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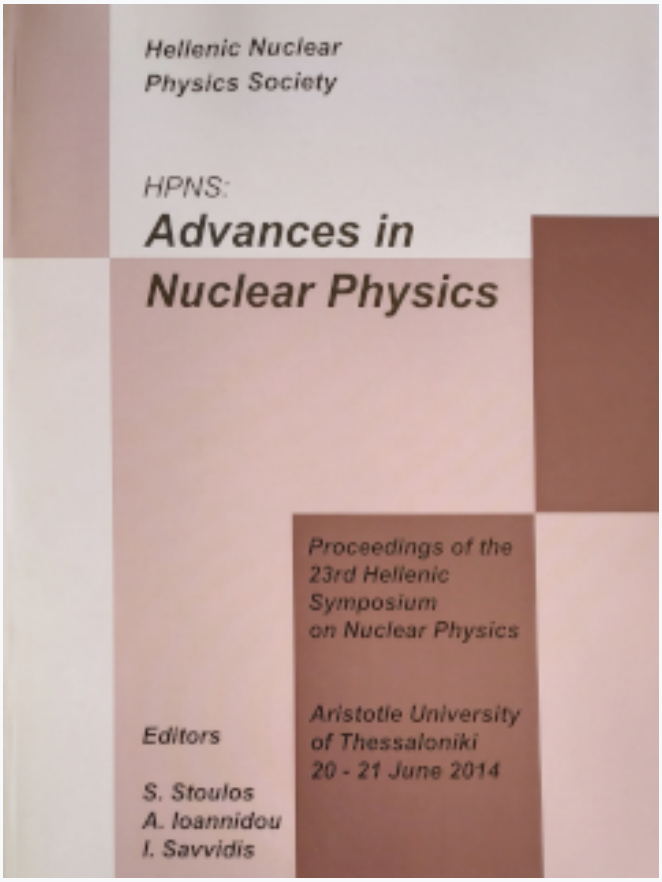

Systematic cross section measurements of (α,γ) reactions for astrophysics

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Systematic cross section measurements of (α,γ) reactions for astrophysics

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1. Introduction

The nucleosynthesis of the 35 proton-rich nuclei known as "p nuclei" is described by the so called "p-process" mechanism [1]. The latter takes place at explosive stellar environments of temperatures in the range 1.8-3.3×10^9 K and evolves through a complex sequence of (γ,n), (γ,p) and (γ,α) photodisintegration reactions, along with the inverse capture reactions (n,γ), (p,γ) and (α,γ), followed by β^+ decays or electron capture reactions. All the aforementioned reactions extend within a network of more than 20000 reactions involving about 2000 nuclei in the mass range 12<A<210. In this mass region the experimental data are scarce, as most of the cross sections to be determined are in the μb region due to Coulomb barrier penetration. Consequently, the determination of almost all reaction rates has to rely on cross sections calculated by the nuclear reaction theory of Hauser-Feshbach (HF) [2].

At p-process sites the α-particles contributing in the nucleosynthesis are found with energies of a few MeV, within the so-called Gamow Window, far below the Coulomb barrier. At such low energies the α-induced HF cross sections are governed by the a-particle transmission coefficient which is determined by solving the Schrodinger equation using the appropriate Optical Model Potential (OMP). Therefore the a-particle OMP plays a significant role in the explanation of the observed in the solar system p-nuclei abundances that are the imprints of the p-process mechanism. Aiming at determining a global α-particle OMP that is able to reproduce accurately all existing experimental data, over the whole mass region, several models have been developed so far. The range of the different models defines the uncertainty level up to which global α-particle induced reactions cross sections can be predicted. The measurement and comparison of experimental cross-section data is of great importance in order to constrain the determination of a global α-particle OMP. Additional experimental data at astrophysically relevant energies are required, especially for radioactive capture reactions at high mass regions (A>100). In this context, the present work reports on the measurement of the cross section of the reactions ^{58,60}Ni(α,γ)^{62,64}Zn, ^{64,66,68}Zn(α,γ)^{68,70,72}Ge, ^{102}Pd(α,γ)^{106}Cd and ^{106}Cd(α,γ)^{110}Sn.

