Emission probability and kinetic energy of long range alpha particles from even-even $^{238\text{-}244}$Pu isotopes

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Introduction

The ternary fission with α particle emission was observed for the first time by Alvarez *et al.* (see Ref. [1]) in ^{236}U isotope. Most common ternary fission process occurs with the emission of long range alpha particle, in which α particle is emitted in a direction perpendicular to the main fission fragments. The long range emission of α particle is possible only if α cluster is formed inside the fissioning nucleus and should gain enough energy to overcome the Coulomb barrier of the scission nucleus.

Emission probability of long range alpha particle

The emission probability of long range alpha particle *LRA* is determined with the number of fission events *B*, and the usual notation for the emission probability is *LRA/B*. The absolute emission probability is given by,

$$\frac{LRA}{B} = S_\alpha P_{LRA} \tag{1}$$

where S_α is the spectroscopic factor or α cluster preformation factor, which can be calculated in a semi-empirical way proposed by Blendowske *et al.* [2] as, $S_\alpha = b\lambda_e / \lambda_{WKB}$. Here b is the branching ratio for the ground state to ground state transition, λ_e is the experimental α decay constant and λ_{WKB} is the α decay constant calculated from the WKB approximation.

The probability of the alpha particle P_{LRA} when it is already present in fissioning nucleus is given as,

$$\mathrm{P}_{LRA} = \exp\left\{-\frac{2}{\hbar}\int_{z_0}^{z_1}\sqrt{2\mu(V-Q)}dz\right\} \tag{2}$$

where Q is the decay energy, μ is the reduced mass of three fragments. Here the first turning point is determined from the equation $V(z_0)=Q$ and the second turning point $z_1 = 0$ represents the touching configuration. For the internal (overlap) region, the potential V is taken as a simple power law interpolation.

The calculated emission probabilities of long range alpha particle in the case of ^{238}Pu, ^{240}Pu, ^{242}Pu and ^{244}Pu isotopes are listed in table1 and are found to be in good agreement with the experimental data [3].

Table 1. The calculated emission probability and spectroscopic factor of alpha particle in the ternary fission of different plutonium isotopes are listed.

Isotope	S_α	$\frac{LRA}{B}$ $[10^{-3}]$	$\left(\frac{LRA}{B}\right)_{EXP.}$ $[10^{-3}]$
^{238}Pu	0.0317	3.42	2.76 ± 0.13
^{240}Pu	0.0421	4.49	2.51 ± 0.14
^{242}Pu	0.0426	5.69	2.17 ± 0.07
^{244}Pu	0.0378	5.70	1.17 ± 0.09

Kinetic energies of long range alpha particle

The kinetic energy of long range alpha particle emitted in the ternary fission of $^{238\text{-}244}$Pu isotopes is computed using the formalism reported by Fraenkel [4]. Considering the conservation of the total momentum in the direction of light particle and in a direction perpendicular to light particle, the kinetic energy of the long range alpha particle E_α is given as,

$$E_\alpha = E_L\left(\frac{m_L}{m_\alpha}\right)\left(\sin\theta_L \cot\theta_R - \cos\theta_L\right)^{-2} \tag{3}$$

where E_L represents the kinetic energy of light fragment, m_L and m_α are the masses of the light and the α particle respectively. Here θ_L is the angle between the alpha particle and the light particle and θ_R is the recoil angle.

The kinetic energy of light fragment E_L is related to the total kinetic energies of fission fragments TKE as,

$$E_L = \frac{A_H}{A_L + A_H} TKE \qquad (4)$$

Table 2. The calculated kinetic energy of alpha particle in the ternary fission of $^{238\text{-}244}$Pu isotopes and the corresponding experimental data [3] are listed.

Fragmentation channel	E_α (MeV)	
	Calc.	Expt.
$^{238}Pu \rightarrow ^{100}Zr + ^{4}He + ^{134}Te$	14.76	15.91 ± 0.22
$^{238}Pu \rightarrow ^{102}Mo + ^{4}He + ^{132}Sn$	14.88	
$^{238}Pu \rightarrow ^{104}Mo + ^{4}He + ^{130}Sn$	14.98	
$^{238}Pu \rightarrow ^{106}Mo + ^{4}He + ^{128}Sn$	15.08	
$^{240}Pu \rightarrow ^{102}Zr + ^{4}He + ^{134}Te$	14.91	16.55 ± 0.27
$^{240}Pu \rightarrow ^{104}Mo + ^{4}He + ^{132}Sn$	15.02	
$^{240}Pu \rightarrow ^{106}Mo + ^{4}He + ^{130}Sn$	15.12	
$^{240}Pu \rightarrow ^{108}Mo + ^{4}He + ^{128}Sn$	15.20	
$^{242}Pu \rightarrow ^{104}Zr + ^{4}He + ^{134}Te$	15.06	15.79 ± 0.21
$^{242}Pu \rightarrow ^{106}Mo + ^{4}He + ^{132}Sn$	15.16	
$^{242}Pu \rightarrow ^{108}Mo + ^{4}He + ^{130}Sn$	15.25	
$^{242}Pu \rightarrow ^{110}Mo + ^{4}He + ^{128}Sn$	15.33	
$^{244}Pu \rightarrow ^{106}Zr + ^{4}He + ^{134}Te$	15.21	16.04 ± 0.25
$^{244}Pu \rightarrow ^{108}Mo + ^{4}He + ^{132}Sn$	15.30	
$^{244}Pu \rightarrow ^{110}Mo + ^{4}He + ^{130}Sn$	15.38	
$^{244}Pu \rightarrow ^{112}Ru + ^{4}He + ^{128}Cd$	15.45	

Here A_L and A_H are the mass numbers of light and heavy fragments respectively. The total kinetic energies of fission fragments TKE can be computed using the expression taken from Herbach et al. [5] given as,

$$TKE = \frac{0.2904(Z_L + Z_H)^2}{A_L^{1/3} + A_H^{1/3} - (A_L + A_H)^{1/3}} \frac{A_L A_H}{(A_L + A_H)^2} \qquad (5)$$

where Z_L and Z_H are the atomic numbers of light and heavy fragments respectively.

The computed TKE values are found to be around 170MeV and according to Fraenkel [4], for the mean total energies of fission fragments ($\approx 168 MeV$), the maximum value of the recoil angle θ_R=4.5^0, and this maximum value is obtained for θ_L=92.25^0. For this reason, in the present manuscript we have taken θ_R = 4.5^0 and θ_L = 92.25^0.

The kinetic energy of the long range alpha particle emitted in the ternary fission of $^{238\text{-}244}$Pu isotopes are calculated and listed in table 2. It is to be noted that, our calculated values are found to be in good agreement with the experimental data [3].

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