CROSS SECTIONS OF LOW ENERGY (P,γ) AND (P,N)-REACTIONS ON SELENIUM ISOTOPES FOR THE ASTROPHYSICAL γ-PROCESS

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The cross sections of the proton radiative captures $^{74}Se(p, \gamma)^{75}Br$, $^{76}Se(p, \gamma)^{77}Br$, and $^{77}Se(p, \gamma)^{78}Br$ as well as the threshold $^{77}Se(p, n)^{77}Br$ and $^{80}Se(p, n)^{80}Br$ reactions have been measured in the astrophysical relevant energy range (up to 3.6 MeV) using the Kharkiv and Debrecen Van de Graaff accelerators and thin targets of enriched selenium isotopes. The activation technique using high resolution gamma spectrometry of reaction products was applied to determine the cross sections of the above reactions. Astrophysical S-factors and reaction rates were derived from the experimental values of the cross sections. The experimental data are compared with the earlier measurements if available and with the statistical theory predictions using the NON-SMOKER computer code with the standard parameter set. Good agreement was found in general.

1. Introduction

The origin of the chemical elements is ascribed to a number of astrophysical nuclear mechanisms occurring in hot stars over a stellar evolution. Isotopes up to the iron-nickel region are created in hydrostatic nuclear burning, encompassing hydrogen, helium, carbon, neon, oxygen, and silicon burning. The overwhelming majority of heavier elements are produced in stars via *slow* (*s*) and *rapid* (*r*) processes with neutron capture and β^- decays [1]. However, there exist 35 proton rich stable isotopes in the mass number region between ^{74}Se and ^{196}Hg which are screened from β^- decays by their stable isobars. These isotopes are called *p-nuclei* and, in addition to other nucleosynthesis processes [2], can be synthesized in the so-called *γ-process*, involving photodisintegration of preexisting seed nuclei by (γ, n)-, (γ, p)- and (γ, α)-reactions in explosive O/Ne-burning of core-collapse supernovae [2] at stellar temperatures of 2 - 3 GK (GK = 10^9 Kelvin).

The comparison to natural abundances of stable isotopes is a test of nucleosynthesis models. Nuclear physics has to supply cross sections for a large network of nuclear reactions. Reaction rates are derived from the cross sections and enter the differential equations [3] of nucleosynthesis models to describe the temperature dependence of the isotopic composition in a stellar medium. Knowledge of (p, γ)-reaction cross sections are important because the photonuclear reaction rates can be derived from the *stellar* capture rates by applying the detailed balance theorem. (p, n)-Reactions, as it was demonstrated recently [4], also affect the abundances of light p-nuclei (up to Sn) in the γ-process and thus they have a direct impact on γ-process studies. Furthermore, they can be used to study the proton optical potential which determines the astrophysically relevant low-energy (p, γ) cross sections. In spite of large efforts concerning experimental measurements of low energy charged particle reaction cross sections undertaken by several groups of Europe and USA in the last decade (see [5 - 13] and references therein), current databases (cf. KADoNIS database [14]) show the need for further measurements because the quantity of required reactions is estimated as tens of thousands. Since the majority of these reactions occur on radioactive nuclei in the stellar interior, they cannot be measured in the laboratory and therefore theoretical calculations of nuclear reaction cross sections in the framework of the statistical Hauser-Feshbach (H-F) model [15] remain important. The computer codes [16-18] implementing H-F theory can be put to test by comparison with known experimental data.

In this report we present the results of the cross section measurements of the proton capture reactions $^{74}Se(p, \gamma)^{75}Br$, $^{76}Se(p, \gamma)^{77}Br$ and $^{77}Se(p, \gamma)^{78}Br$ as well as preliminary results on the $^{77}Se(p, n)^{77}Br$ and $^{80}Se(p, n)^{80}Br$ reactions in the astrophysically relevant energy range.

2. Experimental

The experimental measurements were carried out employing Van de Graaff (VdG) accelerators of NSC KIPT (Kharkiv) and ATOMKI (Debrecen). The former of these facilities supplies the incident proton energies up to 3.0 MeV, the latter one up to 3.6 MeV. The astrophysically interesting energy interval of reactions is determined by the Gamow window [19] which is 1.3 - 3.8 MeV for the proton reactions on selenium isotopes at the stellar temperatures 1.8 - 3.3 GK typical for γ-process. So these two accelerators practically fully cover this energy interval.

