Heavy-ion emission in spontaneous decays of ^{249,252}Cf nuclei

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(Received 14 April 1999; published 16 November 1999)

Theoretical possibilities for exotic cluster emissions from ^{249}Cf and ^{252}Cf parents are explored on the basis of the very much used preformed cluster model of one of us (R.K.G.) and collaborators. The calculated α-decay half-life time for ^{252}Cf match the experiments exactly and the same for ^{249}Cf within an order of 3. The most probable heavy cluster decay for both the parents is predicted to be ^{46}Ar or ^{48}Ca, with the predicted decay half-life times far more than the presently available experimental upper limiting values. In other words, the predicted heavy-ion emission probabilities for both the parents are so small that there seem to be very little chance for their exotic cluster decays to be observed in the very near future. [S0556-2813(99)03211-2]

PACS number(s): 23.70.+j, 25.85.Ca, 25.85.Ec, 27.90.+b

I. INTRODUCTION

Heavy ions, i.e., nuclei heavier than the α nucleus (commonly called clusters) are emitted spontaneously in decays of radium (Ra), actinium (Ac), and other heavier actinides upto plutonium (Pu). The heaviest cluster observed so far is ^{32}Si emitted from ^{238}Pu parent nucleus [1,2]. Many early attempts [3–6] to detect a heavier ^{34}Si cluster decay of the next heavier element ^{241}Am resulted in only an upper limiting value (decay half-life $T_{1/2} > 1.73\times 10^{25}$ s), whereas the same, rather the Si isotopes ^{33,34,35}Si, are observed recently [7] in ternary fission of ^{243}Am*, produced in thermal neutrons induced reaction ^{242}Am$(n_{\rm th},f)$. No ternary particles heavier than the above noted Si isotopes were detected. The negative results of cluster dcecay experiments for ^{241}Am and the ever decreasing cluster decay probability [the decay constant $\lambda(s^{-1})$] with increasing size (mass) of the emitted cluster seem to have deterred experimentalists to attempt cluster decay measurements of transplutonium or transamericium parents (except for what is discussed in the next paragraph). Theoretically, however, in spite of the increasing competition with spontaneous fission which becomes comparable at (cluster) mass $A_2 \sim 42$ [8], the cluster preformation probability is shown to reach a minimum value at $A_2 \sim 28$ but then increases and becomes nearly constant for $A_2 > 34$ [9–11]. It may be mentioned here that such calculations are available only for the preformed cluster model (PCM) of Gupta and Malik [12–14]. The predictions of another preformed cluster model due to Blendowske and Walliser [15] stop at $A_2 = 28$. Apparently, any experimental and/or theoretical cluster decay study for parents heavier than Pu (or Am) and clusters heavier than ^{32}Si would be of interest for knowing the limits of this process with respect to binary (and/or ternary) fission [7,16–18] and to test the predictions of various available mechanisms for understanding this new phenomenon of heavy-ion emission, the cluster radioactivity.

Californium (Cf) nuclei offer interesting possibilities for the heavier cluster decay studies since the closed shell effects of the doubly magic ^{48}Ca nucleus are expected to come into play. So far it is the closed shell effects of the daughter nuclues (^{208}Pb or ^{100,132}Sn) that have been observed [1,2] or predicted [11,19–21]. Spontaneous binary and ternary fission of ^{252}Cf have been studied quite extensively recently [7,16,17,18], with ^{4}He, ^{10}Be, and ^{14}C nuclei observed as ternary fission particles. For the light nucleus accompanied binary decay of ^{252}Cf, however, the only experimental attempt of Ortlepp *et al.* [22] resulted in an upper limit on branching ratio $[B = T_{1/2}(\alpha)/T_{1/2}(\text{cluster}) \leqslant 10^{-8}]$ for ^{46}Ar or ^{48}Ca cluster. For ^{249}Cf, more recently, Ardisson *et al.* [23] first attempted an indirect experiment to interpret the existence of an unassigned γ line (1554.2 KeV energy) in the spontaneous fission spectrum, following the ^{249}Cf α decay, as a possible signature of ^{50}Ca emission from ^{249}Cf and deduced a branching ratio $B = 4.9\times 10^{-9}$ [or $T_{1/2}(^{50}\text{Ca}) = 2.2\times 10^{18}$ s], which in a later direct experiment [24] is pushed down (or up) to $B \leqslant 1.5\times 10^{-12}$ [or $T_{1/2}(^{50}\text{Ca}) \geqslant 7.4\times 10^{21}$ s]. Apparently, a theoretical cluster decay study of these Cf nuclei is warranted both for the guidance of future experiments and for investigating the above mentioned novel closed shell feature of the emitted cluster.

We have used here the preformed cluster model of Gupta and collaborators [12–14,25], which is described briefly in Sec. II. Also, a simplification of this model to an alternative model, called unified fission model (UFM), is discussed. Our calculations are presented in Sec. III and a summary and discussion of results is given in Sec. IV.

