α-decay chains of recoiled superheavy nuclei: A theoretical study

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A systematic theoretical study of α-decay half-lives in the superheavy mass region of the periodic table of elements is carried out by extending the quantum-mechanical fragmentation theory based on the preformed cluster model (PCM) to include temperature (T) dependence in its built-in preformation and penetration probabilities of decay fragments. Earlier, the α-decay chains of the isotopes of Z = 115 were investigated by using the standard PCM for spontaneous decays, with “hot-optimum” orientation effects included, which required a constant scaling factor of 104 to approach the available experimental data. In the present approach of the PCM (T ≠ 0), the temperature effects are included via the recoil energy of the residual superheavy nucleus (SHN) left after x-neutron emission from the superheavy compound nucleus. The important result is that the α-decay half-lives calculated by the PCM (T ≠ 0) match the experimental data nearly exactly, without using any scaling factor of the type used in the PCM. Note that the PCM (T ≠ 0) is equivalent of the dynamical cluster-decay model for heavy-ion reactions at angular momentum ℓ = 0. The only parameter of model is the neck-length parameter ΔR, which for the calculated half-lives of α-decay chains of various isotopes of Z = 113 to 118 nuclei formed in “hot-fusion” reactions is found to be nearly constant, i.e., ΔR ≈ 0.95 ± 0.05 fm for all the α-decay chains studied. The use of recoiled residue nucleus as a secondary heavy-ion beam for nuclear reactions has also been suggested in the past.

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I. INTRODUCTION

Identification and characterization of α-decay chains form a crucial part of the nuclide identification in the synthesis of superheavy elements, achieved via “cold-” or “hot-fusion” reactions. In cold-fusion reactions, isotopes of elements with Z up to 112 have been produced by using Pb or Bi targets with different projectiles, namely, 48Ca, 50Ti, 54Cr, 58Fe, 62,64Ni, and 70Zn, in reactions performed at GSI (Darmstadt, Germany) [1] and Z = 113 at RIKEN (Japan) [2], and in hot-fusion reactions, isotopes of elements with Z = 112 to 118 have been produced by using 48Ca projectiles on actinide targets such as 233,238U, 237Np, 242,244Pu, 243Am, 245,248Cm, 249Bk, and 249Cf in reactions performed at JINR-FLNR (Dubna, Russia) and later at GSI in collaboration with Oak Ridge (Tennessee, USA) and Livermore (California, USA) laboratories [3–5]. In all these reactions, a complete fusion process, with the formation of a compound nucleus, is used.

In a heavy-ion reaction between a projectile of mass Aproj and energy Eproj on target of mass A targ at rest, i.e., Eproj = 0, in complete fusion of two nuclei, full momentum transfer occurs from the projectile to compound nucleus (CN) with mass ACN = Aproj + Atarg. Then, if x-neutron emission takes place from the CN, the maximum of cross section of the evaporation residue product, the superheavy nucleus (SHN), corresponds to the projectile energy just close to the Coulomb barrier, and the recoil of SHN occurs with a recoil energy

\[ E_R = E_{\text{proj}} \frac{A_{\text{proj}}}{A_{\text{CN}}}, \]

such that the residue SHN moves forward with this much kinetic energy. If the target nucleus is a heavy nucleus of a thin layer, the recoiled residue SHN may leave the target and get collected at the focal plane of the separator [6]. The residue SHN, carrying the kinetic energy ER, undergoes the observed α-decay chain(s) with an excitation energy Eα = ER + Qα, the chain is considered to end at either a known α-decaying nucleus or a known spontaneous fissioning nucleus, thereby identifying the SHN uniquely. It is relevant to recall here that the recoiled residue nucleus has also been proposed to be used as a secondary heavy-ion beam for nuclear reactions [7,8]. Alternatively, on a different timescale, the neutron-emission (or light-particle n, p, α, or γ decay, the evaporation residue ER) competes with the fusion-fission (ff) process, and the noncompound nucleus (nCN) decay [like the quasi-fission (Qf), deep-inelastic collision (DIC) or orbiting, incomplete fusion, pre-equilibrium decay, etc.], if the CN were not formed [9–12]. The two possible decay modes of CN are schematically illustrated in Fig. 1.

