A=14 ACCOMPANIED TERNARY FISSION OF $^{242}$Pu IN THE COLLINEAR AND EQUATORIAL GEOMETRIES USING PROXIMITY AND YUKAWA POTENTIALS

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Abstract. The cold ternary fission of $^{242}$Pu, accompanied by A=14 isobars is investigated by using the three-cluster model in the equatorial and collinear configurations. According to the height of the potential barriers, the two mentioned structures (equatorial and collinear) are compared for two kinds of nuclear potential, proximity and Yukawa plus exponential potentials. The obtained results reveal that the overall shape of the fragmentation potential barriers and the location of the minima are independent of selecting the nuclear potential. Also it is indicated that between five isobars of A=14, $^{14}$C possesses the lowest potential barrier that verifies the important role of the shell effects in the cold ternary fission. Yields and Q values for each fragmentation in the $^{14}$C accompanied ternary fission of $^{242}$Pu are also estimated in this study.

Key words: ternary fission, three-cluster model, equatorial, collinear, proximity, Yukawa potential.

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1. INTRODUCTION

For many years there has been a great deal of interest in studying and investigating of the ternary fission in heavy and superheavy nuclei [1–9]. The spontaneous cold ternary fission processes have a common feature i.e., the emitted fragments are in their ground or low-lying states and also they are almost neutronless processes. Poenaru et al. [10–17] extended a macroscopic-microscopic method based on the two (three) center shell model to study $\alpha$ decay, cluster radioactivity, and spontaneous fission in the superheavy nuclei. They also studied and calculated half lives of multi cluster fission of various heavy and superheavy nuclei using the three center phenomenological model [18–24]. As well as they obtained the equilibrium (saddle point) shapes in true ternary fission [25–27].

According to Sândulescu [28, 29], cold ternary fission is similar to cluster radioac-
tivity [30, 31], i.e. it is a process of cold re-arrangement of a large group of nucleons from the ground state of the initial nucleus to the ground state of the three final fragments.

Delion et al. [32] provided a quantum description for cold ternary fission of $^{252}$Cf, within a stationary scattering formalism. Sândulescu et al. [33–36] have also used double folding potential plus M3Y nucleon-nucleon forces to study the isotopic yields in the cold ternary fission of $^{248}$Cm, without including the preformation factors. After that, Floreșcu et al. [37] calculated the preformation amplitude for $^4$He and $^{10}$Be clusters formed in the ternary fission of $^{252}$Cf.

The ‘Three-Cluster Model’ (TCM) that was recently proposed by Balasubramaniam and Manimaran [38], is a development of the PCM that was proposed by Gupta et al. [39] many years ago. This approach has been used extensively to study the different aspects of ternary fission for various isotopes of Cf, U, Pu, and Cm [40–46].

In our recent investigation [47], we studied cold ternary fission of the $^{250}$Cm by using three-cluster equatorial geometry model and light charged particles as the fixed third fragment. But in Ref. [48], we also considered a relatively heavy nucleus ($^{34}$Mg) as the fixed third fragment to examine the validity of equatorial geometry in ternary fission of the $^{242}$Pu isotope for heavy third fixed fragments. The results revealed that ternary fission of $^{242}$Pu accompanied by $^{34}$Mg as a heavy third fragment, occur with very low probability in the equatorial configuration.

In the present study we attempt to compare equatorial and collinear configurations in the relatively heavy (A=14) accompanied ternary fission of $^{242}$Pu. We also compare two types of potentials as the nuclear part of the total potential.

In Section 2, we present the theoretical aspects of the model. In section 3, a brief comparison between various decay modes of $^{242}$Pu is presented. The obtained results are discussed in Section 4. Finally, summary of the present study along with the concluding remarks are provided in Section 5.

