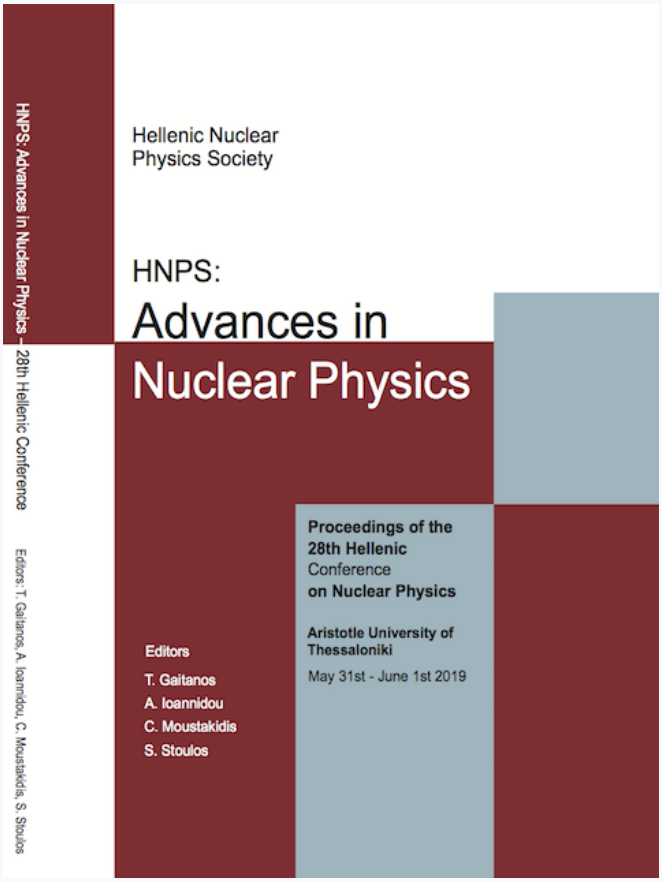
HNPS Advances in Nuclear Physics

Vol 27 (2019)

HNPS2019



natMg(p,p0) differential cross-section measurement relevant to the EBS technique

Eleni Alvanou, Anastasios Lagoyannis, Michael Axiotis, Natalia Bligoura, Sotirios Harissopulos, Michael - Kokkoris, Fotis Maragkos, Eleni Ntemou, Kostas Preketes-Sigalas

doi: 10.12681/hnps.3014

^{nat}Mg(p,p$_0$) differential cross–section measurement relevant to the EBS technique

E. Alvanou[1,2], A. Lagoyannis[1], M. Axiotis[1], N. Bligoura[2], S. Harissopulos[1], M. Kokkoris[2], F. Maragkos[2], E. Ntemou[1,2], K. Preketes–Sigalas[1,2]

[1] *Institute of Nuclear & Particle Physics, NCSR "Demokritos", 15310 Agia Paraskevi, Athens, Greece*
[2] *Department of Physics, National Technical University of Athens, Zografou Campus 15780, Athens, Greece*

Abstract *In the present work the ^{nat}Mg(p,p$_0$)^{nat}Mg reaction was investigated in the energy range $E_{p,lab}$ ~2700–4250 keV, at six backward detection angles (120°–170°) suitable for analytical purposes. The measurements were performed using the 5.5 MV TN11 HV Tandem Accelerator of N.C.S.R. ''Demokritos", Athens, Greece and a high–precision goniometer. The experimental data are compared to data from the literature, when available, and similarities and discrepancies are presented and analyzed.*

Keywords *p–EBS, IBA, Magnesium*

Corresponding author: E. Alvanou (elalv91@gmail.com) | *Published online:* May 1st, 2020

