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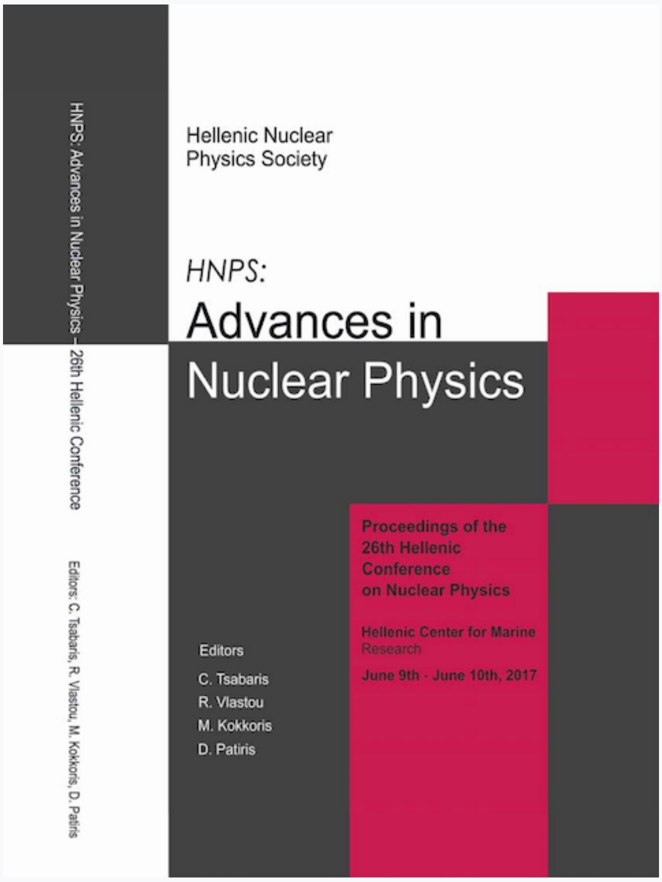

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Study of the differential cross section of the ^{25}Mg(p,p'γ)^{25}Mg reaction for PIGE purposes

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Abstract In the present work, the differential cross sections of the ^{25}Mg(p,p'γ)^{25}Mg reaction 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.

Keywords Differential cross section, 25-Magnesium, PIGE

INTRODUCTION

Magnesium is a light element found in many industrial, technological, medical, geological and environmental applications, as well as in archaeological studies. Thus, the quantitative determination of magnesium in various heavy element matrices is crucial. The most common non-destructive techniques that are 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 co-exists 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 highly depends on the matrix composition. Therefore, there emerges the need for using multiple different reference targets. In order to overcome this problem and obtain standard-less measurements, it is necessary to know the differential cross section of the studied reaction with adequate accuracy.

In the past, there were only two published works concerning the differential cross section of the ^{25}Mg(p,p'γ)^{25}Mg reaction [1,2] which present significant discrepancies. These two studies was carried out only for one angle (90° and 135°, respectively) and for proton beam energies up to 3.8 MeV. The purpose of the present work is to clarify the discrepancies as

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well as to extend the available data 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. Moreover, a thick-target experiment was conducted to validate the determined differential cross sections by comparing the present measurements with previous thick-target yield datasets existed in literature [3-5].

