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# A Study of Binary Fission and Ternary Fission in $^{232\text{-}238}$U

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**Abstract.** We studied the binary fission and ternary fission of uranium isotopes $^{232-238}$U. The total potential for binary and ternary fission of different fission fragments of uranium are calculated using recent proximity potential. The binary and ternary fission half-life of uranium isotopes for the different fission fragment combinations are calculated. The variation of logarithmic half-life of binary and ternary fission as a function of mass number is graphically represented. Branching ratios correspond to ternary and binary fission is also calculated. A detail study of branching ratio of binary fission with respect to ternary fission is also helps us to predict the dominant mode of fission in the uranium. The calculated parameters are compared with the experiments and it agrees well with the calculations.

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## 1 Introduction

Spontaneous fission was discovered by two Russians [1]. Ternary fission was discovered by Chinese scientists in cooperation with French researchers [2]. Cluster decay was predicted in 1980 [3] and was experimentally confirmed in 1984 [4]. Alpha decay was discovered in France by Henri Becquerel [5] and it was identified as $^{4}$He emission by the UK professor Ernest Rutherford [6]. Wahl [7] measured the neutron induced fission of $^{235}$U, $^{238}$U and $^{239}$Pu. Pellereau et al. [8] used SOFIA (Studies On Fission with Aladin) program to study fission yields of $^{238}$U. Khan [9] studied the fission of $^{238}$U induced by the proton and bremsstrahlung photon. Clarke [10] measured neutron multiplicity distribution from photo fission of $^{235}$U by induced high energy gamma rays. Duke et al. [11] studied correlations between fragment mass and kinetic energy in neutron induced fission of $^{238}$U. Tsien et al. [12] experimentally proved the existence of tri-partition and quadri-partition of $^{235}$U. Makarenko et al. [13] studied spontaneous fission half lives of uranium.

 

Muga et al. [14] studied ternary fission of $^{236}$U and $^{234}$U using triple coincidence technique. Todorović and Antanasijević [15] studied cross sections of binary and ternary fission fragments of U and Th. Bonetti et al. [16] measured the spontaneous fission half-life and decay constant of $^{232}$U. Frank Asaro and Perlman [17] studied decay properties of $^{232}$U by using alpha particle spectrograph and counters. Kikunaga et al. [18] studied the half life of $^{229}$Th from the activity ratio of $^{232}$U and $^{233}$U. Nethaway and Mendoza [19] measured the mass yield distributions in fission of $^{234}$U and $^{236}$U. Tischler et al. [20] measured time spectra of fission fragments of $^{236}$U and $^{238}$U. Maslov [21] observed the excitation of two quasi particle states at saddle deformations of fissioning nuclei such as $^{238}$U. McNally et al. [22] measured neutron induced fission cross section of $^{237}$U.

Blocki et al. [23] formalized a theorem for interaction potential between two curved surfaces. Blocki and Switecki [24] improved the nuclear proximity potentials for the surfaces having large curvature. Using various proximity potentials Raj kumar [25] studied effects of iso-spin on nuclear fusion cross sections. Yao et al. [26,27] theoretically studied cluster and alpha decay half-lives of even-even nuclei using fourteen different proximity potentials and compared with that of experimental values. Dutt and Puri [28] using twelve different proximity potentials, studied fusion barrier heights and fusion cross sections for 60 known reactions. Within the preformed cluster decay model, Kumar and Sharma [29] studied cluster radioactivity in $^{208}$Pb using different proximity potentials. Majunatha and Sowmya [30] theoretically studied ternary fission in fermium using different proximity potentials. Previous workers [31–33] studied different decay modes in superheavy element.

Aim of the present work is to predict the dominant fission mode of uranium isotopes $^{232-238}$U. In the present work, we have studied the binary fission and ternary fission of uranium isotopes $^{232-238}$U. The total potential for binary and ternary fission of different fission fragments of uranium are calculated using recent proximity potential. The binary and ternary fission half-life of uranium isotopes for the different fission fragment combinations are calculated. Branching ratios correspond to ternary and binary fission is also calculated. A detail study of branching ratio of binary fission with respect to ternary fission is also helps us to predict the dominant mode of fission in the uranium. The calculated parameters are compared with the experiments and it agrees well with the calculations.

