CHITKARA

Journal of Nuclear Physics, Material Sciences, Radiation and Applications

Journal homepage: https://jnp.chitkara.edu.in/

Heavy Particle Accompanied Fission of ^{284}Og - A Statistical Model Study

S. Subramanian[1*] and S. Selvaraj[2]

[1]*Department of Physics, V. O. Chidambaram College, Thoothukudi, Tamil Nadu-628008, India*

[2]*Department of Physics, The Madurai Diraviyam Thayumanavar Hindu College, Tirunelveli, Tamil Nadu-627010, India*

*ssmanian73@gmail.com (Corresponding Author)

ARTICLE INFORMATION

Received: February 11, 2021
Accepted: May 25, 2021
Published Online: August 31, 2021

Keywords:
Superheavy nuclei, Ternary fission, Statistical theory, Level density, Single particle energy, Relative yield

DOI: 10.15415/jnp.2021.91003

ABSTRACT

The structural characteristics of SHN can be investigated through the decay of SHN. In the present work ternary fission of SHN ^{284}Og for two proton magic fixed third fragment ^{48}Ca and ^{68}Ni is studied at three different excitation energies 20, 35 and 50 MeV. Interestingly, ^{169}Yb + ^{67}Ni + ^{48}Ca is having larger yield values and hence it is the most favoured way of fragmentation at intermediate excitation energy 35 MeV. It is observed that, asymmetric fission is favoured over symmetric fission at all the excitation for the third fragment ^{48}Ca. Asymmetric fission is the most favoured with the fragment combination ^{148}Sm + ^{68}Ni + ^{68}Ni for fixed A_3 = ^{68}Ni at all the excitations. Unlike the Ca third fragment, near symmetric fission is also favoured with ^{113}Ag + ^{103}Tc + ^{68}Ni for A_3 = ^{68}Ni at all the three excitation energies.

1. Introduction

The systematic study on superheavy nuclei (SHN) has become one of the frontiers of modern nuclear science. Several experimental investigations have been carried out to explore the 'island of stability' of SHN; Particularly to study more neutron-rich isotopes closer to the region of spherical SHN during the last few decades [1–3]. The stability of the superheavy elements are enhanced due to the microscopic shell effects since the liquid drop barrier already vanishes. Generally, the superheavy elements are synthesised using two reaction mechanisms viz., cold fusion and hot fusion. The elements from Bohrium (Z=107) to Coppernicium (Z=112) were synthesised by cold fusion reactions with the closed shell lead and bismuth targets [4, 5]. In the hot fusion reactions, neutron-rich ^{48}Ca is used as projectile with the actinide targets to synthesis the elements from Nihonium (Z=113) to Oganesson (Z=118) [8–10]. The rapid fall in fusion cross-sections and half life with increasing charge, make the production and detection of SHN a difficult task. The search for heaviest of transuranic elements called the superheavy elements ($104 \geq Z \geq 120$) is one of the thrust area of nuclear dynamics. The decay of SHN is also a fascinating field in nuclear physics. The rare process of tripartition of a nucleus is termed as ternary fission. Og was first synthesised in hot fusion reaction Cf + Ca reaction during 2002 in JINR, Dubna and it was named in 2016 to honour Yuri. Ts. Oganessian for his pioneeering contributions in SHN research.

In the recent past, ternary fission of giant nuclear system $^{466}_{184}$X were studied at two arbitrary temperatures T = 1 and 2 MeV using level density approach [11]. Recently, the ternary fission of proton closed shell SHN with Z = 114, 120 and 126 for the fixed fragments ^{52}Ca and ^{72}Ni were investigated at two different excitation energies E = 20, 50 MeV [12]. In the present work, ternary mass distribution of SHN ^{284}Og with ^{48}Ca and ^{68}Ni as third fragments at three different excitations E = 20, 35 and 50 MeV have been studied within the scope of level density approach.

2. Methodology

Fong studied the probability P of a fission mode as function of density of the quantum states available for the fissioning nucleus at the scission point using statistical theory of nuclear fission[13]. This probability is defined as the product of nuclear level densities as,

$$P\left(A_j, Z_j\right) \propto \prod_{i=1}^{3} \rho\left(A_i, Z_i\right). \qquad (1)$$

ISSN No.: 2321-8649(Print) ISSN No.: 2321-9289(Online); Registration No. : CHAENG/2013/51628

Here A_j and Z_j refer to a ternary fragmentation involving three fragments with mass and charge numbers as A_1, A_2, A_3 and Z_1, Z_2, Z_3 and ρ corresponds to nuclear level density. The fragment combinations are generated by the usual assumption of charge to mass ratio of the fission fragments to be same as that of parent nucleus, [14]

$$\frac{Z_p}{A_p} \approx \frac{Z_i}{A_i}, \tag{2}$$

where Z_p, A_p and Z_i, A_i (i = 1, 2, 3) are charge and mass numbers of parent and three fission fragments respectively. Repetition in fragment combinations are avoided by imposing the condition that always $A_1 \geq A_2 \geq A_3$.