II. THE MODEL

In the preformed cluster model (PCM) of Gupta *et al.*, the decay constant λ (related to the decay half-life $T_{1/2} = \ln 2/\lambda$) is the product of three factors: the cluster preformation probability P_0, the barrier impinging frequency ν_0, and the barrier penetration probability P,

$$\lambda = P_0 \nu_0 P. \tag{1}$$

The P_0 and P are calculated by introducing a coupled motion in dynamical collective coordinates of mass asymmetry $\eta = (A_1 - A_2)/(A_1 + A_2)$ and relative separation R via the stationary Schrödinger equation

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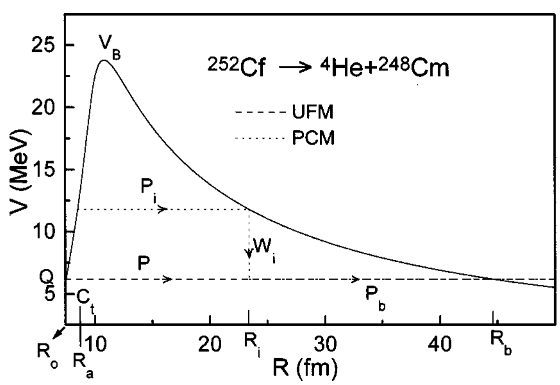

FIG. 1. An illustrative scattering potential $V(R)$, showing for the preformed cluster model (PCM) and unified fission model (UFM), the penetration paths and other characteristic quantities.

$$H(\eta,R)\Psi^n(\eta,R)=E^n\Psi^n(\eta,R). \tag{2}$$

The potentials entering this equation are given by

$$V(\eta,R)=-\sum_{i=1}^{2} B_i(A_i,Z_i)+\frac{Z_1Z_2e^2}{R}+V_p, \tag{3}$$

defined by the sum of binding energies, the Coloumb and the proximity [26] potentials. The charges Z_i are fixed by minimizing the potential [given by Eq. (3), without V_p, for fixed η and R] in the charge asymmetry coordinate $\eta_Z=(Z_1-Z_2)/(Z_1+Z_2)$.

In view of the definition (1), Eq. (2) is solved in the decoupled approximation, $\Psi^n(\eta,R)=\Psi^n(\eta)\Psi^n(R)$, such that the stationary Schrödinger equation for, say, η-motion, at a fixed R value, is

$$\left(-\frac{\hbar^2}{2\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta}\frac{1}{\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta}+V(\eta)\right)\Psi^n(\eta)=E_\eta^n\Psi^n(\eta), \tag{4}$$

with $E^n=E_\eta^n+E_R^n$. The mass parameters $B_{\eta\eta}(\eta)$ are the classical hydrodynamical masses of Kröger and Scheid [27]. Then, the cluster preformation probability P_0, for the η motion, is $P_0\propto|\Psi(\eta)|^2$. Only the ground state ($n=0$) solution is relevant for the cluster decay to occur in the ground state of the daughter nucleus. Then, the properly normalized fractional cluster preformation probability P_0 at a fixed R ($=R_a$, the first turning point) is

$$P_0(A_2)=|\Psi^0(A_2)|^2\sqrt{B_{\eta\eta}(A_2)}\frac{2}{A}. \tag{5}$$

For R motion, instead of solving the corresponding radial Schrödinger equation, as usual, the penetration probability P is the WKB penetrability. For the tunneling path shown in Fig. 1 (marked PCM), the penetrability

$$P=P_iP_b \tag{6}$$

with

$$P_i=\exp\left[-\frac{2}{\hbar}\int_{R_a}^{R_i}\{2\mu[V(R)-V(R_i)]\}^{1/2}dR\right], \tag{7}$$

$$P_b=\exp\left[-\frac{2}{\hbar}\int_{R_i}^{R_b}\{2\mu[V(R)-Q]\}^{1/2}dR\right]. \tag{8}$$

This means that tunneling begins at $R=R_a$ and terminates at $R=R_b$ with $V(R_b)=Q$-value. The deexcitation probability (W_i) between P_i and P_b is taken to be unity [28]. Both Eqs. (7) and (8) are solved analytically [13,14,25].

The impinging frequency ν_0 in this model is obtained from the experimental Q value, taken as total kinetic energy shared between the two fragments. Then, for the light fragment (the cluster),

$$\nu_0=\frac{\text{velocity}}{R_0}=\frac{\sqrt{2Q/mA_2}}{R_0}, \tag{9}$$

with R_0 as the radius of the parent nucleus and m as the nucleon mass. For more details, see the recent reviews [1,11].

