends on the matrix composition. Thus, there emerges the need for using multiple different reference targets. To overcome this problem and obtain standardless measurements, it is necessary to know the differential cross section of the studied reaction with adequate accuracy.

The only two published works concerning the differential cross section of the $^{25}Mg(p,p'\gamma)^{25}Mg$ reaction in the past [1,2] present significant discrepancies. Each of the previous studies for the determination of the differential cross section was carried out only for one angle (90° and 135°, respectively) and for proton beam energies up to 3.8 MeV. The present work aims at clarifying these discrepancies as well as extending the available data of the differential cross sections of the $^{25}Mg(p,p'\gamma)^{25}Mg$ reaction in the proton beam energy range E_{lab} = 2420–4550 keV at θ_{lab} = 55° and 90°, in order to enrich the literature and to render possible a deeper magnesium detection in a sample. Furthermore, a thick-target experiment was conducted to verify the validity of the determined differential cross sections by comparing the present measurements with previous thick-target yield datasets evidenced in literature [3–5].

2. Experimental setup

The experiment was conducted at the 5.5 MV T11/25 Tandem Accelerator of the Institute of Nuclear and Particle Physics (INPP), National Centre of Scientific Research (NCSR) "Demokritos", Athens, Greece, using a proton beam in the energy range E_{lab} = 2420–4550 keV with a variable step of 5–20 keV. The accuracy of the beam was ~0.2% as it was measured using the narrow resonances of $^{27}Al(p,\gamma)^{28}Si$ and $^{32}S(p,p'\gamma)^{32}S$ at E_p = 991.9 [6] and 3379 keV [7–9], respectively. The intensity of the beam did not exceed 150 nA in order to keep the ADC dead time below 5% and avoid pile-up effects. The target was placed in the center of a

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chamber which was electrically isolated in order to act as a Faraday cup. A tantalum collimator was placed at ~1 m before the target, so that the diameter of the beam spot on the target would be ~3 mm. Due to the fact that the connection between the tube and the chamber has ~1 cm diameter, a voltage of −300 V applied on the collimator was adequate to suppress the emission of secondary electrons from the target. For the detection of the γ-rays two (2) HPGe detectors of 100% relative efficiency were used at the angles of 55° and 90° and at a distance of ~15 cm from the target, so an angular acceptance of about ±20° was achieved. The efficiency of these detectors was determined using a calibrated point source of ^{152}Eu. The data acquisition was accomplished using standard NIM electronics.

The target used for the cross-section measurements was a thin enriched ^{25}Mg target evaporated on a nickel (Ni) foil. However, the nominal thickness (~15 μg/cm^2) and the enrichment of the target presented large uncertainties. Thus, a target of MgF_2 onto a polymer membrane, with a nominal thickness of 53.2 μg/cm^2 ±5% given by the manufacturer, MICROMATTER CO., was used in order to determine the thickness of the thin ^{25}Mg target. Firstly, the thickness of the MgF_2 target had to be verified, so it was measured using the EBS (Elastic Backscattering Spectrometry) technique and was found to be 69.6 μg/cm^2, with a total uncertainty of ~7%, and that was the value implemented afterwards. For this measurement, a deuteron beam with an energy of E_d = 1770 keV was used and the backscattered deuterons were detected by a 1000 μm thick SSB detector placed at 170°. The spectrum that resulted from this measurement was analyzed with the SIMNRA code [10] (Fig. 1), using for the ^{nat}Mg(d,d$_0$)^{nat}Mg reaction the differential cross-section dataset by Patronis et al. [11] available for downloading through the IBANDL nuclear database from IAEA [www-nds.iaea.org/ibandl/]. Following the measurement, the thickness of the thin enriched ^{25}Mg target was calculated by directly comparing the γ-ray yields of the 585 keV line of the two targets at various bombarding energies and it was found to be 2.89 μg/cm^2 or 71.6 × 10^{15} at/cm^2, with a total uncertainty of ~7%.

Finally, a thick ^{nat}Mg target prepared by pressing amorphous high-purity natural magnesium powder was used for a benchmarking experiment and the γ-ray spectra were detected for the beam energies of E_p = 2600, 2980, 3300, 3600, 3930, 4260 and 4550 keV.

