Dynamics of 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, A. Nazirov, et al. (FLNR, JINR, Dubna)
and M. Balasubramanian et al. (Bharathiar University, Coimbatore, India)

Y.V. Pyatkov, D. Kamanin , W von Oertzen et al. , Eur. Phys. J. A **45** (2010) 29
K. Manimaran and M. Balasubramanian, Phys.Rev. C **83** (2011) 034609

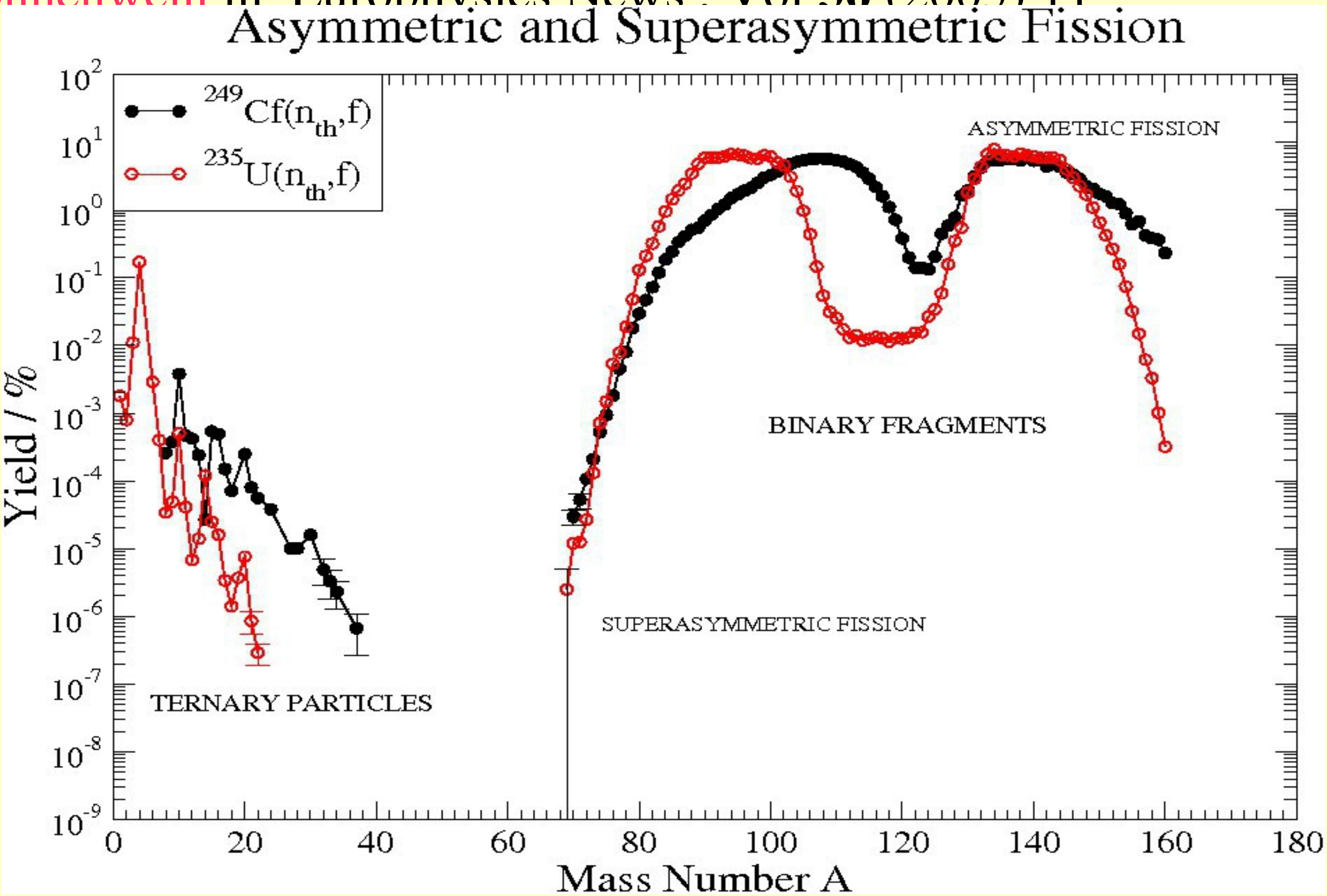
Some Milestones in the Physics of Fission

- 1938 - Binary fission of (^{235}U+n), *Hahn/Strassman*
- 1939 - Liquid Drop model for binary fission *Frisch/Meitner, J. Wheeler, N. Bohr,…*
- 1948 - Shell-Model, mean field of all nucleons (*Maria G.Mayer, H. Jensen*).
- 1965 – deformed Shell Model (*Nilsson-model*), Rotational bands (*A. Bohr-B. Mottelson,…*).
- 1970-80 *fission isomers*, *Strutinsky,* super, hyper deformation, *Ragnarson, Nielsson, Sheline*, Phys.Rep. **45** (1978)
- 1988 – Fission modes of *U. Brosa* et al., Phys. Reports Vol **197** (1990) 167
- ^{252}Cf, U. Brosa: " has it all "! : Super short(Clusters, SuperDef), standard (SuperDef), and superlong (hyperdef, 3rd minimum) decay modes
- 1960– 2004 Fission modes with ligth-particle emission in *perpendicular direction*, summary 2004 : named "Ternary Fission" : *G. Gönnenwein,* Nucl. Phys. **A 734** (2004) 213
- 1970 - 2011, ***True ternary fisson***, *Swiatecki 1960. Diehl+Greiner,*(1974)NPA, ***3 heavy fragments***, *Poenaru, Pashkevitch, Balasubramanian, Zagrebaev+Greiner (2012)…*
- **Experiment: Collinear Cluster Tripartion (CCT),** *Y. V. Pyatkov,* D. Kamanin, et al,

