Search for possible fusion reactions to synthesize the superheavy element $Z = 121$

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We have studied the α-decay properties of superheavy nuclei $Z = 121$ in the range $265 \leqslant A \leqslant 316$. A detailed study of competition between α decay and fission enables us to identify the possible isotopes for superheavy element $Z = 121$. The nuclei $^{299-304}121$ were found to have long half-lives and hence they could be detected if synthesized in a laboratory. After identifying the possible isotopes, we have identified the most probable projectile-target combinations by studying the fusion cross section, evaporation residue cross section, compound nucleus formation probability (P_{CN}), and survival probability (P_{Surv}) of different projectile-target combinations to synthesize the superheavy element $Z = 121$. The most probable projectile-target combinations to synthesize the superheavy nuclei $^{299-305}121$ is V + Cf. The predicted α-decay half-lives and projectile-target combinations play a vital role in the synthesis of the superheavy element $Z = 121$.

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I. INTRODUCTION

A study of the possible fusion reactions and to identify potential superheavy nuclei, especially ones with $Z > 118$, is one of the eminent problems in the present nuclear physics. Superheavy nuclei up to $Z = 118$ were produced either by cold fusion reaction with target ^{208}Pb and ^{209}Bi at GSI [1,2] and RIKEN [3] or by hot fusion with projectile ^{48}Ca at JINR [4–6]. The synthesis of superheavy nuclei $Z = 119$, 120 was previously attempted by other researchers [7,8]. However, the scope to explore further and search for distinct features beyond $Z > 120$ is limitless. The superheavy element $Z = 121$ is expected to be the first of the superactinides, and the third element in the eighth period: analogously to lanthanum and actinium [9]. The synthesis of the superheavy element $Z = 121$ was first attempted by bombarding a target of ^{238}U with ^{65}Cu at Germany [10].

Previous researchers [11–13] proposed that the compound nucleus formation is based on the dinuclear system (DNS) concept. In the dinuclear system concept, fusion is assumed as a transfer of nucleons (or clusters) from the lighter nucleus to the heavier one in a dinuclear configuration. Adamian *et al.* [14] studied the possibilities of synthesis of superheavy nuclei in actinide based fusion reactions within the dinuclear system model for compound nucleus formation. The use of light and medium mass, neutron-rich radioactive beams may produce superheavy nuclei. Such a possibility is also provided by the multinucleon transfer processes in low-energy damped collisions of heavy actinide nuclei, if the shell effects really play an important role in such reactions [15]. Multinucleon transfer reactions occurring in low-energy collisions of heavy ions are considered as an important method for the production of superheavy elements [15,16]. Wang *et al.* [17] theoretically studied the synthesis of superheavy nuclei with $Z = 119$ and 120 in heavy-ion reactions with trans-uranium targets.

The evaporation-residue cross section of fusion reactions depends on the projectile-target combinations and incident energy. Therefore, finding favorable reactions and optimal beam energy range are very important for synthesis of superheavy elements. The study of dependencies of fusion reactions depends on the projectile target, is interesting, and is useful while synthesizing the superheavy nuclei with $Z > 118$, because the evaporation-residue cross section of reactions with these nuclei is very small, which makes the experiment much more difficult. The previous workers studied the possible projectile target combinations to synthesize the superheavy nuclei and competition between different decay modes of superheavy nuclei [18–31].

Viola *et al.* [32] developed a semiempirical formula for α-decay half-lives in the following form:

$$\log T_{1/2} = Az Q_{\text{eff}}^{1/2} + Bz + \log F \quad (1)$$

Q_{eff} is the effective α-decay energy inside the nucleus (MeV), the constants Az and Bz are Z dependent coefficients, and log F is the hindrance factor for nuclei with unpaired nucleons.

Literature survey also shows the following empirical formulas for α-decay half-lives.

Taagepera and Nurmia's formula [33]:

$$\log T_T = 1.61\left(\frac{Z_d}{\sqrt{E_\alpha}} - Z_d^{2/3}\right) + C_T, \quad (2)$$

where Z_d, E^α, and C_T are the atomic number of the daughter nuclei, the energy released, and the constant dependent on

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nuclei, respectively. Taagepera and Nurmia's formula [33] was improved by Keller and Munzel [34] as follows:

$$\log T_k = H_k\left(\frac{Z_d}{\sqrt{Q}} - Z_d^{2/3}\right) + C_k. \quad (3)$$

Hornshoj *et al.* [34] have proposed the formula for α-decay half-lives:

$$\log T_H = 0.803\,07\left(\frac{A_d^{4/3} Z_d}{A}\right)^{1/2} \times \left(\frac{\arccos\sqrt{x}}{\sqrt{x}} - \sqrt{1-x}\right) + C_H, \quad (4)$$

in which $x = 0.538\,243 Q A_d^{1/3}/Z_d$.

In 1980, Poenaru [35] formulated the equation for logarithmic α-decay half-lives as follows:

$$\log T_P = 0.434\,294K - 20.446 + C_P,\ K = \chi K_s$$
$$K_s = 2.529\,56 Z_d (A_d/AQ)^{1/2} \times [\arccos\sqrt{x_p} - \sqrt{x_p(1-x_p)}], \quad (5)$$

where

$$x_p = 0.4253 Q\big(1.5874 + A_d^{1/3}\big)/Z_d$$

and χ depends on neutron and proton number. Poenaru [36] *et al.* evaluated the deviations of the formulas proposed by the earlier workers [33–35]. Earlier workers [37] have shown that preformed-cluster models are equivalent with fission models, used to describe in a unified way cluster radioactivities and α decay. Parkhomenko and Sobiczewski [38] studied the α-decay properties for odd mass number superheavy nuclei.

Poenaru *et al.* [39] improved the formula for α-decay half-lives around magic numbers by using the SemFIS formula:

$$\log T_{1/2} = 0.434\,29\chi(x,y)K - 20.446 + H^f, \quad (6)$$

where H^f is a hindrance factor which takes different values $H^f = -0.025$ for even-even emitters, $H^f = -0.420$ for even-odd, $H^f = -0.280$ for odd-even emitters, and $H^f = -0.810$ for odd-odd ones:

$$K = 2.529\,56 Z_1\left(\frac{A_1}{AQ}\right)^{1/2} \times (\arccos\sqrt{r} - \sqrt{r(1-r)}),$$
$$r = 0.423 Q\big(1.5874 + A_1^{1/3}\big)/Z_1. \quad (7)$$

The numerical coefficient χ is close to unity. Sobiczewski and Pomorski [40] reviewed the theoretical studies on α decay of superheavy nuclei, which are based on both traditional macroscopic-microscopic and purely microscopic and self-consistent approaches. Ni *et al.* [41] proposed a general formula of half-lives for α decay and cluster radioactivity in the following form:

$$\log_{10} T_{1/2} = \log_{10}(\hbar \ln 2/P_0 F) + \frac{2}{\ln 10}\frac{\sqrt{2\mu e^2}}{\hbar} Z_c Z_d Q^{-1/2} \times [\arccos(x) - x\sqrt{1-x^2}], \quad (8)$$

where $x = \sqrt{R_t/R_C}$.

