Proton Capture on ^{64}Zn, ^{66}Zn, and ^{67}Zn between 1 and 3 MeV

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Cross sections were determined by the activation technique for the reactions ^{64}Zn(p,γ)^{65}Ga, ^{66}Zn(p,γ)^{67}Ga, and ^{67}Zn(p,γ)^{68}Ga in the center of mass energy range between 1 and 3 MeV using the proton beam of the Van de Graaff accelerator at KIPT, Kharkiv. Thin enriched targets of zinc isotopes on thick tantalum backings were used in the experiment. The radioactivities of ^{65}Ga, ^{67}Ga, and ^{68}Ga were measured by high-resolution γ-ray spectrometry. S-factors and reaction rates were derived from the experimental cross sections and compared with the statistical theory predictions using the new computer code NON-SMOKER^{WEB}. Despite the largely different magnitudes of the cross sections of the first two reactions, theory reproduces the experimental values equally well. Best agreement of the predictions with the experimental data was achieved with a modification of the optical model potential and variation of radiative widths The sensitivity of the results on different theory parameters is studied. This is an important test of the model for proton capture at energies relevant in *p*-process nucleosynthesis.

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1. Introduction

Simulation of nucleosynthesis in stellar environments requires knowledge of astrophysical S-factors and reaction rates of a large amount of nuclear reactions induced by different particles at low energies. Due to the absence of a Coulomb barrier in neutron capture reactions, the so-called slow (*s*) and rapid (*r*) processes give the major contribution to the stellar synthesis of isotopes of the medium heavy and heavy elements. However, there is a group of natural isotopes (called *p-nuclei*) which cannot be produced in this scenario since they are screened by their stable isobars from the β^- decay side of the valley of stability. It is assumed that a special mechanism called *p*-process can be responsible for the production of these nuclei located on the proton-rich side of the stable isotopes between ^{74}Se and ^{196}Hg. The *p*-process scenario involves complicated sequences of photonuclear reactions which occur on preexisting more neutron-rich nuclei at high stellar temperatures T = (2-3) GK (GK=10^9 K) in O/Ne layers of massive stars during their presupernova phase or in the explosion as type II supernovae [1]. The photodisintegration rates can be derived from the *stellar* capture rates by applying detailed balance. Large efforts aimed at measurements of low energy charged particle reaction cross sections were undertaken by several groups in Europe and USA (see, e.g., [2-5] and references therein) in recent years. However, current databases (e. g. KADoNIS [6]) show the scarcity of available relevant data. These circumstances call for new measurements and underline the significance of theoretical calculations. The statistical model of Hauser-Feshbach (H-F) is usually used for this aim. There are computer codes like NON-SMOKER [7,8] and MOST [9] implementing H-F theory which are especially tailored for the calculation of astrophysical cross sections and reaction rates. These codes, in turn, can be put to the test by comparison with known experimental data.

To derive the astrophysical S-factors and reaction rates of the proton capture reactions ^{64}Zn(p,γ)^{65}Ga, ^{66}Zn(p,γ)^{67}Ga, and ^{67}Zn(p,γ)^{68}Ga we have measured their cross sections in the proton energy range between 1 and 3 MeV which covers a considerable part of the Gamow window for Zn isotopes: the lower edge amounts to 1.14 MeV at 1.8 GK stellar temperature and the upper one to 3.59 MeV at 3.3 GK. The experimental data are compared with H-F statistical theory predictions using the new computer code NON-SMOKER^{WEB} v5.2.1w [10].

