Structure effects in the region of superheavy elements via the $\alpha$-decay chain of $^{293}118$

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Abstract

The $\alpha$-decay chain of $^{293}118$, first proposed in the Berkeley cold fusion experiment $^{208}$Pb($^{86}$Kr,1n) and now retracted, is calculated by using the preformed cluster model (PCM) of one of us (RKG). Also, the possible branchings of $\alpha$-particles to heavier cluster decays of all the parents in this chain are calculated for the first time. The calculated Q-values, penetrabilities and preformation factors for $\alpha$-decays suggest that the $^{285}114$ nucleus with $Z=114, N=171$ is a magic nucleus, either due to the magicity of $Z=114$, or of $N=172$ or of both. The $N=172$ is proposed to be a magic number in certain relativistic mean-field calculations, but with $Z=120$. The calculated cluster decays point to new interesting possibilities of $^{14}$C decay of the $^{281}112$ parent, giving rise to a (reasonably) deformed $Z=106, N=161$, $^{267}106$ daughter ($N=162$ being now established as the deformed magic shell) or to a doubly magic $^{48}$Ca cluster emitted from any of the parent nucleus in the $\alpha$-decay chain. Apparently, these are exciting new directions for future experiments.
The synthesis of Z=118 element in the cold fusion reaction $^{208}\text{Pb}(^{86}\text{Kr},1\text{n})$ via the observed $\alpha$-decay chains had created much excitement recently. This reaction was first made at Berkeley [1], establishing three decay chains, with a resulting very high fusion cross section of $2^{+2.6}_{-0.8}$ pb compared to the limiting value of $\sim 1$ pb for the cold fusion reactions leading to the heaviest Z=112 element. However, this experiment is now retracted [2, 3], since many other subsequent attempts [4, 5, 6, 7] at various other laboratories (GSI, RIKEN, GANIL) around the World failed to reproduce these data and "one event" upper limit of $<0.5$ pb has now been put for this reaction. Such a resulting situation has some consequences for what has been the cause for a large excitement for nuclear structure studies in the region of superheavy elements [8, 9, 10, 11, 12, 13, 14], discussed below.

The measured large cross section for Z=118 element, now retracted, was considered [13] as a possible signature of our approaching the centre of island of stability for superheavy elements (SHE) around Z=120, predicted by the well founded relativistic mean-field (RMF) calculations [8, 9, 10, 11, 12]. However, the lowering down of the fusion cross section for this reaction to $<0.5$ pb means that we must go up the ladder of SHE rather steadily, as was proposed by another calculation of some of us [15], based on the well accepted Quantum Mechanical Fragmentation Theory [16, 17, 18, 19, 20, 21]. The surprises, if any, were expected to lie in the overshooting of this centre of island of SHE by means of (neutron-rich) radioactive nuclear beams for the magic N=184. Then the question would arise for protons, whether Z=110 or 114 is magic, as has been predicted since the early days of this subject, or it is around Z=120, as is predicted more recently by the above mentioned RMF calculations.

In this paper, we attempt to look for an answer to the question raised in the last paragraph above, regarding the nuclear structure effects in SHE, as well as to the cause for the failure of Z=118 experiment. We do this by analysing theoretically the $\alpha$-decay chain for $^{293}118$. This is only an exploratory study and can be extended to other heavy nuclei in this region. Also, we have calculated for the first time the possible branching of $\alpha$-decay to any heavy cluster decay, at any stage of the $\alpha$-decay chain of $^{293}118$. Such a process of, so-called, cluster radioactivity should open new vistas for the decay studies of SHE, with a possible landing at some new or known
magic daughter nucleus. We have used here for our decay calculations the Preformed Cluster Model (PCM) of Gupta [22, 23, 24].