INTRODUCTION

Magnesium (^{24}Mg 78,99%, ^{25}Mg 10%, ^{26}Mg 11,01%) is the lightest of all light metal alloys, has good heat dissipation, good damping and is readily available. Due to these properties, magnesium is a widely used metal, implemented mainly as an alloy in electronic devices and in the field of research of superconducting materials and applications. Thus, the precise quantitative determination of magnesium depth profile concentrations is of high importance. However, due to its low z and its highly reactive character, its quantification, when present in high–Z matrices, presents a strong challenge for most of the analytical techniques. Among the commonly used Ion Beam Analysis methods for magnesium depth profiling, proton elastic backscattering spectroscopy (p–EBS) is the most promising one along with deuteron probed nuclear reaction analysis (d–NRA). Nuclear Reaction Analysis is more suitable when magnesium coexists with other light elements in the under–study sample, as the peaks of the detected products are well–separated. On the other hand, regarding radiation safety precautions arising from the neutron producing reactions, proton EBS is preferable. The use of the latter technique for the depth profiling of magnesium has been enhanced by the existence of evaluated and benchmarked differential cross sections produced via SigmaCalc [1]. By examining the literature, one can discover the lack of coherent experimental differential cross–section datasets for magnesium, over a broad angular range, for energies above ~2.7 MeV, (i.e. above the existing SigmaCalc evaluation), which restricts the use of the technique and its advantageous probing depth. Towards the goal of extending the evaluation, in the present work we report on the differential cross section measurements of the ^{nat}Mg(p,p$_0$) reaction, in the proton beam energy range between 2500 to 4200 keV and at six detection angles (120° to 170° with a 10° step). The obtained results are compared with the existing ones from the literature.

EXPERIMENTAL DETAILS

The measurement was carried out using the proton beam of the 5.5MV Tandem Accelerator Laboratory of the N.C.S.R. "Demokritos" Athens, Greece. Protons were accelerated to $E_{p,lab}$ = 2550–4240 keV in steps of maximum 40 and minimum 10 keV (when close to strong resonances) and were

directed to a large size cylindrical scattering chamber (R~40 cm). Before the cross section measurements the accelerator was calibrated using the Nuclear Magnetic Resonance (NMR) technique with an estimated ripple of 4.7 keV via the 991.89 keV strong, narrow resonance of the ^{27}Al(p,γ) reaction, using a 18% relative efficiency HPGe detector. Since non–linear deviations of the magnet have not been observed in the past, the determined energy offset (~5.1 keV) and ripple were taken as constant for the proton beam energy range studied in the present work. These values were subsequently used for the ADC energy calibration, whose linearity was proven to be excellent (better than 0.4%) for all angles, except at 170°, where the fitting was performed for two energy regions but still a deviation from linearity was present to a much lesser degree.

The backscattered protons were detected by 6 SSB detectors (resolution ~13 keV) mounted on a high precision goniometer (~0.1°) at 120°–170°, along with the corresponding electronics .The spectra from all the detectors were recorded simultaneously, repeating the same procedure for every $E_{p,lab}$.

The target was fabricated at the Tandem Laboratory of the N.C.S.R. "Demokritos" by evaporating ^{nat}Mg on top of a thin C stripping foil. An ultra–thin layer of Au was evaporated on its surface for normalization purposes. It was placed at 11–15.5 cm from the detectors as a compromise between the optimal angular resolution and an acceptable counting rate. Orthogonal slits (4.5x8 mm^2) were placed in front of the silicon detectors aiming at reducing the azimuth angular uncertainty (<±1°), while allowing for an adequate effective solid angle to be subtended by the SSB detectors. In front of the detectors, in order to avoid any excessive background under the magnesium elastic peaks due to multiple scattering in the chamber walls and/or in the Faraday cup, small cylindrical tubes, variable in length (~4–9 cm) and having a diameter of ~1.1 cm, were placed in front of the detectors.

The vacuum was kept constant ~10^{-6} Torr. SIMNRA (v.7.01) [2] was used for the analysis of the EBS spectra (taking into account a very small energy step for the incoming and outgoing protons, the effect of multiple scattering, the beam ripple, ZBL stopping power data, and Chu and Yang's straggling model as implemented in the code). For the calculation of the mean proton beam energy at half the target's thickness, Monte–Carlo simulations were performed using SRIM2013 [3].

RESULTS AND DISCUSSION

The determination of the differential cross section for the ^{nat}Mg(p,p$_0$) elastic scattering was carried out following the formula for the relative measurements technique, that is, the values were deduced relative to the elastic scattering of protons in ^{197}Au. The differential cross section of the ^{197}Au(p,p$_0$) reaction at the energies studied in the present work, is purely Rutherford (including the screening corrections), so the following formula was finally implemented:

$$\left(\frac{d\sigma}{d\Omega}\right)^{E,\theta}_{nat_{Mg}} = \left(\frac{d\sigma}{d\Omega}\right)^{E',\theta}_{Au} \frac{Y_{nat_{Mg}}}{Y_{Au}} \frac{N_{t,Au}}{N_{t,nat_{Mg}}}$$

where, θ corresponds to the scattering angle, E and E´ represent the energies at the half of the target's thickness and at the surface of the target (following the accelerator energy calibration) respectively, Y_{natMg} and Y_{Au} are the integrated yields as obtained from the experimental spectra and $N_{t,Au}/N_{t,natMg}$ is the ratio of the total number of ^{197}Au versus ^{nat}Mg nuclei present in the target.

