DOI: 10.17725/rensit.2021.13.501

Joint transmutation of stable Cs and Sr isotopes in microbiological systems and prospects for accelerated deactivation of liquid radioactive waste

Alla A. Kornilova, Sergey N. Gaydamaka, Marina A. Gladchenko
Lomonosov Moscow State University, http://msu.ru/
Moscow 119991, Russian Federation
E-mail: prfnart@mail.ru, s.gaidamaka@gmail.com, gladmarina@yandex.ru
Vladimir I. Vysotskii
Shevchenko Kiev National University, http://www. univ.kiev.ua/
Kiev 01033, Ukraine
E-mail: vivysotskii@gmail.com

Received December 04, 2021, peer-reviewed December 10, 2021, accepted December 14, 2021

Abstract: **It was found during the research that in the experimental and control bioreactors, which at the beginning of the experiments contained only cesium and strontium, by the end of the experiments, yttrium and barium were found. These isotopes are formed as a result of low-energy nuclear reactions involving protons. In addition, in experimental bioreactors with an optimal composition, a two to threefold increase in the concentration of yttrium was recorded in comparison with the control non-optimal experiments. Accumulation of strontium and cesium in biomass was registered, which is explained by the process of biosorption. It is known that biosorption is the first step towards nuclear transformation (biotransmutation). At the same time, one of the main conditions for the nuclear transformation of biomass elements is its maximum efficient growth. An unexpected fact discovered during the experiment is that yttrium and barium were also found in the control bioreactor, where no biomass was added before the experiment, but only deionized water, glucose, and the initial stable cesium and strontium salts. It is important to note that these elements were not detected in the analysis of the initial salts, substrates, and deionized water. Most likely, the presence of yttrium and barium is due to inoculation of the control fluid of the bioreactor (where no biomass pellets were added) with microorganisms from the experimental bioreactors during their periodic opening for taking current pH samples and adding glucose. Also, the work recorded a decrease in the content of cesium and strontium in the liquid by 20% and 55%, respectively, which goes beyond the statistical error.**

Keywords: **bioreactor, biosorption, low energy isotope transmutation, coherent correlated states, seeding with microorganisms**

PACS: 25.60.PJ; 25.70.−Z; 28.41.KW; 28.52.−S; 28.60.+S; 82.90.+J; 87.17.−D; 87.17.EE; 87.80.−Y; 89.60.−K

For citation: Alla A. Kornilova, Vladimir I. Vysotskii, Sergey N. Gaydamaka, Marina A. Gladchenko. Joint transmutation of stable Cs and Sr isotopes in microbiological systems and prospects for accelerated deactivation of liquid radioactive waste. *RENSIT: Radioelectronics. Nanosystems. Information technologies*, 2021, 13(4):501-508. DOI: 10.17725/rensit.2021.13.501.

Contents

1. INTRODUCTION

It is well known that one of the most actual problems of modern energy and ecology is the deactivation of radioactive waste (RW) generated in large quantities during the normal operation of nuclear reactors. The formation of liquid radioactive waste (LRW) is associated, in particular, with the technology of keeping fuel elements (fuel elements) after their removal from the reactor core for several years for the decay of the shortest-lived radioactive isotopes. An even greater scale of LRW formation is associated with accidents at nuclear power plants. A typical example is the accident at the Fokushima-2 nuclear power plant, on the territory of which, over 10 years after the destruction of the reactor, more than 600000 tons of radioactive water has been accumulated, formed during the continuous cooling of the damaged reactor.

It is also well known that the most dangerous for humans of all long-lived isotopes contained in such wastes are gamma-active cesium Cs^{137} and beta-active strontium Sr^{90}, the half-life of which is about 30 years, and the required exposure time to achieve an acceptable conditionally safe radiation level is hundreds of years old.