Jad. Fizika Vol. **66** (2003) 1679, Y.V. Pyatkov, D. Kamanin , W von Oertzen et al. , Eur. Phys. J. A **45** (2010) 29

- 1960– 2004 Fission modes with ligth-particle emission in *perpendicular direction.* Summary 2004 : *“Ternary Fission”* : **F. Gönnenwein,** Nucl. Phys. **A 734** (2004) 213,

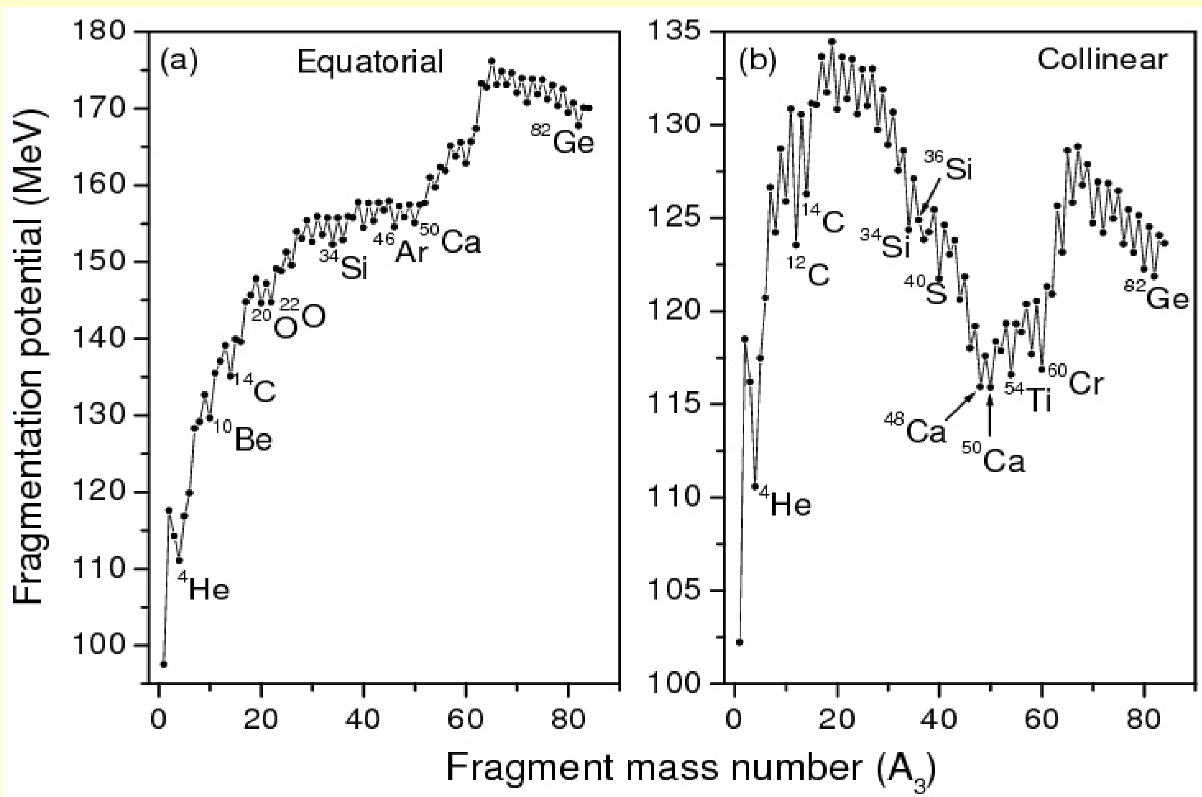
F. Gönnenwein in Europhysics News , Vol **36** (2005) 11

