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ScienceDirect
Nuclear Data Sheets 119 (2014) 245–248
Nuclear Data Sheets
www.elsevier.com/locate/nds

Absolute Cross Sections for Proton Induced Reactions on ^{147,149}Sm Below the Coulomb Barrier

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Cross sections for ^{147,149}Sm(p,n)^{147,149}Eu and ^{147,149}Sm(p,γ)^{148,150}Eu were measured using the activation method. The results are compared to the predictions of the Hauser-Feshbach statistical model. Different γ-ray strength functions have been tested against the experimental values. In the case of ^{150}Eu, in order to reproduce the experimental isomeric population cross sections, various scenarios for unknown branching ratios of certain discrete states have been discussed. The results provide constraints for the optical model parameters dedicated to this insufficiently known area of isotopes. Such cross sections for (p,γ) reactions at energies below the Coulomb barrier are valuable for *p*-process nucleosynthesis calculations.

I. INTRODUCTION

The astrophysical *p*-process essentially involves the transformation of pre-existing stable nuclei located at the bottom of the valley of nuclear stability - *s* nuclei - and those located on the neutron-rich side of the valley - *r* nuclei - into proton rich species by series of (γ,n), (γ,p), (γ,α) photodisintegrations and beta decays [1]. Cross sections for reactions relevant to the *p*-process are generally calculated using optical model potentials (OMPs) for the direct interaction and the Hauser-Feshbach statistical model for describing the compound nucleus mechanism.

Cross section measurements on proton and α captures by targets above Z=50 at sub-Coulomb energies are needed to provide reliable predictions on photodisintegrations rates of stable and unstable proton rich elements. Experimental data on such reactions are scarce and difficult to measure due to their small reaction cross sections. In the rare earth region and particularly for the Samarium isotopes, there are insufficient experimental data.

The Samarium region presents a large family of stable isotopes suited to an extended experimental study of charged particle induced reactions. A particular interest should be paid to proton induced reactions, as the beta active ^{142}Sm has been considered to be a (γ,n)/(γ,p) branching point inside the Sm isotopic chain for the *p*-process [2].

Proton differential elastic scattering measurements performed on seven Sm isotopes [3–5] provide an experimental basis for constraining OMPs but, up to now, there are not enough experimental data on reaction cross sections to test the statistical model calculations for the stable Sm isotopes, therefore predictions for unstable species like ^{142}Sm are uncertain. The study performed by Katoh [6, 7] on the (p,n) and (p,2n) reactions on ^{147}Sm provides the only two sets of data on such cross section measurements.

Recently, we measured proton induced reaction cross sections for ^{147,149}Sm by the activation method [8] at energy values below the Coulomb barrier. We obtained the absolute cross section for the ^{147}Sm(p,n)^{147}Eu and ^{149}Sm(p,n)^{149}Eu reactions and the combined cross section of the ^{147,149}Sm(p,γ)^{148,150}Eu and ^{148,150}Sm(p,n)^{148,150}Eu reactions at four incident energy values between 3.6 and 8.6 MeV. The present article provides an extended set of experimental results and an improved data analysis method which includes γ-ray summing corrections.

II. EXPERIMENTAL PROCEDURE

The activation method involves the irradiation of the selected targets and the off beam measurement of the induced activity of the reaction products. The data anal-

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http://dx.doi.org/10.1016/j.nds.2014.08.067
0090-3752/

ysis method and the experimental procedure are found in Ref. [9, 10]. We will only mention that for obtaining the reaction cross section one must know the incident proton flux, the number of target particles and the activity of the reaction products.

We irradiated stacks of thin metallic self-supporting highly enriched (approx. 95%) ^{147}Sm and ^{149}Sm targets with proton beams delivered by the TANDEM accelerator at IFIN - HH. A Faraday cup was used for current integrations. Each foil stack contained two Sm targets alternating with two Al foils and, in the back, a Cu and a Ta foil. The Al foils acted as recoil nuclei catchers and energy degraders. The ^{nat}Cu(p,x)^{63}Zn and ^{nat}Cu(p,x)^{65}Zn monitor reactions [11] were used for beam renormalization. The target thicknesses were measured by α transmission, using a mixed ^{241}Am - ^{244}Cm source.