For peak fitting/integration and linear background subtraction SPECTRW [4] was used. As shown in Fig. 1, there was no peak overlap, or significant induced background contribution under the magnesium and gold elastic peaks for the whole energy range under study. Moreover, the carbon and oxygen unavoidable parasitic contributions were separated from the magnesium peak. The statistical error in Y_{natMg} and Y_{Au} did not exceed 4%.

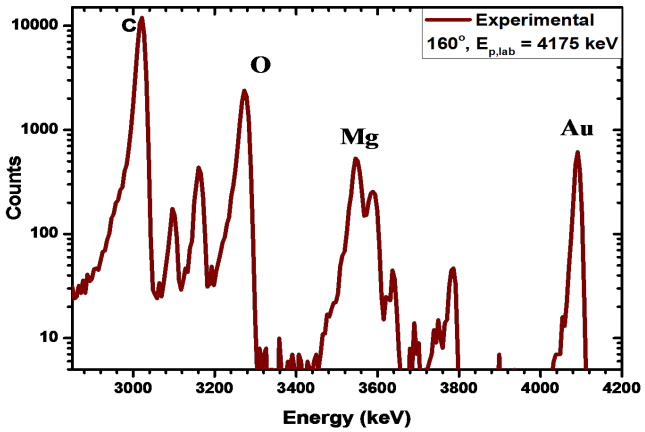


Figure 1. *A typical experimental spectrum taken at 170°, for $E_{p,lab}$=4175 keV.*

In order to determine the ratio $\frac{N_{t,Au}}{N_{t,nat_{Mg}}}$, 9 proton elastic scattering spectra were collected for the proton beam energies 1900, 2300, and 2550 keV (these energies were chosen to be far from existing sharp, Breit–Wigner type resonances) and angles 150°–170°, where the values of differential cross sections of natural magnesium are evaluated and benchmarked. The resulting spectra were analyzed using SIMNRA.

The derived average value was adopted for the subsequent calculations, while the inherent statistical and systematic errors in the evaluated results were not taken into account. The average value of the $\frac{N_{t,Au}}{N_{t,nat_{Mg}}}$ ratio was determined to be 0.0445±0.0024, i.e. with a relative statistical error of ~2.7%.

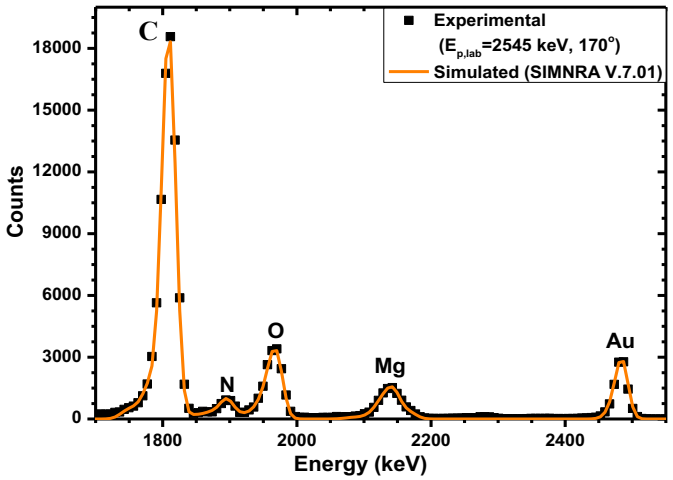


Figure 2. *Analysis of the target structure and composition, at 170° and $E_{p,lab}$=2545 keV.*

The differential cross section values for the six detection angles (120°, 130°, 140°, 150°, 160° and 170°), as obtained in the present study for the ^{nat}Mg(p,p$_0$) elastic scattering, are presented in Fig. 3. The indicated combined experimental errors correspond to ±1σ. The combined experimental statistical uncertainty did not exceed 6.9% in all cases. Results from previous measurements on proton elastic scattering from ^{24}Mg, which is the most abundant stable isotope in natural magnesium, according to the closest experimental angle under study, are also included in the graphs. The most significant result, however, is that strong deviations from the Rutherford formula reveal the existence of several –