2. METHODOLOGY

In the cold ternary fission, within the TCM [38], the fragmentation potential is defined by

$$V = \sum_{i=1}^{3} \sum_{j>i}^{3} \left( m^i_x + V_{C_{ij}} + V_{N_{ij}} \right). \quad (1)$$

Here $m^i_x$ are the mass excesses of three fragments in energy units, taken from the latest version of the atomic mass table [49] and $V_{C_{ij}}$ and $V_{N_{ij}}$ are Coulomb and nuclear potentials between each pair of fragments, respectively. The repulsive Coulomb
potential between each pair of fragments, $V_{Cij}$ is given by

$$V_{Cij} = \frac{Z_i Z_j e^2}{C_{ij}},$$

(2)

where $Z_i$ and $Z_j$ are the atomic numbers and $C_{ij}$ is the center-to-center distance between two fragments $i$ and $j$, respectively:

$$C_{ij} = C_i + C_j + s_{ij},$$

(3)

Here, $C_i$ and $C_j$ are the Süssmann central radii of each fragments, and $s_{ij}$ is the distance between near surfaces of the fragments $i$ and $j$. Note that $s = 0$, $s < 0$, and $s > 0$ correspond to 'touching configuration', 'overlap region', and 'separated fragments', respectively. The Süssmann radius is taken from Ref. [50]:

$$C_x = R_x \left[ 1 - \left( \frac{b}{R_x} \right)^2 \right],$$

(4)

where the subscript $x$ indicates the fragments ($i$ and $j = 1, 2$ or 3), and

$$R_x = 1.28 A_x^{1/3} - 0.76 + 0.8 A_x^{-1/3}$$

(5)

is the sharp radius of the fragment 'x' with the mass $A_x$, and $b$ is the nuclear surface diffuseness parameter ($b = 0.68$ fm is considered here). Note that in TCM all fragments are considered as spherical [38].

In this work, two kinds of nuclear potential are considered and each of them will be explained in detail. For the nuclear proximity potential, the latest version labeled as Prox2010 [51] has been used in this study. Thus, $V_{Nij}$ is given by

$$V_{Nij} = V_{Pij}(s) = 4 \pi b \gamma \Phi \left( \frac{s}{b} \right),$$

(6)

The specific nuclear surface tension, $\gamma$ is given by

$$\gamma = 1.25284 \left[ 1 - 2.345 (N - Z)^2 / A^2 \right] \text{ MeV/fm}^2,$$

(7)

where $N$, $Z$, and $A$ are the neutron, proton, and mass numbers of the compound system, respectively.

$\overline{C}$ is the mean curvature radius, which is defined as follows

$$\overline{C} = \frac{C_i C_j}{C_i + C_j}.$$

(8)

Finally, $\Phi(\xi) = \Phi \left( \frac{\xi}{b} \right)$, the universal proximity potential function that depends only on the distance between two interacting fragments is defined by

$$\Phi(\xi) = \left\{ \begin{array}{ll}
-1.7817 + 0.9270\xi + 0.0169\xi^2 - 0.05148\xi^3 & \text{for } 0 \leq \xi \leq 1.9475 \\
-4.41 \exp(-\xi/0.7176) & \text{for } \xi > 1.9475.
\end{array} \right.$$

(9)
Here, $\xi = s/b$ is a function of the distance between nascent fragments.

In the equatorial configuration (Fig. 1(a)), for simplicity as a reliable approximation, it can be considered that the three fission products are separated from each other with the same speed [40, 41, 45]. Therefore, one may consider the same separation distances between each pair of fragments: i.e., $s = s_{12} = s_{13} = s_{23}$.

However, in the collinear configuration with $A_3$ in the middle (Fig. 1(b)), the surface distance between fragments 1-3 and 2-3 is $s = s_{13} = s_{23}$. But for fragments 1-2, this parameter is given by

$$s_{12} = 2(C_3 + s).$$  \hspace{1cm} (10)

The second type of nuclear potential used in this study, is Yukawa plus exponential attractive potential among the three fragments as following

$$V_{Nij} = -4\left(\frac{b}{r_0}\right)^2 \sqrt{a_i a_j} [g_i g_j (4 + \kappa) - g_j f_i - g_i f_j] \times \frac{\exp(-\kappa)}{\kappa},$$  \hspace{1cm} (11)

where

$$\kappa = \frac{C_i + C_j + s_{ij}}{b} = \frac{C_{ij}}{b},$$  \hspace{1cm} (12)

and the functions $g$ and $f$ are defined as

$$g_x = \left(\frac{C_x}{b}\right) \cosh\left(\frac{C_x}{b}\right) - \sinh\left(\frac{C_x}{b}\right),$$  \hspace{1cm} (13)

$$f_x = \left(\frac{C_x}{b}\right)^2 \sinh\left(\frac{C_x}{b}\right).$$  \hspace{1cm} (14)