The activity of each reaction product was measured in close geometry with a pair of large volume HPGe detectors of 55% relative efficiency each. The population of the reaction products was determined using the strongest γ-ray transitions from their subsequent decays.

Coincidence summing effects needed to be considered due to the fact that the γ-ray spectroscopy measurements were performed with high efficiency HPGe detectors in close geometry on nuclei which decay through fast γ-ray cascades. Corrections were applied to the intensity of the measured γ-ray transitions from the subsequent decays of the calibration sources and the reaction products. The GESPECOR [12] code was used to perform Monte Carlo simulations on the photon transport using as input the geometry of the detection setup including the HPGe detectors and the measured decay schemes. Fig. 1 shows a comparison between two efficiency calibrations performed with and without summing correction for the same detector. The corrected values present much lower variations as function of energy.

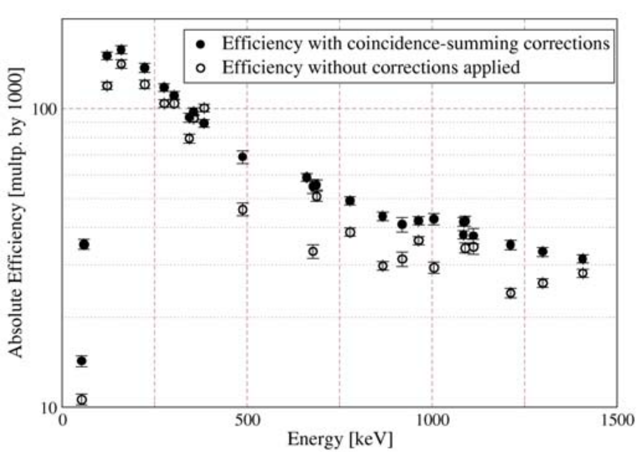

FIG. 1. Efficiency measurements for a HPGe detector using ^{133}Ba, ^{137}Cs, ^{152}Eu and ^{241}Am standard calibration sources.

The uncertainty for the measured cross section is determined by the uncertainty of γ detection efficiency, the target thickness, the intensity of γ transitions and the statistical contribution.

III. REACTION MODELING

Cross sections of the reactions induced by protons on ^{147,149}Sm targets have been calculated with the modular system EMPIRE 3.1 Rivoli [13]. The optical model calculations of the direct cross section and particle transmission coefficients were performed with the ECIS06 code incorporated into the EMPIRE 3.1 system. Pre-equilibrium emission was taken into account by module PCROSS featuring one-component exciton model with gamma, nucleon and cluster emissions. The compound nucleus mechanism was described by Hauser-Feshbach statistical model.

We tested the Koning and Morillon regional OMPs for protons and neutrons (RIPL 5405/2405 and 5410/2410 [14]). The nuclear level densities were calculated with the Enhanced Generalized Superfluid Model (EGSM) [13]. The parametrization of Gamma Ray Strength Functions (GSF) is particularly important for the study of capture reactions, especially at excitation energies where γ-ray emission is in strong competition with the other open decay channels. Thus we tested three closed expression GSFs, namely Enhanced Generalized Gamma Lorentian (EGLO), Modified Lorentian (MLO) and Standard Lorentian (SLO). Additional required input parameters were retrieved from the RIPL-3 database [14].

IV. RESULTS AND DISCUSSION

The enriched ^{147,149}Sm targets contained small shares of other Sm isotopes besides the desired ones, including ^{148,150}Sm. At the incident energies used for our measurements, the ^{148,150}Sm(p,n) channels were open and had a significant contribution to the production of ^{148,150}Eu. Thus we measured the population cross section of ^{148,150}Eu due to both ^{147,149}Sm(p,γ)^{148,150}Eu and ^{148,150}Sm(p,n)^{148,150}Eu reactions.

