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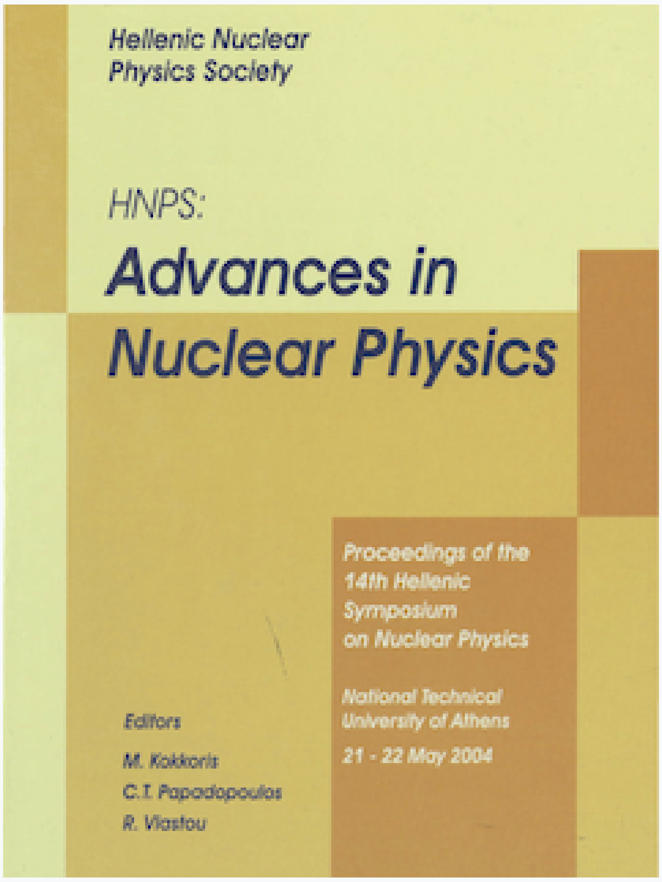

Proton-capture Reaction Cross Sections on the Sr Isotopes Relevant to the p-process Nucleosynthesis

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Proton-capture Reaction Cross Sections on the Sr Isotopes Relevant to the p-process Nucleosynthesis

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Abstract

Proton-capture reaction cross sections on the ^{86,87,88}Sr isotopes have been determined at energies from 1.4 to 5 MeV by measuring γ-angular distributions at the 4 MV single-ended Dynamitron accelerator of the University of Stuttgart as well as at the 5 MV VdG Tandem accelerator of NCSR "Demokritos", Athens. In the former case an array of 4 HPGe detectors with relative efficiency $\varepsilon_r \approx 100\%$, each shielded with BGO crystals, were used. In the case of the measurements carried out at "Demokritos" we used only one HPGe detector ($\varepsilon_r \approx 80\%$) with no BGO shield. Cross sections ranging from 0.5 μb to 5 mb as well as the relevant S factors were obtained. The data were compared with statistical model calculations using the code MOST. In the calculations, various combinations of microscopic and phenomenological models of the nucleon-Nucleus Optical Model Potentials (OMP) and Nuclear Level Densities (NLD) were used and a good agreement between the data and theoretical predictions was found.

1 Introduction

Statistical model calculations based on the Hauser-Feshbach (HF) theory are used almost exclusively to provide cross sections for the reactions involved in astrophysical abundance calculations of various p-process nucleosynthesis

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models [1]. These models aim at reproducing the solar system abundances of the so called p nuclei, i.e., a class of 35 stable nuclei heavier than iron which cannot be produced via the s or the r process [2]. Instead, p nuclei are produced via neutron, proton or alpha-particle photodisintegrations as well as via proton capture reactions at explosive stellar sites under certain temperature and density conditions [1]. The reproduction of the p-nuclei abundances is one of the major puzzles of all models of p-process nucleosynthesis. So far, all p-process models have been successful in reproducing the abundances of a variety of p nuclei within a factor of 3, but they fail in the case of light p nuclei, for which significant discrepances are observed. Thus, it is of major importance, independently of any improvements in the modelling of the p process, to investigate the reliability of the nuclear physics properties entering the HF calculations. These refer mainly to the Nucleon-Nucleus and α-particle-Nucleus Optical Model Potentials (OMPs) as well as to the Nuclear Level Densities (NLDs). For this purpose, systematic cross section measurements of proton and α-particle capture reactions were carried out by the Nuclear Astrophysics Group of NCSR "Demokritos" during the last five years. In this report we present the results of the (p,γ) cross section measurements in the ^{86,87,88}Sr isotopes.

