Synthesis and study of the decay properties of isotopes of superheavy elements Ds and Lv

Currently, the study of superheavy nuclei has become one of the most interesting and rapidly developing areas of nuclear physics. The synthesis of new elements 119 and 120 requires acceleration of heavier ions, such as ^{50}Ti, ^{51}V, ^{54}Cr. However, the transition from a doubly magic ^{48}Ca to such projectiles is accompanied by an additional drop in reaction cross sections. Unfortunately, the theoretical values of the reaction cross sections leading to elements 119 and 120 differ by 2-3 orders of magnitude. However, for planning such experiments, it is extremely important to have more definite estimates of the cross sections.

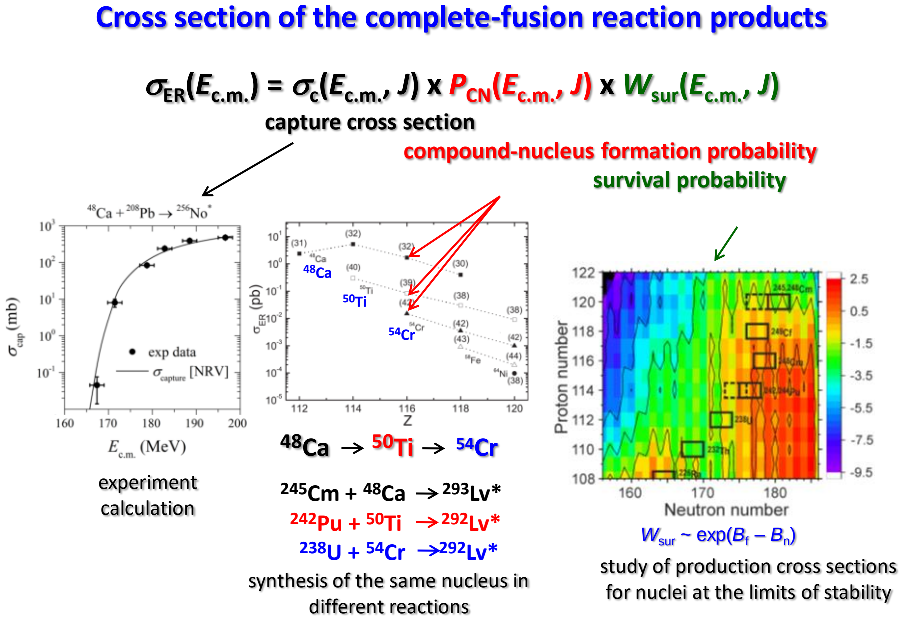


FIG. 1. Cross section of the complete-fusion reaction products. The methods of evaluating various processes that determine the cross section of the formation of the final reaction products are shown.

In theory, the fusion-evaporation reaction cross section is divided into three interrelated processes: the capture of interacting nuclei, the formation of an excited composite nucleus and its survival during neutron evaporation (see Fig. 1). The capture cross section can be measured experimentally or calculated theoretically. To assess the probability of compound-nucleus formation, the synthesis of the same nucleus in reactions with different ions is essential, since the probability of its survival will be almost the same. To study the probability of nuclear survival, which is largely determined by fission barriers and neutron binding energies, it is desirable to study reaction cross sections in a wide range of proton and neutron numbers of nuclei. Of particular importance is the study of reactions that lead to nuclei located at the boundary of their stability (with minimal barriers). The experiments were aimed at studying the listed processes of the complete-fusion reaction.

The ^{232}Th + ^{48}Ca reaction has been studied at four projectile energies at the new gas-filled separator DGFRS-2 on-line to the cyclotron DC280 at the SHE Factory at FLNR JINR. Some parameters of the experiments performed at three lowest energies are listed in Table I.

TABLE I. The ^{232}Th target thickness, laboratory-frame energies of ^{48}Ca in the middle of the target layer, resulting excitation energy intervals, total beam doses, the numbers of observed decay chains of ^{277}Ds (3*n*) and ^{276}Ds (4*n*) and the cross sections of their production.

