Possibilities for Synthesis of New Superheavy Nuclei Using Stable Beams and Stable or Long-Lived Targets

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In our previous article [1], we presented a simple phenomenological model for the description of production cross sections of superheavy nuclei in a wide range of excitation energies including cold, warm and hot fusion. The model assumes that the fusion hindrance, observed in cold fusion reactions where only one neutron is emitted prior to the formation of evaporation residue (ER), can be explained by the competition of fusion with a fast fission-like process which can be identified with quasi-fission. Then the fusion probability can be expressed using the level densities in compound and scission configurations as

$$P_{fus}^{stat} = \frac{\rho(E_{CN}^*)}{\rho(E_{CN}^*) + \rho(E_{sc,eff}^*)}. \qquad (1)$$

The excitation energy in the scission configuration is estimated using the systematics of neutron multiplicities in spontaneous fission. Proportionality of the number of neutrons emitted from the fission fragments to the excitation energy in the scission configuration is

$$E_{sc,eff}^{E} = \left(\nu_n^{s.f.}(A_{CN}) + \Delta\nu_n(E_{CN}^*)\right)E_n, \qquad (2)$$

assumed. Then the excitation energy in the scission configuration can be expressed as

Where $\nu_n^{s.f.}(A_{CN})$ is the linear extrapolation of the available spontaneous fission neutron multiplicity data to given A_{CN} $(\nu_n^{s.f.}(A_{CN}) = 3.316 + 0.0969(A_{CN} - 250))$, $\Delta\nu_n(E_{CN}^*)$ is the additional increase of the post-scission neutron multiplicity at a given E_{CN}^* which can be expressed approximately as $\Delta\nu_n(E_{CN}^*) = 0.035\, E_{CN}^*$, as follows from the available post-scission neutron multiplicity data [2], and E_n is the amount of excitation energy per emitted neutron. This is a free parameter and was estimated from the comparison of production cross sections of transfermium nuclei produced in cold and hot fusion. The production cross sections of evaporation residues with Z=100-110 produced in hot fusion reactions can be explained by a conventional statistical calculation using a modified version of HIVAP code [3] with fission barriers expressed as

$$B_f(l) = C\left(B_f^{LD}(l) + \Delta B_f^{Shell}\right) \qquad (3)$$

The value of parameter C was 0.85 - 0.9. The liquid drop component of the fission barrier B_F^{LD} has been calculated according to the rotating charged liquid drop model of Cohen-Plasil-Swiatecki [4]. The shell component of the fission barrier ΔB_f^{Shell} has been taken from the calculation [5]. The fusion cross sections have been calculated using WKB approximation with Gaussian barrier width distribution [3].

The fusion probabilities for cold fusion were obtained by comparing the measured evaporation residue cross sections with those calculated using hot fusion systematics. The parametrization $E_n = 3.795 + 0.04(A_{CN} - 260)$ was obtained and used in further calculation for nuclei with Z>110. No angular momentum dependence for description of the scission point was assumed and the cross sections were evaluated in the maxima of the excitation functions obtained from statistical calculations with no fusion hindrance assumed.

Table 1 gives the production cross sections of several new superheavy nuclei [6], reported since our previous article was published, compared to the maximum evaporation residue cross sections in xn channels estimated in the initial work. One can see that the calculation predicted production cross sections lower by up to one order of magnitude since there is systematic shift in the dominating xn evaporation residue channel towards higher number of emitted neutrons.

Table 1: Comparison of several recently reported production cross sections of elements with Z>110 to the predictions given in [1].

Reaction	Experiment		Calculation	
	ER	σ ER	ER	σ ER
^{48}Ca+^{238}U	^{283}112	5 pb	^{283}112	1.5 pb
^{48}Ca+^{242}Pu	^{287}114	2.5 pb	^{286}114	0.25 pb
^{48}Ca+^{244}Pu	^{288}114	0.7 pb	^{287}114	0.1 pb
^{48}Ca+^{248}Cm	^{292}116	0.3 pb	^{291}116	0.01 pb

In the present work, the model is improved by implementing an angular momentum into the description of the scission configuration. The moment of inertia of symmetric touching rigid spheres was used. The fusion probability for a given partial wave can be further used as an input into the statistical calculation. This allows to obtain more realistic shapes of excitation functions for evaporation residue channels. In the initial work, the maxima of excitation functions have been shifted towards significantly higher values of excitation energy.

Table 2: Comparison of recently reported production cross sections of elements with Z>110 to the results of improved calculations.