and possibly overlapping– resonances that mainly correspond to the exited energy states of the compound nucleus ^{25}Al for the center–mass energy range covered in the present work. Especially, the broad maximum in the yield around $E_{p,lab}$ ~3200 keV can be attributed to the energy state of the compound nucleus ^{25}Al with $E^*_{25_{Al}}$=5285 keV (Γ=185 keV). In the region 3400–3900 keV there is a fluctuation in the values of the differential cross sections which may be due to the existence of overlapping levels existing e.g. 5526 keV (Γ~18 keV), 5597 keV (Γ=55 keV) and 5686 keV. For $E_{p,lab}$~3700 keV and ~4000 keV, the observed cross–section structures can be attributed to the excited states $E^*_{25_{Al}}$=5785 keV (Γ=15 keV) and $E^*_{25_{Al}}$=6122 keV (Γ=51 keV) respectively.

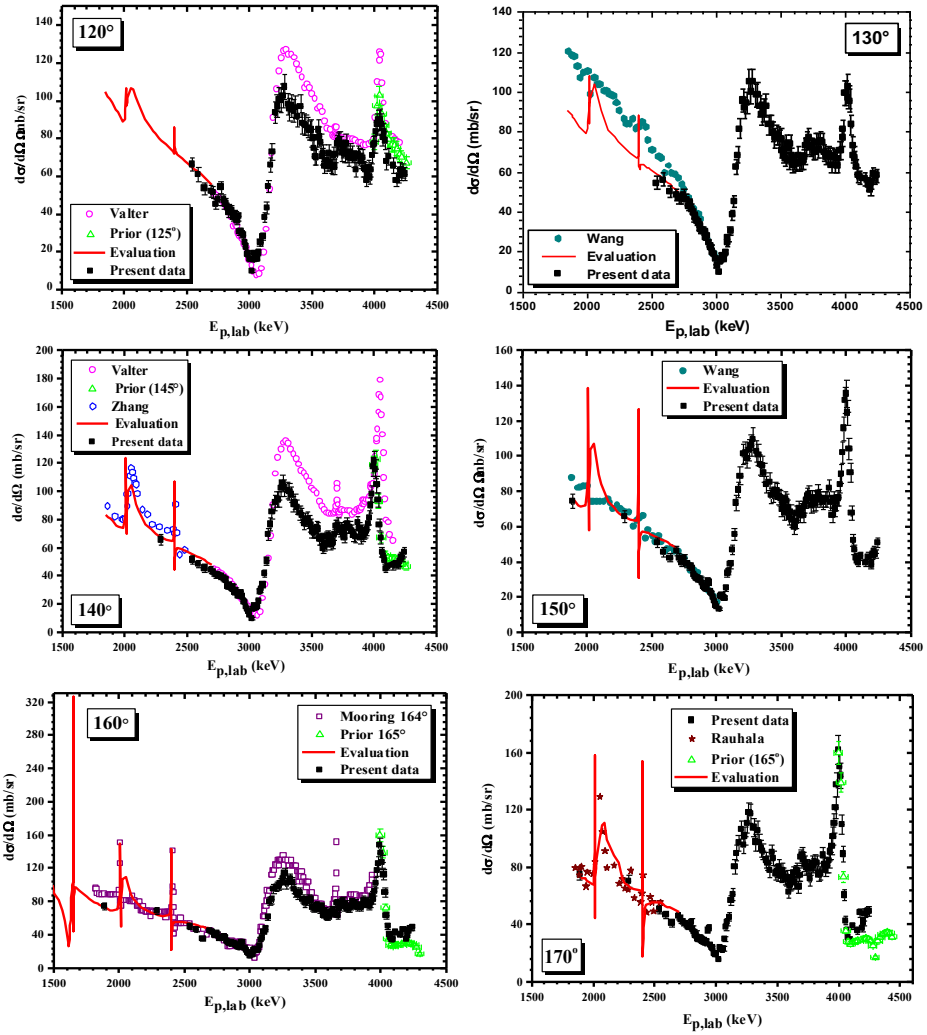


Figure 3. *Experimental differential cross section values for ^{nat}Mg(p,p$_0$) elastic scattering from the present work at various backward detector angles, along with data from literature (when available).*

