Astrophysical production of $^{146}\text{Sm}$ in nuclear p-processes

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Abstract

The large time of life of $^{146}\text{Sm}$ suggests the possibility to use this p - nuclide as astrophysical chronometer to study the geochemical galactic evolution. Due to the high temperature and large densities of gamma quanta, neutrons and protons in stellar environment $^{146}\text{Sm}$ nucleus can be obtained in $(\gamma n), (n 2n), (p 2n)$ processes on $^{147}\text{Sm}$. The knowledge of corresponding cross sections of gamma rays, neutrons and alpha induced processes is of a great importance for the explanation of $(^{146}\text{Sm}/^{144}\text{Sm})$ ratio uncertainties observed on the Earth, meteorites, Moon and other celestial bodies. Cross sections of $(\gamma n), (n 2n), (n \gamma)$ processes induced by fast gamma rays, neutrons and alphas on $^{147}\text{Sm}$ and $^{142}\text{Nd}$, from threshold up to 25 MeV were evaluated and predicted in the frame of Hauser-Feshbach statistical model by using Talys software and own computer programs. For each nuclear reaction contribution of direct, compound and pre-equilibrium mechanisms were determined. Theoretical evaluations are compared with existing experimental data. Parameters of optical potential in the incident and emergent channels and of nuclear densities were extracted. Calculated cross sections together with corresponding nuclear data were used in the evaluation of astrophysical rates necessary in the determination of elemental abundances as needed by nuclear astrophysical networks.

Keywords: reaction mechanisms, Wood – Saxon potential, level density, Sm ratio uncertainties, nuclear network

1. Introduction

Samarium is a chemical element (Z = 62 number of protons) which has five stable isotopes ($^{144},^{149},^{150},^{152}\text{Sm}$) and three long lived isotopes ($^{146},^{147},^{148}\text{Sm}$), which mainly are decaying by alpha particle emission [1-3]. The theoretical analysis of nuclear reactions leading to the production of $^{146}\text{Sm}$ nucleus are of interest for nuclear reaction mechanisms and structure of atomic nuclei studies as well as for many applications. Cross sections, levels density, parameters of optical potential, effective stellar rates are useful in the development of future nuclear network necessary for improvement of astrophysical models, for explanation of abundance for $^{146}\text{Sm}$ nucleus and of other isotopes in the Universe [4,5].

Trace element $^{146}\text{Sm}$, together with many other elements heavier than Iron, cannot be formed in slow processes and their natural abundance can be explained by rapid p – processes. Due to the relative short half life of $^{146}\text{Sm}$, compared with period of cosmic processes, this nucleus can be used in radiometric dating in Solar System. Furthermore, explanation of discrepancy
of the $^{144}$Sm/$^{146}$Sm ratio observed on the samples from the Earth, meteorits and other celestial bodies can provide new information on the formation of Solar System [6].

Production of $^{146}$Sm nucleus in the $^{147}$Sm($\gamma$,n), $^{147}$Sm(n,2n) and $^{142}$Nd($\gamma$/g74,\gamma)\g68 nuclear reactions will be investigated. The $^{147}$Sm(n,2n)$^{146}$Sm process has the heat of reaction $Q = -6.34$ MeV and $^{142}$Nd($\gamma$/g68,\gamma)$^{146}$Sm has $Q = -2.58$ MeV. Target nucleus $^{147}$Sm has the spin and parity $J^{π} = (7/2)^{-}$ and half life $\tau = 1.06 \times 10^{11}$ y. Further, $^{142}$Nd nucleus is stable with spin and parity $J^{π} = 0^{+}$. Residual nucleus, $^{146}$Sm has also $J^{π} = 0^{+}$ and $\tau = 6.8 \times 10^{7}$ y [7].

Cross sections, yields and astrophysical rates were evaluated for incident energies starting from threshold up to 25 MeV. Obtained theoretical results are compared with existing experimental data and will be used in nuclear network for astrophysics as necessary for the evaluation of $^{146}$Sm abundance.