Figure 1 demonstrates that the existence of a long-lived SHN is controlled mainly by the spontaneous fission and α-decay processes. Thus, in order to produce a SHN in the laboratory, one needs the theoretical understanding of such dominant decay modes of nuclei. Bohr and Wheeler [13] described the mechanism of nuclear fission on the basis of the liquid-drop model and established a limit Z2/A ≈ 48 for spontaneous fission, beyond which nuclei are unstable against spontaneous fission. As already noted, the other dominant decay mode of SHN is α decay [for other decay modes of SHN, such as heavy-particle radioactivity (HPR), which has not yet been observed, see Refs. [14–18]]. Of the total of 135 isotopes (including 20 isomeric states) of SHN (Z > 103) observed to date, 119 nuclei decay via α emission and 58 via fission. For 42 of these nuclei, both the modes of fission
and $\alpha$ decay have been observed [19]. In this paper, we are interested in the $\alpha$ decay of SHN, which occurs as a chain consisting of two to three or more, up to five, $\alpha$ decays leading to an already known transuranium nucleus that is identified by ordinary means. Therefore, in order to determine the primary SHN, it is necessary to trace in detail the entire $\alpha$-decay chain by measuring as precisely as possible the $\alpha$-decay energies and the respective decay half-lives.

Theoretically, according to the one-body model of Gurney and Condon [20], $\alpha$ particles are supposed to be preformed within the nucleus and leak through the Coulomb barrier generated by the electrostatic interaction of the $\alpha$ particle with the constituent protons of the daughter nucleus. The $\alpha$ decay of SHN is possible if the shell effects supply the extra binding energy and increase the barrier height for fission [21–25].

The identification of superheavy elements (SHEs) in cold-fusion reactions is based on the identification of the products via alpha correlations with known $\alpha$ emitters at the end of the decay sequence(s), but in hot-fusion reactions, the nuclei at the end of the decay sequences are neutron-rich isotopes that have not been obtained yet in any other kind of experiment. Thus, in the hot-fusion type of reactions, an $\alpha$-decay systematic based on theoretical calculations could provide a useful tool for an ulterior identification of the reaction products. Furthermore, the observation and characterization of the $\alpha$-decay properties of the SHEs are very important because they give valuable information on nuclear binding energies, nuclear structure, and the nuclear decay mechanisms.

During the past years, several experimental [1–5] and theoretical works [26–38] have been devoted to understand the formation of SHN and their $\alpha$-decay half-lives. For $\alpha$-decay half-lives, a universal decay law (UDL), relating the half-lives with the $Q$ value of emitted charged particle and masses and charges of nuclei involved in the decay, is obtained which also explains the observed exotic cluster decays from radioactive nuclei [31], a generalization of the Geiger–Nuttall law of $\alpha$ radioactivity, first pointed out by Kumar et al. [39,40] for possible $\alpha$-nucleus ($A = 4n$) cluster decays of neutron-deficient rare-earth nuclei. In a recent work [37], the half-lives of $\alpha$-decay chains of $^{289,288,287}_{115}$ were calculated by two of us and collaborators, using the preformed cluster model (PCM), where fragments are considered to be in the ground state ($T = 0$), as in spontaneous $\alpha$ decay. However, the calculated half-lives are found to agree with experimental data only within a constant empirical factor of $10^4$. On the other hand, the decay-product produced after $xn$-emission, i.e., the residue SHN has a recoil energy $E_R$ associated with it before the $\alpha$-decay chain starts. This calls for the possibility of including temperature effects in PCM, which is then equivalent of using the dynamical cluster-decay model (DCM) for $\ell = 0$ case. Such a calculation is being carried out here for the first time.

