SUPERHEAVY ELEMENTS PRODUCTION IN HIGH INTENSIVE NEUTRON FLUXES*

YU.S. LUTOSTANSKY

National Research Center "Kurchatov Institute", Moscow, 123098 Russia

V.I. LYASHUK

Institute for Nuclear Research, Russian Academy of Science, Moscow, 117312 Russia; National Research Center "Kurchatov Institute", Moscow, 123098 Russia

I.V. PANOV

Institute for Theoretical and Experimental Physics, Moscow, 117259 Russia; National Research Center "Kurchatov Institute", Moscow, 123098 Russia

The possibility of superheavy elements production in high intensive neutron fluxes is being studied. A model of the transuranium isotopes production under conditions of pulse nucleosynthesis in a neutron flux with densities of up to ~10^{25} neutron/cm^2 is considered. The pulse process allows us to divide it in time into two stages: the process of multiple neutron captures (with $t < 10^{-6}$ *s*) and the subsequent β-decay of neutron-rich nuclei. The modeling of the transuranium yields takes into account the adiabatic character of the process, the probability of delayed fission, and the emission of delayed neutrons. A target with a binary composition of ^{238}U and ^{239}Pu, ^{248}Cm, and ^{251}Cf isotopes is used to predict the yields of heavy and superheavy isotopes.

1. Introduction

In nature heavy and superheavy elements, (HE) and (SHE), production takes place under conditions of super high neutron fluxes, e.g., in supernova stars explosion where neutron density exceeds 10^{20} neutron/cm^3 at temperatures of ~10^9 K. The production of these elements occurs in the process of rapid

---

* This work is supported by grants RFBR 11-02-00882 and 12-02-00955

nucleo-synthesis (the *r*-process) due to multiple neutron captures in the (n,γ)-reaction and following β^-–decay of neutron-rich (*N*-rich) heavy nuclei [1]. In trans-uranium region *N*-induced fission [2] and beta-delayed processes [3] as well as α-decay and spontaneous fission will be added to the process of nucleosynthesis [4]. Last processes are very important for the predictions of SHE [5]. The traces of SHE may still exist in meteorites, earth crust [6] and in the cosmic-ray nuclei [7]. Searches for SHE would make it possible to impose constraints on the mass models and to furnish experimental data required for obtaining deeper insight both into fission physics and the structure of SHE.

The perspective way of SHE production experimentally is in using the high intensive neutron fluxes of nuclear facilities, operating in stationary or in pulse regimes. For example: the pulse reactor Jaguar can give the density up to $2.5 \cdot 10^{18}$ neutron/(cm^{2}s) per pulse (duration ~ 10^{-3} s); the steady flux reactor PIK ensures the year fluence of ~ $1.2 \cdot 10^{23}$ neutron/cm^2.

Realization of the *r*-process in nuclear explosions allows to produce neutron fluencies above 10^{24} neutron/cm^2 in a time of ~ 10^{-6} s. Transuranium isotopes (up to ^{255}Fm) were found for the first time in the "Mike" thermonuclear explosion in 1952 [8]. The most complete data on transuranium yields up to A = 257 were obtained in the "Par" experiment [9]. In the "Hutch" tests, a maximum fluence of 2.4×10^{25} neutrons/cm^2 was achieved [10], but no isotopes with $A > 257$ were found. Nuclides created during pulse nucleosynthesis are very neutron-rich and fast decaying. But specific of the analyses for the created nuclides composition is that the analyses were completed about two days after nucleosynthesis; in this time, nuclei with high numbers of neutrons are decayed [10, 11]. In modeling of the *r*-process under astrophysical conditions [1 - 4], we must consider the (n, γ)-reaction and the inverse (γ, n)-process; induced and spontaneous fission; the β-decay of *N*-rich nuclei accompanied by delayed neutron emission (β, n) - DN and delayed fission (β, f) – DF [12], and to know a majority of the parameters and reaction rates for more than 4000 nuclei [13, 14].

2. The model of superheavy isotopes production in the pulse process

In modeling of the HE (SHE) creation under artificial conditions [15, 16] (nuclear, thermonuclear explosions [17]) the significant simplification were made due to the fact that the processes of multiple neutron capture (duration ~

10^{-6} *s* [18]) and beta-decay are strongly separated in time: ($t_{n,\gamma} << t_{\beta}$), that can significantly limit the range of nuclei involved in the *r*-process.

