Conference Paper

Nucleosynthesis of Heavy Elements in Thermonuclear Explosions "Mike", "Par" and "Barbell"

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Abstract

The formation of transuranium nuclides in pulsed neutron fluxes of thermo-nuclear explosions is investigated in the kinetic model of the astrophysical *r*-process, taking into account time dependence of the external parameters and including the processes accompanying the β-decay of neutron-rich nuclei. Time-dependent neutron fluxes in the interval $\sim 10^{-6}$ s were modeled within the developed adiabatic binary model. Probabilities of β-delayed processes were calculated using the microsco-pic theory of finite Fermi systems. Calculations of the yields of transuranium nuclides $Y(A)$ are made for three experimental USA thermonuclear explosions "Mike" (Y_M), "Par" (Y_P) and "Barbel" (Y_B). The standard (r.m.s.) deviations of calculations with the experimental data are 91% for Y_M, 33% for Y_P, 29% for Y_B, which is significantly lower than for other known calculations. The exponential approximation of the experimental dependences $Y(A)$ is carried out and the values of r.m.s. are equal to 56%, 86.8% and 60.2% for Y_M, Y_P and Y_B, which is better or comparable with other calculations. An even-odd anomaly in the observed yields of heavy nuclei is explained by the influence of the β-delayed processes in the heavy neutron-rich isotopes.

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1. Introduction

In the process of nuclear/thermonuclear (N/TN) explosion, new nuclides are formed due to multiple neutron capture as in stellar nucleosynthesis [1]. The difference of stellar impulse nucleosynthesis from the process of nuclei formation in N/TN explosion [2-6] is primarily in the time parameters of the process. The explosive N/TN-process has small duration time ($t < 10^{-6}$s), that allows splitting it into two phases: neutron capturing process and the following decays of *N*-rich nuclei [7]. Such a process can be called "prompt rapid" or *pr*-process and solution of the equations for the concentration $N_{A,Z}(t)$ of formed nuclei is greatly simplified.

Studies of the formation of transuranium nuclei in this process were carried out in the USA in 1952 – 1964 in thermonuclear tests. Transuranium isotopes (up to ^{255}Fm)

were first detected in the TN explosion "Mike" [2, 3] in 1952. The most complete data on the yields of transuraniums up to A = 257 were obtained in "Par" experiment [4, 5]. In the "Barbel" test [6], a similar fluency was achieved as in "Par", but isotopes with A = 257 had a smaller yield [5].

In Figure 1 shows the normalized experimental data on $Y(A)$ yields for three explosions Mike" [3], "Barbel" [6] and "Par" [4]. The decreasing dependence of $Y(A)$ is fitted as follows:

$$Y(A)/Y(A_i) = \exp\{-b_i \cdot A + c_i\} \tag{1}$$

$$i = 1(\text{"}Mike\text{"})A_1 = 239, b_1 = 1.570, c_1 = 375.491 \tag{1a}$$

$$i = 2(\text{"}Barbel\text{"})A_2 = 244, b_2 = 1.395, c_2 = 340.584 \tag{1b}$$

$$i = 3(\text{"}Par\text{"})A_3 = 245, b_3 = 1.388, c_3 = 341.015 \tag{1c}$$

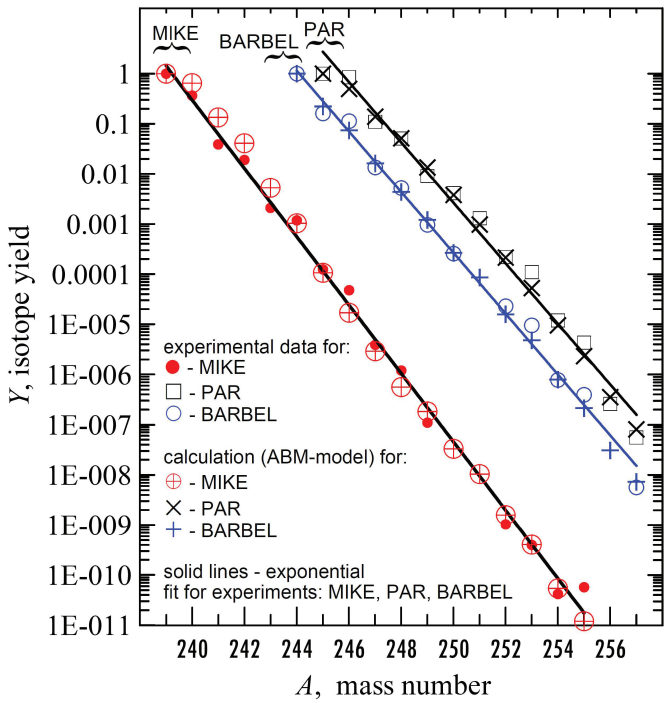

Figure 1: Yields of nuclides in experiment "Mike", "Par" and "Barbel" and result in ABM model.