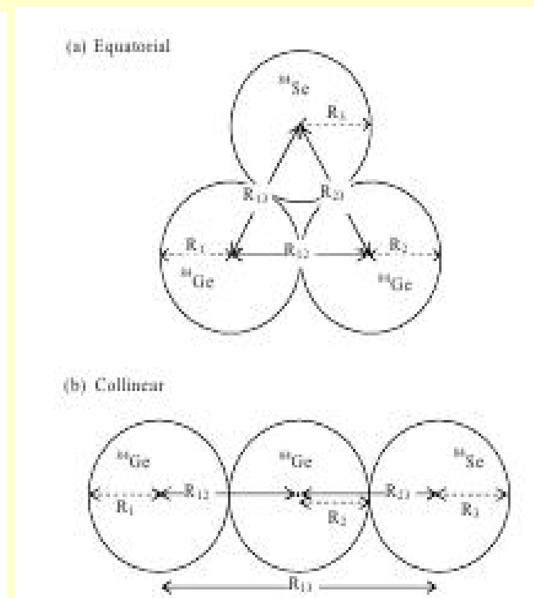


Comparison of Potentials for *Oblate* (Equat.) and *Prolate*

Hyperdef- and Super-deformed (Collinear) Fission configurations

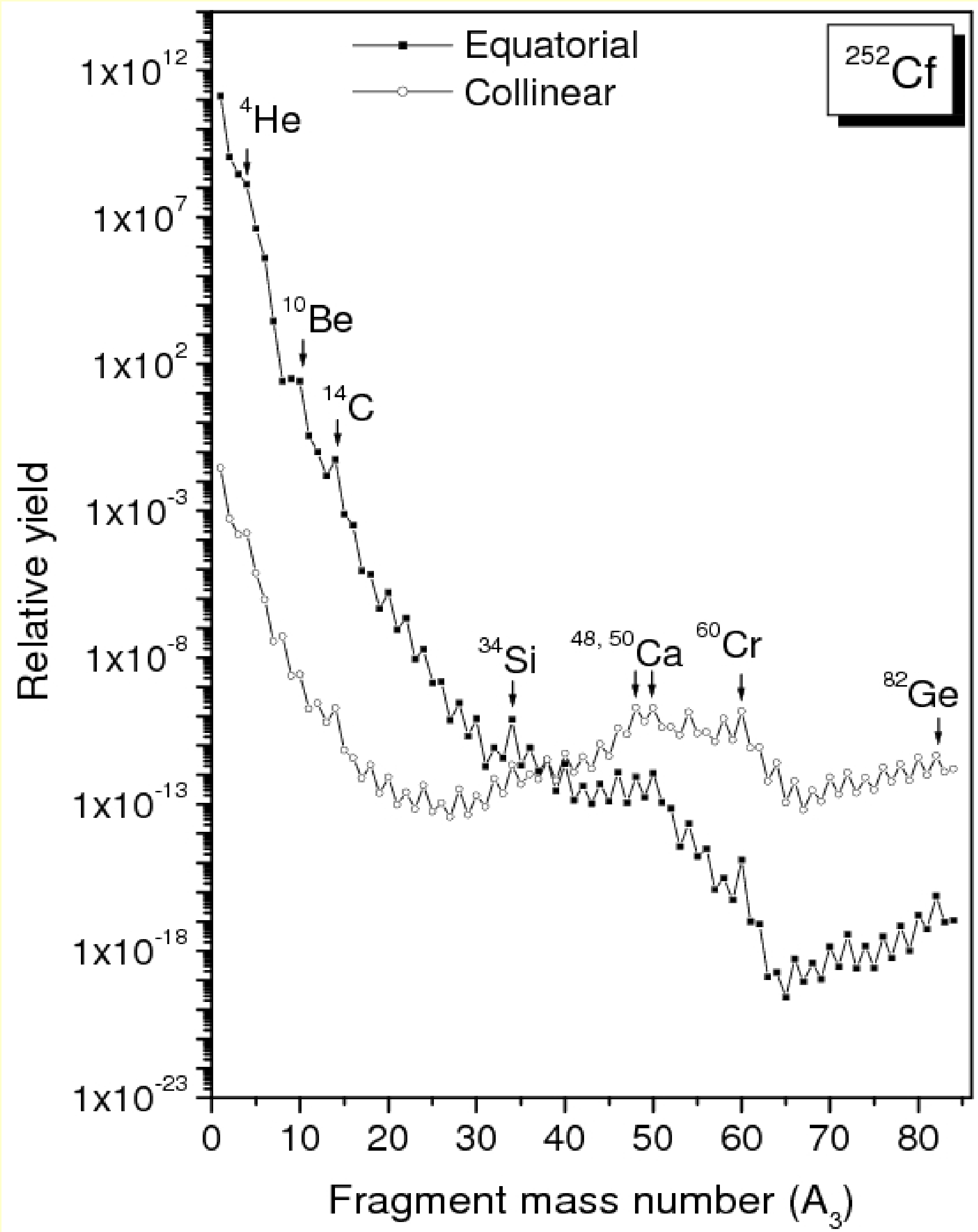
as function of mass A3, in the center (ternary mass)





K. Manimaran and M. Balasubramanian, Phys.Rev. C **83** (2011) 034609

true ternary fission



- -- Other Heavy and **super-heavy** nuclei, Zagrebaev, Karpov, Greiner: Phys.Rev. C 81(2010)
- – Kinetic energies of fragments.
- -- Experiments with 3 clusters in coincidence: INVERSE KINEMATICS. Fission in fligth (FRS – GSI, FAIR)
- -- Higher mass resolution
- -- Definition of fission modes (BROSA): Hyper-deformation!

- -- At high spins, fission from super—and hyper-deformation will occur as CCT

H. Diehl and W. Greiner,

Nucl.Phys. **A229** (1974), 29

In the liquid drop model:

collinear cluster decay favoured

True Ternary Fission is favoured in *collinear- geometry, due to Coulomb interaction and formation of clusters!*

CCT of Pyatkov et al.

Collinear Cluster Tripartition.