Target thickness (mg/cm^2)	E_{lab} (MeV)	E^* (MeV)	Beam dose $\times 10^{19}$	No. of chains 3*n* / 4*n*	σ_{3n} (pb)	σ_{4n} (pb)
0.89	231.1	32.3-36.6	2.4	0 / 1	<0.2	$0.07^{+0.17}_{-0.06}$

0.76	237.8	37.9-42.1	1.9	0 / 5	<0.5	$0.7^{+1.1}_{-0.5}$
0.65	250.6	48.9-52.3	2.0	0 / 1	–	$0.11^{+0.46}_{-0.09}$

Three new superheavy nuclides ^{268}Sg, ^{272}Hs, and ^{276}Ds were synthesized for the first time, see Fig. 2.

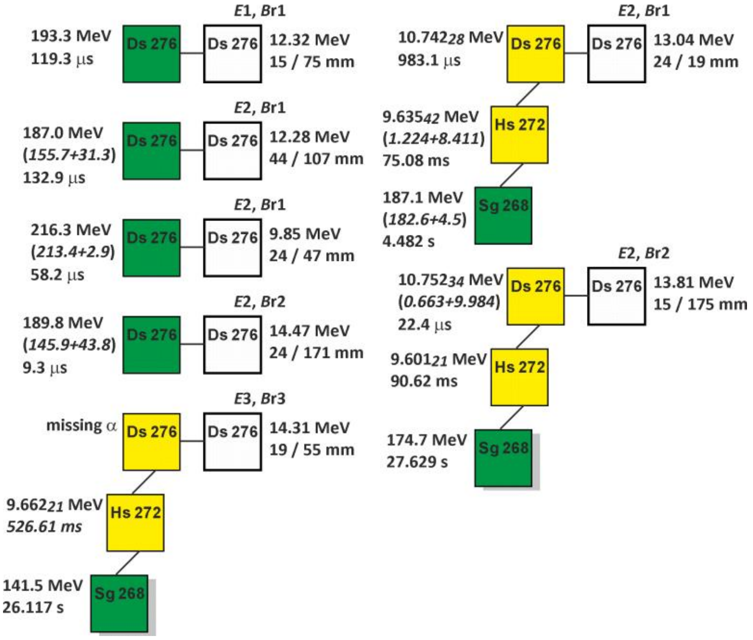


FIG.2. Decay properties of ^{276}Ds, ^{272}Hs, and ^{268}Sg. The upper rows for each chain show the ^{48}Ca energy ($E1 = 231$ MeV, $E2 = 238$ MeV, $E3 = 251$ MeV) and the separator magnetic rigidity ($B\rho1 = 2.42$ T m, $B\rho2 = 2.45$ T m, $B\rho3 = 2.43$ T m) (on the top of the blank square with a mark "Ds 276"). On the right side of the square, the ER energy and vertical and horizontal positions on the detector (in mm) are given. The rows on the left side provide the α-particle (in yellow) and SF-fragment (in green) energies and time intervals between the events. The energies of the summed signals are given in parentheses. The events marked with a shadow were registered during the beam-off periods. The α-particle energy errors are shown by smaller italic numbers.

The summary decay properties of new nuclei in the ^{276}Ds decay chain are given in Table II.

TABLE II. The first three columns show nucleus, decay mode and branch, as well as half-life. The next four columns show α-particle energy E_α, α-decay energy Q_α, and partial half-lives.

Nucleus	Decay mode, branch (%)	Half-life	E_α (MeV)	Q_α (MeV)	T_α	T_{SF}
^{276}Ds	SF: 57^{+15}_{-18}	$0.15^{+0.10}_{-0.04}$ ms	10.746(28)	10.904(28)	$0.36^{+0.32}_{-0.15}$ ms	$0.27^{+0.23}_{-0.10}$ ms
^{272}Hs	α	$0.16^{+0.19}_{-0.06}$ s	9.628(21)	9.772(21)		
^{268}Sg	SF	13^{+17}_{-4} s				

The cross sections for the formation of the heaviest elements (the maximum of the total cross section of the xn-channels) are shown in Fig 3. The data were obtained during the synthesis of elements with Z=108 and 112-118 in the fusion reactions of target nuclei from ^{226}Ra to ^{249}Cf with ^{48}Ca. Now they are complemented for the first time with data on the synthesis of the new isotope of element 110 in the ^{232}Th + ^{48}Ca reaction. The isotope ^{276}Ds is formed with a cross section an order of magnitude lower than that for the lighter nuclide ^{270}Hs (N = 162) in the ^{226}Ra(^{48}Ca, 4n)^{270}Hs reaction. On the contrary, when moving to the region of heavier elements (Z > 110), the cross section increases.