2 Experimental procedures

The measurements have been performed at the 4 MV single-ended Dynamitron accelerator of the University of Stuttgart as well as at the 5 MV Tandem accelerator of NCSR "Demokritos", Athens, at proton beam energies ranging from 1.4 to 5 MeV. This energy region is relevant to p-process studies. The targets used in the measurements were isotopically enriched and they have been produced by evaporating the target material ($^{86}SrCO_3$, $^{87}SrCO_3$ and $^{88}Sr(NO_3)_2$) on 0.4 mm thick Ta backings which were cooled with water during all runs. The thickness ξ, of the targets employed was determined by means of the XRF technique and they are given in table 1.

Table 1
Thickness ξ of Sr targets measured via the XRF technique.

Reaction	Target material	Enrichment (%)	ξ(Sr) (μg /cm^2)
^{88}Sr(p,γ)^{89}Y	$^{88}Sr(NO_3)_2$	99.84	168 $\pm$ 12
^{87}Sr(p,γ)^{88}Y	$^{87}SrCO_3$	91.55	80 $\pm$ 5
^{86}Sr(p,γ)^{87}Y	$^{86}SrCO_3$	96.89	103 $\pm$ 6

In the Stuttgart runs, the current of the proton beam was ranging from 5 to 10 μA (on target) whereas in the measurements carried out in Athens it was between 1 and 2 μA. The setup used in Stuttgart [3] consisted of 4 HPGe detectors with relative efficiency $\varepsilon_r \approx 100\%$ all shielded with BGO crystals for Compton background suppression. The detectors were placed at a rotating table at distances between 10 and 20 cm from the target as shown in Fig. 1.

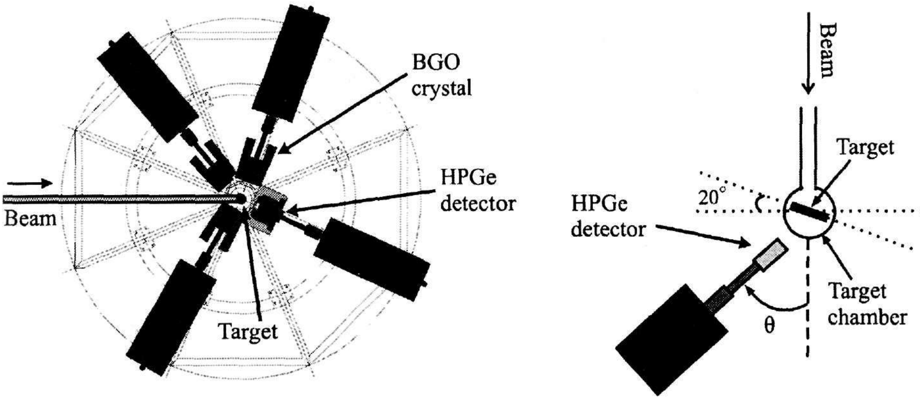

Fig. 1. Left: The experimental setup used at the IfS of the University of Stuttgart [3]. Right: The experimental setup used at NCSR "Demokritos".

By rotating the table by 15°, γ-singles spectra were measured at 8 angles with respect to the beam direction. This way, the angular distributions of the γ rays of interest were determined. The setup used in Athens consisted of one HPGe detector of relative efficiency $\varepsilon_r \approx 80\%$ with no BGO shields. The detector was placed on a goniometric table that could rotate around the target. A typical spectrum of the ^{88}Sr(p,γ)^{89}Y reaction is shown in Fig. 2.