Here, $r_0 = 1.28$ fm, and $a_k = 21.13(1 - 2.3(I_k)^2)$, where $I_k = (N_k - Z_k)/A_k$ is the asymmetry parameter. The rest of the parameters are exactly the same ones as defined above.

The Q-value of the cold ternary fission is given by

$$Q = M - \sum_{i=1}^{3} m_i,$$  \hspace{1cm} (15)

which should be positive to make the spontaneous reaction possible. $M$ is the mass excess of the decaying nucleus and $m_i$’s are the mass excesses of the product fragments, expressed in the energy units. Also, since the parent and all the fragments are considered in their ground state, Q-value appears as the kinetic energy of the three fragments (by ignoring neutrons and other types of radiations) and can be defined as $Q = E_1 + E_2 + E_3$ with $E_i (i = 1, 2, 3)$.

The relative yield for each fragmentation channel is calculated as following

$$Y(A_i, Z_i) = \frac{P(A_i, Z_i)}{\sum P(A_i, Z_i)},$$  \hspace{1cm} (16)
where $P(A_i, Z_i)$ is the penetrability through the three-body potential barrier for the fragment $i$. The penetrability is obtained by using the one-dimensional W.K.B. approximation [38],

$$
P = \exp \left\{ -\frac{2}{\hbar} \int_{s_1}^{s_2} \sqrt{2\mu(V - Q)} \, ds \right\}. \tag{17}
$$

The first turning point $s_1 = 0$ represents the touching-fragments configuration and the second turning point $s_2$ satisfies the $V(s_2) = Q$ condition.

The reduced mass of the three fragments system is given by

$$
\mu = m \frac{A_1 A_2 A_3}{A_1 A_2 + A_1 A_3 + A_2 A_3}, \tag{18}
$$

where $m$ is the average mass of the nucleon and $A_1$, $A_2$, and $A_3$ are the mass numbers of the three nascent fragments.

3. COMPETING DECAY MODES OF $^{242}\text{Pu}$

The ternary fission of $^{242}$Pu isotope, with $^4\text{He}$ as the light charged particle, in equatorial and collinear configurations has been studied in detail within the unified ternary fission model [52]. For the $\alpha$-accompanied ternary fission of $^{242}\text{Pu}$, the highest yield was found for the fragment combination with doubly magic nuclei $^{132}\text{Sn} + ^4\text{He} + ^{106}\text{Mo}$, $(Z = 50, N = 82; Z = 2, N = 2)$. The deformation and orientation of fragments have also been taken into account, and it has been found that, in addition to the closed-shell effect and excitation energy, ground-state deformation also plays an important role in determining the isotopic yield in the $\alpha$-accompanied ternary fission process. The most common fragment in ternary fission is the $\alpha$-particle, which is almost 90% from the total production of small fragments. This high incidence is connected with great stability of the $\alpha$-particle that provides more reaction energy. In the $\alpha$-accompanied ternary fission of $^{240-244}\text{Pu}$ isotopes, the mean kinetic energy of the $\alpha$-particle is about 15 MeV [53–57], which is much greater than the $\alpha$-decay energy of about 5 MeV. For the $^{242}\text{Pu}$ isotope we estimated the $\alpha$-decay and spontaneous fission half-lives using the empirical and theoretical models [53–62]. Thus, using the notations of [60] we get: $T_{\alpha}^{SM} = 0.344 \times 10^{14}$ s and $T_{\alpha}^{exp} = 0.101 \times 10^{15}$ s for the reaction energy $Q_\alpha = 4.984$ MeV. These estimates are in a good agreement with experimental value of $T_{\alpha}^{exp} = 0.118 \times 10^{14}$ s. For the spontaneous fission half-life we get $T_{SF} = 0.207 \times 10^{18}$ s. We didn’t estimate precisely the half-life for the $\alpha$-accompanied ternary fission of $^{242}\text{Pu}$ ($^{132}\text{Sn} + ^4\text{He} + ^{106}\text{Mo}$) since it depends on many unknown factors like the nuclear deformations and excitation energies. However, a rough estimation can be done assuming that one ternary event corresponds to 1000 fission events (like in the nuclear reactor). Consequently, the half-life for the $\alpha$-ternary fission of $^{242}\text{Pu}$ isotope is at least of $\sim 10^{20}$ s.
4. RESULTS AND DISCUSSIONS