Such variation is in full agreement with theoretical models predicting the closed shells at Z=108, N=162 and Z=114, N=184. At the mass limits of the atomic nuclei, the effect of these shells significantly increases the survival of the heaviest compound nuclei and thus determines the existence of superheavy elements. In this regard, a significant rise in the cross section from Ds to the isotopes of Fl and Mc, observed in fusion reactions with ^{48}Ca, is essentially an ascent to the "island of stability" and a step towards the magic numbers at Z=114 and N=184.

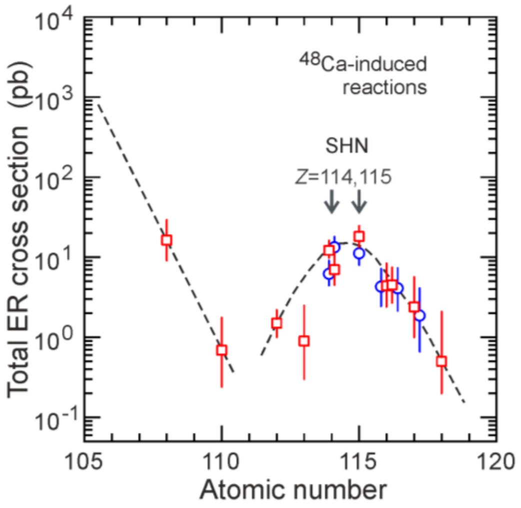


FIG. 3. Maximum production cross sections for the isotopes of heavy elements in the ^{48}Ca-induced reactions with ^{226}Ra, ^{232}Th, ^{238}U, ^{242,244}Pu, ^{243}Am, ^{245,248}Cm, ^{249}Bk, and ^{249}Cf. Data measured at DGFRS and DGFRS-2 are shown by red squares, the results obtained at SHIP, BGS, TASCA, and GARIS are shown by blue circles. The lines are drawn to guide the eye.

During the experiment at 231-MeV ^{48}Ca energy lasting less than a month, a sensitivity of about 70 fb was achieved, which indicates a strong potential for the research of superheavy nuclei with low production cross sections.

In the ^{232}Th + ^{48}Ca reaction studied at two of the four largest projectile energies, the new nuclide ^{275}Ds, a product of the 5n channel, was synthesized for the first time.

Some parameters of the experiments are listed in Table III.

TABLE III. The ^{232}Th and ^{238}U target thicknesses; reaction-specific laboratory-frame projectile energies E_{lab} in the middle of the target layers; resulting excitation energy E^* intervals; total beam doses; the numbers of observed decay chains of ^{276}Ds (4n), ^{275}Ds (5n), and ^{273}Ds (5n), and the cross sections σ of their production.

Reaction	Target thickness (mg/cm^2)	E_{lab} ^{a} (MeV)	E^* (MeV)	Beam dose ×10^{19}	No. of chains 4n/5n	σ_{4n} (pb)	σ_{5n} (pb)
^{232}Th+^{48}Ca	0.65	250.6	48.9-52.3	2.0	1/1	$0.11^{+0.46}_{-0.09}$	$0.11^{+0.46}_{-0.09}$
–	–	257.0	54.2-57.5	3.2	0/5	<0.2	$0.34^{+0.59}_{-0.16}$
^{238}U+^{40}Ar	0.69	212.2	47.5-50.7	3.2	0/2	<0.3	$0.18^{+0.44}_{-0.12}$

The energies of α particles or spontaneous fission fragments and decay times of nuclei in the decay chains of ^{275}Ds are shown in Fig. 4.

