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Yields of Rare Earth Elements Isotopes Under the Actinide Nuclei Fission

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Rare earth elements (REE) form a special class of chemical elements relatively common in the earth's crust (~1-10 parts per million), but only in trace impurities. Their production requires the processing of significant amounts of ore at high costs. Recent events indicate the considerable strategic importance of REM with broad prospects for producing effective magnets, electronic components for the military and consumer sectors, lasers, dosimeters, etc.

For nuclear physics research, the interest in REM is due to the presence of a number of isomeric states in them, the study of which is important for understanding the structure of the energy levels of atomic nuclei and the kinetics of transitions between them.

In this work, the subject of study is four chemical elements out of 17 known REM –^{62}Sm, ^{66}Dy, ^{67}Ho, ^{70}Yb, the yield of which is studied in the fission of a number of actinides: U, Th, Am. Thus, for Sm, three short-lived isomers $^{139,141,143m}Sm$ are distinguished, one for Dy –^{135m}Dy, a whole series of Ho isomers –158,159,160-164,166mHo and three isomers for Yb: $^{169,176,177m}Yb$. For each of these isotopes, the Weitzeker formula can be used to determine the sets at which the nucleus has the lowest energy:

(Equation 1)

It can also be noted that these isotope isomers fall into the class of neutron-proficient and neutron-deficient nuclei. Using the formula (1) for each of these isotopes, the optimal sets of, which are calculated from the liquid drop model, can be determined. Thus, for Sm, Z=62 value is ~152, stable isotopes are A=144, 150, 154; for Dy, Z=66 value is ~162, stable isotopes are A=158, 160-164; for Ho, Z=67 value is ~164, stable isotope is A=165; for Yb, Z=70 value is ~170-173, stable isotopes are A=168, 170-174.

There are various assumptions about the origin of REE in the Earth's crust, ranging from cosmogenic to actinide fission fragments. Since most REE are heavier than iron, it is possible that they were formed due to supernova nucleosynthesis or s-processes of stellar nucleosynthesis. On the other hand, the fission of heavy nuclei can also be a source of their origin since the entire Periodic Table of Chemical Elements is generated in this process. Establishing the peculiarities of REE isotope yields during actinide fission requires studying the role of nuclear shells and the nature of inter-nucleon interaction.

This paper presents the results of calculations of the yields of Sm, Dy, Ho, and Yb isotopes in the separation of ^{238}U, ^{232}Th, and ^{241}Am isotopes using the statistical method proposed in [1]. The NuFi package was used, which considers the fission parameters of fission of the isotopes of fissile nuclei U, Th, Am: nuclear temperature TT, as well as the possibility of emission of beta particles and fission neutrons.

The calculation algorithm involves the stage of creating an ensemble of all possible two-fragment clusters during the fission of the initial nucleus, determining the distribution function of the probability of their realization, and the procedure for separating nuclear clusters containing at least one REE isotope from this ensemble.

After that, a distribution function for each REE normalized by 100% is formed separately, determining the probability of its release for constructing the mass spectrum. In other words, when constructing a mass spectrum of a particular REE, it is essential to determine the probability of a cluster containing both the REE isotope and another isotope whose charge is complementary to the charge number of the fissile actinide. For example, in the fission of a paired ^{238}U nucleus, the probability of yielding clusters {$_{62}Sm$, $_{30}Zn$}, {$_{66}Dy$, $_{26}Fe$}, {$_{67}Ho$, $_{25}Mn$}, {$_{70}Yb$, $_{22}Ti$} is determined; for the even-pair ^{232}Th, respectively, {62Sm, $_{28}Ni$}, {$_{66}Dy$, $_{24}Cr$}, {$_{67}Ho$, $_{23}V$}, {$_{70}Yb$, $_{20}Ca$}, and, finally, for the odd-even isotope ^{241}Am –{$_{62}Sm$, $_{33}As$}, {$_{66}Dy$, $_{29}Cu$}, {$_{67}Ho$, $_{28}Ni$}, {$_{70}Yb$, $_{25}Mn$}. Therefore, the mass spectrum of Sm, Dy, Ho, and Yb isotope yields during heavy nuclear fission will be formed under the influence of various factors: dependence of their specific energy on the isotope mass, core temperature, influence of magic proton/neutron numbers 20, 28, 50, 82, and 126, as well as entropic effects that determine the equilibrium state of the 2-fragment cluster.

Fig. 1 shows the results of calculating the mass spectra of Sm, Dy, Ho, Yb isotopes in the fission of ^{238}U, ^{232}Th, and ^{241}Am isotopes obtained using the database [2].
As can be seen, the emission of nuclear particles and the increase in the initial nucleus's excitation energy (temperature) shifts the REE isotope spectra to the region of mass numbers determined by formula (1).
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Fig. 1. Mass spectra of Sm, Dy, Ho, and Yb isotopes at different fission schemes of actinide nuclei: a) Ho isotopes during the separation of isotopes ^{238}U*,* ^{232}Th*,* ^{241}Am*; b) Sm, Dy, Ho, Yb isotopes at* ^{238}U *fission; c) mass spectra of Ho isotopes without and including* ^{238}U *neutron emission; d) the same Ho spectra obtained for different fission temperatures of* ^{232}Th*.*

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