The 2nd Asian Nuclear Reaction Database Development Workshop

CNDC of CIAE
and
AASPP of JSPS

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Bharathiar University
Coimbatore. India.

A comparison of ternary fragmentation potential energy surface in equatorial and collinear configuration

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This document was prepared as an account of work to present in the 2nd Asian Nuclear Reaction Database Development Workshop

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Thanks

THANKS FOR THIS OPPORTUNITY

Our nuclear data activities

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In 2008, I got an opportunity to interact with Prof. S. Ganesan in a meeting at Tirunelveli and initiated a project proposal which was later sanctioned and supported by DAE-BRNS, Govt. of India in 2009. (On going)

In 2008 we at BU, attended couple of nuclear data related meetings at Manipal University, Manipal during 25th to 28th February, 2008 and the other one during October 2-4, 2008.

The first meeting was on Covariance error matrices (Prof. Leeb) and in the later meeting Dr. R. Capote conducted a demonstrative program for the use of EMPIRE code.

In 2009, we actively participated in the third DAE-BRNS Theme Meeting on EXFOR Compilation of Nuclear Data, November 03-07, 2009, Jaipur, Rajastan, India.

Dr. D. Svetlena, IAEA demonstrated about how to make entries in the EXFOR and also about the digitizer software. (Inpgraph)

All the participants with the support of Dr. D. Svetlena and other experts made several entries during that meeting.

Following entries were made by us

ENTRY	D6022
TITLE	Measurement of near and above barrier fusion excitations for 7-Li+28-Si
AUTHOR	H.Majumdar, Mandira, Sinha, P.Basu, R.Bhattacharya, Subinit Roy, S.Santra, M.Biswas, V.V.Parkar, B.R.Behra, K.S.Golda, S.K.Datta, S.Kailas
Compiled by	K. Manimaran, Megha Bhike, C. Karthik
ENTRY	D6062
TITLE	Proton and alpha evaporation spectra in low energy C-12 and O-16 induced reactions
AUTHOR	E.T.Mirgule, D.R.Chakrabarty, V.M.Datar, Suresh Kumar, Mitra, H.H.Oza
Compiled by	Megha Bhike, K. Manimaran,C. Kartik
ENTRY	D6089
TITLE	13-C(alpha,neutron)16-O recation cross section between 1.95 and 5.57 MeV
AUTHOR	K.K.Sekheran, A.S.Divatia, M.K.Metha, S.S.Kerekatte, K.B.Nambiar
Compiled by	K. Manimaran, Megha Bhike, C. Karthik
ENTRY	D6021
TITLE	Direct and compound reactions induced by unstable helium beams near the Coulomb barrier
AUTHOR	A.Navin, V.Tripathi, Y.Blumenfeld, V.Nanal, C.Simenel, M.Casandjian, G.de France, R.Raabe, D.Bazin, A.Chatterjee, M.Dasgupta, S.Kailas, R.C.Lemmon, K.Mahata, R.G.Pillay, E.C.Pollacco, K.Ramachandran, M.Rejmund, A.Shrivastava, J.L.Sida, E.Tryggestad
Compiled by	G.Pandikumar, Dr. S. Ganesan, Dr.M.Balasubramaniam, Joseph Jermiah

ENTRY	D6039
TITLE	Complete and Incomplete Fusion Reactions of O-16 with As-75 at Incident Energies below 7MeV/A
AUTHOR	R.Gun, D S.K.Saha
Compiled by	G.Pandikumar, Dr.S.Ganesan, Dr.M.Balasubramaniam, J.Joseph Jeremiah, P.Balaji
ENTRY	D6051
TITLE	Sub-barrier fusion excitation for the system 7Li+28Si
AUTHOR	Mandira Sinha, H.Majumdar, P.Basu, Subinit Roy, R.Bhattacharya, M.Biswas, M.K.Pradhan, S.Kailas
Compiled by	G.Pandikumar, Dr.S.Ganesan, Dr.M.Balasubramaniam, J.JosephJeremiah
ENTRY	D6085
TITLE	REACTION 55-MN(P,N)55-FE FROM EP=1.35 TO 5.42 MEV
AUTHOR	Y.P.Viyogi, P.Satyamurthy, N.K.Ganguly, S.Kailas, S.Saini, M.K.Mehta
Compiled by	G.Pandikumar, Dr.S.Ganesan, Dr. S.Kailas, J.Joseph Jeremiah, Dr.M.Balasubramaniam

In April 2011, Chanidgarh Exfor meeting

Thanks to **GSYS**

We made couple
of entries, In particular
D6121 was coded
by us with 41 subentries

We helped others
To the Exfor, Inpgraph
And Gsys.

D6121 - Notepad

File Edit Format View Help

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ENTRY              D6121   20110404                          D6121  0     1
SUBENT          D6121001   20110404                          D6121  1     1
BIB                   11         19                          D6121  1     2
TITLE        Fission time scale from prescission neutron, proton, D6121  1  3
             and a particle  multiplicities in 28Si+175Lu    D6121  1     4
AUTHOR       (K.Ramachandran,A.Chatterjee,A.Navin,K.Mahata,  D6121  1     5
             A.Shrivastava, V.Tripathi,S.Kailas,V.Nanal,R.G.Pillay, D6121  1  6
             A.Saxena,R.G.Thomas, Suresh Kumar,P.K.Sahu)     D6121  1     7
INSTITUTE    (3INDTRM,3INDTAT)                               D6121  1     8
REFERENCE    (J,PR/C,73,064609,2006)                         D6121  1     9
             #doi:10.1103/PhysRevC.73.064609                 D6121  1    10
FACILITY     (VDG,3INDTAT)                                   D6121  1    11
SAMPLE       Target 1.5 mg/cm2 self-supporting foil of 175 Lu D6121  1   12
DETECTOR     (SISD)centered at 140 degree                    D6121  1    13
METHOD       (EDE)neutron,proton alpha emission measurement  D6121  1    14
INC-SOURCE   (POLIS)pulsed 159-MeV 28Si beam from LINAC booster D6121  1 15
HISTORY      (20110404C)  M.Balasubramaniam,Vijayaraghavan,  D6121  1    16
             Karthikraj,Bharathiar  Univ.,Rajeshkumar NIT Hamirpur, D6121  1 17
             S.Mahadevan Amrita  Univ.,S.Subramanian VOC College TN,D6121  1 18
             G.Pandikumar, IGCAR                             D6121  1    19
COMMENT      Figure 2 measurement at different angles at same D6121  1   20
             energies                                        D6121  1    21
ENDBIB                19          0                          D6121  1    22
NOCOMMON               0          0                          D6121  1    23
ENDSUBENT             22          0                          D6121  199999
SUBENT          D6121002   20110404                          D6121  2     1
BIB                    2          2                          D6121  2     2
REACTION     (71-LU-175(14-SI-28,X)0-NN-1,PR,MLT,NU/DA/DE)   D6121  2     3
STATUS       (APRVD)                                         D6121  2     4
ENDBIB                 2          0                          D6121  2     5
COMMON                 2          3                          D6121  2     6
EN           ANG                                             D6121  2     7
MEV          ADEG                                            D6121  2     8
 159.         105.                                           D6121  2     9
ENDCOMMON              3          0                          D6121  2    10
DATA                   2         10                          D6121  2    11
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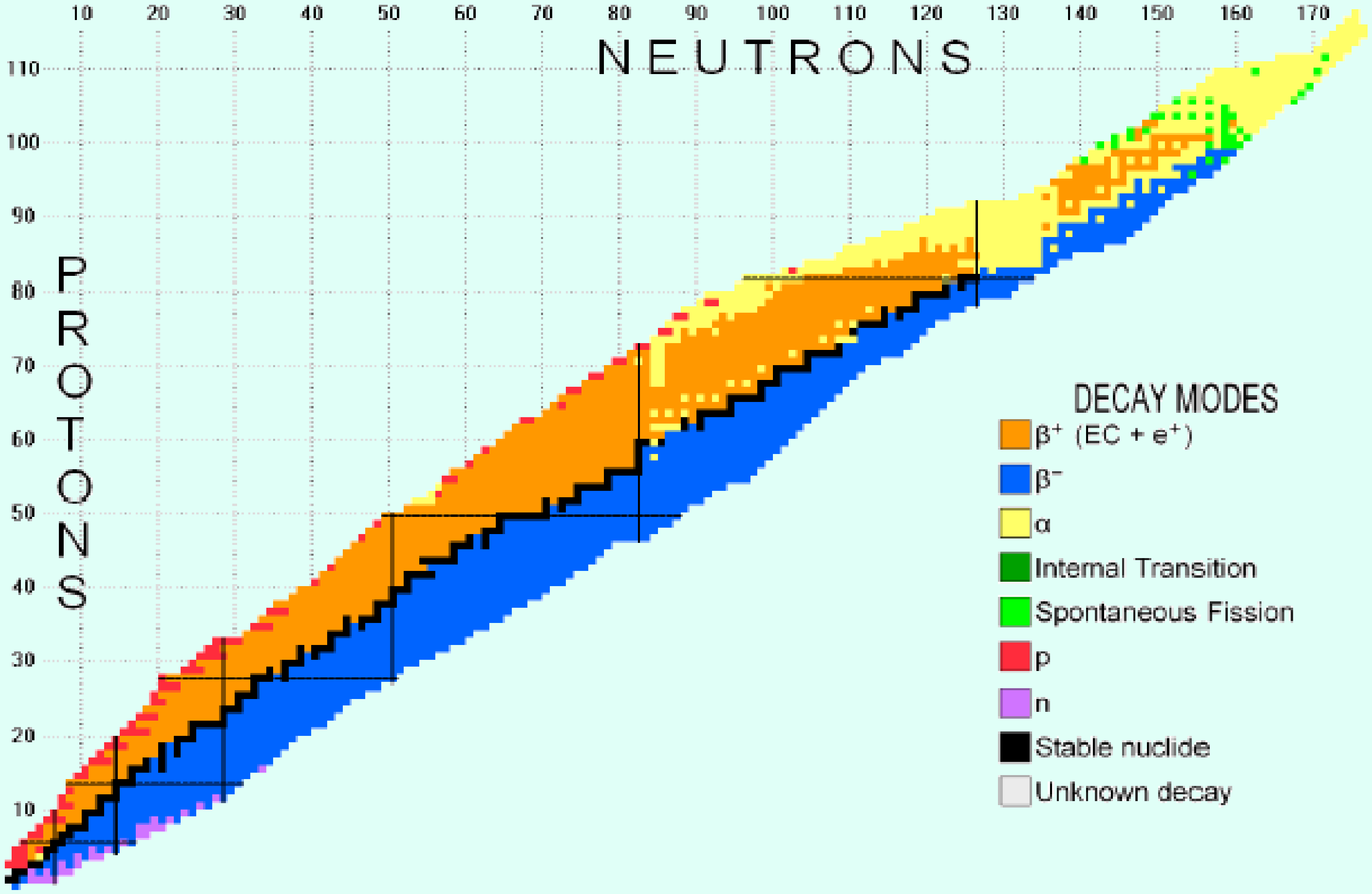
Bharathiar University
Coimbatore. India.

1. Introduction

Bharathiar University
Coimbatore. India.



Superheavy Elements

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Superheavy elements are the trans-actinide elements beginning with Rutherfordium (Z=104). They have all been made artificially and currently have no practical purpose because of their very short life times from few minutes to few milliseconds making the studies very hard and serve purpose only for research.

The fundamental interest in heavy element research is connected to the questions

How many elements may exist in nature ?
How heavy can nuclei be ?
How do nuclei behave in the presence of strong Coulomb forces?
What would be the next magic numbers for proton and neutron?