## 2 Theory

The total interacting potential between two nuclei of fission fragments is taken as the sum of the coulomb potential and proximity potential is given as [30]

$$V = V_{\mathrm{N}ij}(R) + V_{\mathrm{C}ij}(R) \tag{1}$$

The Coulomb interaction energy $V_{\mathrm{C}ij}$ describes the force of repulsion between the two interacting charges and we consider the pairwise interaction of the three fragments. The Coulomb energy expression [34] is defined as

$$V_{Cij} = \begin{cases} \dfrac{Z_i Z_j e^2}{R_{ij}} & R_{ij} \geq R_i + R_j, \\ \dfrac{Z_i Z_j e^2}{R_{ij}} \Delta & R_i - R_j \leq R_{ij} \leq R_i + R_j \\ Z_i Z_j e^2 \lambda & R \leq R_{ij} \leq R_i - R_j \end{cases} \tag{2}$$

with [34]

$$\begin{aligned} \Delta &= \left[ 1 - \frac{(R_i + R_j - R_{ij})^4 \Delta_1}{160 R_i^3 R_j^3} \right] \\ \Delta_1 &= R_{ij}^2 + 4R_{ij}(R_i + R_j) + 20 R_i R_j - 5R_i^2 - 5R_j^2 \\ \lambda &= \frac{15R_i^2 - 3R_j^2 - 5R_{ij}^2}{10R_i^3} \end{aligned}$$

where $R_{ij}$ is the centre-to-centre distance between the fragments $i$ and $j$. For the nuclear part of the potential $V_{\mathrm{N}ij}$, we have used the proximity potential $V_{\mathrm{P}ij}$ or the short-range Yukawa plus exponential nuclear attractive potential $V_{\mathrm{P}ij}$ amongst the three fragments.

The proximity potential $V_{\mathrm{P}ij}$ is defined as

$$V_{Pij}(Z) = 4\pi\gamma \bar{R}_{ij} \Phi \left( \frac{z}{b} \right) \tag{3}$$

In the above equation, $\gamma$ is the specific nuclear surface tension and it is given by

$$\begin{aligned} \gamma &= \gamma_0 \left[ 1 - K_S \left( \frac{N - Z}{A} \right)^2 \right] \quad \mathrm{MeV/fm}^2; \\ \gamma_0 &= 1.460734 \ \text{ and } \ K_s = 4.0. \end{aligned} \tag{4}$$

In the above equation (3), $\Phi$ is the universal proximity potential and $z$ is the distance between the near surfaces of the fragments. $b = 0.99$ is the nuclear surface thickness. $\Phi$ in above equation is the universal function, independent of the shapes of nuclei or the geometry of the nuclear system, but depends on the minimum separation distance $\xi = z/b$. In the present work, we have used the following universal function $\varphi(\xi)$

$$\Phi(\varepsilon) = \begin{cases} -4.41 \exp\left( \dfrac{-\varepsilon}{0.7176} \right) & \text{for } 0 \leq \varepsilon \leq 1.9475 \\ -1.7817 + 0.9270\varepsilon + 0.0169\varepsilon^2 - 0.05148\varepsilon^3 & \text{for } 0 \leq \varepsilon \leq 1.9475 \end{cases} \tag{5}$$