2. Elements of theory

Cross sections, yields and astrophysical rates were mainly calculated with Talys code which is a free software, working under Linux, with a friendly user interface dedicated to nuclear reactions and structure of atomic nuclei evaluations. In Talys are implemented the main nuclear reaction mechanisms (compound, direct and pre-equilibrium), together with a wide database of nuclear structure parameters for a large number of natural and synthesized nuclei. Incident particles, in the last version of Talys, can be neutrons, protons, deuterons, $^3$He, $^3$H, alpha particles and gamma quanta with energies starting from 0.001 MeV up to 1000 MeV. This software allows to evaluate inclusive and exclusive cross sections. In a binary nuclear reaction of type $A(a,b)B$, inclusive process defines the situation when the emergent particle “b” is considered not only from “b + B” channel but from all emergent ones with participation of “b”. In comparison, in the case of exclusive processes, the final state of channel “b + B” is well defined. Both, inclusive and exclusive processes are important in the analysis of experimental nuclear astrophysical data [8].

In the investigated nuclear reactions the main contribution in the cross sections are compound processes. In this case, cross section can be evaluated in the frame of Hauser – Feshbach formalism with the following formula [9]:

$$\sigma_{ab} = g \sum_{c} W_{ab} = \frac{T_{ab}}{\sum_{c} T_{ab}}$$

(1)

where: $g = (2J + 1)\Gamma(2s_{a} + 1)(2l + 1)$ = statistical factor; $J$, $s_{a}$, $l$ = spin of compound nucleus, incident particle and target nucleus, respectively; $T_{s}$ = transmission (penetrability) coefficient ($x = \text{channel}$); $W_{ab}$ = width fluctuation correction factor; sum on denominator is taken over all open channels ($c$) at given incident energy; $\approx_{a}$ = reduced wave number.

An important parameter of the cross section are the transmission coefficients, $T_{s}$. Transmission coefficient is defined as the probability of a particle to pass through a potential barrier and therefore it has the values between 0 and 1. Evaluation methods of transmission coefficients are described in [10] and applied for (n,$\gamma$/g68) reaction in [11].

Width fluctuation correction factor $W_{ab}$ represents the correlation between incident and emergent channels. Near the reaction threshold this coefficient is equal with 1. Usually, with the increasing of incident particle energy, $W_{ab}$ is slowly decreasing [8,12].

Cross section theoretical values are used for astrophysical rates (as effective stellar rates) evaluation. Expression of astrophysical rate is [8]:

$$N_{A} (\sigma \nu)_{ab}^{\star} (T) = \frac{8}{\pi m} \frac{N_{A}}{(k_{B}T)^{2}} \Gamma G (T) \sum_{0}^{\infty} \frac{(2J^{\mu} + 1)}{\sum_{0}^{\infty} (2J^{\mu} + 1)} \sigma_{ab}^{\mu} (E) E \exp \left( -\frac{E + E_{\nu}^{\mu}}{k_{B}T} \right) dE$$

(2)

Normalized partition function $G(T)$ is [8]:

$$G (T) = \sum_{\mu} \frac{2J^{\mu} + 1}{2J^{\mu} + 1} \exp \left( -\frac{E_{\nu}^{\mu}}{k_{B}T} \right)$$

(3)

where: $m$ = channel reduced mass; $k_{B}$ = Boltzmann constant; $N_{A}$ = Avogadro number; $J^{\mu}, F^{\mu}$ = spin of excited and fundamental states, respectively, corresponding to excitation energy $E_{\nu}$.
Relation (2) is obtained taking into account excited states of target nucleus at thermodynamic equilibrium and assuming that the energies of both the target and projectile, as well as their relative energies, have a Maxwell – Boltzmann distribution at a given temperature $T$ [8].

