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α-INDUCED CROSS SECTIONS OF ^{63}CU FOR ASTROPHYSICAL P PROCESS

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Abstract. We have studied the ^{63}Cu$(\alpha,\gamma)^{67}$Ga reaction in the 4.5-to 5.8 Mev energy range. For this kind of experiment we created three types of experimental setup for measuring the total cross sections and the experimental astrophysical factor that can be compared with the theoretical results from NON-SMOKER code.

We emphasized that besides the previously used (p,γ) and (α,γ) reactions we can also use other types of reactions, mainly (α,n) and (α,p). Most crucial, also for this kind of reaction are the preparation and the characterization of the target. The subsequent γ counting reqires carefully calibrated detectors.

Key words: s, r and p nuclei, seed abundance distribution, associated section rates, α-photodisosiation.

1. INTRODUCTION

Stable heavy isotopes above iron (Z > 26) can be classified into three categories s, r, and p nuclei. The s nuclei are locatated along the valley of stability, whereas the r and p nuclei can be found on the neutron-rich and proton-rich sides of the valley, respectively. The names refer to the production process synthesizing the corresponding isotopes. The s-process isotopes are produced by the s (slow) neutron capture process in stellar helium-and carbon-burning environment with steady neutron production through the ^{13}C, ^{17}O and ^{22}Ne (α,n) reactions. The r isotopes are produced by the r (rapid) neutron capture process that takes place in explosive stellar environment providing a high neutron flux. For the production of a number of isotopes located along the valley of stability both the s and r process have their contribution. The p nuclei, however, cannot be produced by neutron capture reaction. Their production mechanism, the p-process, has been identified as a sequence of photodisintegration process in a high γ-flux scenario. The initial abundance distribution of s and r nuclei at the p-process site is covered by subsequent (γ,n) reactions towards the neutron- deficient region. As the neutron threshold increases,competing (γ, α) and (γ,p) photodisintegration process branch the reaction flow toward lower mass regions. The final p-nuclei abundance distribution depends critically on the seed abundance distribution as well as on the reaction flow, which is determined by the associated reaction rates and reaction branchings.

The nuclear synthesis of p type nuclei is a process defined in nuclear astrophysics as a p process [1, 2]. This process consists of different nuclear synthesis scenarios, in which each p type nucleus is preceded by a (γ,n), (γ,p) or (γ, α) reaction. (p,γ), (α, γ), (p,nγ) and (α,nγ) reaction may be present in some of these scenarios. There are 32 stable p type nuclei, heavier than iron and we can find them between ^{74}Se and ^{136}Hg (Fig. 1).

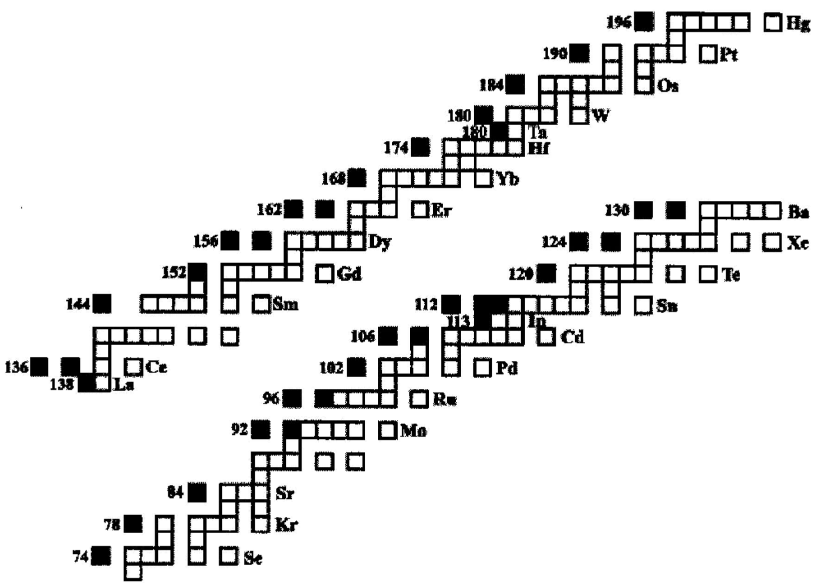

Fig. 1 – Chart of the p-nuclei (black rectangles).