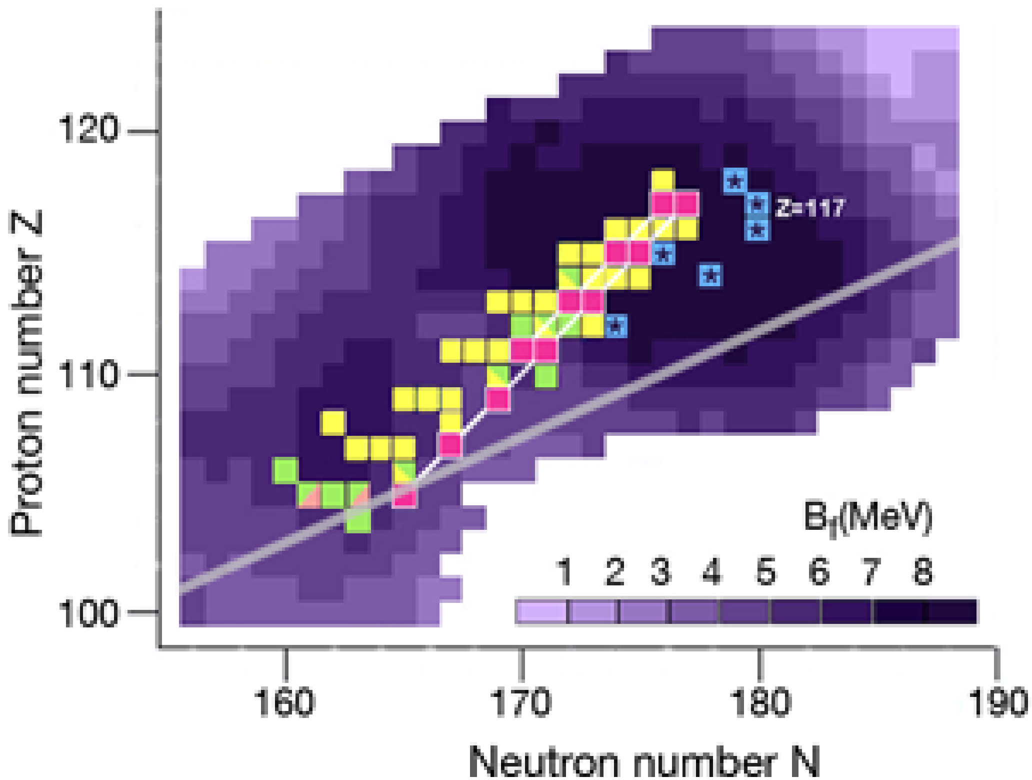
These kind of studies helps as a stringent test to know the validity of existing theoretical models.

Why because

- No consensus: (For Island of stability)
- In mid-1960s, a number of theoretical calculations predicted that an atom with the doubly-magic nucleus containing 114 protons and 184 neutrjons should be extra stable.
- Different parametrization within the Skyrme HF and RMF produce quite different predictions for the next spherical doubly magic nuclei
- namely Z =114, 120 and/or 126 with N =172 or 184. (Spherical RMF, Axially deformed RMF, SHF with different parameter sets which reproduces the g.s. properties)
- effective field theory predicts Z =120 and N =172 and Z =120 and N =258 as possible spherical doubly magic superheavy nuclei.

Experimental challenge

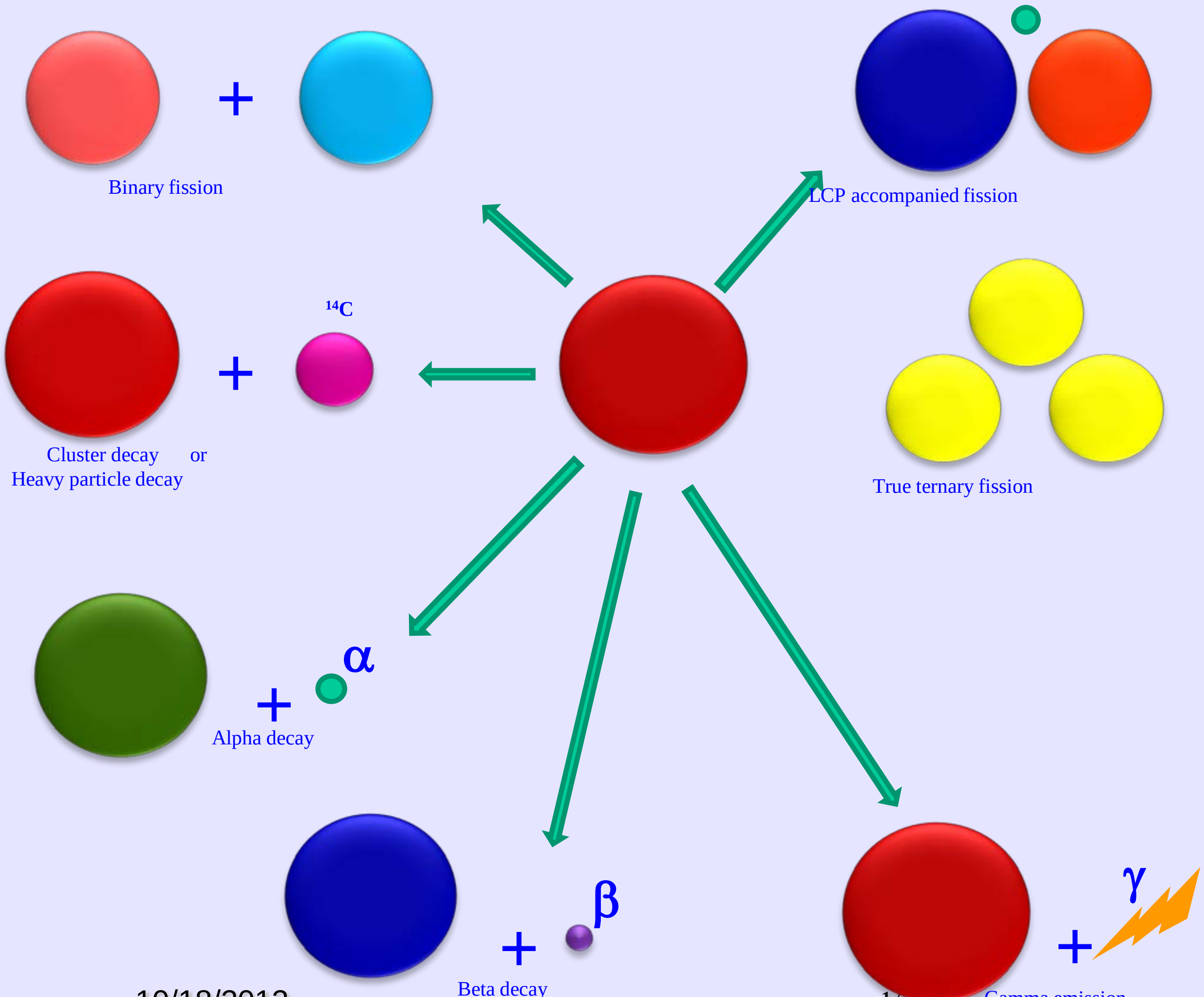
- Over the last thirty years, experimentalists are undergoing an expedition to explore the predicted “island of superheavy elements”—a region of increasingly stable nuclei around atomic number 114
- So far they have reported, on average, the discovery of one new element every two and a half years.

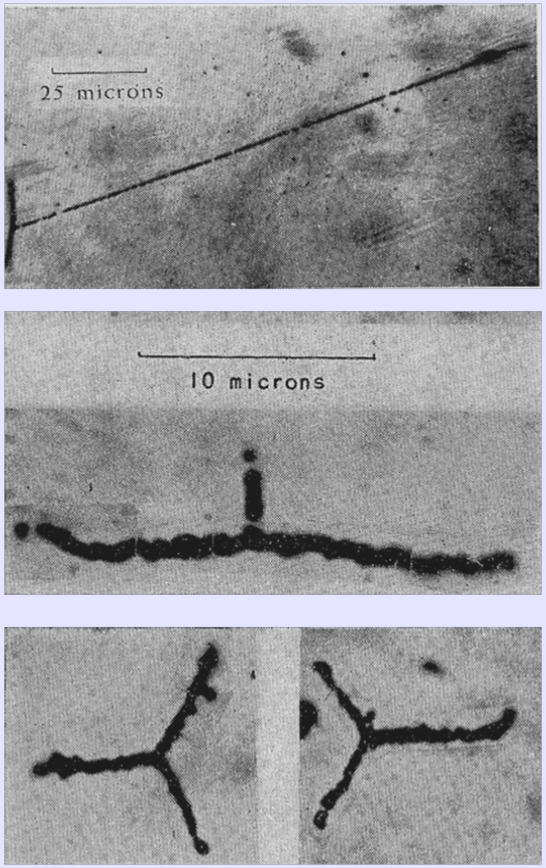


Latest discovery

- a new element with atomic number 117. Two isotopes of the new, still unnamed, element were produced from **nuclear fusion reactions** from a beam of ^{48}Ca ions that impinged on target nuclei of ^{249}Bk. (Published in PRL 104(2010)142502). (JINR, RIAR, LLNL, ORNL, VU and UON) – Lead by Yu.Ts. Oganessian
- This was a 2 year campaign began at the High Flux Isotope Reactor in Oak Ridge with a 250-day irradiation to produce 22 mg of berkelium. (3.5 Million dollars, J. Hamilton, A.V. Ramayya of VU)
- followed by 90 days of processing at ORNL to separate and purify the berkelium, target preparation at Dimitrovgrad,
- 150 days of bombardment at most powerful HI accelerators at Dubna
- Data analysis at Livermore and Dubna, and assessment and review of the results by the team.
- This discovery fills the gap between elements 116 and 118, so that now elements are continuously known from Z=1 up to element 118

Different decay modes





S. L. Muga *et.al*. (1961)

True Ternary Fission:

Collinear Cluster Tripartition (CCT)

A new kind of radioactive cluster decay

Wolfram von Oertzen
Helmholtz-Zentrum BERLIN (former HMI)
and Freie Universität Berlin

In collaboration with:
Y. V. Pyaktkov, D. Kamanin et al. (FLNR, JINR, Dubna)
and M. Balasubramanian (Bharathiar University, Coimbatore, India)

Y.V. Pyatkov, D. Kamanin , W von Oertzen et al. , Eur. Phys. J. A •• (2010) 29
K. Manimaran and M. Balasubramanian, Phys.Rev. C•• (2011) 034609

Slide: 1

- Ternary fission is defined as a nuclear break-up into three fragments which covers a spectrum of fission events from one end in which a scission neutron accompanies two main fission fragments, to the other in which three fragments of about equal masses are emitted.
- The ternary fission process with three charged particles in the outgoing channel, with the third particle being very light compared to the fission fragments are called as particle accompanied fission or light charged particle accompanied fission.
- The spontaneous break-up into three nuclei of about equal mass the so called true ternary fission has not yet been observed but theoretically is being studied.

First evidence of TF was reported by Alvarez in 1943, $^{235}U(n,TF)$ with the emission of alpha particles along with main fission fragments.

(Based on LDM in 1958, Swiatecki predicted TF, Quaternary and Quinary Fission)

In TF, the light charged particles are born along with main fragments at scission configuration.

The Coulomb force will then expel the light particle roughly at right angles to the heavy fragments motion (also supported by the measured energy spectra and angular distribution.) (U -> Ba + Kr + Alpha)

This process is a rare one as it occurs about once in ~260 binary fission events, in ^{252}Cf.

In TF in some cases the light cluster is also born in an excited state, and decays to ground state by emitting gamma rays.