Poenaru *et al.* [42] formulated the expression for half-lives for heavy-particle radioactivity (HPR) and α decay using the Wentzel-Kramers-Brillouin (WKB) quasiclassical approximation as follows:

$$T = [(h \ln 2)/(2E_\upsilon)] \exp(K_{ov} + K_s),$$
$$K = K_{ov} + K_s \quad (9)$$

with

$$K = \frac{2}{\hbar}\int_{R_a}^{R_b} \sqrt{2B(R)E(R)}dR,$$

where $E\nu$ is the zero-point vibration energy.

Poenaru *et al.* [43] studied the half-lives of superheavy nuclei and predicted that for some of superheavy nuclei, cluster radioactivity dominates over α decay. A study of α and cluster decay is important to predict the decay mode of superheavy nuclei [44,45]. Hourani [46] measured the cluster radioactivity in heavy elements. Poenaru *et al.* [47] studied the α decay in heavy and superheavy elements. Earlier workers [48] proposed the universal curve for α-decay and cluster radioactivities based on the fission approach. Poenaru *et al.* [49] studied the nuclear inertia and the decay modes of superheavy nuclei.

Akrawy and Poenaru [50] modified the Royer's α-decay half-life formula [51] by introducing $I = (N - Z)\,A$ *as* follows:

$$T_{1/2} = a + bA^{1/6}\sqrt{Z} + \frac{cZ}{\sqrt{Q_\alpha}} + dI + eI^2, \quad (10)$$

where a, b, c, d, and e are constants. Poenaru *et al.* [52] studied cluster radioactivity and α decay of some superheavy nuclei with atomic numbers $Z = 119$ and 120 using ASAF (analytical superasymmetric fission) and UNIV (universal formula).

A detailed theoretical study is useful before the synthesis of superheavy nuclei $Z = 121$. Hence in the first part of the present work, we have studied the α-decay properties of superheavy nuclei $Z = 121$ in the range $265 \leqslant A \leqslant 316$. By studying the α-decay properties, we have identified the possible isotopes for superheavy element $Z = 121$. After identifying the possible isotopes, we have searched for the best projectile-target combinations to synthesize these superheavy nuclei. We have identified the most probable projectile-target combination by studying the fusion cross section, evaporation residue cross section, compound nucleus formation probability (P_{CN}), and survival probability (P_{Surv}) of different projectile target combinations to synthesize the superheavy element $Z = 121$.

II. THEORETICAL FRAMEWORK

A. Competition between fission and α-decay process

The interacting potential between two nuclei of fission fragments is taken as the sum of the Coulomb potential and proximity potential. To study the ternary and binary fission, we have used Denisov nuclear potential $Vp(r)$ [53]. We have explained the detailed procedure of calculation of α decay half-life and spontaneous fission half-life in the previous work [21].

B. Projectile-target combinations to synthesize SHN Z = 121 via fusion

The total interaction potential for fusion is calculated as

$$V = V_N(R) + V_C(R). \tag{11}$$

The Coulomb potential $V_c(R)$ is calculated by [54]

$$V_C(R) = \frac{Z_1 Z_2 e^2}{R} + 3Z_1 Z_2 e^2 \sum \frac{1}{2\lambda+1}\frac{R_i^\lambda(\alpha_i)}{R^{\lambda+1}} Y_\lambda^0(\theta_i) \times \left[\beta_{\lambda i} + \frac{4}{7}\beta_{\lambda i}^2 Y_\lambda^0(\theta_i)\right]. \tag{12}$$

It obviously depends on the deformation parameters $\beta_{\lambda i}$ and the spherical harmonic terms $Y_\lambda^0(\theta_i)$. The nuclear potential $V_N(R)$ is calculated from the proximity potential. We have used the Myers and Swiatecki [55] modified the proximity potential. The fusion barrier has two basic features: one is the barrier position (R_B) and the other is barrier height (V_B). The knowledge of the analytical form of the total interaction potential enables us to determine the exact values of these parameters. Since fusion happens at a distance larger than the touching configuration of the colliding pair, the above form of the Coulomb potential is justified. One can extract the barrier height V_B and barrier position R_B using the following conditions:

$$\left.\frac{dV(r)}{dr}\right|_{r=R_B} = 0 \quad \text{and} \quad \left.\frac{d^2V(r)}{dr^2}\right|_{r=R_B} \leqslant 0. \tag{13}$$

To study the fusion cross sections, we shall use the model given by Wong [56]. In this formalism, the cross section for complete fusion is given by

$$\sigma_{\text{fus}} = \frac{\pi\hbar^2}{2\mu \times E_{\text{cm}}} \sum_{l=0}^{l_{\max}} (2l+1) \times T_l(E_{\text{cm}}) P_{\text{CN}}(E_{\text{cm}}, l), \tag{14}$$

where μ is the reduced mass. The center of mass energy is denoted by E_{cm}. In the above formula, $l_{\max}$ corresponds to the largest partial wave for which a pocket still exists in the interaction potential and $T_l(E_{\text{cm}})$ is the energy-dependent barrier penetration factor. P_{CN} is the probability for the compound nucleus (CN) formation by two nuclei coming in contact. The probability of compound nucleus formation P_{CN} suggested by previous workers [15,57–62] is used in the present calculation. The calculation of P_{CN} requires effective fissility which in turn depends on x_{thr} and c. x_{thr} and c are adjustable parameters [18–20]. These parameters were suggested by Loveland [57]. This form of energy dependence of fusion probability is similar to the one proposed by Zargrebeav *et al.* [15].

After the fusion of two nuclei, the corresponding compound nuclei come to the ground state by emitting neutrons. The evaporation residue cross section of SH element production in a heavy-ion fusion reaction with subsequent emission of x neutrons is given by [15]

$$\sigma_{\text{ER}}^{xn} = \frac{\pi}{k^2} \sum_{l=0}^{\infty} (2l+1) T(E,l) P_{\text{CN}}(E,l) P_{\text{sur}}^{xn}(E^*, l). \tag{15}$$

P_{sur} is the survival probability and it is the compound nucleus to decay to the ground state of the final residual nucleus

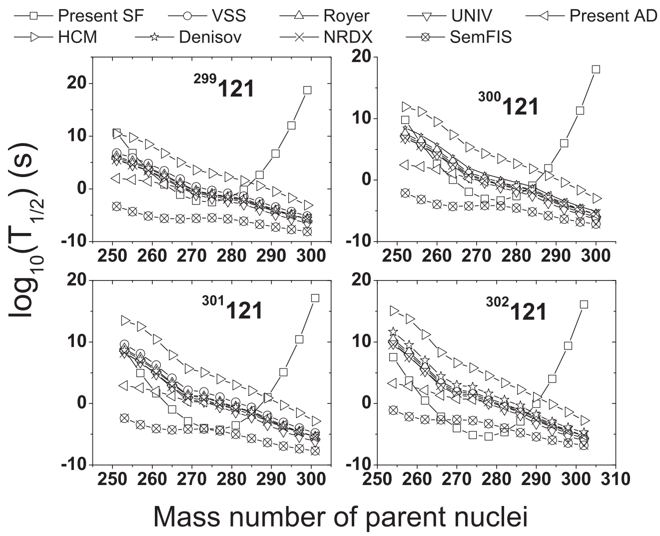

FIG. 1. Plot for the comparison of the calculated α-decay half-lives (VSS, Royer, UNIV, present AD, HCM, Denisov, NRDX, and SemFIS) with the corresponding spontaneous fission half-lives (present SF) of the isotopes $^{299-302}$121 and their decay products.

