Ternary Fission

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Abstract: In this review, an account of the ternary fission phenomenon is discussed. Conventionally, ternary fission refers to the emission of very light charged α-particles from the neck formed between the main fission fragments. Further, the third particle emission is always identified to emit in a direction perpendicular to that of the axis of main fission fragments. However, recently, heavy charged particle accompanied fission has been reported to be emitted collinearly along with other fission fragments. The theoretical understanding of conventional ternary fission and collinear ternary fission based on three cluster model and statistical approach is presented.

1 Historical Perspective

1.1 Fission

Nuclear physics bifurcated from the domain of atomic physics after the discovery of radioactivity, a process in which an unstable atomic nucleus disintegrates to result in another isotope by emitting particles spontaneously. The remarkable experiments of Rutherford and his collaborators put forth concrete evidence of the presence of a nucleus at the center of the atom. Since then, the quest has been to understand the sub-atomic structure through various possible reactions. However, the probe to investigate were limited and are available mainly from other radioactive sources. The development of voltage multipliers by Cockcroft and Walton expanded the avenue of investigation. The discovery of neutron by Chadwick further kindled the

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scientific community to probe the nuclear structure as well as to synthesize possible transuranic elements. If a chargeless neutron is bombarded on a heavy target like Uranium, it was thought, that, after the capture of the neutron by the target, subsequent emission of β^- particle would result in a new element increasing the ladder of atomic number by one. Several people had shown interest in neutron based reactions. One such research group of two people Hahn and Strassmann, though not physicists, were also investigating bombardment of neutron on Uranium and analyzed the outcome by chemical means to look for elements heavier than Uranium. However, the substances looked like Radium or Barium, two known and almost chemically identical elements. As stated by Hahn,

"we didn't dare to think it as barium those days, rather, we always tried to explain what was wrong in our experiments, not to say we do have barium, but we always thought it can't be there and therefore we have to say, "What is the nonsense that we are doing?" and we were so afraid of these physics people".

Because, they were of the opinion that, a small rearrangement of the nucleons resulting in Radium could be more convincing to the people. Baffled by their results, they decided to have the opinion of their erstwhile colleague cum collaborator Lise Meitner, who had left the laboratory of Hahn from July 1938 to Sweden. Meitner was equally baffled at the first look of the results of the experiment of Hahn and Strassmann. Her nephew Otto Frisch a physicist, who worked at Niels Bohr's famous Institute for Theoretical Physics in Denmark, visited her for the Christmas vacation. Meitner shared and discussed the results of Hahn and Strassman with Frisch. Meitner was drawing a dotted circle within a circle as shown in Fig. 1 (a) and asked Frisch, *"Couldn't it be this sort of thing?"*. Frisch realized that she is looking the nucleus from the poles and the dotted line was indicating the equator being pushed inwards. Frisch also came up with the same idea and drew a shape like a circle squashed in at two opposite points as shown in Fig. 1 (b). Meitner consented that this is what she meant and they decided to write a research paper. The three papers published in the journal Nature[1, 2, 3], by Hahn and Strassmann, Meitner and Frisch, which announced the discovery and physical confirmation of fission, had a profound impact on mankind. Frisch communicated the results to Bohr, and he

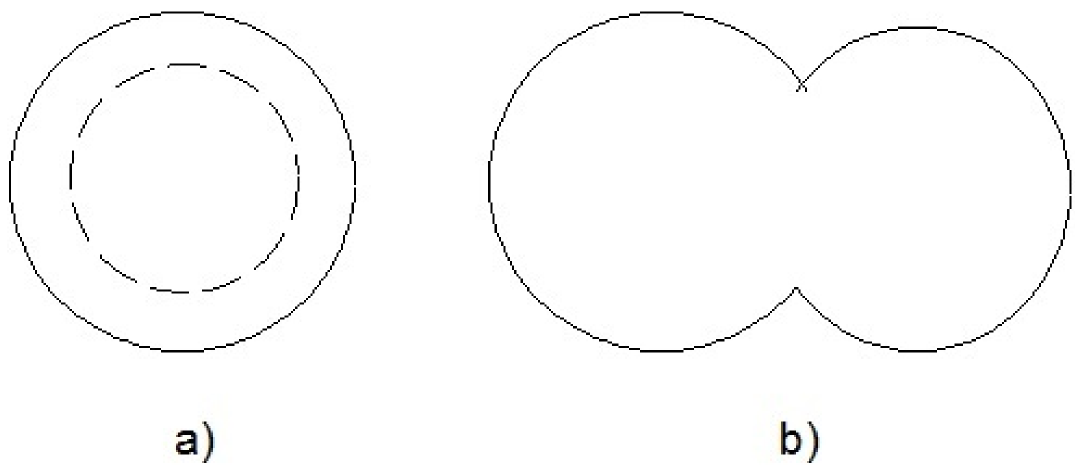

Figure 1: (a) Meitner's view of nuclear fission (b) Frisch's view of nuclear fission

was very happy, as he already envisaged the nucleus to behave like a liquid drop. Hence, a liquid drop hit hard enough, might stretch until it broke in two. Similarly, if that happened to a nucleus, a lot of energy would be released atom for atom, far more energy than any process seen till then. Later, Bohr, along with Wheeler [4] put forth a theory that could explain satisfactorily many of the features associated with the new discovery. Since then, with the advent of different probes other than neutrons, resulted in many features associated with the fission process.