Coordinated by the IAEA (International Atomic Energy Agency), a technique for the disposal of high-level waste due to their intense irradiation with neutrons with the possibility of converting long-lived radioactive isotopes into rapidly decaying shorter-lived isotopes requires the creation of a large number of very expensive high-current accelerators for high-energy protons with their subsequent conversion into neutrons.

Simple estimates show that in order to implementation of such solution and utilize of 300-500 thousands of tons of high-level radioactive reactor waste, it is necessary to create in such systems a very large number (thousands of tons (!)) of very fast neutrons, which is very expensive and difficult. This problem was actively discussed 15-20 years ago, and it was shown that only for preliminary work until 2050 for the implementation of such mega-projects in all countries where nuclear power systems are developed, total costs exceeding $ 200-300 billion are required [1-4]. Now this idea is practically forgotten.

At present, the only real method of RW disposal is a "deferred solution" – primary processing and long-term storage of RW in special storage facilities in order to reduce the specific activity of RW due to the radioactive decay of isotopes contained in RW with subsequent final disposal of RW into deep geological formations (to a depth of about 500 m and more). Such controlled storage requires very large ongoing costs for their maintenance and safety, and is potentially environmentally hazardous due to possible accidents that have repeatedly occurred in the most developed countries of the world when the conditions for servicing the storage facilities are violated. The largest accident occurred at the Mayak chemical plant in 1957 with the release of a large amount of radioactive waste and the formation of the "Kyshtym radioactive trace". It should also be noted that deep geological disposal of radioactive waste is acceptable only for countries with large territories, since the choice of the location for creating a radioactive waste repository must be justified by long-term safety forecasts and certain specific requirements are imposed on the characteristics of geological massifs suitable for disposal of radioactive waste.

Over the past 25 years, we have been investigating a fundamentally different, environmentally friendly and controllable method for the conversion of isotopes at low energy, including the mechanism of disposal of long-lived radioactive waste by converting (transmutation) of radioactive isotopes into stable isotopes of other elements in the process of nuclear transmutation, stimulated by internal topological structural processes in nano-scale (at the level of biomolecules) in growing microbiological systems. It was shown (e.g. in [5,6]) that for atomic and nuclear particles located in nonstationary nanosized potential wells, in the process of deformation of these wells (their rapid expansion or contraction), such quantum-mechanical coherent correlated states (CCS) can arise, which are accompanied by very sharp increase in the probability of one of the interacting nuclei passing through the Coulomb barrier of another nucleus. The presence of this barrier is the main obstacle to nuclear processes at low (thermal) energy of the environment. Such dynamic systems with a rapidly changing internal structure can be created artificially, but it is much more efficient to use fast-growing radiation-resistant microbiological cultures, in which similar processes occur naturally due to, for example, cell division, DNA replication, and ion transport processes at the entrance of heterogeneous channels in membranes. cells, etc.

The physical (quantum mechanical) illustration of such processes is the Schrödinger-Robertson uncertainty relation for different pairs of dynamic variables A and B

$$\sigma_A\sigma_B \geq \left|<[\hat{A}\hat{B}]>\right|^2 / 4(1-r^2), \quad (1)$$

which was obtained in 1930 and differs from the "standard" Heisenberg-Robertson uncertainty relation

$$\sigma_A\sigma_B \geq \left|<[\hat{A}\hat{B}]>\right|^2 / 4 \quad (2)$$

by the presence of the correlation coefficient $|r| \leq 1$. This coefficient characterizes the dynamic relationship of these variables A and B and is determined by the relation

$$r = \sigma_{AB} / \sqrt{\sigma_A\sigma_B},$$
$$\sigma_{AB} = (<\hat{A}\hat{B} + \hat{B}\hat{A}>)/2 - <A><B>, \quad (3)$$
$$\sigma_C = <(\hat{C} - <C>)^2>, \quad C = A, B.$$