In the present work, we consider the following $\alpha$-decay chains of hot-fusion reactions:

(a) $^{294}_{118}$ formed via $^{249}_{92}$Cf $+ ^{48}_{20}$Ca after the $3n$ emission;
(b) $^{291}_{117}$ and $^{293}_{117}$ formed via $^{249}_{92}$Bk $+ ^{48}_{20}$Ca after the $3n$ and $4n$ emission, respectively;
(c) $^{291}_{116}$ formed via $^{245}_{92}$Cm $+ ^{48}_{20}$Ca after $2n$ emission;
(d) $^{288}_{115}$ and $^{287}_{115}$ formed via $^{243}_{92}$Am $+ ^{48}_{20}$Ca after the $3n$ and $4n$ emission, respectively;
(e) $^{287}_{114}$ formed via $^{244}_{92}$Pu $+ ^{48}_{20}$Ca after $5n$ emission; and
(f) $^{282}_{113}$ formed via $^{237}_{93}$Np $+ ^{48}_{20}$Ca after the $3n$ emission.

In these experiments [3–5,11,41,42], the synthesized SHN, before the $\alpha$-decay chain begins, possess a recoil energy $E_R = 7$ to 18 MeV in reactions (a) and (b) for $^{294}_{117}^*$, $E_R = 7$ to 16 MeV in reactions (b) for $^{293}_{117}^*$, (c), (d), and (f), and $E_R = 6.5$ to 14.5 MeV in reaction (e), which is used here to provide the temperature effects for $\alpha$-decay chains. Therefore, the $\alpha$-decay chains, analyzed first by using the PCM ($T = 0$) [37], are analyzed in the present work, for the first time, by using the PCM ($T \neq 0$) with deformations included up to $\beta_2$ and hot-optimum orientations of nuclei, except when stated otherwise. The interesting result of using the PCM ($T \neq 0$), an equivalent of DCM ($\ell = 0$), is that now no empirical factor is required to fit the data.

The paper is organized as follows: Section II gives the very relevant details of the theoretical model used, the PCM ($T \neq 0$) $\equiv$ DCM ($\ell = 0$). The $\alpha$-decay chains of SHN with $Z = 113$ to 118 is studied in Sec. III. A summary of our results is given in Sec. IV. Brief reports of this work were made at a national symposium [43] and at an international conference [44] on nuclear physics.

II. TEMPERATURE-DEPENDENT PREFORMED CLUSTER MODEL ($T \neq 0$)

In the PCM ($T \neq 0$), the decay constant $\lambda$ and half-life $T_{1/2}$ are defined as [37,45]

$$\lambda = \nu_0P_0P, \quad T_{1/2} = \ln2/\lambda,$$

(2)

where $P_0$ is the preformation probability and $P$ is the barrier penetrability which refer, respectively, to motions in mass asymmetry $\eta = (A_1 - A_2)/(A_1 + A_2)$ and relative separation $R$. The frequency $\nu_0$ is the barrier assault frequency. Equivalently, in the DCM ($\ell = 0$ case), the CN decay cross
In the PCM, the assault frequency for the nucleus radius \( R_0 \) is \( v_0 = \frac{v_0}{R_0} = \frac{(2E/\mu)^{1/2}}{R_0} \) with \( \mu \) being the reduced mass, and kinetic energy, which is related to the \( Q \) value, is \( E_2 = (A_1/A)Q \). The structure information of the compound nucleus enters the model via the preformation probability \( P_{0} \) (also known as the spectroscopic factor) of the decay fragments, given by the solution of the stationary Schrödinger equation in \( \eta \) at fixed \( R = R_{\eta} \),

\[
\begin{aligned}
\left[-\frac{\hbar^2}{2B_{\eta}} \frac{\partial}{\partial \eta} \frac{1}{\sqrt{B_{\eta}}} \frac{\partial}{\partial \eta} + V(R,\eta,T)\right] \psi^v(\eta) = E^v \psi^v(\eta),
\end{aligned}
\]

(5)

with \( v = 0,1,2,3 \ldots \) referring to the ground-state \( (v = 0) \) and excited-state solutions. Then, for \( B_{\eta \eta} \) as the mass parameter, the preformation probability

\[
P_0(A_i) = |\psi[\eta(A_i)]|^2 \sqrt{B_{\eta \eta}(\eta)} \left( \frac{2}{A} \right).
\]