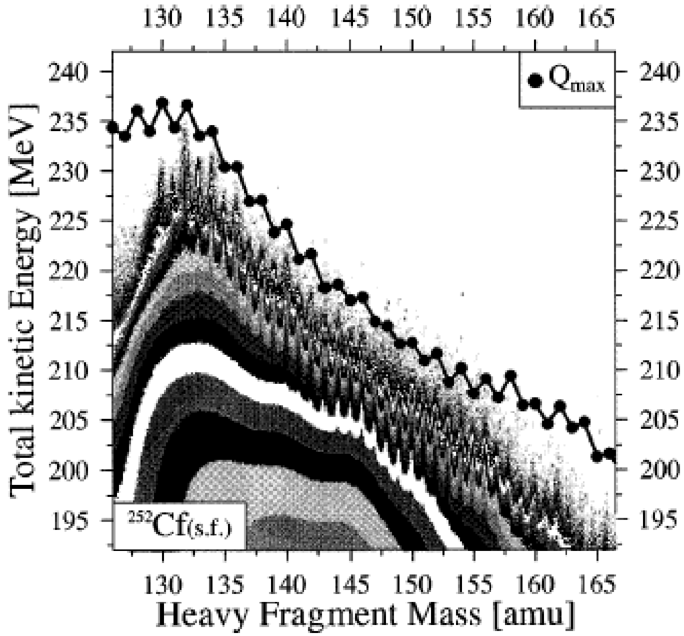
Though a rare process, a major interest has been mounted to obtain additional data to know more about the dynamics.

Experiments on TF gives, evidence for two different modes of ternary fission, hot and the cold.

In alpha accompanied fission of ^{252}Cf the majority of the fissions are hot, while for ^{10}Be-accompanied fission the cold process dominates – as supported by theory

In the limiting case of cold fission, the fission process proceeds with no neutron evaporation and in some cases gamma emission is virtually absent, resulting in the formation of fragments into their g.s.

Cold ternary decays should produce all the three fragments at very low excitation energy and, consequently, with very high kinetic energies – very compact shapes at the scission point and deformations close to those of their g.s.



(F. Gonnenwein et al)

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

LCP	Reaction	Energy (MeV)	MPE (MeV)	Yield
^{3}H	$^{235}U(n,f)$	-	8.0±0.2	-
^{3}H	$^{235}U(n,f)$	5-18	15.8±0.1	-
^{3}H	$^{233}U(n,f)$	5-18	15.8±0.1	-
^{3}H	$^{239}Pu(n,f)$	5-18	15.9±0.2	-
^{3}H	$^{241}Pu(n,f)$	5-18	15.9±0.3	-
^{4}He	$^{233}U(n,f)$	10-34	15.8±0.1	-
^{4}He	$^{235}U(n,f)$	8-26	15.4±0.2	-
^{4}He	$^{235}U(n,f)$	10-32	15.8±0.1	-
^{4}He	$^{239}Pu(n,f)$	8-34	15.9±0.1	-
^{4}He	$^{241}Pu(n,f)$	10-35	15.9±0.1	-
^{4}He	$^{232}Th(n,f)$	8-28	15.8±0.2	-
^{5}He	$^{235}U(n,f)$	11	11.6±1.4	-
^{8}Li	$^{249}Cf(n,f)$	-	15.1±1.4	$2.6\pm0.7\times10^{-6}$
^{9}Li	$^{249}Cf(n,f)$	-	12.5±0.9	$3.8\pm1.6\times10^{-6}$
^{10}Be	$^{249}Cf(n,f)$	-	17.5±0.4	$3.8\pm0.7\times10^{-5}$
^{11}Be	$^{249}Cf(n,f)$	-	16.5±1.3	$4.7\pm1.2\times10^{-6}$
^{12}Be	$^{249}Cf(n,f)$	-	15.1±1.1	$2.7\pm0.7\times10^{-6}$
^{12}Be	$^{249}Cf(n,f)$	-	21.8±0.3	$1.5\pm0.4\times10^{-6}$
^{13}B	$^{249}Cf(n,f)$	-	20.1±1.1	$2.4\pm0.6\times10^{-6}$
^{14}B	$^{249}Cf(n,f)$	-	17.0±1.2	$1.4\pm0.4\times10^{-5}$
^{15}B	$^{249}Cf(n,f)$	-	16.8±1.9	$9.1\pm4.1\times10^{-6}$
^{14}C	$^{249}Cf(n,f)$	-	27.6±0.3	$1.3\pm0.2\times10^{-5}$
^{15}C	$^{249}Cf(n,f)$	-	25.1±0.5	$5.3\pm1.1\times10^{-6}$
^{16}C	$^{249}Cf(n,f)$	-	24.4±1.1	$4.8\pm1.1\times10^{-6}$
^{17}C	$^{249}Cf(n,f)$	-	21.3±1.7	$7.5\pm2.8\times10^{-7}$
^{18}C	$^{249}Cf(n,f)$	-	20.4±2.8	$2.4\pm0.7\times10^{-7}$
^{16}N	$^{249}Cf(n,f)$	-	25.9±2.2	$1.5\pm0.4\times10^{-7}$
^{17}N	$^{249}Cf(n,f)$	-	25.0±1.6	$8.1\pm2.0\times10^{-7}$
^{18}N	$^{249}Cf(n,f)$	-	23.8±1.5	$4.5\pm1.1\times10^{-7}$
^{20}O	$^{249}Cf(n,f)$	-	31.4±1.7	$25.0\pm0.7\times10^{-8}$
^{21}O	$^{249}Cf(n,f)$	-	24.2±1.2	$6.4\pm1.3\times10^{-7}$
^{22}O	$^{249}Cf(n,f)$	-	33.0±7.4	$4.2\pm1.6\times10^{-7}$
^{21}F	$^{249}Cf(n,f)$	-	26.0±2.1	$1.6\pm0.4\times10^{-7}$
^{22}F	$^{249}Cf(n,f)$	-	33.8±10.5	$1.4\pm0.8\times10^{-7}$
^{24}F	$^{249}Cf(n,f)$	-	26.3±2.8	$8.3\pm4.0\times10^{-8}$
^{24}Ne	$^{249}Cf(n,f)$	-	33.9±2.9	$2.4\pm0.6\times10^{-7}$
^{27}Na	$^{249}Cf(n,f)$	-	38.4±8.2	$8.2\pm3.2\times10^{-8}$
^{30}Na	$^{249}Cf(n,f)$	-	31.7±8.6	$2.2\pm2.2\times10^{-8}$
^{30}Mg	$^{249}Cf(n,f)$	-	34.9±3.7	$1.3\pm0.4\times10^{-7}$

2. Three Cluster Model

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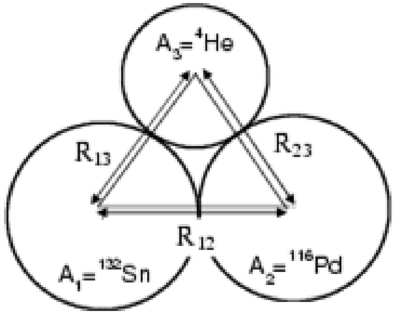
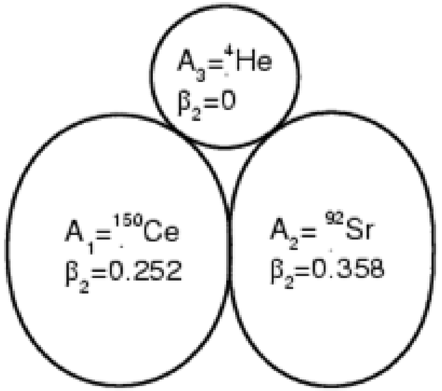
Three cluster model is worked out in terms of:

I. Mass asymmetry (η)
II. Charge asymmetry (η_Z)
III. Relative separation (R)
IV. Deformation (β_2)
V. Orientation angle (θ)
VI. Fragment mass number (A_3)

a) Spherical



b) With β_2, 90° - 90°



$$\eta = \frac{A_1 - A_2}{A_1 + A_2} \qquad \eta_z = \frac{Z_1 - Z_2}{Z_1 + Z_2}$$

$Q = E_1+E_2+E_3$ with Q-value for the three decay products defined as

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

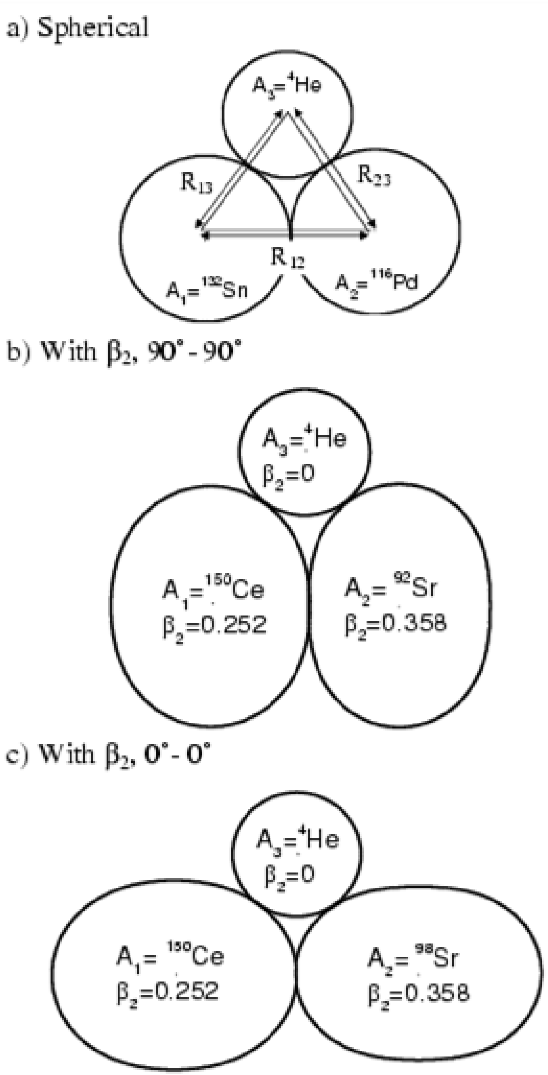
M – Mass excess of decaying nucleus
m – mass excesses of product nuclei.