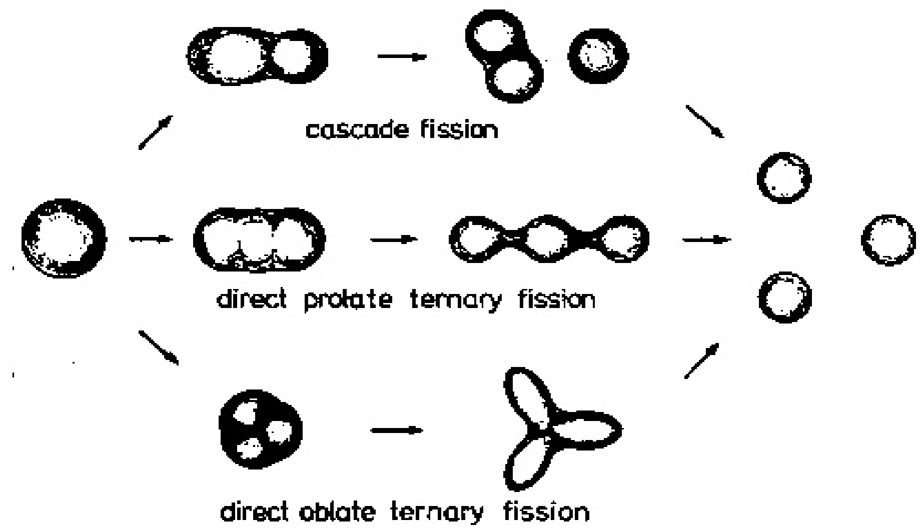


Fig. 1. Possible modes of ternary fission.

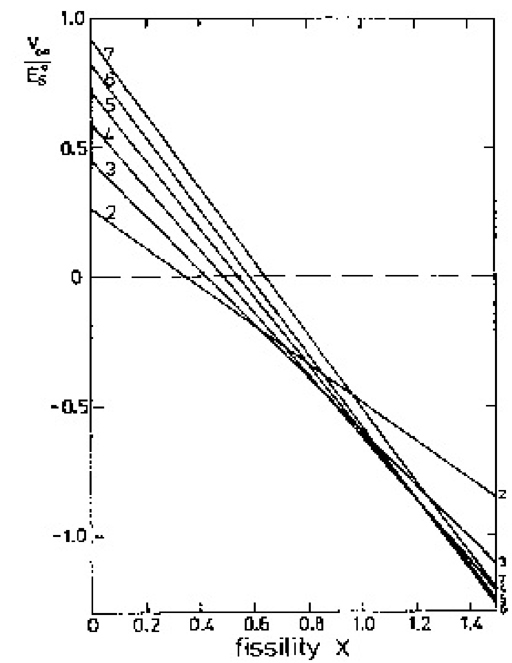


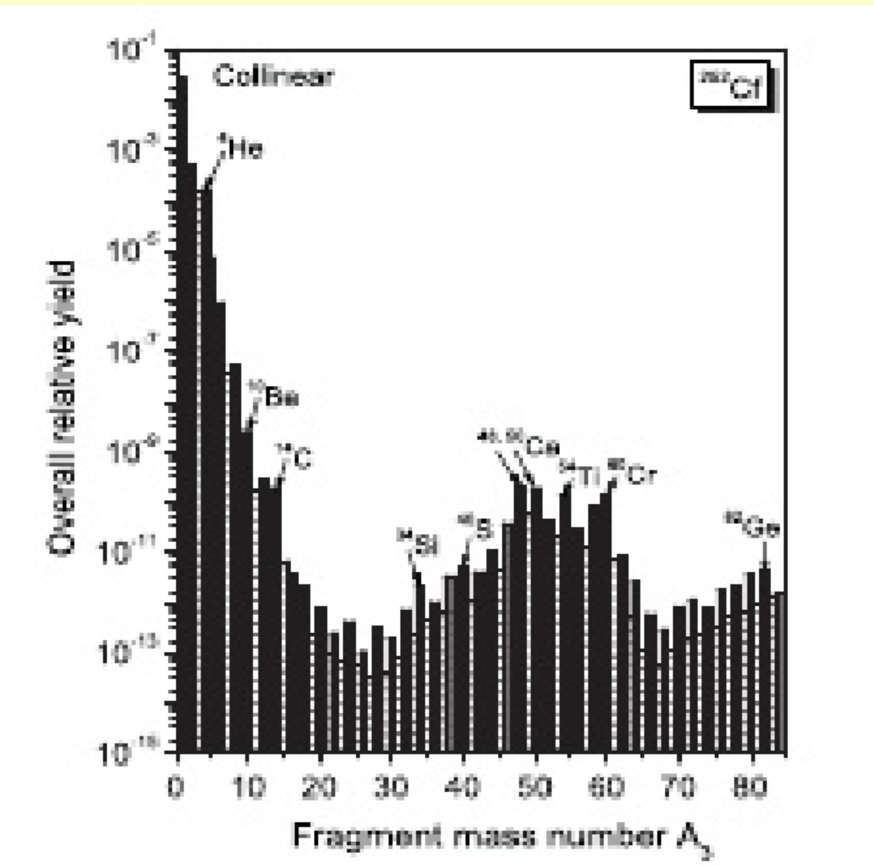
Fig. 2. The energy release according to fission into n equal fragments is given as a function of the fissility parameter in units of E_s^0.