The preformed cluster model (PCM) uses the dynamical collective coordinates of mass and charge asymmetries

\[ \eta = (A_1 - A_2)/(A_1 + A_2) \]

and

\[ \eta_Z = (Z_1 - Z_2)/(Z_1 + Z_2), \]

first introduced in the Quantum Mechanical Fragmentation Theory [16, 17, 18]. These are in addition to the usual coordinates of relative separation R and deformations \( \beta_i \) (\( i = 1, 2 \)). Then, in the standard approximation of decoupled R- and \( \eta \)-motions [22, 23, 24, 25], the decay half-life \( T_{1/2} \) or the decay constant \( \lambda \) in PCM is defined as

\[ \lambda = \frac{\ln 2}{T_{1/2}} = P_0 \nu_0 P. \]  

(1)

Here \( P_0 \) is the cluster (and daughter) preformation probability and P the barrier penetrability which refer, respectively, to the \( \eta \) and R motions. The \( \nu_0 \) is the barrier assault frequency. The \( P_0 \) are the solutions of the stationary Schrödinger equation in \( \eta \),

\[ \left\{ -\frac{\hbar^2}{2\sqrt{B_{\eta\eta}}} \frac{\partial}{\partial \eta} \frac{1}{\sqrt{B_{\eta\eta}}} \frac{\partial}{\partial \eta} + V_R(\eta) \right\} \psi^{(\nu)}(\eta) = E^{(\nu)} \psi^{(\nu)}(\eta), \]  

(2)

which on proper normalization are given as

\[ P_0 = \sqrt{B_{\eta\eta}} \left| \psi^{(0)}(\eta(A_i)) \right|^2 \frac{2}{A}, \]  

(3)

with \( i = 1 \) or 2 and \( \nu = 0, 1, 2, 3, \ldots \). We are interested here only in the ground state solution (\( \nu = 0 \)) since the \( \alpha \) (as well as the proposed heavy cluster) emissions in the considered decay chain are the ground state decays. Eq. (2) is solved at a fixed \( R = R_a = C_t(= C_1 + C_2) + d \), the first turning point in the WKB integral for penetrability P (see Fig. 1 and Eq. 5), since this value of R (instead of \( R = R_0 \), the compound nucleus radius) assimilates to a good extent the effects of both the deformations of two fragments and neck formation between them [26]. In this way, the two-centre nuclear shape is simulated through a neck-length parameter \( d \) added.
to scission configuration, which for actinides is nearly zero [26], and is taken to be so for superheavy nuclei. The role of deformation in the scattering potential $V(R)$ is shown [26] to lower the interaction barriers but not the relative formation yields. The $C_i$ are Süssmann central radii $C_i = R_i - (1/R_i)$, with the radii $R_i = 1.28A_i^{1/3} - 0.76 + 0.8A_i^{-1/3} \text{fm}$.

The fragmentation potential $V_R(\eta)$ in (2) is calculated simply as the sum of the Coulomb interaction, the nuclear proximity potential [27] and the ground state binding energies of two nuclei,

$$V(R_a, \eta, \eta_Z) = \frac{Z_1Z_2e^2}{R_a} - \sum_{i=1}^{2} B(A_i, Z_i, \beta_i) + V_P,$$

with B’s taken from the 1995 experimental compilation of Audi and Wapstra [28] and from the 1995 calculations of Möller et al. [29] whenever not available in [28]. Thus, full shell effects are contained in our calculations that come from the experimental and/or calculated [29] binding energies. The shell effects in the calculated binding energies of Möller et al. [29] are obtained in Strutinsky way [30] by using the folded-Yukawa single-particle potential and macroscopic finite-range droplet model (FRDM). The model parameters are fitted to the ground-state masses of 1654 nuclei, ranging from $^{16}O$ to $^{263}106$, and to 28 fission-barrier heights. Hence, their extrapolation to heavier elements, studied here in this paper, is expected to be a realistic one. Note that the familiar magic numbers $N=Z=50$, 82 and $N=126$ are given by these calculations and there is no assumption made about the magic numbers in the extrapolated region of SHE. The center of the superheavy region in these calculations is found to be located at $^{294}115179$ [29].

The charges $Z_1$ and $Z_2$ in (4) are fixed by minimizing the potential in $\eta_Z$ coordinate, which automatically minimizes the $\beta_i$ coordinates. Note that the minimized $\beta_i$‘s are not always for the spherical nuclei since the total binding energy $B_1 + B_2$ of the decay products is minimized and not their individual $B_1$ or $B_2$. The Coulomb and proximity potentials in (4) are for spherical nuclei. The mass parameters $B_{\eta\eta}(\eta)$, representing the kinetic energy part in (2), are the classical hydrodynamical masses [31]. The shell effects in masses are shown [24] not to affect the order of calculated preformation yields.