2. Experimental

To measure the cross sections of the above (p,γ)-reactions by the activation technique the targets were irradiated with the proton beam of the Van de Graaff accelerator of the Kharkiv Institute of Physics and Technology. Metallic layers 0.5 to 1.5 mg/cm^2 in thickness and 17 mm in diameter were made from enriched zinc isotopes (supplied by the State Fund of Stable Isotopes, Russia) by vacuum evaporation onto 500 μm tantalum backings. Enrichment and major contaminants of the targets are listed in Table 1. The targets were mounted in a Faraday cup with secondary electron suppression. The beam current of typically 3 to 4 μA was measured by charge integration in one-minute intervals to be able to take into account fluctuations. The proton energy ranges (0.99-2.81) MeV, (1.20-2.68) MeV, and (1.25-2.93) MeV for ^{64}Zn, ^{66}Zn, and ^{67}Zn, respectively, were covered in energy steps of 50 to 130 keV. The energy stability of the incident beam was better than 1 keV and the proton energy losses in the Zn layers were between 10 and 110 keV, depending on a target and beam energy.

TABLE 1. Enrichment of zinc target material (in percent)

Mass	64	66	67	68	70
64	**98.3**	1.1	0.2	0.4	<0.1
66	2.1	**96.9**	0.4	0.6	<0.1
67	5.6	7.1	**39.8**	47.2	0.3

The activity of each irradiated target was measured with a Ge(Li) detector located at a low background counting area far from the accelerator. The targets were placed at a distance assuring a low dead time (<4%). The half-lives, energies, and branching ratios of the strongest γ-transitions following the β-decay of the produced ^{65}Ga, ^{67}Ga, and ^{68}Ga isotopes are listed in Table 2 [11]. Additionally a calibrated thin HPGe detector was used to discriminate the 91 and 93 keV lines from the decay of ^{67}Ga. The data of both detectors were in accordance with each other. Experimental cross sections of the reactions studied were derived using the activation equation, taking into account the decay of the activity during irradiation, cooling, and measurement time.

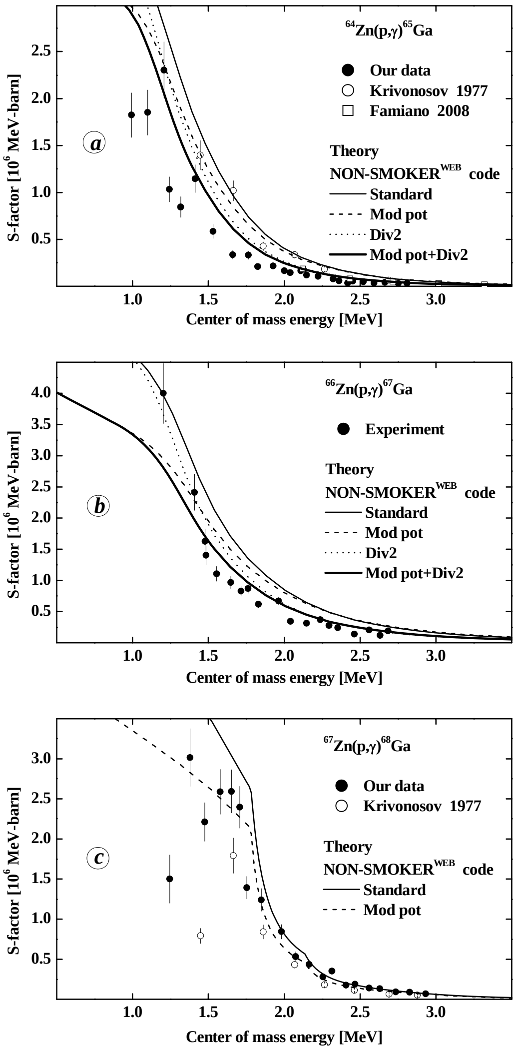
TABLE 2. Spectroscopic data of the residual gallium nuclei used in the data analysis [11]

Isotope	Half-life	E_γ, keV	$I_\gamma(\Delta I_\gamma)$, %
^{65}Ga	15.2 min	115 153	54(10) 8.9(9)
^{67}Ga	3.26 d	91 93 185 300 394	3.11(4) 38.81(3) 21.41(1) 16.64(12) 4.56(24)
^{68}Ga	67.7 min	1077	3.22(3)