via evaporation of neutrons/light particles. The survival probability is the probability that the fused system emits several neutrons followed by observing a sequence of α decay from the residue. The survival probability under the evaporation of x neutrons is

$$P_{\text{sur}} = P_{xn}(E_{\text{CN}}^*) \prod_{i=1}^{i_{\max}=x} \left(\frac{\Gamma_n}{\Gamma_n + \Gamma_f}\right)_{i,E^*}, \tag{16}$$

where the index "i" is equal to the number of emitted neutrons. The calculation of P_{sur} requires the probability of evaporation of x neutrons from the compound nucleus (P_{xn}). To calculate the P_{xn}, we have adopted the procedure explained

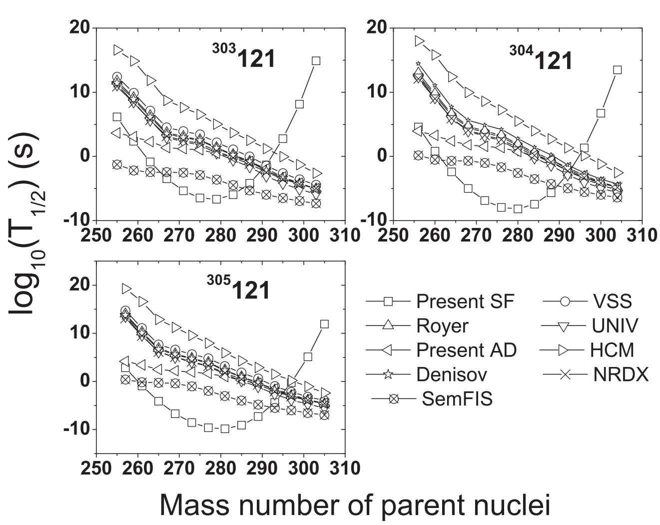

FIG. 2. Plot for the comparison of the calculated α-decay half-lives (VSS, Royer, UNIV, present AD, HCM, Denisov, NRDX, and SemFIS) with the corresponding spontaneous fission half-lives (present SF) of the isotopes $^{303-305}$121 and their decay products.

TABLE I. Comparison of the α-decay half-lives with SF half-lives of $^{299-304}121$ and their decay products. A prediction on the mode of decay is given by comparing the α-decay half-lives with the SF half-lives.

Parent nuclei	Q (MeV)	T_{SF} (s)	$T^{\alpha}_{1/2}$ (s) VSS	Royer	UNIV	Present	HCM	Denisov	NRDX	SemFIS	Mode of decay
$^{299}121$	13.62	5.2×10^{18}	7.2×10^{-6}	1.8×10^{-6}	3.2×10^{-7}	1.9×10^{-6}	8.0×10^{-6}	2.0×10^{-6}	2.3×10^{-6}	8.6×10^{-9}	$\alpha1$
$^{295}119$	12.95	1.0×10^{12}	4.7×10^{-5}	1.1×10^{-5}	1.8×10^{-6}	1.3×10^{-5}	1.9×10^{-3}	1.1×10^{-5}	1.1×10^{-5}	2.0×10^{-8}	$\alpha2$
$^{291}117$	12.28	5.0×10^{6}	3.5×10^{-4}	7.8×10^{-5}	1.2×10^{-5}	1.0×10^{-4}	3.1×10^{-4}	7.6×10^{-5}	6.0×10^{-5}	5.8×10^{-8}	SF
$^{287}115$	11.58	4.7×10^{2}	3.4×10^{-3}	7.1×10^{-4}	1.1×10^{-4}	1.1×10^{-3}	3.7×10^{-2}	6.5×10^{-4}	4.3×10^{-4}	2.0×10^{-7}	SF
$^{300}121$	13.53	1.1×10^{18}	9.1×10^{-7}	2.6×10^{-6}	4.3×10^{-7}	2.7×10^{-6}	1.0×10^{-6}	8.0×10^{-6}	3.2×10^{-6}	7.1×10^{-8}	$\alpha1$
$^{296}119$	12.86	2.1×10^{11}	6.0×10^{-6}	1.6×10^{-5}	2.5×10^{-6}	1.9×10^{-5}	2.4×10^{-5}	5.1×10^{-5}	1.5×10^{-5}	1.7×10^{-7}	$\alpha2$
$^{292}117$	12.18	9.6×10^{5}	4.9×10^{-5}	1.2×10^{-4}	1.8×10^{-5}	1.7×10^{-4}	4.0×10^{-4}	4.2×10^{-4}	9.2×10^{-5}	4.7×10^{-7}	SF
$^{288}115$	11.46	8.7×10^{1}	5.6×10^{-4}	1.3×10^{-3}	1.9×10^{-4}	2.1×10^{-3}	5.3×10^{-3}	5.0×10^{-3}	7.6×10^{-4}	1.7×10^{-6}	SF
$^{301}121$	13.44	1.4×10^{17}	1.6×10^{-5}	3.7×10^{-6}	6.1×10^{-7}	3.8×10^{-6}	1.3×10^{-5}	4.1×10^{-6}	4.5×10^{-6}	1.9×10^{-8}	$\alpha1$
$^{297}119$	12.78	2.7×10^{10}	1.1×10^{-4}	2.3×10^{-5}	3.6×10^{-6}	2.7×10^{-5}	3.0×10^{-4}	2.4×10^{-5}	2.2×10^{-5}	4.5×10^{-8}	$\alpha2$
$^{293}117$	12.09	1.2×10^{5}	9.1×10^{-4}	1.8×10^{-4}	2.8×10^{-5}	2.5×10^{-4}	5.2×10^{-4}	1.8×10^{-4}	1.4×10^{-4}	1.3×10^{-7}	SF
$^{289}115$	11.35	1.1×10^{1}	1.2×10^{-2}	2.3×10^{-3}	3.2×10^{-4}	3.8×10^{-3}	7.6×10^{-3}	2.1×10^{-3}	1.3×10^{-3}	4.5×10^{-7}	SF
$^{302}121$	13.34	1.3×10^{15}	2.1×10^{-6}	5.5×10^{-6}	8.8×10^{-7}	6.1×10^{-6}	1.7×10^{-5}	1.8×10^{-5}	6.5×10^{-6}	1.6×10^{-7}	$\alpha1$
$^{298}119$	12.69	2.4×10^{9}	1.4×10^{-5}	3.4×10^{-5}	5.1×10^{-6}	4.3×10^{-5}	3.8×10^{-5}	1.2×10^{-4}	3.2×10^{-5}	4.0×10^{-7}	SF
$^{294}117$	12.00	1.0×10^{4}	1.2×10^{-4}	2.8×10^{-4}	4.1×10^{-5}	4.1×10^{-4}	6.8×10^{-5}	1.0×10^{-3}	2.1×10^{-4}	1.1×10^{-6}	SF
$^{303}121$	13.24	7.7×10^{14}	3.9×10^{-5}	8.4×10^{-6}	1.3×10^{-6}	9.4×10^{-6}	2.2×10^{-6}	9.2×10^{-6}	9.8×10^{-6}	4.4×10^{-8}	$\alpha1$
$^{299}119$	12.59	1.4×10^{8}	2.5×10^{-4}	5.1×10^{-5}	7.6×10^{-6}	6.6×10^{-5}	5.0×10^{-5}	5.3×10^{-5}	4.7×10^{-5}	1.1×10^{-7}	SF
$^{295}117$	11.91	5.8×10^{2}	2.3×10^{-3}	4.3×10^{-4}	6.1×10^{-5}	6.3×10^{-4}	8.9×10^{-4}	4.2×10^{-4}	3.1×10^{-4}	3.2×10^{-7}	SF
$^{304}121$	13.13	3.0×10^{13}	5.5×10^{-6}	1.3×10^{-5}	2.0×10^{-6}	1.6×10^{-5}	2.9×10^{-5}	4.8×10^{-5}	1.5×10^{-5}	3.8×10^{-7}	$\alpha1$
$^{300}119$	12.49	5.2×10^{6}	3.6×10^{-5}	8.0×10^{-5}	1.2×10^{-5}	1.0×10^{-4}	6.5×10^{-4}	3.0×10^{-4}	7.2×10^{-5}	1.0×10^{-6}	SF
$^{296}117$	11.82	2.1×10^{1}	3.2×10^{-4}	6.7×10^{-4}	9.4×10^{-5}	1.0×10^{-3}	1.2×10^{-3}	2.7×10^{-3}	4.8×10^{-4}	3.0×10^{-6}	SF