Five isobars of A=14 accompanied ternary fission of $^{242}$Pu are considered in this study, in the equatorial and collinear geometries by using proximity nuclear potential. For each isobar, all of the possible combinations in the mass (charge) asymmetry coordinates are considered. The results are shown in Figs. 2 and 3. Comparison between the height of the potential barriers of $^{14}$Be, $^{14}$B, $^{14}$C, $^{14}$N, and $^{14}$O in each graph reveals that in both equatorial and collinear geometries, the lowest potential barriers belong to the $^{14}$C isobar. Since $^{14}$C is a nucleus with the neutron closed shell (N=8), this fact can be interpreted as the important role of the shell effects in ternary fission.

For $^{14}$C accompanied ternary fission of the $^{242}$Pu isotope, fragmentation potentials for all possible combinations, using Yukawa plus exponential and proximity nuclear potentials are calculated and the results are represented in Fig. 4. It is clear that the overall shape of the potential barriers and the location of the minima are independent from choosing the nuclear part of potential (proximity or Yukawa), but it leads to a shift in height of the potential barrier. In the collinear structure, the lightest fragment is always considered between two heavier fragments (according to the results of Ref. [44]). It is clear from Fig. 4 that in the mass region of $4 \leq A_1 \leq 24$, the compact shape (equatorial) is preferable, and as the first fragment becomes heavier, the collinear formation would have lower potential barrier. This fact can be interpreted by the Coulomb repulsion forces between fragments. Note that it doesn’t mean the separation of all fragments are in the same line, because these graphs are for touching configuration. To specify the exact direction of fragments movement after separation, the trajectory calculation is needed. Almost the same results are obtained for Yukawa potential, with this minor exception that by using Yukawa plus exponential potential, the collinear formation of fragments is always preferable than the compact shape (Fig. 4).

Relative yields and Q values for $^{14}$C accompanied cold ternary fission of $^{242}$Pu are also estimated in this study, and are given in the Tables 1 and 2. For the mass region of $4 \leq A_1 \leq 70$, the relative yields of $^{14}$C accompanied cold ternary fission of $^{242}$Pu are very low (near zero), so one may have to look for that event only in the mass region of heavier than $A_1 = 70$. As can be seen in Figs. 5 and 6, the maximum yield in both equatorial and collinear configurations belongs to the $^{96}$Sr$+^{14}$C$+^{132}$Sn combination, due to the double magic nucleus $^{132}$Sn ($Z=50$ and $N=82$). Also it is seen in the Tables 1 and 2, that the maximum Q-values belong to the mentioned combinations with double magic nucleus $^{132}$Sn. This fact can lead us to use this simple macroscopic model for ternary fission in superheavy nuclei and investigate the nuclear structures and magic numbers in those mass regions.

The variation of potential barrier ($V_C + V_P$) as a function of separation parameter
(s) is represented in Fig 7, for the combination $^{96}\text{Sr}+^{14}\text{C}+^{132}\text{Sn}$ in the equatorial geometry, using proximity potential. According to Refs. [38] and [39], in this decoupled model (TCM), the touching configuration is considered as the first turning point ($s_1 = 0$), and the second turning point would be $s_2$ ($V(s_2) = Q$). Indeed, the potentials of overlap region are not favored in this model. For more information about turning points, the interested readers are referred to our recent publication [47]. Also more details about calculation of penetrability by using the two turning points are presented in Refs. [38], [39], [47], and [48]. Note that shifting the first turning point from touching point ($s_1$), to a point like $s_0$ ($V(s_0) = Q$), will lead to the model of Shi and Swiatecki (Ref. [63]) for penetrability calculations.