3 Data analysis and results

In order to determine the cross section of a reaction of interest the angular distributions of all the γ-transitions feeding the ground state of the produced nuclei have to be measured. For this purpose γ spectra were measured at 8 different angles. From these spectra, the intensities of the γ transitions mentioned above have been derived. These intensities have been subsequently normalized to the number of the incident beam particles and have been corrected for the corresponding detector efficiency. This procedure has been repeated at each beam energy measured. This way, γ-angular distributions of all transitions of interest have been derived. Typical angular distributions measured in the present work are shown in Fig. 3. In order to obtain the total number of the photons emitted by the reaction of interest, the angular distribution of each γ transition feeding the ground state was fitted by Legendre polynomials of

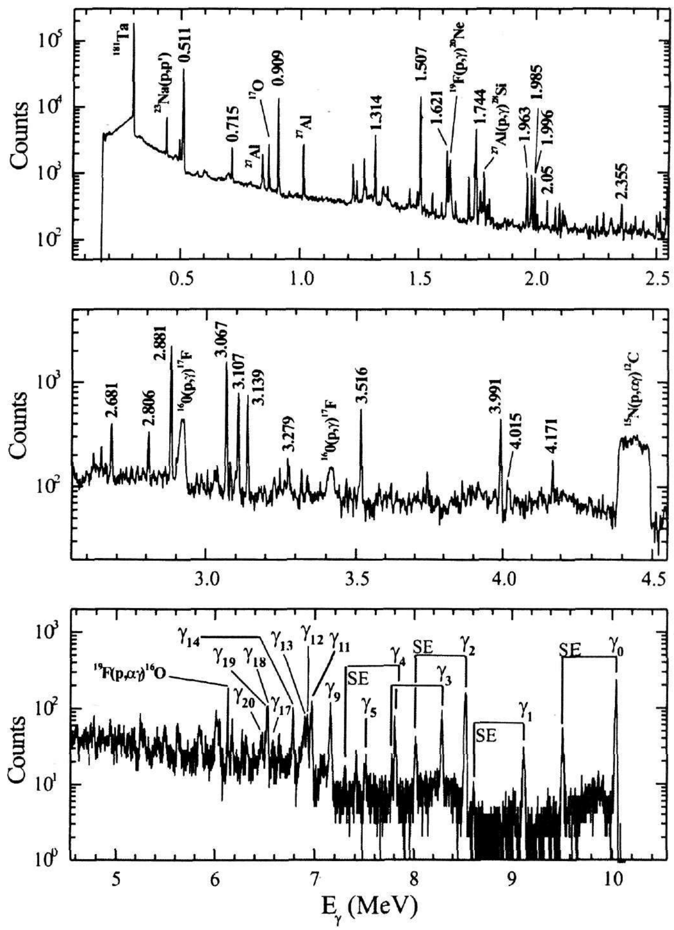

Fig. 2. Typical spectrum of the ^{88}Sr(p,γ)^{89}Y reaction taken at the energy of 3 MeV, at 90° with respect to the beam direction. The γ transitions relevant to the determination of the cross section are labeled by their energy. In addition to these the γ_0 transition at $\approx$ 10 MeV was taken also into account.

proper order using the expression,

$$W(\theta) = A_0(1 + \alpha_2 P_2(\cos\theta) + \alpha_4 P_4(\cos\theta)) \ . \tag{1}$$

