

Proton capture cross section of Sr isotopes and their importance for nucleosynthesis of proton-rich nuclides

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Abstract

The (p,γ) cross sections of three stable Sr isotopes have been measured in the astrophysically relevant energy range. These reactions are important for the p -process in stellar nucleosynthesis and, in addition, the reaction cross sections in the mass region up to 100 are also of importance concerning the rp -process associated with explosive hydrogen and helium burning. It is speculated that this rp -process could be responsible for a certain amount of p -nuclei in this mass region. The (p,γ) cross sections of $^{84,86,87}\text{Sr}$ isotopes were determined using an activation technique. The measurements were carried out at the 5 MV Van de Graaff accelerator of the ATOMKI, Debrecen. The resulting cross sections are compared with the predictions of statistical model calculations. The predictions are in good agreement with the experimental results for

$^{84}\text{Sr}(p,\gamma)^{85}\text{Y}$ whereas the other two reactions exhibit differences that increase with mass number. The corresponding astrophysical reaction rates have also been computed.

I. INTRODUCTION

Most of the stable proton rich nuclides with charge number $Z \geq 34$ are the so-called p -nuclei. Their production by the s - or r -process is blocked by stable nuclei and hence they are 10 to 100 times less abundant than the more neutron-rich isotopes. The main stellar mechanism synthesizing these neutron-deficient nuclei is a process called γ - or p -process [1,2] involving a series of (γ,n) , (γ,p) and (γ,α) reactions on pre-existing more neutron-rich nuclei. The most favourable site for such a process to occur is the O/Ne-layers of massive stars during presupernova phase [2,5,6] or during their explosion as supernovae type II [2,7–9]. Recent investigations of the rp -process associated with explosive hydrogen and helium burning in X-ray bursters have shown that it could also produce p -nuclei in the mass region up to 100. However, it is yet unclear if and in what amount these nuclides could be ejected into the interstellar medium [3,4].

Describing the synthesis of p -nuclei and calculating their abundances requires an extended reaction network calculation involving more than 10000 reactions, many of which are photodisintegrations releasing protons, the inverse of radiative proton capture (see e.g. [10–12]). In contrast to neutron capture reactions which are comparatively well studied over the complete mass range of stable isotopes (see, e.g. [13]), low-energy charged particle reaction data are scarce for the mass region above iron. Hence, so far, nucleosynthesis calculations of processes involving charged particles (either by directly interacting with target nuclei or as a result of photodisintegration) are based on theoretical predictions of the Hauser-Feshbach model (e.g. [14–16]). Therefore, a systematic experimental study of charged particle reactions was initiated in several laboratories in order to obtain an extensive and reliable experimental data base of proton and α -capture cross sections [17–21]. Considerable differences with the theoretical predictions were found for certain (α,γ) reactions while the measured proton capture cross sections exhibited less differences. The α optical model potential at low energies was identified as the main source of the difference [22] and this also led to the idea of systematically studying the low-energy α optical model potential in

(n, α) reactions [23,24], whereas the proton optical model potential is considered to be more reliable [25,14]. However, due to the rareness of experimental data in the intermediate and heavy mass range we are still far from obtaining complete systematics which would provide the basis for a thorough test of the theoretical descriptions and therefore it is necessary to pursue further investigations of (p, γ) reactions close to the astrophysically relevant energy range.

In this work we present for the first time measurements of the (p, γ) cross sections of three stable Sr isotopes, $^{84,86,87}\text{Sr}$, in the astrophysically relevant energy range using an activation technique. Our results are compared with statistical model (Hauser-Feshbach) calculations.