The WKB tunnelling probability, calculated for the tunneling path shown
in Fig. 1, is \( P = P_i P_b \) with

\[
P_i = \exp\left[-\frac{2}{\hbar} \int_{R_a}^{R_i} \{2\mu[V(R) - V(R)]\}^{1/2} dR\right] \tag{5}
\]

\[
P_b = \exp\left[-\frac{2}{\hbar} \int_{R_i}^{R_b} \{2\mu[V(R) - Q]\}^{1/2} dR\right]. \tag{6}
\]

These integrals are solved analytically [23] for \( R_b \), the second turning point, defined by \( V(R_b) = Q \)-value for the ground-state decay.

The assault frequency \( \nu_0 \) in (1) is given simply as

\[
\nu_0 = (2E_2/\mu)^{1/2}/R_0, \tag{7}
\]

with \( E_2 = (A_1/A)Q \), the kinetic energy of the lighter fragment, for the \( Q \)-value shared between the two products as inverse of their masses. Eq. (7), used here, results in \( \nu_0 \approx 3 \times 10^{21} \text{s}^{-1} \), whereas the more often used value in literature is \( \sim 10^{22} \text{s}^{-1} \) for even parents and \( \sim 10^{20} \text{s}^{-1} \) for odd parents [32].

Figure 2 shows the calculated (logarithms of) \( \alpha \)-decay half-lives, \( \log_{10} T_{1/2}^{\alpha} \) (s), as a function of the masses of parent nuclei for the whole decay chain of \( ^{293}\text{118} \). Also shown in Fig. 2 are the results of another recent calculation by Royer [33] based on the generalized liquid drop model (GLDM) with the binding energies for \( Q \)-values taken from the Thomas-Fermi (TF) model [34]. The TF model uses the well known Seyler-Blanchard effective nucleon-nucleon interaction where the momentum-dependent and density-dependent terms are also included. The model parameters are fitted again to ground-state masses of 1654 nuclei with \( N,Z \geq 8 \) and the 40 fission-barrier heights.

We notice in Fig. 2 that the calculated numbers for both the models present an interesting result: the \( \alpha \)-decay half-life for \( Z=114, A=285 \) is very high, which means that the parent nucleus \( ^{285}_{171}114 \) is very stable against \( \alpha \)-decay. This stability can be attributed to either the magicity of protons at \( Z=114 \) or of neutrons at \( N \approx 172 \) or to both, perhaps more so to \( Z=114 \) since \( N=172 \) is predicted to be magic only when \( Z=120 \) [8, 9, 10, 11, 12, 14]. The predicted half-lives in the two models differ by about four orders of magnitude, which is partly due to different choices of \( \nu_0 \)-values.

The stability at \( Z=114 \) in the calculations arises due to the \( Q \)-values involved, as is evident from Fig. 3(a) where the calculated \( Q \)-values are plotted as a function of the parent nuclear masses \( ^A_Z \) for both the PCM and GLDM models, as well as that of another calculation by Smolańczuk.
The Q-values are similar for the PCM and GLDM models and are very small (minimum) for the α-decay of $^{285}_{114}$ parent. However, this is contrary to the predictions of Smolańczuk [35], which guided the Berkeley retracted experiment. Smolańczuk [35] predicted the Q-values as an ever increasing function of the parent nucleus charge (or mass), and became an apparent cause for the failure of this experiment [1].

Smaller Q-value should also mean a relative decrease in the penetrability $P$. This is shown to be the case in our calculations presented in Fig. 3(b) where $-\log_{10} P$ vs. $A_{\overline{Z}}$ is plotted. It is further interesting to find that the calculated preformation factor $P_0$ in Fig. 3(c) is also minimum for the α-nucleus preformation in $^{285}_{114}$ parent. The $P_0$ factors in present calculations are shown smaller by a few orders of magnitude ($\sim 10^{-9}$), compared to that for the actinides [36].