From this fitting procedure we obtained for each relevant γ transition the corresponding A_0 coefficient in order to derive the cross section using the equation

$$\sigma_T = \frac{A}{N_A}\frac{1}{\xi}\sum_i A_0^i \ , \tag{2}$$

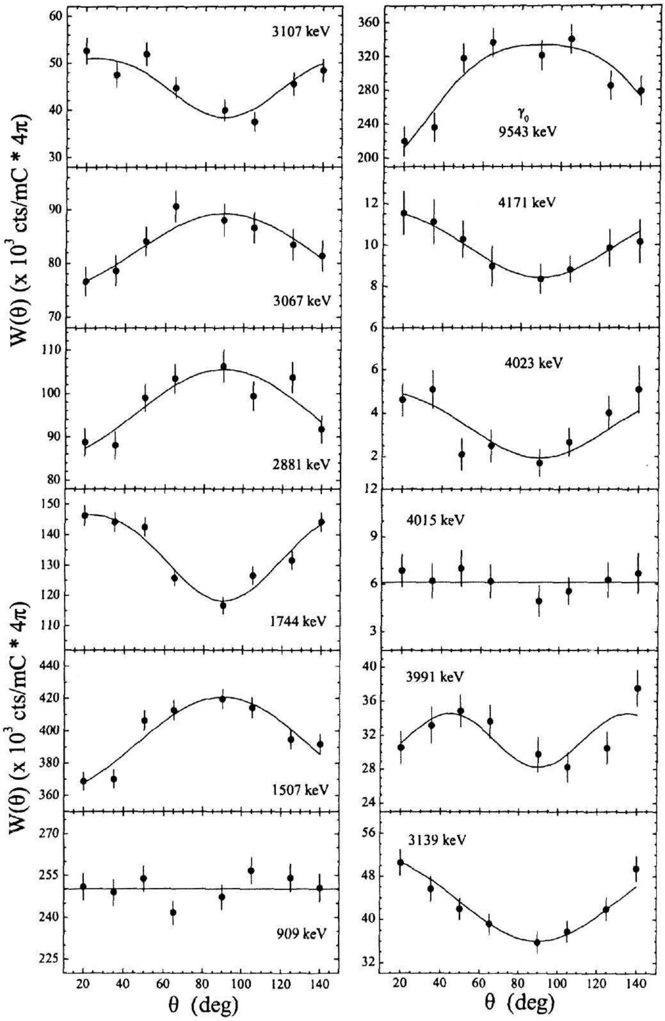

Fig. 3. Angular distributions of the 12 γ transitions observed to contibute to the cross section of the $^{88}Sr(p,\gamma)^{89}Y$ reaction at the proton energy of 2.5 MeV.

where, index i runs for all γ transitions feeding the ground state, A is the atomic weight of the target nucleus, N_A is the Avogadros's number and ξ is the Sr thickness in the target. The reaction cross sections σ_T were then transformed to the corresponding astrophysical S factors via the relation

$$S(E) = \sigma_T(E) \cdot E \cdot e^{2\pi\eta} , \tag{3}$$

where η is the so called Sommerfeld parameter and $\sigma_T(E)$ is the reaction cross section at the center of mass energy E. In fig. 4 the S factors of all reactions studied are plotted.