The only variable in our calculations is the value of first turning point $R=R_a$. We have varied it from $R_a=C_1+C_2=C_t$ to $R_a=C_t-\Delta R=R_0$ in order to fit the only experimental number known, the α-decay half-life. This means that the maximum value of ΔR is determined by $R_a=R_0$, the parent nucleus radius. Here C_t is the touching configuration of two nuclei, with C_i as the Süsmann central radii

$$C_i=R_i-\frac{1}{R_i}, \tag{10}$$

$$R_i=1.28A_i^{1/3}-0.76+0.8A_i^{-1/3}\ \text{fm}. \tag{11}$$

Note that C_t is different for different cluster+daughter configuration. Also, the choice $R_a\approx C_t$ assimilates the effects of both deformations of the two fragments and neck formation between them [25].

The PCM simplifies to an alternative description, called unified fission model (UFM) [1], if the preformation factor $P_0=1$ and the penetration path is straight to Q value i.e., $R_a=R_0$, as shown in Fig. 1 (marked UFM), such that

$$P=\exp\left[-\frac{2}{\hbar}\int_{R_a}^{R_b}\{2\mu[V(R)-Q]\}^{1/2}dR\right], \tag{12}$$

with $V(R_a=R_0)=V(R_b)=Q$ value. R_a and R_b are, respectively, the first and second turning points. This calculation is referred to as UFM, in the following.

III. CALCULATIONS

We have made our calculations for the ^{249}Cf nucleus by using the 1995 Audi and Wapstra tables of experimental binding energies [29], and for the ^{252}Cf nucleus, the 1995 theoretical binding energies of Möller *et al.* [30], supplemented by experimental numbers from Audi and Wapstra [29] for $Z\leqslant 8$. It may be mentioned here that a similar calculation for ^{252}Cf was made recently by Kumar, Gupta, and

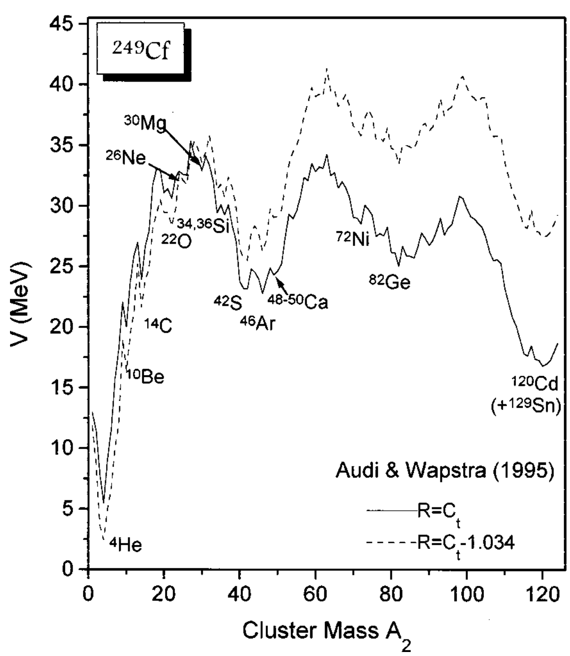

FIG. 2. The fragmentation potential, normalized to the parent nucleus binding energy, for the ^{249}Cf parent, calculated at two $R=R_a$ values of the first turning point. The minima are marked by light mass fragments, with the corresponding heavy fragment for Cd also shown in braces. The binding energies are taken from Audi and Wapstra [29].

Scheid [8] by using the 1988 Möller and Nix tables of binding energies [31], which resulted in underestimated cluster decay branching ratios with respect to α decay. No fitting of α-decay half-life was attempted in this early calculation.

Figures 2 and 3 give, respectively, the normalized frag-

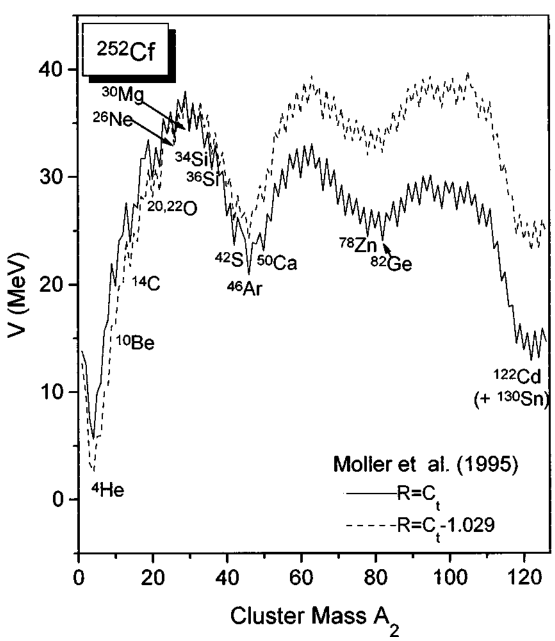

FIG. 3. The same as for Fig. 2, but for the ^{252}Cf parent. The binding energies are taken from Möller *et al.* [30], supplemented from Audi and Wapstra [29] for $Z \leqslant 8$.