As shown in fig. 3 the results from the present work at 130° and 150° are in good agreement with those obtained in the past by Wang et al. [5] for energies 1851 – 2999 keV (the discrepancy does not exceed 16% and 9% respectively). At 120° the values of differential cross section of the present work are lower than those of Valter et al. [6] and Prior et al. [7] from 3200 keV. The same applies to fig. 3 at 140° with the results of Valter et al. [6], but not with the ones of Prior et al. [7], which are below the experimental values of this work above 4200 keV (for 140°) and above 4000 keV for 160° and 170°. Moreover, the resonances at the proton beam lab energies of ~3200 keV and ~4000 keV were found to be slightly shifted towards lower values, as compared to the measurements by Valter et al. [6] at 120° and 140°. At 160° there is good agreement with the measurements of Mooring et al. [8] except

for the resonance regions, i.e. at ~3200 keV there exists a 12% discrepancy and at ~3700 keV this discrepancy reaches or exceeds ~48%. Furthermore, with respect to the already existing evaluated values of the differential cross section, the measurements obtained in the present work show good agreement at all angles except at 2638 keV, where there is a strong indication for a resonance.

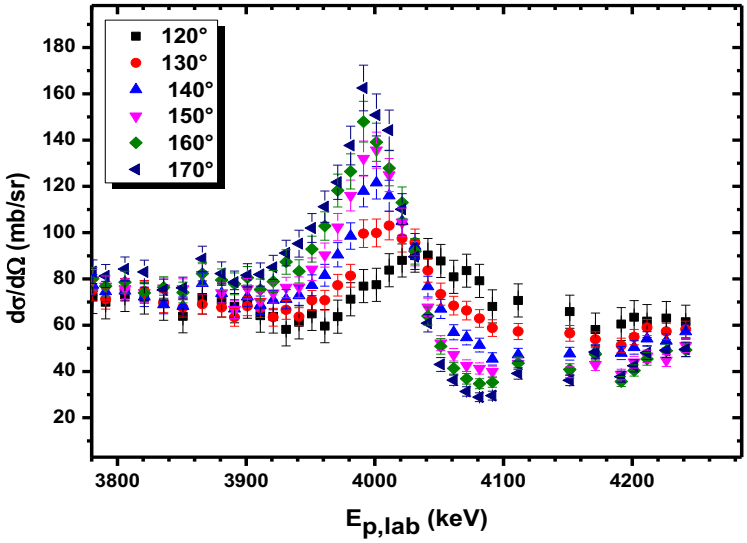


Figure 4. *Angular distribution of the determined differential cross–section values.*

Fig. 4 shows the angular distributions of the obtained differential cross sections, in order to examine the extent of their dependence on the detection angle. It follows that above 3900 keV there exists a strong angular dependence of the cross section on the scattering angle, which makes this energy region rather difficult for the accurate depth profiling of magnesium in conventional IBA experimental setups.

CONCLUSIONS

A detailed, coherent study of the differential cross section of the $^{nat}Mg(p,p_0)$ elastic scattering for $E_{p,lab}$ ~2700–4250 keV and at six backward detection angles, namely at 120°, 130°, 140°, 150°, 160° and 170°, suitable for magnesium depth profiling has been presented. The obtained values showed large deviations from the Rutherford formula, which can be mainly attributed to the resonances of the compound nucleus ^{25}Al. The datasets obtained in the present work are expected to facilitate future analytical depth profiling studies of magnesium. Moreover, the fact that they constitute a coherent set of measurements will also facilitate future evaluation efforts for proton elastic scattering on natural magnesium.

References

[1] A.F. Gurbich et al., Nucl. Instr. Meth. Phys. B 268, 1703 (2010), doi: 10.1016/j.nimb.2010.02.011
[2] M. Mayer, Nucl. Instr. Meth. Phys. B 332, 176 (2014), doi: 10.1016/j.nimb.2014.02.056
[3] J.F. Ziegler, J.P. Biersack, M.D. Ziegler, '*The Stopping and Range of Ions in Matter*', Lulu Press Co, Morrisville, NC, 27560 USA, 2015.
[4] C.A. Kalfas, M. Axiotis, C. Tsabaris, Nucl. Instr. Meth. Phys. A 830, 265 (2016), doi: 10.1016/j.nima.2016.05.098
[5] W.N. Wang, E.K. Lin, C.L. Tung, Chin. J. Phys. 10, 1 (1972)
[6] A.K. Valter, V.E. Storizhko, A. I. Popov, JETP 44, 57 (1963)
[7] R.M. Prior et al., Nucl. Phys. A 533, 411 (1991), doi: 10.1016/0375-9474(91)90525-B
[8] F.P. Mooring et al., Phys. Rev. 84, 703 (1951), doi: 10.1103/PhysRev.84.703