Binary Fission fragmentation of $^{466,476}_{184}X$

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Abstract Based on the statistical theory of fission, we discuss here the binary fission fragmentation of these giant nuclear systems formed in low energy $U + U$ collisions. Here, the mass and charge distribution of fragments from the binary fission of these systems are studied at $T = 1$ and $2\ MeV$. From our results at $T = 1\ MeV$, fragments in the near-asymmetric and near-symmetric regions pronounce higher yield values. However, at $T = 2\ MeV$, our results are grossly different. Furthermore, the binary fragmentation with the largest yield consists of at least one closed shell nucleus. Different possible binary fission modes are presented to look for $U + U$ giant nuclear systems.

1. INTRODUCTION

The mass and charge distribution of fission fragments are the two important aspects in the fission studies. Since the breakup of a nucleus into two *viz*., binary fission, several models account for the mass distribution which are either dynamical or statistical in nature [1, 2, 3]. Fong [1] has proposed a statistical theory to study the asymmetric mass division of the fission fragments. According to this theory, the relative fission probability is considered to be the product of density of quantum states of the fissioning nuclei at scission stage. This theory agreed very well with the experimental values for the fission of ^{236}U but it failed in some other cases. Hasse [2] has proposed a dynamic model for the studies of nuclear asymmetric fission in ^{236}U. Using the two

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center shell model and Strutinsky's shell correction, Maruhn and Greiner [3] have developed a microscopic theory and calculated the mass distribution of the fission fragments of ^{226}Ra, ^{236}U, and ^{258}Fm nuclei giving rise to a triple-humped, asymmetric and symmetric fission mass distribution respectively. With the introduction of certain modifications and refinements in the statistical theory, Rajasekaran and Devanathan [4] studied the binary fission mass distribution of ^{236}U, ^{226}Ra and ^{258}Fm and obtained a qualitative agreement with the experimental data.

Based on the liquid drop model, the dynamic behavior of binary and ternary fission of $^{238}U + {}^{238}U$ is investigated [5]. Within the relativistic mean field formalism Gupta et al. [6] studied the matter density distributions for $^{466,476}_{184}X$ giant system and obtained a kind of triple fission with the cluster appearing in the neck region of two equal fragments. Using the time-dependent Hartee-Fock theory, Golabek and Simenel studied [7, 8] the collision dynamics of $^{238}U + {}^{238}U$ at $E_{c.m.} = 900~MeV$ for three different orientations and observed the emission of ^{16}C like light third fragment from the neck of two symmetric heavy fragments. They reported that the formation of light third fragment due to the presence of excess density in the neck region. Further, they concluded that the study of this giant nuclear system would sign for nuclear ternary fission. Experimentally using the VAMOS spectrometer (GANIL), deep inelastic reactions in $^{238}U + {}^{238}U$ collisions at 6.09, 6.49, 6.91, 7.1 and 7.35 X A MeV are investigated [9].

Zagrebaev et al. [10] studied the ternary fission of $^{466,476}_{184}X$ formed in $^{233,238}U + {}^{233,238}U$ low energy collisions. Their study revealed that the potential energy has a deep minimum for $Pb + Ca + Pb$ and $Hg + Cr + Hc$ like ternary configurations besides the two-body $Pb + No$ configuration. It is worth to be mentioned, we already studied [11] the ternary fission of $^{466,476}_{184}X$ for different heavy third fragments and the results qualitatively agreed with the results of Zagrebaev et al.[10]. However, we focus here to study the possible binary fission fragmentation of $^{466,476}_{184}X$ giant nuclear systems.

The aim of the present work is to study the mass and charge distribution of fragments from the binary fission of giant nuclear systems within the scope of statistical theory. The paper is organized as follows. A brief description about the formalism is presented in Sec. 2 and the results are discussed in Sec. 3. The summary of the results follow in Sec. 4.

2. FORMALISM

Within the statistical theory of fission, Devanathan and Rajasekaran [4] studied the binary fission mass distribution of ^{236}U, ^{240}Ra and ^{258}Fm. For the

calculation of mass distribution, they have used the Nilsson's model single particle energies. The probable fragment combinations were generated from the charge to mass ratio of the parent and fission fragments, which satisfies the following condition,

$$\frac{Z_p}{A_p} \approx \frac{Z_i}{A_i} \tag{1}$$

where Z_p, A_P and Z_i, Z_i (i = 1 and 2) are charge and mass numbers of parent and two fission fragments respectively. We have also used the same formalism of Devanathan and Rajasekaran, but with the use of finite range droplet model (FRDM)[12] single particle level energies.

2.1 Statistical Theory

In the statistical theory of Fong [1], the fission probability at the scission stage is considered to be proportional to the product of nuclear level densities of the fission fragments as,

$$P(A_j, Z_j) \propto \prod_{i=1}^{2} \rho(A_i, Z_i) \tag{2}$$

Here, A_j and Z_j refer to a binary fragmentation involving two fragments with mass and charge numbers as A_1, A_2 and Z_1, Z_2 and ρ corresponds to nuclear level density.