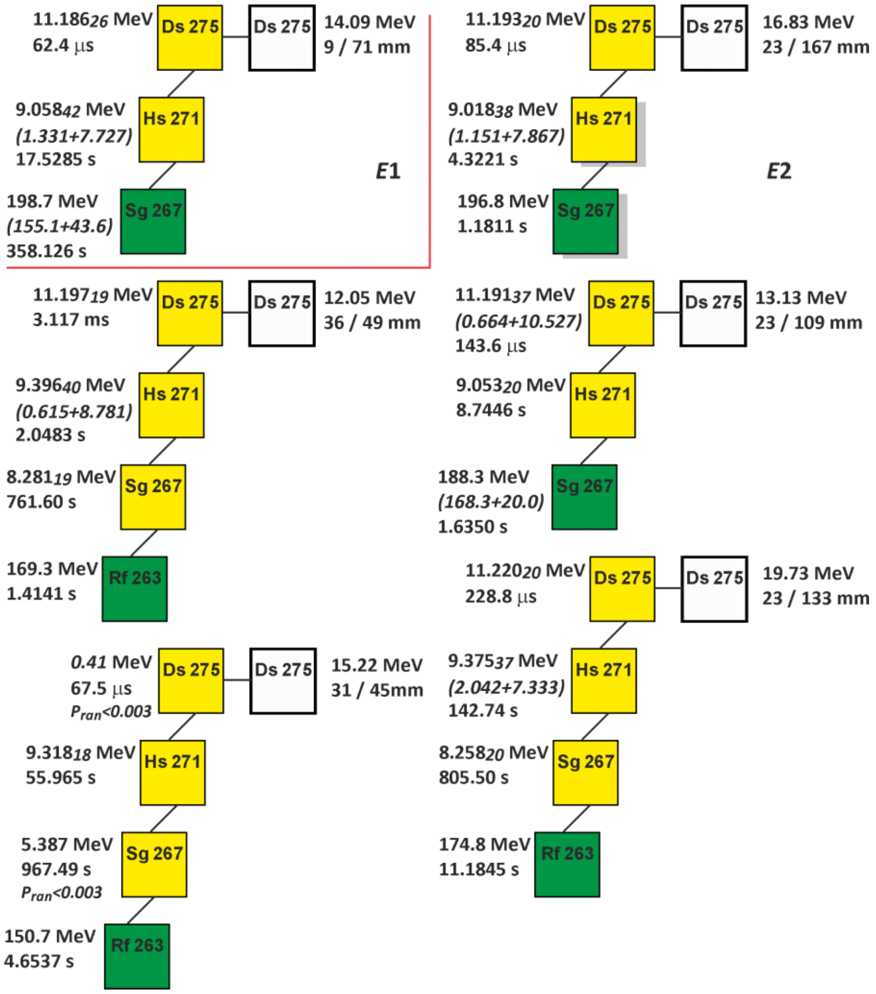


FIG. 4. The same as in Fig. 2 but for ^{275}Ds produced in the ^{232}Th + ^{48}Ca reaction at the projectile energies $E1$ = 251 MeV and $E2$ = 257 MeV. The probabilities of random origin of two events P_{ran} are shown; these particles escaped the focal detector, leaving low energy in it, but did not enter the side detector.

The decays of ^{275}Ds led to the previously synthesized daughter nuclei ^{271}Hs, ^{267}Sg, and ^{263}Rf, which means the first observation and identification of the superheavy nucleus, the product of the fusion of ^{48}Ca with the actinide nuclide, by the method of genetic correlations with known nuclei.

The measured α-particle energies of the mother nucleus ^{275}Ds are similar, and the decay times do not indicate possible decays with different half-lives. However, some difference in the α-particle energy of ^{271}Hs and in the decay mode of the subsequent isotope ^{267}Sg suggests the presence of decays through different excited levels.

We evaluated the properties of isotopes ^{271}Hs and ^{267}Sg separately for different decay branches. It turned out that not only do these isotopes decay with different α-particle energies (^{271}Hs) or decay modes (^{267}Sg), but their half-lives also differ markedly, see Table IV.

TABLE IV. Summary of decay properties of nuclei synthesized in the ^{232}Th+^{48}Ca reaction. The first three columns show the nucleus, decay mode, and experimental half-life. The next five columns show α-particle energy E_α, α-decay energy Q_α, as well as calculated spin and partial half-lives with respect to α decay and SF.