3. Results and discussions

Cross sections, yields, astrophysical rates and other physical values were evaluated with Talys for $^{147}\text{Sm}(\gamma,n)^{146}\text{Sm}$, $^{147}\text{Sm}(n,2n)^{146}\text{Sm}$ and $^{142}\text{Nd}(\alpha,\gamma)^{146}\text{Sm}$ nuclear reaction starting from threshold up to 25 MeV. In the calculations all nuclear reaction mechanisms were enabled. Compound processes are described by Hauser – Feshbach formalism [8,9], direct by distorted wave Born approximation (DWBA) [8,13] and pre-equilibrium processes by two component exciton model [8,14]. Level density is obtained using Fermi gas model with constant temperature [8]. In the evaluation all open emergent channels are considered. For elastic and inelastic channels 30 discrete states of residual nucleus are taken into account. For reaction channels the first 10 discrete states of residual nucleus are chosen. For excitation energies higher than the last discrete level, residual nucleus states are in continuum.

For incident and emergent channels, Wood – Saxon (WS) optical potential with volume (V), surface (S) and spin – orbit (SO) components, each with real (V) and imaginary (W) part, was used [8]. Parameters of optical potentials for $^{147}\text{Sm}(\gamma,n)^{146}\text{Sm}$, $^{147}\text{Sm}(n,2n)^{146}\text{Sm}$ and $^{142}\text{Nd}(\alpha,\gamma)^{146}\text{Sm}$ processes, obtained in the evaluations are given in Table 1.

### Table 1. Parameters of optical potential. Channels (Ch.): 1 – n + $^{147}\text{Sm}$; 2 – n + $^{146}\text{Sm}$; 3 - $\alpha$ + $^{142}\text{Nd}$. For channels 1 and 2 radius parameter ($r$) and surface thickness ($a$) for volume and surface WS components with real and imaginary part are: $r_{V,W} = 1.227$ fm, $a_{V,W} = 0.656$ fm. For channel 3, $r_{N} = 1.187$ fm, $a_{N} = 0.627$ fm.

|        | Volume | Surface | Spin - orbit |
|--------|--------|---------|--------------|
|        | Re     | Im      | Re           | Im           | Re   | Im    |
| Ch.    | V\text{V} [MeV] | W\text{V} [MeV] | V\text{S} [MeV] | W\text{S} [MeV] | V\text{SO} [MeV] | W\text{SO} [MeV] |
| 1      | 49.81  | 0.11    | 0            | 3.38         | 6.10 | 0.01  |
| 2      | 49.94  | 0.11    | 0            | 3.42         | 6.17 | 0.01  |
| 3      | 152.1  | 0.00    | 0            | 4.00         | 0.00 | 0.00  |

3.1. $^{147}\text{Sm}(\gamma,n)^{146}\text{Sm}$ reaction

Results of $^{147}\text{Sm}(\gamma,n)^{146}\text{Sm}$ process are presented. In Figure 1 inclusive cross section (XS) of $^{147}\text{Sm}(\gamma,n)$ process is decomposed in exclusive cross section of $^{147}\text{Sm}(\gamma,xn)$ processes ($x = 1,2,3,4$). Curve 1 from Figure 1 represents the production cross section of $^{146}\text{Sm}$.

**Figure. 1.** Inclusive and exclusive XS in $^{147}\text{Sm}(\gamma,n)$ reaction. Exclusive processes $^{147}\text{Sm}(\gamma,xn)$ and production of: 1- $^{146}\text{Sm}$; 2- $^{145}\text{Sm}$; 3- $^{144}\text{Sm}$; 4 - $^{143}\text{Sm}$. 5 – Inclusive XS as sum of exclusive processes ($x = 1,2,3,4$).
Cross section of $^{147}\text{Sm}(\gamma,n)^{146}\text{Sm}$ reaches the maximum around 12 - 14 MeV. At higher energies other $(\gamma,xn)$ channels are opening and the cross section of $^{147}\text{Sm}(\gamma,n)^{146}\text{Sm}$ is decreasing.