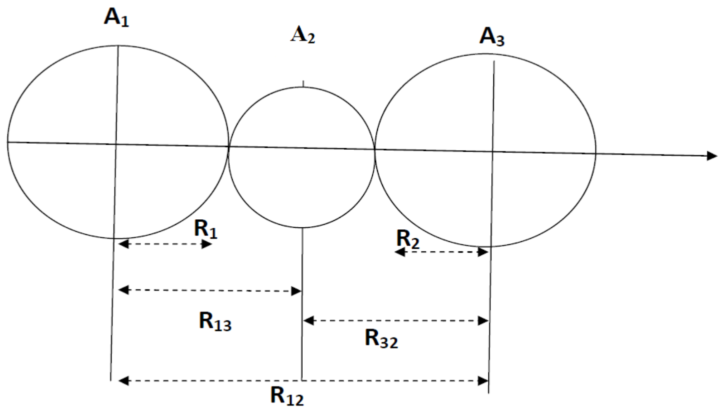


Figure 1. Schematic configurations of three nuclei.

where $\bar{R}$ is the mean radius of curvature. The arrangement of fission fragments considered in the present work is as shown in Figure 1. The distance between the centers of the interacting fragments $R_{ij}$ can be denoted as $R_{32} = R_3 + R_2$, $R_{31} = R_1 + R_3$ and $R_{12} = R_{32} + R_{31}$.

The radius of each fragment is defined as

$$R_i = 1.28 A_1^{1/3} - 0.76 + 0.8 A_2^{-1/3} \tag{6}$$

("$i$" taking the values of 1, 2 and 3 corresponding to fragments $A_1$, $A_2$ and $A_3$).

For process such as binary fission and alpha ternary fission the barrier penetrability $P$ is given as [35]

$$P = \exp\left\{ -\frac{2}{\hbar} \int_a^b \sqrt{2\mu(V-Q)} dz \right\} . \tag{7}$$

Here $\mu = mA_1A_2/A$, where $m$ is the nucleon mass and $A_1$, $A_2$ are the mass numbers of fragments respectively and $A = A_1 + A_2$. For fission process, first turning point is determined from the equation $V(a) = Q$ and second turning point $b = 0$.

For ternary fission, the penetrability calculations of all the three fragments are fixed and the motion with respect to the separation distance of the three fragments. The penetrability is the WKB integral [36],

$$P = \exp\left\{ -\frac{2}{\hbar} \int_{St}^{S2} \sqrt{2\mu(V-Q)} dz \right\} . \tag{8}$$

In the above equations (7) and (8), $V$ is the total interacting potential which is calculated from equation (1) with $St = 0$, the touching configuration, as the first

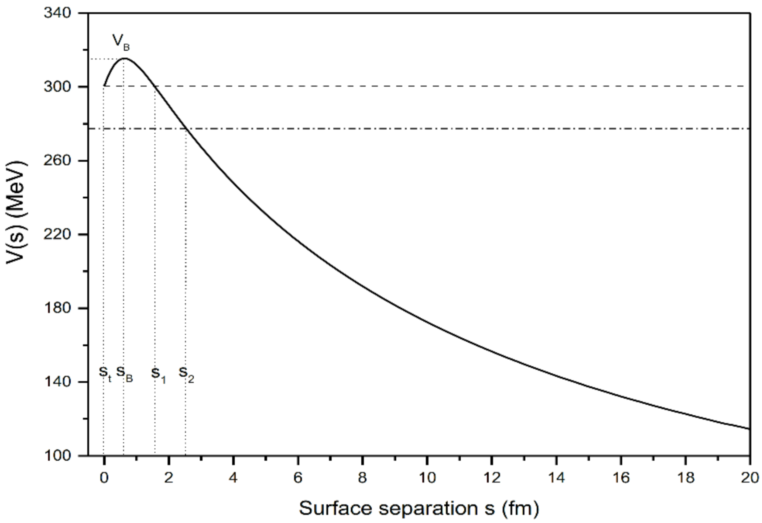


Figure 2. The interaction potential as a function of the surface separation $S$ of all the three spherical fragments.

turning point, $S2$ as the second turning point and $S1$ is an intermediate point (see Figure 2) satisfying $V(S1) = V(St)$ and $V(S2) = Q$.