by the previous workers [61,62]. The term $[\Gamma_n/(\Gamma_n+\Gamma_f)]$ in Eq. (16) is calculated by the knowledge of the ratio of the emission width of a neutron to the fission width (Γ_n/Γ_f). In the present work, we have used the expression for Γ_n/Γ_f based on the level densities of the Fermi-gas model [62].

III. RESULTS AND DISCUSSION

We have identified the possible isotopes of superheavy element $Z = 121$ by comparing the α-decay half-lives with that of spontaneous half-lives. The energy released during an α decay (Q_α) is calculated using the procedure explained in our previous work [22–24]. We have used experimental mass excess values [63]. For those nuclei, where experimental mass excess was unavailable, we have used recent theoretical values [25,64]. We have calculated the α-decay half-lives and spontaneous fission half-lives for different isotopes of a superheavy element with mass number $Z = 121$ ranging from $265 \leqslant A \leqslant 316$. A comparison of α-decay half-lives with the corresponding SF half-life makes it clear that the nuclei $^{265-279}121$ could not survive against fission. Even though the nuclei $^{280-298}121$ survive against fission and show α chains, they could not be detected due to shorter α-decay half-lives ($<10^{-8}$ s). The nuclei $^{299-304}121$ will survive against fission. The nuclei $^{299-301}121$ and $^{302-305}121$ show 2α and 1α chains, respectively. The variation of $\log_{10}(T_{1/2})$ against the mass

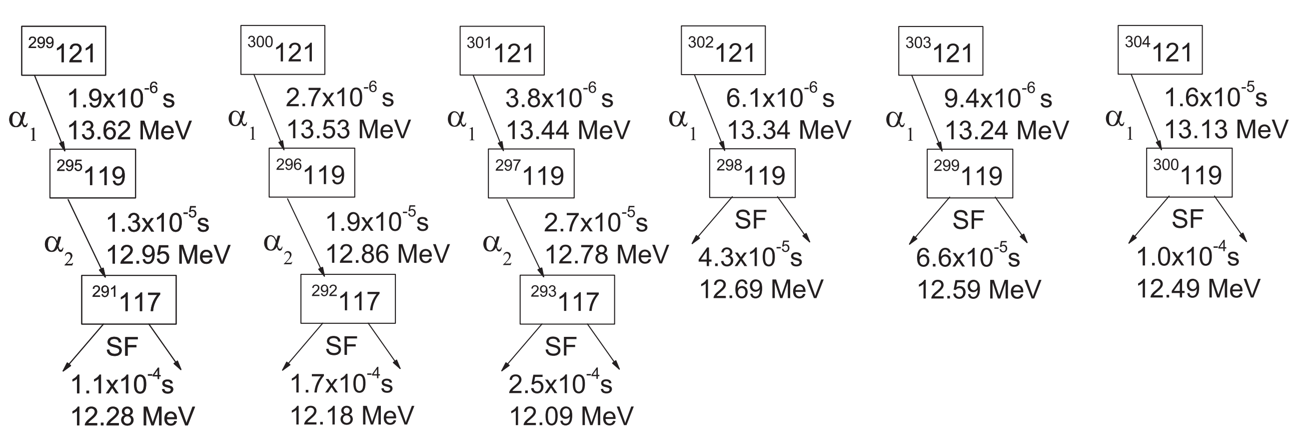

FIG. 3. Decay chain of the predicted probable isotopes for $Z = 121$.

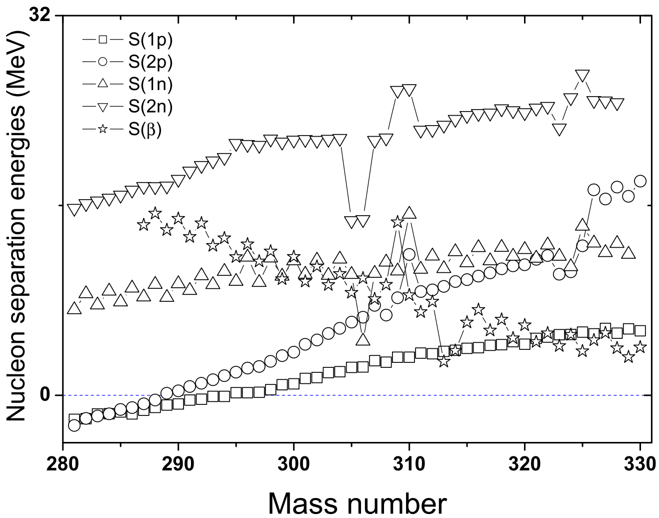

FIG. 4. Nucleon separation energies as a function of mass number for $Z = 121$.