The nuclear level density [13] is,

$$\rho(E) = \frac{1}{12} (\pi^2 / a)^{1/4} E^{-5/4} \exp\left(2\sqrt{aE}\right) \tag{3}$$

In Eq. 3, the level density parameter 'a' and the excitation energy 'E' are given as,

$$a = E / T^2 \tag{4}$$

$$E = E_{tot} - E_0 \tag{5}$$

Here the ground state energy E_0 and total energy E_{tot} are given as,

$$E_0 = \sum_{k=1}^{Z} \varepsilon_k^Z + \sum_{k=1}^{N} \varepsilon_k^N \quad , \tag{6}$$

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$$E_{tot} = \sum_{k=1}^{Z} n_k^Z \varepsilon_k^Z \quad + \quad \sum_{k=1}^{N} n_k^N \varepsilon_k^N \quad , \tag{7}$$

where n_k^Z and n_k^N are the occupation probabilities of Z protons and N neutrons of a particular fragment and the summation is for all the single particle energies considered. The energy Eqs. 6 and 7 are based on statistical considerations. The particle number conservation equations are given as,

$$Z = \sum_k n_k^Z \quad ; \quad N = \sum_k n_k^N \quad . \tag{8}$$

The particle occupation probabilities,

$$n_k^X = \left[1 + \exp\left(-\alpha^X + \beta \varepsilon_k^X \right) \right]^{-1} ; X = Z \ or \ N \tag{9}$$

are numerically solved to determine the Lagrangian multipliers α^Z and α^N at a given temperature, $T = 1/\beta$. The single particle energies of protons ε_k^Z and neutrons ε_k^N necessary for our calculations are retrieved from the Reference Input Parameter Library (RIPL- 3) database [14].These single particle energies are calculated using the finite range droplet model (FRDM)[12] which takes into account the ground state deformations as well. The deformation of the fragments are entering in the calculations only through the single particle energies.

The relative fission yield, the ratio between the probability of the given binary fragmentation and the sum of the probabilities of all the possible binary fragmentation, is given as,

$$Y(A_j, Z_j) \quad = \quad \frac{P(A_j, Z_j)}{\sum P(A_j, Z_j)} \tag{10}$$

3. RESULTS AND DISCUSSION

In the present work, we have studied the binary fission mass and charge distribution of $^{466,476}_{184}X$ giant nuclear systems with the use of the statistical theory of fission. using Eq. 1, the binary fragment combinations of $^{466,476}_{184}X$ are generated. However, due to the nonavailability of single-particle level energies below A = 16 and above A = 299, our results cover all possible combinations with A_1 and $A_2 \geq 16$ and A_1 and $A_2 \leq 299$. For these

combinations, as stated earlier, the single particle energies are retrieved from the RIPL-3 database [14]. By employing the statistical theory of fission, we have calculated the excitation energy, level density parameter and total nuclear level densities using Eqs. 5, 4, and 3 respectively. Further, by employing Eq. 2, we have calculated the probability of fission and using Eq. 10 we have calculated the relative yield values. The binary fission relative yield values of $^{466,476}_{184}X$ are presented in Figs. 1 and 2.

In Fig. 1, the calculated yields from the binary fission of $^{466}_{184}X$ (panel a) and $^{476}_{184}X$ (panel b) are plotted as a function of fragment mass numbers A_1 and A_2. Here, the solid lines and dashed lines correspond to $T = 1$ and $2MeV$. In the binary fission mass distribution of $^{466}_{184}X$ at $T = 1MeV$, the prominent peaks are noted around the near-asymmetric (Ir + Bh, Yb + Fl and Er + Lv) region. In addition, peaks are also seen in the symmetric ($U + U$) and near-symmetric (Ra + Cm) regions as well.
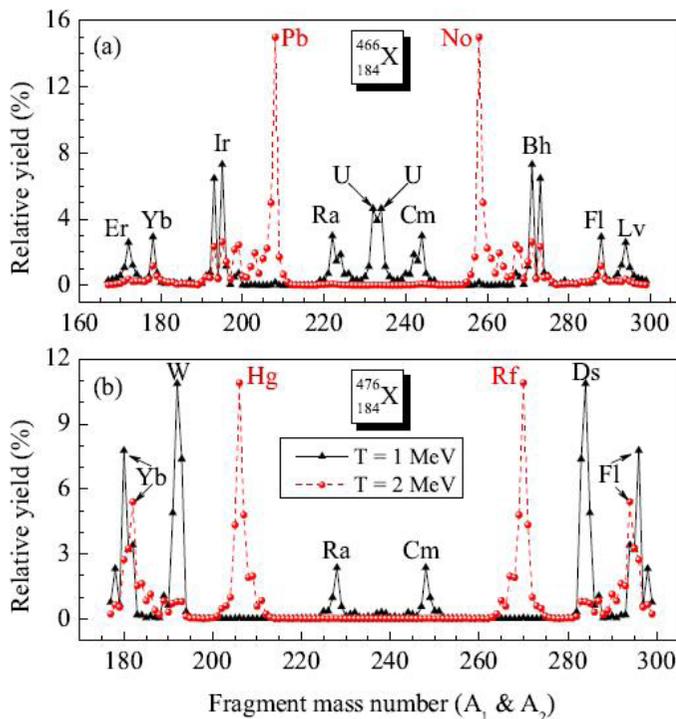
Figure 1: Binary fission mass distribution of $^{466}_{184}X$ (panel a) and $^{476}_{184}X$ (panel b) are plotted as a function of accompanying fission fragments A_1 and A_2. Here the solid lines and dashed lines correspond to $T = 1$ and $2\ MeV$.