For ternary fission reduced mass is calculated from following equation [37]:

$$\mu_{123} = \frac{\mu_{12}\,(Z_3 m_p + N_3 m_n)}{\mu_{12} + Z_3 m_p + N_3 m_n} \quad \text{with}$$
$$\mu_{12} = \frac{(Z_1 m_p + N_1 m_n)\,(Z_2 m_p + N_2 m_n)}{Z_1 m_p + N_1 m_n + Z_2 m_p + N_2 m_n} \; .$$

The above integral can be evaluated numerically or analytically, and the half-life time is given by

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{\ln 2}{\upsilon P} \; , \tag{9}$$

where $\upsilon$ is assaults frequency, in case of binary fission and ternary fission is given as [36]

$$\upsilon = \frac{\sqrt{2Q/\mu}}{2(C_1 + C_2)} \; , \tag{10}$$

$$\upsilon = \frac{\sqrt{2Q/\mu}}{2(C_1 + C_2 + C_3)} \; , \tag{11}$$

where $C_1$, $C_2$ and $C_3$ are the Scissmann radii of the fragments.

## 3 Results and Discussion

The energy released ($Q$) during the binary and ternary fission is calculated using the following equation:

$$Q = \Delta M(A, Z) - \sum_{i}^{n} \Delta M(A_i, Z_i) \ , \tag{12}$$

where $\Delta M(A, Z)$ and $\Delta M(A_i,\ Z_i)$ are mass excess of the parent and emitted nuclei, respectively. For ternary fission $n$ varies from 1 to 3 and for binary fission $n$ varies from 1 to 2. In the present work, we have used experimental mass excess data [39]. Some of the experimental mass excess values are not available, for those nuclei we have used theoretical values [40–42]. The variation of driving potential for binary and ternary fission of $^{232-238}$U as a function of mass number of fragment $A_1$ is as of shown in Figures 3 and 4, respectively. The variation of logarithmic half-life of binary and ternary fission of $^{232-238}$U as a function of mass number $A_1$ are as shown in Figures 5 and 6, respectively. The calculated yield for binary and ternary fission for different fragment combination as a function of mass number $A_1$ is as shown in Figures 7 and 8, respectively for different isotopes of $^{232-238}$U. The calculated ternary fission of $^{235}$U→$^{4}$He+$^{138}$Ba+$^{93}$Se is 56.06 and it agrees well with the experimental value [43, 44].

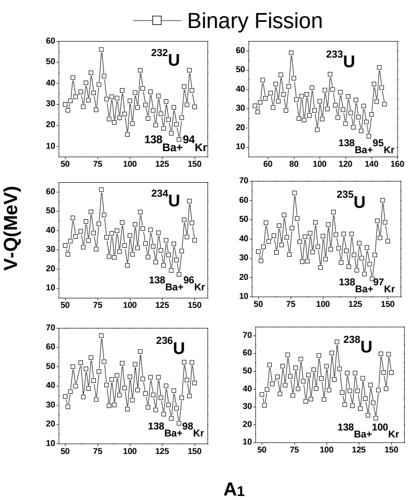


Figure 3. Variation of driving potential for binary fission as a function of mass number $A_1$ for the isotopes of $Z = 92$.

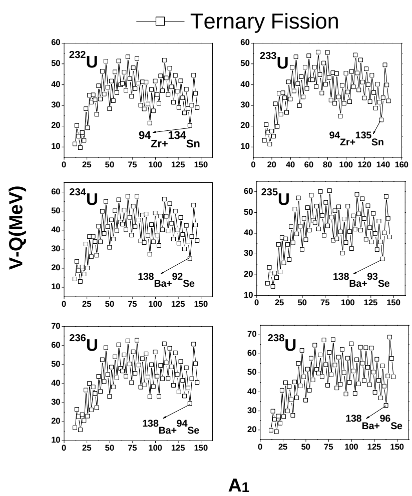


Figure 4. Variation of driving potential for ternary fission as a function of mass number $A_1$ for the isotopes of $Z = 92$.