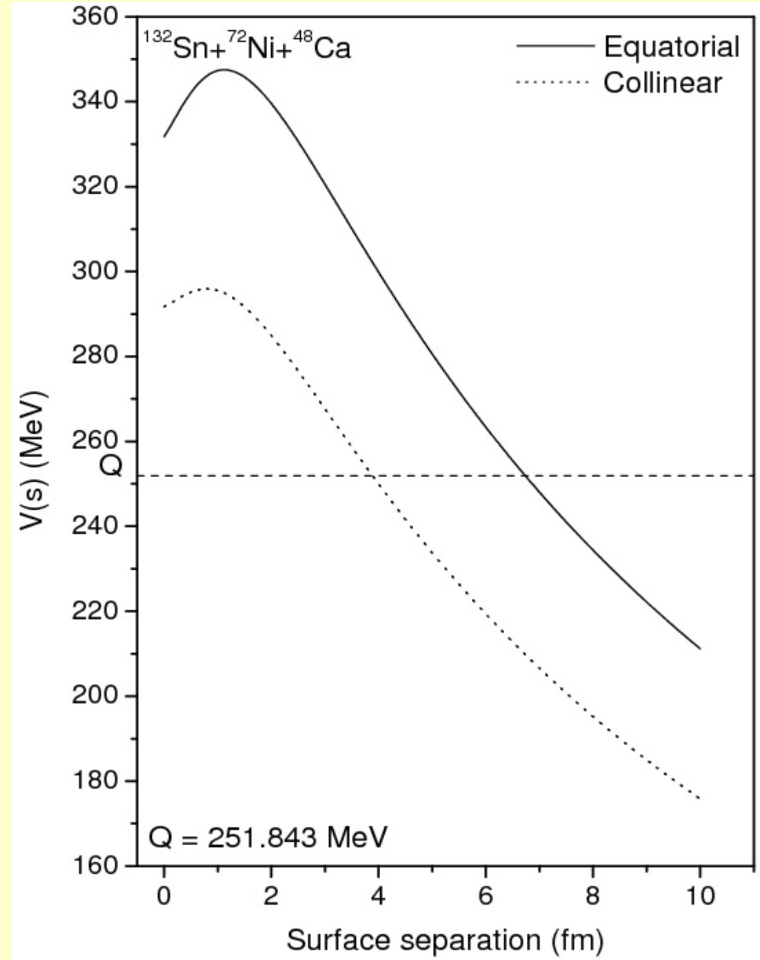
Why CCT has not been observed previously??

Relative yields of prolate/oblate (equat.)

Potentials barriers for oblate and prolate shapes, are compared

They are lower!! *for collinear* configurations by (20-30 MeV!) (1)





(1) K. Manimaran and M. Balasubramanian, Phys.Rev. C **83** (2011) 034609

True Ternary Fission in the Physics of Fission

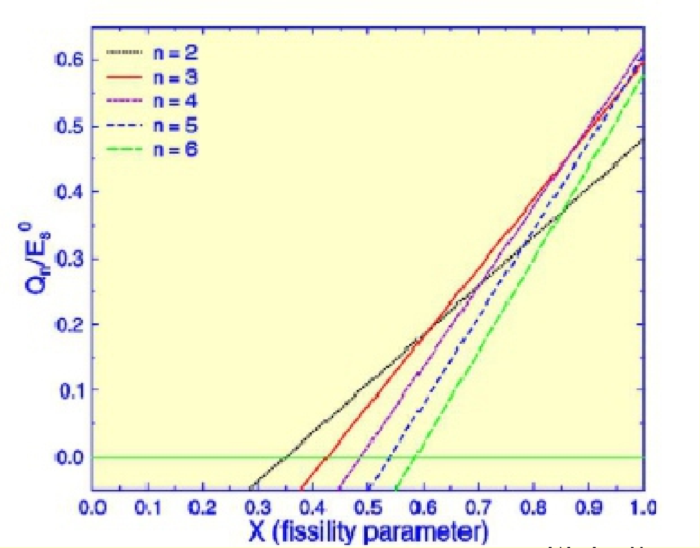
- With three comparable Masses : larger Q-values than binary by (20-30MeV)
- Exp.: Phys. Letters **B 191**(1987)339, Mutterer et al., "oblate" e.g. ***triangle*** configuration, A1=20, A2=132, A3= 95 : Tri-Partition limit < 8x10**(-8)!!
- Predictions : Collinear fff: Swiatecki (1958) (x > 0.61). Strutinski (1963), H. Diehl and W. Greiner, Nucl.Phys. **A**(1974),

  V.I. Zagrebaev, A.V. Karpov, W. Greiner Phys.Rev. C **81 (2010**) 004608.
- ***3 heavy fragments***, Y. V. Pyatkov, D. Kamanin, et al, Jad. Fizika Vol. 66 (2003) 1679, Y.V. Pyatkov, D. Kamanin , W von Oertzen et al. Eur. Phys. J. A **45** (2010) 29

  Swiatecki, for X>0.6, n > 3 more favourable than n=2

  Poenaru (2005): "Complex Fission Phenomena":