![Figure 2](image_url)

**Figure 2.** Contribution to the exclusive XS of $^{147}\text{Sm}(\gamma,n)^{146}\text{Sm}$ of discrete and continuum states of residual nucleus. 1 – Discrete; 2 – Continuum; 3 – Exclusive XS as sum of 1 and 2

In the next figure, contribution of nuclear reaction mechanisms in the exclusive cross section of $^{147}\text{Sm}(\gamma,n)^{146}\text{Sm}$ reaction is evidenced.

![Figure 3](image_url)

**Figure 3.** Contribution of nuclear reaction mechanisms in the production of $^{146}\text{Sm}$ in $^{147}\text{Sm}(\gamma,n)$ exclusive process. 1 – Direct; 2 – Compound; 3 – Pre-equilibrium

From Figure 3 it can be observed that direct processes can be neglected. Starting from the threshold cross section is given by compound processes. At energies higher then 10 -12 MeV, cross section is given mainly by multistep compound pre-equilibrium processes. In Figure 3 curves 2 and 3 are practically the same.

For gamma incident energy starting from neutron threshold up to 12 MeV theoretical evaluations for $^{147}\text{Sm}(\gamma,n)^{146}\text{Sm}$ cross section are in good agreement with existing experimental data [15] (see Figure 4).
Figure 4. Comparison between theoretical evaluation and experimental data of $^{147}$Sm($\gamma$,n)$^{146}$Sm: 1 – Talys evaluation; 2 - Experimental data

In the analysis of experimental data inclusive and exclusive cross sections are very useful. Also, other parameters of interest for experimental data processing are the neutrons production and neutron yields (neutrons multiplicity) as function of incident gamma energy. Results are shown in Figures 5 and 6. We mention that the done evaluations includes neutrons from all open channels not only from $^{147}$Sm($\gamma$,n)$^{146}$Sm one. In the Figure 6 one can observe that neutron yields are increasing with energy by opening of new emergent channels with neutrons participation.

Figure 5. XS of neutrons production in $^{147}$Sm($\gamma$,n) process

Figure 6. Dependence of neutrons yields (multiplicity) of incident gamma energy
Using cross section evaluated with Talys, astrophysical rates were estimated by using relation (2). Temperature dependence of astrophysical rates is represented in Figure 7.

In the interaction of gamma quanta with $^{147}$Sm nucleus a large number of daughter nuclei are formed (isotopes of Sm, Nd, Pr, Pm, Ce). In Figure 7 are shown only the effective stellar rates for the production of Sm isotopes. Production of $^{146}$Sm is given by curve 2.

![Figure 7. Astrophysical rates of Sm isotopes production: 1 – $^{147}$Sm; 2 – $^{146}$Sm; 3 – $^{145}$Sm; 4 – $^{144}$Sm; 5 – $^{143}$Sm](image)

In the next figure temperature dependence of the normalized partition function in according with relation (3) is represented. From relation (2) it can be observed that this function is necessary in astrophysical rates calculation for any produced nucleus in the final state. Normalized partition function results are given in Figure 8.

![Figure 8. Normalized partition function in the interaction of gamma quanta with $^{147}$Sm nucleus](image)

### 3.2. $^{147}$Sm(n,2n)$^{146}$Sm reaction

Samarium isotope $^{146}$Sm can be produced in $^{147}$Sm(n,2n) process. Theoretical evaluations of production cross section of $^{146}$Sm nucleus are shown in Figure 9. Contribution of direct processes is very low and can be neglected (curve 1). Compound processes, represented by curve 2 are dominant up to about 22 MeV. Around 19 MeV pre - equilibrium multistep compound mechanism starts to contribute to the cross section and can be observed that “pure” compound processes cross section is decreasing very fast. For $^{147}$Sm(n,2n)$^{146}$Sm reaction, for neutrons energy from threshold up to 25 MeV, compound processes give the main contribution to the cross section. Although cross section has large values, there are not available experimental data in the literature.
As in the case of previous photoneutron reaction, using cross section theoretical evaluation and relations (2), (3), astrophysical rates were calculated.