The three body ternary fragmentation potential is defined as

$$V_{tot} = \sum_{i=1}^{3}\sum_{j>i}^{3}\left(B_{ii} + V_{ij}\right)$$

B_{ii} are binding energies

$$V_{ij} = V_{Cij} + V_{Nij}$$



The Coulomb interaction between the three spherical nuclei is given as

$$V_{Cij} = \frac{Z_i Z_j e^2}{R^s{}_{ij}}$$

For deformed and oriented case

$$V_C \underset{i\;j}{=} \frac{Z_i Z_j e^2}{R^s_{i\,j}} + 3 Z_i Z_j e^2$$

$$\times \sum_{\lambda,\,k=i,j} \frac{1}{2\lambda+1} \frac{R_k^{\lambda}(\alpha_k)}{R^{\lambda+1}} Y_\lambda^{(0)}(\theta_k)$$

$$\times \left[\beta_{\lambda k} + \frac{4}{7} \beta_{\lambda k}^2 Y_\lambda^{(0)}(\theta_k) \right]$$

With,

$$R^{s}_{ij} = R_{ij} + s_{ij}$$

$$R_{ij} = r_0\left(A_i^{1/3} + A_j^{1/3}\right)$$

the relative separation between fragments,

Radius of the fragments

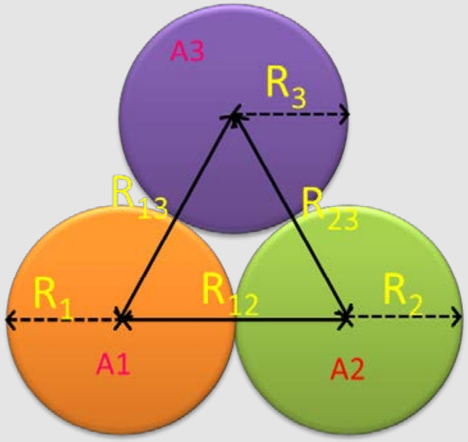
$$R_{0i} = 1.28A_i^{1/3} - 0.76 + 0.8A_i^{-1/3}$$ Spherical case

$$R_i(\alpha_i) = R_{0i}\left[1 + \sum_{\lambda} \beta_{\lambda i} Y_{\lambda}^{(0)}(\alpha_i)\right]$$ Deformed case

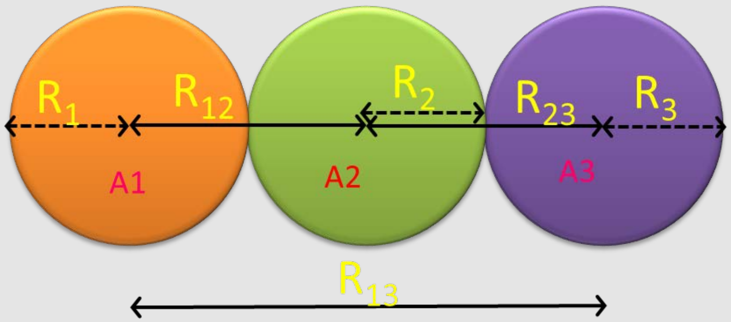
S_{ij} - surface separation

For touching configuration, $s = s_{12} = s_{13} = s_{23} = 0$

Equatorial configuration



Collinear configuration



$$s_{12} = s_{23} = s_{13} = s$$

$$s_{12} = s_{23} = s; \qquad s_{13} = 2(R_2 + s)$$

For attractive part

Nuclear interaction potential (V_{Nij})

Yukawa plus exponential potential (For spherical fragments)

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

Nuclear Proximity potential (For deformed fragments)

$$V_P = 4\pi \bar{R} \gamma b \phi(\xi)$$

In TCM the decay constant and half-life are defined as

$$\lambda = PP_0 P_3 \upsilon; \qquad T_{1/2} = \frac{\ln 2}{\lambda}$$

ν ⟶ is the assault frequency

P_3⟶ is the preformation probability of the third fragment (assumed to be equal to unity)

P_0 ⟶ is the preformation probability of the other two fragments calculated by solving Schrodinger equation

P⟶ is the penetration probability of the fragments to cross the interaction barrier

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

The relative yield for all the charge minimized ternary fragmentation channels are calculated

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

3. α-accompanied fission of ^{252}Cf

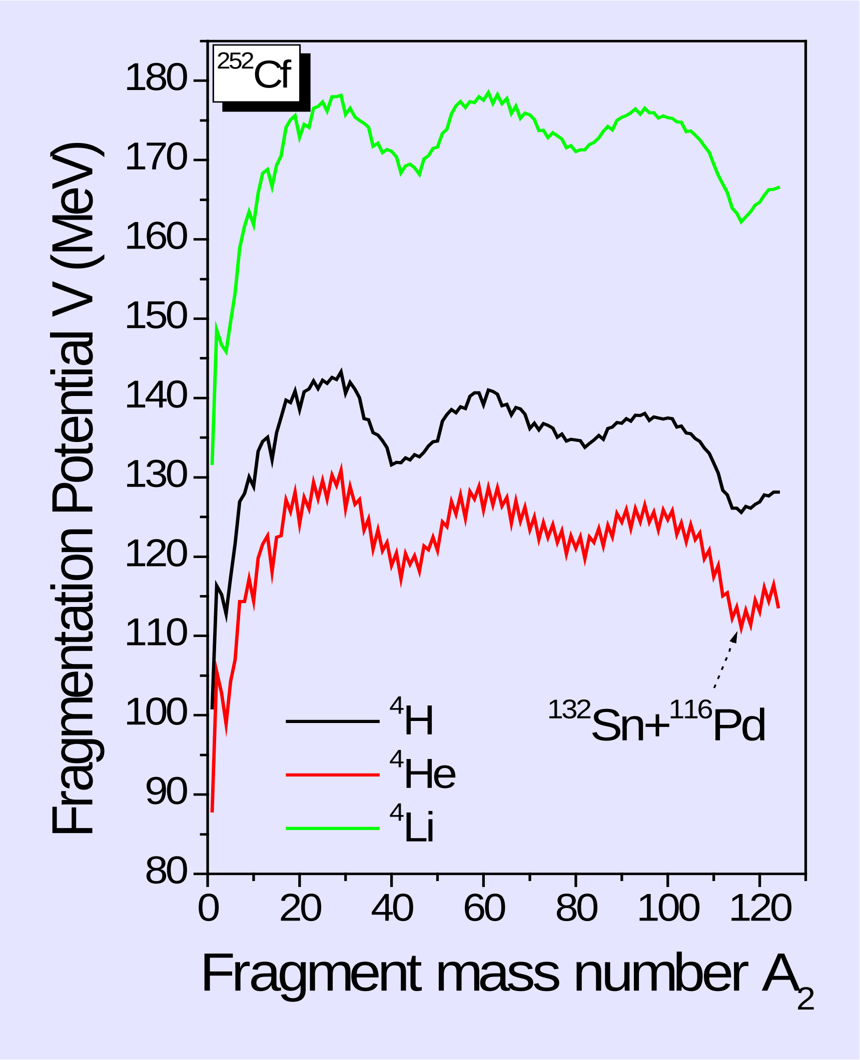
Bharathiar University
Coimbatore. India.

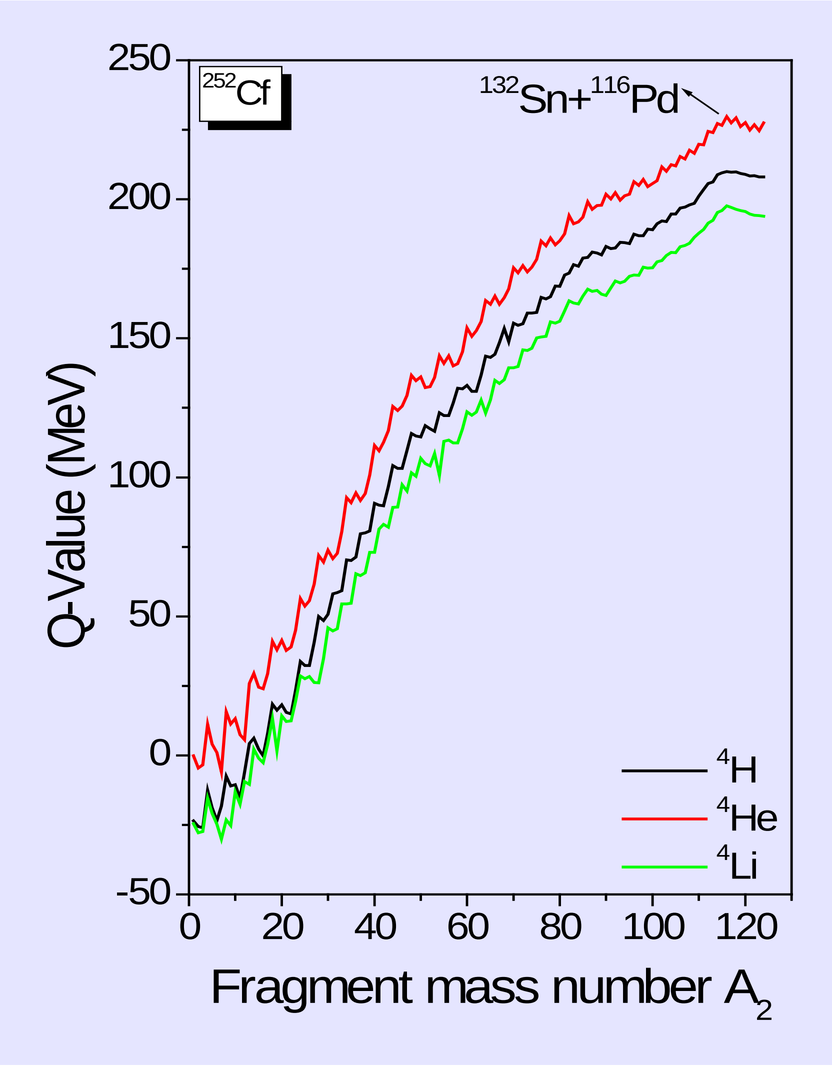
Californium (Cf) nuclei offer interesting possibilities for both the theoretical and experimental investigations of various spontaneous decay modes such as Spontaneous binary fission , ternary fission and cluster radioactivity.

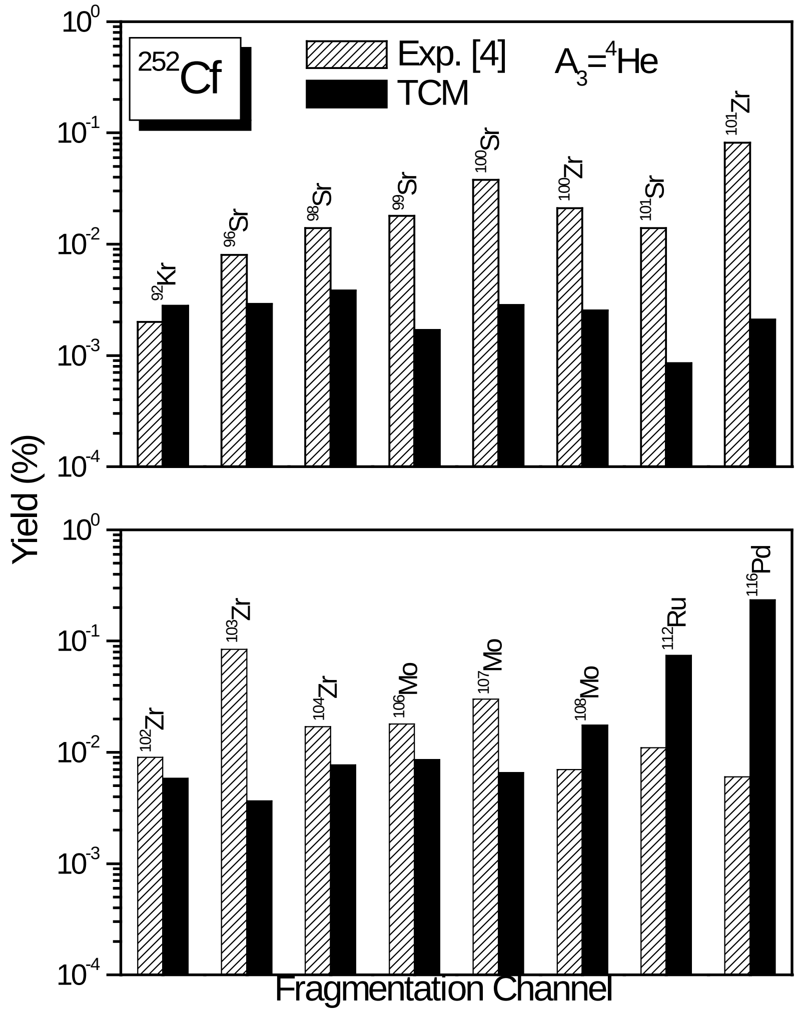
Spontaneous ternary fissions of ^{252}Cf have been recently studied quite extensively with ^{4}He, ^{10}Be and ^{14}C nuclei as third particle.

