ISSN 0021-3640, JETP Letters, 2013, Vol. 98, No. 8, pp. 446–449. © Pleiades Publishing, Inc., 2013.
Original Russian Text © I.V. Panov, A.D. Dolgov, 2013, published in Pis'ma v Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki, 2013, Vol. 98, No. 8, pp. 504–507.

Effect of Spontaneous Fission Models on the Production of Cosmochronometer Nuclei in the r-Process

I. V. Panov[a–c] and A. D. Dolgov[c–e]

[a] *Alikhanov Institute for Theoretical and Experimental Physics, ul. Bol'shaya Cheremushkinskaya 25, Moscow, 117218 Russia*
e-mail: igor.panov@itep.ru

[b] *National Research Centre Kurchatov Institute, pl. Akademika Kurchatova 1, Moscow, 123182 Russia*

[c] *Novosibirsk State University, ul. Pirogova 2, Novosibirsk, 630090 Russia*

[d] *Departimento di Fisica, Università di Ferrara and INFN, I-44124 Ferrara, Italy*

[e] *Moscow Institute of Physics and Technology (State University), Institutskii per. 9, Dolgoprudnyi, Moscow region, 141700 Russia*

Received September 3, 2013

The dependence of the yields of cosmochronometer nuclei on the spontaneous fission model has been considered. It has been shown that the spontaneous fission rates estimated within a phenomenological model constructed on the basis of the calculations of the spontaneous fission rates for superheavy nuclei within the macroscopic–microscopic model are in good agreement with the observations.

DOI: 10.1134/S0021364013210091

Heavy nuclei above the iron peak are produced in nature primarily in neutron capture reactions and subsequent beta decay. Analysis of the abundance curve of elements in the solar system shows that the neutron-induced synthesis of elements heavier than iron occurs in two different processes under different conditions [1]. The first, slow, process (called s-process) occurs when the β-decay rates are much higher than the (n, γ)-reaction rates, $\lambda_\beta \gg \lambda_{n\gamma}$ (at the neutron density $n_n < 10^{16}$ cm^{-3}). The second, rapid, process (called r-process) occurs under the conditions of high neutron densities and temperatures such that $\lambda_\beta \ll \lambda_{n\gamma}$. Nuclei involved in this nucleosynthesis have a significant excess of neutrons and a short lifetime.

There are at least two natural scenarios of the r-process [2] differing in the important parameter R_n, which is the ratio of the numbers of free neutrons and seed nuclei at the beginning of the r-process.

The main r-process ($R \gg R_n \approx 10$–15) is responsible for the production of the elements of the second peak on the abundance curve ($A \sim 130$) and heavier elements. The "additional" or "weak" r-process ($R < R_n$) produces some heavy nuclei with the mass number $A < 130$.

The nuclei of all chemical elements involved in the rapid neutron-induced nucleosynthesis (r-process) capture neutrons through radiative capture until the photodissociation rate becomes equal to the neutron capture rate. Neutron-rich nuclei being in statistical equilibrium undergo beta decay, which results in the production of a new chemical element with the same or smaller (if delayed neutrons are emitted) mass number. An additional beta-decay channel exists for transuranium nuclei. This is delayed fission, which competes with the emission of delayed neutrons. Delayed fission is important for understanding of the process of termination or branching of the r-process in the transuranium region.

One of the most important subjects of the investigation of the r-process is the character of nucleosynthesis in the region of transuranium nuclei, where fission impedes both the passage of the nucleosynthesis wave in the region of actinides and the production of superheavy elements. The inclusion of fission results in change in the yields of actinides, in particular, cosmochronometer nuclei and, thereby, in the age of the Galaxy determined by the isotopic ratio method.

After the appearance of the observation results for the abundance of chemical elements in very old stars with a low metallicity [3], it became obvious that the characteristic time of the rapid nucleosynthesis τ_r in at least one natural scenario of the r-process is larger than the time τ_f in which the nucleosynthesis wave reaches the region of fissile nuclei. As a result, owing to high fission rates, the r-process returns to the region of the nuclei of fission products with the establishment of a quasistationary current of nuclei at the number of cycles $n_{cycl} = \log_2(Y_{fin}/Y_{init}) \geq 1$.

When the nucleosynthesis wave in the r-process driven by alternating multiple captures of neutrons and beta decays reaches the region of actinides, the nucleosynthesis of heavier nuclei is suspended because of fission.