II. INVESTIGATED REACTIONS

The element Sr has four stable isotopes with mass numbers $A = 84, 86, 87,$ and $88,$ having isotopic abundances of 0.56%, 9.86%, 7.00%, and 82.58%, respectively. Only the (p, γ) cross section of the first 3 isotopes can be determined by activation because in the case of $^{88}\text{Sr}(p,\gamma)$ reaction the product nucleus ^{89}Y is stable and its isomer is short lived ($T_{1/2}=16.06\text{s}$). In the case of ^{84}Sr and ^{86}Sr the partial cross sections leading to the isomer and ground state of the corresponding Y isotopes can be determined separately because of the different decay pattern of the isomeric and ground state.

The relevant part of the chart of nuclides can be seen in Fig.1 where the decay of the reaction products can also be seen. The decay parameters used for the analysis are summarized in Table I.

III. EXPERIMENTAL PROCEDURE

A. Target properties

As mentioned above, the isotope ^{88}Sr which cannot be investigated by activation, has the highest natural abundance of about 80%. Thus, in case of natural targets only 20%

of the material is effective for the activation. However, the use of natural Sr targets has the advantage that the isotopic abundances are very well known and natural Sr is easily available in many chemical forms.

In our measurements we used natural SrF₂ targets, evaporated onto thick carbon backings. The fluorine content of the target causes no disturbance because in the investigated energy range there is no activity produced by proton bombardment on F and it has a low mass number, thus it is well separated from Sr in Rutherford Backscattering (RBS) spectra that were also measured during the irradiations in order to monitor the target stability as described below. Carbon causes no disturbing long-lived activity and due to its low mass number, the C edge lies far below the Sr and F peaks in the RBS spectra.

The number of target atoms was determined by proton induced X-ray emission (PIXE) at the PIXE set-up of the ATOMKI [26]. The results were checked by α -RBS determining the width of the Sr peak. In most cases we found good agreement. The method in ref. [18] which compares the area of the Sr peak and the height of the backing (carbon) edge in the proton-RBS spectrum is not applicable because of the non-Rutherford behavior of p-C elastic scattering. Altogether 33 targets were prepared, some of them were only used for test runs.

Using natural Sr targets the (p, γ) cross section of ⁸⁴Sr, ⁸⁶Sr and ⁸⁷Sr can be determined simultaneously in a single activation procedure. At $E_p=2.67$ MeV bombarding energy the ⁸⁷Sr(p,n)⁸⁷Y channel opens, which results in the same product nucleus as ⁸⁶Sr(p, γ). Consequently, above this energy the cross section of ⁸⁶Sr(p, γ) reaction cannot be deduced. However, this is the only disturbing proton induced reaction channel on Sr isotopes which is open in the investigated energy range.

B. Activation

The activations were carried out at the 5 MV Van de Graaff accelerator of the ATOMKI. The energy range from $E_p=1.5$ to 3 MeV was covered with 100 keV steps. The schematic

view of the target chamber can be seen in Fig.2. After the last beam defining aperture the whole chamber served as a Faraday-cup to collect the accumulated charge. A secondary electron suppression voltage of -300 V was applied at the entrance of the chamber. The irradiations lasted between 6 and 24 hours with a beam current of typically 5 to 10 μ A. Thus, the collected charge varied between 120 and 650 mC. The current was kept as stable as possible but to follow the changes the integrator counts were recorded in multichannel scaling mode, stepping the channel in every minute.

A surface barrier detector was built into the chamber at $\Theta=150^\circ$ relative to the beam direction to detect the backscattered protons and this way to monitor the target stability. The RBS spectra were taken continuously and stored regularly during the irradiation. In those cases when target deterioration was found, the irradiation was repeated with another target. Fig. 3 shows a typical RBS spectrum.

The beam was wobbled across the last diaphragm to have a uniformly irradiated spot of diameter of 8 mm on the target. The target backing was directly water cooled with an isolated water circulating system.

Between the irradiation and γ -counting, a waiting time of 1 to 2 hours was inserted in order to let the disturbing short lived activities decay out.

C. Detection of induced γ -radiation

The γ -radiation following the β -decay of the produced Y isotopes was measured with a HPGe detector of 40% relative efficiency. The low intensity gamma radiation necessitated the use of a very close geometry: the target was mounted in a holder directly onto the end of the detector cap. The whole system was shielded by 10 cm thick lead against laboratory background.