  Differences: (Ecoulomb-Esurfaces) For (n=i/n=2)



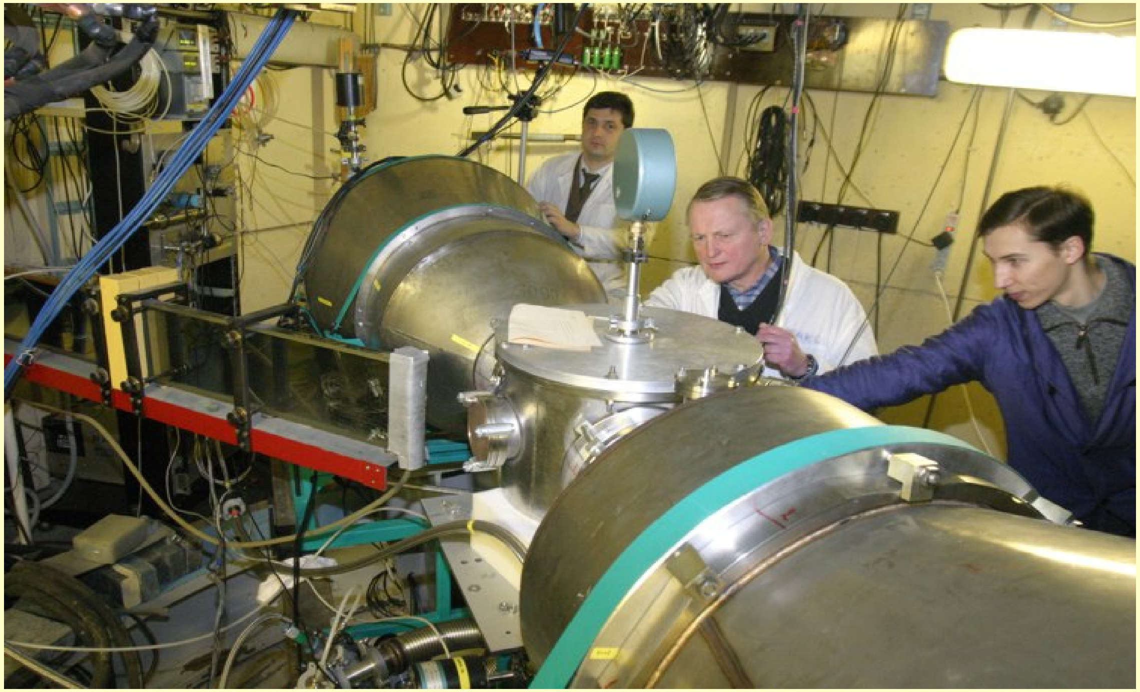
True Ternary Fission: *collinear- geometry* !!

Experiment (Ex1) binary coincidences at 180°

***How to measure collinear decay*!!??**

Missing mass approach,

^{252}Cf(sf,fff) (2xTOF+2 FOBOS – modules, at 180 °, Parallelplate-detectors, Bragg ionisation chambers)



From the left: Dimitri Kamanin, Yuri Pyatkov, ….

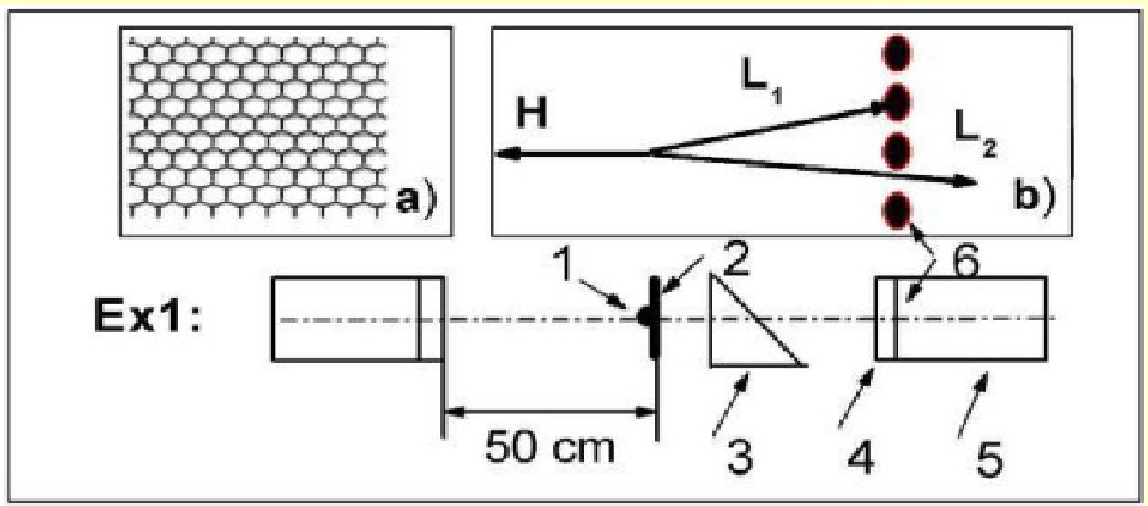
Experiment (Ex1) binary coincidences at 180°