In the interaction of fast neutrons with $^{147}\text{Sm}$ nucleus isotopes of Sm, Pr, Pm, Nd, Ce are obtained. The production astrophysical rates for Sm isotopes can be seen in Figure 10. Effective stellar rates for other isotopes are not represented here. By curve 2 astrophysical rates of $^{146}\text{Sm}$ are shown. Comparatively, astrophysical rates in the case of neutron induced processes are much lower than in the case of photoneutron reaction (see Figures 7 and 10).

Neutrons production, neutrons multiplicity and other physical values necessary in data processing were also evaluated but not shown in the present report.

### 3.3 $^{142}\text{Nd}(\alpha,\gamma)^{146}\text{Sm}$ reaction

Production of $^{146}\text{Sm}$ isotope in $^{142}\text{Nd}(\alpha,\gamma)$ process was investigated for incident energies of alpha particles starting from threshold up to 25 MeV (Figure 11).

Calculations have demonstrated that the main contributions to the cross section are given by compound processes and continuum states of residual nucleus. The cross section values of direct, pre-equilibrium mechanisms and of discrete states of residual nucleus can be neglected in the given energy interval.

In comparison with two other investigated reactions, cross section of $^{142}\text{Nd}(\alpha,\gamma)^{146}\text{Sm}$ process is much lower (see curve 1 from Figure 1, curve 4 from Figure 9 and Figure 11) which make the determination of $^{146}\text{Sm}$ more difficult in the experiment.
Production of $^{146}$Sm in alpha capture process by $^{142}$Nd nucleus is possible not only by transitions on the ground state of $^{146}$Sm but also by different cascade transitions of type ($\alpha, \gamma \gamma$). Results of theoretical evaluations are shown in the Figure 12. Cross section of ($\alpha, \gamma \gamma$) process is higher than ($\alpha, \gamma$) but still is lower than the cross sections of the other two above investigated reactions. Curve 1 from Figure 12 is the same as the energy dependence in Figure 11. Such results are of interest in the processing of experimental data. In the capture process of alpha particles many isotopes are produced in excited states which will lead also to the production of gamma particles. Our evaluation showed that at the energy of alpha particles of 25 MeV cross section of total gamma production (from all open channels) is 2500 mb (gamma multiplicity about 2.5) which is with more than 3 order of magnitude larger than the cross section of $^{142}$Nd($\alpha, \gamma$)$^{146}$Sm reaction at the same alpha incident energy. These results indicate a large gamma background which should be considered in the processing of experimental data.

The analysis of gamma production in the capture process of alpha particles by $^{142}$Nd nucleus must be considered in the calculation of astrophysical rates. In this process many isotopes of Sm, Nd, Pr, Pm, Ce are produced also. In the Figure 13 astrophysical rates for production of Sm isotopes are shown.

Results for effective stellar rates for $^{146}$Sm are shown by curve 1 from Figure 13. Because alpha capture cross section is much lower than in the case of ($\gamma, n$) and (n,2n) processes astrophysical rates for $^{146}$Sm are also much smaller.
In the case of $^{142}$Nd($\alpha$,γ) process, production of $^{146}$Sm nucleus was modeled considering a $^{142}$Nd target with transversal area, $S = 1 \text{ cm}^2$ irradiated by alpha beams with intensities 1 μA and 100 μA, respectively. Results are shown in Figure 14.