5. CONCLUSION

The cold ternary fission of $^{242}\text{Pu}$, accompanied by A=14 isobars as the fixed fragments have been studied by using the three-cluster model. In each case, the equatorial and collinear configurations were compared according to the height of the potential barriers. Since the lowest potential barriers in both structures belong to $^{14}\text{C}$, the obtained results verify the important role of the neutron shell closure (N=8) in ternary fission. Also among all possible combinations of $^{14}\text{C}$ accompanied ternary fission of the $^{242}\text{Pu}$ isotope, the most yield always belongs to $^{96}\text{Sr}+^{14}\text{C}+^{132}\text{Sn}$ combination, another verification of closed shell effect on the ternary fission. It is found that the overall shape of potential barriers and locations of the minima are independent from choosing the type of the nuclear potential. However, the Yukawa potential possess higher potential barrier compared to proximity potential.

In the $^{14}\text{C}$ accompanied ternary fission of $^{242}\text{Pu}$, the collinear formation of three fragments is more favorable than the compact shape, due to the Coulomb repulsion. This fact, will verify the formation of the lightest fragment in the neck region between two heavy fragments. However, for determining the direction of movement after touching point, the trajectory calculation is needed.

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Fig. 1 – Schematic diagrams of (a) equatorial and (b) collinear geometries.

Fig. 2 – Comparison between potential barriers for five isobars of A=14 third fragment in the equatorial touching configuration, using proximity potential.
Fig. 3 – Comparison between potential barriers for five isobars of A=14 third fragment in the collinear touching configuration, using proximity potential.

Fig. 4 – Comparison between equatorial and collinear touching configurations for $^{14}$C accompanied ternary fission of $^{242}$Pu, using proximity and Yukawa potentials.
Fig. 5 – Relative yields for $^{14}$C accompanied ternary fission of $^{242}$Pu in the equatorial geometry, as a function of fragment mass numbers $A_1$ and $A_2$.

Fig. 6 – Relative yields for $^{14}$C accompanied ternary fission of $^{242}$Pu in the collinear geometry, as a function of fragment mass numbers $A_1$ and $A_2$. 
A=14 accompanied ternary fission of $^{242}$Pu in the collinear and equatorial geometries

Fig. 7 – The potential barrier $(V_C + V_P)$ as a function of the surface separation $s(=s_{12} = s_{13} = s_{23})$ of all three fragments for the fragmentation $^{242}$Pu$\rightarrow$ $^{96}$Sr+$^{14}$C+$^{132}$Sn. The decay path, turning points and the Q value are also labeled.
Table 1. Interaction potentials, Q values and yields for the $^{14}$C accompanied ternary fission of $^{242}$Pu in equatorial touching configuration, using proximity potential.

<table>
<thead>
<tr>
<th>$A_1$</th>
<th>$A_2$</th>
<th>V (MeV)</th>
<th>Q (MeV)</th>
<th>Yield (%)</th>
</tr>
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<td>$^{75}$Cu</td>
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<td>173.745</td>
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<td>181.614</td>
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<td>$^{116}$Ru</td>
<td>106.029</td>
<td>191.397</td>
<td>$2.682 \times 10^{-5}$</td>
</tr>
<tr>
<td>$^{113}$Ru</td>
<td>$^{115}$Ru</td>
<td>107.534</td>
<td>189.869</td>
<td>$4.104 \times 10^{-6}$</td>
</tr>
<tr>
<td>$^{114}$Ru</td>
<td>$^{114}$Ru</td>
<td>105.252</td>
<td>192.143</td>
<td>$6.953 \times 10^{-5}$</td>
</tr>
</tbody>
</table>
Table 2. Interaction potentials, Q values and yields for the $^{14}$C accompanied ternary fission of $^{242}$Pu in collinear and equatorial geometries...
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