***How to measure collinear decay*!!??**

Missing mass approach,

angle straggling in backing"2", and **blocking** of one of 2 fragments L1, L2 in arm1

^{252}Cf(sf,fff) (2xTOF+2 FOBOS - Detectors)



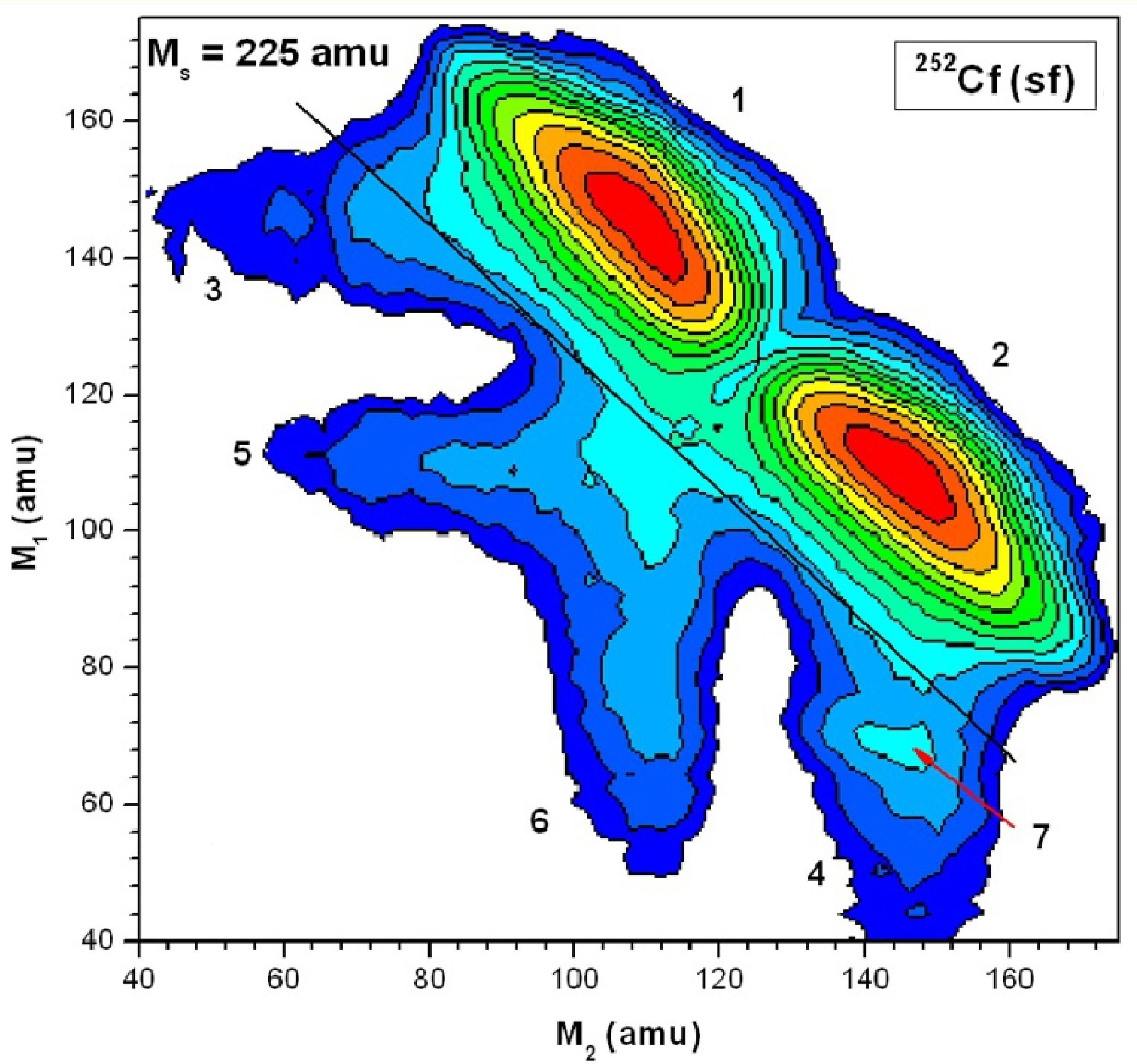
1 – source, 2 – backing of source. 3-**TOF**, pointing to **arm 1** only

3 – TOF-start, material in the path towards FOBOS(4,5) in **arm1**

4 – PPAC , Position and TOF-stop, 5 - Bragg-Ionisation chambers,

6 – support-grid, a), b) - front and side view of support-grid in gas-counters.

Experiment (Ex1) binary coincidences at 180°,



$^{252}Cf(sf,fff)$

Difference between arm1 and arm2

Correlations of two masses M1, M2.