2 Ternary fission

Based on the liquid drop picture, Present [5] in 1941, predicted that, for increasingly heavier radioactive nuclei, fission into three charged fragments is dynamically possible. Later, it has been shown that fission into four and more fragments also becomes energetically more favorable than binary fission. The experimental observations indicated the possibility of the existence of ternary / quaternary fission modes which could be grouped as

1. ternary fission in which the third fragment is a long-range alpha particle

2. tripartition in which the third fragment is a short-range charged particle of small mass

3. fission into three charged fragments of roughly equal mass

4. multiple fission in which fragmentation into four or more charged particle emits.

The break up of a radioactive nucleus into three or more than three fragments would release more energy; but, it is seen that the ternary to binary fission ratio is very low from the observed cases. Ternary fission is defined as a nuclear break-up into three fragments and this definition cover a spectrum of three particles fission events from one end in which a scission neutron accompany the two main fission fragments, to the other end in which three fragments of about equal masses are emitted; a process generally known as true ternary fission. The break-up into three nuclei of about equal masses have not been detected but theoretically is being investigated. The ternary fission process with three charged particles in the outgoing channel, with the third particle being very light compared to the main fission fragments is situated between these two extremes called as light charged particle (LCP) accompanied fission. This very asymmetric ternary fission is a competing decay mode for binary fission and is observed in spontaneous and induced ternary fissions.

2.1 Experimental status

In 1943, the first emission of light charged particle accompanying the fission (slow neutrons induced in a foil of ^{235}U) was reported by Alvarez [6] and simultaneously by Tsien San -Tsiang *et al.,* [7, 8]. After these observations, extensive experimental work has been done on various radioactive isotopes in different induced reactions as well as in spontaneous fission. The distinguished, light charged particles observed in the above mentioned spontaneous and induced ternary fission are listed in Tables 1 and 2 respectively. Predominantly observed light charged particle in the process of spontaneous as well as in induced ternary fission is α particle. The energy spectra of α particle emitted in ternary fission of various parent nuclei are ranging from 6 to 40 MeV and averagely peaked around 16 MeV. The measured angular distribution of the light charged particle shows that they are emitted orthogonally close to the right angles (80°-90°) to the fission axis in the laboratory frame of reference and only a small fraction of about 3 % are emitted along the fission axis.

Other light particles such as H, He, Li, Be and C were also observed in small traces. But only ^{4}He, ^{10}Be and ^{14}C alone were confirmed as light charged particle accompanying the spontaneous ternary fission. From the experimental signature it is seen that the fission fragments in ternary fission associates with either spherical or deformed closed shell, consequently, the study of this exotic decay mode will give structural information of nuclear species.

This indicates that they are formed between the main fission fragments and emitted at the last moment of scission, otherwise it would be emitted collinear to the fragment axis.

2.2 Experimental methods

The experimental methods for identifying ternary fission include nuclear emulsion method, triple coincidence method, method of radiochemical analysis and missing mass method.

2.2.1 Track and Radiochemical methods

When ionizing radiation passes through an emulsion, it interacts with the silver halide grains in the gelatin present on a photographic plate. When this plate is developed, the affected silver halide grains change into black grains of metallic silver in the nuclear emulsion method and a combination of such grains looks like a track. The ternary fission can be identified by observing the three-pronged tracks of ternary fission fragments. The size of the fragments is identified from the thickness of the tracks and the kinetic energy is identified from the length of the track. However, this method is not an unambiguous method, since, 85 % of such tracks are due to scattering or recoil phenomena.

Earlier experiments on ternary fission by Muga [24], photographed the tracks of three fragments emitted in the spontaneous ternary fission of ^{252}Cf using a nuclear emulsion technique. In this experiment, they photographed both long range and short range light charged particles and few tracks of symmetric tripartition. Figure 2 (a), shows the photomicrograph of three tracks left by the fragments in ternary fission of ^{252}Cf. Of these three tracks observed, two were found to be in the opposite

Table 1: Observed ternary particles in spontaneous fission. Column 3-5 presents the energy range and maximum particle energy (MPE) and angle of LCPs w.r.to to any of the fission fragments.