As starting isotopes the binary composition of ^{238}U and ^{239}Pu was used. Half-life periods, probability of emission for one – DN and two delayed neutrons (2DN), probability of DF for *N*-rich isotopes were calculated taking into account the β-strength function, which obtained from the finite-Fermi system theory [19]. The model involves the elements of dynamics, which accounts for the change in (*n*,γ)-cross-sections over the time (~10^{-6} *s*) of multiple neutron captures due to increase in the volume *V* (a sphere with radius 5 *cm* [20]) of highly heated plasma (which temperature *T* falls adiabatically [15, 21, 22]: $T = (Const\ /\ V)^{\gamma - 1}$, where γ ranged from 1.5 to 2.0 [23], a reduction in ($T_1 - T_2$) temperature [22] was fixed in the range from 60 to 1 keV.

Following pulse nucleosynthesis, neutron-rich isotopes undergo β-decay, upon which two processes DN and DF leading to a change in concentration. These processes lead to isotopes losing in isobaric chains with the constant mass number *A* and, as a result, the distribution of the isotope yields according to the mass number *A* changes considerably. The losing effect summarized by the isobar chain gives a relative reduction in concentrations for a given *A* and is expressed as the *L*(*A*) coefficient (the "losing factor", where $L(A) \leq 1$) and the concentration of isotopes with given *A*, calculated at the moment of the end of multiple captures, must be multiplied by the factor $R(A)=1–L(A)$. In calculations with the initial isotope ^{238}U, the factor $L_U(A)$ increases at *A* = 252, 254, 256, 258 (i.e., at even *A* isotopes). In this case, the main contribution comes from the (β, *f*) processes on even *A* neptunium isotopes, which explains the abnormality (even–odd effect) in the distribution of yields, which were identified experimentally after explosions. Spontaneous fission was not considered in our calculations of *L*(*A*), but it is significant for mass number $A \geq 256$ of isotopes ^{256}Cf, ^{258}Fm, and heavier nuclei [24]. In calculations of the *L*(*A*) coefficients we used the data from [25, 26]. So, the even-odd anomaly can be explained by influence of DF-effect and partly by influence of plutonium impurity in starting isotopes.

For searching a promising way for synthesis of HE and SHE elements we include the admixtures of some HE to the target [27].

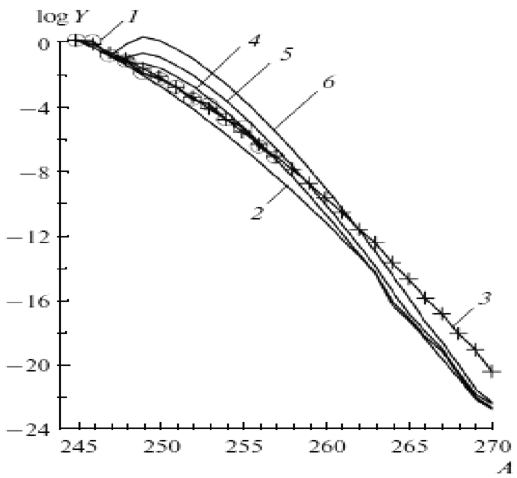

Figure 1. Comparison of the calculated relative yields *Y* for (U+Cm) and (U+Pu) targets at a flux of $6x10^{24}$ neutrons/cm^2. Curve *1*– the "Par" experimental data; curves *2*–*6* – calculations using targets of various composition. (*2*) ^{238}U(100%), (*3*) ^{238}U(95%) + ^{239}Pu(5%), (*4*) ^{238}U + ^{248}Cm(0.1%), (*5*) ^{238}U + ^{248}Cm(0.5%), (*6*) ^{238}U + ^{248}Cm(5.0%).

The inclusion of small masses of curium into the seed mixture with ^{238}U (Figure 1) enables us to increase the yields of isotopes with mass numbers $A >$ 250 by an order of magnitude at 0.5% concentration of ^{248}Cm, and up to two orders of at concentrations of 5%. But this type of admixture does not have a great effect on more heavy transuranium nuclides as does an (U + Pu) binary target.

3. Conclusion

So, the adiabatic binary model for of transuranium elements production in the pulse neutron fluxes was developed and tested.

The calculations of isotope yields (up to A = 257) for "*Par*", "*Barbel*" and "*Mike*" thermonuclear explosions were realized for the binary target. The obtained results are in good agreement with the experimental data. The possible isotope yields up to A = 280 was calculated in the modeling with start ^{238}U and ^{239}Pu isotopes and small admixture of ^{248}Cm and ^{251}Cf.

It was shown that account of the $L(A)$ – "losing factor" (which is associated with the observed even-odd inversion in yields for the transuranium nuclides with A > 250) improve the data fit of calculated yields to experimental results.