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Mass distribution of $^{466}_{184}X$ at $T = 1MeV$, the prominent peaks are noted around the near-asymmetric (Ir + Bh, Yb + Fl and Er + Lv) region. In addition, peaks are also seen in the symmetric ($U + U$) and near-symmetric (Ra + Cm) regions as well. These peaks are due to large deformation values of the fragments. Strikingly, this scenario completely gets changed when the temperature is increased to 2 MeV due to the increase in excitation energies of the fission fragments. At $T = 2MeV$, the enhanced yield values are noted for the Pb + No fragmentation. This may be due to the fact of rapid increase in level density values for the doubly closed shell nucleus Pb (Z = 82 and N = 126) and its associated partners. It is worth to be mentioned here, the largest yield for the Pb + No fragmentation agreed well with the results of Zagrebaev et al [10]. For $^{476}_{184}X$ at $T = 1MeV$, peaks are also noted around near-asymmetric (W + Ds and Yb + Fl) and near-symmetric (Ra + Cm) regions as well. However, the symmetric fragmentation ($U + U$) gets suppressed. At $T = 2MeV$, the enhanced yield values are noted for Hg(Z = 80 and N = 126) + Rf and Yb + Fl fragmentations.
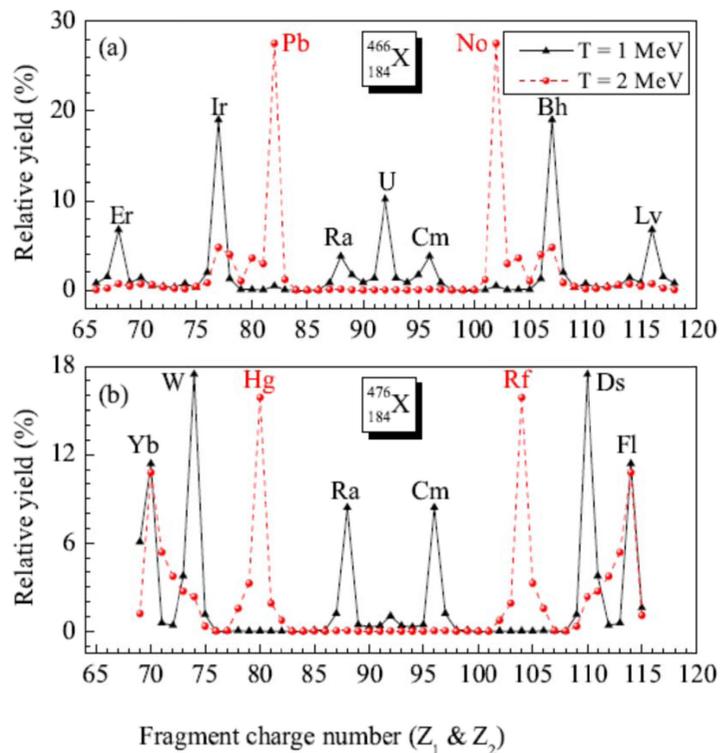
Figure 2: Same as fig. 1, but for fragments charge distribution.

In fig. 2 the calculated yield values from the binary fission of $^{466}_{184}X$ (panel a) and $^{476}_{184}X$ (panel b) is also presented as a function of fragment charge numbers Z_1 and Z_2 at $T = 1MeV$ (solid lines) and $2MeV$ (dashed lines), in Fig. 2. As discussed in the mass distribution, similar kind of results are also obtained for the charge distribution.

4. SUMMARY

Within the framework of statistical theory of fission, we have studied the binary fission fragmentation of $^{466,476}_{184}X$ giant nuclear systems at $T = 1MeV$ and $2\ MeV$. The peaks obtained for both systems at $T = MeV$ are due to large deformation values of the fragments A_1 and A_2. However, our calculated mass and charge distribution results at $T = 2MeV$ is grossly different. In other words, the binary fragmentation with the largest yield consists of at least one closed shell nucleus. This may be due to the rapid increase of excitation energy, level density parameter and hence the corresponding level density values for the closed shell nucleus. The qualitative results from our study indicate that the binary fragmentation favors the closed shell (either in proton or neutron) nucleus as one of its partners. The favorable binary fragmentations are presented to look for $U + U$ giant nuclear systems.

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