LCP	**Reaction**	**Energy** (MeV)	**MPE** (MeV)	**Angle**	**Reference**
^{1}H	^{252}Cf(sf)	3.3-12	3.5±0.5	91°	[9]
^{1}H	^{252}Cf(sf)	3.18-19.62	9±2	-	[10]
^{2}H	^{252}Cf(sf)	3.83-18.22	7±2	-	[10]
^{2}H	^{252}Cf(sf)	4.2-18	-	91°	[9]
^{3}H	^{252}Cf(sf)	3.89-23.13	8±1	-	[10]
^{3}H	^{252}Cf(sf)	5–24	-	91°	[9]
^{3}He	^{252}Cf(sf)	10.75-33.75	17±1	-	[10]
^{4}He	^{252}Cf(sf)	7.75-34.75	16±0.5	-	[10]
^{4}He	^{252}Cf(sf)	9–26	16.0±0.3	-	[11]
^{4}He	^{252}Cf(sf)	7.1-41	-	92°	[9]
^{4}He	^{252}Cf(sf)	-	-	82°	[12]
^{4}He	^{252}Cf(sf)	11–40	15.6±0.2	-	[13]
^{4}He	^{252}Cf(sf)	8–30	15.7±0.2	90°	[14]
^{4}He	^{252}Cf(sf)	9–30	-	-	[15]
^{4}He	^{252}Cf(sf)	0-30	18.0±0.5	-	[16]
^{4}He	^{252}Cf(sf)	12–32	15.6±0.2	-	[17]
^{4}He	^{250}Cf(sf)	14–30	16.1±0.1	-	[17]
^{4}He	^{256}Fm(sf)	14.5-31	15.5±0.4	-	[17]
^{4}He	^{257}Fm(sf)	15-35	15.9±0.6	-	[17]
^{4}He	^{244}Pu(sf)	12–40	15.5±0.55	-	[13]
^{5}He	^{252}Cf(sf)	-	12.3±0.9	30-150°	[18]
^{5}He	^{252}Cf(sf)	-	12.4±0.3	-	[14]
^{5}He	^{252}Cf(sf)	11-12	11±0.5	-	[11]
^{5}He	^{252}Cf(sf)	10.75-33.25	13±1	-	[10]
^{6}He	^{252}Cf(sf)	14.6-43	-	93°	[9]
^{6}He	^{252}Cf(sf)	10–22	12.3±0.5	90°	[14]
^{8}He	^{252}Cf(sf)	12–36	≤13	-	[10]
^{8}He	^{252}Cf(sf)	9.6-46	-	-	[9]
Li	^{252}Cf(sf)	19–39	-	-	[10]
Li	^{252}Cf(sf)	15.7-65	-	-	[9]
Li	^{252}Cf(sf)	17-35	14.3±10	84.9°	[14]
Be	^{252}Cf(sf)	33-41	-	-	[10]
^{10}Be	^{252}Cf(sf)	24-73	-	-	[9]
^{10}Be	^{252}Cf(sf)	18.8±0.4	-	-	[19]
B	^{252}Cf(sf)	-	20.5±1	-	[19]
B	^{252}Cf(sf)	25-50	26±0.5	-	[15]
C	^{252}Cf(sf)	32-34	-	-	[19]
^{14}C	^{252}Cf(sf)	30-50	34±0.5	-	[15]

Table 2: Observed ternary particles in neutron induced fission. Column 3-5 presents the energy range, maximum particle energy (MPE) and yield.

LCP	Reaction	Energy (MeV)	MPE (MeV)	Yield	Reference
^{3}H	^{235}U(n,f)	-	8.0±0.2	-	[20]
^{3}H	^{235}U(n,f)	5-18	15.8±0.1	-	[21]
^{3}H	^{233}U(n,f)	5-18	15.8±0.1	-	[21]
^{3}H	^{239}Pu(n,f)	5-18	15.9±0.2	-	[21]
^{3}H	^{241}Pu(n,f)	5-18	15.9±0.3	-	[21]
^{4}He	^{233}U(n,f)	10-34	15.8±0.1	-	[21]
^{4}He	^{235}U(n,f)	8-26	15.4±0.2	-	[20]
^{4}He	^{235}U(n,f)	10-32	15.8±0.1	-	[21]
^{4}He	^{239}Pu(n,f)	8-34	15.9±0.1	-	[21]
^{4}He	^{241}Pu(n,f)	10-35	15.9±0.1	-	[21]
^{4}He	^{232}Th(n,f)	8-28	15.8±0.2	-	[22]
^{5}He	^{235}U(n,f)	11	11.6±1.4	-	[11]
^{8}Li	^{249}Cf(n,f)	-	15.1±1.4	2.6±0.7×10^{-6}	[23]
^{9}Li	^{249}Cf(n,f)	-	12.5±0.9	3.8±1.6×10^{-6}	[23]
^{10}Be	^{249}Cf(n,f)	-	17.5±0.4	3.8±0.7×10^{-5}	[23]
^{11}Be	^{249}Cf(n,f)	-	16.5±1.3	4.7±1.2×10^{-6}	[23]
^{12}Be	^{249}Cf(n,f)	-	15.1±1.1	2.7±0.7×10^{-6}	[23]
^{12}Be	^{249}Cf(n,f)	-	21.8±0.3	1.5±0.4×10^{-6}	[23]
^{13}B	^{249}Cf(n,f)	-	20.1±1.1	2.4±0.6×10^{-6}	[23]
^{14}B	^{249}Cf(n,f)	-	17.0±1.2	1.4±0.4×10^{-6}	[23]
^{15}B	^{249}Cf(n,f)	-	16.8±1.9	9.1±4.1×10^{-6}	[23]
^{14}C	^{249}Cf(n,f)	-	27.6±0.3	1.3±0.2×10^{-5}	[23]
^{15}C	^{249}Cf(n,f)	-	25.1±0.5	5.3±1.1×10^{-6}	[23]
^{16}C	^{249}Cf(n,f)	-	24.4±1.1	4.8±1.1×10^{-6}	[23]
^{17}C	^{249}Cf(n,f)	-	21.3±1.7	7.5±2.8×10^{-7}	[23]
^{18}C	^{249}Cf(n,f)	-	20.4±2.8	2.4±0.7×10^{-7}	[23]
^{16}N	^{249}Cf(n,f)	-	25.9±2.2	1.5±0.4×10^{-7}	[23]
^{17}N	^{249}Cf(n,f)	-	25.0±1.6	8.1±2.0×10^{-7}	[23]
^{18}N	^{249}Cf(n,f)	-	23.8±1.5	4.5±1.1×10^{-7}	[23]
^{20}O	^{249}Cf(n,f)	-	31.4±1.7	25.0±0.7×10^{-6}	[23]
^{21}O	^{249}Cf(n,f)	-	24.2±1.2	6.4±1.3×10^{-7}	[23]
^{22}O	^{249}Cf(n,f)	-	33.0±7.4	4.2±1.6×10^{-7}	[23]
^{21}F	^{249}Cf(n,f)	-	26.0±2.1	1.6±0.4×10^{-7}	[23]
^{22}F	^{249}Cf(n,f)	-	33.8±10.5	1.4±0.8×10^{-7}	[23]
^{24}F	^{249}Cf(n,f)	-	26.3±2.8	8.3±4.0×10^{-8}	[23]
^{24}Ne	^{249}Cf(n,f)	-	33.9±2.9	2.4±0.6×10^{-7}	[23]
^{27}Na	^{249}Cf(n,f)	-	38.4±8.2	8.2±3.2×10^{-8}	[23]
^{30}Na	^{249}Cf(n,f)	-	31.7±8.6	2.2±2.2×10^{-8}	[23]
^{30}Mg	^{249}Cf(n,f)	-	34.9±3.7	1.3±0.4×10^{-7}	[23]