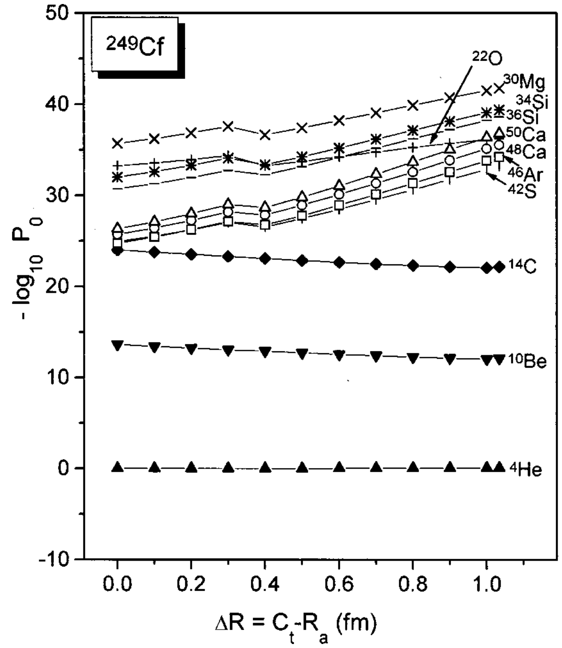

FIG. 4. The (negative) logarithm of the preformation factor P_0 for different clusters, plotted as a function of ΔR, the value of the first turning point R_a with respect to C_t, the touching configuration, for the ^{249}Cf parent.

mentation potentials $V(\eta)$ for ^{249}Cf and ^{252}Cf parents, calculated at two different R_a values. We notice that, almost independent of the R_a value, in each case, deep potential energy minima occur not only at the doubly or singly closed shell nuclei [α particle, $^{46}_{18}Ar_{28}$ (or neighboring $^{42}_{14}S_{28}$ and $^{48,50}_{20}Ca_{28,30}$), $^{82}_{32}Ge_{50}$ and $^{130-132}_{50}Sn_{80,82}$], but also at light clusters ^{10}Be, ^{14}C, ^{20,22}O, ^{26}Ne, ^{30}Mg, and ^{34,36}Si. We are interested here only in the potential energy minima because the preformation factors P_0 for nuclei at the minima are largest compared to their neighbors. This is depicted in Figs. 4 and 5 for the ^{249,252}Cf nuclei, where $-\log_{10}P_0$ is plotted as a function of $\Delta R(=C_t-R_a)$. Only the clusters for mass $A_2 \leqslant 50$ are considered. We notice that the P_0 are largest for ^{4}He, ^{10}Be, and ^{14}C nuclei (the clusters observed [17,18] in ternary fission of ^{252}Cf) but then ^{42}S, ^{46}Ar, or ^{48,50}Ca nuclei get preformed more probable than O, Mg, or Si nuclei. However, we shall see in the following that, other than for α particle, the decay probabilities are largest (or decay half-life smallest) for ^{46}Ar or ^{48,50}Ca clusters. The decay probabilities for the best preformed light clusters ^{10}Be and ^{14}C are very small compared to many other clusters. This happens due to the penetrability factor P.

Figures 6 and 7 give the results of our calculation for the barrier penetrability P. We notice that, for both the parents, the penetrabilities are largest for ^{46}Ar, or ^{48,50}Ca clusters, larger than even for the α particle. The penetrabilities for the ^{10}Be and ^{14}C clusters are particularly very small. The measurable decay probabilities λ (or half-life times $T_{1/2}$) are, however, a combined effect of P_0 and P (the impinging frequency ν_0 being almost constant), which we discuss in the following for each parent nucleus separately.

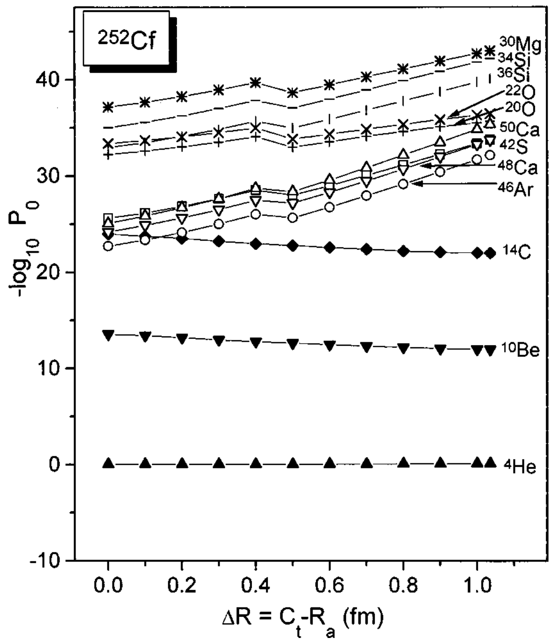

FIG. 5. The same as for Fig. 4, but for the ^{252}Cf parent.