The γ -spectra were taken for at least 48 hours and stored regularly in order to follow the decay of the different reaction products.

The efficiency curve of the detector was determined with ^{133}Ba , ^{56}Co and ^{152}Eu sources

in the same close geometry. The measured points were fitted with a third degree logarithmic polynomial to yield the efficiency curve for the whole energy region of interest. The efficiency measurements were checked with Monte Carlo simulations and good agreement was found in the whole energy range [27].

Fig. 4 shows an off-line γ -spectrum taken after irradiation with 3 MeV protons. γ -lines used for the analysis are indicated by arrows.

IV. EXPERIMENTAL RESULTS

Tables II,III,IV summarize the experimental cross sections of the three Sr isotopes, while Figs. 5,6,7 show the derived astrophysical S -factors as a function of center-of-mass energy. In the figures, the predictions of the Hauser-Feshbach statistical model codes MOST [28] and NON-SMOKER [29,16] can also be seen.

A. $^{84}\text{Sr}(\text{p},\gamma)^{85}\text{Y}^{g,m}$

Proton capture of ^{84}Sr populates the ground ($T_{1/2} = 2.68$ h) and isomeric ($T_{1/2} = 4.86$ h) state of ^{85}Y . The isomeric state decays directly to ^{85}Sr without internal transition to the ground state. In principle, the cross sections to the isomer (m) and ground (g) state can be determined independently using the 231.65 keV and 504.4 keV lines. However, at low bombarding energies the intensity of the latter transition is very low compared to the strong 511 keV annihilation line. Therefore the subsequent decay of ^{85}Sr had to be investigated. This decay results in the emission of 151.16 keV radiation with high intensity only when the ground state of the original ^{85}Y was populated. Thus by detecting this line, the ground and the isomeric state can be distinguished.

Here we should point out a discrepancy observed among the decay data in the literature [30] (see Table I). At the highest energies the above analysis can be performed independently with both methods: with detection of the direct 231.65 keV and 504.4 keV lines and with the delayed 151.16 keV transition. The results from the two methods were found to be

different by a factor of about 2. This indicates that at least one of the adopted relative γ -ray intensity values is incorrect. A test measurement was performed in order to resolve this discrepancy. The precision of this measurement was not enough to provide new values to these γ -ray intensities, however, we could determine which data are incorrect. We found that the relative intensity of the 151.16 keV line is wrong. Thus the analysis was performed by using the 231.65 keV and 504.4 keV lines and the 151.16 keV line was used only for relative measurements where the weak 504.4 keV line could not be detected with sufficient precision.

Fig. 5 shows the measured and calculated S -factor values of the $^{84}\text{Sr}(p,\gamma)^{85}\text{Y}$ reaction. The results of both model calculations are in satisfactory agreement with the measured values.

B. $^{86}\text{Sr}(p,\gamma)^{87}\text{Y}^{g,m}$

For this isotope the two partial cross sections can be derived easily since the 380.79 keV γ -line comes entirely from the internal transition of the isomer.

As mentioned above, at $E_p=2.67$ MeV bombarding energy the $^{87}\text{Sr}(p,n)$ channel opens, hence above this energy only the sum of the cross section of $^{86}\text{Sr}(p,\gamma)^{87}\text{Y}$ and $^{87}\text{Sr}(p,n)^{87}\text{Y}$ reactions (weighted with the isotopic abundances) can be deduced. However, calculations show that in the investigated energy region the (p,n) channel is much (about two orders of magnitude) weaker than the (p, γ). Hence the points above the threshold are included in Tab. IV and Fig. 6 although in brackets.

The resulting cross sections are significantly lower than the values of the model calculations.

