Examination of the decay modes of $^{293-295}$Og

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The α-decay chains of the isotopes ^{293,294,295}Og are studied in the present paper. The modified generalized liquid drop model (MGLDM) is used to study the α-decay half-lives. The results are then compared with other theoretical formalisms. The decay chains of these isotopes are predicted by comparing the α half-lives with the corresponding spontaneous fission half-lives. The study predicted a 5α chain from the isotope ^{293}Og, a 3α chain from ^{294}Og, and a 2α chain from ^{295}Og. The agreement between theoretical and experimental results emphasizes the applicability of the MGLDM in a superheavy region. Since the predicted half-lives are within the experimental limit, these isotopes can be detected in laboratories via α decay.

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I. INTRODUCTION

The discovery of radioactivity by Henry Becquerel in the year 1986 [1] heralds the study of nuclear physics. The spontaneous disintegration of an unstable nucleus with the emission of energetic particles or radiation is usually referred to as nuclear decay. Nuclear reactions always produce daughter nuclei that are more stable than parent nuclei. Nuclear decay can occur in a variety of ways such as alpha decay, beta decay, gamma decay, positron emission, electron capture, spontaneous fission and cluster decay.

Among the studies of nuclear decay, the decay properties of superheavy nuclei is one of the fast developing fields in the current nuclear physics. The prediction on the island of stability of superheavy nuclei [2–4], which was developed from the microscopic theory of the nucleus, has paved a way to look into the unexplored regions of the nuclear chart. Elements with $Z > 104$ are referred to as superheavy elements. Studies on shell closure of nuclei will give enough theoretical evidence for explaining the structure and stability of such nuclei.

The rapid development of accelerator and detector technologies lead to the synthesis of superheavy elements up to Og ($Z = 118$). Two kinds of fusion-evaporation reactions, namely, the cold fusion reaction [5] and the hot fusion reaction [6], are used for the synthesis of superheavy elements [7,8].

Studies on the decay properties play a vital role in identifying superheavy nuclei. Superheavy nuclei usually decay via alpha emissions followed by spontaneous fission (SF), so alpha decay and SF are considered as the experimental signatures for the observation of superheavy nuclei. Several theoretical models are available for studying the alpha decay [9–20] as well as SF [21–27] in the superheavy region. The alpha decay chains provide clear signatures of the nucleus in the beginning of the decay chain, so the studies on the decay modes are very relevant for designing the experiments which can be used to explore the limits of the predicted island of stability [28,29]. In addition to these decay modes there are regions in superheavy nuclei where cluster radioactivity will be dominant [30–33]. Studies on cluster radioactivity will help to identify the shell closures in superheavy region.

The present work deals with the studies of alpha decay and SF half-lives of three different isotopes of Og (oganesson, $Z = 118$). Oganessian *et al.* [34] had reported the synthesis of ^{294}Og using hot fusion reaction with ^{48}Ca as projectile and ^{249}Cf as target. In this work three possible isotopes of Og are studied including ^{294}Og. The masses of the nuclei under study are taken from the recent AME2020 atomic mass evaluation [35]. The modified generalized liquid drop model (MGLDM) [36,37] is used for the calculation of alpha decay half-lives of these isotopes and their daughter nuclei. The results obtained are then compared with other theoretical formalisms. For calculating the SF half-lives, the semiempirical formula of Xu *et al.* [23] is used. The decay chains are predicted by comparing the alpha decay half-lives with the corresponding SF half-lives.

The paper is organized as follows: Section II deals with the detailed description of the model used in the study. Section III gives the results and discussion obtained from the study. Summary of the entire work is presented in Sec. IV.

II. MODIFIED GENERALIZED LIQUID DROP MODEL

In MGLDM, for a deformed nucleus, the macroscopic energy [38] is defined as

$$E = E_V + E_S + E_C + E_R + E_P. \quad (1)$$

Here the terms E_V, E_S, E_C, E_R, and E_P represents the volume, surface, Coulomb, rotational, and proximity energy terms respectively.

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TABLE I. Predictions on the decay modes of superheavy nucleus ^{294}Og and its daughter nuclei and their comparison with the experimental results [34].