A. ^{249}Cf parent

In an attempt to fit the α-decay half-life, we have calculated the decay half-life times $T_{1/2}$(s) as a function of the only variable R_a of the model. This is displayed in Fig. 8, where $\log_{10} T_{1/2}$(s) is plotted as a function of $\Delta R = C_t - R_a$(fm). The value of R_a lies in the range $R_0 \leqslant R_a \leqslant C_t$, which gives a limiting (maximum) value of $\Delta R = 1.034$ fm for the ^{4}He cluster decay of ^{249}Cf. It may be reminded here that C_t is different for different cluster+daughter configuration.

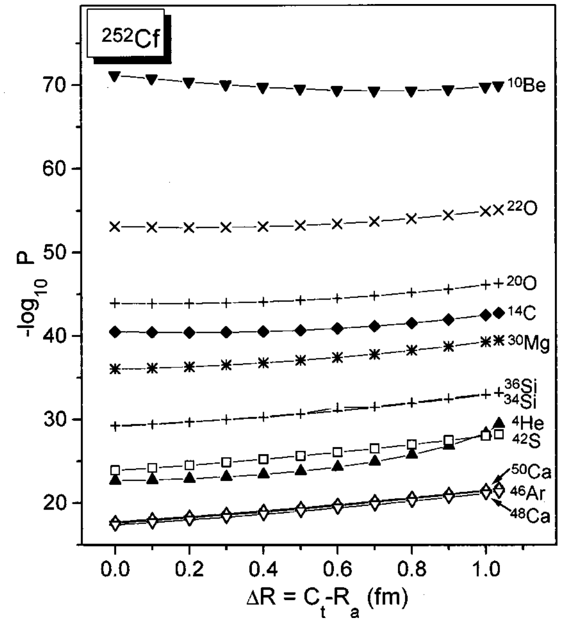

FIG. 7. The same as for Fig. 5, but for the penetration probability P.

We notice in Fig. 8 that $T_{1/2}(\alpha)$ increases as ΔR increases, attaining a maximum value $T_{1/2}^{\rm cal}(\alpha) = 4.04 \times 10^7$(s) at the limiting value of $\Delta R = 1.034$ fm or $R_a = R_0 = C_t - 1.034$ fm. This value falls short of the experimental value $[T_{1/2}^{\rm expt}(\alpha) = 1.108 \times 10^{10}$ (s)] by an order of 3, and is the best fit that could be obtained within the PCM used here. Figure 4 and Table I show that the calculated preformation factor P_0 for ^{4}He cluster is of the order of unity, which means that the predictions of this model and that of the unified fission model (UFM) for α-decay are identical. This means that both

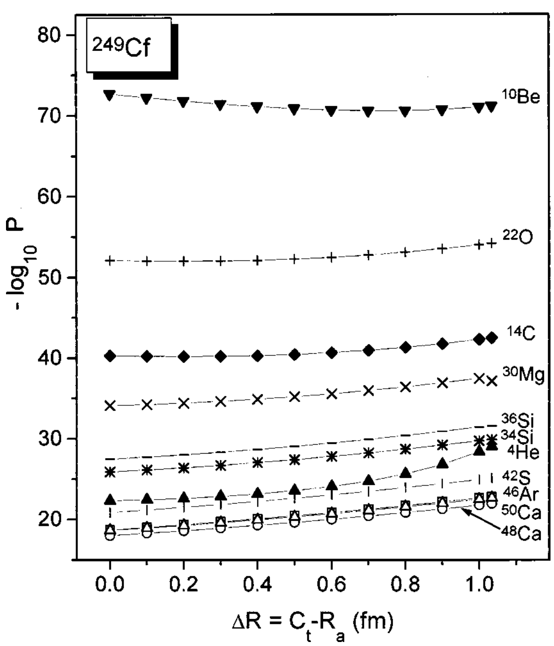

FIG. 6. The same as for Fig. 4, but for the penetration probability P.

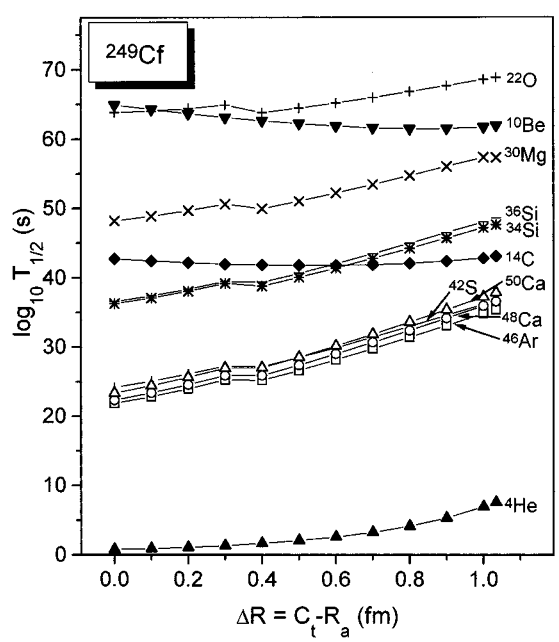

FIG. 8. The same as for Fig. 4, but for the decay half-life times $T_{1/2}$(s).