2. Experimental Setup

The measurements reported in this work were carried out at the Dynamitron Accelerator laboratory of the University of Bochum (RUBION) by applying the γ-ray angle integrated technique developed in previous work [3]. The experimental setup consisted of a 12"×12" NaI(Tl) single-crystal of cylindrical shape with a bore hole of 35 mm along its axis. This detector covers a solid angle of almost 4π (98%) for γ-rays emitted from its center. The fluorescent light emitted from the crystal was collected by six photomultipliers. The energy resolution of the detector at 10 MeV was measured to be ~2%. The targets were mounted onto a holder made of Tantalum located at the end of the experimental line. The beam was stopping behind the targets at the end of the beam line onto a thick Au foil. The end of the beam tube served as a Faraday cup and it was electrically isolated by the collimators using ceramic insulators. In order to suppress secondary electrons a voltage of -300 V was applied on the last collimator and the charge was measured by a calibrated current integrator with an accuracy of 3%. The beam current was kept between 3.5 and 13 nA, rendering the dead time lower than 5%, and the total accumulated charge ranged from 18 to 120 μC depending on the beam energy. The targets, consisting of highly enriched material (>80%) formed in self-supporting layers of ~500 μg/cm^2, were manufactured at the University of Cologne by applying the rolling technique. Both the areal densities

of the targets as well as the enrichment of the ^{106}Cd foil were measured by means of RBS technique. The comparison of RBS spectra before and after the measurements revealed no deterioration of the targets during the experiments. The targets analysis measurements were performed at the Tandem Laboratory of INPP "Demokritos" using the corresponding RBS setup.

The working principle of the 4π γ-summing technique is based on the large volume of the detector and its long decay time (typically ~250 ns). The high detection efficiency, resulting from the large volume of the crystal, allows almost complete absorption of the emitted γ-rays, while, due to its long response time, γ-rays detected during shorter time intervals, i.e. γ-rays emitted from the same cascade, cannot be distinguished and are recorded as a single event. As a result in the collected γ spectrum, a summing peak arises at energy equal to that of the entry state. Considering a capture reaction, due to the large Q value, the resulting summing peak is located at the end of the spectrum sitting on a low background as it is shown for the case of ^{106}Cd(α,γ)^{110}Sn reaction in the spectrum given in Fig.1.

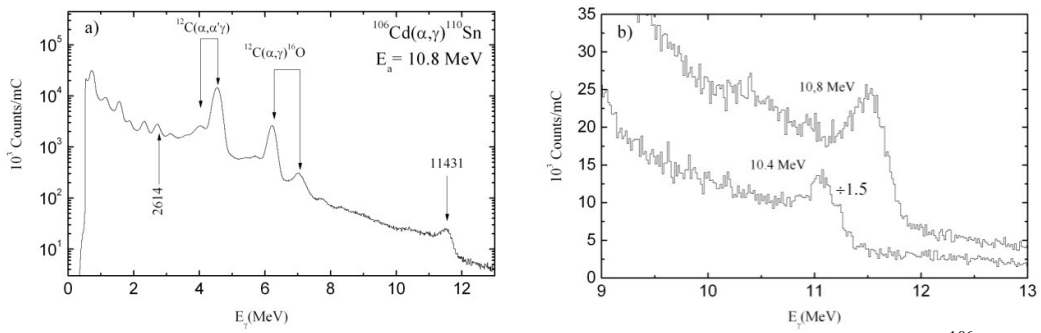

Fig 1: (a) Typical measured spectrum of 4π angle integrated γ-singles for the reaction ^{106}Cd(α,γ)^{110}Sn at $E_α$=10.8 MeV using the γ-summing NaI(Tl) crystal, (b) The same spectrum focused at the sum-peak energy range and a second one (scaled by a factor of 1.5) collected at Eα=10.4 MeV.

This spectrum contains the natural background peaks at 1461 keV and 2614 keV as well as several peaks originating from the interaction of the beam with impurities of the target, the collimator and the beam-stop. From these peaks the most prominent arise due to reactions of the beam with carbon impurities that are present in the materials and these are: 1) The peak at 4438.9 keV from ^{12}C(α,α'γ)^{12}C followed by its first escape peak at 4438.9-511.2= 3927.7 keV, 2) the peaks at 6129.9 and 6917.1 keV coming from the reactions ^{13}C(α,n)^{16}O and ^{12}C(α,γ)^{16}O, respectively.

