^{34}Si decay of the ^{242}Cm nucleus

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The emission of the ^{34}Si cluster, with respect to the α particle, in the spontanous decay of the ^{242}Cm nucleus is studied within a preformed cluster model developed by one of us (R.K.G.) and collaborators. The preformation factors are predicted to be very small, $\sim 10^{-9}$ and $\sim 10^{-24}$, respectively, for the α particle and ^{34}Si cluster. With no parameter of the model fitted to experimental data, the half-life times for both the α particle and ^{34}Si decays of ^{242}Cm are predicted within only one to two orders of magnitude of the experimental values.

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^{32}Si is the heaviest cluster observed so far [1,2], emitted from $^{238}_{94}$Pu parent with a measured [3] decay half-life $T_{1/2} = 1.89\times10^{25}$ s or branching ratio with respect to the α particle $B = T_{1/2}(\alpha)/T_{1/2}(\text{cluster}) = (1.38\pm1.44)\times10^{-16}$. Many early attempts [4–7] to detect a heavier ^{34}Si cluster decay of the next heavier element $^{241}_{95}$Am resulted in only an upper limiting value ($T_{1/2}>1.73\times10^{25}$ s or $B<7.4\times10^{-16}$ [7]). The negative results of such experiments and the ever-decreasing cluster decay probability 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 one early experimental attempt of Ortlepp *et al.* [8] for ^{46}Ar or ^{48}Ca decay of the $^{252}_{98}$Cf parent which again resulted only in an upper limit on $B\leqslant1.05\times10^{-8}$ or $T_{1/2}>7.91\times10^{15}$ s. Furthermore, an unpublished search of ^{34}Si decay of $^{242}_{96}$Cm [9] and the very recent experiments of Ardisson *et al.* [10,11] for ^{50}Ca emission from $^{249}_{98}$Cf also ended in negative results, with $B<8\times10^{-17}$ or $T_{1/2}>5.67\times10^{24}$ s for $^{242}\text{Cm}\rightarrow{}^{34}\text{Si}+{}^{208}\text{Pb}$ and $B\leqslant1.5\times10^{-12}$ or $T_{1/2}>7.4\times10^{21}$ s for $^{249}\text{Cf}\rightarrow{}^{50}\text{Ca}+{}^{199}\text{Pt}$.

^{34}Si decay of the ^{242}Cm parent nucleus offers the best possibilty of cluster decay study since the daughter nucleus involved is once again the doubly magic ^{208}Pb nucleus. However, in the early experiment [9], there were difficulties in preparing the ^{242}Cm source and the detectors available had limitations. This experiment is now repeated [12] with a more intense ^{242}Cm source and better and carefully calibrated solid state nuclear track detectors. The huge fission fragments background is rejected by using an energy absorber technique, which resulted in $B=1.0\times10^{-16}$ or $T_{1/2}(^{34}\text{Si}) = 1.4^{+0.5}_{-0.3}\times10^{23}$ s, very close to the result of the earlier experiment [9] mentioned above. This small difference, however, eluded the first experimental signatures of this next heavier cluster ^{34}Si for more than about seven years.

Theoretically, in spite of the increasing competition with spontaneous fission, predicted to become comparable at cluster mass of ~42 [13], the cluster preformation probability in the preformed cluster model (PCM) of Gupta *et al.* [14–16] is shown to reach a minimum value at the cluster mass $A_2\sim28$ but then increases and becomes nearly constant for $A_2>34$ [17–19]. It may be mentioned here that this is the only prediction available to date and the only other prediction of another preformed cluster model due to Blendowske and Walliser [20] stops at $A_2=28$. Apparently, any experimental and/or theoretical cluster decay study for clusters heavier than ^{32}Si (or parents heavier than Pu or Am) would be of interest for knowing the limits of this process and to test the predictions of various theories available for this new and exotic phenomenon of cluster radioactivity.

In this paper, we discuss the results of a calculation performed on the basis of the preformed cluster model (PCM) of Gupta and collaborators [14–16,21].