In this study, the considered level densities are for separated fragments. However a rigorous study would involve the dynamical evolution of the fragments as done in Refs. [15, 16] which would account for the overlapping of the fragments as well. It is to be mentioned here that, if the state density of a system is to be divided into three distinct parts, then energy of each part can be added to give the total energy of the system. Further, if the state space is assumed to be continuous, then the state densities can be calculated in a folding procedure as shown in Eqns. 1.3.3 and 1.3.5 of the Ref. [17]. Such approach is not considered here.

According to Bethe [18], the nuclear level density can be defined as [18]

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

Balasubramaniam et al., [19] used this form nuclear level density for the ternary ssion of ^{252}Cf and their results are in good agreement with experimental data. [20-22]. In our earlier work [11] using this formula, we obtained largest yield values corresponding to ^{208}Pb + ^{208}Pb + ^{50}Ca combination which qualitatively agrees well with the results of Zagrebaev et al., in the decay of $^{466}_{184}$X at T = 2 MeV. The level density parameter a and the excitation energy E defined in Eqn. 3 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,

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

$$E_{tot} = \sum_k n_k^Z \epsilon_k^Z + \sum_k n_k^N \epsilon_k^N, \tag{7}$$

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 Eqns. 6 and 7 are based on statistical considerations. The particle number equations,

$$Z = \sum_k n_k^Z = \left[1 + \exp\left(-\alpha^Z + \beta \epsilon_k^Z\right)\right]^{-1}, \tag{8}$$

$$N = \sum_k n_k^N = \left[1 + \exp\left(-\alpha^N + \beta \epsilon_k^N\right)\right]^{-1}, \tag{9}$$

are numerically solved to determine the Lagrangian multipliers α^Z and α^N at a given temperature, T = 1/β. The necessary single particle energies of protons ϵ_k^Z and neutrons ϵ_k^N, for our calculations, are retrieved from Reference Input Parameter Library (RIPL- 3) database [23]. These single particle energies are calculated using the finite range droplet model (FRDM) of Möller et al. [24] which takes into account the ground state deformations as well.

The ternary fission yield, the ratio between the probability of a given ternary fragmentation and the sum of the probabilities of all the possible ternary fragmentation for a fixed third fragment, is given by,

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

3. Results and Discussion

With the use of Eqn. 2, the ternary fragment combinations of ^{284}Og are generated. For these combinations, the single particle energies are retrieved from the RIPL-3 database. By employing the statistical theory of fission, the excitation energy, level density parameter and total nuclear level densities are calculated using Eqns. 5, 4, and 3 respectively. Further, by employing Eqn. 2, we have calculated the probability of fission and with the use of Eqn. 10 we have calculated the relative yield values. The ternary fission of ^{284}Og with ^{48}Ca and ^{68}Ni as third fragments at three different excitation energies 20, 35 and 50 MeV were studied within the scope of statistical theory.

Ternary fission relative yield of ^{284}Og for the fixed third fragment ^{48}Ca is presented in Fig. 1. It is interesting to note that, for fixed A_3 = ^{48}Ca, ^{169}Yb + ^{67}Ni + ^{48}Ca is the most favoured fragmentation at higher excitations E = 35 and 50 MeV where as ^{168}Yb + ^{68}Ni + ^{48}Ca are the more favoured fragment combinations at the lower excitation energy E = 20 MeV. It is known that Ni is a proton magic nucleus. However the fragment combination ^{156}Tb + ^{80}As + ^{48}Ca are also preferred at all the three excitations. The other probabilities include ^{180}Rh + ^{56}V + ^{48}Ca and

ISSN No.: 2321-8649(Print) ISSN No.: 2321-9289(Online); Registration No. : CHAENG/2013/51628

^{148}Pm + ^{88}Rb + ^{48}Ca for which ternary yield is found to decrease with increase in excitation. The value of relative yield almost remains the same at all the three excitations for other fragment combinations.

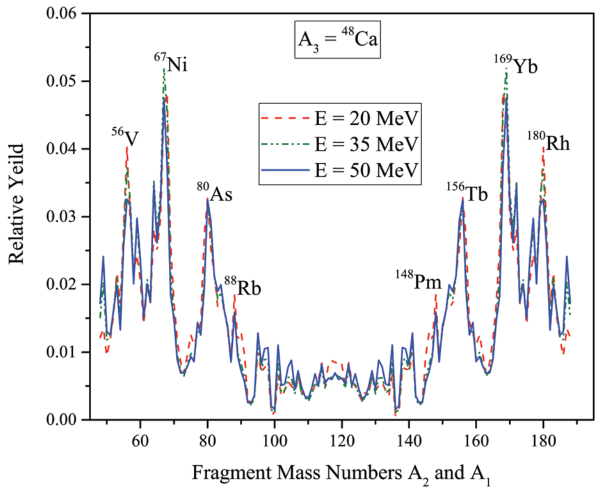

Figure 1: Ternary fission of ^{284}Og with ^{48}Ca as third fragment at three different excitation energies.