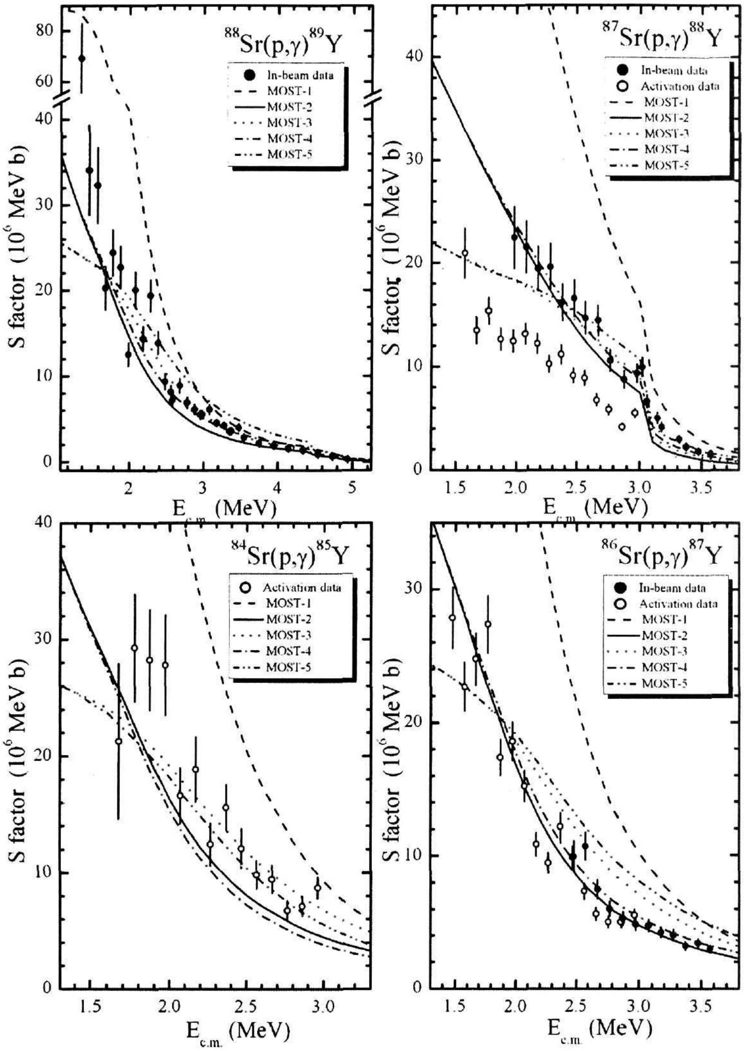

Fig. 4. S factors of the proton capture reactions on Sr isotopes at energies relevant to p process. The data obtained in the present work are shown as solid circles whereas those with open circles are activation data taken from [4]. The statistical model calculations performed using different combinations of OMPs and NLDs are indicated by curves.

4 Discussion

In the present work the cross sections of $^{86,87,88}\mathrm{Sr}(\mathrm{p},\gamma)^{87,88,89}\mathrm{Y}$ reactions were measured at energies relevant to the p-process nucleosynthesis. These reactions proceed through the formation and decay of a compound nucleus system. The evaporation of a compound nucleus mainly depends on the transmission coef-

ficients and the NLDs of the rediual nuclei. The transmission coefficients for particle emission are calculated from appropriate OMPs, whereas the transmission coefficients for γ-ray emission are calculated from the γ-ray strength functions assuming the dominance of dipole transitions according to [5]. The transmission coefficients for particle emission as well as the NLDs were derived from phenomenological or microscopic models. In our work the data are compared with the HF calculations performed with the code MOST [6]. Hereby, different combinations of OMPs and NLDs were applied, which are labeled as MOST-1,2,3,4,5. MOST-1,2,3 are respectively the combinations of the microscopic NLD of Demetriou and Goriely [7] with the phenomenological OMP of Bauge *et al.* [8], the microscopic one of Jeukkene *et al.* [9] and the phenomenological one of Koning *et al.* [10]. The two remaining calculations, MOST-4 and MOST-5 are the combinations of the phenomenological NLD of Thielemann *et al.* [11] with the microscopic OMPs of Jeukkene *et al.* [9] and Koning *et al.* [10].
In Fig. 4 the Hauser-Feshbach (HF) calculations of the S factors are compared with the data of each reaction studied. From this comparison one can conclude that the HF calculations obtained using the microscopic OMP of Jeukenne, Lejeunne, and Mahaux [9] in combination with the microscopic NLD of Demetriou and Goriely [7] or the phenomenological of Thielemann, Arnould, and Truran [11] seem to give the best description of the data over the whole energy range. Thus, they can be considered as suitable for HF calculations at low energies. On the other hand the phenomenological OMP of Koning and Delaroche [10] in combination with either the microscopic NLD of Demetriou and Goriely [7] or the phenomenological of Thielemann, Arnould, and Truran [11] seem not to have the energy dependence shown by the data. The HF predictions obtained by the semi-microscopic OMP of Bauge, Girod, and Delaroche [8] together with the microscopic NLD of Demetriou and Goriely [7] overestimate the data by a factor ≈ 2 for all reactions studied. These findings are in agreement with those derived by other (p,γ) cross section measurements performed on other nuclei in the same mass region.

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