The current measured cross section for ^{147}Sm(p,n)^{147}Eu is presented in Fig. 2(a) together with the EMPIRE calculations and the existing evaluations and measurements [6]. Good agreement between our measurements and those of Katoh *et al.,* is highly encouraging, considering that no renormalization has been applied on the present data. Our experimental data are also in good agreement with the existing evaluations. The best EMPIRE prediction was obtained with the Koning OMPs for the proton and neutron channels, therefore it was used in all further calculations.

Fig. 2(b) shows the combined ^{148}Eu production cross section and the EMPIRE calculations performed with the three GSFs mentioned above. The proton capture cross section shows a strong sensitivity to different GSFs models. The calculations performed with SLO GSF re-

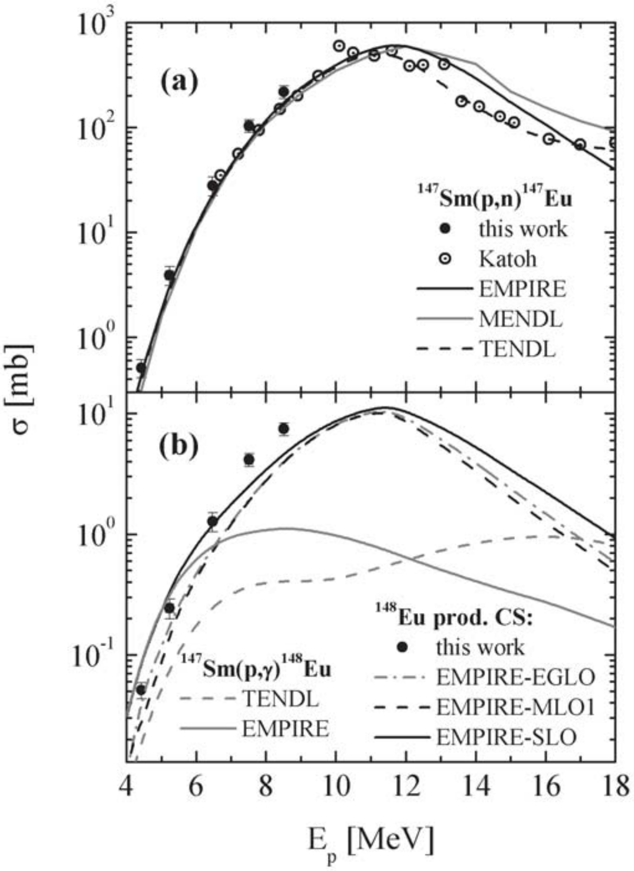

FIG. 2. (a) The ^{147}Sm(p,n)^{147}Eu experimental data (present and existing [6]) compared with the present EMPIRE evaluation and the MENDL [15] and TENDL [16] ones. (b) The experimental data for the combined ^{148}Eu production cross section compared with EMPIRE evaluations performed with the EGLO, MLO1 and SLO GSFs and also the EMPIRE and TENDL evaluations for the ^{147}Sm(p,γ)^{148}Eu cross section.