In a particular case

$$A = x,\ B = p,\ <x - <x>> = 0,\ <p - <p>> = 0 \quad (4)$$

this relation is reduced to a modified form of the well-known Heisenberg uncertainty relation with an overdetermined (multiplied by $G = 1/\sqrt{1-r^2}$ times) Planck constant [7]

$$\sigma_p\sigma_x \geq \hbar^2 / 4(1-r^2) \equiv (\hbar^*)^2 / 4,$$
$$\delta p\delta x \geq \hbar / 2\sqrt{1-r^2} \equiv \hbar^* / 2, \quad (5)$$
$$\hbar^* = G\hbar, \quad \delta C \equiv \sqrt{\sigma_C}.$$

From these relations, in particular, it follows that when a particle with mass m is within a nonstationary nanowell with a size $\delta x = \sqrt{\sigma_x}$, the fluctuation ΔE of its kinetic energy exceeds the minimum value

$$\Delta E \approx \sigma_p / 2m \geq \Delta E_{\min} = \hbar^2 G^2 / 8m\sigma_x. \quad (6)$$

In particular, if a proton is within this deformable potential well with a size of $\delta x \approx 1$ nm, then in the initial uncorrelated state, for which $r = 0$ and $G = 1$, the amplitude of kinetic energy fluctuations is very small and amounts to 10^{-4} eV, which is much less than the thermal energy at room temperature (~0.025 eV). On the other hand, for a really attainable value $G \approx 10^4$ [7], this amplitude exceeds 10 keV, which is sufficient for nuclear fusion and isotope conversion in the presence of microbiological cultures.

The early [5,8-11], as well as subsequent optimized experiments [12], confirmed the reality and high efficiency of such isotope transmutation in the presence of growing microbiological cultures. These experiments were carried out with the participation of light ($Mn^{55} + d = Fe^{57}$), medium-mass ($Na^{23} + P^{31} = Fe^{54}$) and heavy ($Cs^{133} + p = Ba^{134}$) stable isotopes.

2. SIMULTANEOUS TRANSMUTATION OF STABLE Cs AND Sr ISOTOPES AT LOW ENERGY IN THE PRESENCE OF MICROBIOLOGICAL SUBSTANCES

Below are presented the results of the first biostimulated experiments on the implementation of the nuclear transmutation reaction of stable strontium, which is the stable analogue of another extremely dangerous long-lived reactor radioactive Sr^{90} isotope. Taking into account the fact that the main component (82.6%) of stable strontium is the Sr^{88} isotope, and also taking into account that the reactions stimulated by the giant energy fluctuations considered above are most likely to occur when the daughter product of such reactions is a stable isotope [7], it should be expected that the most probable is the transmutation reaction

$$Sr^{88} + p = Y^{89} \quad (7)$$

with the formation of a stable isotope Y^{89}.

The fundamental difference and an important feature of the processes under study is that these experiments were first carried out under controlled conditions with the simultaneous presence of stable isotopes of both elements – strontium and cesium. This circumstance is an important prerequisite for the implementation of the disposal process using biotechnology for the joint deactivation of both and the most dangerous radioactive isotopes that are always present in reactor RW.

The experiments were carried out in the following way.

To carry out the experiments, salts containing stable isotopes of cesium and strontium at a concentration of 100 mg/liter were dissolved in deionized water. In identical experimental (basic) bioreactors "1", "2" and "3" (as well as in the control bioreactor "0"), 75 ml of the prepared solution was introduced.

After that, dry granules containing 0.4 gram of dried syntrophic anaerobic microbiological association were added to bioreactors "1-3". The salts Na_2CO_3 and Na_2HPO_4 were added as necessary trace elements. In bioreactor "0" were introduced similar components, with the exception of the dried microbiological granules.

After that, all bioreactors were placed in a laboratory thermostat, where they were kept for 33 days at a temperature of 55°, which is optimal for these microbiological associations.

On the outer surface of the transparent bioreactors, liquid levels were recorded, and when it decreased, the volume was replenished by adding similar deionized water to the appropriate level during manipulations with the bioreactors throughout the experiment. Every 4 days the bioreactors stayed in a thermostatically controlled chamber, water was added to the initial level, the pH of the liquid in each bioreactor was measured, and 0.05-0.15 ml of glucose was added. The experiment with periodic repetition of such procedures lasted 33 days.