In the preformed cluster model of Gupta and collaborators, cluster decay is seen as a process composed of two independent parts—formation of the two fragments (the cluster and daughter nuclei) in their ground states with a probability P_0 and their tunnelling of the confining nuclear interaction barrier $V(\eta,\eta_Z,R)$ with probability P, by assaulting it with a frequency ν. The decay constant can then be written as the product of these three factors:

$$\lambda = P_0 \nu P, \tag{1}$$

with the decay half-life $T_{1/2}=\ln 2/\lambda$. The two variables η and η_Z on which V depends are the mass and charge asymmetry coordinates, $\eta=(A_1-A_2)/A$ and $\eta_Z=(Z_1-Z_2)/Z$, while R is the relative separation coordinate between the two fragments. Thus, the process that leads to the calculation of decay constant or decay half-life is divided into four steps: the calculation of the fragmentation potential and the inertia parameters, the preformation probability P_0, the assault frequency ν, and the tunnelling probability P.

Fragmentation potential. Considering a two touching spheres approximation, the fragmentation potential $V(\eta,\eta_Z,R)$ is given by the sum of the binding energies of

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the two fragments, Coulomb interaction, and the nuclear proximity potential [22] which describes the attraction between the two surfaces

$$V(\eta,\eta_Z,R)=-B_1(A_1,Z_1)-B_2(A_2,Z_2)+\frac{Z_1Z_2e^2}{R}+V_P, \tag{2}$$

where $R=C_1+C_2=C_t$, with $C_i=R_i-1/R_i$ $(i=1,2)$, the Süssman central radii, and each

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

The charge asymmetry coordinate η_Z is fixed by minimizing in η_Z itself the sum of the two binding energies and the Coulomb potential, for each value of η. In this way the process takes place at the bottom of the potential valley. The binding energies used to determine the potential are the theoretical ones from Möller *et al.* [23] for $Z\geqslant 8$ and the experimental (or extrapolated) ones from Audi *et al.* [24] for $Z<8$. It has not been possible to use only the experimental values since, of the large number of binding energies needed, only a small number was available.

Preformation probability. For calculating the preformation probability, we solve the stationary Schrödinger equation in η for the fixed η_Z and R values

$$\left[\frac{-\hbar^2}{2\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta}\frac{1}{\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta}+V(\eta,\eta_Z,R)\right]\phi^{(\omega)}_{R,\eta_Z}(\eta)=E^{(\omega)}_R\phi^{(\omega)}_{R,\eta_Z}(\eta), \tag{4}$$

where the quantum number ω counts the vibrational states in the potential $V(\eta,\eta_Z,R)$. The mass parameters $B_{\eta\eta}$ are the classical hydrodynamical masses from Kröger and Scheid [25].

Then, the probability of finding each of the two fragments at a position R is $|\phi^{(\omega)}_{R,\eta_Z}(\eta)|^2$. From this probability, the formation probability P_0 in the ground state $(\omega=0)$ is obtained by scaling it to a fractional mass yield of the mass number (say, A_2) of one fragment $(d\eta=2/A)$:

$$P_0(A_2)=|\phi^{(0)}_{R,\eta_Z}(A_2)|^2\sqrt{B_{\eta\eta}(A_2)}\,\frac{2}{A}. \tag{5}$$

Assault frequency. We define the assault frequency

$$\nu=\frac{v}{R_0}=\sqrt{\frac{2E_2}{\mu}}\frac{1}{R_0}, \tag{6}$$

under the assumption that both the emitted cluster and the daughter nucleus are produced in the ground state, and the kinetic energy $E_2=(A_1/A)Q$ since the Q value $(=E_1+E_2)$ is shared in the (inverse) ratio of their masses. R_0, the compound nucleus radius, is given by Eq. (3).