The fission process becomes important for astrophysical scenarios under the conditions for the main r-process when the neutron capture rates, which are determined by the product of the cross section, density, and fraction of neutrons ($\langle \sigma_{nf} v \rangle n_n Y_n$), are comparable with the delayed fission rate $\lambda_{\beta df}$ and are higher than the beta decay rate.

The importance of this previously discussed process [4] for nucleosynthesis was understood only recently [5]. The induced-fission rate of transuranium isotopes in a number of astrophysical scenarios is so high that it exceeds the beta decay rate even near the neutron stability line and is possibly only lower than the spontaneous fission rate for a narrow region of transactinides.

Interest in superheavy elements has increased recently owing not only to advances in experiments on the investigations of new nuclei near the stability region and new methods for seeking superheavy elements in nature [6], but also to new calculations of radiative capture rates of neutrons and main fission reactions for a large number of superheavy elements (see, e.g., [7] and references therein). The latter circumstance makes it possible to begin to study the r-process in the region of transactinides.

Noticeable advances both in the development of models of the main r-process and in forecasting of nuclear data for short-lived neutron-rich actinides in the region of which the r-process proceeds allows not only the investigation of the production of superheavy nuclei but also the analysis of the effect of nuclear data on the production of heavy and superheavy nuclei [8–10].

The forecasts of the spontaneous fission rates are the least accurate among the forecasts of fission rates. This possibly does not refer only to spontaneous fission rates for the region of superheavy elements calculated in [11] only on the basis of the macroscopic–microscopic model for a number of isotopes of superheavy elements with even charge numbers $Z > 100$. Various models were used in [9, 10] to forecast spontaneous fission rates. It was found that, although the contribution of spontaneous fission to the total number of fission events is small [12] and hardly affects the production of most heavy nuclei lighter than isotopes of the platinum peak, the yield of superheavy nuclei strongly depends on the spontaneous fission model used in the calculations of the r-process.

The yield of cosmochronometer nuclei, particularly $^{235,238}U$, ^{232}Th, and ^{244}Pu, which are used to determine the age of the Universe [13], appears to even more strongly depend on the spontaneous fission model used in the calculation of nucleosynthesis. In order to clarify this problem, the calculations of nucleosynthesis were performed for one scenario but with the forecasts of spontaneous fission rates obtained within different models.

For definiteness, only one scenario—the coalescence of neutron stars [14]—was considered. This process results in the ejection of strongly ionized matter. All conditions for the r-process appear in this matter in the process of expansion and cooling. The excess of neutrons is so large that not only the elements of the third peaks are produced, but also the quasistationary regime of the r-process is approached owing to fission. The fission products are again involved in the nucleosynthesis process as seed nuclei, ensuring the closed current of nuclei. To simplify the consideration, we used only one consistent set of forecasted nuclear data, which is mainly based on the use of masses and fission barriers obtained within the generalized Thomas–Fermi model with the Strutinsky correction [15, 16].

To determine the final yields of cosmochronometer nuclei (thorium, uranium, and plutonium), we consider four spontaneous fission models.

The approximations of spontaneous fission rates proposed in [10, 17] are based on the dependence of the logarithm of the spontaneous fission rate on the fission barrier height and were obtained by the least squares method. These are the approximation of the experimental data on the fission barriers B_f,

$$\log(\lambda_{sf}) = (33.3\text{–}7.77)B_f^{exp}, \quad (1)$$

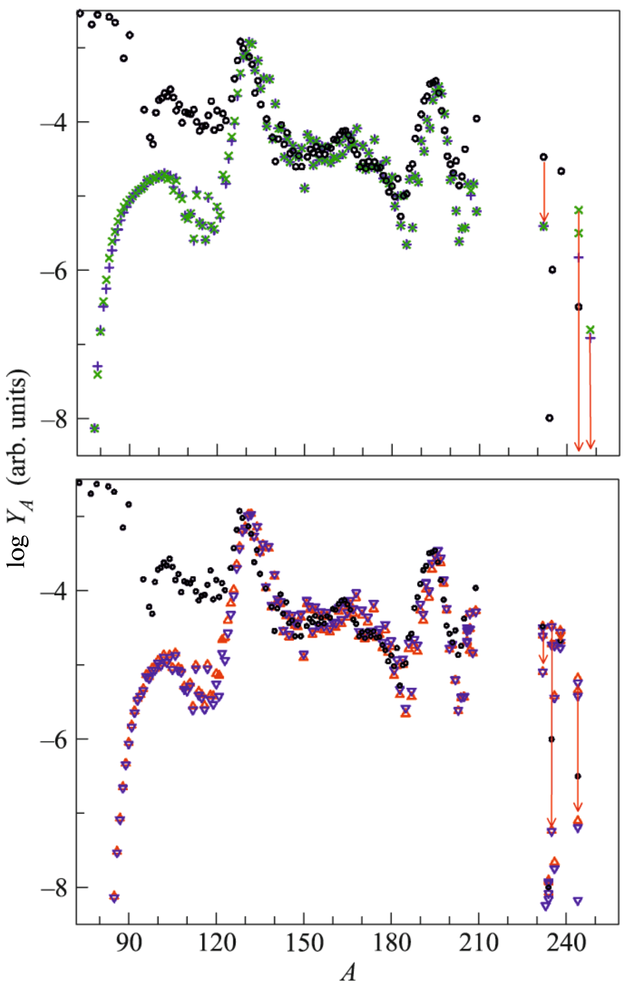
and the approximation based on the forecasts of B_f values within the extended Thomas–Fermi Strutinsky-integral model [15, 16]:

$$\log(\lambda_{sf}) = (50.127\text{–}10.145)B_f^{etfsi}. \quad (2)$$

The calculations of the spontaneous fission periods [11] within the macroscopic–microscopic model [18] are also used for transactinides.

In contrast to the phenomenological models based on the dependence of the spontaneous fission time on the fissionability parameter, the macroscopic–microscopic model includes shell effects. This model predicts an increase in the lifetime T_{sf} with respect to spontaneous fission for nuclei close to the stability island in the region of superheavy elements. Fission barriers increase strongly here, particularly with respect to the binding energy of a neutron in a nucleus with an increase in the neutron excess in the region of the closed neutron shell $N = 184$. The predicted lifetimes are close to the T_{sf} values measured for a number of isotopes of superheavy elements in the experiments reported in [19].

As is known [20], the dependence of the logarithm of the spontaneous fission periods of actinides is quite well described by a linear function of the fissionability parameter Z^2/A. In this work, we used the Swiatecki formula [21] for $\log T_{sf}$, which includes the dependence both on the fission barrier and on the fissionability parameter fitted [22] to the calculations of



Logarithm of the abundance of heavy elements produced in the r-process according to (○) the observations reported in [1] and the following spontaneous fission models: (×) approximation (1), (+) approximation (2), (∇) approximation (3), and (Δ) macroscopic–microscopic model [11]. The arrows show changes in the yields of isotopes of the corresponding masses with an increase of the nucleosynthesis time from 3×10^8 to 4×10^9 yr.

spontaneous fission within the macroscopic–microscopic model [18]:

$$\log(\lambda_{sf}) = -1146.4 + 75.3Z^2/A - 1.638(Z^2/A)^2 + 0.012(Z^2/A)^3 - (7.24 - 0.095Z^2/A)B_f. \quad (3)$$

Here, $B_f = B_f^{LDM} + \delta U_{gs}$ is the barrier height determined within the liquid-drop model (B_f^{LDM}) with the shell corrections (U_{gs}). The coefficients in Eq. (3) were obtained by fitting both experimentally known barriers and calculations [18] for the region $Z > 100$.

The set of main cosmochronometer nuclei includes eight isotopes with the half-lives from 10^7 to 10^{11} yr [13]. Uranium ($A = 235, 238$) and thorium ($A = 232$) isotopes are usually used to determine the age of the Galaxy. Plutonium-244 is also sometimes considered, but data on its abundance have a large error [23, 24]. We considered variation of the calculated abundances of these elements for the duration of nucleosynthesis from 3×10^8 to 4×10^9 yr.

It was found that, in the case of cycling of the r-process in matter with a high neutron excess, the yield of heavy nuclei in the region from the second to third peaks is almost independent of the spontaneous fission model used in the calculations. A slight dependence on the model is manifested in the yields of the lightest isotopes with mass numbers less than 110. This is hardly important for galactic nucleosynthesis because isotopes with mass numbers less than 110 are produced under different conditions (primarily in the weak r-process). At the same time, the yields of cosmochronometer nuclei obtained with the spontaneous fission rates obtained within different models differ by orders of magnitude.

The calculation results are shown in the figure.