The standard r.m.s. deviations of this approximation are: δ_1 = 56% ("Mike"), δ_2 = 60.2% ("Barbel"), δ_3 = 86.8% ("Par"), which is better than many previous calculations and comparable to the accuracy of our calculations of the presented ABM model (see section 3).

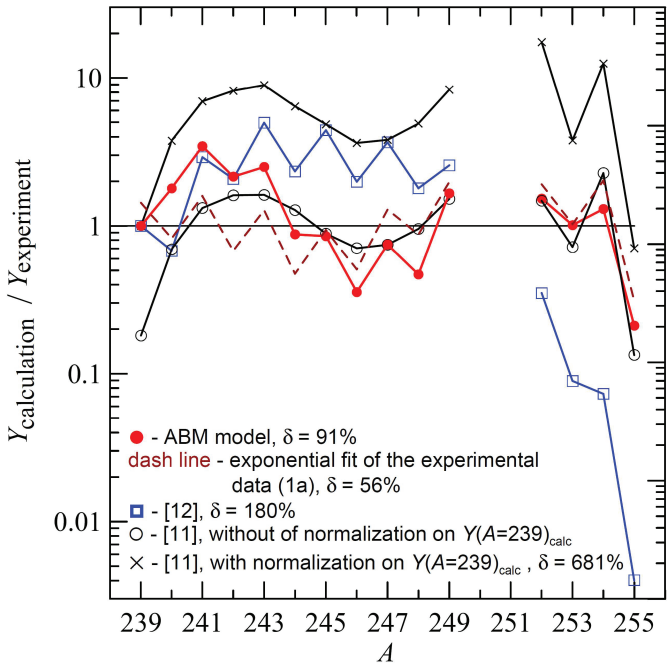

Figure 2: Relation of normalized (on $Y(A=239)_{calc}$) calculated yields to nor-malized on $Y(A=239)_{exper}$ experimental yield for "Mike" (see in the section 2).

2. Method of calculation

In the modeling the *pr*-process of nuclear/thermonuclear explosions, were made serious simplification due to the fact that neutron capture and decay of the nuclides are separated in time. So the system of equations for the time dependence of the concentrations $N(A; Z; t)$ of nuclei with the mass number A and the charge Z has the form:

$$\begin{aligned} dN(A,Z,t)/dt \; = & -\lambda_{n\gamma}(A,Z,t)\cdot N(A,Z,t) + \lambda_{n\gamma}(A-1,Z,t)\cdot N(A-1,Z,t) + \\ & \lambda_{n.2n}(A+1,Z,t)\cdot N(A+1,Z,t) - \lambda_{n.2n}(A,Z,t)\cdot N(A,Z,t) - \\ & \lambda_{n.f}(A,Z,t)\cdot N(A,Z,t) - \\ & \Phi[\lambda_{\beta}, \lambda_{\beta n}, \lambda_{\beta f}, \lambda_{\alpha}, \lambda_{sf}], \end{aligned} \tag{2}$$

where $\lambda_{n\gamma}$ – is the capture rate of neutron in the (n, γ)-reaction, $\lambda_{n,2n}$ is the same for the $(n, 2n)$ reaction, and $\lambda_{n.f}$ is the neutron fission rate. The reactions with γ-quantum were not taken into account because of lower temperatures in comparison with astrophysical processes. The term $\Phi[\lambda_{\beta}; \lambda_{\beta n}; \lambda_{\beta f}; \lambda_{\alpha}; \lambda_{sf}]$ in the system of equations (2) does not depend on time, since it includes the processes occurring after the active phase of the explosion: β-decay processes, (β,n)-emission of β-delayed neutrons (DN), α-decay, (β, f) β-delayed fission (DF) and (s, f)-spontaneous fission. The DN and DF probabilities were calculated in the microscopic theory of finite Fermi systems [8]. The effect of the

resonant structure of the β-decay strength function, including the pigmy resonances, was taken into account [9].