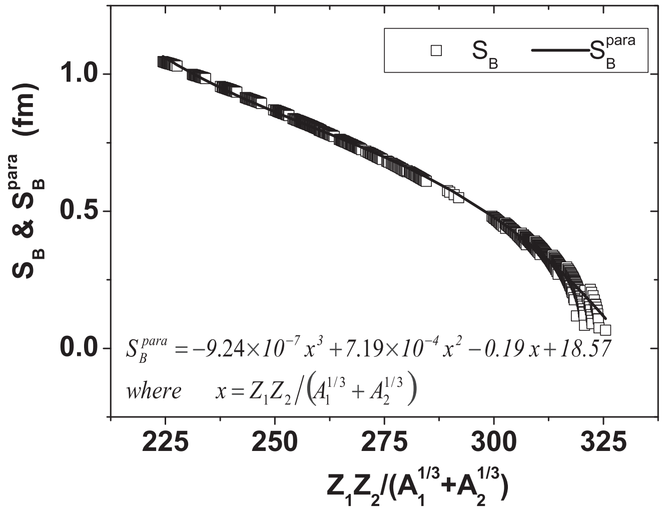

FIG. 6. Reduced fusion barrier positions S_B (fm) as a function of $\frac{Z_1 Z_2}{A_1^{1/3}+A_2^{1/3}}$.

number of the parent nuclei is shown in Figs. 1 and 2. Along with these, we have plotted the decay half-lives evaluated using the Viola-Seaborg semi (VSS) empirical formula [32]; the universal decay formula [65] and the analytical formulas of Royer [66], the Ni-Ren-Dong-Xu (NRDX) formula [41], the Denisov formula [67], the SemFIS formula [68], and the Manjunatha- Sridhar (HCM) semiempirical formula [31]. Among the studied nuclei in the range $265 \leqslant A \leqslant 316$, the nuclei $^{299\text{–}304}121$ were found to have long half-lives and hence it could be sufficient to detect them if synthesized in a laboratory. These predictions are highlighted in Table I. The calculated α-decay chains are also shown in Fig. 3.

To check isotopes for the stability against the proton, neutron, and beta emission, we have calculated the corresponding separation energies. The calculated separation energies for different isotopes of superheavy nuclei $Z = 121$ are shown in Fig. 4. From this calculation, it is found that the one proton $[S(1p)]$ and two-proton separation energies $[S(2p)]$ are negative for isotopes within the range $280 \leqslant A \leqslant 294$. The nuclei $^{280\text{–}294}121$ comes outside the proton drip line and thus may easily decay through proton emission. The nuclei $^{295\text{–}316}121$ were found to be stable against neutron, proton, and beta decay. The summary of the decay mode of isotopes of superheavy elements SHN $Z = 121$ is also shown in Fig. 5.

After identifying the most possible isotopes and different decay modes for the superheavy element $Z = 121$, we have studied the possible fusion reactions for their synthesis. We have studied more than 1000 possible projectile target combinations to synthesize superheavy nuclei $^{299\text{–}304}121$. For all projectile-target combinations, we have calculated the fusion barrier heights (V_B) and positions (R_B). Once fusion barrier

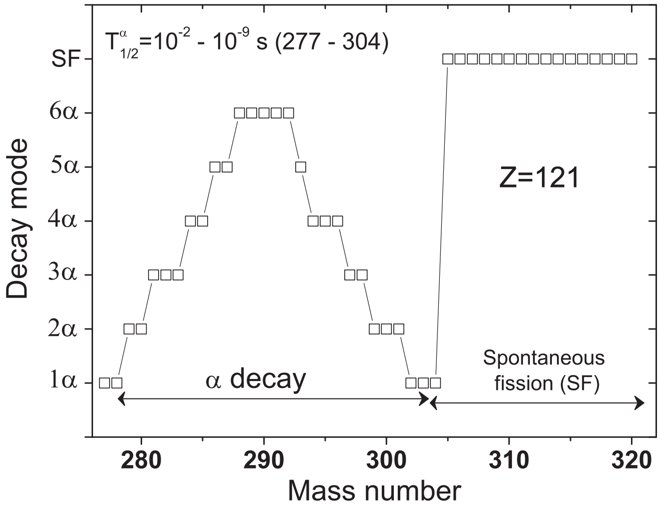

FIG. 5. Decay modes of superheavy nuclei for $Z = 121$. The vertical axis denotes the number of α particles corresponding to the decay mode, i.e., 1-α chain, 2-α chain, etc.

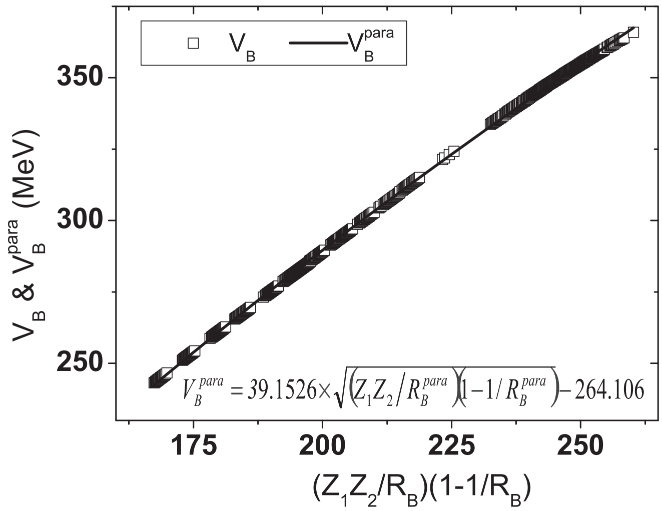

FIG. 7. Fusion barrier heights V_B (fm) as a function of $\frac{Z_1 Z_2}{R_B^{\text{par}}}(1 - \frac{1}{R_B^{\text{par}}})$.

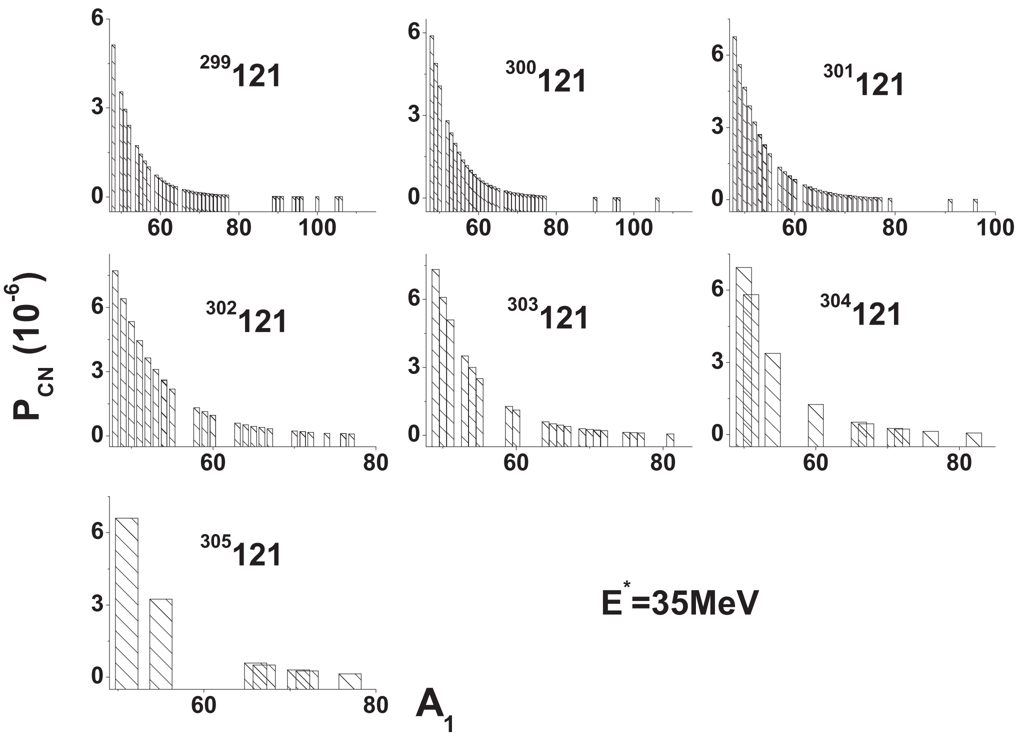

FIG. 8. Variation of compound nucleus probability (P_{CN}) at 35 MeV with mass number of projectile.