One of the major enigmas of all the nuclear synthesis p process models is the abundance prediction of p type nuclei. At the present time, it is well known that the nuclear synthesis models are capable of reproducing the p-nuclei within a factor of three [3, 4]. These discrepancies exists due to uncertainties in the astrophysical side of modeling the p process or can result from uncertainties of the input side of nuclear physics, used in abundance calculation. We have to say that the capture cross section measurements are still rare due to measurements difficulties. If we refer to (p,γ) and (α, γ) measurements for nuclei having $A > 90$, we have to underline that they have to be done using energies smaller than 2 MeV for protons and 8 MeV for alpha particles, that is, in a region in which the reaction cross section becomes extremely small. In this case, the beam intensities have to be in the micro ampere range and the irradiation time has to be in the few hours range. In conceiving and building an experimental setup for measuring the total capture cross section for protons, which may take into account the previous difficulties, one has to respect three important aspects: a) study such experimental setups used at this moment in other laboratories, b) select and test the equipment that our group owns and which can be assembled in an experimental setup having optimum parameters and c) finish building the experiment setup which may be tested and used in our group projects regarding nuclear astrophysics. In the next chapter we will describe the most commonly used setups.

2. EXPERIMENTAL SETUP AND PROCEDURES

a) The first experimental setup and the entire experimental process is presented in S. Harissopulos article [5]. The article describes the proton capture cross-section. This can be realized in satisfactory conditions, if the calibration and the efficiency are well known. For the ^{63}Cu case, the calibration and the efficiency calculation, to which we can add a precise knowledge of the target thickness, are crucial for calculating the total reaction cross section:

$$\sigma_T = A_0 \frac{A}{N_A} \frac{1}{\varepsilon}, \tag{1}$$

where A is the atomic mass of the target, N_A Avogadro number and ε is the mass of the used target. We understand why in all total cross-section measurements one has to measure the thickness of the target before, during and after experiment was done by different means. Regarding to the A_0 value, this can be obtained from the experimental angular distribution or from the excitation function to the 55 degrees angle.

Based on the total experimental cross section values, one can calculate the astrophysical factors S, using the following equation:

$$S(E) = \sigma_T(E) E e^{2\pi\eta}, \tag{2}$$

where η is the Sommerfeld parameter, σ_T the total reaction cross section in the center mass. These values are compared with those obtained by calculation using NONSMOKER code [6].

b) Another studied experimental setup is shown in Fig. 2 similar to that used by P. Tsagari [7]. As can be seen, the NaI(Tl) detectors are different from those in the previous paragraph. We have to say that we already tested such type of detectors and they can function in optimum condition. We have in our department 4π NaI(TI) detectors with dimensions around 12 in by 12 in. We prepared this type of experimental setup for the case in which we can not succeed in obtaining proton or alpha particle with the desired intensity.

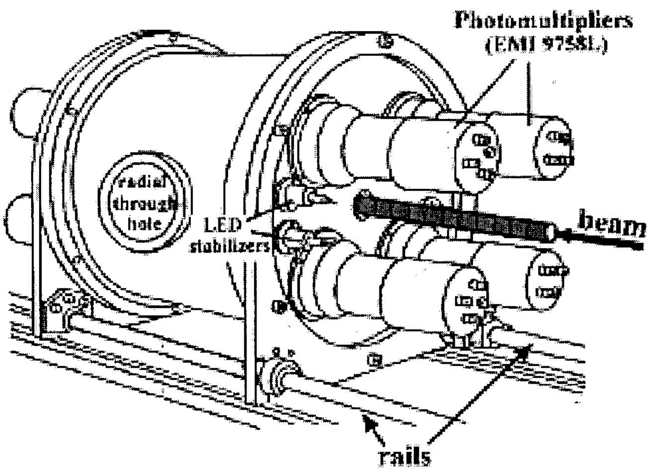

Fig. 2 – Side view of the 4π NaI (Tl) summing detector.

c) The third method we take into account is that of activating the targets, method recently introduced in nuclear astrophysics. This method uses the (n,γ),(p,γ) and (α, γ) type of reactions for studing the p process. For the capture reactions, the resulting gamma radiation observation became a standard technique due to the excellent resolution and efficiency of high purity germanium detectors. This technique has a great advantage. It allows us to use targets with many isotopes, those being easy to produce. This is the case of the (p,γ) reaction, used for simultaneously measurement of ^{92}Mo, ^{94}Mo, ^{95}Mo and ^{96}Mo. It is also possible to measure the partial cross section for the long lived isomers, having lifetimes longer than the time scale for the p processes. In those cases, the fundamental state and the isomeric state can be considered in the reaction network as different species. A sketch is shown in Fig. 3.

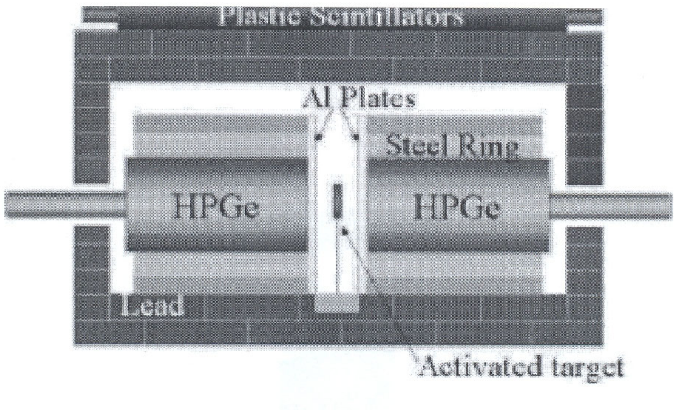

Fig. 3 – A schematic diagram of the counting setup for activation measurements.