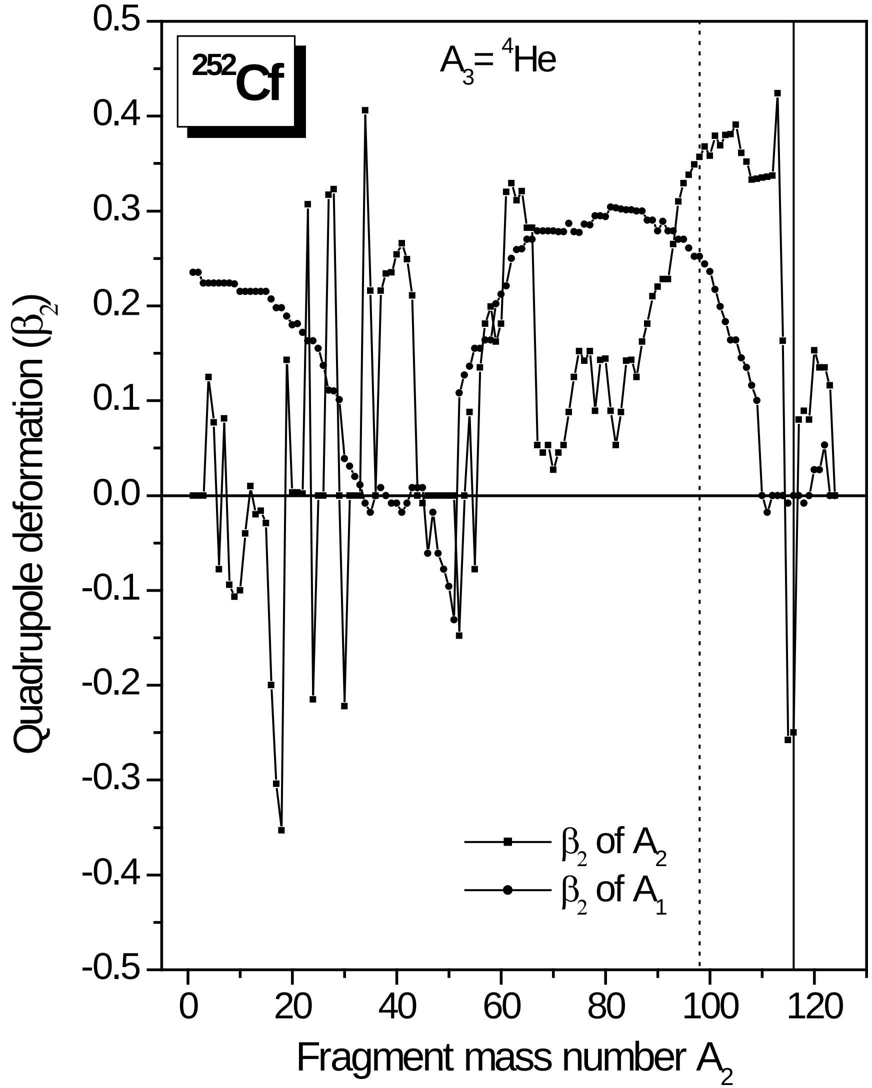
The cold a-accompanied TF of ^{252}Cf was recently observed by Ramayya *et al* in which the yields for correlated pair of Kr-Nd, Sr-Ce, Zr-Ba, Mo-Xe, Ru-Te, Pd-Sn associated with ^{4}He as the third particle has been measured.

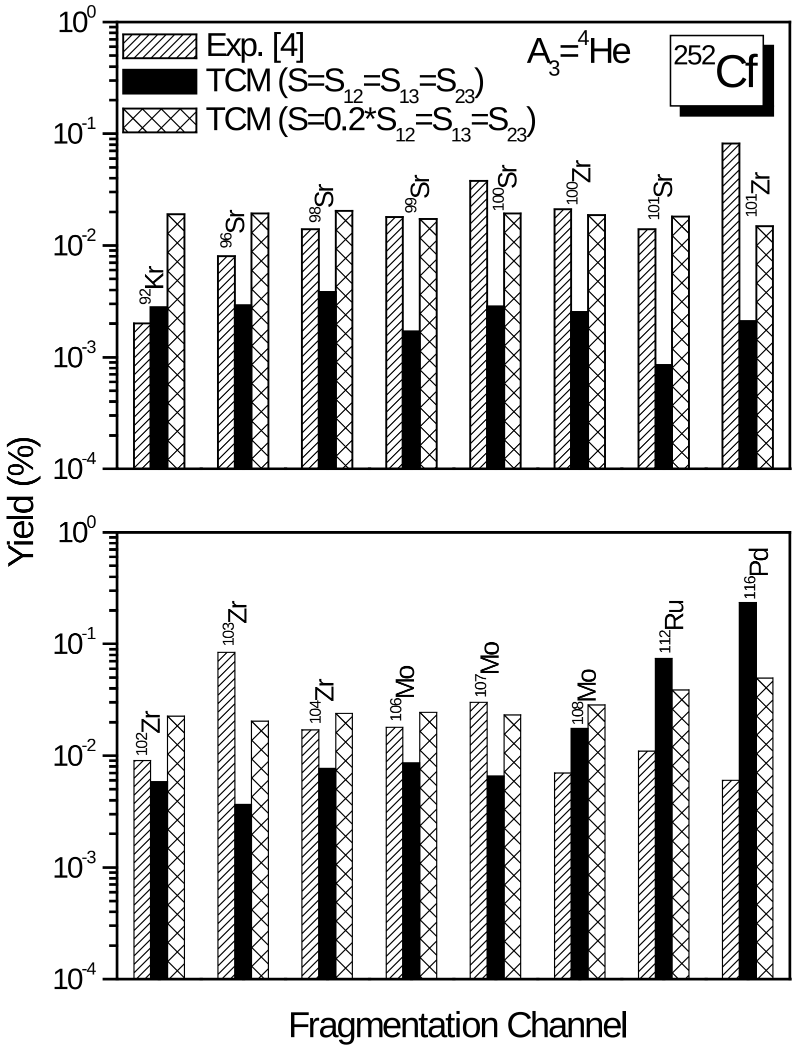
This experiment was the first evidence for the cold (neutron less) ternary fission.


^{252}Cf
Fragmentation Potential V (MeV)
Fragment mass number A_2
^{4}H
^{4}He
^{4}Li
^{132}Sn+^{116}Pd
180
170
160
150
140
130
120
110
100
90
80
0
20
40
60
80
100
120


^{252}Cf
Q-Value (MeV)
Fragment mass number A_2
^{132}Sn+^{116}Pd
^{4}H
^{4}He
^{4}Li
250
200
150
100
50
0
-50
0
20
40
60
80
100
120


252Cf
Exp. [4]
TCM
A3=4He
92Kr
96Sr
98Sr
99Sr
100Sr
100Zr
101Sr
101Zr
102Zr
103Zr
104Zr
106Mo
107Mo
108Mo
112Ru
116Pd
Yield (%)
Fragmentation Channel


252Cf
A3= 4He
Quadrupole deformation (β2)
Fragment mass number A2
β2 of A2
β2 of A1
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
0
20
40
60
80
100
120


Exp. [4]
TCM (S=S12=S13=S23)
TCM (S=0.2*S12=S13=S23)
A3=4He
252Cf
92Kr
96Sr
98Sr
99Sr
100Sr
100Zr
101Sr
101Zr
102Zr
103Zr
104Zr
106Mo
107Mo
108Mo
112Ru
116Pd
Yield (%)
Fragmentation Channel

4. Role of deformation and orientation

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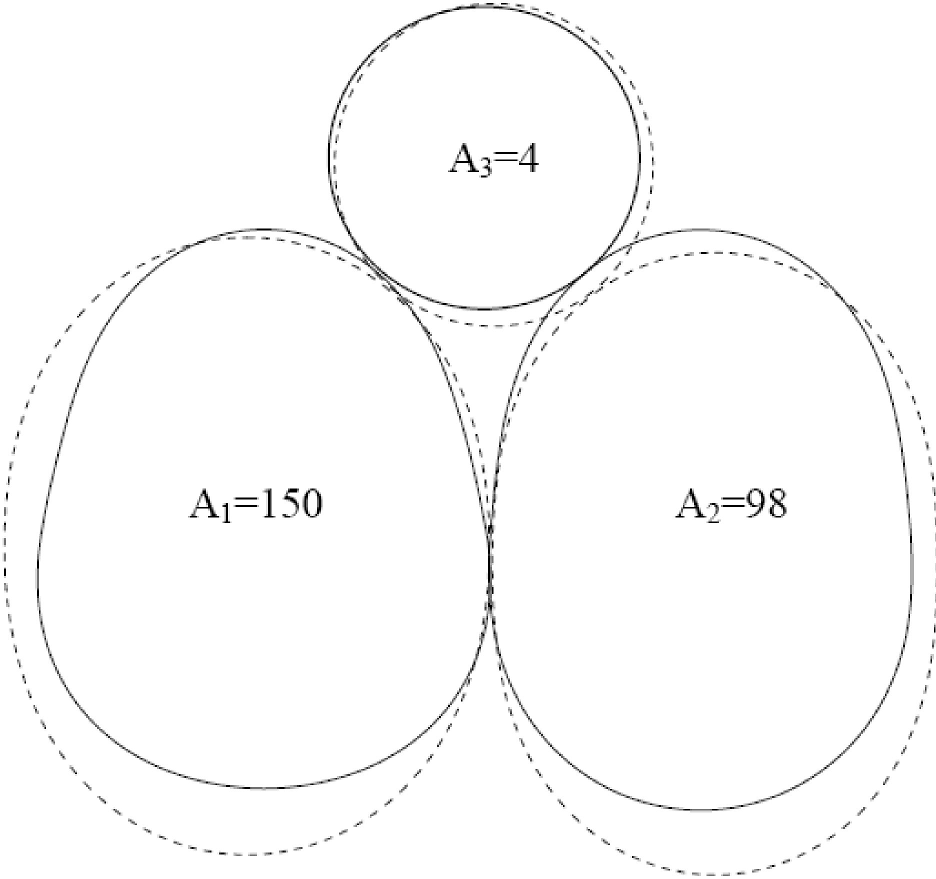
Coimbatore. India.

In TCM, we are considering the heavy (A_1) and light (A_2) fragments as deformed (and the LCP (A_3) as spherical). Their interaction potentials are calculated by including these effects.

With incorporation of deformation,

we studied 90-90 (Belly-Belly) and 0-0 (Pole-Pole) orientations.