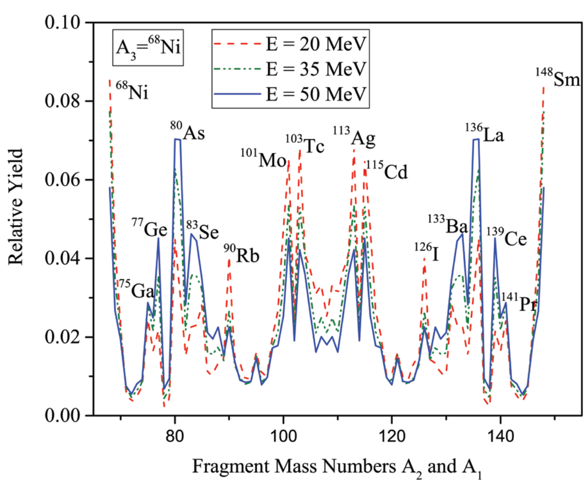

Figure 2: Ternary fission of ^{284}Og with ^{68}Ni as third fragment at three different excitation energies.

Fig. 2 depicts the ternary yield of the same SHN but for the third fragment ^{68}Ni. For the fixed third fragment A_3 = ^{68}Ni, ^{148}Sm + ^{68}Ni + ^{68}Ni is the most preferred way of breakup at all the excitations. It is observed that near symmetric fission with ^{113}Ag + ^{103}Tc + ^{68}Ni and ^{115}Cd + ^{101}Mo + ^{68}Ni are also preferred at all the excitations, with decreasing values of ternary yield with increasing excitation. The relative ternary yield values are found to increase with increase in excitation for the ternary fission of ^{136}La + ^{80}As + ^{68}Ni. The fragment combinations ^{133}Ba + ^{83}Se + ^{68}Ni and ^{139}Ce + ^{77}Ge + ^{68}Ni are also preferred way of ternary breakup. The relative yield of asymmetric spiltup combinations ^{126}I + ^{90}Rb + ^{68}Ni is found to decrease with increase in excitation energy and ^{136}La + ^{80}As + ^{68}Ni are also favoured with small values of relative yield. It is evident that, ternary yield value increases with increasing excitation for the combination ^{141}Pr + ^{75}Ga + ^{68}Ni.

Summary

The ternary fission fragmentation of ^{284}Og is studied within the framework of statistical theory at three different excitations E = 20, 35 and 50 MeV, for the fixed third fragments ^{48}Ca and ^{68}Ni. Asymmetric fission is favoured at all the three excitations when ^{48}Ca is fixed as third fragment. Interestingly, ternary yield value is largest for asymmetric fission at intermediate excitation E = 35 MeV. But for other combinations, the value of relative yield is found to be the same at all excitations. Asymmetric as well as near symmetric fission is favoured for the third fragment ^{68}Ni. It is striking to note that, the relative yield is found to decrease with increasing excitation for some fragment combinations where as yield is found to increase by rising excitation.

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CHITKARA

Journal of Nuclear Physics, Material Sciences, Radiation and Applications

Chitkara University, Saraswati Kendra, SCO 160-161, Sector 9-C, Chandigarh, 160009, India

Volume 9, Issue 1 **August 2021** **ISSN 2321-8649**

In Memory: Dr. S. Selvaraj

Prof S. Selvaraj passed away as a victim of Covid during May, 2021 at the age of 59 years. Hailing from a small village in Tirunelveli District, Tamilnadu, he completed his schooling and PUC respectively in the years 1971 and 1976. He graduated UG and PG Physics in the years 1981 and 1983. He started his teaching career as a lecturer at National Engineering College, Kovilpatti, for a brief stint before he joined The M.D.T. Hindu College, Pettai, Tirunelveli as a lecturer in the year 1984. He held many positions like Principal In-Charge of the College, Head of the Department of Physics, Chairman PG Board of Studies, College Committee Member, Member SCAA, etc., during his more than three decades of association with the college. During his teaching career he completed M. Phil, PGDCA and Ph. D degree. His Ph.D. thesis deals with the studies on hot and rotating system using statistical theory formalism. He has published nearly 24 research article in national, international journals and many of them were also presented in national and international meetings. He has guided six students for Ph.D. and equal number of students for M.Phil. For his contribution in teaching and research he will be remembered and will be greatly missed.

(**Memory Note by:** Prof. M. Balasubramaniam, Department of Physics, Bharathiar University, Coimbatore – 641046, Tamilnadu)