heights and positions were calculated, a search was made for their parametrization. We have calculated the reduced fusion barrier $S_B = R_B - C_1 - C_2$ and plotted reduced fusion barrier as a function of $Z_1Z_2/(A_1^{1/3} + A_2^{1/3})$ and it is shown in Fig. 6. We have fitted the function for the reduced fusion barrier in terms of $x = Z_1Z_2/(A_1^{1/3} + A_2^{1/3})$ as follows:

$$S_B^{\text{para}} = 18.57 - 0.19x + 7.19 \times 10^{-4}x^2 - 9.24 \times 10^{-7}x^3, \quad (17)$$

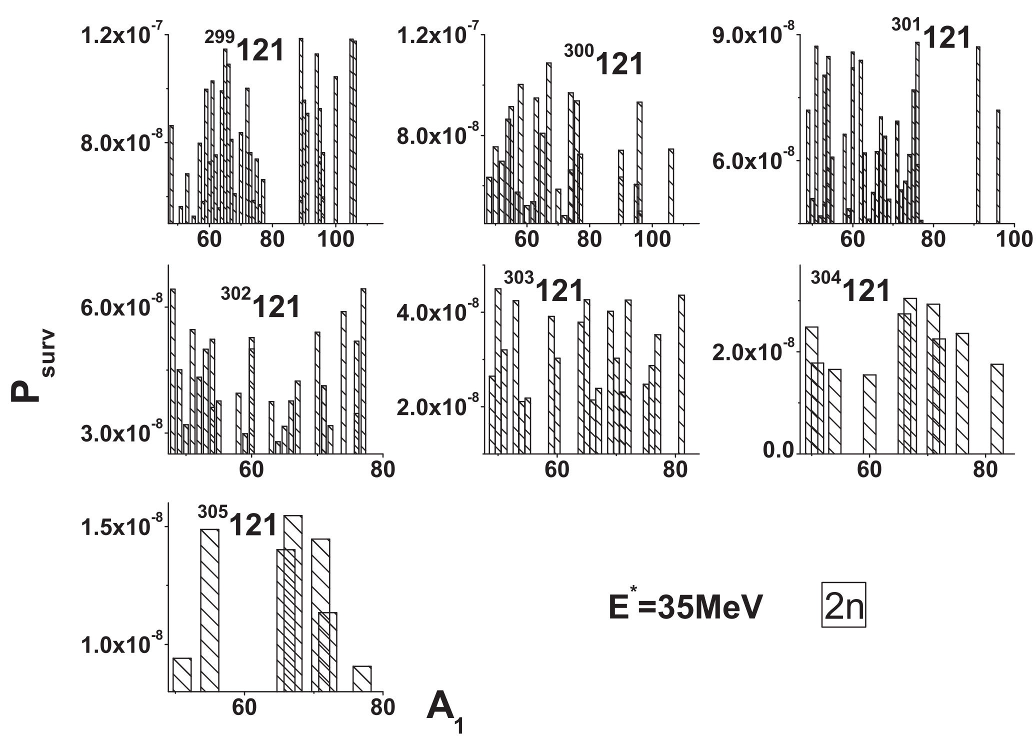

FIG. 9. Variation of survival probability (P_{surv}) at 35 MeV with mass number of projectile (2n channel).

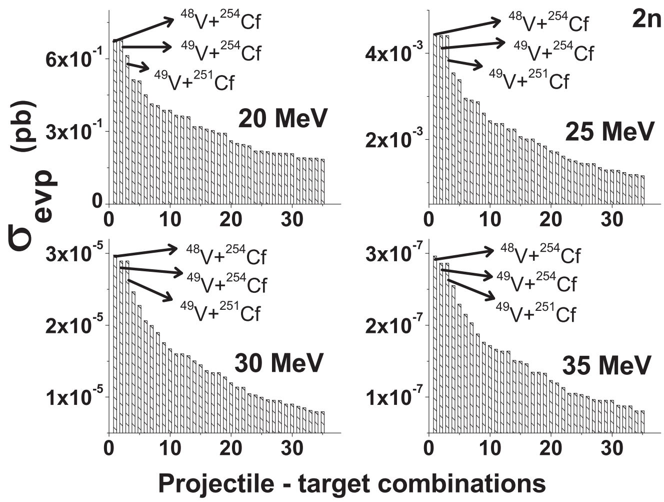

FIG. 10. Evaporation residue cross section for different projectile-target combinations at different energies E^* for $2n$ channel (1 – ^{48}V + ^{254}Cf, 2 – ^{49}V + ^{254}Cf, 3 – ^{49}V + ^{251}Cf, 4 – ^{49}V + ^{252}Cf, 5 – ^{48}V + ^{251}Cf, 6 – ^{48}V + ^{252}Cf, 7 – ^{48}V + ^{253}Cf, 8 – ^{49}V + ^{253}Cf, 9 – ^{50}V + ^{253}Cf, 10 – ^{51}V + ^{250}Cf, 11 – ^{50}V + ^{250}Cf, 12 – ^{50}V + ^{249}Cf, 13 – ^{51}Cr + ^{249}Bk, 14 – ^{51}V + ^{251}Cf, 15 – ^{54}Cr + ^{249}Bk, 16 – ^{50}V + ^{251}Cf, 17 – ^{49}V + ^{250}Cf, 18 – ^{52}Mn + ^{248}Cm, 19 – ^{50}Cr + ^{249}Bk, 20 – ^{50}V + ^{252}Cf, 21 – ^{51}V + ^{252}Cf, 22 – ^{50}V + ^{254}Cf, 23 – ^{53}Cr + ^{248}Bk, 24 – ^{51}V + ^{249}Cf, 25 – ^{51}V + ^{248}Cf, 26 – ^{52}Cr + ^{247}Bk, 27 – ^{52}Cr + ^{248}Bk, 28 – ^{52}Mn + ^{250}Cm, 29 – ^{60}Fe + ^{243}Am, 30 – ^{54}Mn + ^{247}Cm, 31 – ^{53}Cr + ^{249}Bk, 32 – ^{53}Mn + ^{250}Cm, 33 – ^{52}Cr + ^{249}Bk, 34 – ^{53}Mn + ^{246}Cm, 35 – ^{53}Mn + ^{247}Cm).

hence, fusion barrier position (R_B) becomes $R_B^{\text{para}} = S_B^{\text{para}} + C_1 + C_2$.