(6)

where, for a Boltzmann-like function,

\[
|\psi(\eta)|^2 = \sum_{i=0}^{\infty} |\psi^v(\eta)|^2 \exp \left( -\frac{E^v}{T} \right).
\]

(7)

The mass parameters \( B_{\eta \eta} \) for \( \eta \) motion, representing the kinetic energy in the stationary Schrödinger equation (5), are the smooth classical hydrodynamical masses [46], although, in principle, the shell-corrected masses, like the cranking masses, which depend on the underlying shell-model basis, should be used. However, in quantum-mechanical fragmentation theory (QMFT) [47], on which the PCM and/or DCM are based, the shell effects in \( B_{ij} \), \((i,j = \eta,R)\), do not play much of a role [48,49].

### TABLE I. PCM \((T \neq 0)\) calculated preformation probability \( P_{0} \), penetration probability \( P \), \( \alpha \)-decay half-life \( T_{\alpha}^{1/2} \) (calc.) and the neck-length parameter \( \Delta R \) for \( \alpha \)-decay of \( ^{207}_{82}\text{Bi} \) at different \( E_\gamma \) values. Like in the PCM \((T = 0)\) [37], \( v_0 = 10^{21} \) s\(^{-1}\). The experimental \( \alpha \)-decay half-life \( T_{\alpha}^{1/2} \) (expt.) = 27 \pm 2 ms.

<table>
<thead>
<tr>
<th>( \Delta R ) (fm)</th>
<th>( P_{0} )</th>
<th>( P )</th>
<th>( T_{\alpha}^{1/2} ) (calc.) (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_\gamma = 7 ) MeV</td>
<td>( E^* = 15.628 ) MeV</td>
<td>1.023</td>
<td>4.28 \times 10^{-14}</td>
</tr>
<tr>
<td>( T = 0.747 ) MeV</td>
<td>( E_\gamma = 10 ) MeV</td>
<td>( E^* = 18.628 ) MeV</td>
<td>0.9936</td>
</tr>
<tr>
<td>( T = 0.814 ) MeV</td>
<td>( E_\gamma = 13 ) MeV</td>
<td>( E^* = 21.628 ) MeV</td>
<td>0.9805</td>
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<td>0.9655</td>
</tr>
</tbody>
</table>
The penetrability $P$ in Eq. (2) is the Wenzel–Kramers–Brillouin (WKB) integral,

$$ P = \exp \left[ -\frac{2}{\hbar} \int_{R_a}^{R_b} \left( 2\mu \left[ V(R,T) - Q_{\text{eff}} \right] \right)^{1/2} dR \right], $$

(8)
solved analytically, with the second turning point $R_b$ satisfying $V(R_b) = V(R_a) + Q_{\text{eff}}$. This means that $V(R_a)$ acts like an effective $Q$ value, $Q_{\text{eff}}(T)$.

For $\alpha$ decay of the recoiled superheavy nucleus, the temperature $T$ (in MeV) is related to its excitation energy $E_R^*$ as

$$ E_R^* = \frac{1}{10} AT^2 - T, \quad (\text{MeV}), $$

(9)

**TABLE II.** $\alpha$-decay half-lives for $Z = 106$ to 118 SHEs occurring in $\alpha$-decay chains of SHN $Z = 113$ to 118 synthesized in different heavy-ion reactions via $\alpha$ emission, compared with experimental data and other available theoretical results.