So far, the $Z=114$ element ($A=287-289$) is synthesized only in hot fusion reactions made at Dubna, using a $^{48}$Ca beam on $^{242,244}$Pu targets [37, 38, 39], which are found to result in larger production cross sections [4]. The cold synthesis of $Z=114$, in the proposed reaction $^{76}$Ge + $^{208}$Pb [19], is still an open question experimentally where the measured cross section could throw some light on its magic structure, if any. Apparently, the cold identification of $Z=114$ will prove a testing ground for many structure calculations.

Figures 4 and 5 give the results of our calculations for heavy cluster decays of each of the parents in the α-decay chain of $^{293}_{118}$, for a few illustrative clusters. The choice of clusters is based on the minima in the fragmentation potentials $V(\eta)$ and hence for the cases of largest preformation factors $P_0$, illustrated as an example for $Z=118$ in Fig. 6. The heaviest cluster included here in Figs. 4 and 5 is with $Z=20$ ($^{48-50}$Ca) because the earlier calculations on PCM show that the two processes of cold fission and cluster decay are almost indistinguishable for clusters heavier than of mass $A_2 > 48$ [40].

First of all we notice in Fig. 4(a) that the Q-value increases as the size of cluster increases, but is almost independent of the parent mass (the increase with parent mass is smooth, linear and with a very small slope). However, the calculated cluster decay half-lives, $\log_{10} T_{1/2}$, in Fig. 4(b) present some interesting results: (i) The decay half-lives for all the light clusters, other than the $^{14}$C from $Z=112-116$ parents, are rather high and hence the studied parents could be said as stable against most of the light cluster decays. The
shell stabilizing effect, if any, is seen for $^{10}$Be decay of $^{289}\text{116}$ or $^{273}\text{108}$ nucleus, since $T_{1/2}$ show strong peaking at these two parent nuclei. (ii) The $^{14}$C decay, in particular from $^{281}\text{112}$ parent, seems to present an interesting case of (possibly, a reasonably) deformed magic daughter $^{267}\text{106}$ with $N \approx 162$. This means to say that for the known deformed magic shell at $N=162$ [4], the $^{267}\text{Sg}$, not yet synthesized, could also be deformed and observed as $^{14}$C decay of $^{281}\text{112}$ parent. (iii) The heavier clusters $^{48-50}\text{Ca}$ are predicted to decay with further smaller half-lives and hence present themselves as further interesting cases of cluster decay measurements. The calculated half-lives for $^{48-50}\text{Ca}$ decays lie far below the present limits of experiments, which go upto $\sim 10^{28}\text{s}$ [32] for nuclei where enough atoms are available. Here the closed shell effects of cluster (not daughter) are playing the role, for which at present no measurements exist in radioactive cluster decay studies. The heaviest cluster observed so far is $^{32}\text{Si}$ from $^{238}\text{Pu}$ parent.

Figure 5 gives the cluster preformation ($P_0$) and penetration ($P$) probabilities. Knowing that $T_{1/2}$ is a combined effect of both $P_0$ and $P$ ($\nu_0$ being almost constant), we notice in Fig. 5 that though $^{10}$Be is better preformed (larger $P_0$) than both $^{14}$C and Ca nuclei, but its penetration probability $P$ is so small that the $T_{1/2}$ for $^{10}$Be decay is much larger than for either of the two other clusters. Thus, in experiments one should consider the possibility of $^{14}$C and/or $^{48}$Ca decays in addition to $\alpha$-decay or fission of any of the parents in $^{293}\text{118}$ $\alpha$-decay chain.

Summarizing, we have calculated the $\alpha$-decay of $^{293}\text{118}$ and its subsequent parents ending the chain in $^{269}\text{106}$, as well as the heavy cluster decays of all the parents in the $\alpha$-decay chain. Though the experimental data for this $\alpha$-decay chain is retracted, the calculated $\alpha$-decay half-lives are found to contain interesting nuclear structure information. For the Q-values calculated from experimental binding energies, supplemented by the Finite Range Droplet Model (FRDM) or the Thomas-Fermi (TF) Model calculations, the $\alpha$-decay half lives show that there is a magic shell structure at either or both Z=114, N$\approx$172, since the calculated $T_{1/2}$ value for $\alpha$-decay of $^{285}\text{114}$ shows a strong peaking structure. This is supported by a small Q-value and small (deeper minima) penetrability and preformation factors for $\alpha$ in the $^{285}\text{114}$ parent.

