Absolute cross sections of the ^{86}Sr(α,n)^{89}Zr reaction at energies of astrophysical interest

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Abstract. Absolute cross sections for the ^{86}Sr(α,n)^{89}Zr reaction at energies close to the Gamow window are reported. Three thin SrF$_2$ targets were irradiated using the 9 MV Tandem facility in IFIN-HH Bucharest that delivered α beams for the activation process. Two high-purity Germanium detectors were used to measure the induced activity of ^{89}Zr in a low background environment. The experimental results are in very good agreement with Hauser-Feshbach statistical model calculations performed with the TALYS code.

1. Introduction

Nucleosynthesis of the neutron-deficient isotopes, the so-called *p*-nuclei, from ^{74}Se to ^{196}Hg, which is bypassed by the *s*low and *r*apid processes [1, 2], is still an open question in the field of nuclear astrophysics.

Unlike most nuclei above iron, *p*-nuclei [3, 4] are produced through an alternative mechanism known as the *p* process, consisting of an astrophysical scenario in which multiple nucleosynthesis processes contribute.

P nuclei can be synthesised via proton capture of lighter nuclei [5–7], or via the γ process. The latter starts with sequences of (γ,n) reactions followed by (γ,p) and (γ,α) reactions or even β decays, as the neutron separation energy decreases [7].

The γ process involves about 2000 nuclei and almost 20000 nuclear reaction rates. Unfortunately, due to the lack of experimental data, description of the γ process relies heavily on theoretical reaction rates, which typically have large uncertainties. For p-nuclei, theoretical predictions are traditionally based on the Hauser-Feshbach statistical model [8, 9], which either overestimates [5,6,10–23] or underestimates [5,6,10,15–17,19–22,24,25] the experimental cross sections. In order to reduce these uncertainties, additional experimental data is needed. The latest are used to put constraints on the theoretical models, which in turn improves the predictive power for unmeasured reactions. The nuclear physics input parameters for the Hauser-Feshbach statistical model include particle and nucleus optical model potentials, nuclear level densities and gamma-ray strength functions.

The aim of the experiment described in this paper was to test such input parameters for an area of the nuclear chart which was very little studied, although nuclei are important in the *p* process: strontium. Its importance is due to the fact it has several isotopes in the middle zone delimited by ^{74}Se and ^{92}Mo, which is of great interest for the p-process close to the Gamow window energy range. This region exhibits differences up to a factor 10 between theoretical calculations and experimental data [21].

For the present experiment we intend to obtain α induced reactions on strontium isotopes in order to calculate the corresponding reaction cross sections.

A particular feature of strontium is that it is very reactive in atmospheric environment, so alternate methods to the pure element, such as the use of chemical compounds like SrF$_2$ or SrCO$_3$ have to be employed. For this experiment both kinds of targets were prepared and characterised by different methods (Alpha transmission measurements, X-ray diffraction (XRD) and Scanning Electron Microscopy/Energy Dispersive X-ray analyses (SEM/EDX)) in order to see which one is more adapted in terms of thickness, chemical purity and surface morphology. Chemical investigations are not the purpose of the present paper, we just intend to point out that SrF$_2$ target are suitable for our astrophysical experiment. Since the targets contain natural strontium, we were able to detect several (α,n) and (α,p) reactions on different isotopes. Data analysis is still in progress and here we only report results for the ^{86}Sr(α,n)^{89}Zr reaction for some of the measured incident energies. We believe that these first results will be very useful since only a few alpha capture reactions of this type have been studied [26].

The next sections provide details on the experiment, data acquisition and data analysis.