As a conclusion, we consider that we created three types of experimental setups for measuring the total cross sections and the experimental astrophysical factors that can be compared with the results from NONSMOKER calculation code. Before getting to the next chapter we have to emphasize that besides the previously mentioned (p,γ) and (α,γ) reactions, one can also use other types of reactions, mainly (α,n) and (α,p) type. These last examples provide useful information for nuclear astrophysics [8].

3. TARGET PREPARATION AND IRRADIATION

Natural Cu foils of thickness $\sim$1 mg/cm^2 used in this experiment were produced at Legnaro Laboratory. The foils were floated on water from glass slides and mounted on circular aluminium holders. Two stocks of targets, each having four nat Cu and one nat Ti foil of thickness 3 mg/cm^2 were prepared. The target stock was mounted on a thick water-cooled copper support. One stock was irradiated for 6 h with 6 MeV beam energy and 0.1 μA current of NIPNE accelerator. The uncertainity in the beam energy was about 1%. The incident α beam energy on the successive foil was calculated based energy loss through Cu foil using dE/dx values estimated using the TRIM (the transport of ions in matter) code. In average, the loss for Cu foil was about 350 keV. The titanium foil, at the end of each stock was used for beam current calibration using ^{48}Ti(α,n)^{51}Cr reaction and for catching the recoil ^{67}Ga radioisotopes from the preceding copper foil to estimate the recoiled fraction.

The target chamber was designed as a Faraday cup to ensure the accurate registration of the beam current (Fig. 4). The emission of secondary electrons

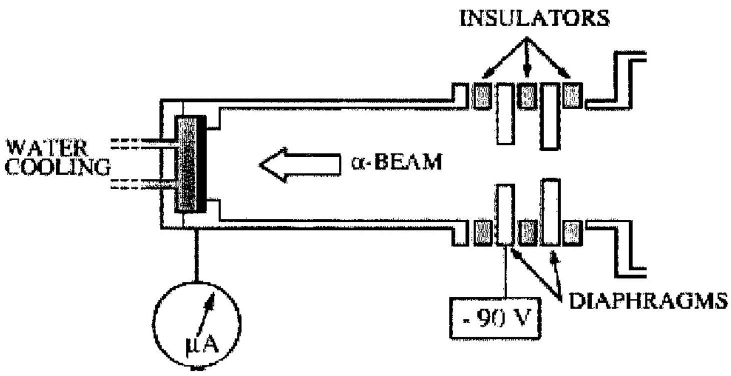

Fig. 4 – Activation scheme of the NIPNE accelerator.

from target was suppressed by a bias voltage of −90 V. The activity measurements were carried out with HPGe detector to measure the ^{65}Cu(α,n)^{68}Ga reaction. All the copper foil were later recounted for lower periods of time to measure the ^{67}Ga activity using another HPGe detector, 65% relative efficiency. In both experiments, the induce activities were counted off-line with calibrated high purity germanium detectors. Because of the rather small induced activities, a close counting geometry had to be chosen. In order to determine the counting efficiency, in close geometry and to assess the sensitivity of sample detector position the setup was simulated with the GEANT 3.1 package. The studies led us to chose a distance of 11 mm between sample and the entrance window of HPGe detector. The detector efficiencies were mea-

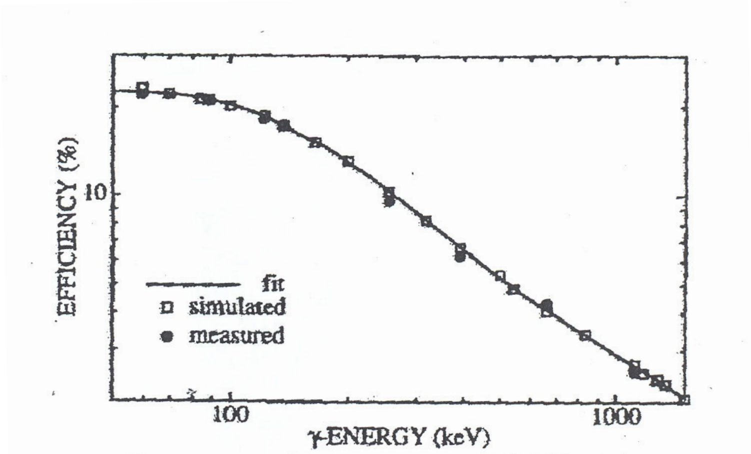

Fig. 5 – The absolute efficiency of the 263 cm^3 HPGe detector was measured with calibration sources (black circles). These values were compared by GEANT simulations (open squares), which were found in a good agreement with the experimental results.

sured with weak γ sources in order to minimize corrections for pile up and dead time. The measurements were carried by using single line decay, i.e., ^{241}Am (59.5 keV), ^{137}Cs (661.7 keV) as well as 8 cascades from ^{57}Co (122.1-136.5 keV). As shown in Fig. 5 for the large HPGe detector, absolute efficiencies between 2% and 20% could be achieved in the relevant energy range.