<table>
<thead>
<tr>
<th>SHN</th>
<th>Ref. expt.</th>
<th>$T_{\alpha/2}$ (expt.)</th>
<th>$T_{\alpha/2}$ (this work)</th>
<th>$T_{\alpha/2}$ (this work) × 10$^4$</th>
<th>DDM3Y Ref. [37]</th>
<th>GLDM Ref. [50]</th>
<th>CYEM Ref. [51]</th>
<th>CPPMDN Refs. [53,54]</th>
</tr>
</thead>
<tbody>
<tr>
<td>284$^{118}$</td>
<td>[42]</td>
<td>0.69$^{+0.04}_{-0.02}$ ms</td>
<td>0.68 ms</td>
<td>0.66$^{+0.23}_{-0.18}$ ms</td>
<td>0.15$^{+0.05}_{-0.10}$ ms</td>
<td>2.188 ms</td>
<td>0.53$^{+0.16}_{-0.22}$ ms</td>
<td>191.9$^{+216}_{-189}$ ms</td>
</tr>
<tr>
<td>280$^{116}$</td>
<td>[42]</td>
<td>8.3$^{+3.5}_{-1.9}$ ms</td>
<td>8.3 ms</td>
<td>13.4$^{+7.7}_{-6.2}$ ms</td>
<td>3.47$^{+1.99}_{-1.26}$ ms</td>
<td>56 ms</td>
<td>20.8$^{+8.2}_{-11.8}$ ms</td>
<td>32.8$^{+21.5}_{-12.8}$ ms</td>
</tr>
<tr>
<td>286$^{114}$</td>
<td>[42]</td>
<td>0.12$^{+0.04}_{-0.02}$ s</td>
<td>0.12 s</td>
<td>0.93$^{+0.48}_{-0.32}$ ms</td>
<td>0.17$^{+0.06}_{-0.09}$ ms</td>
<td>1.21 s</td>
<td>0.54$^{+0.21}_{-0.13}$ s</td>
<td>7.2$^{+4.1}_{-3.3}$ s</td>
</tr>
</tbody>
</table>
| 289$^{117}$ | [42] | 51$^{+31}_{-16}$ ms | 51.2 ms | 106 to 118 SHEs occurring in $\alpha$-decay chains of SHN $Z = 113$ to 118 synthesized in different heavy-ion reactions via $\alpha$ emission, compared with experimental data and other available theoretical results.

589.5x792.0
where \( E_R^a = E_R + Q_\alpha \). Here, \( Q_\alpha \) denotes the \( Q \) value of \( \alpha \) decay, and for the implantation (or recoil) energy \( E_R \) we take the value obtained in experiments. The \( Q \) value for \( \alpha \) decay can be calculated from the reaction, say \( ^{293}117^* \rightarrow ^{289}115 + \alpha \), which gives the relation \( E_{B,E}(^{293}117^*) = E_{B,E}(^{289}115) + E_{B,E}(\alpha\text{-particle}) + Q_\alpha \). Here, \( E_{B,E} \) stand for binding energies calculated within the framework of DCM (see, e.g., Ref. [38]) which is based on QMFT [47], whose main ingredients are the microscopic shell effects plus the macroscopic liquid-drop energy.

III. CALCULATIONS AND DISCUSSION

As already mentioned in the Introduction, \( \alpha \)-decay chains of SHN \( ^{289}118^* \), \( ^{291}117^* \), \( ^{291}116^* \), \( ^{288}287^{155^*} \), \( ^{287}114^* \), and \( ^{282}113^* \), formed after \( xn \) emission, with a measured recoil energy \( E_R \), populate various \( \alpha \)-decay products with measured decay half-lives \( T_{\alpha}^{1/2} \). Since \( E_R \) is not fixed, but given as a certain range, we make our calculations at the four values of \( E_R = 7, 11, 15, \) and 18 MeV for \( \alpha \)-decay chains of SHN \( ^{294}118^* \) and \( ^{292}117^* \), \( E_R = 7, 10, 13, \) and 16 MeV covering the measured \( E_R \) range for \( \alpha \)-decay chains of SHN \( ^{294}117^* \), \( ^{291}116^* \), \( ^{288}287^{155^*} \), and \( ^{282}113^* \), and \( E_R = 6.5, 9, 12, \) and 14.5 MeV for \( \alpha \)-decay chains of SHN \( ^{287}114^* \), since the measured recoil-energy ranges in experiments are different for the three sets. For comparisons with experimental \( T_{\alpha}^{1/2} \) (expt.), we take the average of four values as our PCM \( (T \neq 0) \) calculated \( \alpha \)-decay half-lives \( T_{\alpha}^{1/2} \) (calc.). In Table I, we illustrate our PCM \( (T \neq 0) \) calculations of \( \alpha \)-decay half-lives at \( T \) values estimated from the chosen \( E_R \) for one case, say, \( ^{289}115^* \), obtained in \( \alpha \) decay of \( ^{291}117^* \), and present the average result for all chosen SHN in Table II, compared with available PCM \( (T = 0) \) and other model calculations [37,50–54].