3. Data analysis and Results

The total cross section for any reaction at specific beam energy is given as the ratio of the total reaction yield at this energy divided by the areal density of the target nuclei in the irradiated samples. Typically the areal density of the target nuclei is given in gr/cm^2 and the total reaction cross section is determined using the formula:

$$\sigma_T = \frac{A}{N_A}\frac{Y}{\xi}$$

where A is the atomic weigh of the nucleus in a.m.u, N_A is the Avogadro's number, Y the yield of the reaction and ξ the areal density of the target in gr/cm^2. Employing the 4π γ-summing technique the total reaction yield is deduced from:

$$Y = \frac{I_\Sigma}{N_b \varepsilon_\Sigma}$$

where $I_Σ$ is the intensity of the summing peak obtained for a number of N_b beam particles and $ε_Σ$ is the summing peak efficiency. The efficiency of the summing peak depends strongly not only on the geometry of the measurement and the energy of the entry state of the produced nuclei but also on the average multiplicities of the γ cascades de-exciting the entry state. A systematic study of the used NaI(Tl) crystal in previous works lead to the development of a new method for the determination of the summing peak efficiency. The method is described in detail in [3,4] and is realized in two steps. Firstly an experimental procedure is employed in order to obtain the average multiplicity of the γ cascades summed by the NaI(Tl) crystal and then the sum-peak efficiency is determined by means of

Monte Carlo simulations using GEANT4. By applying this method the efficiency for the ^{60}Ni(α,γ)^{64}Zn, ^{64,66}Zn(α,γ)^{68,70}Ge reactions was obtained. The total sum-peak efficiencies determined in the present work along with the efficiencies of several capture reactions measured in a systematic study of the crystal is presented in Fig.2. From this diagram it can be observed that the data points can be grouped into three classes corresponding to even-even, even-odd or odd-odd compound nucleus formed by the reaction. The dependence of the total summing efficiency by the energy of the sum-peak is described by the following function

$$\varepsilon_{\Sigma} = \varepsilon_0 + \alpha e^{\frac{-E_{\Sigma}}{\beta}}$$

where E_Σ is the sum-peak energy and the values of the parameters ε_0, α and β are determined by fitting each class of experimental data with the above function. The total efficiencies for the reactions studied in the present work ranged between 6.8% ± 1.2% and 26.9% ± 5.4%.

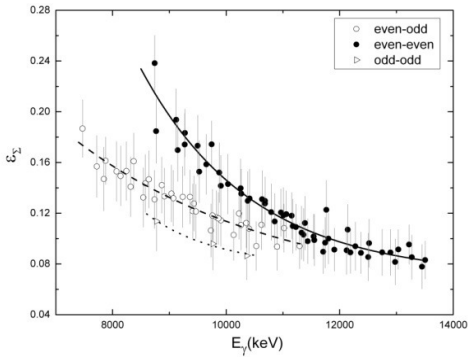

Fig 2: Sum-peak efficiencies determined by a systematic study using the method described in [3,4] for several capture reactions. The continuous lines correspond to fits of the exponential function, see text for more details, according to the type (even-even, even-odd or odd-odd) of the formed compound nucleus.

For nuclear reactions studied in the laboratory the Coulomb repulsion between the incident beam particles and the target nucleus is suppressed due to electron-screening effect leading to an enhancement of the corresponding cross sections. This increase is calculated by applying the electron screening factor given in [5]

$$f(E) = \frac{E}{E + U_S} \times exp\left[\frac{\pi\eta(E) \times U_S}{E}\right]$$

where η(E) is the Sommerfeld parameter, E is the center-of-mass energy and U_S is the electron screening potential. The latter is obtained by scaling the observed screening energy of the d+d system, measured as 300 eV [5], according to the charge of the target, Z_1, and the beam, Z_2, and is given by U_S=300Z_1Z_2 keV. The screening correction factor f(E) ranged from 1.032 to 1.106 for the reactions reported in this work.