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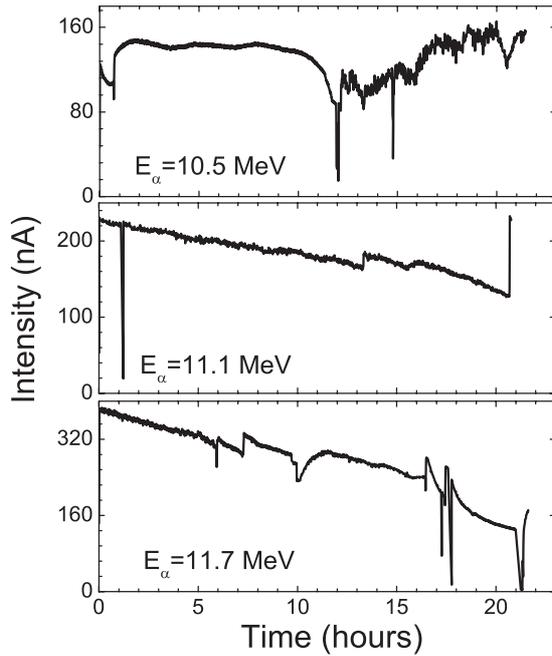
Figure 1. Time dependence of beam intensity monitored in steps of one second during each irradiation.

2. Experimental approach

For the data presented here we used three SrF_2 targets of thickness $\sim 2 \, mg/cm^2$ on Al backings of $0.5 \, mg/cm^2$. The preparation method was based on the evaporation-condensation procedure.

In the α irradiation experiment each target was supported first by a a titanium foil and then by an aluminium one. The Al backing respectively Al foils are used as incident α beam energy degraders and catchers for recoil nuclei from the SrF_2 targets, in order to estimate the recoil fraction. The stack was placed within a Faraday cup provided with a guard ring kept at $-300V$ in order to monitor the beam current. The energy of the incident alpha beams was in the range of 10.5–11.7 MeV; the irradiation time was about 23 hours. This energy range is close to the estimated position of the Gamow window at 2.9 GK (6.93 MeV with a width of 2.44 MeV).

In order to check the accuracy of the measured cross-sections titanium served as a reference for the beam current integration. The absolute cross sections obtained for the $^{48}Ti(\alpha,n)^{51}Cr$ reaction were compared with those from [27–31].

Besides sample weighing, the α transmission measurement technique was applied; Monte Carlo simulations with the SRIM package (The Stopping and range of ions in matter) [32] were performed, particularly using TRIM calculations (transport of ions), in order to obtain an accurate value for the target thickness, which is a very important parameter in the cross section determinations.

TRIM calculations were also used to estimate the alpha beam energies within the targets. The minima and maxima provided the energy range through the targets, while the mean value of the energy provided the target irradiation energy. - The distribution of the medium energy of alpha particle in each foil was simulated using TRIM code, and then the distribution was fitted with Gaussian function to get the mean value.
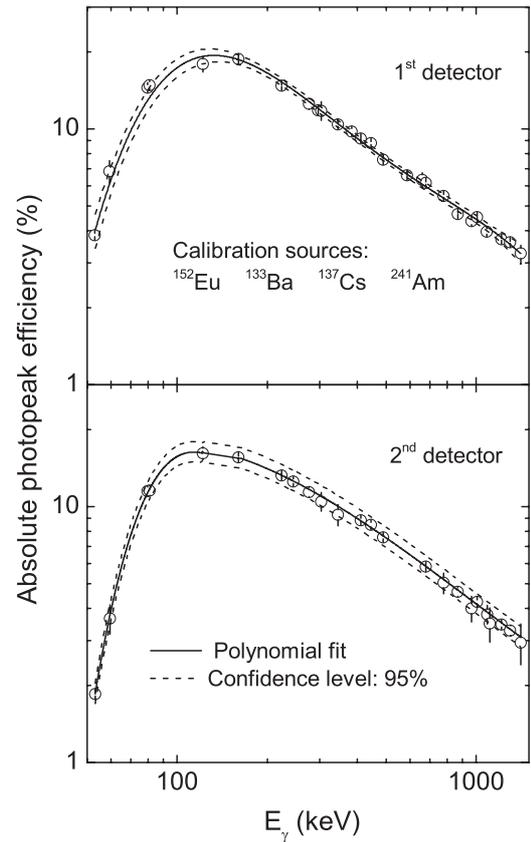
Figure 2. Absolute photopeak efficiency for both HPGe detectors used in our experiment.