C. $^{87}\text{Sr}(p,\gamma)^{88}\text{Y}$

The isomer of ^{88}Y is very short-lived ($T_{1/2} = 13.9$ ms) and it decays with internal transitions to the ground state. Thus, with the activation technique the total proton capture

cross sections can be determined. The analysis was carried out with the two cascading γ -rays from the ^{88}Y decay.

The statistical model calculations strongly overestimate the measured data as can be seen in fig. 7.

V. DISCUSSION

A. Dependence on nuclear properties

The comparison of the S -factor data with the theoretical predictions seems to exhibit a trend depending on the nuclear mass: the more heavy and neutron-rich the measured Sr isotopes become, the more the cross sections are overestimated by the statistical model calculations. The differences between the theoretical models is less grave, they differ by about 30%, nearly independently of mass and projectile energy. While most of the descriptions of nuclear properties used in the two codes are similar, the nuclear level densities are different. The standard NON-SMOKER calculations use a global level density based on the shifted Fermi-gas model [25], while the MOST code makes use of a microscopic global model level density based on a Hartree-Fock-BCS method [33,34]. This may explain the difference in the two results. It is evident that both predictions seem to become worse for isotopes approaching the closed neutron shell $N = 50$. The level densities also depend on microscopic properties like pairing and shell effects. It is known [25,35–37] that those are often predicted inaccurately at closed shells, often overestimating the effect.

Apart from the nuclear level densities, the proton optical model potential also plays a crucial role. Further studies of the optical potential dependence in comparison to the measured data are shown in Figs. 8, 9 for the reactions $^{86}\text{Sr}(p,\gamma)^{87}\text{Y}$ and $^{87}\text{Sr}(p,\gamma)^{88}\text{Y}$. In both figures we plot the S -factor data and the values obtained with the standard NON-SMOKER and MOST potential JLM [38], an equivalent square well potential (ESW) of [39], and the two Saxon-Woods type phenomenological potentials of PER [40] and BEC [41].

While the ESW potential and the PER potential do not reproduce the energy dependence of the S -factors well, it is reproduced by the BEC potential more accurately. Among the 4 potentials considered, the JLM potential leads to the best overall description of the energy dependence of the experimental data, except for the low-energy region where the ESW potential does better. The above findings hold for all the reactions considered in this work.

B. Astrophysical reaction rates

It is premature to try to derive an improved global proton potential from these three measured isotopes and the scarce data available for other elements. From the results of Sec. V. A. it is clear that an optical potential can be found to reproduce the data presented in this work. Unfortunately, such a potential would only describe these reaction data and will not be a global one. In order to calculate the integral for the astrophysical reaction rate with sufficient numerical accuracy it is only necessary to reproduce the experimental data by the theoretical calculation well. This can be achieved by dividing the results obtained with the JLM potential and shown in Figs. 8, 9 by a constant factor of 1.7 for the reaction $^{86}\text{Sr}(p,\gamma)^{87}\text{Y}$ and a factor of 2.2 for the reaction $^{87}\text{Sr}(p,\gamma)^{88}\text{Y}$, respectively. The astrophysical reaction rates obtained from those renormalizations are given in Tab. V. A similar renormalization procedure was used for the reaction $^{84}\text{Sr}(p,\gamma)^{85}\text{Y}$. The fit to the experimental data quoted in Tab. V produced values which lie halfway between the NON-SMOKER and MOST results, yielding mean cross sections and rates which are equivalent to a renormalization of the MOST values by a factor of 1.15 and a downscaling of the NON-SMOKER values by the appropriate factor. The extensions to lower and higher temperatures are obtained by renormalizing the NON-SMOKER values [16] by the above values.