Nucleus	Decay mode	$T_{1/2}^{exp}$	E_α (MeV)	Q_α (MeV)	Spin	T_{a}^{calc}	T_{SF}^{calc}
^{275}Ds	α	$0.43^{+0.29}_{-0.12}$ ms	11.20(2)	11.37(2)	3/2	0.22 ms	2.0 s
^{271}Hs	α	$7.1^{+8.4}_{-2.5}$ s	9.05(2)	9.18(2)	3/2	5.1 s	6.0 min
^{271}Hs	α	46^{+56}_{-16} s	9.34(2)	9.48(2)	11/2	63 s	21 h

^{267}Sg	SF	100^{+92}_{-39} s	–	–	1/2	16 h	140 s
^{267}Sg	α	$9.8^{+11.3}_{-4.5}$ min	8.27(2)	8.40(2)	9/2	6 min	2.9 h
^{263}Rf	SF	$5.1^{+4.6}_{-1.7}$ s	–	–	1/2	0.5 h	6.4 s

In the ^{238}U(^{40}Ar,5n) reaction, two decay chains of ^{273}Ds were observed (see Table III and Fig. 5). The decay properties of the nuclei in one of them are in good agreement with the properties of the nuclei measured in the five decay chains of the parent nucleus ^{277}Cn produced in the cold-fusion reaction ^{208}Pb(^{70}Zn,1n). In the second chain, the energy of the α particle of ^{273}Ds turned out to be approximately 0.2 MeV lower than that measured for ^{273}Ds ($E_\alpha \approx 11.10$ MeV), and the decay time (41.7 ms) is two orders of magnitude higher than its average decay time ($T_{1/2} = 0.18^{+0.11}_{-0.05}$ ms), determined from six decays. Based on these results, the working hypothesis of the isotope decay pattern has been proposed (see Table V).

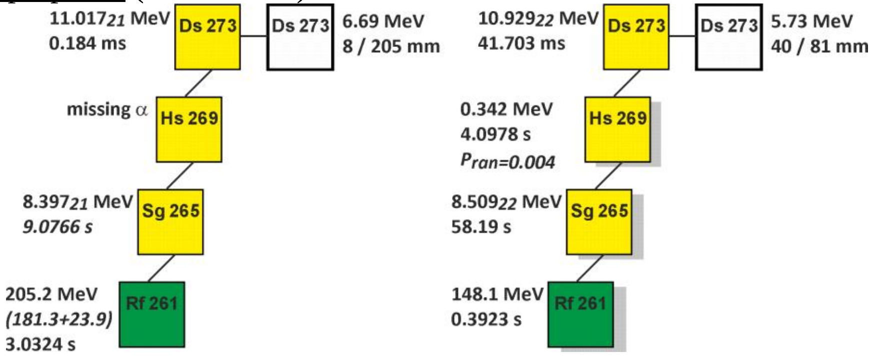


FIG. 5. The same as in Fig. 4 but for ^{273}Ds observed in the ^{238}U + ^{40}Ar reaction at the projectile energy of 212 MeV (see Table III).

TABLE V. The same as Table IV but for ^{273}Ds.

Nucleus	Decay mode	$T_{1/2}^{exp}$	E_α (MeV)	Q_α (MeV)	Spin	T_{a}^{calc}	T_{SF}^{calc}
^{273}Ds^{a}	α	30^{+140}_{-15} ms	10.93(2)	11.09(2)	11/2	87 ms	110 s
^{273}Ds^{b}	α	$0.18^{+0.11}_{-0.05}$ ms	11.10(7)	11.27(7)	1/2	0.21 ms	47 s
^{269}Hs^{a}	α	13^{+10}_{-4} s	9.20(4)	9.34(4)	9/2	15 s	2.2 h
^{269}Hs^{b}	α	$2.8^{+13.6}_{-1.3}$ s	9.08(15)	9.22(15)	1/2	3 s	14 min
^{265}Sg^{a}	α	$8.5^{+2.6}_{-1.6}$ s	8.84(5)	8.97(5)	11/2	11 s	14 h
^{265}Sg^{b}	α	$14.4^{+3.7}_{-2.5}$ s	8.69(5)	8.82(5)	3/2	12 s	59 min
^{261}Rf^{a}	α	68±3 s	8.28(2)	8.41(2)	11/2	87 s	12 min
^{261}Rf^{b}	SF	$2.6^{+0.7}_{-0.5}$ s	8.51(6)	8.64(6)	3/2	7.4 s	3.7 s

The production cross sections of nuclei in the ^{232}Th + ^{48}Ca and ^{238}U + ^{40}Ar reactions are shown in Fig. 6. As can be seen, the cross sections of the 5n reaction channels at $E^{*} \approx 50$ MeV are similar within the experimental uncertainties.