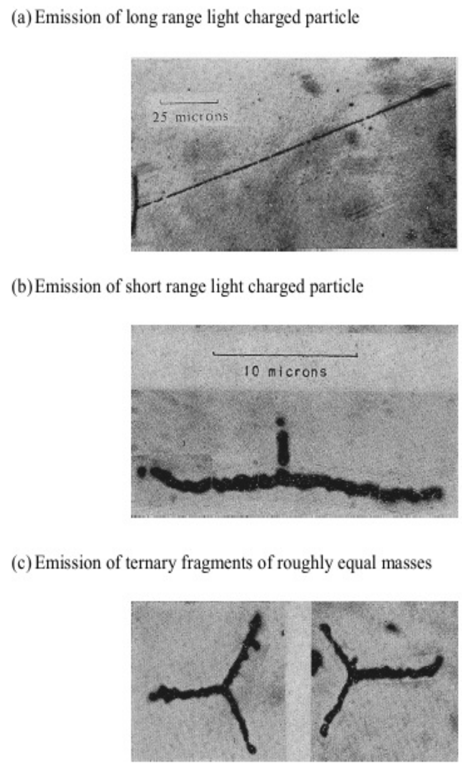

Figure 2: (a) and (b) shows the photomicrograph of tracks for long and short range light charged particle in the fission of ^{252}Cf. (c) shows the photomicrograph of tracks for ternary fragments of roughly equal masses in the fission of ^{252}Cf. These tracks are taken from the work done by Muga *et al.,* in Ref. [24].

direction possessing a short range. These two tracks indicate the two main fission fragments. The third track was observed strongly at 90° from the vertex of the other two indicating that it must be an α particle possessing a long range. Figure 2 (b) shows the short range light charged particle emitted in the same experiment. Figure 2 (c) shows the photomicrograph of tracks for ternary fragments of roughly equal masses in the fission of ^{252}Cf. These tracks are taken from Ref. [24].

However, this technique may not be useful to identify collinear cluster tri-partition, where the tracks of the three fragments coincide with one another. In radiochemical methods, after fission, the irradiated samples were dissolved in hot water containing nitric acid, and aliquots of this solution were taken for separation of the various fission products. The fission products were isolated by the standard radiochemical procedure of adding a known amount of inactive isotopic exchange carrier. The carrier element was finally precipitated in a form suitable for weighing and counting, and the fraction recovered was determined from the weight. The radiochemical analysis gives unambiguous results on the relative yield of fission products.

2.2.2 Detectors and coincidence

With the advent of technology, later experiments used, solid state detectors to observe and measure the angular distribution of the long range alpha particles, semiconductor $\Delta E \times E$ counter telescopes to identify the light charged particles in spontaneous ternary fission, surface barrier $\Delta E \times E$ telescope detectors to study the energy characteristics and the emission probabilities of triton and alpha particles emitted in thermal neutron induced fission.

Singer *et al.,* studied [25] high energy gamma rays emitted in the alpha accompanied fission of ^{252}Cf. In this experiment,the light charged particles emitted from ternary fission were measured by a ring of 12 $\Delta E \times E$ telescopes. The fragment mass dependence on the mean γ-ray multiplicity in ternary fission modes in this experiment indicated the disintegration of equilibrated fission fragments in a narrow mass range around doubly magic ^{132}Sn nucleus as the source of these γ-rays. Gönnenwein *et al.,*, measured [26] the yields of light charged particles (isotopes of F, Ne, Na, Mg, Al and Si) emitted as ternary particles in the ternary fission of ^{242}Am induced by thermal neutrons and reported that emission of all light charged particles is due to a cold process with all the three fragments being born in their ground states or very close to their ground states.

Using γ-γ-γ coincidences technique and γ-γ-LP coincidences technique Ramayya *et al.,* observed [16, 27, 28, 29] the emission of α particle and ^{10}Be in cold neutronless spontaneous ternary fission of ^{252}Cf. In the triple coincidence method, the fragments are detected using three semiconductor detectors arranged symmetrically at 120°, or asymmetrically in a plane. These experiments provided evidence for two different modes for ternary fission, one hot and the other cold. In alpha particle accompanied fission of ^{252}Cf [27] the majority of the fissions are hot, while for ^{10}Be-accompanied fission [28] the cold process appears to dominate which is well supported by different theoretical results.