In the present work the cross sections of the ^{58,60}Ni(α,γ)^{62,64}Zn, ^{64,66,68}Zn(α,γ)^{68,70,72}Ge, ^{102}Pd(α,γ)^{106}Cd and ^{106}Cd(α,γ)^{110}Sn reactions were measured for center of mass beam energies in the range 4.41-10.50 MeV. These energies correspond to an energy region within the Gamow Window of the aforementioned reactions, extending to energies between 3.18 and 10.73 MeV. The obtained cross sections for the case of the reaction ^{58}Ni(α,γ)^{62}Zn are plotted in Fig.3 (black circles). Also in this plot data obtained from previous work [6] are included. Apart from experimental data HF cross sections calculated with the nuclear reaction code TALYS [7] are also presented for comparison. In TALYS different models can be used to obtain Nuclear Level Densities, γ-ray Strength Functions, nucleon-nucleus Optical Potential as well as alpha particle-nucleus Optical Potential. Aiming at testing the sensitivity of alpha particle capture reactions cross sections to those models a systematic study was carried out. For this study all models available in TALYS were considered. The shaded area in Fig.3 corresponds to the range of all calculations. In addition, in these figures a specific microscopic combination is plotted with a solid line, the combination with JLM-B n-OMP, OMP-III a-OMP, HFBCS/QRPA γSF, HFBCS NLDs. Considering beam energies lower than the (α,n) threshold it was observed that the data obtained in the present work are well within the range of the predictions using the OMP-III of [8] as α-OMP, while the calculations performed by considering the rest models for the α-OMP overestimate the cross sections.

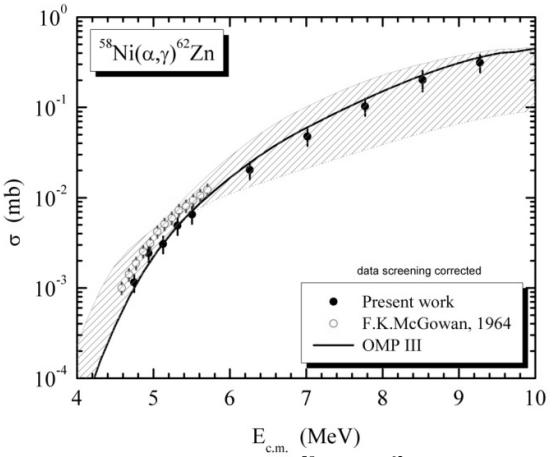

Fig 3: Comparison of experimental data of the reaction ^{58}Ni(α,γ)^{62}Zn obtained from the present work (solid circles). The cross sections obtained from [6] are denoted with open circles while the curve and the shaded area correspond to theoretical predictions calculated using the TALYS code, see text for more details.

The predictions at higher energies, where the neutron emission channel is open, depend on all nuclear parameters entering HF formula and several models combinations spread within the data range. However, considering the data over the entire range of measurements for all the reactions studied in the present work, it was found that the aforementioned microscopic combination could reproduce the majority of the data fairly well.

4. Conclusions

In the present work the cross section of alpha capture reactions in Ni-Cd region were measured at energies ranging from 4.41 to 10.50 MeV. The obtained data were compared with cross sections calculated by the HF theory, using the most updated version of the nuclear reaction code TALYS. Aiming to test the sensitivity of the predictions to the nuclear parameters entering HF calculations, all available models were taken into account for the nucleon-nucleus OMP, the α-OMP, the NLDs and the γSFs. The results showed that at energies lower than the neutron threshold the cross sections are mostly sensitive to the α-OMP, with the dispersive semi-microscopic OMP-III describing the data fairly well while the rest α-OMPs tend to overestimate them. At higher energies it was shown that the calculations show strong dependence on the NLDs and γSFs as well. According to the findings of this work the semi-microscopic OMP-III can successfully reproduce the experimental data, however additional experimental data, in particular of capture reactions extending at higher mass regions (A>100), are needed so as to compare the predictions of the model and test if it is trustworthy to extend the calculations at regions where there are no data available.

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