TABLE I. Calculated decay half-life and other characteristic quantities for various heavy-ion emissions from ^{249}Cf, using the preformed cluster model (PCM) of Gupta and collaborators. The impinging frequency is nearly constant, with an average value of $\nu_0 = 2.8 \times 10^{21}\ \mathrm{s}^{-1}$. The experimental α-decay half-life time $T_{1/2}^{\mathrm{expt}}(\alpha) = 1.11\times 10^{10}$ s.

Cluster + daughter	Q value (MeV)	Performation probability P_o: $R_a = C_t$	P_o: $R_a = C_t - 1.034$	Penetration probability P: $R_a = C_t$	P: $R_a = C_t - 1.034$	Half-life times $T_{1/2}(s)$: $R_a = C_t$	$T_{1/2}(s)$: $R_a = C_t - 1.034$
^{4}He+^{245}Cm	6.30	9.42×10^{-1}	8.22×10^{-1}	4.73×10^{-23}	8.88×10^{-30}	6.62×10^{0}	4.04×10^{7}
^{4}Be+^{239}Pu	8.53	2.28×10^{-14}	7.87×10^{-13}	1.97×10^{-73}	6.58×10^{-72}	8.92×10^{64}	7.74×10^{61}
^{14}C+^{235}U	25.79	9.64×10^{-25}	7.09×10^{-23}	4.86×10^{-41}	3.09×10^{-43}	5.83×10^{42}	1.25×10^{43}
^{22}O+^{227}Th	34.63	5.43×10^{-34}	6.11×10^{-37}	7.53×10^{-53}	6.78×10^{-55}	7.22×10^{63}	7.12×10^{68}
^{30}Mg+^{219}Rn	69.77	1.92×10^{-36}	1.80×10^{-42}	7.51×10^{-35}	6.62×10^{-38}	1.68×10^{48}	2.04×10^{57}
^{34}Si+^{215}Po	90.22	9.76×10^{-33}	4.10×10^{-40}	1.20×10^{-26}	1.23×10^{-30}	1.94×10^{36}	4.53×10^{47}
^{36}Si+^{213}Po	88.78	1.90×10^{-31}	2.59×10^{-39}	3.14×10^{-28}	2.38×10^{-32}	3.96×10^{36}	3.83×10^{48}
^{42}S+^{207}Pb	109.42	1.15×10^{-25}	6.32×10^{-34}	1.33×10^{-21}	7.33×10^{-26}	1.50×10^{24}	4.96×10^{36}
^{46}Ar+^{203}Hg	124.72	1.63×10^{-25}	6.47×10^{-35}	1.88×10^{-19}	1.55×10^{-23}	7.35×10^{21}	2.24×10^{35}
^{48}Ca+^{201}Pt	137.69	1.83×10^{-26}	2.95×10^{-36}	9.47×10^{-19}	1.08×10^{-22}	1.26×10^{22}	6.84×10^{35}
^{50}Ca+^{199}Pt	136.69	4.43×10^{-27}	1.65×10^{-37}	2.15×10^{-19}	1.95×10^{-23}	2.36×10^{23}	6.92×10^{37}

the PCM and UFM predict the α-decay half-life time for ^{249}Cf parent within an order of 3. Such a disagreement might have its origin in the charge redistribution effects, suggested to be important for α decay by some authors [32], or simply in the use of different radius expression (11) for the odd mass ^{249}Cf nucleus or a small error in the Q value used here, since the α-decay half-life time for the ^{252}Cf parent is fitted almost exactly (see below). For the heavier cluster decays, however, the two model predictions (that of PCM and UFM) could not be similar, since compared to $P_0 = 1$ for UFM, very low preformation factors are obtained for the PCM.