The time-dependent part of the system of equations (2) was solved using the adiabatic binary model (ABM) [10] where numerical simulation is performed by dividing duration of *pr*-process by small nanosecond time steps with calculations of isotope yields in succession for each step. The initial conditions are also determined by the isotope composition of the target and are determined by the yield of the preceding isotopes in the previous time step. In view of the binary, two-stage character of the TN explosion: the nuclear explosion (the first stage with the fission reaction) and the second stage associated with thermonuclear reaction, two neutron fluxes and two sets of initial concentrations were used in the calculations.

3. Results

In all calculations of this work, a unified approach was used within the framework of the adiabatic binary model (ABM) - it was assumed that there was an admixture of ^{239}Pu in the primary ^{238}U target. The specificity of the binary, two-stage explosion process also allowed modeling of irradiation of uranium-plutonium target by two different fluxes. In accordance with the experimental data, all model yields of the isotopes $Y(A)_{calc}$ are normalized (see (1)). The calculated yields and experimental data are presented in the Table, where the standard (r.m.s.) deviations δ are also given for ABM calculations and for approximation (1).

To illustrate the degree of agreement between calculations and experiments "Mike", "Par" and "Barbel", the calculated yields (normalized to experimental data) are presented on Figures 2-4, where calculations of other authors are given for comparison. The fitting of the experiments (1) (see Figure 1) is also presented in the normalized form.

Yields calculations for "Mike" experiment were performed earlier more than once and the best ones are shown in Figure 2. The accuracy of these calculations is small, so for [11] r.m.s. $\delta > 600\%$, and for [12] $\delta \approx 180\%$, which is much lower than $\delta = 91\%$ in the present calcu-lations using the ABM model and $\delta = 56\%$ according to the exponential fit (1a) (see Table).

The most successful for nucleosynthesis was "Par" experiment [4], where nuclides with all mass numbers up to $A = 257$ were detected. The ABM model allowed to reduce signi-ficantly the deviations from the experiment (up to 33%) and to provide a discrepancy for each isotope better than in two times for neutron fluxes of $5.31.10^{24}$

Table 1: Experimental and calculated in ABM model yield of transuranium nuclides.

"Mike"			"Par"			"Barbel"		
A	$Y(A)_{exper}$ [3]	$Y(A)_{calc}$ ABM	A	$Y(A)_{exper}$ [4]	$Y(A)_{calc}$ ABM	A	$Y(A)_{exper}$ [6]	$Y(A)_{calc}$ ABM
239	1.00	1.00	245	1.00	1.00	244	1.00	1.00
240	$3.63.10^{-01}$	$6.48.10^{-01}$	246	$8.50.10^{-01}$	$4.93.10^{-01}$	245	$1.61.10^{-01}$	$2.21.10^{-01}$
241	$3.90.10^{-02}$	$1.34.10^{-01}$	247	$1.10.10^{-01}$	$1.39.10^{-01}$	246	$1.13.10^{-01}$	$7.38.10^{-02}$
242	$1.91.10^{-02}$	$4.11.10^{-02}$	248	$5.10.10^{-02}$	$5.15.10^{-02}$	247	$1.35.10^{-02}$	$1.63.10^{-02}$
243	$2.10.10^{-03}$	$5.25.10^{-03}$	249	$9.00.10^{-03}$	$1.35.10^{-02}$	248	$5.22.10^{-03}$	$4.36.10^{-03}$
244	$1.18.10^{-03}$	$1.03.10^{-03}$	250	$4.10.10^{-03}$	$3.79.10^{-03}$	249	$9.57.10^{-04}$	$1.20.10^{-03}$
245	$1.24.10^{-04}$	$1.06.10^{-04}$	251	$1.30.10^{-03}$	$9.69.10^{-04}$	250	$2.57.10^{-04}$	$2.65.10^{-04}$
246	$4.78.10^{-05}$	$1.70.10^{-05}$	252	$2.20.10^{-04}$	$2.13.10^{-04}$	251	–	$8.59.10^{-05}$
247	$3.90.10^{-06}$	$2.91.10^{-06}$	253	$1.10.10^{-04}$	$5.31.10^{-05}$	252	$2.30.10^{-05}$	$1.58.10^{-05}$
248	$1.20.10^{-06}$	$5.61.10^{-07}$	254	$1.20.10^{-05}$	$9.58.10^{-06}$	253	$9.57.10^{-06}$	$4.82.10^{-06}$
249	$1.10.10^{-07}$	$1.83.10^{-07}$	255	$4.30.10^{-06}$	$2.32.10^{-06}$	254	$7.83.10^{-07}$	$7.87.10^{-07}$
250	–	$3.33.10^{-08}$	256	$2.60.10^{-07}$	$3.54.10^{-07}$	255	$3.96.10^{-07}$	$2.14.10^{-07}$
251	–	$1.04.10^{-08}$	257	$5.60.10^{-08}$	$8.07.10^{-08}$	256	–	$3.08.10^{-08}$
252	$1.03.10^{-09}$	$1.58.10^{-09}$				257	$5.65.10^{-09}$	$7.24.10^{-09}$
253	$4.0.10^{-10}$	$4.05.10^{-10}$						
254	$4.2.10^{-11}$	$5.44.10^{-11}$						
255	$5.7.10^{-11}$	$1.20.10^{-11}$						
δ %	56 (1a)	91		87 (1c)	39		60 (1b)	29