In the course of the experiment, the analysis of similar samples of glucose, salts of the nutrient medium, supernatants and biomasses was also carried out by the method of *X*-ray fluorescence analysis (XRF) in order to determine the concentration of all chemical elements. The results of such an analysis of the liquid phase taken after centrifugation of the liquid from the bioreactors and separation of the sediment present in the samples are shown in **Table 1**.

It follows from these results that in all bioreactors, including the bioreactor "0", into which no syntrophic association granules were introduced, a large amount of Ba and Y ions was found. It is important to note that the content of Cs and Sr in the liquid phase in the volume bioreactors "1-3" with the optimal composition

Table 1

Results of chemical analysis of the liquid phase after the end of the experiment and after separation of the sediment from the liquid

Sample name	Concentration, mg/liter			
	Cs	Sr	Ba	Y
Bioreactor "0"	107.5	93.1	0.42	0.16
Average values for bioreactors "1", "2" и "3"	89.2	45.2	0.23	0.23

are significantly less than in bioreactor "0", which formally lacked microcultures. This logical conclusion is in good agreement with the initial assumption about the possibility of accelerated biotransmutation reactions in bioreactors "1-3". On the other hand, the presence of Ba and Y ions in the control bioreactor "0", which does not contain syntrophic association granules, requires appropriate explanations.

This interesting circumstance is most likely associated with the uncontrolled ingress of very small amounts of microorganism spores from the working tanks of bioreactors "1"-"3" into a nearby container with bioreactor "0" during short-term but repeated depressurization of these bioreactors during biogas extraction, produced by anaerobic microorganisms. A very small number of such microorganisms that got from the air into the bioreactor "0" could rapidly increase, taking into account the optimal conditions of a long-term experiment, to the amount that would ensure the implementation of the process of sufficiently effective isotope transmutation. This mechanism of self-population of bioreactor "0" is quite reasonable, given the circumstances that under optimal conditions, with all vital components, the absence of competitors and the presence of a comfortable temperature for these microorganisms, 8-10 cycles of extended reproduction of these microorganisms occur during the entire experiment.

For the most complete understanding and explanation of the obtained effects, the *X*-ray fluorescence analysis of the sediments

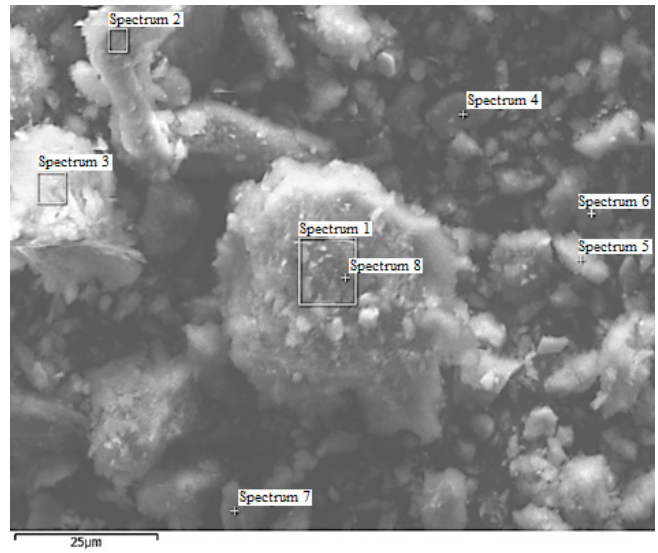

Fig. 1. *Electronic image and sampling points in the sediment of bioreactor "1".*

in the bioreactors after the completion of the experiments was carried out. The results of the analysis of the sediment previously washed from the mother liquor and dried at a temperature of 100°C in bioreactor "1" are shown in **Fig. 1** and **Fig. 2**, as well as in **Table 2**.