The activation technique was used to measure the cross sections of the proton induced reactions. The targets represented thin (0.3 - 1.0 $mg \cdot cm^{-2}$) layers of enriched selenium isotopes electrolitically deposited on thick (500 μm) tantalum foils. Enrichments of the ^{74}Se, ^{76}Se, ^{77}Se, and ^{80}Se targets amounted to 33.8, 80.1, 76.0, and 95.7 %, respectively.

The activity of each irradiated target was measured with large volume Ge(Li) (at Kharkiv) and HPGe (in Debrecen) detectors located at a low counting areas far from accelerators. The absolute efficiencies of the detectors were measured with standard sources in the same geometry as used for the measurements. The half-lives, energies and branching ratios of the strongest γ-transitions following the β-decay of the produced bromine radioactive isotopes are listed in the Table [20].

Spectroscopic data of residual bromine nuclei used in the data analysis			
Isotope	Half-life	E_γ, keV	$I_\gamma(\Delta I_\gamma)$, %
^{75}Br	96.7 min	287 377 428 432	88(6) 3.9(3) 4.4(5) 3.9(3)
^{77m}Br	4.28 min	106	13.8(4)
^{77g}Br	57.036 h	239 297 521	23.1(5) 4.16(22) 22.4(8)
^{78}Br	6.45 min	614	13.6(4)
^{80m}Br	4.42 h	37	39.1(8)
^{80g}Br	17.68 min	616 666	6.7(7) 1.08(14)

Experimental cross sections of the reactions studied were derived using the activation equation, taking into account the decay of activity during irradiation, cooling, and measurement time. The total cross sections of the ^{74}Se(p, γ)^{75}Br reaction were determined analyzing the intensities of 287, 377 and (428 + + 432) keV γ-peaks in the measured γ-spectra. The ^{77}Br nuclide has two long-lived states. The total cross sections of the ^{76}Se(p, γ)^{77}Br and ^{77}Se(p, n)^{77}Br reactions were determined using the γ-spectra measured after long cooling time when the 4.28 min isomer entirely decayed to the ground state by only the isomeric transition. However, a specified difficulty to determine the individual cross sections of these two reactions lies in the fact that each of them produces the same residual nucleus at the incident proton energies exceeding the threshold value E_{th} = 2.146 MeV of the latter one, the excitation function of which is sharply increasing depending on the bombarding energy. It is the measurements on both enriched targets (^{76}Se and ^{77}Se) that enable us to calculate an effective cross section σ_{eff} of the ^{77}Br production for each target and then to derive individual cross sections for each reaction.

For the pair of the ^{76}Se and ^{77}Se enriched targets, irradiated by protons of the same incident energy, the equation system can be worked out:

$$C_{in\,76}^{76}\cdot\sigma\left[{}^{76}Se(p,\gamma)^{77}Br\right]+C_{in\,76}^{77}\cdot\sigma\left[{}^{77}Se(p,n)^{77}Br\right]=\sigma_{eff}\quad for\ {}^{76}Se\quad target,$$

$$C_{in\,77}^{76}\cdot\sigma\left[{}^{76}Se(p,\gamma)^{77}Br\right]+C_{in\,77}^{77}\cdot\sigma\left[{}^{77}Se(p,n)^{77}Br\right]=\sigma_{eff}\quad for\ {}^{77}Se\quad target,$$

where $C_{in\,76}^{76}$ and $C_{in\,76}^{77}$ are the ^{76}Se and ^{77}Se isotopes concentrations in the ^{76}Se isotope enriched target, and $C_{in\,77}^{76}$ and $C_{in\,77}^{77}$ are the ^{76}Se and ^{77}Se isotopes concentrations in the ^{77}Se isotope enriched target, respectively. The decision of this equation system results the individual cross sections for both ^{76}Se(p, γ)^{77}Br and ^{77}Se(p, n)^{77}Br reactions beyond the threshold energy of the latter one.

The ^{80}Se(p, n)^{80}Br reaction has the threshold value E_{th} = 2.69 MeV and its cross sections were determined only from the data of the Debrecen VdG accelerator. The ^{80}Br nuclide has two long-lived states (see Table) connected each with other by the isomeric transition of the 39 keV energy. Since the half-life of the isomeric state is longer ($T_{1/2}$ = 4.42 h) than ground one ($T_{1/2}$ = 17.68 min) we had to use the activation equation for genetically connected activities determining the production cross sections of the lower state. Below the total cross sections ($\sigma = \sigma_m + \sigma_g$) of the (p, n)-reaction are presented and the contribution of the high-spin ($J^\pi = 5^-$) isomeric state into the total cross sections amounted to (1.4 - 13) % for the incident proton energies 3.1 - 3.6 MeV. It is in accordance with the isomeric ratios measured for this reaction at slightly higher energies [21].