In addition to the laboratory rates obtained when the target is in the ground state, the stellar rates calculated for a thermally excited target are also shown in Tab. V. As the measured reactions only involve targets in the ground state, it was assumed that the stellar rates scale like the laboratory rates. By re-adjustment of the reaction rate parametrization

of Ref. [14] to the new data, we arrive at new values for the parameters a_0 of the stellar rate: 250.84 for $^{84}\text{Sr}(p,\gamma)^{85}\text{Y}$, 245.13 for $^{86}\text{Sr}(p,\gamma)^{87}\text{Y}$, and 208.87 for $^{87}\text{Sr}(p,\gamma)^{88}\text{Y}$. All other fit parameters remain the same since the energy dependence is reproduced well by the theory.

In general, it should be noted that even modern *global* statistical model predictions – which are not locally tuned to experimentally known nuclear properties – bear an uncertainty of a factor of 1.3–2.0. Thus, the deviations from experimental data found in this work are not surprising and still within the expected uncertainties. Nevertheless, the observed discrepancies underline the importance of carrying out experimental studies in order to test the reliability of Hauser-Feshbach and improve the accuracy of the calculated reaction rates used in astrophysical applications.

VI. SUMMARY

We have measured proton capture cross sections on the Sr isotopes with mass numbers 84, 86, and 87 in the astrophysically important energy range of $1.5 \leq E_{\text{c.m.}} \leq 3$ MeV (this corresponds to a temperature range of about $T \simeq (1.0 - 4.0) \times 10^9$ K). While we find good agreement between experiment and theory for the reaction $^{84}\text{Sr}(p,\gamma)^{84}\text{Y}$, the predictions for the other two reactions differ considerably from our results although not as much as in the case of previous α capture measurements. The reason for these inaccuracies could be attributed to uncertainties in the optical potentials and nuclear level densities used in the statistical model calculations. Although the uncertainties in global reaction rate calculations are expected to be of the magnitude found in the current investigation, further investigation is required in order to resolve the discrepancies and arrive at improved global predictions of nuclear properties. The newly derived reaction rate can be directly used in astrophysical applications.

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TABLES

TABLE I. Decay parameters of the Y product nuclei taken from the literature

Product nucleus	Half life [hour]	Gamma energy [keV]	Relative intensity per decay [%]	Reference
$^{85}\text{Y}^g$	2.68 ± 0.05	231.65	84 ± 8	[30]
		504.4	60 ± 4	
		151.16	12.9 ± 0.3	
$^{85}\text{Y}^m$	4.86 ± 0.13	231.67	22.8 ± 2.2	[30]
		504.4	1.5 ± 0.1	
$^{87}\text{Y}^g$	79.8 ± 0.03	388.53	82.1 ± 0.5	[31]
		484.81	89.7 ± 0.6	
$^{87}\text{Y}^m$	13.37 ± 0.03	380.79	78.1 ± 0.1	[31]
$^{88}\text{Y}^g$	106.7 ± 0.04	898.04	98.6 ± 0.3	[32]
		1836.06	99.2 ± 0.3	

TABLE II. Experimental cross section of the $^{84}\text{Sr}(p,\gamma)^{85}\text{Y}$ reaction

$E_{\text{c.m.,eff.}}$ [keV]	Cross section [μbarn]		
	Ground state	Isomer	Total
2962	574.8 ± 47.7	424.6 ± 99.7	999.4 ± 147.4
2836	210.5 ± 18.7	372.5 ± 65.8	583.0 ± 84.5
2764	133.5 ± 11.9	251.9 ± 47.5	385.4 ± 59.4
2664	140.0 ± 12.8	228.1 ± 44.1	368.1 ± 56.9
2566	95.4 ± 8.4	161.9 ± 30.3	257.3 ± 38.7
2468	87.0 ± 7.3	119.9 ± 28.0	206.9 ± 35.3
2368	67.6 ± 6.0	101.6 ± 20.2	169.2 ± 26.2
2267	34.5 ± 2.9	47.8 ± 11.6	82.3 ± 14.5
2170	29.6 ± 2.5	45.6 ± 10.7	75.2 ± 13.2
2071	18.5 ± 1.7	19.5 ± 5.2	38.0 ± 6.9
1973	13.0 ± 1.2	22.0 ± 5.3	35.0 ± 6.5
1871	7.54 ± 0.7	10.9 ± 2.7	18.4 ± 3.4
1774	4.39 ± 0.4	5.22 ± 1.5	9.61 ± 1.9
1673	0.851 ± 0.27	2.30 ± 0.9	3.15 ± 1.2