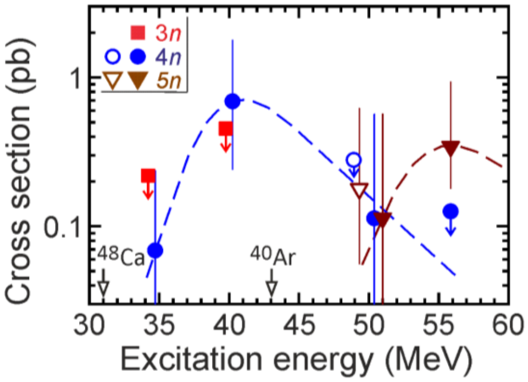
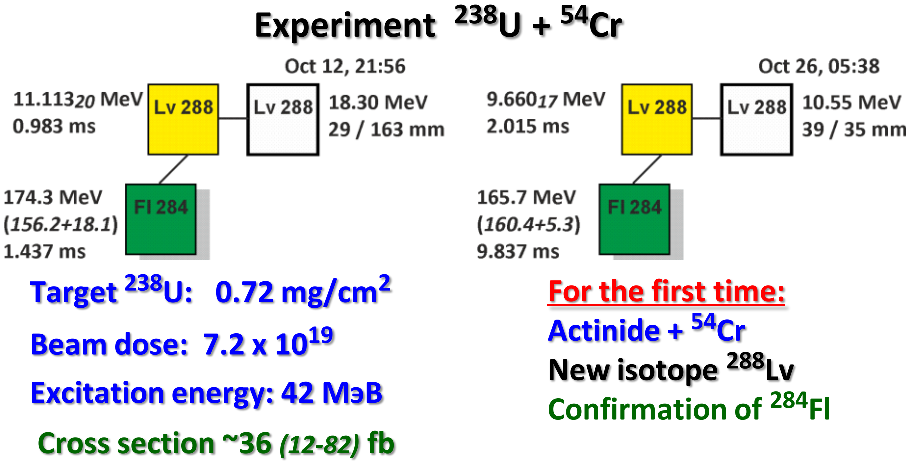


FIG. 6. Cross sections for the 3*n*- to 5*n*-evaporation channels for the ^{232}Th + ^{48}Ca (closed symbols) and ^{238}U + ^{40}Ar (open symbols) reactions. The symbols with arrows show the upper cross-section limits. The dashed lines through the data are drawn to guide the eye. The Bass barriers are shown by open arrows for comparison.

The second part of the experiments was related to the study of the compound-nucleus formation. To understand the possibilities of synthesizing new elements 119 and 120, it is of particular importance to determine the most optimal reactions. This issue depends both on the reaction cross-section value and the availability of the necessary target isotopes and accelerated ions. To do this, it is important to measure the cross sections of reactions that lead to lighter elements, but whose cross sections are obviously higher, for example, ^{242}Pu(^{50}Ti,*x*n)$^{292\text{-}x}$Lv and ^{238}U(^{54}Cr,*x*n)$^{292\text{-}x}$Lv. The cross sections of these reactions can be compared with, e.g., the cross section of the ^{245}Cm(^{48}Ca,2-3n)^{290,291}Lv reaction, which could determine the degree of decrease in the production cross section for element 116 during the transition from ^{48}Ca to ^{54}Cr. This will help to obtain more reliable information about the process of the compound-nucleus formation (the second stage of the fusion-evaporation process, see Fig. 1). Note, so far no cross section of the reaction of complete fusion of actinide nuclei with ions heavier than ^{48}Ca has been measured.

Some parameters of the ^{238}U(^{54}Cr,*x*n)$^{292\text{-}x}$Lv experiment and two observed decay chains of new synthesized isotope ^{288}Lv are shown in Fig. 7.



Target ^{238}U: 0.72 mg/cm^2

Beam dose: 7.2 x 10^{19}

Excitation energy: 42 МэВ

Cross section ~36 *(12-82)* fb

For the first time:

Actinide + ^{54}Cr

New isotope ^{288}Lv

Confirmation of ^{284}Fl

FIG. 7. Experimental parameters and properties of nuclei in the decay chains of a new isotope ^{288}Lv. In the second chain, the total α-particle energy was not registered (data are under analysis).