Tunnelling probability. We use the WKB approximation for calculating the tunnelling probability of a cluster through the potential barrier. Once the decay channel is established i.e., η and η_Z are fixed, the nuclear interaction potential

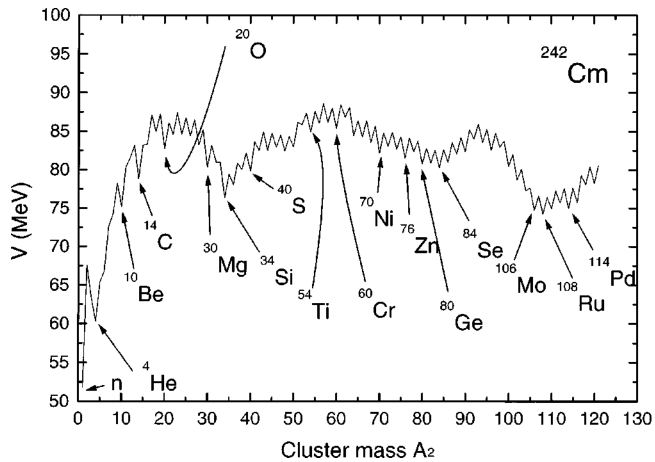

FIG. 1. The fragmentation potential V (MeV) for ^{242}Cm parent nucleus, calculated at the touching configuration $R=C_t$ by using Eq. (2).

$V(R)$ for $R\geqslant C_t$ is given by Eq. (2), by normalizing it to the sum of the binding energies. In the region $R_0<R<R_t$, since nothing better is known [21] and in PCM this part of the potential is not actually used, the potential $V(R)$ calculated at $R=C_t$ is joined to the Q value at the parent nucleus radius $R=R_0$ via a second order polynomial

$$V(R-R_0)=a_0+a_1(R-R_0)+a_2(R-R_0)^2, \tag{7}$$

with the constants a_0, a_1, and a_2 determined from the known $V(R\geqslant C_t)$ and the Q value. For the inertia parameter in this coordinate, we have used the reduced mass $\mu=mA_1A_2/(A_1+A_2)$, with m as the nucleon mass, since we are dealing here with an (almost) asympototic situation. For further details, we refer the reader to original papers [14–17,21] and a recent review [19].

In Fig. 1 the fragmentation potential $V(\eta)$ as a function of the cluster mass for the decay of ^{242}Cm parent nucleus is presented, calculated at the touching configuration $R=C_t$. We notice that, in addition to the usual fission valleys at ^{84}Se and ^{108}Ru (or ^{114}Pd), the ^{34}Si and ^{4}He valleys are quite deep, pointing out of their being the very favorable decay channels. This is further evident in Fig. 2 where the preformation probability P_0 is plotted as a function of the cluster mass. Both the ^{4}He and ^{34}Si clusters are preformed with large probabilities, as compared to their neighboring clusters. The other possible decay channels are ^{10}Be, ^{14}C, ^{20}O, ^{30}Mg, and ^{40}S, since deeper minima occur in the fragmentation potential $V(A_2)$ and the preformation factors $P_0(A_2)$ are also strongly peaked at these clusters. However, in view of the present experimental situation [12], we consider here only the α particle and ^{34}Si decays, i.e.,

$$^{242}\text{Cm}\rightarrow\alpha+{}^{238}\text{Pu}, \tag{8}$$

$$^{242}\text{Cm}\rightarrow{}^{34}\text{Si}+{}^{208}\text{Pb}. \tag{9}$$

Figure 3 shows the interaction potential $V(R)$ for the ^{34}Si decay (9). The solid line corresponds to the quadratic fit [Eq. (7)] while the dotted line refers to $V(R\geqslant C_t)$, calculated by