3. Results and discussion

The results of our investigation of (p, γ)-reactions are presented in Fig. 1. The excitation functions of the ^{74}Se(p, γ)^{75}Br, ^{76}Se(p, γ)^{77} and ^{77}Se(p, γ)^{78}Br reactions are shown in the left column of the panels and the astrophysical S-factors in the right one, respectively. The experimental values of the studied quantities are given by the points with uncertainty bars, while the theoretical ones calculated with the NON-SMOKER code [16, 17] are depicted by curves.

For the ^{74}Se(p, γ)^{75}Br reaction the experimental cross sections measured at Kharkiv and Debrecen VdG accelerators are presented by the dark circles and square points, respectively (panel *a*). The light points show the experimental data measured earlier on the natural selenium targets [9]. All three sets of the experimental data are in satisfactory agreement while the theoretical prediction has a tendency of a slight underestimation at the higher energies. A small difference between our present and Gyürky et al. data is seen for the astrophysical S-factor (panel *b*) at the smallest energies. The relevant energy window for this reaction in the *γ*-process is between 1.2 and 3.1 MeV [22]. The data allow computing the rate to almost the lowest temperature and it is found to be in excellent agreement with the prediction because the underestimation at higher energies enters the rate only in a suppressed manner at *γ*-process temperatures.

The cross sections of the ^{76}Se(p, γ)^{77}Br reaction (panel *c*, the same type of points) also represent a smooth excitation function. The present results are in good agreement with the earlier publication [9] (the circle light points) only to the threshold of the ^{77}Se(p, n)^{77}Br reaction. As it was pointed out in the work [9], at the higher energies the cross section values measured with natural targets are actually the weighted sum of the two cross sections:

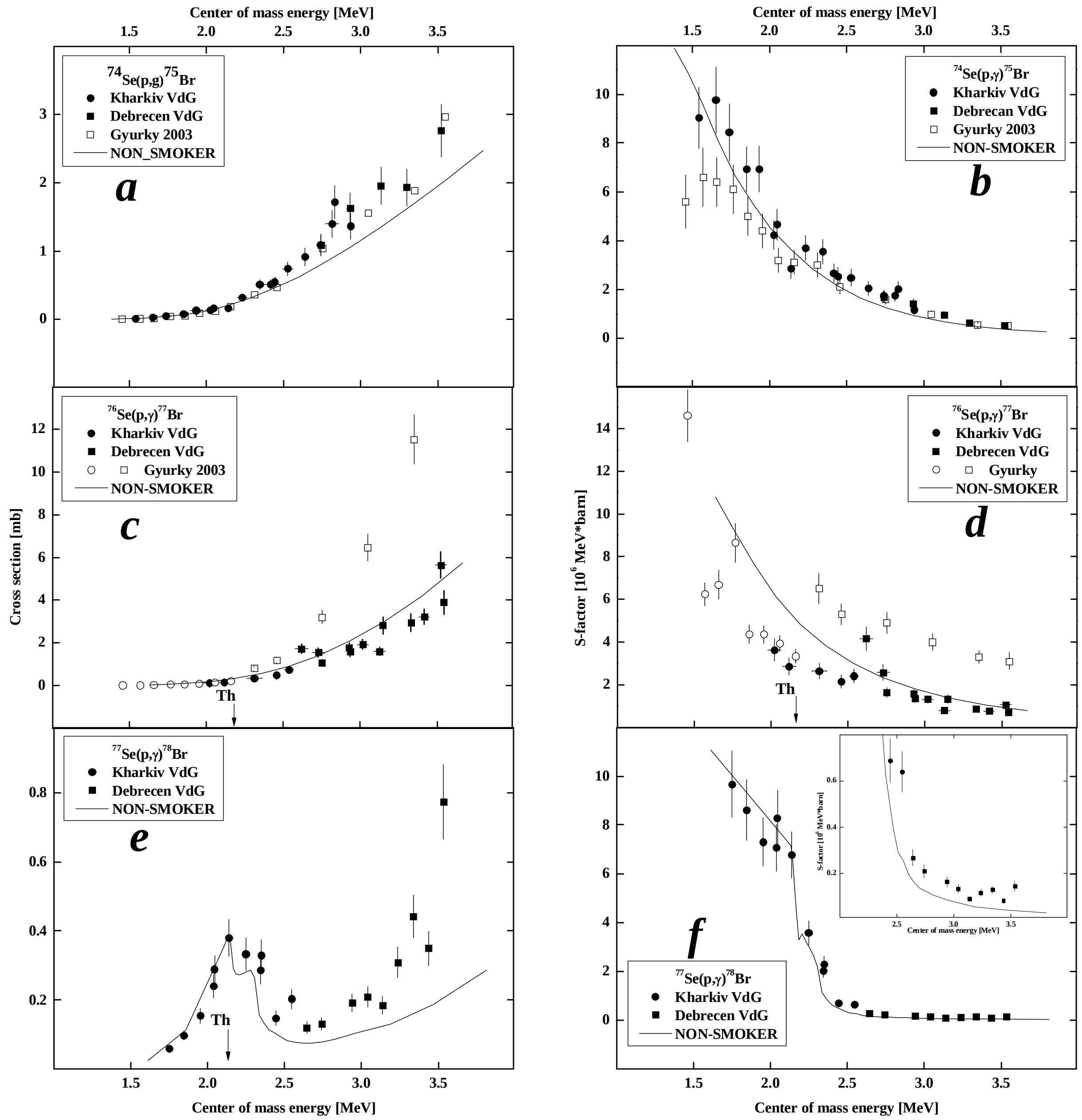

Fig. 1. Cross sections (*left column*) and astrophysical S-factors (*right column*) for the reactions ^{74}Se(p, γ)^{75}Br (*upper row*), ^{76}Se(p, γ)^{77}Br (*middle row*) and ^{77}Se(p, γ)^{78}Br (*lower row*). Points are the experimental values; curves are the statistical theory predictions.

$\sigma_{exp} = \sigma[^{76}\mathrm{Se(p, \gamma)}^{77}\mathrm{Br}] + 0.82\cdot\sigma[^{77}\mathrm{Se(p, n)}^{77}\mathrm{Br}]$. Therefore, disagreement for the S-factors at the higher energies (panel *d*) is expected. The theoretical prediction is in good agreement with the VdG data above 2.5 MeV. The prediction is overestimating the S-factors around the neutron threshold and below whereas it is in good agreement with experiment at the higher energies. However, at the lowest energies the data show some structure which can never be reproduced by a smooth statistical model S-factor. Therefore it is not possible to straightforwardly compare theory and experiment and to derive a renormalization for theory at low energy.

The results of our measurements and theoretical calculations for the ^{77}Se(p, γ)^{78}Br reaction are shown in panels *e, f* of Fig. 1. The excitation function of this reaction (panel *e*) has a distinctive maximum which is the Wigner cusp [23] located at the threshold energy of the competitive ^{77}Se(p, n)^{77}Br reaction. It represents a powerful confirmation of consistency and predictive power of the H-F theory. The relation between the experimental and theoretical excitation functions of this reaction is considered by us as satisfactory although the theory underestimates the cross sections and S-factor (the insert of panel *f*) at the higher energies. However, the upper edge of the Gamow window at 3 GK is at only 2.4 MeV [22] and therefore this deviation is inconsequential for the reaction rate.

Analogous results of the preliminary experimental measurements and theoretical calculations for the ^{77}Se(p, n)^{77}Br and ^{80}Se(p, n)^{80}Br reactions are depicted in Fig. 2. The measurements for the latter reaction were performed only with the Debrecen VdG accelerator. Satisfactory correlation between theory and experiment was found but the scatter in the experimental points motivates additional measurements.