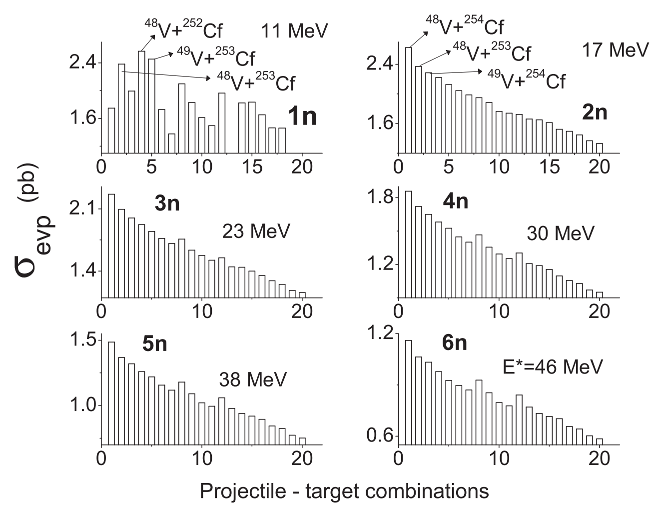

FIG. 11. Maximum evaporation residue cross section for different projectile-target combinations at maximum E^* for different neutron evaporation channels (1 – ^{48}V + ^{254}Cf, 2 – ^{48}V + ^{253}Cf, 3 – ^{49}V + ^{254}Cf, 4 – ^{48}V + ^{252}Cf, 5 – ^{49}V + ^{253}Cf, 6 – ^{48}V + ^{251}Cf, 7 – ^{49}V + ^{252}Cf, 8 – ^{50}V + ^{254}Cf, 9 – ^{50}V + ^{253}Cf, 10 – ^{49}V + ^{251}Cf, 11 – ^{50}V + ^{252}Cf, 12 – ^{51}V + ^{254}Cf, 13 – ^{51}V + ^{253}Cf, 14 – ^{49}V + ^{250}Cf, 15 – ^{50}V + ^{251}Cf, 16 – ^{51}V + ^{252}Cf, 17 – ^{50}V + ^{250}Cf, 18 – ^{51}V + ^{251}Cf, 19 – ^{50}V + ^{249}Cf, 20 – ^{51}V + ^{250}Cf).

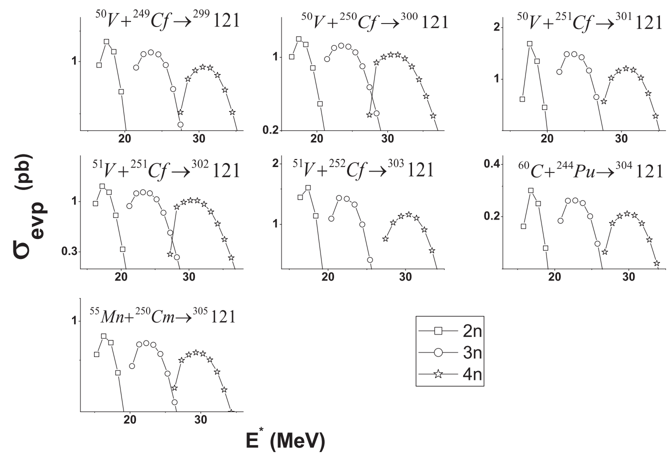

FIG. 12. Evaporation residue cross section for selected projectile-target combinations as a function of energy E^* for $2n$, $3n$, and $4n$ channels.

Finally, the parametrized fusion barrier position can be expressed as

$$R_B^{\text{para}} = 18.57 - 0.19x + 7.19 \times 10^{-4}x^2 - 9.24 \times 10^{-7}x^3 + C_1 + C_2. \quad (18)$$

The calculated fusion barrier height (V_B) is plotted as a function of $(Z_1Z_2/R_B^{\text{para}})(1 - 1/R_B^{\text{para}})$ and it is shown in Fig. 7. We have fitted the nonlinear function for the fusion barrier height as follows:

$$V_B^{\text{para}} = 39.1526 \times \sqrt{\left(Z_1Z_2/R_B^{\text{para}}\right)\left(1-1/R_B^{\text{para}}\right)} - 264.106. \quad (19)$$

The constructed formula for the fusion barriers may be used to produce R_B and V_B of fusion reactions to synthesize superheavy nuclei $Z = 121$.

The variation of calculated compound nucleus formation probability (P_{CN}) with mass number of projectile for super-

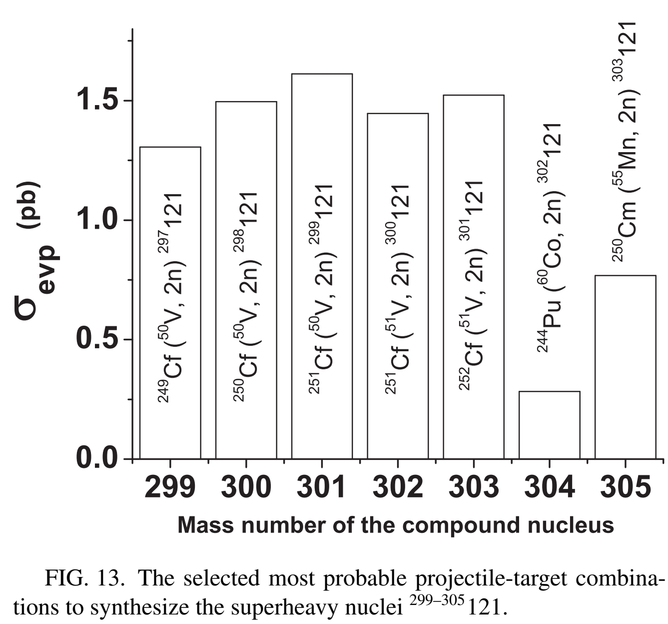

FIG. 13. The selected most probable projectile-target combinations to synthesize the superheavy nuclei $^{299-305}$121.

TABLE II. Presynthesis parameters of most probable fusion reactions to synthesis SHE $Z = 121$.