EXPERIMENTAL DETAILS

The experiment was carried out 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. The proton beam energy range was E_{lab} = 2420 - 4550 keV (5 - 20 keV variable step). The accuracy of the beam 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, and it was ~0.2%. The beam intensity did not exceed 150 nA to keep the ADC dead time below 5% and avoid pile-up effects. The target was placed in the center of a chamber which is 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 was ~3 mm. Due to the fact that the connection between the tube and the chamber has ~1 cm diameter, a voltage of -300 V was applied on the collimator to suppress the emission of secondary electrons from the target. Two HPGe detectors of 100% relative efficiency were placed for the detection of the γ-rays at 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 target used for the cross-section measurements consists of a thin enriched ^{25}Mg layer evaporated on a nickel foil. However, its nominal thickness (~15 μg/cm^2) and the enrichment presented large uncertainties. For this reason, 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 for the thickness determination of the thin ^{25}Mg target. Firstly, the thickness of the MgF_2 target was verified by using the EBS (Elastic Backscattering Spectrometry) technique and was 69.6 μg/cm^2 (~7\% total uncertainty) and that was the value implemented afterwards. For this measurement, a deuteron beam with 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 accumulated spectrum was analyzed with the SIMNRA code [10] (Fig. 1), using the differential cross-section dataset by Patronis et al. [11] for the $^{nat}Mg(d,d_0)^{nat}Mg$ reaction. 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 benchmarking experiment was conducted using a thick ^{nat}Mg target prepared by pressing amorphous high-purity natural magnesium powder and for the proton beam energies of E_p = 2600, 2980, 3300, 3600, 3930, 4260 and 4550 keV.

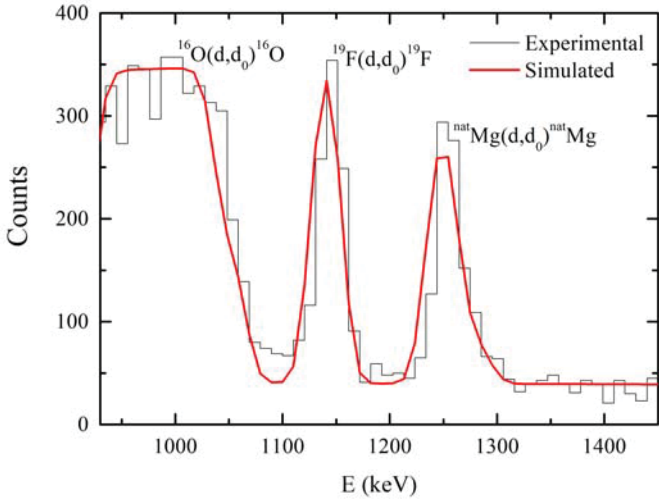

Fig. 1. The spectrum from EBS measurement for the estimation of the thickness of the MgF_2 target, using the SIMNRA code [10].

ANALYSIS AND RESULTS

The 390, 585 and 975 keV γ-ray photopeaks, which are emitted from the de-excitation of the second excited state to the first one and the first and second excited states to the ground state, respectively, of the $^{25}Mg(p,p'\gamma)^{25}Mg$ reaction were integrated using two different codes, namely SPECTRW [12] and TV [13], to avoid any systematic uncertainties. The differences between the integration yields of the two codes were lower than 1% in all studied cases. Because of energy loss effects, the proton beam energy was corrected according to SRIM 2013 [14] calculations by applying the usual convention of the reaction occurring in the middle of the thin target. For the differential cross-section derivation the following well-known formula was used:

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

where N corresponds to the integrated peak, Q to the accumulated beam charge, ϵ_{abs} to the detector absolute efficiency and ξ to the target thickness. In order to calculate the efficiency, the yields from the emitted γ-rays from a calibrated ^{152}Eu point source were fitted with the suggested by International Atomic Energy Agency (IAEA) polynomial equation:

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

In Fig. 2 the resulting differential cross sections of the $^{25}Mg(p,p'\gamma)^{25}Mg$ reaction are presented which are already available at IBANDL database, and in Table 1 the systematic errors along with the total resulting uncertainty of this dataset are shown.

The differential cross sections reveal the existence of many overlapping resonances throughout the entire energy range implying a wealth of excited states of the compound nucleus ^{26}Al. However, due to this overlap, the correlation between these resonances and the compound nucleus levels is very difficult. Only the two isolated narrow resonances appearing at $E_p \simeq 2510$ and 3140 keV, which correspond to the excited state of the compound nucleus at ~8.72 and 9.32 MeV, respectively, could be attributed to the reported values (8.75 and 9.31 MeV) in literature [15]. It should also be mentioned that these resonances appear in all of the three studied γ-rays. Furthermore, the data from both detection angles (55° and 90°) revealed that there is no any strong angular dependence throughout the whole studied energy range.