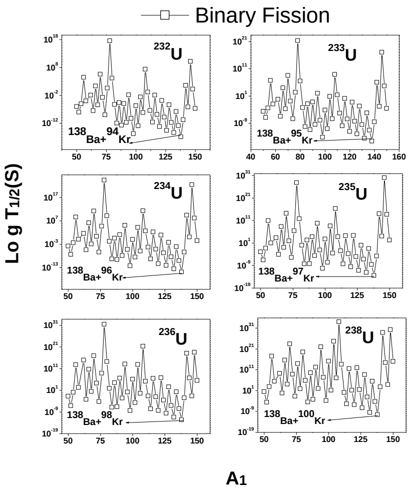


Figure 5. Variation of logarithmic half-life of binary fission as a function of mass number $A_1$ for different isotopes of $Z = 92$.

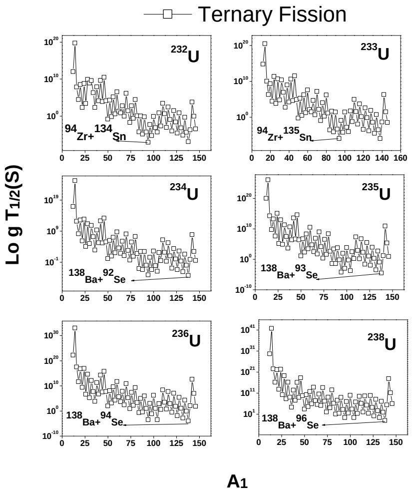


Figure 6. Variation of logarithmic half-life of ternary fission as a function of mass number $A_1$ for different isotopes of $Z = 92$.

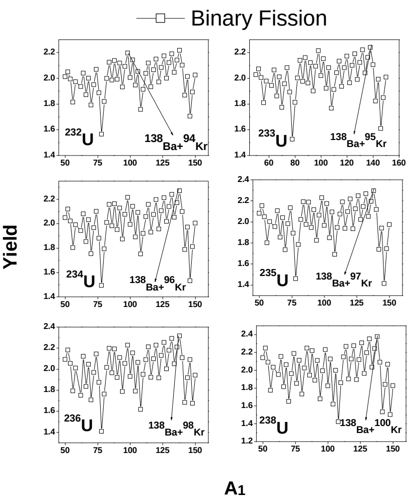


Figure 7. Calculated binary fission yield as a function of mass number $A_1$ for different isotopes of $Z = 92$.

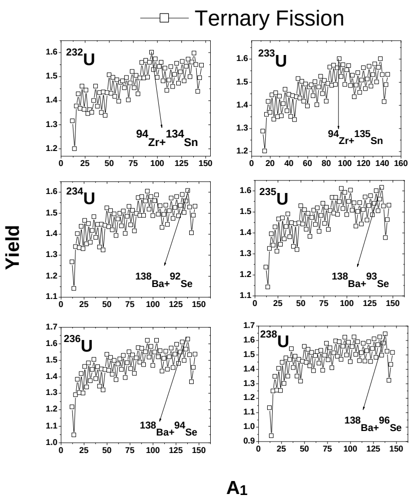


Figure 8. Calculated ternary fission yield as a function of mass number $A_1$ for different isotopes of $Z = 92$.

Table 1. Comparison of calculated binary fission half-life of $^{232-238}$U using different proximity potentials with the experiments