Figure 3 illustrates the mass-fragmentation potential \( V(A_i) \) (i = 1,2) for the SHN \( ^{293}117^* \), formed via a hot-fusion reaction \( ^{249}\text{Bk} + ^{48}\text{Ca} \) after the \( 4n \) emission, at \( R = R_o = R_t + \Delta R \) and \( T = 0.876 \text{ MeV} \) equivalently, \( E_R = 13 \text{ MeV} \), calculated for both cases of spherical (open spheres) and deformations \( \beta_2 \) and hot-optimum orientations (solid spheres) for all possible combinations of two nuclei at \( \ell = 0 \). \( \Delta R = 0.9805 \text{ fm} \) for the best fit to \( \alpha \)-decay data (see Table I).

The systematics of \( \Delta R, R_0 \), and \( P \) are presented later through Figs. 5–7.

Note that \( P_0 \) is a relative quantity, normalized to unity for all the possible fragmentations \( (\eta \) values) from zero to one. In other words, say, for an \( \alpha \) fragment (and the complementary heavy fragment), it is calculated as relative to all other possible \( (A_1,A_2) \) of the decaying system, as illustrated in Fig. 4 for the fragmentation potential of Fig. 3 for both the cases of spherical as well as deformed-oriented configurations. We notice in Fig. 4 (also in Table I) that \( P_0 \sim 10^{-11} \) for \( \alpha \) particle in the case of deformed and oriented configurations (solid spheres).
FIG. 5. The best-fit neck-length parameter $\Delta R$ as a function of mass number of $\alpha$-decay chains at different $E_R$ values for various SHN. For example, in panel (a), the excited SHN $^{294}118^*$ formed via a hot-fusion reaction $^{249}$Cf + $^{48}$Ca, after 3$n$ emission, results in excited superheavy systems $^{290}116^*$, $^{286}114^*$, and $^{282}112^*$ after subsequent $\alpha$ decays. Our calculations refer to PCM ($T \neq 0$), and consider in all cases the hot-optimum configuration.
FIG. 6. Same as for Fig. 5, but for preformation probability $P_0$. 

Mass Number A
FIG. 7. Same as for Fig. 5, but for penetrability $P$. 
spheres), which for spherical configurations (open spheres, in Figs. 3 and 4) becomes much larger, \( \sim 10^{-6} \). The same is true for fragments with mass number \( A = 1 \), here neutron \([P_0(\text{def.})] \sim 10^{-7}\) and \( P_0(\text{sph.}) = 0.982\). Apparently, such a small preformation for \( 1n \) or \( \alpha \) particle is due to the deformed and oriented configurations. For cluster decays, including \( \alpha \) particles, the decrease of \( P_0 \) due to deformation of decay products is a known result \[58\]. However, \( P_0(\alpha) \) is still very small (deformed or spherical nuclei), which arises due to the presence of a strong minimum in Fig. 3 (or maximum in Fig. 4) at \( ^{17}\text{B} \) having large \( \beta_2 \) value \((\sim -0.398)\), taking away almost all of the preformation strength \([P_0 > 0.99; \text{note that } P_0(^{17}\text{B}) \text{ reduces to } \sim 10^{-34} \text{ for spherical configurations}]\), although it is known that \( ^{17}\text{B} \) decay is not a viable process since the penetration \( P \) is very small \( \sim 10^{-38} \) for the deformed configuration \[59,60\]. Furthermore, the preformation factor \( P_0 \) is a model-dependent quantity. This result stems from the fact that, whereas in some fission-like models (see, e.g., Ref. [61]), empirically \( P_0 = 0.01 \) to 0.1 for \( \alpha \) decay of radioactive nuclei, the same in the PCM is \( \sim 10^{-8} \) (see, e.g., Table 1 in Ref. [62]), which fits in with the systematics of \( \alpha \) for SHN with decay products treated as deformed and oriented nuclei.