Parent nuclei	Q_α (MeV)	T_{SF} (s)	$T^{\alpha}_{1/2}$ (s) MGLDM	VSS	Royer	UDL	Expt. [34]	Mode of decay
^{294}Og	11.660[a]	$3.048 \times 10^{+08}$	1.014×10^{-03}	1.428×10^{-03}	8.641×10^{-04}	1.059×10^{-03}	6.900×10^{-04}	α
	11.925[b]		2.462×10^{-04}	3.471×10^{-04}	2.107×10^{-04}	2.366×10^{-04}		
^{290}Lv	10.850[a]	$6.392 \times 10^{+03}$	2.695×10^{-02}	3.662×10^{-02}	2.156×10^{-02}	3.079×10^{-02}	8.300×10^{-03}	α
	11.054[b]		8.096×10^{-03}	1.112×10^{-02}	6.557×10^{-03}	8.701×10^{-03}		
^{286}Fl	10.210[a]	2.372×10^{00}	3.518×10^{-01}	4.514×10^{-01}	2.618×10^{-01}	4.152×10^{-01}	1.200×10^{-01}	α
	10.412[b]		9.723×10^{-02}	1.266×10^{-01}	7.345×10^{-02}	1.078×10^{-01}		
^{282}Cn	10.211[a]	1.277×10^{-02}	8.264×10^{-02}	1.041×10^{-01}	6.002×10^{-02}	8.287×10^{-02}		SF

[a]Experimental Q value [34].
[b]Q value calculated using Ref. [35].

For the prescission region the volume, surface, and Coulomb energies in MeV are given by

$$E_V = -15.494(1 - 1.8I^2)A, \tag{2}$$

$$E_S = 17.9439(1 - 2.6I^2)A^{2/3}\left(S/4\pi R_0^2\right), \tag{3}$$

$$E_C = 0.6e^2(Z^2/R_0) \times 0.5 \int [V(\theta)/V_0][R(\theta)/R_0]^3 \sin\theta\, d\theta. \tag{4}$$

Here I is the relative neutron excess and S is the surface of the deformed nucleus, $V(\theta)$ is the electrostatic potential at the surface, and V_0 is the surface potential of the sphere.

For the postscission region,

$$E_V = -15.494\left[\left(1 - 1.8I_1^2\right)A_1 + \left(1 - 1.8I_2^2\right)A_2\right], \tag{5}$$

$$E_S = 17.9439\left[\left(1 - 2.6I_1^2\right)A_1^{2/3} + \left(1 - 2.6I_2^2\right)A_2^{2/3}\right], \tag{6}$$

$$E_C = \frac{0.6e^2Z_1^2}{R_1} + \frac{0.6e^2Z_2^2}{R_2} + \frac{e^2 Z_1 Z_2}{r}. \tag{7}$$

Here A_i, Z_i, R_i, and I_i are the masses, charges, radii, and relative neutron excess of the fragments, and r is the distance between the centers of the fragments.

The nuclear proximity potential E_P is given by Blocki *et al.* [39] as

$$E_p(z) = 4\pi\gamma b\left[\frac{C_1C_2}{(C_1 + C_2)}\right]\Phi\left(\frac{z}{b}\right), \tag{8}$$

with the nuclear surface tension coefficient,

$$\gamma = 0.9517[1 - 1.7826(N - Z)^2/A^2]\,\mathrm{MeV/fm^2}, \tag{9}$$

Where N, Z, and A represent neutron, proton, and mass number of parent nucleus respectively; Φ represents the universal proximity potential [39] given as

$$\Phi(\varepsilon) = -4.41e^{-\varepsilon/0.7176}, \text{ for } \varepsilon > 1.9475, \tag{10}$$

$$\Phi(\varepsilon) = -1.7817 + 0.9270\varepsilon + 0.01696\varepsilon^2 - 0.05148\varepsilon^3, \text{ for } 0 \leqslant \varepsilon \leqslant 1.9475, \tag{11}$$

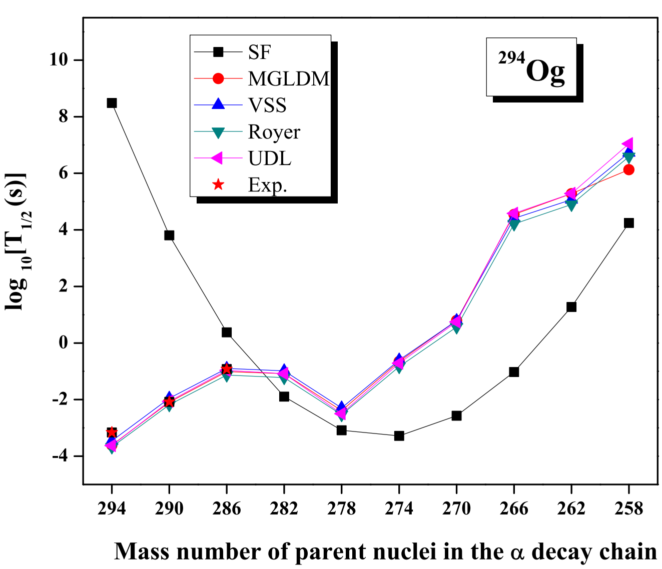

FIG. 1. The comparison of calculated alpha decay half-lives with the spontaneous fission half-lives for the isotope ^{294}Og and its daughter nuclei.