The cluster decay calculations for a decaying superheavy nucleus formed in heavy ion reactions is made for the first time, with a view to see if there
is any branching of $\alpha$-decay to another light nucleus due to the (spherical/deformed) magicity of the corresponding heavy daughter nucleus or due to the magicity of the light nucleus itself. Interesting enough, the $^{293}\text{118}$ decay chain offers two such possibilities: firstly, the $^{14}\text{C}$ decay of the inbetween parent $^{281}\text{112}$, and secondly, the doubly magic $^{48}\text{Ca}$ decay of any parent nucleus obtained after the $\alpha$-decay(s) in the investigated chain. The first possibility points out to the deformed magicity of the daughter product $^{267}\text{106}$ at $N=162$ and the second possibility to a first time observation of the doubly magic emitted cluster $^{48}\text{Ca}$. These are exciting new possibilities for future studies.

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**Figure Captions**

Fig. 1: The scattering potential for α-decay of $^{293}\text{118}$, calculated as the sum of Coulomb and nuclear proximity potential. The tunneling path used by the PCM is also shown with the first and second turning point radii marked as $R_a$ and $R_b$, respectively.

Fig. 2: The α-decay half-lives calculated on PCM and compared with GLDM model [33] plotted as a function of the parent nucleus mass for the α-decay chain of $^{293}\text{118}$.

Fig. 3: (a) The Q-values calculated on FRDM [29], compared with TF [34] and Smolańczuk [35] calculations, (b) the penetration probability $P$, and (c) the preformation factor $P_0$ calculated on PCM, plotted as a function the parent nucleus mass for the α-decay chain of $^{293}\text{118}$.

Fig. 4: The calculated Q-values on FRDM [29] and decay half-lives on PCM for some cluster decays of the parents of α-decay chain for $^{293}\text{118}$ plotted as a function of the parent nucleus mass.

Fig. 5: Same as for Fig. 4, but for the penetration probability $P$ and the preformation factor $P_0$.

Fig. 6: (a) The fragmentation potential $V(\eta)$ for $^{293}\text{118}$, using the experimental and FRDM binding energies [28, 29]. Only half of the potential as a function of the cluster mass $A_2$ is shown. The other (symmetrical) half is a function of the daughter mass $A_1$. Some of the minima are marked, showing the cluster mass.
(b) The preformation factor $P_0$, plotted as a function of both the cluster and daughter masses, for the decaying $^{293}\text{118}$ parent.
Fig. 1
$\alpha$-decay chain

$log_{10} T_{1/2}$ (s)

$A_Z$ (Parent nucleus mass)

PCM Calculation

GLDM [32]

$^{293}118$
293

a) $^{293}\text{118} : \alpha$-decay chain

- $Q_{\text{(MeV)}}$

b) $-\log_{10} P$

c) $-\log_{10} P_0$

FRDM [28]
TF model [32,33]
Smolanczuk [34]
a) \(^{293}\text{118 chain : Cluster decay}\)

\[
\begin{align*}
-\log_{10} P_0 \quad &\quad \text{vs. } A_Z (\text{Parent nucleus mass}) \\
&\
\end{align*}
\]

- \( ^{10}\text{Be} \)
- \( ^{49}\text{Ca} \)
- \( ^{48}\text{Ca} \)
- \( ^{47}\text{Ca} \)
- \( ^{34}\text{Si} \)
- \( ^{50}\text{Ca} \)

b) \[
\begin{align*}
-\log_{10} P \quad &\quad \text{vs. } A_Z (\text{Parent nucleus mass}) \\
&\
\end{align*}
\]

- \( ^{10}\text{Be} \)
- \( ^{49}\text{Ca} \)
- \( ^{48}\text{Ca} \)
- \( ^{47}\text{Ca} \)
- \( ^{34}\text{Si} \)
- \( ^{50}\text{Ca} \)