Figure 5 shows the variation of the best-fit neck-length parameter \( \Delta R \) as a function of mass number for various \( \alpha \)-decay chains at different \( E_R \) values. We first notice that the change of \( \Delta R \) within a decay chain is very small (2%-8%) and that it changes by about 5%-6% for the change in \( E_R \) by a factor of two. Also, \( \Delta R \approx 0.95 \pm 0.05 \) fm, i.e., lies between 0.89 to 1.032 fm, for all the \( \alpha \)-decay chains. This small variation of a few percent in \( \Delta R \) could also be taken care of through a polynomial fitting of degree one or two, which in turn could be used to make predictions by extrapolating or interpolating the calculated values of \( \Delta R \), and possibly provide directions for new experiments \[63,64\].

Figures 6 and 7 show, respectively, the variation of calculated \( P_0 \) and \( P \) with mass number of various \( \alpha \)-decay chains at different \( E_R \) values. The \( P_0 \) values are of the order of \( 10^{-11} \) to \( 10^{-15} \), whereas \( P \) values are of the order of \( 10^{-7} \) to \( 10^{-11} \). An interesting result is that smaller \( P_0 \) goes together with larger \( P \), and larger \( P_0 \) with smaller \( P \), so that the product \( P_0P \) is nearly of the same order for all the chosen \( \alpha \)-decay chains.

Table II gives the calculated half-lives of all the chosen \( \alpha \)-decay chains, using the PCM \((T \neq 0)\), compared with experimental data, PCM \((T = 0)\), and results of other model calculations \[37,50–54\]. Similarly, Fig. 8 illustrates the same comparison of half-lives of \( \alpha \)-decay chains of our PCM \((T \neq 0)\) calculated ones, with PCM \((T = 0)\) and experiments for \(^{289}\text{115}\) and \(^{287}\text{115}^*\), respectively, the \( 3n \) and \( 4\alpha \) decay channels of \(^{291}\text{115}^*\) formed in the \(^{48}\text{Ca} +^{243}\text{Am}\) reaction. It is clear from Fig. 8, as well as from Table II, that the calculations agree nicely with experiments within a constant empirical factor for the PCM \((T = 0)\) but without any multiplying factor for the PCM \((T \neq 0)\). This successful inclusion of temperature in the calculations of \( \alpha \)-decay half-lives has been achieved in PCM \((T \neq 0)\). The temperature arises from the measured recoil energy of SHN. In these calculations, deformations are included up to \( \beta_2 \), with hot-optimum orientations. No other calculation is so complete and close to experiments as the PCM \((T \neq 0)\) presented here.

IV. SUMMARY AND CONCLUSIONS

The successful application of the PCM \((T \neq 0)\), equivalently, the DCM \((\ell = 0)\), to \( \alpha \) decay of superheavy nuclei produced in heavy-ion reactions has been examined in detail through the \( \alpha \)-decay chains of the various superheavy nuclei with \( Z = 113 \) to 118. In the PCM \((T \neq 0)\), the temperature effects arise due to the measured recoil energy of the residue product (the SHN) after \( xn \) emission from the compound system, i.e., before the \( \alpha \)-decay chain starts. As studied earlier \[37\], PCM \((T = 0)\) fits the \( \alpha \)-decay half-life of \(^{289,288,287}\text{115}^*\) chains within a factor of \( 10^4 \), but the PCM \((T \neq 0)\) gives an exact fit to the \( \alpha \)-decay half-life data for all of the above-mentioned superheavy nuclei with a fixed recoil energy that lies within the measured limits. The \( \alpha \)-decay half-lives calculated within the framework of PCM \((T \neq 0) \equiv \text{DCM} (\ell = 0)\) are compared with the experimental results and the other theoretical models and are found to be in good agreement with experimental results and are comparable to the other theoretical model calculations. The accurate reproduction of experimental half-lives after inclusion of temperature emphasizes the credibility of both the PCM and DCM models.

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