2.2.3 Missing mass method

In the missing mass approach, the third particle is identified from the distribution of the fission fragments. In binary fission, the two fragments are observed in the opposite direction in the center of mass frame. The difference in the angle between the fragments is around 180°. In most of the binary fission, the angular difference between two binary fragments is about 180°. Hence, the plot between the difference in the angle and the number of fragments detected gives a sharp peak around 180° for the binary fission. If a light charged particle is emitted along with the two fission fragments, then the full width half maximum seems to be increased. If the number of light charged particle increases in the fission, then the full width half maximum is also increased. Pyatkov *et al.*,, has recently observed [30, 31] collinear cluster tripartition (CCT) of ^{252}Cf(*sf*) in the fragment mass space. A new island with a high yield of collinear cluster tripartition with fragment masses close to the magic ^{132}Sn, ^{70}Ni and ^{48}Ca isotopes were observed.

The experimental observations can be summarized as,

- Besides the scission neutrons, about 90% of ternary particles are α particles; about 7% are triton and the rest is heavier nuclei.
- The α particles are emitted from almost all the parent nuclei from which ternary fission is observed.
- ^{4}He, ^{10}Be, and ^{14}C are alone confirmed as light charged particle accompanying the spontaneous ternary fission.
- In induced reactions, the light charged particles, ^{10}Be, ^{14}C, ^{20}O, ^{24}Ne, ^{28}Mg, ^{34,37}Si and ^{37}S have been observed.

3 Theoretical status

3.1 Trajectory models

Earlier models mainly focused on the trajectory calculations of the long range alpha particle, which allows, in principle, a connection of the kinematic variables of fission products with the initial conditions in the scission point. In three point charge model

[32, 33] the trajectories were calculated backward from the experimentally observed angular distribution and the energy distribution to obtain the initial configuration. By the statistical theory of fission [34, 35] the trajectories of the alpha particle and the main fission fragments were calculated on the basis of initial conditions. Earlier calculations were limited only to α-particle trajectories. Very recently, the trajectories for heavy charged particles were discussed by Vijayaraghavan *et al.,* [36] the results of which supports the possibility of observing the heavy charged particle in collinear emission.

3.2 Phenomenological models

Halpern [37] suggested that the energy required to emit ternary fission particles is transferred through the sudden collapse of the neck which stubs into the main fragments after scission. Based on liquid drop model Diehl *et al.,* studied [38] three possible ternary fission modes, in that, two are direct modes, the oblate, and prolate modes and the third one is cascade fission. Degheidy *et al.,* developed [39] a phenomenological shell model to study the ternary fission. Săndulescu *et al.,* developed [40, 41] a coplanar three body cluster model to explain ternary fission, and according to them, the cold ternary fission events are characterized by high kinetic energies of the final fragments and consequently, their scission configuration should be associated with compact shapes. Poenaru *et al.,* developed [42] a three center phenomenological model, to explain qualitatively the quasi-molecular stage of light particle accompanied fission process. This model is derived from the liquid drop model under the assumption that the aligned configuration, with the emitted particle between the light and heavy fragment, is obtained by increasing continuously the separation distance, while the radii of the heavy fragment and of the light particle are kept constant. Employing the three center phenomenological model Poenaru *et al.,* [42] roughly estimated the half-lives of some quasi-molecular states which could be formed in the ^{10}Be and ^{12}C accompanied fission of ^{252}Cf which is of the order of 1 ns and 1 ms respectively. Florescu *et al.,* estimated [43] the preformation probabilities for α and ^{10}Be clusters in the cold ternary fission of ^{252}Cf within a microscopic model starting from single particle spherical Saxon-Woods wave functions and with a large space BCS-type configuration mixing.

3.3 Dynamical and Statistical models

Rubchenya *et al.,* developed [44] a new dynamic model in which they assumed that light particles are formed as a result of two random neck ruptures. In this model, the mechanism of light charged particle formation at the late stage of fission is governed by the properties of the fissioning nucleus at the descent stage from the saddle to the scission point. Lestone proposed [45] a combined statistical and dynamical model of nuclear fission, which is a blending of two models, similar, but not identical, to those proposed by Halpern [37] and Fong [46]. In this model, the light particle is generated statistically by sudden neck rupture. Statistically generated particles that are between the main fragments and sufficiently far from the scission axis can fail to be reabsorbed by either of the retracting neck stubs, and can find themselves outside the Coulomb barrier of the post-scission configuration and they accelerate away from each other after scission. Algora *et al.,* studied [47] the dependence of ternary clusterization based on a microscopic (real and effective SU(3)) selection rule and energetic stability. Andreev *et al.,* developed [48] a model (based on potential energy calculations of ternary systems at scission and on statistical analysis) to calculate the charge distribution, total kinetic energy (TKE) of the fission fragments, and neutron multiplicity distribution from the fission fragments in a ternary fission. In this model, the ternary fission is assumed as a two-step process. In the first step, the binary system is formed, in the second step the third light nucleus originates in the region between the two separating heavy fragments. A three cluster model and statistical approach have been put forth recently by Balasubramaniam and collaborators [49, 50, 51, 52, 53, 54, 56, 57, 58, 59, 60]. A brief account of these model details and the important results obtained thereof will be discussed.