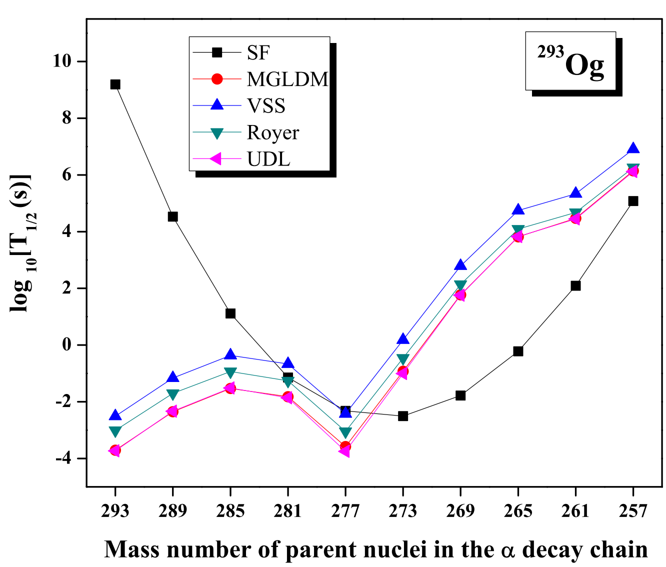

FIG. 2. The comparison of calculated alpha decay half-lives with the spontaneous fission half-lives for the isotope ^{293}Og and its daughter nuclei.

TABLE II. Predictions on the decay modes of superheavy nucleus ^{293}Og and its daughter nuclei.

Parent nuclei	Q_α (MeV)	T_{SF} (s)	$T^{\alpha}_{1/2}$ (s) MGLDM	VSS	Royer	UDL	Mode of decay
^{293}Og	11.975	$1.564 \times 10^{+09}$	1.971×10^{-04}	3.111×10^{-03}	9.770×10^{-04}	1.861×10^{-04}	α
^{289}Lv	11.164	$3.384 \times 10^{+04}$	4.466×10^{-03}	6.892×10^{-02}	1.989×10^{-02}	4.627×10^{-03}	α
^{285}Fl	10.612	$1.296 \times 10^{+01}$	2.941×10^{-02}	4.340×10^{-01}	1.167×10^{-01}	3.058×10^{-02}	α
^{281}Cn	10.491	7.205×10^{-02}	1.510×10^{-02}	2.171×10^{-01}	5.497×10^{-02}	1.386×10^{-02}	α
^{277}Ds	10.949	4.782×10^{-03}	2.635×10^{-04}	3.772×10^{-03}	9.034×10^{-04}	1.786×10^{-04}	α
^{273}Hs	9.708	3.129×10^{-03}	1.194×10^{-01}	1.517×10^{00}	3.479×10^{-01}	9.974×10^{-02}	SF
^{269}Sg	8.626	1.671×10^{-02}	$5.926 \times 10^{+01}$	$6.193 \times 10^{+02}$	$1.385 \times 10^{+02}$	$5.737 \times 10^{+01}$	SF
^{265}Rf	7.855	6.053×10^{-01}	$6.571 \times 10^{+03}$	$5.596 \times 10^{+04}$	$1.239 \times 10^{+04}$	$6.733 \times 10^{+03}$	SF

with $\varepsilon = z/b$, where the width (diffuseness) of the nuclear surface $b \approx 1$ fm and Süsmann central radii C_i of fragments related to sharp radii R_i as

$$C_i = R_i - \left(\frac{b^2}{R_i}\right). \tag{12}$$

For R_i we use semiempirical formula in terms of mass number A_i as [40]

$$R_i = 1.28A_i^{1/3} - 0.76 + 0.8A_i^{-1/3}. \tag{13}$$

The barrier penetrability P is calculated with the action integral [38],

$$P = \exp\left\{-\frac{2}{\hbar}\int_{R_{\rm in}}^{R_{\rm out}} \sqrt{2B(r)[E(r) - E(\text{sphere})]}dr\right\}, \tag{14}$$

Where $R_{\rm in} = R_1 + R_2, B(r) = \mu$ and $R_{\rm out} = e^2 Z_1 Z_2/Q$. R_1, R_2 are the radius of the daughter nuclei and emitted alpha particle respectively, and μ is the reduced mass and Q is the released energy.