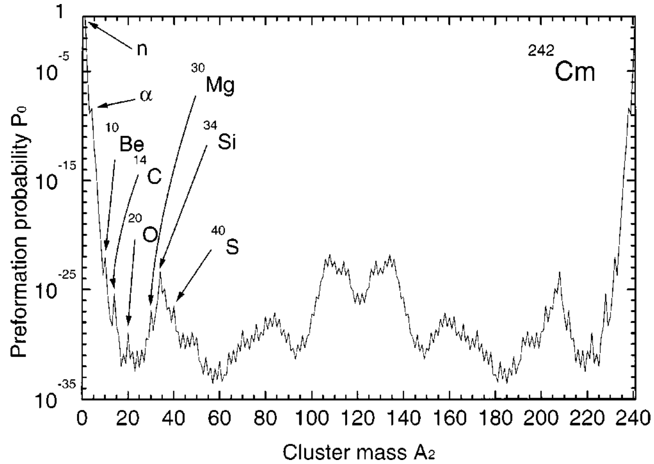

FIG. 2. The same as for Fig. 1, but for the preformation probability P_0.

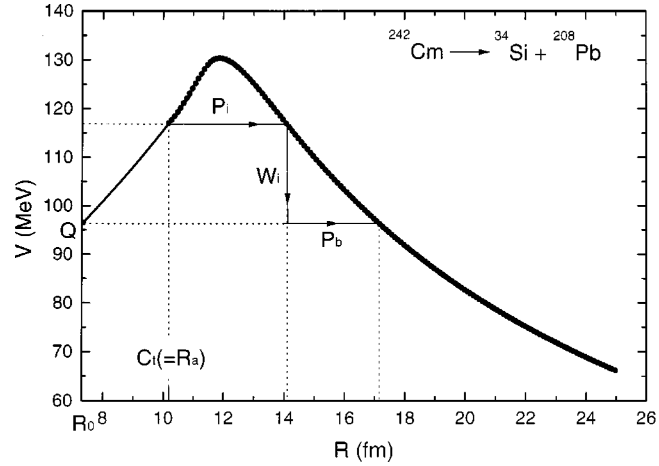

FIG. 3. The scattering potential V(R) for ^{34}Si decay of ^{242}Cm. The penetration path is also shown.

using Eq. (2) and normalizing to the sum of the binding energies of two decay products. The WKB penetrabilty is calculated analytically by parametrizing the potential $V(R \geqslant C_t)$, as in Refs. [16,21]. Here, the penetration path is considered to begin at $R=C_t$. In other words, the first turning point $R_a=C_t$. This choice of first turning point at $R\sim C_t$ is found to assimilate the deformation and neck formation effects of the two fragments [21], which are otherwise taken to be zero here. Apparently, due to different deformations involved in the two decays [refer to Eqs. (8) and (9)], the R_a value could be different in the two cases. However, we first take $R_a=C_t$ and then study the effect of changing the R_a value. The use of different R_a values for different cluster decays of the same parent is also suggested by our very recent calculation for the ^{249,252}Cf parents [26].

Table I summarizes the results of our calculation for the ^{4}He and ^{34}Si decays of ^{242}Cm parent, for $R_a=C_t$ and the neighboring $C_t\pm 0.4$ values. The results of the recent experiment [12] are also shown for comparisons. No attempt is made to fit the data. Actually, once R_a is fixed, there is no free parameter to be fitted in the theory.

First of all, we look at the results for $R_a=C_t$. We notice that the numerical values of P_0 are very small ($\sim 10^{-9}$ and $\sim 10^{-24}$) for both the α and ^{34}Si decays and that the α-decay half-life is given within one order of magnitude but the ^{34}Si-decay half-life is off by two orders of magnitude. In terms of branching ratio *B*, the calculations are off from experiments by three orders of magnitude (compare $B^{\mathrm{cal}}=3.41\times 10^{-13}$ with $B^{\mathrm{expt}}=1.0\times 10^{-16}$). However, if we vary R_a, i.e., increase or decrease it slightly, we notice that whereas there is no improvement in the α-decay results, the ^{34}Si-decay results improve considerably for $R_a=C_t-0.4$. The ^{34}Si-decay half-life is now within less than one order of magnitude and it could apparently be improved further by reducing R_a slightly more. Perhaps, a small improvement in the α-decay half-life could also be effected by varying R_a in the neighborhood of C_t, but the PCM is, in general, found to underestimate or overestimate it for some parents [19]. This may be due to the charge redistribution effects, suggested to be important for α decay by some authors [27], or simply require the use of another radius expression [an alternative of Eq. (3)] for very light nuclei such as the α particle. A recent calculation for the ^{249}Cf parent, however, made within the PCM [28], shows that the charge redistribtion effects do not