4 Three Cluster Model

The three cluster model (TCM) is an extension of the preformed cluster model (PCM) of Gupta and collaborators for ground state decays in cluster radioactivity and related phenomena [61, 62, 63]. TCM is based on the dynamical or quantum mechanical fragmentation theory [64, 65] of cold phenomenon. This theory is worked out in terms of

(i) the collective coordinate of mass (and charge) asymmetry

$$\eta = \frac{A_1 - A_2}{A_1 + A_2}; \qquad \eta_Z = \frac{Z_1 - Z_2}{Z_1 + Z_2}. \tag{1}$$

Here 1 and 2 stand respectively, for heavy and light fragments and the third fragment in TCM is denoted by 3 and is fixed; hence only the mass asymmetry between 1 and 2 is considered.
(ii) relative separation R, in TCM characterizes: (a) the nucleon-division (or -exchange) between the outgoing fragments, and (b) the sharing of the available Q value to the kinetic energies E_i of the three fragments, i.e., $Q = E_1 + E_2 + E_3$, with Q value for three decay products defined as

$$Q = M - \sum_{i=1}^{3} m_i, \tag{2}$$

where M is the mass excess of the decaying nucleus and m_i the mass excesses of the product nuclei, expressed in MeV.

The ternary fragmentation potential between the three nuclei defined as

$$V_{tot} = \sum_{i=1}^{3} \sum_{j>i}^{3} (B_i + V_{ij}), \tag{3}$$

where B_i are the binding energies of the three fragments in energy units and $V_{ij} = V_{Cij} + V_{Nij}$. The Coulomb interaction energy V_{Cij} between the three nuclei is defined as

$$V_{Cij} = \frac{Z_i Z_j e^2}{R^s_{ij}}, \tag{4}$$

with $R = R^s_{ij} = R_{ij} + s_{ij}$, where R^s_{ij} is the distance between the centers of the interacting fragments. R_{ij} is the sum of the radii of interacting fragments ($R_{12} = R_1 + R_2$; $R_{13} = R_1 + R_3$; $R_{23} = R_2 + R_3$ with $\mathrm{R}_i = \mathrm{r}_0 \times \mathrm{A}_i^{1/3}$; $\mathrm{r}_0 = 1.16\ fm$) and s_{ij} is the surface separation distance between the fragments.

In TCM the calculations are made in two different ways, namely equatorial (orthogonal) and collinear (polar) configuration. The separation distances for equatorial configuration are considered as $s_{12} = s_{13} = s_{23} = s$ and for collinear configuration as $s_{12} = s_{23} = s; \quad s_{13} = 2(R_2 + s)$ with $s = 0$ corresponding to the touching configuration of three fragments. For V_{Nij} the short range Yukawa plus exponential nuclear attractive potential is used and is given by,

$$V_{Nij} = -4\left(\frac{a}{r_0}\right)^2 \sqrt{a_{2i}a_{2j}} \times \left[g_i g_j\left(4+\xi\right) - g_j f_i - g_i f_j\right] \frac{\exp\left(-\xi\right)}{\xi}, \qquad (5)$$

where $\xi = R^s{}_{ij}/a$, and the functions g and f are $g_k = \zeta\cosh\zeta - \sinh\zeta$, and $f_k = \zeta^2\sinh\zeta$, where $\zeta = R_k/a$ with the radius of nucleus $R_k = r_0 A_k^{1/3}$. a=0.68 fm is the diffusivity parameter and the asymmetry parameter $a_{2k} = a_s(1-\omega I^2)$ with a_s=21.13 MeV, ω=2.3 and $I = \frac{N-Z}{A}$.

In TCM, the decay constant is defined as,

$$\lambda = P_0 P\nu P_3, \qquad (6)$$

where, P_0, the preformation probability refers to η and P the penetrability, to R motion. One of the assumptions of the TCM model is that the preformation probability of the third fragment P_3=1 (here the third fragment is α-particle). The preformation probability P_0 of fragment 2 (equivalently, of fragment 1) can also be calculated as below by solving the stationary Schrödinger equation in η coordinate, at a fixed R.

The preformation probability P_0 in Eq. (6) is the solution of stationary Schrödinger equation given below in η, at a fixed R (i.e. in touching configuration) for the ternary fragmentation potential defined in Eq. (3)

$$\left\{-\frac{\hbar^2}{2\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta}\frac{1}{\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta} + V_R(\eta)\right\}\psi^\nu(\eta) = E^\nu\psi^\nu(\eta), \qquad (7)$$

with ν=0, 1, 2, 3... referring to ground state ($\nu = 0$) and excited state solutions. The solution

$$P_0(A_i) = \mid \psi_R(\eta(A_i)) \mid^2 \sqrt{B_{\eta\eta}}\frac{2}{A}, \qquad (8)$$

where (i= 1 or 2). The mass parameters $B_{\eta\eta}(\eta)$, representing the kinetic energy part in Eq. (7), are the smooth classical hydrodynamical mass parameters of Kröger and Scheid [66].