Belly – Belly

90^o-90^o

Dashed line - β_2

Solidline – $\beta_2+\beta_4$

$A_1={}^{150}Ce$ $A_2={}^{98}Sr$

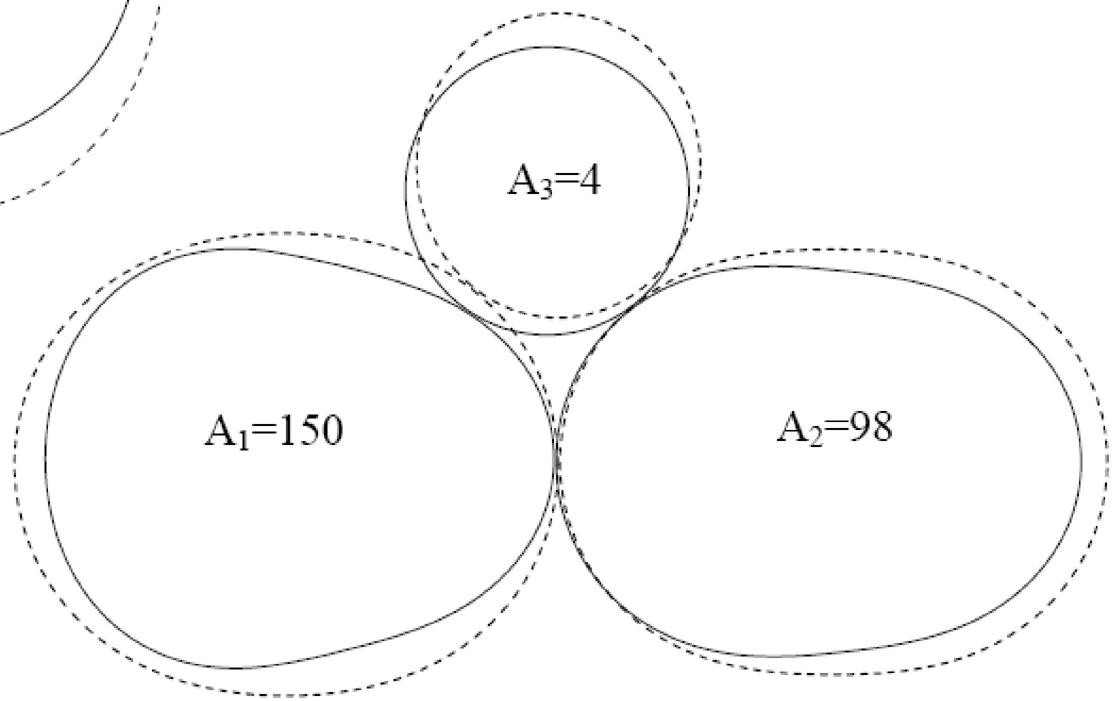
Pole – Pole

0^o-0^o

Dashed line - β_2

Solidline – $\beta_2+\beta_4$

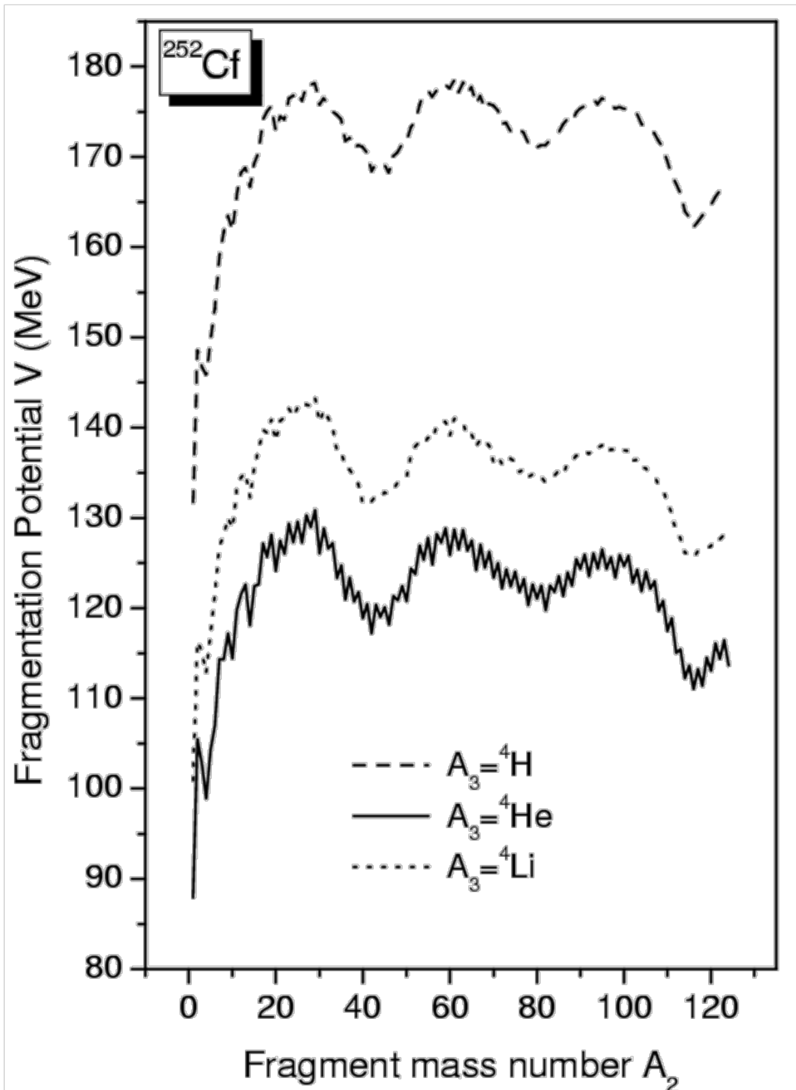
$A_1={}^{150}Ce$ $A_2={}^{98}Sr$

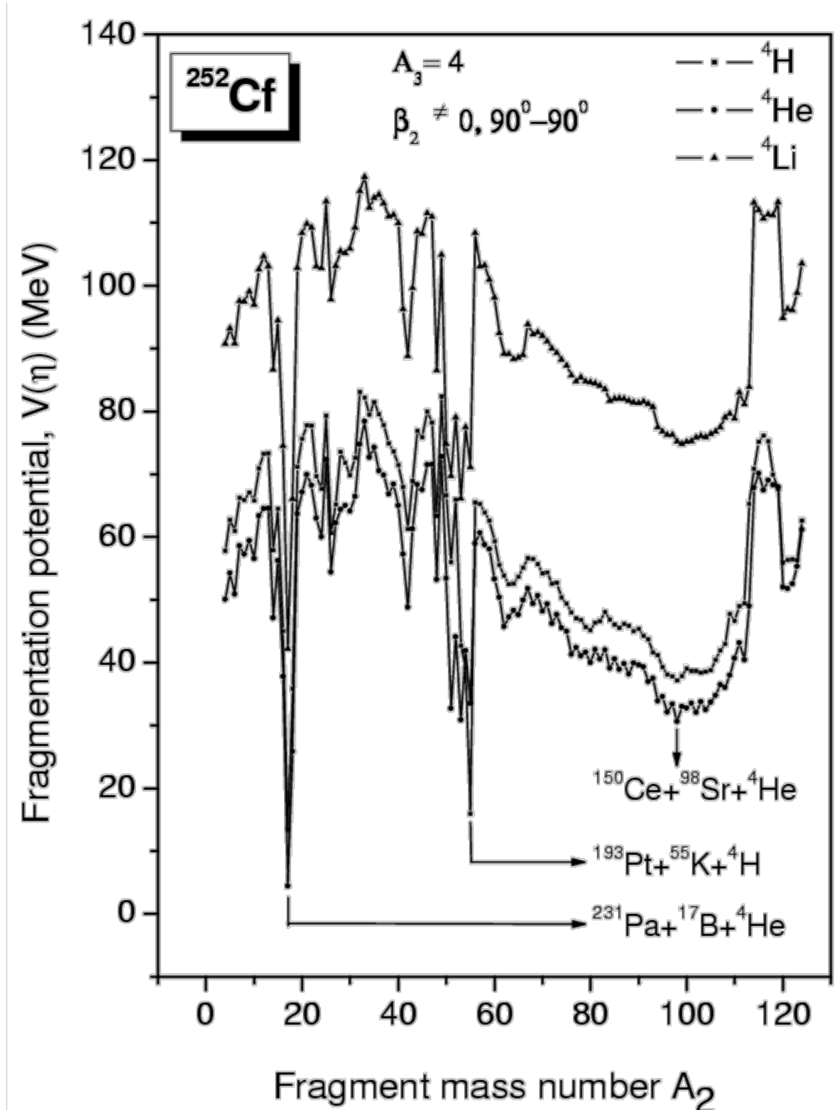


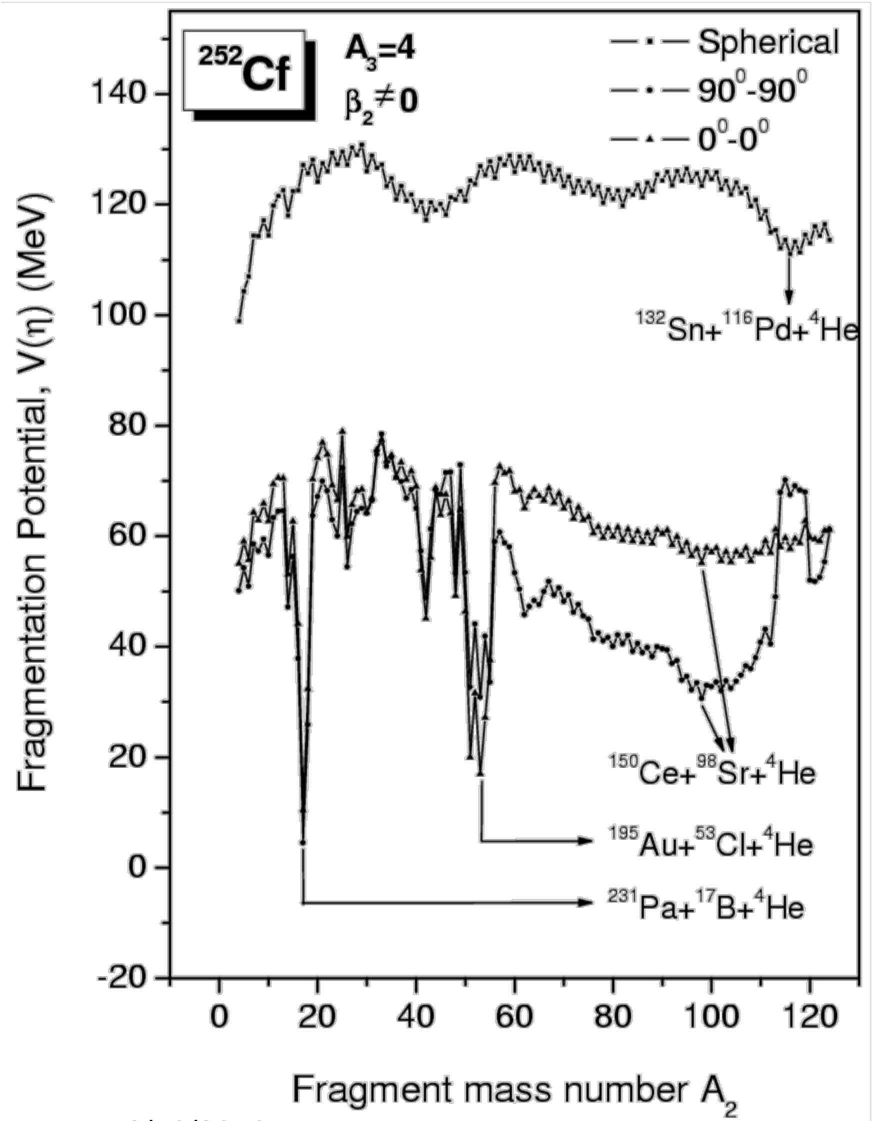
For Spherical case the deep minima in PES - Sn+ Pd+ He (^{4}He accompanied TF of ^{252}Cf)

The experimentally measured yields, has largest yields for the fragment combinations like Zr-Ba, Sr-Ce.