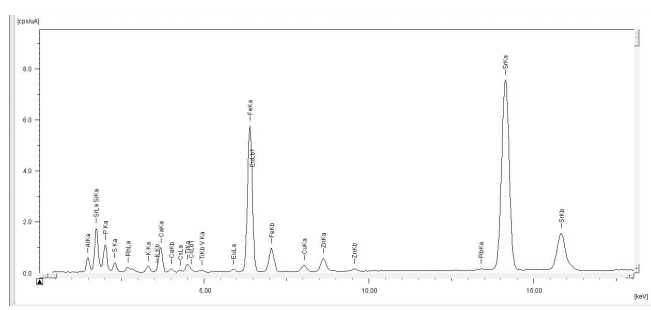

Fig. 2. *Roentgenogram of sediment in bioreactor "1".*

It follows from these data that almost all studied points of the sediment sample contain Cs and Sr salts, which got there as a result of

Table 2

Elemental (mass %) chemical composition of the sediment in bioreactor "1".

Spectrum label	Na	Mg	Al	Si	P	S	K	Ca	Ti	Fe	Sr	Y	Cs	Ba	Total
Spectrum 1	0.95	0.91	19.04	31.06	21.81	4.64	3.34	5.08	1.26	6.48	3.70	0.56	0.83	0.34	100.00
Spectrum 2	1.76	0.98	17.23	31.11	19.11	5.47	3.39	6.89	1.13	7.50	3.49	0.73	1.23	0.00	100.00
Spectrum 3	1.61	0.82	19.68	23.91	20.97	11.04	1.89	6.36	1.61	6.82	2.70	1.01	1.09	0.49	100.00
Spectrum 4	0.33	1.06	25.11	40.05	1.44	0.29	20.62	0.48	2.01	7.00	1.09	0.26	0.16	0.11	100.00
Spectrum 5	1.11	1.20	21.03	35.52	20.14	3.18	2.07	3.30	1.43	4.64	3.60	1.57	1.08	0.12	100.00
Spectrum 6	0.27	0.15	2.37	86.55	4.07	0.50	0.56	0.76	0.04	1.54	1.16	1.96	0.06	0.00	100.00
Spectrum 7	0.26	0.21	1.77	83.24	7.02	1.00	0.00	1.36	0.44	2.69	1.61	0/41	0.00	0.00	100.00
Spectrum 8	0.54	0.89	16.07	33.26	19.33	6.95	2.85	5.87	1.24	6.92	4.55	0.12	0.96	0.45	100.00

sorption into the volume of microcultures. The formal absence of Ba in spectra 2, 6, 7 is most likely associated with its very low concentration due to the selectivity of its sorption or because of the low concentration of Cs at these points.

Similar results were obtained when studying sediments in bioreactors "2" and "3".

For the purpose of "evaluating the purity" of the experiment (the absence of compounds Cs, Sr, Y, and Ba in the reagents), the same RFA of the reagents used in the experiments was carried out. The data of these measurements confirmed the complete absence (with the accuracy guaranteed by the XRF-based measurement technology) of these chemical elements (**Fig. 3-5**, **Table 3, 4**).