It can be seen that the calculations with approximations (1) and (2) give almost the same yields of nuclei with mass numbers $100 < A < 200$ (upper panel) as the macroscopic–microscopic model [18] and fit (3) (lower panel). The largest difference in these two pairs of models is observed in the yields of cosmochronometer nuclei (arrows indicate the direction of a decrease in the abundance of isotopes with an increase in the duration of the cooling phase from 3×10^8 to 4×10^9 yr). The calculation with the use of spontaneous fission model (1) or (2) gives the abundances of isotopes with mass numbers of 238 and 244 that are many orders of magnitude below the observed abundances. According to this calculation, the isotope with $A = 235$ is not produced and only ^{232}Th is produced in an amount close to the observed abundance. On the contrary, the calculation with forecasts (3) based on the macroscopic–microscopic model is in very good agreement with the data on the abundances of ^{232}Th and ^{238}U. Agreement for ^{235}U and ^{244}Pu is somewhat worse, but the corresponding calculated abundances are around the observed values in the time range under consideration. The further study of fission chains should provide information for the improvement of the existing approximation and development of theory.

To conclude, we note that the forecasts of spontaneous fission rates within the phenomenological model based on the calculations of spontaneous fission rates of superheavy nuclei in the macroscopic–microscopic model are in good agreement with observations and should be used in the calculations of nucleosynthesis.

We are grateful to Blinnikov, Nadezhin, Martínez-Pinedo, and Thielemann for stimulating discussions. This work was supported by the Ministry of Education and Science of the Russian Federation (contract no. 11.G34.31.0047) and, in part, by the Russian Foundation for Basic Research (project nos. 11-02-

00882-a, 12-02-00955-a, and 13-02-12106-ofi-m) and by the Swiss National Science Foundation (grant no. IB7320-110996 SCOPES).

REFERENCES

1. J. Simmerer and C. Sneden, Astrophys. J. **617**, 1091 (2004).
2. G. J. Wasserburg, M. Busso, and R. Gallino, Astrophys. J. **466**, L109 (1996).
3. C. Sneden, J. J. Cowan, I. I. Ivans, et al., Astrophys. J. **533**, 139 (2000).
4. F.-K. Thielemann, A. G. W. Cameron, and J. J. Cowan, in *Proceedings of the International Conference on 50 Years with Nuclear Fission*, Ed. by J. Behrens and A. D. Carlson (Amer. Nucl. Soc., La Grange Park, L, 1989), p. 592.
5. I. V. Panov and F.-K. Thielemann, Nucl. Phys. A **718**, 647 (2003).
6. V. P. Perelygin, Yu. V. Bondar, W. Ensinger, et al., Nucl. Phys. A **718**, 410 (2003).
7. I. V. Panov, I. Yu. Korneev, F.-K. Thielemann, et al., Astron. Astrophys. **513**, id.A61 (2010).
8. I. V. Panov, I. Yu. Korneev, and F.-K. Thielemann, Phys. At. Nucl. **72**, 1026 (2009).
9. I. Yu. Korneev and I. V. Panov, Astron. Lett. **37**, 864 (2011).
10. I. Petermann, K. Langanke, G. Martínez-Pinedo, et al., Eur. Phys. J. A **48**, 122 (2012).
11. R. Smolanczuk, Phys. Rev. C **56**, 812 (1997).
12. I. Petermann, G. Martínez-Pinedo, A. Arcones, et al., J. Phys.: Conf. Ser. **202**, 012008 (2010).
13. J. J. Cowan. F.-K. Thielemann, and J. W. Truran, Phys. Rep. **208**, 267 (1991).
14. S. Rosswog, M. Liebendörfer, F.-K. Thielemann, et al., Astron. Astrophys. **341**, 499 (1999).
15. Y. Aboussir, J. M. Pearson, A. K. Dutta, et al., At. Data Nucl. Data Tables **61**, 127 (1995).
16. A. Mamdouh, J. M. Pearson, M. Rayet, et al., Nucl. Phys. A **679**, 337 (2001).
17. I. V. Panov, I. Yu. Korneev, G. Martinets-Pinedo, et al., Astron. Lett. **39**, 150 (2013).
18. Z. Patyk, R. Smolanczuk, and A. Sobiczewski, Nucl. Phys. A **626**, 337 (1997).
19. Yu. Ts. Oganessian, J. Phys. G **34**, R165 (2007).
20. Y. Ronen, Ann. Nucl. Energy **31**, 323 (2004).
21. W. J. Swiatecki, Phys. Rev. **100**, 937 (1955).
22. V. I. Zagrebaev, A. V. Karpov, I. N. Mishustin, et al., Phys. Rev. C **84**, 044617 (2011).
23. B. Hudson, C. M. Hohenberg, B. M. Kennedy, et al., Luna Planetary Sci. **13**, 346 (1982).
24. G. J. Wasserburg, J. C. Huneke, and D. S. Burnett, J. Geophys. Res. **74**, 4221 (1969).

Translated by R. Tyapaev