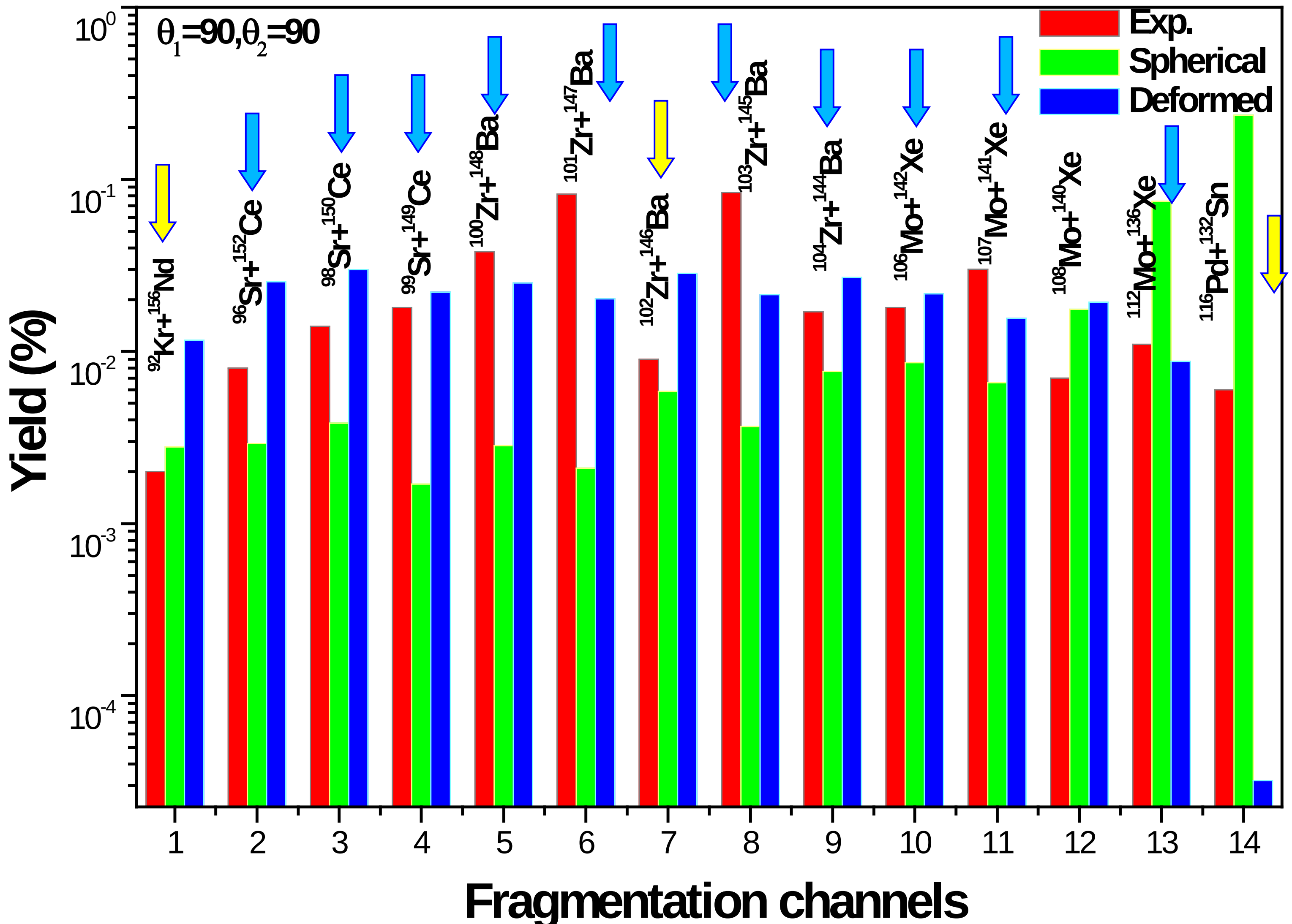
With deformation and orientation included the minima in spherical case were no longer present rather new cold valleys are seen in the PES.


^{252}Cf
Fragmentation Potential V (MeV)
Fragment mass number A_2
A_3=^{4}H
A_3=^{4}He
A_3=^{4}Li


^{252}Cf
A_3= 4
$\beta_2 \neq 0, 90^0$–90^0
^{4}H
^{4}He
^{4}Li
Fragmentation potential, V(η) (MeV)
Fragment mass number A_2
^{150}Ce+^{98}Sr+^{4}He
^{193}Pt+^{55}K+^{4}H
^{231}Pa+^{17}B+^{4}He



90^o-90^o is the Minimum Among all


θ1=90,θ2=90
Exp.
Spherical
Deformed
92Kr+156Nd
96Sr+152Ce
98Sr+150Ce
99Sr+149Ce
100Zr+148Ba
101Zr+147Ba
102Zr+146Ba
103Zr+145Ba
104Zr+144Ba
106Mo+142Xe
107Mo+141Xe
108Mo+140Xe
112Mo+136Xe
116Pd+132Sn
Yield (%)
10^0
10^-1
10^-2
10^-3
10^-4
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Fragmentation channels

These results clearly shows that, the inclusion of deformation indeed increases the yield values favourable to the experimental values and in particular corresponding to 90-90 orientation matches well with that of experimental results.

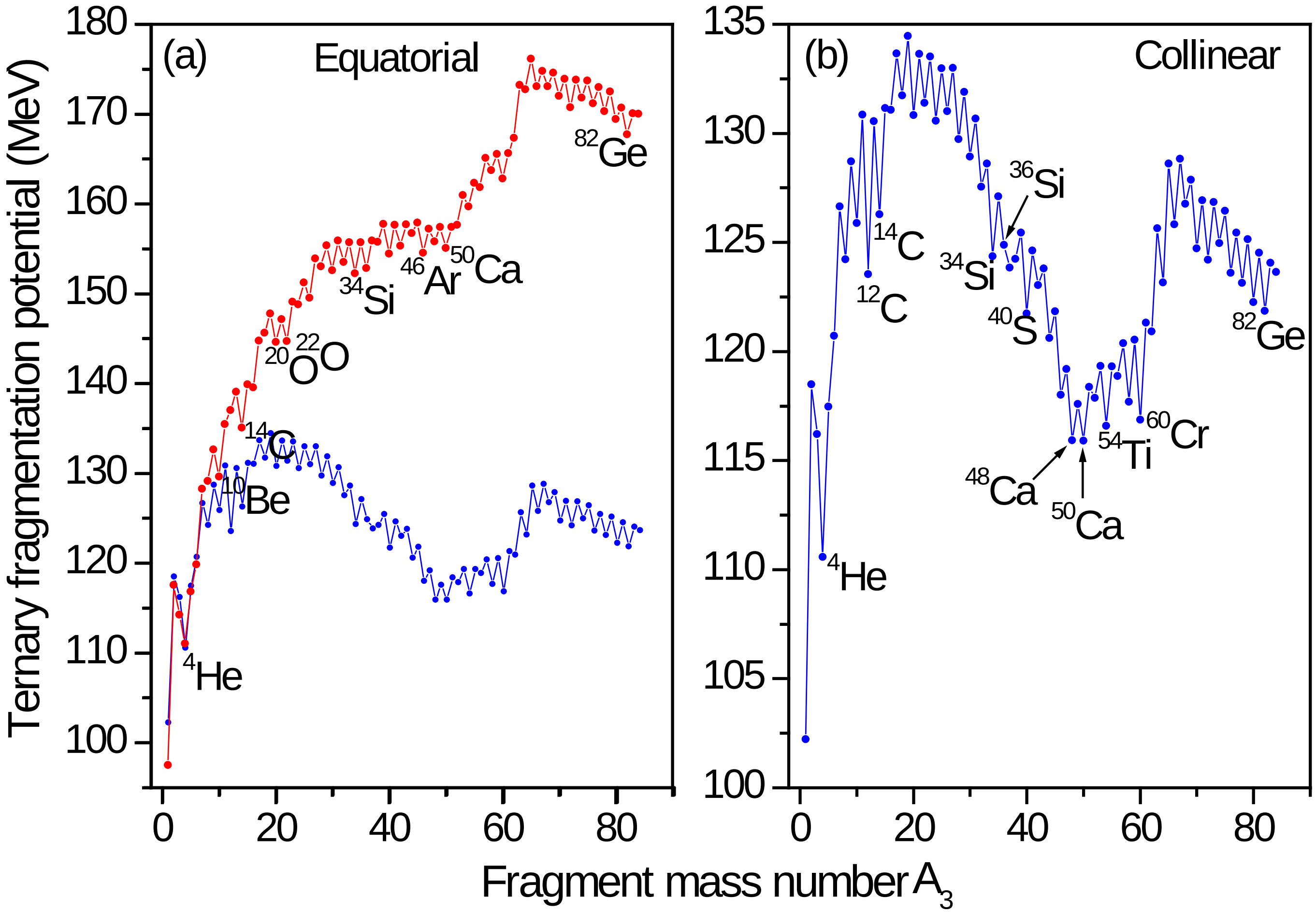
- If a system A undergoes ternary fission it can have thousands possibilities with respect mass asymmetries and charge asymmetries.

- To avoid the repetition of fragmentation

$$A_1 \geq A_2 \geq A_3$$

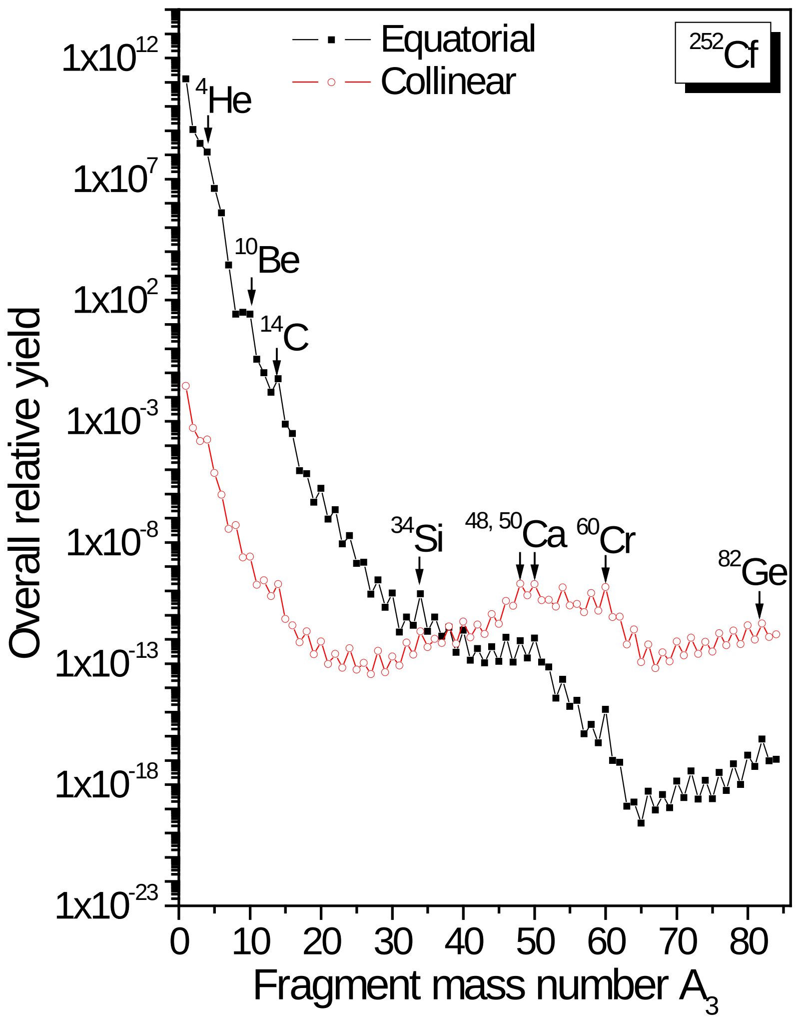
- All the possible ternary fragmentations of ^{252}Cf in two different configurations (Equatorial and Collinear) are studied

- The third fragment can have mass number $A_3 = 1$ to 84.