3. Experimental Results and Theoretical Predictions

The experimental astrophysical S-factors of the ^{64}Zn(p,γ)^{65}Ga, ^{66}Zn(p,γ)^{67}Ga, and ^{67}Zn(p,γ)^{68}Ga reactions (in 10^6 MeV·barn) together with theoretical predictions of the new H-F code NON-SMOKER^{WEB} v5.2.1w using different inputs for nuclear properties are compared in Fig. 1 with previous data [12,13]. The results of the standard calculations with the JLM optical potential [14] are given by the thin solid lines while the dashed lines show the quantities calculated with a new low-energy modification of potential [15,16] with subsequent improvement to Lane-consistency [17]. Despite large differences in magnitude between the experimental S-factors of the reactions studied, the correlation between theory and experiment is similar. As expected, the optical potential modification is more essential at the lower energies of incident protons drawing the calculated S-factor values nearer to the experiment. Similarly to the earlier determined ^{70}Ge(p,γ)^{71}As reaction [5] the impact of the γ-width variation is more important in the higher energy range: decreasing the averaged width of the γ-channel by a factor of 2 appreciably approaches the theoretical predictions (the dotted curves) to the experimental points in the high energy part of panels *a* and *b* of Fig. 1. The thick curves of these panels depict

Figure 1. Astrophysical S-factors of the reactions $^{64}Zn(p,\gamma)^{65}Ga$, $^{66}Zn(p,\gamma)^{67}Ga$, and $^{67}Zn(p,\gamma)^{68}Ga$. Points are the experimental values derived from the cross sections, curves are the statistical theory predictions at different combinations of input parameters (see text).



the results of the theoretical calculations using both the modified potential and the reduced gamma strengths. As it can be seen in panel *c* the gamma strength had not to be varied for the $^{67}Zn(p,\gamma)^{68}Ga$ reaction.

From the experimental astrophysical S-factors of the proton capture reactions studied the reaction rates were derived in the temperature range between 1.8 and 3.3 GK. Since the higher energy edge of the Gamow window amounts to 3.59 MeV at T=3.3 GK, the theoretical S-factor values were used in the rate calculations above 2.81, 2.68, and 2.93 MeV proton energies for the ^{64}Zn, ^{66}Zn, and ^{67}Zn targets, respectively. The contributions of these energy intervals to the reaction rate values are 14, 14, and 3%, at 3.3 GK for the above targets, respectively, and are certainly less at lower temperatures. The theory overestimates the experimental reaction rates by (47-39)% and (15-23)% for the $^{64}Zn(p,\gamma)^{65}Ga$ and $^{66}Zn(p,\gamma)^{67}Ga$ reactions, respectively, and underestimates them by (7-18)% for the $^{67}Zn(p,\gamma)^{68}Ga$ reaction in the considered temperature range.

4. Conclusion

The cross sections of the proton capture reactions ^{64}Zn(p,γ)^{65}Ga, ^{66}Zn(p,γ)^{67}Ga, and ^{67}Zn(p,γ)^{68}Ga have been measured by the activation technique and the astrophysical S-factors were derived in the center of mass energy range (0.99-2.81) MeV, (1.20-2.68) MeV, and (1.25-2.93) MeV, respectively, and compared with previous data. A satisfactory description of the astrophysical S-factors by the statistical model code NON-SMOKER^{WEB} v5.2.1w was obtained by modification of the optical model potential and variation of radiative widths for the former two reactions, whereas only the optical potential had to be modified for the last one. The optical potential modification plays the important role in the low energy range of the studied interval while the variation of the radiative width affects the cross section at higher energies.

The present calculations overestimate the astrophysical reaction rates for the ^{64}Zn(p,γ)^{65}Ga and ^{66}Zn(p,γ)^{67}Ga to a smaller extent than the previous published ones [7,8] which did not provide the modification of the JLM potential and the variation of the γ-widths. The reaction rates of the ^{67}Zn(p,γ)^{68}Ga reaction are slightly underestimated by the present calculations.

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