In the decoupled approximation an equivalent Schrödinger equation for R motion can be used to find the probability $\mid \psi_\eta(R) \mid^2$. However instead of solving the Schrödinger equation in R, the penetration probability is obtained using WKB approximation as discussed below. The Penetrability (i.e. the probability in which the ternary fragments cross the three body potential barrier) is the WKB integral,

$$P = \exp\left[-\frac{2}{\hbar}\int_{s_1}^{s_2}\{2\mu[V(s)-Q]\}^{1/2}ds\right], \tag{9}$$

which is solved analytically [62], with $s_1 = 0$, the touching configuration, as the first turning point and s_2 as the second turning point satisfying

$$V(s_2) = Q. \tag{10}$$

It is to be mentioned here that this action integral depends only on the variable 's'. The first (inner) turning point is at touching configuration and the second (outer) turning point corresponds to the Q value of the reaction. This means that the fragments penetrate three body potential first from s_1 (s=0) to s_i, then de-excite at s_i and then penetrate from s_i to s$_2$ with the energy Q value. The reduced mass of the three fragments is defined as

$$\mu_{123} = \left(\frac{\mu_{12}A_3}{\mu_{12}+A_3}\right)m, \tag{11}$$

m is the nucleon mass and

$$\mu_{12} = \frac{A_1A_2}{A_1+A_2}. \tag{12}$$

The relative yields for all the charge minimized fragmentation channels are calculated as the ratio between the penetration probability of a given fragmentation over the sum of penetration probabilities of all possible fragmentation as,

$$Y(A_i, Z_i) = \frac{P(A_i, Z_i)}{\sum P(A_i, Z_i)}. \tag{13}$$

Here $P(A_i, Z_i)$ is same as the penetration probability corresponding to a fragmentation as defined in Eq. (9); here A_i denotes $A_1+A_2+A_3$; Z_i denotes $Z_1+Z_2+Z_3$.

5 Statistical approach for ternary fission

5.1 Non-interacting fermions

A nucleus can be represented as a gas of non-interacting fermions confined to the nuclear volume. The energy levels of the neutrons and the protons are represented by ϵ_k^N and ϵ_k^Z respectively. The constants of motion are the neutron and proton numbers N, Z, and the energy E. The logarithm of the grand partition function is,

$$\Omega = \sum \ln \left[1 + \exp\left(\alpha_N - \beta\epsilon_k^N\right)\right] + \sum \ln \left[1 + \exp\left(\alpha_Z - \beta\epsilon_k^Z\right)\right]. \qquad (14)$$

The particle numbers and the energy of the system can be obtained as,

$$N = \sum \frac{1}{1 + \exp\left\{-\left(\alpha_N - \beta\epsilon_k^N\right)\right\}}, \qquad (15)$$

$$Z = \sum \frac{1}{1 + \exp\left\{-\left(\alpha_Z - \beta\epsilon_k^Z\right)\right\}}, \qquad (16)$$

$$E = \sum \frac{\epsilon_k^N}{1 + \exp\left\{-\left(\alpha_N - \beta\epsilon_k^N\right)\right\}} + \sum \frac{\epsilon_k^Z}{1 + \exp\left\{-\left(\alpha_z - \beta\epsilon_k^Z\right)\right\}}. \qquad (17)$$

The total level density of a system composed of two kinds of nucleons is given approximately as,

$$\rho(E) \simeq \frac{\sqrt{\pi}}{12} \frac{\exp 2\sqrt{aE}}{E^{5/4} a^{1/4}}, \qquad (18)$$

where a is the level density parameter. The explicit dependence of the level density upon excitation energy arises from the simple relation between excitation energy and statistical temperature: $E = aT^2$. Generally, in a Fermi gas, the single particle level density increases approximately as the square root of the particle kinetic energy, while in the present model it is a constant. It is to be mentioned here that, the energy E represents the internal energy of a nuclear system. Fong assumes this internal energy as the excitation energy of a nuclear system to calculate the mass distribution, hence, we represent the internal energy as the excitation energy E^*.

To evaluate the level density, the excitation energy E^* of the nucleus should be calculated from the appropriate microscopic models. Fong suggested that the probability of the particular fragmentation can be calculated from the available density of quantum states as,

$$P \propto \rho_i, \qquad (19)$$

here, $i = 1$, 2 represent the binary fragmentation whereas i =1, 2 and 3 stands for the ternary fission.

6 Convolution of level densities

If a compound nuclear system is divided into two fragments, for each fragment, it is possible to calculate a density of states using the Fermi gas model. According to statistical theory, the probability of fission fragments is proportional to the full micro-state (convoluted) density. To calculate the full micro-state density from the known fragment densities, the convolution integral method is used.

6.1 Binary convolution

Following Cole *et al.,* [67], we derive the full micro-state density for binary fission, where the heavy nucleus breaks into two fragments. The total excitation energy E^* is distributed by putting energy E_1^* to the first subsystem and the E_2^* to the second, the total number of states for this particular energy division is given by,

$$\Omega_{12}\left(E_1^*, E_2^*; E^*\right) = \omega_1\left(E_1^*\right)\omega_2\left(E_2^*\right), \tag{20}$$

and the micro-canonical sum is obtained by summing all possible combinations given in above equation,

$$\omega_{12}\left(E^*\right) = \sum \omega_1\left(E_1^*\right)\omega_2\left(E_2^*\right), \tag{21}$$

where the sum is carried out over all partitions of energy E such as $E_1^* + E_2^* = E^*$. For higher excitation energies the phase space is continuous so that we replace the terms in the above equation as

$$\rho_{12} = \int_0^{E^*}\int_0^{E^*} \rho_1\left(E_1^*\right)\rho_2\left(E_2^*\right)\delta\left(E_1^* + E_2^* - E^*\right)dE_1^* dE_2^*,$$

Applying Dirac delta functions to simplify the above equations we obtain

$$\rho_{12} = \int_0^{E^*} \rho_1\left(E_1^*\right)\rho_2\left(E^* - E_1^*\right)dE_1^*. \tag{22}$$

The above equation is referred to as a binary convolution integral. The binary convolution theorem can be extended to include an arbitrary number of components such as ternary fission and quaternary fission.