Table 1. Nuclear data used to obtain experimental (α,n) cross sections on ^{86}Sr and ^{48}Ti isotopes [34].

Nuclear reaction	$T_{1/2}$ (hours)	E_γ(keV)	$I_\gamma(\%)$
$^{86}Sr(\alpha,n)^{89}Zr$	78.41(12)	909.15 (15)	99.04
$^{48}Ti(\alpha,n)^{51}Cr$	664.82(11)	320.0824(4)	9.91

Particular attention was paid to the monitoring of the α beam intensity with an ORTEC 439 integrator. Time dependence of this current integration is shown in Fig. 1.

Measurements of the characteristic γ-rays of the activated targets were performed with two HPGe detectors of high relative efficiency (50% and 100%) in close geometry. Minimising the distance from the detector to the sample generates higher coincidence rates for the true coincidence summing. A dedicated Monte Carlo software (GESPECOR [33]) for summing corrections was used in order to obtain the appropriate correction coefficients for the efficiency. The background was severely lowered by using the standard lead shielding endowed with successive layers of cooper and aluminium on the inside. The efficiency calibration of the HPGe detectors was achieved with point sources of ^{137}Cs, ^{241}Am, ^{133}Ba and ^{152}Eu, for which the measurement geometry was the same as the target one. The calibration curve for the HPGe detectors can be seen in Fig. 2.

The amount of populated ^{89}Zr nuclei as a function of the irradiation time, waiting time and the measuring time is related to the peak area of the concerned γ radiations by:

$$A_i = I_{\gamma_i}\epsilon_i N^{dez}(t_w, t_m), \qquad (1)$$

Table 2. Absolute cross sections obtained for the ^{86}Sr$(\alpha,$n$)^{89}$Zr and ^{48}Ti$(\alpha,$n$)^{51}$Cr reactions.

Nuclear reaction	E_{lab} (MeV)	$E_{c.m}$ (MeV)	σ (mb)
^{86}Sr$(\alpha,$n$)^{89}$Zr	10.18 ± 0.16	9.72 ± 0.15	16.4 ± 0.8
	10.79 ± 0.15	10.31 ± 0.14	34.0 ± 1.7
	11.40 ± 0.14	10.89 ± 0.13	71.1 ± 3.6
^{48}Ti$(\alpha,$n$)^{51}$Cr	7.26 ± 0.47	6.70 ± 0.43	85.1 ± 5.0
	8.28 ± 0.38	7.64 ± 0.35	247.2 ± 14.5
	9.13 ± 0.39	8.43 ± 0.36	370.4 ± 21.7
	9.75 ± 0.33	8.99 ± 0.30	420.4 ± 24.6
	10.41 ± 0.32	9.61 ± 0.29	407.4 ± 31.6
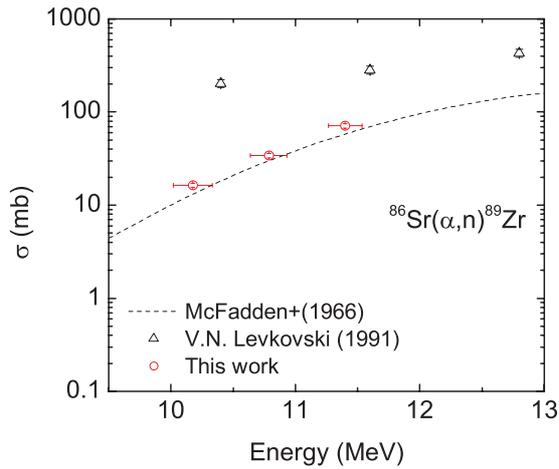
Figure 3. Experimental cross sections for ^{86}Sr$(\alpha,$ n$)^{89}$Zr reactions compared with theoretical ones obtained with the McFadden OMP parameters [39].