Figure 8 and Table I show that the decay half-life times for ^{10}Be,^{14}C, and other lighter clusters are predicted to be too large, beyond the present day experiments. The smallest decay half-life is predicted for ^{46}Ar or ^{48}Ca (both having almost the same value), with ^{42}S and ^{50}Ca being the next most (equally) probable cases, depending on the ΔR value. For the best fit to α-decay half-life, i.e., for $\Delta R = 1.034$ fm or $R_a = C_t - 1.034$ fm, the predicted decay half-life for ^{50}Ca cluster is $T_{1/2}^{\mathrm{cal}}(^{50}\mathrm{Ca}) = 6.92\times 10^{37}$ s, which is much higher than the very recently deduced upper limit of $T_{1/2}^{\mathrm{expt}}(^{50}\mathrm{Ca}) \geqslant 7.4\times 10^{21}$ (s) [24]. However, the predicted $T_{1/2}$(cluster) values are shown to decrease considerably in going from $R_a = C_t - 1.034$ to $R_a = C_t$. In this context, it may be reminded that, as shown by Kumar and Gupta [19], the choice of R_a in the neighborhood of C_t assimilates the effects of deformation and neck formation between the two decay products. In other words, with such effects included, the calculated cluster decay half-life times for, say, ^{50}Ca decay of ^{249}Cf would certainly be $< 10^{37}$ s. In view of this result, we have given in Table I the predictions of PCM for the two extreme ΔR values. A further comparison of this model (PCM) calculation with the results of another recent calculation due to Poenaru *et al.* [33], together with the one obtained for a simple square well model (with parameters taken from Ref. [34]) is given in our other publication [24]. The values quoted there in Ref. [24] for PCM are an early version of the refined results given here in this paper. All these calculations predict the ^{249}Cf nucleus to be a poor parent for exotic cluster emissions, at least for the coming few years.

B. ^{252}Cf parent

Figure 9 and Table II give the results of our calculation for ^{252}Cf parent. As already mentioned above, we have used here the 1995 binding energies of Möller *et al.* [30]. More or less the same results, rather better than what are obtained for ^{249}Cf parent, are given here. For the (nearly) best fit at $\Delta R = 1.029$ fm or $R_a = R_0 = C_t - 1.029$ fm, the calculated α-decay half-life $T_{1/2}^{\mathrm{cal}}(\alpha) = 8.18\times 10^7$ (s) matches the experimental number $[T_{1/2}^{\mathrm{expt}}(\alpha) = 8.33\times 10^7\ \mathrm{s}]$ almost exactly. A further matching of the two numbers can be obtained by choosing ΔR to a next level of accuracy. Since P_0 is nearly

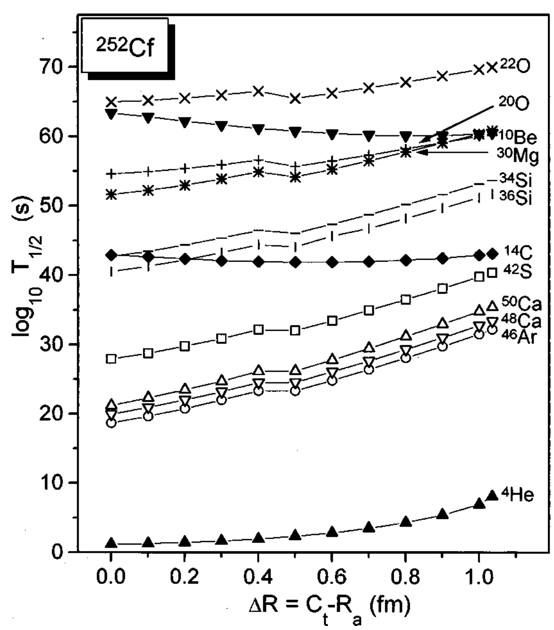

FIG. 9. The same as for Fig. 5, but for the decay half-life times $T_{1/2}$(s).

TABLE II. Calculated decay half-life and other characteristic quantities for various heavy-ion emissions from ^{252}Cf, using the preformed cluster model (PCM) of Gupta and collaborators. The impinging frequency is nearly constant, with an average value of $\nu_0 = 2.7 \times 10^{21}\ \mathrm{s}^{-1}$. The experimental α-decay half-life time $T_{1/2}^{\mathrm{expt}}(\alpha) = 8.33\times 10^7$ s.