TABLE III. Experimental cross section of the $^{86}\text{Sr}(p,\gamma)^{87}\text{Y}$ reaction

$E_{\text{c.m.,eff.}}$ [keV]	Cross section [μbarn]		
	Ground state	Isomer	Total
2963	(496.0 ± 39.7)	(136.5 ± 10.2)	(632.5 ± 49.9)
2864	(311.6 ± 27.0)	(98.0 ± 7.98)	(409.6 ± 35.0)
2765	(227.6 ± 19.4)	(57.9 ± 4.71)	(285.5 ± 24.1)
2665	(172.4 ± 15.0)	(46.1 ± 3.86)	(218.5 ± 18.9)
2567	152.8 ± 12.8	38.8 ± 3.13	191.6 ± 15.9
2468	128.4 ± 10.5	40.7 ± 3.10	169.1 ± 13.6
2368	99.9 ± 8.52	31.7 ± 2.58	131.6 ± 11.1
2268	52.0 ± 4.15	10.7 ± 0.80	62.7 ± 4.95
2171	33.0 ± 2.65	10.3 ± 0.77	43.3 ± 3.42
2072	26.6 ± 2.06	8.39 ± 0.62	35.0 ± 2.68
1973	18.4 ± 1.43	5.11 ± 0.38	23.5 ± 1.81
1871	9.14 ± 0.72	2.13 ± 0.16	11.3 ± 0.88
1774	7.46 ± 0.59	1.49 ± 0.11	8.94 ± 0.70
1673	3.25 ± 0.25	0.462 ± 0.035	3.71 ± 0.29
1577	1.30 ± 0.10	0.206 ± 0.016	1.51 ± 0.12
1477	0.637 ± 0.05	0.095 ± 0.007	0.732 ± 0.06

TABLE IV. Experimental cross section of the $^{87}\text{Sr}(p,\gamma)^{88}\text{Y}$ reaction

$E_{\text{c.m.,eff.}}$ [keV]	Cross section [μbarn]
2963	629.2 ± 47.1
2864	340.3 ± 27.7
2765	332.5 ± 27.1
2665	262.7 ± 22.0
2567	232.0 ± 18.7
2469	156.0 ± 12.0
2369	121.0 ± 9.90
2268	67.7 ± 5.12
2171	48.6 ± 3.71
2072	30.1 ± 2.28
1973	15.7 ± 1.31
1871	8.18 ± 0.67
1775	5.04 ± 0.42
1674	2.03 ± 0.19
1577	1.39 ± 0.16

TABLE V. Astrophysical reaction rates in $\text{cm}^3 \text{s}^{-1} \text{mol}^{-1}$ derived from the new data.