Figure 4. Our experimental cross sections for the ^{48}Ti$(\alpha,$ n$)^{51}$Cr reaction obtained from the Ti foils from the irradiated stack, compared with [27–31].
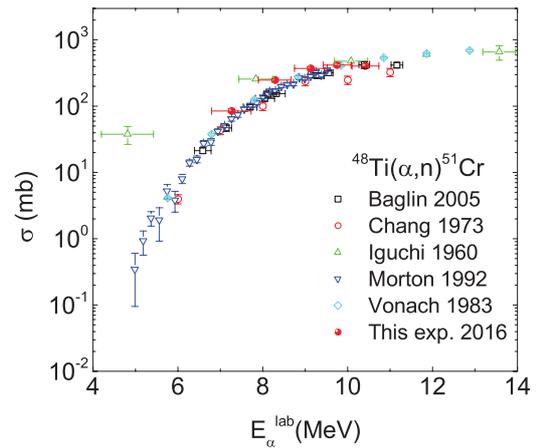
where I_{γ_i} represents the absolute intensity of the γ_i radiation, ϵ_i is the absolute peak efficiency, t_m and t_w are the measuring and waiting time intervals, while N^{dez} is the amount of the populated nuclei.

Table 1 summarises the data involved in cross section calculations for the radioisotopes of interest. Data analysis for the variety of γ spectra in our experiment was performed with the GASPware package.

3. Results

The preliminary absolute cross sections obtained in this work are summarised in Table 2.

Theoretical cross section values for the ^{86}Sr$(\alpha,$n$)^{89}$Zr and ^{48}Ti$(\alpha,$n$)^{51}$Cr reactions were obtained in the framework of Hauser-Feshbach Statistical model using TALYS code [35] (version 1.8). The TALYS package consists of six level density models, five E_1 γ-strength functions models and five models for the α-optical potential(OMP). These three input parameters are of high importance in the prediction of theoretical results; further in the present study the consistency of the TALYS output was tested using as inputs for the parameters of these quantities: the Kopecky-Uhl [36] generalised Lorentzian for the γ-strength function, the Constant temperature and Fermi gas model [37] in the case of level densities, the Koning and Delaroche [38] OMP for neutrons and protons, and the McFadden and Satchler [39] OMP for the alpha particles. The McFadden and Satchler set of OMP is traditionally the

most commonly used in the statistical model calculations for nuclear astrophysics.

The absolute cross sections are shown in Fig. 3 along those of V. N. Lekovski [26] in the same region and with the Hauser-Feshbach model based theoretical estimations that were computed as described above. This figure shows a reasonable agreement between the theoretical and the present measured values for the ^{86}Sr$(\alpha,$n$)^{89}$Zr reaction and a difference of up a factor 10 with data reported by V. N. Lekovski [26] which could not be explained.

Figure 4 shows the experimental cross sections for the ^{48}Ti$(\alpha,$n$)^{51}$Cr reaction together with experimental data available from the literature [27–31].

The agreement between our measured cross sections for the ^{48}Ti$(\alpha,$n$)^{51}$Cr reaction and the corresponding values from the EXFOR database proves the validity of the procedure used to determine the cross-sections for those reactions.

4. Summary

The α induced ^{86}Sr$(\alpha,$n$)^{89}$Zr reaction was measured at energies close to the astrophysical range. Cross-sections of the ^{48}Ti$(\alpha,$n$)^{51}$Cr reaction were determined in the same experiment and used to ascertain the accuracy of the cross-section determination procedure. The measured absolute cross section values are reasonably well matched by statistical Hauser-Feshbach model calculations.