CN	Most probable projectile-target combination	V_B (MeV)	R_B (fm)	Z_pZ_t	χ_{CN}	$\chi_{eff} \times 10^{-3}$	N/A
$^{299}121$	^{50}V(1.5×10^{17}yr) + ^{249}Cf(351yr)	244.8	12.26	2254	1.029	1.37	0.59532
	^{52}Cr(S 83.789%) + ^{247}Bk(1380 yr)	252.7	12.25	2328		1.38	
	^{55}Mn(S 100%) + ^{244}Cm(18.1yr)	260	12.27	2400		1.36	
	^{53}Mn(3.74×10^{6}yr) + ^{246}Cm(4730 yr)	260.8	12.22	2400		1.4	
	^{58}Fe(S 0.28%) + ^{241}Am(432.2 yr)	267.1	12.28	2470		1.34	
	^{57}Fe(S 2.12%) + ^{242}Am(141 yr)	267.5	12.26	2470		1.36	
	^{56}Fe(S 91.75%) + ^{243}Am(7370 yr)	267.9	12.24	2470		1.38	
	^{59}Co(S 100%) + ^{240}Pu(6500 yr)	274.7	12.25	2538		1.36	
	^{60}Co(5.27 yr) + ^{239}Pu(2.41×10^{4}yr)	274.4	12.27	2538		1.34	
$^{300}121$	^{50}V(1.5×10^{17}yr) + ^{250}Cf(13.08 yr)	244.6	12.27	2254	1.0276	1.37	0.59667
	^{51}V(S 99.75%) + ^{249}Cf(351yr)	244.2	12.29	2254		1.35	
	^{53}Cr(S 9.5%) + ^{247}Bk(1380 yr)	252.1	12.28	2328		1.35	
	^{52}Cr(S 83.789%) + ^{248}Bk(>300 yr)	252.5	12.26	2328		1.37	
	^{55}Mn(S 100%) + ^{245}Cm(8500 y)	259.8	12.28	2400		1.35	
	^{53}Mn(3.74×10^{6}yr) + ^{247}Cm(1.56×10^{7}yr)	260.6	12.24	2400		1.39	
	^{58}Fe(S 0.28%) + ^{242}Am(141 yr)	266.9	12.29	2470		1.33	
	^{57}Fe(S 2.12%) + ^{243}Am(7370 yr)	267.3	12.27	2470		1.35	
	^{59}Co(S 100%) + ^{241}Pu(14 yr)	274.5	12.26	2538		1.35	
	^{60}Co(5.27 yr) + ^{240}Pu(6500 yr)	274.1	12.28	2538		1.34	
$^{301}121$	^{50}V(1.5×10^{17}yr) + ^{251}Cf(900 yr)	244.4	12.28	2254	1.02623	1.36	0.59801
	^{51}V(S 99.75%) + ^{250}Cf(13.08 yr)	244	12.3	2254		1.34	
	^{54}Cr(S 2.365%) + ^{247}Bk(1380 yr)	251.5	12.32	2328		1.32	
	^{53}Cr(S 9.5%) + ^{248}Bk(>300 yr)	251.9	12.3	2328		1.34	
	^{55}Mn(S 100%) + ^{246}Cm(4730 yr)	259.6	12.29	2400		1.34	
	^{53}Mn(3.74×10^{6}yr) + ^{248}Cm(3.4×10^{5}yr)	260.3	12.25	2400		1.38	
	^{60}Fe(2.6×10^{6}yr) + ^{241}Am(432.2 yr)	266	12.34	2470		1.29	
	^{58}Fe(S 0.28%) + ^{243}Am(7370 yr)	266.7	12.3	2470		1.33	
	^{59}Co(S 100%) + ^{242}Pu(3.73×10^{5}yr)	274.3	12.28	2538		1.35	
	^{60}Co(5.27 yr) + ^{241}Pu(14 yr)	273.9	12.3	2538		1.33	
$^{302}121$	^{51}V(S 99.75%) + ^{251}Cf(900 yr)	243.8	12.31	2254	1.02489	1.33	0.59934
	^{54}Cr(S 2.365%) + ^{248}Bk(>300 yr)	251.3	12.33	2328		1.31	
	^{55}Mn(S 100%) + ^{247}Cm(1.56×10^{7}yr)	259.4	12.3	2400		134	
	^{60}Fe(2.6×10^{6}yr) + ^{242}Am(141 yr)	265.7	12.35	2470		1.29	
	^{60}Co(5.27 yr) + ^{242}Pu(3.73×10^{5}yr)	273.7	12.31	2538		1.32	
$^{303}121$	^{51}V(S 99.75%) + ^{252}Cf(2.645 yr)	243.6	12.33	2254	1.02358	1.32	0.60066
	^{55}Mn(S 100%) + ^{248}Cm(3.4×10^{5}yr)	259.1	12.31	2400		1.33	
	^{53}Mn(3.74×10^{6}yr) + ^{250}Cm(9000 yr)	159.9	12.27	2400		1.37	
	^{60}Fe(2.6×10^{6}yr) + ^{243}Am(7370 yr)	265.5	12.37	2470		1.28	
	^{59}Co(S 100%) + ^{244}Pu(8.08×10^{7}yr)	273.8	12.3	2538		1.33	
$^{304}121$	^{60}Co(5.27 yr) + ^{244}Pu(8.08×10^{7}yr)	273.2	12.33	2538	1.02231	1.31	0.60197
$^{305}121$	^{55}Mn(S 100%) + ^{250}Cm(9000 yr)	258.7	12.34	2400	1.02106	1.31	0.60328

heavy nuclei $^{299-305}121$ is shown in Fig. 8. From this figure, it is clear that P_{CN} decreases with increasing mass number of projectile. The variation of survival probability (P_{surv}) with mass number of projectile at 35 MeV (for $2n$) for superheavy nuclei $^{299-305}121$ are as shown in Fig. 9.

We have studied the variation of the evaporation residue cross section for the most probable projectile-target combinations. A comparison of evaporation residue cross section among the studied projectile-target combinations is as shown in Fig. 10. Among the studied projectile-target combinations, the fusion reaction $^{48}V + ^{254}Cf$ has a maximum evaporation residue cross section at all energies and at $1n$ to $6n$ evaporation channel. The comparison of evaporation residue cross sections among the studied projectile-target combinations at different energies for $1n$ to $6n$ neutron evaporation channel is as shown in Fig. 11.

From the study, it is found that the projectile-target combination V + Cf has a larger maximum evaporation residue cross section than the other studied projectile-target combinations. It is also observed that the projectile-target combination V + Cf has minimum driving potential, maximum fusion, and evaporation residue cross sections. Hence the selected most probable projectile-target combination to synthesize superheavy nuclei $^{299-305}121$ is V + Cf. Figure 12 shows the evaporation residue cross section for selected projectile-target combinations as a function of energy E^* for $2n$, $3n$, and $4n$ channels. The selected most probable projectile-target combinations to synthesize the superheavy nuclei $^{299–305}121$ are shown in Fig. 13. The parameters which are required to decide the synthesis of these superheavy nuclei such as compound nucleus fissility ($\chi_{\rm CN}$), a charge product in the entrance channel ($Z_p Z_t$), effective entrance channel fissility ($\chi_{\rm eff}$), fusion barrier height (V_B), and fusion barrier width (R_B) for the most probable fusion reactions are calculated using the procedure explained in our previous work [23]. The presynthesis parameters for the suggested most probable projectile-target combination to synthesize $^{299–305}121$ are given in Table II. Tabulated data of compound nucleus fissility ($\chi_{\rm CN}$), the charge product in the entrance channel ($Z_p Z_t$), effective entrance channel fissility ($\chi_{\rm eff}$), fusion barrier height (V_B), and fusion barrier width (R_B) for the most probable fusion reactions are useful in the experiments to synthesize more isotopes SHN $Z = 121$. Superheavy element 121 is also called eka-actinium which is expected to be the first of the superactinides. There were attempts to synthesize the superheavy element $Z = 121$ at RIKEN in Japan. At this moment, it is important to search for the suitable projectile-target combinations and α-decay chains of superheavy nuclei $Z = 121$. The present work predicts the possible isotopes of superheavy element $Z = 121$ and most suitable projectile-target combinations to synthesize superheavy element $Z = 121$. Hence the new physics presented in this paper plays a vital role in the synthesis of the superheavy element $Z = 121$.

IV. CONCLUSION

We have identified the most possible isotopes for superheavy nuclei $Z = 121$ in the range $265 \leqslant A \leqslant 316$. The nuclei $^{299–305}121$ were found to have long half-lives and hence it could be sufficient to detect them if synthesized in a laboratory. The selected most probable projectile-target combinations to synthesize superheavy nuclei $^{299–305}121$ is V + Cf.

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