T [10^9 K]	$^{84}\text{Sr}(p,\gamma)^{85}\text{Y}$		$^{86}\text{Sr}(p,\gamma)^{87}\text{Y}$		$^{87}\text{Sr}(p,\gamma)^{88}\text{Y}$	
	lab.	star	lab.	star	lab.	star
0.10	7.40E-27	7.40E-27	4.92E-27	4.92E-27	3.80E-27	3.80E-27
0.15	2.85E-21	2.85E-21	1.89E-21	1.89E-21	1.46E-21	1.46E-21
0.20	8.85E-18	8.85E-18	5.88E-18	5.88E-18	4.55E-18	4.55E-18
0.30	2.09E-13	2.09E-13	1.39E-13	1.39E-13	1.07E-13	1.07E-13
0.40	1.16E-10	1.16E-10	7.71E-11	7.71E-11	5.95E-11	5.95E-11
0.50	9.82E-09	9.82E-09	6.53E-09	6.53E-09	5.05E-09	5.05E-09
0.60	2.97E-07	2.97E-07	1.98E-07	1.98E-07	1.53E-07	1.53E-07
0.70	4.67E-06	4.67E-06	3.11E-06	3.11E-06	2.40E-06	2.40E-06
0.80	4.51E-05	4.51E-05	3.00E-05	3.00E-05	2.32E-05	2.32E-05
0.90	3.00E-04	3.00E-04	1.99E-04	1.99E-04	1.54E-04	1.54E-04
1.00	1.50E-03	1.50E-03	9.94E-04	9.94E-04	7.68E-04	7.68E-04
1.50	3.54E-01	3.54E-01	2.35E-01	2.35E-01	1.82E-01	1.82E-01
2.00	9.03E+00	9.12E+00	6.00E+00	6.06E+00	4.64E+00	4.68E+00
2.50	8.04E+01	8.26E+01	5.34E+01	5.49E+01	4.13E+01	4.24E+01
3.00	4.00E+02	4.21E+02	2.66E+02	2.80E+02	2.05E+02	2.16E+02
3.50	1.38E+03	1.50E+03	9.18E+02	9.94E+02	7.09E+02	7.68E+02
4.00	3.74E+03	4.15E+03	2.49E+03	2.76E+03	1.92E+03	2.13E+03
4.50	8.53E+03	9.56E+03	5.67E+03	6.35E+03	4.38E+03	4.91E+03
5.00	1.71E+04	1.90E+04	1.14E+04	1.26E+04	8.77E+03	9.77E+03
6.00	5.19E+04	5.27E+04	3.45E+04	3.50E+04	2.67E+04	2.70E+04
7.00	1.22E+05	9.56E+04	8.12E+04	6.35E+04	6.27E+04	4.91E+04
8.00	2.41E+05	1.19E+05	1.60E+05	7.94E+04	1.24E+05	6.14E+04
9.00	4.19E+05	1.13E+05	2.78E+05	7.53E+04	2.15E+05	5.82E+04
10.00	6.62E+05	9.03E+04	4.40E+05	6.00E+04	3.40E+05	4.64E+04

FIGURES

FIG. 1. Part of the chart of nuclides showing the investigated reactions and the decay scheme of reaction products. Stable nuclides are indicated by bold squares.

FIG. 2. Schematic view of the target chamber and the data acquisition.

FIG. 3. A typical RBS spectrum taken at $E_p=2.0$ MeV. The Sr and F peaks and the carbon edge are indicated.

FIG. 4. Off-line γ -spectrum taken after irradiation with 3 MeV protons. The γ -lines used for the analysis are indicated by arrows. All the other peaks correspond to either laboratory background and activity induced on target impurities or lines of Y isotopes which were not used for the analysis.

FIG. 5. Measured and calculated astrophysical S -factor of the $^{84}\text{Sr}(p,\gamma)^{85}\text{Y}$ reaction

FIG. 6. Measured and calculated astrophysical S -factor of the $^{86}\text{Sr}(p,\gamma)^{87}\text{Y}$ reaction. The measured points above the $^{87}\text{Sr}(p,n)^{87}\text{Y}$ threshold are put in parentheses.

FIG. 7. Measured and calculated astrophysical S -factor of the $^{87}\text{Sr}(p,\gamma)^{88}\text{Y}$ reaction.

FIG. 8. Potential comparison for $^{86}\text{Sr}(p,\gamma)^{87}\text{Y}$. Shown are the measured S -factors (EXP) and calculations using different potentials but otherwise unchanged nuclear input: PER [40], BEC [41], JLM [38], and ESW [39].

FIG. 9. Potential comparison for $^{87}\text{Sr}(p,\gamma)^{88}\text{Y}$. Shown are the measured S -factors (EXP) and calculations using different potentials but otherwise unchanged nuclear input: PER [40], BEC [41], JLM [38], and ESW [39].

