and $6.38.10^{24}$ neutrons/cm^2 for ^{238}U (97%) and ^{239}Pu (3%) components of the target, respectively (see Figure 3).

However, in the next experiment, "Barbel" [6], which was supposed to confirm the results of "Par" (and oriented to obtaining transuraniums), where were not detected isotopes with $A > 257$ and also with $A = 251$ and 256. In this simulation (with fluxes of $3.50.10^{24}$ and $6.08.10^{24}$ neutrons/cm^2 at ^{238}U (99.6%) and ^{239}Pu (0.4%) of the starting isotopes) the higher agreement with experiment (δ = 29%) was achieved (with the maximal discrepancy no more than twice - see Figure 4) and it confirmed the working capability of the ABM model.

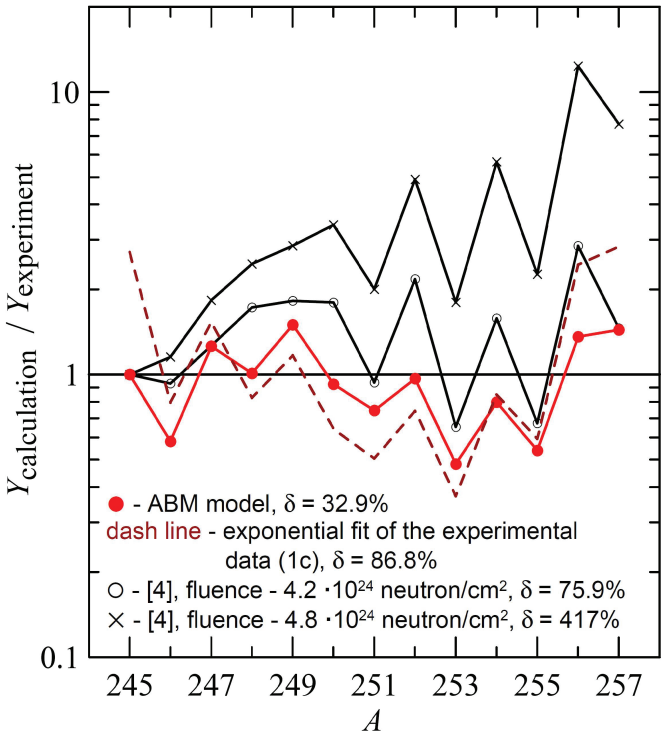

Figure 3: Relation of normalized (on $Y(A=245)_{calc}$) calculated yields to norma-lized experimental yields for "Par".