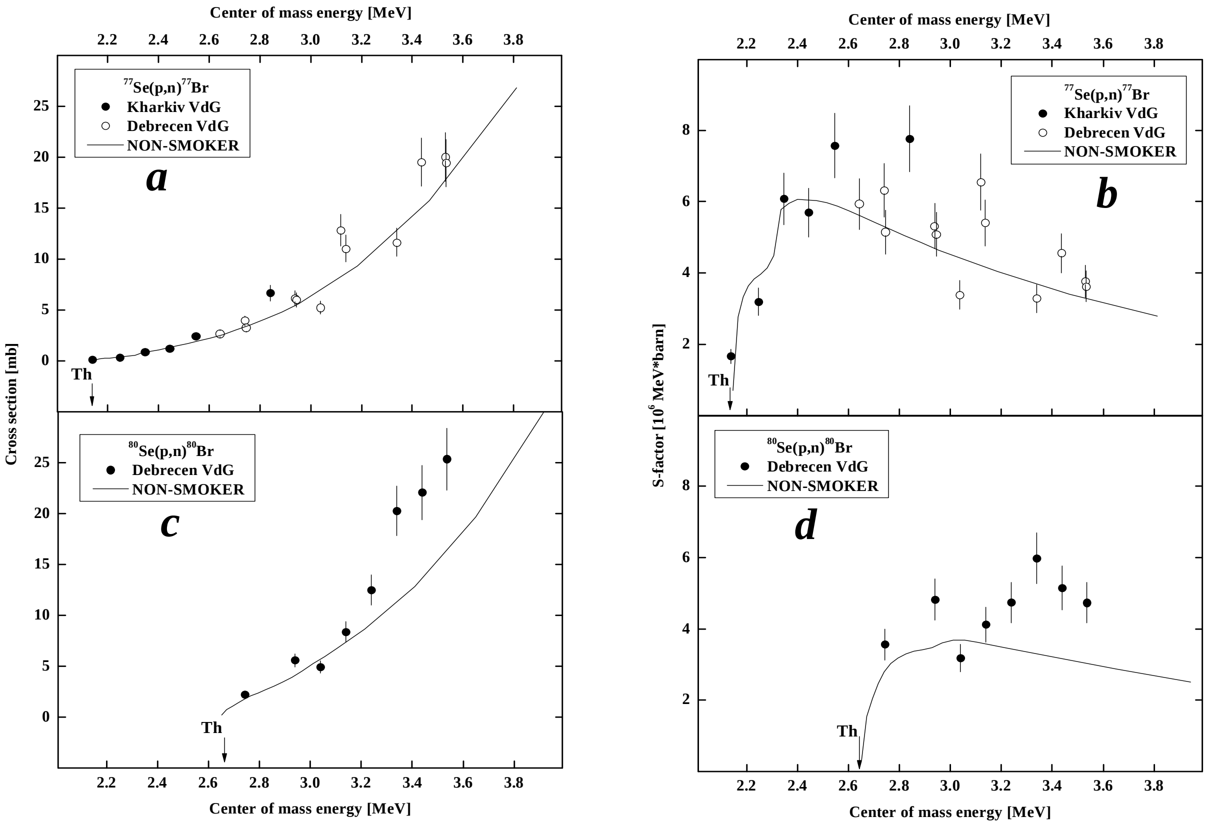

Fig. 2. Cross sections (*left column*) and astrophysical S-factors (*right column*) for the reactions $^{77}Se(p, n)^{77}Br$ (*upper row*) and $^{80}Se(p, n)^{80}Br$ (*lower row*). Points are the experimental values; curves are the statistical theory predictions.

3. Conclusion

The cross sections of the proton capture reactions $^{74}Se(p, \gamma)^{75}Br$, $^{76}Se(p, \gamma)^{77}Br$ and $^{77}Se(p, \gamma)^{78}Br$ and the threshold $^{77}Se(p, n)^{77}Br$ and $^{80}Se(p, n)^{80}Br$ reactions measured in the astrophysical relevant energy range and derived S-factors and reaction rates are in general satisfactorily predicted by a global H-F statistical model.