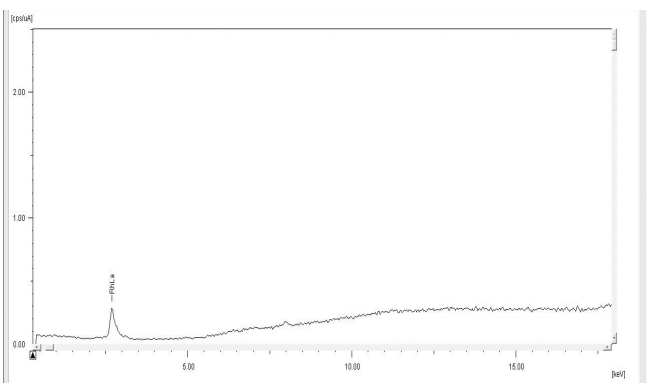

Fig. 3. *Roentgenogram of glucose.*

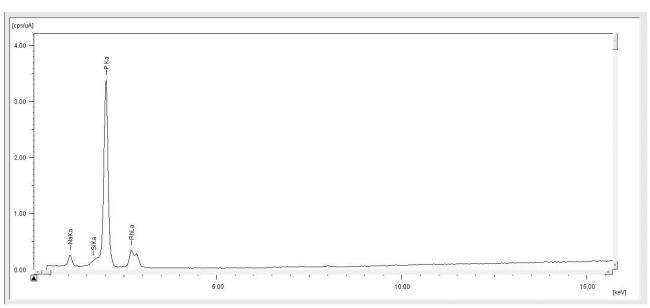

Fig. 4. *Roentgenogram of Na_2HPO_4 solt.*

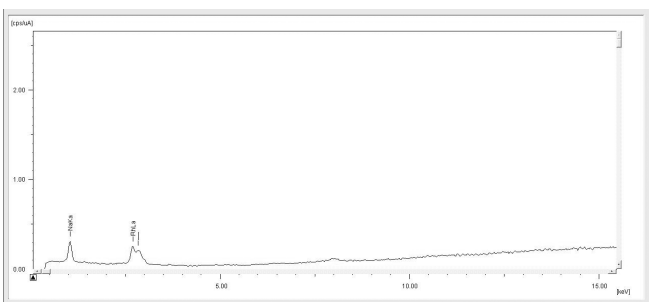

Fig. 5. *Roentgenogram of Na_2CO_3.*

Table 3

Results of the elemental chemical composition Na_2HPO_4, mass. %

1	Elem.	P	66.302%	(0.087)	Quant.-FP	P Ka	11.2593
1	Elem.	Na	29.599%	(0.176)	Quant.-FP	NaKa	0.5928
1	Elem.	Si	4.099%	(0.031)	Quant.-FP	SiKa	0.6122

Table 4

Results of the elemental chemical composition Na_2CO_3, mass.%

1	Elem.	Na	97.887%	(0.398)	Quant.-FP	NaKa	0.7087
1	Elem.	Ca	0.864%	(0.045)	Quant.-FP	CaKa	0.0208
1	Elem.	Al	0.461%	(0.025)	Quant.-FP	AlKa	0.0100
1	Elem.	Mg	0.278	(0.063)	Quant.-FP	MgKa	0.0038
1	Elem.	S	0.266	(0.010)	Quant.-FP	S Ka	0.0294
1	Elem.	Si	0.245	(0.011)	Quant.-FP	SiKa	0.0127

3. CONCLUSION

The results of the analysis of the concentration and composition (redistribution) of chemical elements involved in the natural metabolism of microbiological cultures in different solutions allow us to draw the following conclusions.

1. In the mother liquors and in the sediments present in the bioreactors, Ba and Y ions were found, which are completely absent in the initial components. The only mechanism for the formation of these elements is the nuclear fusion reactions.
2. It was shown that in mother liquors there is a significant (at least 20%) decrease in Cs concentration when comparing the results of the study of liquid samples from the optimal bioreactors "1"-"3" and the sample from the control bioreactor "0". This decrease, if we compare these results with the results of our previous experiments [9-11], is directly related to the nuclear transmutation (nuclear fusion reaction $Cs^{133} + p = Ba^{134}$) of the Cs^{133} isotope to the Ba^{134} isotope.
3. A very significant (at least 50%) decrease in the concentration of Sr in the optimal bioreactors "1-3" in comparison with the non-optimal system of the bioreactor "0" was found, which can be associated with both its transmutation in Y and sorption

into sediments containing the bulk of biocultures.