Cluster + daughter	Q value (MeV)	Performation probability P_0		Penetration probability P		Half-life times $T_{1/2}(s)$	
		$R_a = C_t$	$R_a = C_t - 1.029$	$R_a = C_t$	$R_a = C_t - 1.029$	$R_a = C_t$	$R_a = C_t - 1.029$
^{4}He+^{248}Cm	6.20	9.26×10^{-1}	7.43×10^{-1}	2.04×10^{-23}	4.92×10^{-30}	1.58×10^{1}	8.18×10^{7}
^{10}Be+^{242}Pu	8.69	2.50×10^{-14}	1.12×10^{-12}	6.50×10^{-72}	7.72×10^{-71}	2.45×10^{63}	4.50×10^{60}
^{14}C+^{238}U	25.69	1.07×10^{-24}	1.10×10^{-22}	2.97×10^{-41}	2.21×10^{-43}	8.67×10^{42}	1.13×10^{43}
^{20}O+^{232}Th	37.46	5.90×10^{-33}	2.93×10^{-36}	1.13×10^{-44}	5.77×10^{-47}	4.08×10^{54}	1.97×10^{60}
^{22}O+^{230}Th	34.20	4.07×10^{-34}	3.78×10^{-37}	7.70×10^{-54}	9.43×10^{-56}	9.51×10^{64}	8.36×10^{69}
^{30}Mg+^{222}Rn	68.26	6.99×10^{-38}	1.20×10^{-43}	8.37×10^{-37}	3.95×10^{-40}	4.21×10^{51}	5.22×10^{60}
^{34}Si+^{218}Po	86.63	9.16×10^{-36}	8.07×10^{-43}	4.94×10^{-30}	7.64×10^{-34}	5.15×10^{42}	3.78×10^{53}
^{36}Si+^{216}Po	87.08	1.08×10^{-33}	9.88×10^{-41}	6.56×10^{-30}	5.58×10^{-34}	3.37×10^{40}	4.34×10^{51}
^{42}S+^{210}Pb	105.36	2.28×10^{-26}	2.06×10^{-34}	1.19×10^{-24}	6.25×10^{-29}	8.67×10^{27}	1.82×10^{40}
^{46}Ar+^{206}Hg	126.19	1.90×10^{-23}	8.64×10^{-33}	2.32×10^{-18}	2.41×10^{-22}	5.10×10^{18}	1.08×10^{32}
^{48}Ca+^{204}Pt	138.33	6.19×10^{-25}	2.28×10^{-34}	3.85×10^{-18}	5.56×10^{-22}	9.18×10^{19}	1.73×10^{33}
^{50}Ca+^{202}Pt	137.71	8.22×10^{-26}	5.70×10^{-36}	1.72×10^{-18}	1.90×10^{-22}	1.59×10^{21}	2.07×10^{35}

unity for ^{4}He decay, both the models (PCM and UFM) can be considered to make identically good predictions for the α-decay half-life time. Once again, the decay half-life times for the lighter clusters ^{10}Be,^{14}C, etc. are predicted to be large enough to conclude that these could not be observed as binary decay products. The most probable heavy cluster decays in this case are also predicted to be ^{46}Ar or ^{48}Ca, with predicted half-life times lying in the range of 10^{18}–10^{32} s for ^{46}Ar and 10^{19}–10^{33} s for ^{48}Ca. Also, these predictions for the ^{50}Ca cluster decay half-life time are larger than the only available old time upper limit of $T_{1/2}^{\mathrm{expt}}(^{50}\mathrm{Ca}) > 10^{15}$, calculated by using the $T_{1/2}^{\mathrm{expt}}(\alpha)$ in the deduced upper limit for $B \leqslant 10^{-8}$ [22]. Thus, in spite of our model predictions agreeing better with the available experimental information, ^{252}Cf nucleus is also an equally difficult parent for the detection of an exotic cluster decay with the presently available experimental facilities.

IV. SUMMARY AND DISCUSSION

We have looked into the possibilities of heavy-ion emission from ^{249,252}Cf parents, by using a preformed cluster model (PCM). These heavy nuclei present as novel cases of emitting a doubly magic cluster ^{48}Ca or its neighboring nuclei ^{46}Ar and ^{50}Ca. If observed, the importance of the shell effects of the lighter (cluster) product, instead of the already observed heavier (daughter) product, will be shown for the first time. The calculations show that ^{46}Ar or ^{48}Ca are in fact the most probable decays of ^{249,252}Cf parents, but the estimated decay half-life times are far more than the available upper limits. In other words, the calculations suggest that, with the presently available experimental methods, it will be difficult, if not impossible, to observe the heavy-ion emission from either of these parents. It may, however, be mentioned that the inclusion of the effects of deformations and neck formation between the decay products could lead to a favorable situation.

Another interesting result of these calculations is that, next to α-decay, the lighter clusters ^{10}Be and ^{14}C are performed most favorably as binary decay products, but then, due to the penetrability factor, their decay half-life times are predicted to be very large for the present day experimental facilities. Since these clusters are already observed as ternary fission products, a cascade or sequential decay of the corresponding binary decay daughter products could not be ruled out. Alternatively, it is possible that these lighter clusters are first preformed as binary decay products and then penetrate a three body barrier.

Finally, these calculations also throw some light on the importance of the preformation probabilities P_0. First of all, $P_0 \approx 1$ for the α-decay which means an equivalence of the two approaches (PCM and UFM) of with and without preformation factor. On the other hand, the penetration probabilities P for the heavier clusters ^{46}Ar and ^{48,50}Ca are larger than for the α-particle emission. This means that, if P_0 were fixed as unity, as in UFM, these heavy cluster decays would be more probable than even the α decay, which is contrary to experiments.

ACKNOWLEDGMENTS

One of us (M.B.) is thankful to Dr. N. Arunachalam, Tirunelveli, for financial support and for allowing him to work at the Physics Department, Panjab University, Chandigarh. The hospitality offered by the Panjab University, Chandigarh, is also gratefully acknowledged.

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