4. THEORETICAL CALCULATIONS

The prediction of total reaction cross-section and the S factor from the NONSMOKER model, as we previously stated encorged us by its promising results in using the (α,n) and (α,p) reaction for obtaining astrophysical information [7]. In Fig. 6 we show the cross section variation as a function of E_{CM} (MeV) for the energy range $4.0 < E_{CM} < 7$. One can find out that for

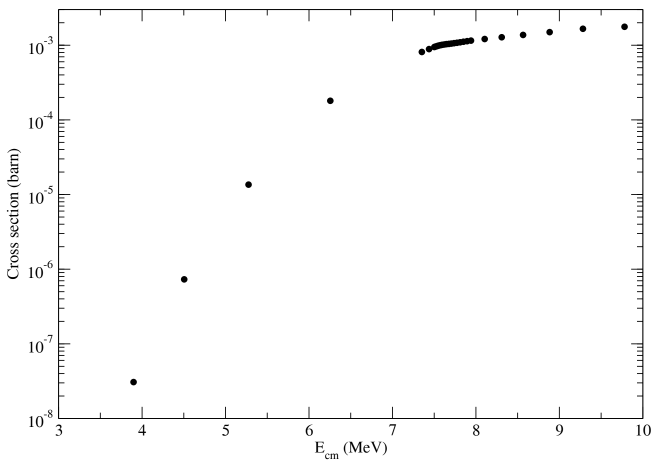

Fig. 6 – The cross section in barn as a funcion of E_{CM}(MeV).

this energy interval σ varies from 10^{-8} to 10^{-3} barns, that is by more than 5 orders of magnitude. This brings out the difficulty in doing such sort of experiments interesting from the astrophysical point of view. This difficulty is even more obvious in the fact that for only 2 MeV (from 4 MeV to 6 MeV) variation for E_{CM} a 5 order magnitude change of the total reaction cross section is registered (from 10^{-8} to 10^{-4} barn). From these difficulties it results out constant effort to obtain higher intensity proton and alpha particle beams for maintaining the irradiation time within reasonable limits (tenths of hours of irradiating the target). In Fig. 7 we present the s astrophysical factor variation.

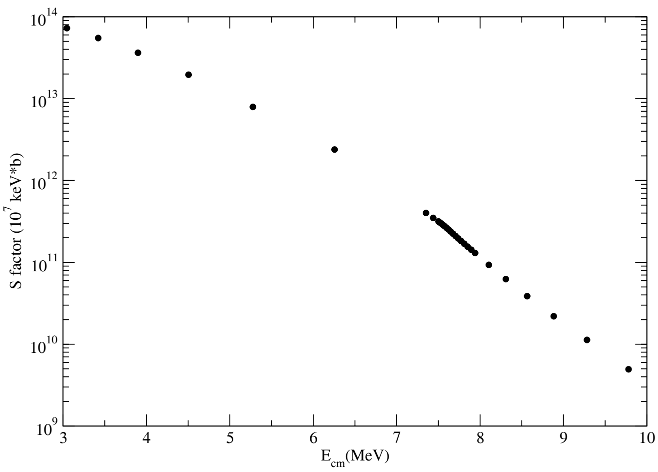

Fig. 7 – The astrophysical factor S (10^9 keV $\times b$) variation as a function of the center of mass energy.

5. CONCLUSIONS

In this work the activation technique was shown to represent an efficient tool for the reliable determination of (p,γ), (α,γ) and (α,nγ) cross section for p-process studies. Though mostly restricted to measurements on stable target nuclei, this method offers the possibility to establish an extended set of data for testing and normalizing the parameter systematic for Hauser-Feshbach interpolation to the actual network of the p process. Despite its formal simplicity, measurements with the activation technique require great care in technical detail if its full potential is to be exploited. Most crucial in this respect is the preparation and characterization of targets, but also monitoring of the proton yield and the target performance through the irradiation are important. The subsequent γ counting requires carefully calibrated detectors, including the verification of count rate correction due to cascade effect and/or coincident observations of the related γ-rays.The cross section are determined with uncertainties of a few percent if this precaution are considered.

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