Revisiting the symmetric reactions for synthesis of super heavy nuclei of $Z \geq 120$

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Introduction

There have been extensive efforts experimentally to synthesize super-heavy elements (SHE) through heavy ion reactions with suitable choice of projectile and target nuclei. The two main routes followed are: 'hot fusion' with actinide target nuclei and highly asymmetric reaction channels [1], and 'cold fusion' with Pb, Bi target nuclei with moderately asymmetric reaction channels [2]. In all these experiments, the compound nucleus (CN) is formed with relatively less neutron numbers as compared to that needed for the extra stability due to the shell effects. Another reason for poor success of the experiments is that the reaction $|Q|$-value is much lower than (for 'hot-fusion'), or similar to (for 'cold-fusion') the Coulomb barrier (V_{Coul}) of the fusing target and projectile nuclei. Hence, at beam energies just above Coulomb barrier, the CN is formed with high excitation energy which is already larger than the neutron emission threshold. The radioactive-ion-beam routes are also being suggested for producing $Z_{\mathrm{CN}} \geq 120$. However, these reactions will have severe limitation on beam intensity.

Symmetric heavy-ion collisions using rare-earth nuclei

There have been some attempts using nearly symmetric collisions, however, the results are not encouraging so far. In the following, we revisit the near symmetric collisions involving rare-earth nuclei that might prove useful for synthesis of cold super-heavy nuclei in the region of $Z \geq 120$. The advantages that these reactions offer are: (i) $V_{\mathrm{Coul}} < |Q|$ value, (ii) Large g.s. deformations of both target and projectile nuclei that might enhance near barrier fusion cross section by channel coupling and lowering of fusion barrier, B_{fus}, (iii) Good n/p ratio of CN, (iv) Stable beams for large beam intensity, (v) Large elemental abundances of rare-earth elements, (vi) Large center-of-mass velocity for better collection of CN residues in forward direction, and (vii) Low neutron background at optimum low bombarding energy.

TABLE I: Relevant data for the reaction routes using the rare-earth nuclei.

Reaction (Z_{CN} A_{CN})	$Z_P Z_T$	Q- Value (MeV)	V_{Coul} (MeV)	S_n (MeV)
^{154}Sm + ^{150}Nd (122, 304)	3720	-377.5	373.9	7.1
^{154}Sm + ^{154}Sm (124, 308)	3844	-394.9	385.5	7.1
^{160}Gd + ^{154}Sm (126, 314)	3968	-412.2	396.2	7.3

Table I shows some relevant data such as the $Z_P Z_T$ value, the fusion Q-value, V_{Coul} and the neutron separation energy (S_n) for certain reaction routes suggested in the present work using rare-earth nuclei fusion channels.

Theoretical estimates

One expects that due to large $Z_P Z_T$ product, fusion will be largely hindered. However, for deformed nuclei there is no clear cut understanding of the fusion hindrance. Fusion-By-Diffusion (FBD) model has been successfully employed in reproducing the measured excitation function for the super-heavy element synthesis up to Z=119 [3]. In the FBD model, the evaporation residue cross section σ_{ER} for pro-

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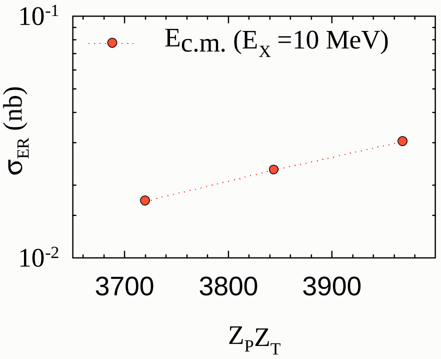

FIG. 1: The cross section for the synthesis of super-heavy nuclei as a function of Z_PZ_T for the reactions discussed in the present work at for $E_{c.m.}$ values for which E_X =10 MeV. The line is shown to guide the eye.

duction of a given final nucleus in its ground state is factorized as the product of the partial sticking cross-section $\sigma_{stick}(\ell)$, the diffusion probability $P_{\rm Diffus}(\ell)$, and the survival probability $P_{surv}(\ell)$ [4]:

$$\sigma_{ER} = \sum_{\ell=0}^{\infty} \sigma_{stick}(\ell) P_{\rm Diffus}(\ell) P_{surv}(\ell) \qquad (1)$$

The sticking cross section is determined by the "diffused barrier formula" based on assumption of Gaussian distribution of the barriers around a mean value [4] and for the present reactions at E_X =10 MeV it varies from 170 to 300 mb. In the FBD model, the probability ($P_{\rm Diffus}$) that the system injected at a point outside the saddle point achieves fusion is calculated using the diffusion process over a parabolic barrier, it is given by [3, 4];

$$P_{\rm Diffus} = \frac{1}{2}\left(1 - erf\sqrt{H/T}\right) \qquad (2)$$

where H is barrier height opposing fusion along the asymmetric fission valley, as seen from the injection point and T is the temperature of the fusing system. At the excitation energy E_X <10 MeV, the temperature T is expected to be <1.0 MeV but definitely >0.5 MeV. It is seen for the present reactions that the hindrance factor, H = 5 ± 1.5 MeV and the corresponding diffusion probability is in between of 10^{-6} and 10^{-3} for 0.5 MeV $\leq T \leq$ 1.0 MeV.

As far as survival probability (P_{surv}) is concerned, it is seen from the systematics of Swiatecki et al. [3] that it has a very weak dependence on the properties of compound nucleus in case of cold fusion reactions. From their work (Fig. 2 of Ref. [3]), we have derived the value of P_{surv} for Z=104 to 119 which are seen to lie in a narrow range of 0.2×10^{-4} to 6×10^{-4}. Since the value of P_{surv} for the cold fusion reactions is not sensitive to the compound nuclear properties, we consider a nominal value of 10^{-4} for the survival probability for all the systems considered in the present work.

Using the above value of P_{surv} and $P_{\rm Diffus}$ to be 10^{-6}, the lower limit of final cross sections for the synthesis of super-heavy nuclei for the present systems is arrived to be in the range of 1.7×10^{-11} barn to 3.0 $\times10^{-11}$ at E_X =10 MeV, as shown in the Fig. 1. The $E_{c.m.}$ values for which E_X =10 MeV increases in the range of 385 to 425 MeV with Z_PZ_T and it is reflected in the behavior of final evaporation residue cross section as a function of Z_PZ_T. Even if we allow for some uncertainties in the calculations, the results seem to be quite encouraging for the $Z \geq 120$ region. Present work suggests it to be definitely worth for experimental investigations using rare-earth nuclear collisions. It is also necessary to carry out full microscopic calculations to understand the fusion mechanism for these heavy systems.

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References

[1] Yu. Ts. Oganessian *et al.*, *Nature* **400** *242 (1999).*

[2] *S. Hofmann et al., Nucl. Phys.* **A 734** *93 (2004).*

[3] *W. J. Swiatecki et al., Phys. Rev.* **C 71** *014602 (2005).*

[4] *T. Cap et al.,Phys. Rev.* **C 83** *054602 (2011) .*