In a $^{142}$Nd target with about 0.2 mm thickness are about $10^{20}$ Nd nuclei. If the target is irradiated 24 hour, number of obtained $^{146}$Sm nuclei is about $10^{10}$ for 1 μA and $10^{12}$ for 100 μA. This is the consequence of the low values of ($\alpha$,γ) cross section. It is easy to see that the concentration of $^{146}$Sm is much lower than 1 ppm and even for 100 μA the experimental evaluation of this isotope will be very difficult. Furthermore, it must be taken into account, the gamma background, purity of the target and other parameters.

3.4. Uncertainties of ($\gamma$,n), (n,2n) and ($\alpha$,γ) reactions

Nuclear reactions ($\gamma$,n), (n,2n), ($\alpha$,γ) leading to the production of $^{146}$Sm are modifying their values if the parameters of optical potential are varied. Results have demonstrated that cross sections are most sensible by variation of real part of volume Wood – Saxon potential, $V_V$ (see Table 1) [8]. For ($\gamma$,n) reaction, $V_V$ parameters corresponding to the neutrons in the emergent channels were modified. For (n,2n) and ($\alpha$,γ) processes, volume potential parameter in incident channels was varried. For each reaction, initial $V_V$ parameter was taken from Table 1. Real part of volume potential was modified from half of initial values up to two times of initial values. For each reaction with modified $V_V$, cross sections were calculated. In order to observe better the fluctuations, cross sections with modified parameters were normed to the cross sections with initial $V_V$ values from Table 1. In the Figures 15 - 17 were represented only the situations with largest modification of the cross section ratios. As shown on the three figures, the ratios equal with 1 denote the cross sections with non modified parameters, from Table 1. It can be observed also that the cross sections are the most sensible near the threshold and few MeV higher. For first two processes from Figures 15 and 16 a sensible region is upper than 15 MeV also.
These last results show the necessity of more reliable experimental and theoretical nuclear data of optical potentials and other parameters necessary for the investigation of reaction mechanisms, structure of atomic nucleus and nuclear astrophysics.
4. Conclusions

Production of $^{146}$Sm nucleus in $^{147}$Sm($\gamma$,n), $^{147}$Sm(n,2n) and $^{142}$Nd($\alpha$,\gamma) processes for incident energies starting from threshold up to 25 MeV were analyzed. Cross sections, yields and multiplicities of emitted neutrons and gamma quanta and astrophysical rates were theoretically calculated.

For each evaluated cross section, the contribution of nuclear reaction mechanisms and of the discrete and continuum states of residual nuclei was determined. For all investigated reactions, compound processes or pre-equilibrium multistep compound processes are dominant and in many cases direct mechanism can be neglected in the given incident energy interval. Also, calculations have demonstrated that discrete states contribute to the cross sections only few MeV around the threshold but at higher incident energies contribution to the cross section is given by continuum states. In the case of ($\gamma$,n) reaction, cross section theoretical evaluations are in good agreement with existing experimental data. From obtained cross section data parameters of optical potential were extracted as well.

For the analysis of future experimental data, yields and multiplicities of emitted gamma quanta and neutrons were evaluated because for energies of incident particles up to 25 MeV a large number of exit channels are open. Furthermore, a large number of isotopes are obtained, including $^{146}$Sm nucleus.

Using cross sections, parameters of optical potentials, structure of atomic nuclei data, astrophysical rates were calculated with Talys. The choice of the Talys software was made since in comparison with other codes for astrophysical rates evaluations it enables all nuclear reaction mechanisms, competition between open channels, considers multi-particle emission which is not included in many similar programs.

In the case of $^{142}$Nd($\alpha$,\gamma) a simple computer simulation was realized for production of $^{146}$Sm. Difficulties of possible future experiments were evidenced, mainly due to the low values of the cross section and high gamma background.

For the all three processes uncertainties due to the real part of volume Wood – Saxon potential were investigated. Cross sections have the largest uncertainties near the threshold and few MeV higher, a region of interest in many astrophysical researches.

Present results were realized in the frame of nuclear physics for astrophysics research program developed at FLNP JINR Dubna and represent future experiment proposal at basic facilities of JINR Dubna.

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