4. In connection with the detected presence of Sr, Ba and Y ions in the sediments, in order to compose the material balance, it is necessary to develop a method for dissolving the sediments in bioreactors.
5. For a more conclusive confirmation of all the processes under consideration, it is necessary to additionally conduct mass spectrometric measurements of all products of nuclear transformations.
6. We believe that the simultaneous transmutation of stable Cs and Sr isotopes in the same volume in the presence of microbiological associations makes it possible to predict with a high probability the possibility and high probability of similar processes of transmutation of Cs^{137} and Sr^{90} radioactive isotopes and to effectively deactivation of LRW.
7. The proposed and logically substantiated hypothesis about the possibility of cross-contamination by optimal microbiological associations of initially biologically neutral containers with a radioactive liquid, followed by the optimal transmutation of radioactive isotopes, makes it possible to predict a similar technology for deactivating large volumes of LRW waste without excessive biological load on an industrial scale.

The authors express their sincere gratitude to the employees of VNIINM JSC V.A. Kashcheev and E.D. Musatov, as well as an employee of TVEL JSC A.I. Ermakov for useful discussion and objective control during these experiments.

REFERENCES

1. Minato K, Ikegami T, Inoue T. Recent research and development activities on partitioning and transmutation of radioactive nuclides in Japan. *Actinide and Fission Product Partitioning and Transmutation. Eight Information Exchange Meeting.* USA, Las-Vegas, November 2004, p.29-47.
2. Ponomarev LI. Overview of Russia P&T Programme. *Actinide and Fission Product Partitioning and Transmutation. Eight Information Exchange Meeting.* USA, Las-Vegas, November 2004, p. 79-90.
3. Stanculescu A. IAEA Activities in the area of partitioning and transmutation. *Actinide and Fission Product Partitioning and Transmutation. Eight Information Exchange Meeting.* USA, Las-Vegas, November 2004, p.101-108.
4. Savage B. Overview of United States P&T Programme. *Actinide and Fission Product Partitioning and Transmutation. Eight Information Exchange Meeting.* USA, Las-Vegas, November 2004, p. 49-56.
5. Vysotskii VI, Kornilova AA. Transmutation of stable isotopes and deactivation of radioactive waste in growing biological systems. *Annals of Nuclear energy,* 2013, 62:626-633.
6. Vysotskii VI, Kornilova AA. Microbial Transmutation of Cs^{137} and LENR in growing biological systems. *Current Science,* 2015, 108(4):142-146.
7. Vysotskii VI, Vysotsky MV. Features of correlated states and a mechanism of self-similar selection of nuclear reaction channels involving low-energy charged particles. *J. of Experim. and Theor. Phys.*, 2019, 128:856-864.
8. Vysotskii VI, Kornilova AA. *Nuclear fusion and transmutation of isotopes in biological systems.* Moscow, MIR Publ., 2003, 302 p. (in English).
9. Kornilova AA, Vysotskii VI, Gaydamaka SN, Gladchenko MA. Nuclear Reactions in Living Nature: The Possibility of Biological Processing and Deactivation of Liquid Radioactive Waste. *Physical and Mathematical Modeling of Earth and Environment Processes (Springer Proceedings in Earth and Environmental Sciences.* Springer, Book series (SPEES), 25 March 2019, pp 213-230.
10. Vysotskii VI, Kornilova AA, Gaydamaka SN, Novakova AA, Novikov DS, Vysotskyy VV, Avdonin VV. Creation of Fe isotopes in

natural geology crusts as the result of self-controlled global biostimulated LENR in oceans and seas. *Journal Condensed Matter Nucl. Science*, 2020, 33:323-332.

11. Vysotskii VI, Kornilova AA. Effective LENR and transmutation of stable and radioactive isotopes in growing biological systems. *Cold Fusion. Advances in Condensed Matter Nuclear Science,* Edited by Jean-Paul Biberian, Elsevier, 2020, Chapter 12, pp. 205-232.
12. Kyu-Jin Yum et all. An Experiment in Reducing the Radioactivity of Radionuclide (Cs^{137}) with Multi-component Microorganisms of 10 Strains. *J. Condensed Matter Nucl. Sci.*, 2019, 28:1-6.