References

[1] F. Kappeler et al., Rev. Mod. Phys. **83**, 157 (2011)

[2] M. Arnould et al., Phys. Rep. **450**, 97 (2007)

[3] M. Arnould and S. Goriely, Phys. Rep. **384**, 1 (2003)

[4] T. Rauscher et al., Rep. Prog. Phys. **76**, 066201 (2013)

[5] Gy. Gyürky et al., J. Phys. G: Nucl. Part. Phys. **37**, 115201 (2010)

[6] Gy. Gyürky et al., Phys. Rev. C **86**, 041601(R) (2012)

[7] L. Netterdon et al., Phys. Rev. C **91**, 035801 (2015)

[8] L. Wolfenstein, Phys. Rev. C **82**, 690 (1951)

[9] W. Hauser and H. Feschbach, Phys. Rev. **87**, 366 (1952)

[10] W. Rapp et al., Phys. Rev. C **78**, 025804 (2008)

[11] W. Rapp et al., Astrophys. J. **653**, 474 (2006)

[12] E. Somorjai et al, Astron. Astrophys. **333**, 1112 (1998)

[13] G.G. Kiss et al., Phys. Lett. B **695**, 419 (2011)

[14] G.G. Kiss et al., Phys. Rev. C **86**, 035801 (2012)

[15] C. Yalcin et al., Phys. Rev. C **79**, 065801 (2009)

[16] Gy. Gyürky et al., Phys. Rev C **74**, 025805 (2006)

[17] S. Harissopulos et al., Nucl. Phys. A **758**, 505c (2005)

[18] A. Sauerwein et al., Proc. Science PoS (NIC XI), 244 (2011)

[19] W. Rapp et al., Phys. Rev C **66**, 015803 (2002)

[20] N. Ozkan et al., Phys. Rev. C **75**, 025801 (2007)

[21] S.J. Quinn et al., Phys. Rev. C **92**, 045805 (2015)

[22] A. Simon et al., Phys. Rev. C **92**, 025806 (2015)

[23] M.S. Basunia et al., Phys. Rev C **71**, 035801 (2005)

[24] Zs. Fülöp et al., Z. Phys. A **355**, 203–207 (1996)

[25] I. Cata-Danil et al., Phys. Rev. C **78**, 035803 (2008)

[26] V.N. Levkovski, Activation cross section nuclides of average masses (A = 40–100) by protons and alpha-particles with average energies (E = 10–50 MEV), Act.Cs.By Protons and Alphas, Moscow (1991)

[27] A. Iguchi, H. Amano, and S. Tanaka, J. Atomic Energy Society Japan **2**, 682 (1960)

[28] C.N. Chang, J.J. Kent, J.F. Morgan, and S.L. Blatt, Nucl. Inst. Meth. **109**, 327-331 (1973)

[29] H. Vonach, R.C. Haight, and G. Winkler, Phys. Rev. C **6**, 2278 (1983)

[30] A.J. Morton et al., Nucl. Phys. A **537**, 167–182 (1992)

[31] C.M. Baglin et al., AIP Conference Proceedings **769**, 1370 (2005)

[32] J.F. Ziegler, J.P. Biersack, and U. Littmark, The Stopping and Range of Ions in Solids (Pergamon, New York, 1985)

[33] O. Sima, D. Arnold, and C. Dovlete, J. Radioanal. Nucl. Chem. **248**(2), 359 (2001)

[34] IAEA-NDS (International Atomic Energy Agency-Nuclear Data Services) https://www-nds.iaea.org

[35] A.J. Koning, S. Hilaire and M.C. Duijvestijn, "TALYS-1.0", Proceedings of the International Conference on Nuclear Data for Science and Technology, April 22-27, 2007, Nice, France, editors O.Bersillon, F.Gunsing, E.Bauge, R.Jacqmin, and S.Leray, EDP Sciences, 2008, p. 211–214

[36] J. Kopecky and M. Uhl, Phys. Rev C **41**, 1941 (1990)

[37] A. Gilbert and A.G.W. Cameron, Can. J. Phys. **43**, 1446 (1965)

[38] A.J. Koning and J.P. Delaroche, Nucl. Phys. A **713**, 231 (2003)

[39] L. McFadden, and G.R. Satchler, Nucl. Phys. **84**, 177 (1966)