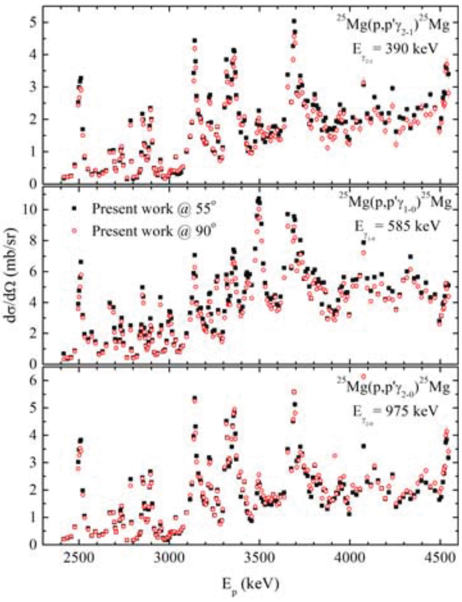

Fig. 2. Differential cross sections of the 25Mg(p,p'γ)25Mg reaction for the two detection angles (55° and 90°) and the 390, 585 and 975 keV γ-rays emitted (top to bottom, respectively).

Quantity	Uncertainty (%)
Integrated Beam Current	4
Target Thickness	7
Detectors Efficiency	3
Total	*8.6*

Table 1. Systematic errors and total systematic uncertainty.

A benchmarking experiment was conducted using a thick ^{nat}Mg pellet to validate the measured differential cross sections. The thick-target experiment was performed for the beam energies of E_p = 2600, 2980, 3300, 3600, 3930, 4260 and 4550 keV and the resulting yields were compared to the respective calculated by integrating the measured differential cross sections. The differences among them were lower than 5% in the least favorable case.

DISCUSSION

In Fig. 3, the differential cross sections of the present work are compared to the already existing ones. The present data are in very good agreement with the data by Zamboni et al. [2] and Jesus et al. [to be submitted, already available in the IBANDL database]. However, in the latter dataset there is a shift at the energy of the resonances that varies from 10 to 30 keV depending on the proton beam energy. Concerning the data of Boni et al. [1], despite the qualitative agreement, there is a difference of a factor ~10 in absolute values which cannot be explained either by the systematic uncertainties of the present work or by the ones reported by Boni et al. (15%). A similar behavior was observed in the cases of the $^{10}B(p,\alpha\gamma)^{7}Be$ and $^{11}B(p,p'\gamma)^{11}B$ reactions as reported in previous works regarding PIGE differential cross-section measurements in boron isotopes [16,17].

The differential cross sections of the present work were verified through a benchmarking measurement, using a thick ^{nat}Mg target. In Fig. 4, the comparison of the integration of the present data with data from literature, including the previously reported thick-target yields [3-5], is presented. The present data have been normalized to the thick-target yield measured at the proton beam energy of E_p = 2600 keV. In the cases of Zamboni et al. and Jesus et al., whose measurements start from very low energies, a normalization was not necessary. There is a good agreement with the data by Zamboni et al. and Anttila et al. [3] for all of the three γ-rays studied and with the data by Kiss et al. [4], except for the case of the 390 keV γ-ray for the proton beam energy above 3 MeV where there is an underestimation by Kiss. In the case of the 585 keV γ-ray there is also an excellent agreement with the data by Savidou et al. [5]

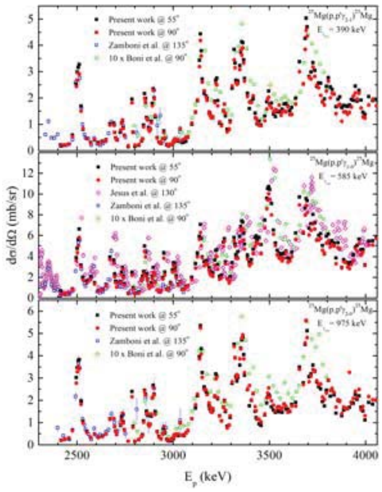

Fig. 3. Comparison of the differential cross sections between present work, Jesus et al., Zamboni et al. and Boni et al. multiplied by a factor of 10.