6.2 Ternary convolution

The binary convolution theorem is extended to the ternary fission, where the compound nucleus is divided into three different fragments for each of which it is possible to calculate a level density (ρ). From the fragment level densities the full micro level density ρ_{123} or ternary convoluted level density is calculated using the ternary fission integral,

$$\rho_{123}\left(E^*\right) = \int_0^{E^*} \rho_3\left(E_3^*\right)\left[\int_0^{E^*}\int_0^{E^*} \rho_1\left(E_1^*\right)\rho_2\left(E_2^*\right)\delta\left(E_1^*+E_2^*-E^*\right)dE_1^* dE_2^*\right]dE_3^*. \tag{23}$$

The double integral in square brackets is a two density convolution which we can write as ρ_{12}. The above equations can be conveniently written as,

$$\rho_{123}\left(E^*\right) = \int_0^{E^*} \rho_3\left(E_3^*\right)\rho_{12}\left(E^*-E_3^*\right)dE_3^*. \tag{24}$$

Here, the ternary fragmentation probability $P(A_j, Z_j)$, is always considered to be proportional to the folded densities as

$$P(A_j, Z_j) \propto \rho_{123}(A_j, Z_j, E^*). \tag{25}$$

In the above equation, the subscript j refers to a ternary fragmentation, involving three fragments with $A_j = A_1 + A_2 + A_3$ and $Z_j = Z_1 + Z_2 + Z_3$. Further, it is not the absolute value of relative yield of one of the fragments. The ternary fission yield at the point of scission is calculated as the ratio between the probability of a given ternary fragmentation and the sum of the probabilities of all the possible ternary fragmentations and it is given by,

$$Y(A_j, Z_j) = \frac{P(A_j, Z_j)}{\sum P(A_j, Z_j)}. \tag{26}$$

7 Summary of Important Results

- The three cluster model has been initially developed [49, 51] for a single third fragment namely ^4He, which has been obtained by properly minimizing the potential energy surface. Assuming the fragments to be spherical, the ternary fission yield was compared with available experimental results for the ^4He

accompanied fission of ^{252}Cf. Our results indicated a preference of ternary partition with one of the fragments as the closed shell nucleus Sn. However, experimental yields are maximum for Zr, Ba as one of the fragments. This discrepancy was addressed by modifying the three cluster model [50, 53] by incorporating deformation degrees of freedom. With the inclusion of deformation, our theoretical results agreed well with experimental yields.

- Later, within the three cluster model, ternary fission of all possible third fragments of ^{252}Cf has been studied [52, 54] for two different geometries of the three fragments, viz., i) equatorial geometry, referring to orthogonal emission and ii) collinear geometry, referring to collinear emission. The important results obtained of this work indicated that, of the two different geometries considered, the collinear configuration is preferred over the equatorial configuration for heavy third fragment accompanied ternary fission of ^{252}Cf.

- The preference of collinear geometry for heavy charged particle accompanied fission was further substantiated in another work [59], where the potential energy as a function of the angle between the fragments leading from collinear configuration to equatorial configuration is studied for various third particle accompanied fission of ^{252}Cf. The obtained results indicated that the collinear configuration is a more favorable arrangement than the equatorial configuration to look for new ternary decay modes. In particular, the collinear arrangement, with the lightest fragment in the middle seems to be a more favorable arrangement for heavy third particle accompanied fission of ^{252}Cf.

- Very recently, based on simple trajectory calculations [36], once again, it was demonstrated that the collinear emission as a favorable mode to look for heavy particle accompanied fission. The trajectory calculations took into account both the effect of Coulomb and nuclear potentials.

- In the above mentioned results, the probable tripartition is identified by charge minimizing the ternary fragmentation potential. Later, the concept of charge and mass bin was developed and has been incorporated to study all possible third fragments. In ref. [58], using two different minimization procedures involving charge and mass bins, the ternary modes of superheavy nuclei are reported. A strong indication of true ternary fission is also revealed.

- Within statistical theory (level density approach) and as an extension to the work of Rajasekaran and Devanathan [68] on binary fission mass distributions, we studied in Ref. [56], the ternary mass distribution of ^{48}Ca accompanied fission of ^{252}Cf using the single particle energies of the finite range droplet model (FRDM). The obtained results indicated the preference of closed shell nucleus as one of the partner fragments.

- As a sequel to that work of Ref. [56], we studied in Ref. [60] the role of all possible fragments in the ternary fission of ^{252}Cf. The selection of ternary fragment combinations is obtained by minimizing the potential energy from all the possible ternary fragment combinations. This is done by using charge bins with different mass partitions as reported in Ref. [58]. Further, the concept of temperature tuning has also been introduced. This work would account as a blend of fragmentation theory and statistical theory attempted for the first time for the study of the complete charge distribution of ternary fission of ^{252}Cf for all possible third fragments.

To conclude, ternary fission not only confines to α-accompanied fission, rather it could be any heavy third particle accompanying the main fission fragments, with a preference for collinear emission than equatorial emission. Our model results clearly indicate the preference of collinear geometry over equatorial geometry for heavy third particle accompanied fission.

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