The partial half-life is related to the decay constant λ by

$$T_{1/2} = \left(\frac{\ln 2}{\lambda}\right) = \left(\frac{\ln 2}{\nu P}\right). \tag{15}$$

The assault frequency ν has been taken as 10^{20} s^{-1}.

III. RESULTS AND DISCUSSION

The decay properties of three isotopes of the superheavy nuclei Og, ^{293}Og, ^{294}Og, and ^{295}Og are studied in the present work. The dominant decay modes of superheavy nuclei are alpha decay and SF. The theoretical predictions of the decay modes are performed by comparing the alpha half-lives with the SF half-lives. The key quantity in determining the alpha decay half-lives is the Q value. In the present study, the latest mass table of Wang *et al.* [35] is used for the calculation of the Q value. The Q values are calculated using the equation

$$Q = \Delta M_p - (\Delta M_\alpha + \Delta M_d) + k(Z_p^\varepsilon - Z_d^\varepsilon). \tag{16}$$

The mass excess of the parent, daughter and the alpha particle are represented by ΔM_p, ΔM_d, and ΔM_α. The electron screening effect on the energy of the alpha particle is included by using the term $k(Z_p^\varepsilon - Z_d^\varepsilon)$ in Eq. (16). The term kZ^ε is the total binding energy of Z electrons in the atom. Here $k =$ 8.7 eV and $\varepsilon = 2.517$ for nuclei with $Z \geqslant 60$ and $k = 13.6$ eV and $\varepsilon = 2.408$ for nuclei with $Z < 60$ [41,42]. The Q value must be positive for alpha decay to occur.

After obtaining the Q values, the alpha half-lives of the isotopes of Og and their daughter nuclei are calculated using the MGLDM [36]. For a theoretical comparison of alpha half-lives, other three formulas, namely, the Viola-Seaborg semiempirical relation (VSS) [9,10], the analytical formula of Royer [11], and the universal decay law (UDL) of Qi *et al.* [12], are also used.

The SF half-lives are calculated using the semiempirical formula of Xu *et al.* [23]. The formula is given by

$$T_{1/2} = \exp\left\{2\pi\left[C_0 + C_1 A + C_2 Z^2 + C_3 Z^4 + C_4 (N - Z)^2 - \left(0.133\,23\frac{Z^2}{A^{1/3}} - 11.64\right)\right]\right\}. \tag{17}$$

The constants are $C_0 = -195.092\,27$, $C_1 = 3.101\,56$, $C_2 = -0.043\,86$, $C_3 = 1.4030 \times 10^{-6}$, and $C_4 = -0.031\,99$.

The decay modes of the isotopes are predicted by comparing the alpha half-lives calculated using the MGLDM with the

TABLE III. Predictions on the decay modes of superheavy nucleus ^{295}Og and its daughter nuclei.

Parent nuclei	Q_α (MeV)	T_{SF} (s)	$T^{\alpha}_{1/2}$ (s) MGLDM	VSS	Royer	UDL	Mode of decay
^{295}Og	11.765	$3.939 \times 10^{+07}$	5.534×10^{-04}	9.430×10^{-03}	2.726×10^{-03}	5.602×10^{-04}	α
^{291}Lv	10.944	$8.005 \times 10^{+02}$	1.483×10^{-02}	2.454×10^{-01}	6.523×10^{-02}	1.653×10^{-02}	α
^{287}Fl	10.222	2.878×10^{-01}	3.130×10^{-01}	4.865×10^{00}	1.203×10^{00}	3.689×10^{-01}	SF
^{283}Cn	9.951	1.502×10^{-03}	4.278×10^{-01}	6.381×10^{00}	1.488×10^{00}	4.657×10^{-01}	SF
^{279}Ds	10.159	9.350×10^{-05}	2.614×10^{-02}	3.855×10^{-01}	8.533×10^{-02}	2.256×10^{-02}	SF

SF half-lives calculated using the formula of Xu *et al.* Those nuclei with alpha decay half-lives less than SF half-lives will survive fission and hence decay through alpha emission.