From a comparison of the production cross sections for isotopes of element 116 in reactions with ^{48}Ca and ^{54}Cr, it follows that the transition to a heavier particle led to a drop in the cross section by more than factor of 100, see Fig. 8.

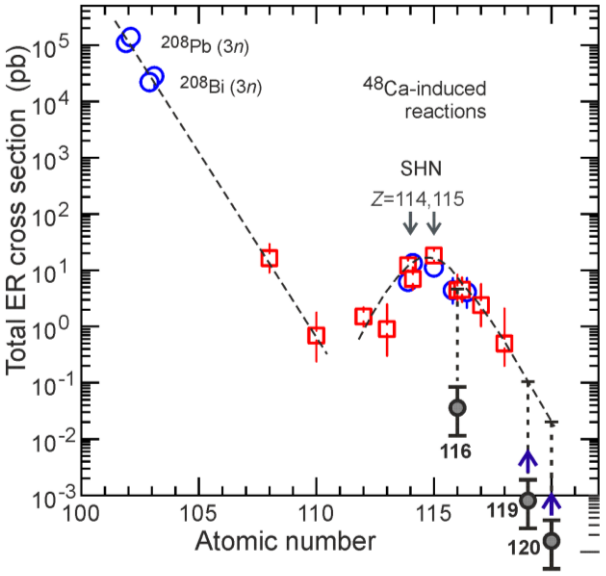


FIG. 8. The same as Fig. 3 but with cross section of the ^{238}U(^{54}Cr,4n)^{288}Lv reaction and tentative estimates for elements 119 and 120 which are shown by black circles.

If we assume that the drop in the cross sections for elements 119 and 120 in reactions with ^{48}Ca will remain the same as it is observed in transition from elements 114, 115 to element 118 and the transition from ^{48}Ca to ^{54}Cr will lead to an additional and similar drop in cross sections, then the expected cross section of the ^{243}Am+^{54}Cr → ^{297}119* reaction will be about 1 fb and will be even lower for the element 120. In this case, to obtain one atom of element 119, the duration of the experiment should be about 3 years.

However, it should be noted that such a formal extrapolation is not entirely justified, since cross sections of reactions ^{245,248}Cm+^{48}Ca→^{293,296}Lv* (N=177, 180) and ^{238}U+^{54}Cr→^{292}Lv* (N=176), which lead to different compound nuclei, are compared. But the survival probability for ^{293,296}Lv*, according to calculations, should be higher (see Fig. 1). If so, then the cross-section drop factor due to the change in the capture cross-section and the formation probability of a compound nucleus during the transition to a heavier ion ^{54}Cr and resulting in ^{292}Lv* should be less.

Based on the above, important areas of research are:

1. When discovering new elements, special attention is paid to their identification. One of the main methods is the registration of α decays of new nuclei, followed by α decays of known nuclei. Alpha decays of ^{293,294}119, products of the ^{243}Am(^{54}Cr,3-4*n*) reaction, lead to unknown isotopes ^{289,290}Ts. The properties of the daughter nuclei in the ^{290}Ts decay chain (^{286}Mc – ^{266}Db) were previously determined by us but the properties of nuclei in the decay chain of ^{293}119 are not known. The most optimal way to solve this problem is the synthesis of ^{281,282}Nh nuclei in the ^{237}Np(^{48}Ca,3-4n) reaction. It is possible not only to obtain more ^{282}Nh nuclei, but also for the first time to synthesize and study the properties of new nuclei ^{281}Nh, ^{277}Rg, ^{273}Mt, ^{269}Bh, ^{265}Db.

2. The cross sections of reactions leading to the isotopes of elements 119 and 120 may differ by a factor of 8 (when the same projectile is used, see Fig. 8). According to calculations, these cross sections may differ by 10 times, using different projectiles ^{50}Ti and ^{54}Cr to synthesize one element (Fig. 1). Experimental estimates of the probability of the compound-nucleus formation in reactions with ^{50}Ti and ^{54}Cr suggest a decrease in the cross section during the transition from ^{50}Ti to ^{54}Cr by about 4 times. To measure this factor, an experiment in which the ^{292}Lv* compound nucleus will be produced in the ^{242}Pu+^{50}Ti reaction, which was observed in the ^{238}U+^{54}Cr → ^{292}Lv* reaction, is of great importance.