| Parent Nuclei | Fragments | Binary fission half-life | | | |
|---|---|---|---|---|---|
| | | Experiments | Refs. | Prox 2010 | Prox 2002 |
| $^{232}$U | $^{138}$Ba+$^{94}$Kr | $(8. \pm 5.5)$E-13 | [45] | 1.30E-14 | 2.06E-13 |
| | | $>$ 0.8E-13 | [46] | | |
| $^{233}$U | $^{138}$Ba+$^{95}$Kr | $>$ 2.7E-17 | [46] | 2.59E-16 | 9.06E-16 |
| | | $(1.2 \pm 0.3)$E-17 | [47] | | |
| | | $>$ 2.7E-17 | [48] | | |
| $^{234}$U | $^{138}$Ba+$^{96}$Kr | $>$ 0.6E-16 | [46] | 1.05E-15 | 1.64E-14 |
| | | $1.6 \pm 0.7$E-16 | [49] | | |
| | | $(1.42 \pm 0.08)$E-16 | [48] | | |
| | | $1.9 \pm 0.15$E-16 | [50] | | |
| $^{235}$U | $^{138}$Ba+$^{97}$Kr | 1.8E-19 | [46] | 3.33E-17 | 1.71E-15 |
| | | $(0.35 \pm 0.09)$E-18 | [51] | | |
| | | $>$ (1.8)E-18 | [52] | | |
| | | $9.8 \pm 2.8$E-18 | [48] | | |
| $^{236}$U | $^{138}$Ba+$^{98}$Kr | $(2 \pm 1.6)$E-16 | [53] | 2.20E-15 | 6.12E-17 |
| | | $(2.7 \pm 0.3)$E-16 | [54] | | |
| | | $(2.43 \pm 0.13)$E-16 | [48] | | |
| | | $(2.7 \pm 0.4)$E-16 | [55] | | |
| $^{238}$U | $^{138}$Ba+$^{100}$Kr | $(8.38 \pm 0.52)$E-17 | [56] | 2.80E-17 | 6.47E-16 |
| | | $(8.60 \pm 0.29)$E-17 | [46] | | |
| | | $(6.85 \pm 0.20)$E-17 | [57] | | |
| | | $(7.03 \pm 0.11)$E-17 | [58] | | |
| | | $(8.42 \pm 0.10)$E-17 | [59] | | |
| | | $(8.66 \pm 0.22)$E-17 | [60] | | |
| | | $(8.46 \pm 0.06)$E-17 | [61] | | |
| | | $(8.49 \pm 0.76)$E-17 | [62] | | |
| | | $(6.8 \pm 0.6)$E-17 | [63] | | |
| | | $(8.66 \pm 0.43)$E-17 | [64] | | |
| | | $(7.30 \pm 0.16)$E-17 | [65] | | |
| | | $(6.82 \pm 0.55)$E-17 | [66] | | |
| | | $(7.12 \pm 0.32)$E-17 | [67] | | |
| | | $(7.2 \pm 0.2)$E-17 | [68] | | |
| | | $(8.7 \pm 0.6)$E-17 | [69] | | |
| | | $(8.57 \pm 0.42)$E-17 | [70] | | |
| | | $(8.22 \pm 0.20)$E-17 | [71] | | |
| | | $(7.9 \pm 0.4)$E-17 | [72] | | |
| | | $(9.26 \pm 0.17)$E-17 | [73] | | |
| | | $(6.6 \pm 0.2)$E-17 | [74] | | |
| | | $(8.6 \pm 0.4)$E-17 | [75] | | |
| | | $(1.18 \pm 0.7)$E-17 | [76] | | |
| | | $(8.35 \pm 0.40)$E-17 | [77] | | |
| | | $(8.23 \pm 0.43)$E-17 | [78] | | |
| | | $(8.29 \pm 0.27)$E-17 | [79] | | |

We have calculated driving potential, half-life and yield of alpha ternary and binary fission of $^{232-238}$U for different fragment configurations. The analysis of binary fission of $^{232-238}$U reveals that the driving potential and logarithmic half-lives are small and yield is maximum for fragment combinations

$$^{232}\text{U} \rightarrow ^{138}\text{Ba} + ^{94}\text{Kr}, \quad ^{233}\text{U} \rightarrow ^{138}\text{Ba} + ^{95}\text{Kr}, \quad ^{234}\text{U} \rightarrow ^{138}\text{Ba} + ^{96}\text{Kr},$$
$$^{235}\text{U} \rightarrow ^{138}\text{Ba} + ^{97}\text{Kr}, \quad ^{236}\text{U} \rightarrow ^{138}\text{Ba} + ^{98}\text{Kr}, \quad ^{238}\text{U} \rightarrow ^{138}\text{Ba} + ^{100}\text{Kr}.$$