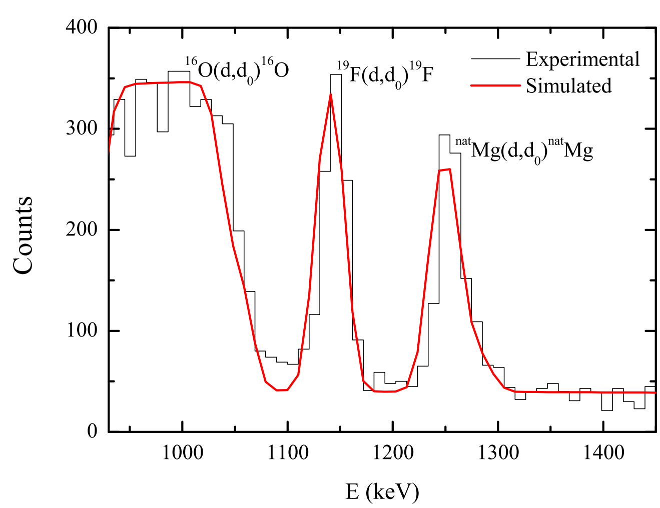

Fig. 1. The spectrum from EBS measurement for the estimation of the thickness of the MgF_2 target, using the SIMNRA code [10].

3. Analysis and results

The photopeaks of the 390, 585 and 975 keV γ-rays, emitted from the de-excitation of the second excited state to the first and the first and the second excited state to the ground one, respectively, of the ^{25}Mg(p,p′γ)^{25}Mg reaction were integrated using two different codes, namely SPECTRW [12] and TV [13], in order to avoid any systematic uncertainties. The differences in the integration yields between the two codes did not exceed 1% in all studied cases. The proton beam energy was corrected, due to energy loss effects, according to SRIM 2013 calculations [14] by applying the usual convention of the reaction occurring in the middle of the thin target. The well known formula:

$$\frac{d\sigma}{d\Omega} = \frac{N}{4 \cdot \pi \cdot Q \cdot \epsilon_{abs} \cdot \xi} \tag{1}$$

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, ϵ_{abs} to the detector absolute efficiency and ξ to the target thickness. For the calculation of the detectors efficiency the yields from the γ-rays emitted from a calibrated ^{152}Eu point source were fitted with the polynomial equation:

$$\epsilon_{abs} = A + \frac{B}{E_\gamma} + \frac{C}{E_\gamma^2} + \frac{D}{E_\gamma^3} \tag{2}$$

The resulting differential cross sections of the ^{25}Mg(p,p′γ)^{25}Mg reaction are presented in Fig. 2 and are already available for downloading through the IBANDL nuclear database from IAEA [www-

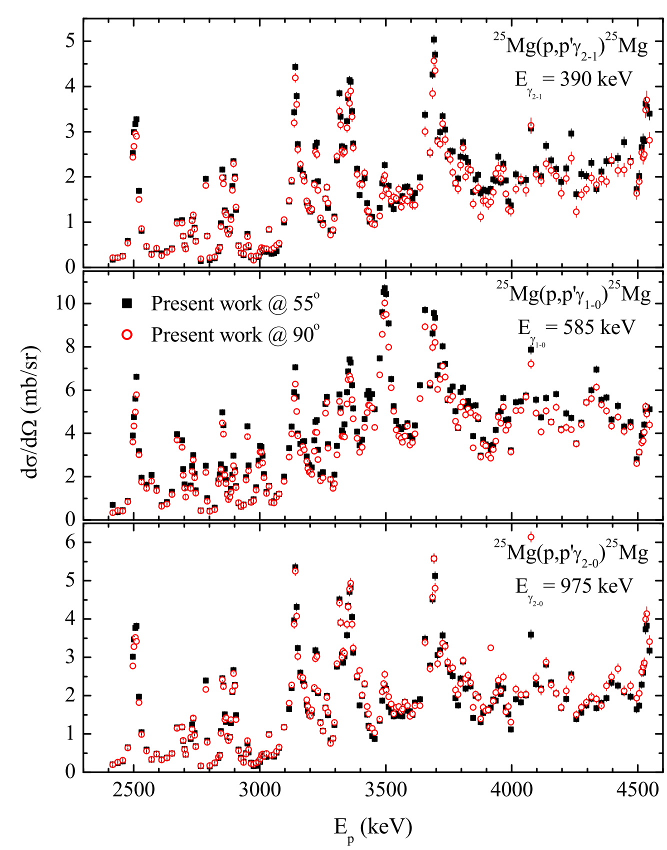

Fig. 2. Differential cross sections of the ^{25}Mg(p,p′γ)^{25}Mg reaction for the two detection angles (55° and 90°) and the 390, 585 and 975 keV γ-rays emitted (top to bottom, respectively).