It was shown that nuclei with $A \approx 270$ can be obtained in the "Par" experiment conditions with the relative yields less than 10^{-22} using uranium target, and – with the relative yields less than 10^{-20}, using binary (U + Pu) and (U + Cm) targets. Heavier nuclei with $A \approx 280$ can be obtained with the relative yields less than 10^{-31} using binary (U + Pu) and (U + Cm) targets. The detection of such low concentrations is problematically by means of modern experimental methods.

Acknowledgments

The authors are grateful to I.V. Korneev, V.N. Tikhonov, S.V. Tolokonnikov, V.V. Samarin, E.E. Sapershtein and A. Sobiczewski for assistance and helpful discussions.

References

1. E. M. Burbidge, G. R. Burbidge, W. A. Fowler, F. Hoyle. *Rev. Mod. Phys.* **29,** 547 (1957).
2. I. V. Panov, et al. *Astronomy and Astrophysics,***513**, id.A61, (2010).
3. Yu. S. Lyutostanskii, et al., *Yad. Fiz.* **42**, 215 (1985).
4. I. Yu. Korneev, I. V. Panov. *Astronomy Letters,***37**, 864 (2011).
5. I. Petermann, K. Langanke, G. Martinez-Pinedo, I.V. Panov, P.-G. Reinhard, F.- K. Thielemann. *Eur. Phys. J.* **A 48,** 122 (2012).
6. G. N. Flerov and G. M. Ter-Akopian. *Rep. Prog. Phys.* **46**, 817 (1983).
7. V. P. Perelygin et al. *Nucl. Phys*. **A 718,** 422 (2003).
8. A. Ghiorso, S. G. Thompson, G. H. Higgins, et al. *Phys. Rev.* **99,** 1048(1955).
9. G. I. Bell. *Phys. Rev*. **B 139,** 1207 (1965).
10. R. W. Hoff. Preprint UCRL–81566, Livermore: Lawrence Livermore Laboratory, p. 30, (1978).
11. A. S. Krivokhatskii, Yu. F. Romanov. *Poluchenie transuranovykh i akti-noidnykh elementov pri neitronnom obluchenii (Transuranium and Actinoid Elements Creation under Neutron Radiation)*. Atomizdat, Moscow, (1970).
12. Yu. S. Lutostansky. *Izv. Akad. Nauk SSSR, Ser. Fiz*. **50**, 834 (1986).
13. I. V. Panov, I. Yu. Korneev, F.-K. Thielemann. *Phys. At. Nucl*.**72**, 1026, (2009).
14. I. V. Panov, I. Yu. Korneev, Yu. S. Lutostansky, F.-K. Thielemann. *Phys. At. Nucl*. **76**, N1 (2013).
15. Yu. S. Lutostansky, V. I. Lyashuk, I. V. Panov. *Bull. Russ. Acad. Sci. Phys*. **74**, 504 (2010).
16. Yu. S. Lutostansky, V. I. Lyashuk, I. V. Panov. *Bull. Rus. Acad. Sci. Phys*. **75**, 533 (2011).

17. P. A. Yampol'skii. *Neitrony atomnogo vzryva (Atomic Explosion Neutrons).* Gosatomizdat, Moscow, (1961).
18. G. I. Bell. *Rev. Mod. Phys*. **39,** 59 (1967).
19. Yu. V. Gaponov, Yu. S. Lutostansky. *Phys. At. Nucl*. **73,** 1360 (2010).
20. V. I. Kukhtevich, I. V. Goryachev, L. A. Trykov. *Zashchita ot pronikayu-shchei radiatsii yadernogo vzryva (Protection against Penetrating Radiation Caused by Atomic Explosion)* – Atomizdat. Moscow 1970, P. 17.
21. V. P. Korobeinikov. *Zadachi teorii tochechnogo vzryva (Problems of Point Explosion Theory).* Nauka, Moscow 1985, P. 133, P. 141.
22. V.I. Lyashuk. Preprint of the Institute for Theor. and Experimental Phys. Moscow, No.7, (1997).
23. Ya. B. Zeldovich, Yu.P. Raizer. *Fizika udarnykh voln i vysokotempera-turnykh gidrodinamiches-kikh yavlenii (Physics of Shock Waves and High–Temperature Hydrodynamic Phenomena).* Nauka, Moscow 1966.
24. I. V. Panov, I. Yu. Korneev, F.-K. Thielemann. *Astron. Lett.* **34**, 213 (2008).
25. P. Moller, J. R. Nix, W. D. Myers, W. J. Swiatecki. *At. Data Nucl. Data Tabl.* **59**, 185 (1995).
26. P. Moller, et al. *Phys. Rev.* **C 79**, 064304 (2009).
27. Yu. S. Lutostansky, V. I. Lyashuk. *Bull. Russ. Acad. Sci. Phys.* **76**, 462 (2012).