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REFERENCES

1. *Burbidge E. M., Burbidge G. R., Fowler W. A., Hoyle F.* Synthesis of the elements in stars // Rev. Mod. Phys. - 1957. - Vol. 29. - P. 547 - 650.
2. *Arnould M., Goriely S.* The p-process of stellar nucleosynthesis: astrophysics and nuclear physics status // Phys. Rep. - 2003. - Vol. 384. - P. 1 - 84.
3. *Käppeler F., Thielemann F.-K., Wiescher M.* Current quests in nuclear astrophysics and experimental approaches // Annu. Rev. Nucl. Part. Sci. - 1998. - Vol. 48. - P. 175 - 251.
4. *Rapp W., Görres J., Wiescher M. et al.* Sensitivity of p-process nucleosynthesis to nuclear reaction rates in a 25 solar mass supernova model // Astrophys. J. - 2006. - Vol. 653. - P. 474 - 489.
5. *Bork J., Schatz H., Käppeler F., Rauscher T.* Proton capture cross sections of the ruthenium isotopes // Phys. Rev. - 1998. - Vol. C58. - P. 524 - 535.
6. *Rapp W., Heil M., Hentschel D. et al.* α- and neutron-induced reactions on ruthenium isotopes // Phys. Rev. - 2002. - Vol. C66. - 015803.
7. *Chloupek F.R., Murphy A.St.J., Boyd R.N. et al.* Measurements of proton radiative capture cross sections relevant to the astrophysical rp- and γ-processes // Nucl. Phys. - 1999. - Vol. A652. - P. 391 - 405.
8. *Ozkan N., Murphy A.St.J., Boyd R.N. et al.* Cross section measurements of the $^{102}Pd(p, \gamma)^{103}Ag$, $^{116}Sn(p, \gamma)^{117}Sb$, and $^{112}Sn(\alpha, \gamma)^{116}Te$ reactions relevant to the astrophysical rp- and γ-processes // Nucl. Phys. - 2002. - Vol. A710. - P. 469 - 485.
9. *Gyürky Gy., Fulop Zs., Somorjai E. et al.* Proton induced reaction cross section measurements on Se isotopes for the

astrophysical *p* process // Phys. Rev. - 2003. - Vol. C68. - 055803.
10. *Harissopulos S.*, *Spyrou A., Lagouannis A. et al.* Systematic measurements of proton- and alpha-capture cross sections relevant to the modeling of the *p* process // Nucl. Phys. - 2005. - Vol. A758. - P. 505 - 508.
11. *Kiss G., Gyürky Gy., Elekes Z. et al.* ^{70}Ge(p, γ)^{71}As and ^{76}Ge(p, n)^{76}As cross sections for the astrophysical *p* process: Sensitivity of the optical proton potential at low energies // Phys. Rev. - 2007. - Vol. C76. - 055807.
12. *Rapp W., Dillmann I., Kappeler F. et al.* Cross section measurements of α-induced reactions on $^{92, 94}$Mo and ^{112}Sn for *p*-process studies // Phys. Rev. - 2008. - Vol. C78. - 025804.
13. *Skakun Ye.* Launch of proton reaction cross section investigation for astrophysical needs at KIPT // Proc. of the 2-nd Int. Conf. “Current Problems in Nuclear Physics and Atomic Energy” (June 9 - 15, Kyiv, Ukraine). - Kyiv, 2009. - Part II. - P. 482 - 488.
14. http://nuclear-astrophysics.fzk.de/kadonis/.
15. *Hauser W., Feshbach H.* The inelastic scattering of neutrons // Phys. Rev. - 1952. - Vol. 87. - P. 366 - 373.
16. *Rauscher T., Thielemann F.-K.* Astrophysical reaction rates from statistical model calculations // At. Data Nucl. Data Tables. - 2000. - Vol. 75. - P. 1 - 351.
17. *Rauscher T., Thielemann F.-K.* Tables of nuclear cross sections and reaction rates an addendum to the paper “Astrophysical reaction rates from statistical model calculations” // At. Data Nucl. Data Tables - 2001. - Vol. 79. - P. 47 - 64.
18. *Goriely S.* Hauser-Feshbach reaction rates for nuclei with Z = 8 - 109 // Proc. of Capture Gamma-Ray Spectroscopy and Related Topics / Ed. by S. Wender. - AIP Conf. Proc. No. 529 - Melville, NY, 2000. - P. 287; see also http://www-astro.ulb.ac.be.
19. *Rolfs C., Trautvetter H.P., Rodney W.S. et al.* Current status of nuclear astrophysics // Rep. Prog. Phys. - 1987. - Vol. 50. - P. 233 - 325.
20. http://nds121.iaea.org/ensdf/.
21. *Skakun E.A., Batij V.G.* Level density parameters from excitation cross sections of isomeric states // Z. Phys. - 1992. - Vol. A344. - P. 13 - 17.
22. *Rauscher T.* Relevant energy ranges for astrophysical reaction rates // Phys. Rev. - 2010. - Vol. C81. - 045807.
23. *Wigner E.P.* On the behavior of cross sections near thresholds // Phys. Rev. - 1948. - Vol. 73. - P. 1002 - 1009.