Reaction	E_{lab} [MeV]	ER	σ ER [pb]	
			Exp.	Calc.
^{48}Ca+^{238}U	231	^{283}112	5	4
^{48}Ca+^{238}U	238	^{282}112	$\leq$7	8
^{48}Ca+^{242}Pu	235	^{287}114	2.5	1.5
^{48}Ca+^{244}Pu	236	^{288}114	0.7	2.0
^{48}Ca+^{248}Cm	240	^{292}116	0.3	0.1
^{86}Kr+^{208}Pb	449	^{293}118	2.2	10^{-4}

In Table 2 are again given production cross sections of the new superheavy nuclei, compared to the results of improved calculation. The production cross sections track quite well with the reported ones with exception of the reaction ^{86}Kr+^{20B}Pb [7] where the reported cross section is larger by several orders of magnitude. The new calculation reproduces correctly not only the absolute values but also the positions of the maxima. Concerning the reaction ^{86}Kr+^{20B}Pb, several additional measurements have been made [8] which did not reproduce the initial result and further investigations are under way.

Table 3: Predictions of production cross sections of elements with Z>110 calculated using improved calculation.

Reaction	E^*, MeV	ER	σ ER (calc)
^{48}Ca+^{249}Cf	47	^{293}118	0.1 pb
^{48}Ca+^{249}Cf	52	^{292}118	0.25 pb
^{48}Ca+^{252}Cf	46	^{296}118	0.02 pb
^{48}Ca+^{252}Cf	53	^{295}118	0.03 pb
^{58}Fe+^{238}U	48	^{292}118	0.2 pb
^{58}Fe+^{244}Pu	56	^{297}120	0.007 pb
^{64}Ni+^{238}U	56	^{297}120	0.007 pb

In Table 3 are given predictions for several reactions which may lead to the synthesis of even heavier nuclei. The improved calculation was used in this ease. Only reactions of stable beams with stable or long-lived targets have been taken into account. The reactions ^{48}Ca+^{249}Cf and ^{58}Fe+^{238}U give promise for the synthesis of the isotope ^{292,293}118 on the cross section level of 0.1-0.2 pb which seems to be an experimental limit for the foreseeable future. Compared to the system ^{58}Fe+^{238}U, the choice of heavier projectile ^{64}Ni or target ^{244}Pu leads to the drop of cross section by one and half orders of magnitude.

Table 4: Predictions of production cross sections of elements with Z> for the reactions induced by ^{136}Xe beam. For details concerning fusion probability see text.

Reaction	E*, MeV	ER	σ ER (calc)
^{136}Xe+^{154}Sm	44	^{286}116	3.5 pb
^{136}Xe+^{160}Gd	47	^{292}118	0.2 pb
^{136}Xe+^{164}Dy	50	^{296}120	0.004 pb

Another possible way to synthesize super-heavy nuclei is to use the nearly symmetric reactions induced by a ^{136}Xe beam. For these systems there is the question if additional fusion hindrance factors play a role, as suggested in [9] where in the symmetric system ^{110}Pd+^{110}Pd a strong fusion hindrance was observed. The fusion model used in the code HIVAP fails to reproduce fusion cross sections for the reaction ^{110}Pd+^{110}Pd. Therefore, we use for evaluation of ER cross sections a simple approximation where only the two lowest partial waves contribute. Such an approach can be realistic if fusion hindrance is correlated with angular momentum. Such values are in principle the lowest limit for the case without additional fusion hindrances. The ER cross sections for the full set of partial waves are typically 30 times higher. In order to obtain a good starting point for further experiments, it would be of great interest to obtain experimental data with ^{136}Xe beam in the transfermium region. The calculation presented here predicts for the reaction ^{136}Xe+^{124}Sn an ER cross section of 4 nb in the 2n channel and for the reaction ^{136}Xe+^{136}Xe an ER cross section of 0.1 nb in the 3n channel. The estimated production cross sections for superheavy nuclei, synthesized using ^{136}Xe beam are given in Table 4. The calculated cross section estimates for elements 116 and 118 are within present experimental limitations, but these elements may happen to be experimentally unreachable if additional fusion hindrances play role.

In summary, the possibilities for synthesis of new superheavy elements using stable or long-lived projectiles and targets seem to be quite limited. There seems to be a possibility to synthesize isotopes of element 118 in hot fusion reactions at the cross section level 0.1 pb. Symmetric reactions may be promising, the experimental studies of fusion processes in symmetric systems are needed in order to make conclusions concerning this topic. A possibility to use exotic beams will be the subject of our further study.

References

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