TABLE I. Half-life times and other characteristic quantities for α and ^{34}Si decays of ^{242}Cm, calculated by using the preformed cluster model (PCM) of Gupta and collaborators [14–16,21] and compared with the recent experimental data [12]. The impinging frequency is nearly constant, with $\nu=2.36\times 10^{21}$ and 3.18×10^{21} s^{-1}, respectively, for α and ^{34}Si decays. The measured half-life time for α decay of ^{242}Cm, $T_{1/2}^{\mathrm{expt}}(\alpha)=1.41\times 10^7$ s.

Cluster	Case $R_a=$ (fm)	Preformation probability P_0	Penetration probability P	Half-life time $T_{1/2}(s)$ Cal.	Half-life time $T_{1/2}(s)$ Expt.
^{4}He	C_t	4.25×10^{-9}	1.47×10^{-22}	4.69×10^{8}	1.41×10^{7}
	$C_t-0.4$	5.91×10^{-9}	7.78×10^{-24}	6.40×10^{9}	
	$C_t+0.4$	1.26×10^{-9}	8.14×10^{-23}	2.87×10^{9}	
^{34}Si	C_t	4.25×10^{-24}	3.73×10^{-20}	1.37×10^{21}	$1.4^{+0.5}_{-0.3}\times 10^{23}$
	$C_t-0.4$	1.41×10^{-24}	2.82×10^{-21}	5.48×10^{22}	
	$C_t+0.4$	6.92×10^{-25}	5.89×10^{-19}	5.34×10^{20}	

at all help in improving the results for α decay. For the present, therefore, if we use the experimental value of α decay half-life $T_{1/2}^{\rm expt}(\alpha)=1.41\times 10^{7}$ s, the calculated branching ratio $B^{\rm cal}=2.56\times 10^{-16}$ for ^{34}Si decay at $R_a=C_t-0.4$, which match the experimental value $B^{\rm expt}=1.0\times 10^{-16}$ rather nicely, within a factor of 2 only. It may be recalled here that there is no other free parameter in this model. Furthermore, it may be noted that the measured branching ratios for ^{32}Si and ^{34}Si decays, respectively, of ^{238}Pu and ^{242}Cm are of the same order (rather, have same values), which may perhaps be taken as a signature of the predictions of PCM for their having constant preformation factor P_0 [17–19].

The other model calculations available in the literature are from Poenaru [29] and Kadmenski [30], respectively, as $B=4.5\times 10^{-17}$ and 2×10^{-19}. Also, we have estimated [31] the same for Blendowske and Walliser [20] by using their DECAY−2 code, obtaining $B=1.2\times 10^{-17}$. All these results are within an order of one to three of the recent experiment. Some of these models involve parameter fittings.

In view of the recent experiment on ^{34}Si decay of ^{242}Cm, we have studied this cluster decay process on the basis of the preformed cluster model (PCM) of one of us and collaborators [14–16,21]. We are able to reproduce the experimental value of half-life time for ^{34}Si emission from ^{242}Cm within two orders of magnitude. This result can be considered very satisfactory, since this model gives pure theoretical predictions for the half-life times without making use of any parameter fit to experimental data. However, allowing for the fact that the deformations of the nuclei in the two decays of ^{242}Cm (α and ^{34}Si decays) are different, a small modification of the interaction barrier, by changing the position of first turning point in the penetration process, makes the ^{34}Si decay half-life fit the experimental value almost exactly, though the α-decay half-life still remains off by a factor of 1 order of magnitude.

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