The detail analysis of alpha ternary fission of $^{232-238}$U also reveals that the driving potential and logarithmic half-life are small and yield is maximum for fragment combinations

$$^{232}\text{U} \rightarrow ^{4}\text{He} + ^{94}\text{Zr} + ^{134}\text{Sn}, \quad ^{233}\text{U} \rightarrow ^{4}\text{He} + ^{94}\text{Zr} + ^{135}\text{Sn},$$
$$^{234}\text{U} \rightarrow ^{4}\text{He} + ^{138}\text{Ba} + ^{92}\text{Se}, \quad ^{235}\text{U} \rightarrow ^{4}\text{He} + ^{138}\text{Ba} + ^{93}\text{Se},$$
$$^{236}\text{U} \rightarrow ^{4}\text{He} + ^{138}\text{Ba} + ^{94}\text{Se} \quad ^{238}\text{U} \rightarrow ^{4}\text{He} + ^{138}\text{Ba} + ^{96}\text{Se}.$$

Thus, these reactions are identified as most probable fission reactions for the isotopes of uranium $^{232-238}$U.

To validate the present calculations, we have compared the calculated binary fission half-life with that of experiments and this comparison is as shown in Table 1. To identify the dominant decay mode of most predicted isotopes of heavy nuclei $^{232-238}$U, we have calculated the branching ratios. Branching ratios are calculated using their decay constants. The branching ratio of binary fission with respect to ternary fission is defined as

$$BR = \frac{\lambda_{\text{SF}}}{\lambda_{\text{TF}}} \,, \tag{13}$$

where $\lambda_{\text{SF}}$ and $\lambda_{\text{TF}}$ are decay constants corresponds to binary fission and alpha ternary fission respectively. The decay constants of binary and ternary fission is studied using equation (7) and (8) by substituting in equation (9). The value of assault frequency in binary fission is taken from equation (10) and for ternary fission (11) respectively. The calculated half-life and branching ratio of binary and ternary fission is as shown in Table 2.

Table 2. Comparison of logarithmic half-life and branching ratio of binary fission with respect to the ternary fission for different isotopes of heavy nuclei $Z = 92$

| Isotope | Binary fragments | Ternary fragments | $(lnT_{1/2})_{\text{BF}}$ | $(lnT_{1/2})_{\text{TF}}$ | $\lambda_{\text{BF}}/\lambda_{\text{TF}}$ |
|---|---|---|---|---|---|
| $^{232}$U | $^{138}$Ba+$^{94}$Kr | $^{94}$Zr+$^{134}$Sn | -16.89 | -7.12 | 5.86E+09 |
| $^{233}$U | $^{138}$Ba+$^{95}$Kr | $^{94}$Zr+$^{135}$Sn | -15.59 | -5.98 | 4.01E+09 |
| $^{234}$U | $^{138}$Ba+$^{96}$Kr | $^{138}$Ba+$^{92}$Se | -14.98 | -5.34 | 4.33E+09 |
| $^{235}$U | $^{138}$Ba+$^{97}$Kr | $^{138}$Ba+$^{93}$Se | -13.48 | -4.55 | 8.55E+08 |
| $^{236}$U | $^{138}$Ba+$^{98}$Kr | $^{138}$Ba+$^{94}$Se | -12.66 | -4.00 | 4.60E+08 |
| $^{238}$U | $^{138}$Ba+$^{100}$Kr | $^{138}$Ba+$^{96}$Se | -10.55 | -2.08 | 2.95E+08 |

## 4 Conclusion

We have studied the binary and ternary fission of uranium $^{232-238}$U. The comparison of half-life for binary and ternary fission reveals that binary fission is having smaller half-life than the ternary fission. It is observed that the branching ratio of binary fission with respect to ternary fission is having larger value. It concludes that the binary fission is dominant than the ternary fission for $^{232-238}$U.

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