(a)
Equatorial
Ternary fragmentation potential (MeV)
180
170
160
150
140
130
120
110
100
0
20
40
60
80
^{4}He
^{10}Be
^{14}C
^{20}O
^{22}O
^{34}Si
^{46}Ar
^{50}Ca
^{82}Ge
(b)
Collinear
135
130
125
120
115
110
105
100
^{4}He
^{12}C
^{14}C
^{34}Si
^{36}Si
^{40}S
^{48}Ca
^{50}Ca
^{54}Ti
^{60}Cr
^{82}Ge
Fragment mass number A_3

Equatorial configuration			Collinear configuration		
Fragmentation channel	$V(\eta)$ (MeV)	Q value (MeV)	Fragmentation channel	$V(\eta)$ (MeV)	Q value (MeV)
$^{130}Sn+^{121}Cd+^{1}n$	97.51	229.36	$^{130}Sn+^{121}Cd+^{1}n$	102.23	229.36
$^{131}Sn+^{119}Ag+^{2}H$	117.59	218.76	$^{131}Sn+^{119}Ag+^{2}H$	118.49	218.76
$^{133}Sb+^{116}Pd+^{3}H$	114.26	219.80	$^{133}Sb+^{116}Pd+^{3}H$	116.20	219.80
$^{132}Sn+^{116}Pd+^{4}He$	111.05	229.76	$^{132}Sn+^{116}Pd+^{4}He$	110.58	229.76
$^{131}Sn+^{116}Pd+^{5}He$	116.82	221.95	$^{131}Sn+^{116}Pd+^{5}He$	117.47	221.95
$^{130}Sn+^{116}Pd+^{6}He$	119.85	218.73	$^{130}Sn+^{116}Pd+^{6}He$	120.71	218.73
$^{133}Sb+^{112}Ru+^{7}Li$	128.28	215.44	$^{133}Sb+^{112}Ru+^{7}Li$	126.65	215.44
$^{132}Sn+^{112}Ru+^{8}Be$	129.16	222.85	$^{132}Sn+^{112}Ru+^{8}Be$	124.22	222.85
$^{131}Sn+^{112}Ru+^{9}Be$	132.68	217.59	$^{131}Sn+^{112}Ru+^{9}Be$	128.70	217.59
$^{134}Te+^{108}Mo+^{10}Be$	129.67	218.00	$^{134}Te+^{108}Mo+^{10}Be$	125.88	218.00
$^{134}Te+^{107}Mo+^{11}Be$	135.48	212.01	$^{133}Sb+^{108}Mo+^{11}B$	130.85	217.61
$^{134}Te+^{106}Mo+^{12}Be$	137.01	210.77	$^{132}Sn+^{108}Mo+^{12}C$	123.54	223.72
$^{133}Sb+^{106}Mo+^{13}B$	139.07	214.96	$^{132}Sn+^{107}Mo+^{13}C$	130.54	222.17
$^{132}Sn+^{106}Mo+^{14}C$	135.08	225.94	$^{134}Te+^{104}Zr+^{14}C$	126.28	223.20
$^{134}Te+^{103}Zr+^{15}C$	139.90	218.27	$^{134}Te+^{103}Zr+^{15}C$	131.15	216.90
$^{134}Te+^{102}Zr+^{16}C$	139.55	218.46	$^{134}Te+^{102}Zr+^{16}C$	131.07	218.46
$^{133}Sb+^{102}Zr+^{17}N$	144.78	219.96	$^{133}Sb+^{102}Zr+^{17}N$	133.66	219.96
$^{132}Sn+^{102}Zr+^{18}O$	145.64	226.05	$^{132}Sn+^{102}Zr+^{18}O$	131.74	226.05
$^{132}Sn+^{101}Zr+^{19}O$	147.79	216.67	$^{131}Sn+^{102}Zr+^{19}O$	134.45	223.08
$^{132}Sn+^{100}Zr+^{20}O$	144.61	226.17	$^{134}Te+^{98}Sr+^{20}O$	130.83	223.24
$^{134}Sn+^{100}Zr+^{21}O$	147.18	220.58	$^{134}Te+^{97}Sr+^{21}O$	133.63	220.58
$^{134}Te+^{96}Sr+^{22}O$	144.74	223.05	$^{134}Te+^{96}Sr+^{22}O$	131.39	223.05
$^{134}Te+^{95}Sr+^{23}O$	149.10	218.90	$^{133}Sb+^{96}Sr+^{23}F$	133.52	224.68
$^{132}Sn+^{96}Sr+^{24}Ne$	148.79	231.40	$^{132}Sn+^{96}Sr+^{24}Ne$	130.58	231.40
$^{131}Sn+^{96}Sr+^{25}Ne$	151.25	228.66	$^{134}Te+^{93}Kr+^{25}Ne$	132.98	224.72
$^{134}Te+^{92}Kr+^{26}Ne$	149.55	226.85	$^{134}Te+^{92}Kr+^{26}Ne$	131.02	226.85
$^{133}Sb+^{92}Kr+^{27}Na$	153.92	228.53	$^{133}Sb+^{92}Kr+^{27}Na$	133.00	228.53
$^{132}Sn+^{92}Kr+^{28}Mg$	153.04	235.41	$^{132}Sn+^{92}Kr+^{28}Mg$	129.73	235.41
$^{132}Sn+^{91}Kr+^{29}Mg$	155.40	232.71	$^{135}Te+^{88}Se+^{29}Mg$	131.90	228.49
$^{134}Te+^{88}Se+^{30}Mg$	152.60	231.38	$^{134}Te+^{88}Se+^{30}Mg$	128.92	231.38
$^{135}Te+^{86}Se+^{31}Mg$	155.90	228.05	$^{133}Sb+^{88}Se+^{31}Mg$	130.68	226.27
$^{134}Te+^{86}Se+^{32}Mg$	153.54	230.30	$^{132}Sn+^{88}Se+^{32}Si$	127.54	239.69
$^{132}Sn+^{87}Se+^{33}Si$	155.70	233.68	$^{135}Te+^{84}Ge+^{33}Si$	128.61	233.21
$^{132}Sn+^{86}Se+^{34}Si$	152.26	242.57	$^{134}Te+^{84}Ge+^{34}Si$	124.35	237.34
$^{134}Te+^{83}Ge+^{35}Si$	155.72	234.47	$^{133}Sb+^{84}Ge+^{35}P$	127.10	237.92

Equatorial configuration			Collinear configuration		
Fragmentation channel	$V(\eta)$ (MeV)	Q value (MeV)	Fragmentation channel	$V(\eta)$ (MeV)	Q value (MeV)
$^{134}Te+^{82}Ge+^{36}Si$	152.86	237.22	$^{134}Te+^{82}Ge+^{36}Si$	124.88	237.22
$^{133}Sb+^{82}Ge+^{37}P$	155.90	239.48	$^{133}Sb+^{82}Ge+^{37}P$	123.83	239.48
$^{132}Sn+^{82}Ge+^{38}S$	155.76	244.79	$^{134}Te+^{80}Zn+^{38}S$	124.25	238.81
$^{131}Sn+^{82}Ge+^{39}S$	157.76	237.47	$^{134}Te+^{79}Zn+^{39}S$	125.44	236.77
$^{134}Te+^{78}Zn+^{40}S$	154.47	240.69	$^{134}Te+^{78}Zn+^{40}S$	121.73	240.69
$^{134}Te+^{77}Zn+^{41}S$	157.69	237.37	$^{133}Sb+^{78}Zn+^{41}Cl$	124.62	240.85
$^{134}Te+^{76}Zn+^{42}S$	155.34	239.70	$^{132}Sn+^{78}Zn+^{42}Ar$	123.04	245.37
$^{133}Sb+^{76}Zn+^{43}Cl$	157.73	242.16	$^{133}Sb+^{76}Zn+^{43}Cl$	123.80	242.16
$^{132}Sn+^{76}Zn+^{44}Ar$	156.76	247.83	$^{134}Te+^{74}Ni+^{44}Ar$	120.61	241.11
$^{131}Sn+^{76}Zn+^{45}Ar$	157.91	246.44	$^{134}Te+^{73}Ni+^{45}Ar$	121.83	240.14
$^{134}Te+^{72}Ni+^{46}Ar$	154.55	244.24	$^{134}Te+^{72}Ni+^{46}Ar$	118.02	244.24
$^{133}Sb+^{72}Ni+^{47}K$	157.22	241.56	$^{133}Sb+^{72}Ni+^{47}K$	119.18	245.88
$^{134}Te+^{70}Ni+^{48}Ar$	155.81	243.02	$^{132}Sn+^{72}Ni+^{48}Ca$	115.93	251.84
$^{131}Sn+^{72}Ni+^{49}Ca$	157.44	250.07	$^{131}Sn+^{72}Ni+^{49}Ca$	117.60	250.07
$^{132}Sn+^{70}Ni+^{50}Ca$	155.07	252.48	$^{132}Sn+^{70}Ni+^{50}Ca$	115.90	252.48
$^{131}Sn+^{70}Ni+^{51}Ca$	157.43	249.94	$^{131}Sn+^{70}Ni+^{51}Ca$	118.38	249.94
$^{130}Sn+^{70}Ni+^{52}Ca$	157.68	249.56	$^{134}Te+^{66}Fe+^{52}Ca$	117.88	243.36
$^{133}Sb+^{66}Fe+^{53}Sc$	160.96	244.49	$^{133}Sb+^{66}Fe+^{53}Sc$	119.34	244.49
$^{132}Sn+^{66}Fe+^{54}Ti$	159.72	249.72	$^{132}Sn+^{66}Fe+^{54}Ti$	116.58	249.72
$^{131}Sn+^{66}Fe+^{55}Ti$	162.32	246.91	$^{131}Sn+^{66}Fe+^{55}Ti$	119.31	246.91
$^{130}Sn+^{66}Fe+^{56}Ti$	161.83	247.23	$^{134}Te+^{62}Cr+^{56}Ti$	118.87	239.64
$^{131}Sn+^{64}Fe+^{57}Ti$	165.13	244.14	$^{133}Sb+^{62}Cr+^{57}V$	120.38	240.55
$^{134}Te+^{60}Cr+^{58}Ti$	163.76	238.81	$^{132}Sn+^{62}Cr+^{58}Cr$	117.69	245.55
$^{133}Sb+^{60}Cr+^{59}V$	165.56	240.82	$^{131}Sn+^{62}Cr+^{59}Cr$	120.53	242.62
$^{132}Sn+^{60}Cr+^{60}Cr$	162.83	247.17	$^{132}Sn+^{60}Cr+^{60}Cr$	116.87	247.17
$^{130}Sn+^{61}Cr+^{61}Cr$	165.63	242.04	$^{130}Sn+^{61}V+^{61}Mn$	121.32	239.49
$^{128}Sn+^{62}Cr+^{62}Cr$	167.35	242.09	$^{128}Sn+^{62}Cr+^{62}Cr$	120.91	242.09
$^{126}Cd+^{63}Mn+^{63}Mn$	173.23	242.75	$^{125}Cd+^{64}Cr+^{63}Fe$	125.64	240.60
$^{110}Mo+^{78}Zn+^{64}Fe$	172.74	243.00	$^{124}Cd+^{64}Cr+^{64}Fe$	123.16	243.00
$^{109}Mo+^{78}Zn+^{65}Fe$	176.15	245.44	$^{121}Pd+^{66}Fe+^{65}Fe$	128.60	245.44
$^{104}Zr+^{82}Ge+^{66}Fe$	173.07	258.73	$^{120}Pd+^{66}Fe+^{66}Fe$	125.81	248.18
$^{103}Zr+^{82}Ge+^{67}Fe$	174.81	256.91	$^{117}Pd+^{68}Fe+^{67}Fe$	128.83	244.31
$^{102}Zr+^{82}Ge+^{68}Fe$	173.11	258.59	$^{104}Zr+^{80}Zn+^{68}Ni$	126.76	259.02
$^{102}Zr+^{81}Ga+^{69}Co$	174.62	257.80	$^{109}Mo+^{74}Ni+^{69}Ni$	127.87	253.29
$^{102}Zr+^{80}Zn+^{70}Ni$	172.00	260.96	$^{102}Zr+^{80}Zn+^{70}Ni$	124.72	260.96



The relative yield corresponding to equatorial emission lies above the relative yield corresponding to the collinear emission of fragments up to third fragments with mass number A_3= 38 and beyond that the yield corresponding to collinear emission lies well above the relative yield of equatorial emission.

Light fragments prefer the equatorial emission and the heavy fragments prefer the collinear emission.

In particular the relative yield corresponding to the fragment ^{48}Ca and its neighboring nuclei is larger in collinear emission.

THANK YOU


05/09/2011