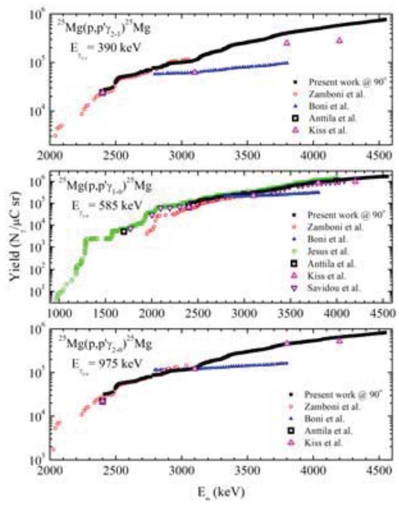

Fig. 4. Comparison of calculated thick-target yields obtained by using the differential cross sections of present work (solid squares) with measured ones from the literature (see text).

and Jesus et al., who have studied only this partial inelastic channel. On the other hand, the data by Boni et al., which have been normalized at 2.6 MeV with the data by Kiss, present a remarkably lower slope, which means that in that work the differential cross sections have been seriously underestimated. All these facts support the validity of the obtained results of the present work.

CONCLUSIONS

In the present work, the differential cross sections of the γ-rays emitted from the $^{25}Mg(p,p'\gamma_{2\text{-}1})^{25}Mg$, $^{25}Mg(p,p'\gamma_{1\text{-}0})^{25}Mg$ and $^{25}Mg(p,p'\gamma_{2\text{-}0})^{25}Mg$ reactions (390, 585 and 975 keV, respectively) at two angles (55° and 90°) and for the proton beam energy range $E_{p,lab}$ = 2420 - 4550 keV were studied. It is the first dataset concerning proton beam energies above 3 MeV, apart from the one by Boni et al. (which does not reproduce the thick-target yields), thus it is important for the deeper magnesium quantification into a target. Moreover, it is the only coherent dataset with all of the three partial γ-ray differential cross sections of the $^{25}Mg(p,p'\gamma)^{25}Mg$ reaction. The data from different angles revealed that there is no any strong angular dependence throughout the whole energy range except in the case of certain narrow resonances, which permits the use of the PIGE technique with experimental setups where the detectors are placed close to the target. Furthermore, a benchmark experiment was performed in order to validate the obtained differential cross-section datasets. Thick-target yields were measured and compared to the calculated ones and those reported in literature.

Acknowledgments

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References

[1] C. Boni et al., NIMB 35 (1), p. 80-86 (1988)
[2] I. Zamboni et al., NIMB 342, p. 266-270 (2015)
[3] A. Anttila et al., J. Radioanal. Chem 62, p. 293-306 (1981)
[4] A. Kiss et al., J. Radioanal. Chem 89, p. 123-141 (1985)
[5] A. Savidou et al., NIMB 152 (1), p. 12-18 (1999)
[6] S. Harissopulos et al., The European Phys. J. A 9 (4), p. 479-489 (2000)
[7] J. W. Olness et al., Phys. Rev. 112, p. 1702-1716 (1958)
[8] C. Tsartsarakos et al., NIMB 45 (1-4), p. 33-35 (1990)
[9] P. Rao et al., NIMB 269 (21), p. 2557-2562 (2011)
[10] M. Mayer, AIP Conference Proceedings 475 (1), p. 541-544 (1999)
[11] N. Patronis et al., NIMB 337, p. 97-101 (2014)
[12] C. Kalfas et al., NIMA 830, p. 265-274 (2016)
[13] J. Theuerkauf et al., University of Cologne
[14] J. F. Ziegler et al., Lulu press (2008)
[15] P. Endt et al., Nucl. Phys. A 633 (1), p. 1-220 (1998)
[16] A. Lagoyannis et al., NIMB 342 (0), p. 271-276 (2015)
[17] K. Preketes-Sigalas et al., NIMB 368, p. 71-74 (2016)