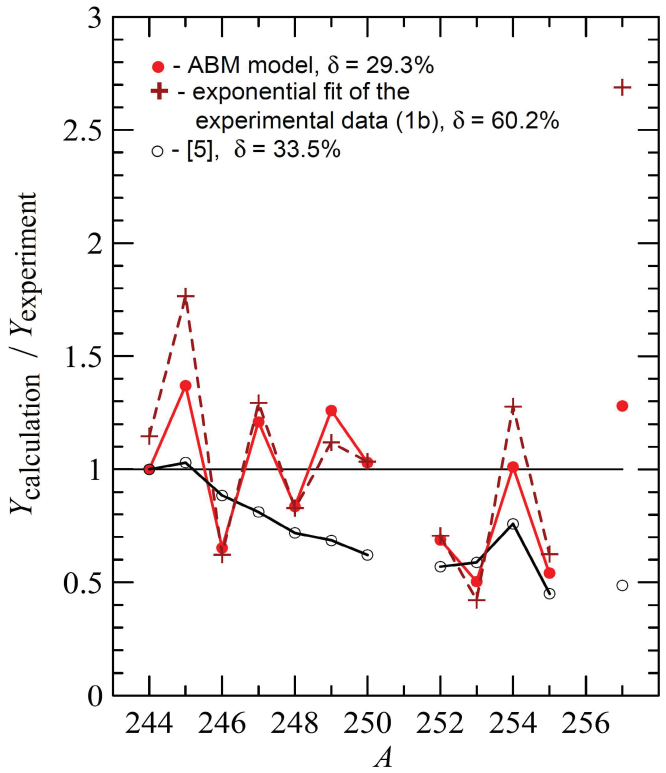

Figure 4: Relation of normalized (on $Y(A=244)_{calc}$) calculated yields to norma-lized experimental yield for "Barbel".

4. Conclusion

The process of heavy elements production under the intensive pulsed neutron fluxes (up to 10^{25} neutrons/cm^2) is considered. Using the previously developed mathematical kinetic model describing the formation of heavy elements in the pulsed nucleosynthesis [13], the proposed adiabatic binary model (ABM) were applied for calculation of transuranium yields in the USA thermonuclear explosions "Mike", "Par" and "Barbel". The results of our calculations using ABM model are compared with the experimental date in all mass number region $A = 239 - 257$. As a result our standard r.m.s. deviation for "Mike" experiment is δ(ABM) = 91% is smaller than the first calculations of Dorn ([11], $\delta > 400\%$), or calculations [12] (δ = 180 %). For "Par" experiment we had obtained δ(ABM) = 33%, compare to δ = 76 % of Dorn and Hoff [4]. For "Barbel" experiment δ(ABM) = 33% and compare to δ = 54% of Bell [5]. So it is possible to conclude that ABM model allows to improve the results in calculations of transuraniums in conditions of thermonuclear explosions.

The calculations include the processes of delayed fission (DF) and the emission of delayed neutrons (DN), which determine the "losing factor" – the total loss of isotopes concentration in the isobaric chains. The DN and DF probabilities were calculated in the microscopic theory of finite Fermi systems [8]. Thus, it was possible to describe the even-odd anomaly in the distribution of concentrations $N(A)$ in the mass number region $A = 251 - 257$. It is shown qualitatively also that the odd-even anomaly may be explained mainly by DF and DN processes in very neutron-rich uranium isotopes.

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References

[1] Burbridge B M, Burbridge G, Fowler W, Hoyle P 1957 *Rev. Mod. Phys.* **29** 547.

[2] Ghiorso A, Thompson S G, Higgins G H *et al.* 1955 *Phys. Rev.* **99** 1048.

[3] Diamond H, Fields P R, Stevens C S *et al. Phys. Rev.* 1960 **119** 2000.

[4] Dorn D W and Hoff R W 1965 *Phys. Rev. Lett.* 1965 **14** 440.

[5] Bell G I 1965 *Phys. Rev.* B **139** 1207.

[6] Los-Alamos Radiochemistry Group 1965 *Phys. Rev. Lett.* 1965 **14** 962.

[7] Lutostansky Yu S, Lyashuk V I, Panov IV 2010 *Bull. Russ. Acad. Sci. Phys.* **74**, 504.

[8] Migdal A B *Theory of Finite Fermi Systems and Applications to Atomic Nuclei* (1983 Nauka Moscow; 1967 Inter-Sci. New York).

[9] Lutostansky Yu S 2017 *JETP Lett.* **106** 7.

[10] Lyashuk V I 2012 *Bull. Russ. Acad. Sci. Phys.* **76** 1182.

[11] Dorn D W 1962 *Phys. Rev.* **126** 693.

[12] Zagrebaev V I, Karpov A V, Mishustin I N, Greiner W 2011 *Phys. Rev.* C **84** 044617.

[13] Lyutostanskii Yu S *et al.* 1985 *Yad. Fiz.* **42** 215 [1985 *Sov. J. Nucl. Phys.* **42**, 136].