Attempts to synthesize the isotopes of Og have been under progress since 1999. The only isotope of Og which was confirmed by the experiments is ^{294}Og. The predicted results on the half-lives and decay modes of ^{294}Og and their comparison with the experimental results are given in Table I. The matching between the theoretical predictions and the experimental observations is evident from the table. Also experimentally, it was seen that the isotope will decay through the 3α chain. This is in good agreement with the theoretical prediction. This clearly indicates that the MGLDM can be used for making meaningful predictions on the alpha half-lives and hence the decay chains in the superheavy region. From the table, it is also clear that the mass table AME 2020 can reproduce the experimental Q values very well. For example, in the case of ^{294}Og, the discrepancy between the experimental and theoretical prediction is 0.315 MeV. For a clear understanding, the decay chain of the same isotope is depicted in Fig. 1.

Since there is an excellent matching between theoretical and experimental results for the isotope ^{294}Og, the same formalism is used for predicting the decay modes and half-lives of the yet to be synthesized isotopes ^{293}Og and ^{295}Og. The prediction on ^{293}Og is given in Table II. From the table it is clear that the isotope will decay via a 5α chain followed by SF. Also the calculated half-lives are well within the experimental limit. This indicates that the isotope ^{293}Og can be synthesized and detected in laboratories via the alpha decay chain.

For an easier look, the decay chain of the isotope is graphically represented and is given in Fig. 2. The agreement between the half-lives calculated using different theoretical methods can be clearly seen from the figure. The predictions on half-lives using the MGLDM and UDL go hand in hand with each other. Even though the trend in half-lives with VSS and Royer is the same, they deviate a bit from the other predictions.

The predictions on the half-lives and decay modes of the isotope ^{295}Og and its daughter nuclei are given in Table III. From the study, the isotope ^{295}Og decay via a 2α chain followed by subsequent SF. The half-life of the parent isotope is in measurable range, so it is possible to detect ^{295}Og via alpha decay in laboratories. The alpha half-lives calculated using other theoretical formalisms agrees with the results obtained with the MGLDM. The decay chain of the same isotope is depicted in Fig. 3.

For the production of superheavy nuclei using fusion reactions, heavy projectile nuclei must be fused with heavy target nuclei. Even though considerable progress has been achieved in the experimental regime, the short lifetime and low production cross section (of the order of picobarns) have posed considerable difficulties in the production of superheavy nuclei.

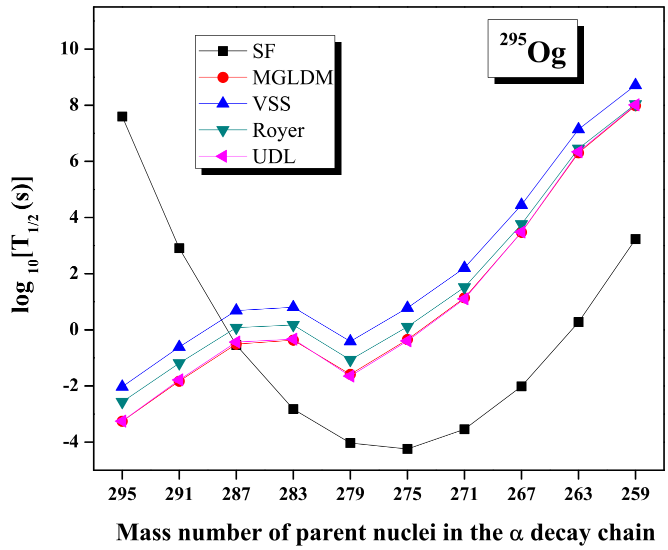

FIG. 3. The comparison of calculated alpha decay half-lives with the spontaneous fission half-lives for the isotope ^{295}Og and its daughter nuclei.

IV. CONCLUSIONS

The decay modes of three isotopes of Og with $A = 293$, 294, and 295 are studied in the present paper. The alpha half-lives are calculated using the MGLDM. The results obtained using the MGLDM are compared with other three theoretical formalisms. It is seen that, for all three isotopes, the half-lives using the MGLDM agree well with the values calculated using these formalisms. The SF half-lives are computed using the semiempirical formula of Xu *et al.* By comparing the alpha half-lives with SF half-lives, the decay modes of the isotopes are predicted. From the study, it is seen that the isotope ^{293}Og decays via the 5α chain, ^{294}Og via the 3α chain, and ^{295}Og via the 2α chain. An excellent matching between theoretical and experimental observations is seen in the case of the decay modes of ^{294}Og. The half-lives of all these isotopes are found to be within the experimental limit. So these three isotopes of Og can be predicted to be synthesized and detected in the laboratory via alpha decay. It is hoped that this study will be helpful in future experimental studies of the isotopes of Og.

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