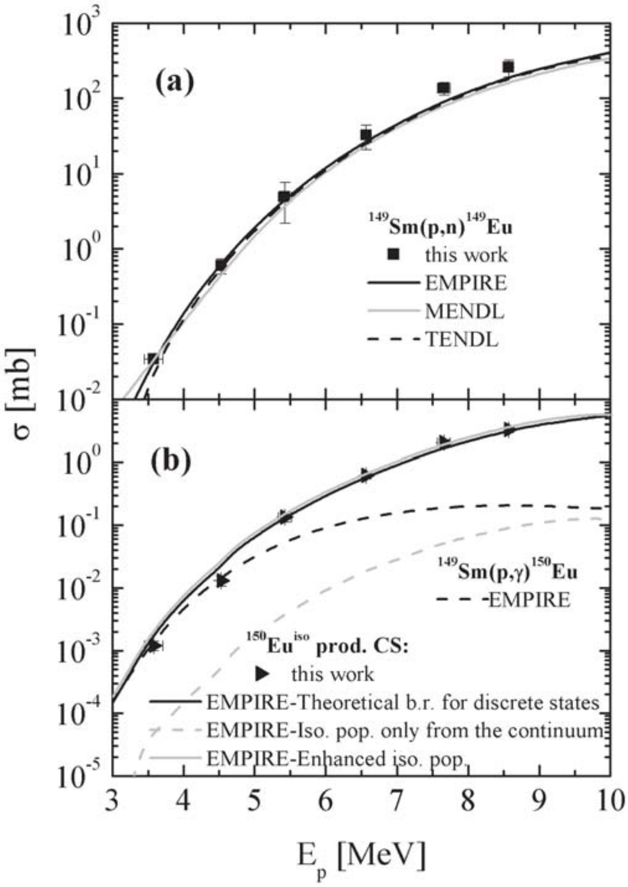

FIG. 3. (a) The present ^{149}Sm(p,n)^{149}Eu experimental data compared with the present EMPIRE evaluation and the MENDL and TENDL ones. (b) The experimental data for the combined ^{150}Eu^{iso} production cross section compared with the present EMPIRE evaluations performed with modified input parameters for the discrete levels of ^{150}Eu, as discussed in the text, and also the EMPIRE evaluation for ^{149}Sm(p,γ)^{150}Eu.

produce best the experimental data and was adopted also for the ^{150}Eu production cross section evaluation. The calculations were performed by taking into account the share of both contributing isotopes: $\sigma_{\rm prod}(^{148}{\rm Eu}) = p_1\sigma(^{147}{\rm Sm}(p,\gamma)) + p_2\sigma(^{148}{\rm Sm}(p,n))$, where p_1 and p_2 denote the Sm isotopic abundances in the target.

Fig. 3(a) illustrates the experimental values for the ^{149}Sm(p,n)^{149}Eu reaction fully supported by the EMPIRE calculations and the existing evaluations.

^{150}Eu is populated in both its isomeric and ground state. The decay of the ground state was not observed due to the long half-life (36.9 years), thus we measured the combined isomeric production cross section. The branching ratios for the discrete states which populate the isomeric level were not supplied by RIPL. We proposed a set of values for branching ratios based on physical arguments such as the energy, the multipolarity and the electric/magnetic character of the γ-ray transitions. From Fig. 3(b), it can be stressed that it is very important to include the γ-ray decay branch towards the isomeric state but the cross section is not sensitive to different values of the branching ratios. We enhanced the population of the isomeric level by forcing all the transitions with unknown branching ratios to decay only to the isomeric state and the difference made was insignificant, see *enhanced iso. pop.* curve from Fig. 3 (b).

V. CONCLUSIONS

Absolute cross sections for the ^{149}Sm(p,n)^{149}Eu reaction have been measured for the first time. The ^{147}Sm(p,n)^{147}Eu reaction has been studied at new energies (4.4 - 6.4 MeV) and the present results are in good agreement with the previous measurement. The combined cross sections of the ^{147,149}Sm(p,γ)^{148,150}Eu and ^{148,150}Sm(p,n)^{148,150}Eu reactions were measured. For the future, we aim to measure in beam the (p,n)/(p,γ) contribution ratio and obtain the cross section for the (p,γ) reaction on ^{147,149}Sm.

The statistical model parameters used in our cross section evaluation performed with EMPIRE were retrieved from the existing systematics due to the lack of experimental data. Measurements of giant dipole resonance parameters for new isotopes and average level spacings at excitations below S_n will be possible at the future gamma beam facility that will be installed at ELI-NP [17] that will extend the systematics of reaction parameters, such as GDRs and level densities.

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