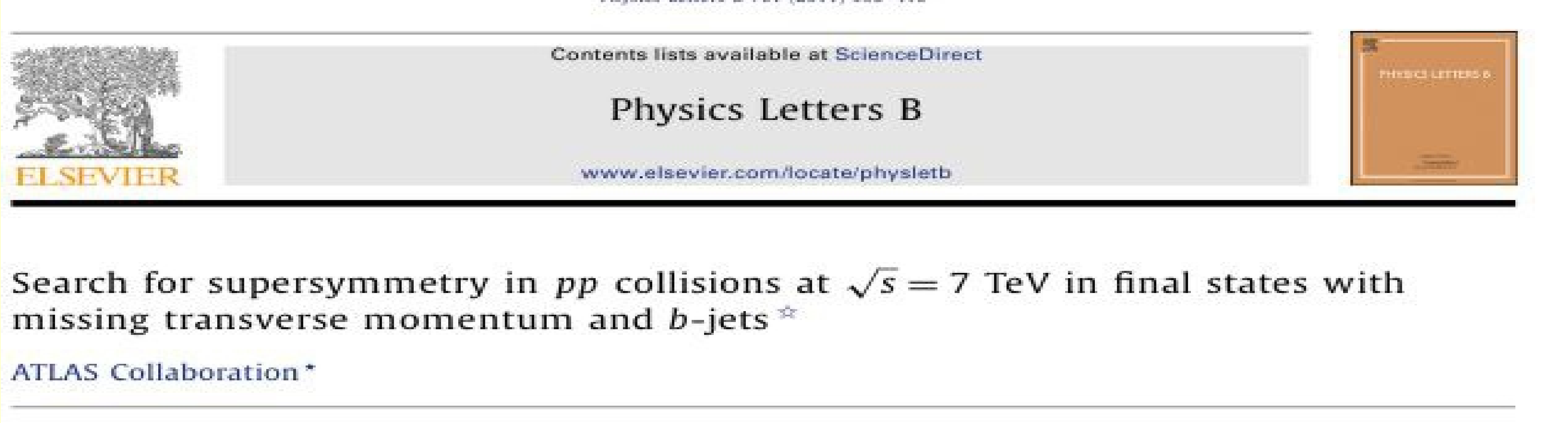
Line for Ms = 225 < 252

Ms-sum of two masses

M1+M2 = Ms

(7) Ms = 64 + 140 = 204

7 - Missing mass: $^{48-52}Ca$


Contents lists available at ScienceDirect
Physics Letters B
www.elsevier.com/locate/physletb

Search for supersymmetry in *pp* collisions at $\sqrt{s} = 7$ TeV in final states with missing transverse momentum and *b*-jets ☆

ATLAS Collaboration *

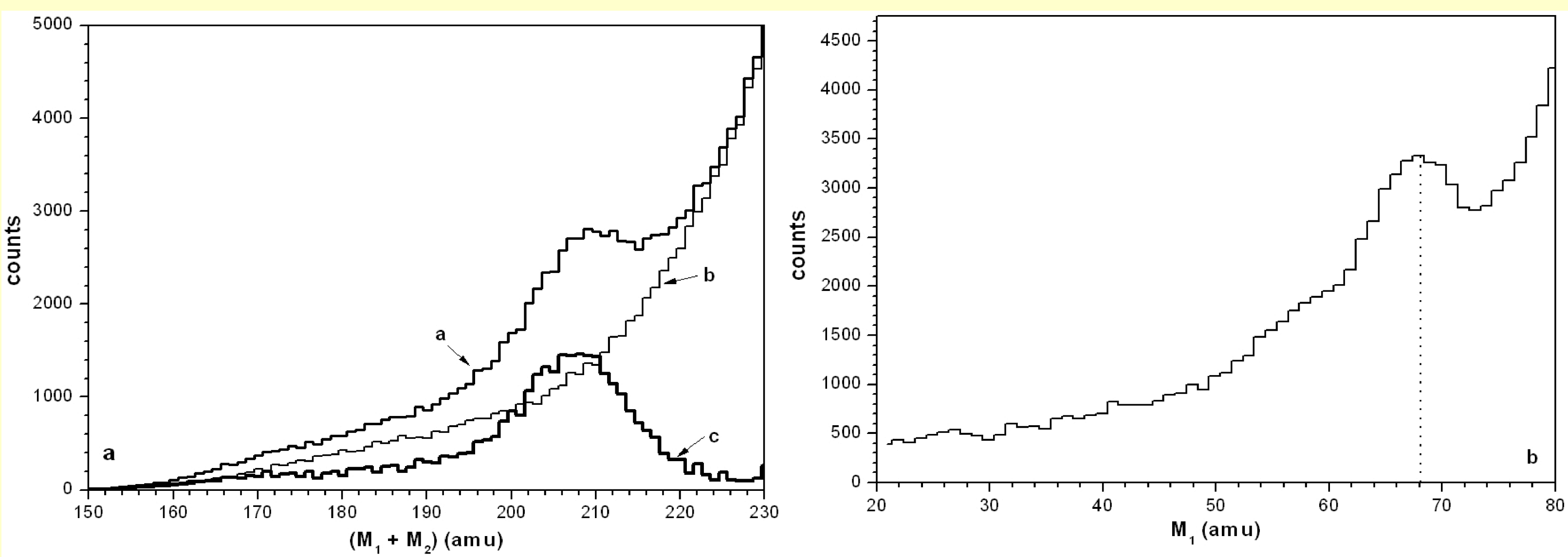
Experiment (Ex1) binary coincidences at 180°, Projections on (M1+M2), and on M1

Missing mass ↔ **complete kinematics**: 3 Masses: M1 + M3 + M2

2xE, -- 2xmasses,---2 vectors(angle, velocities)

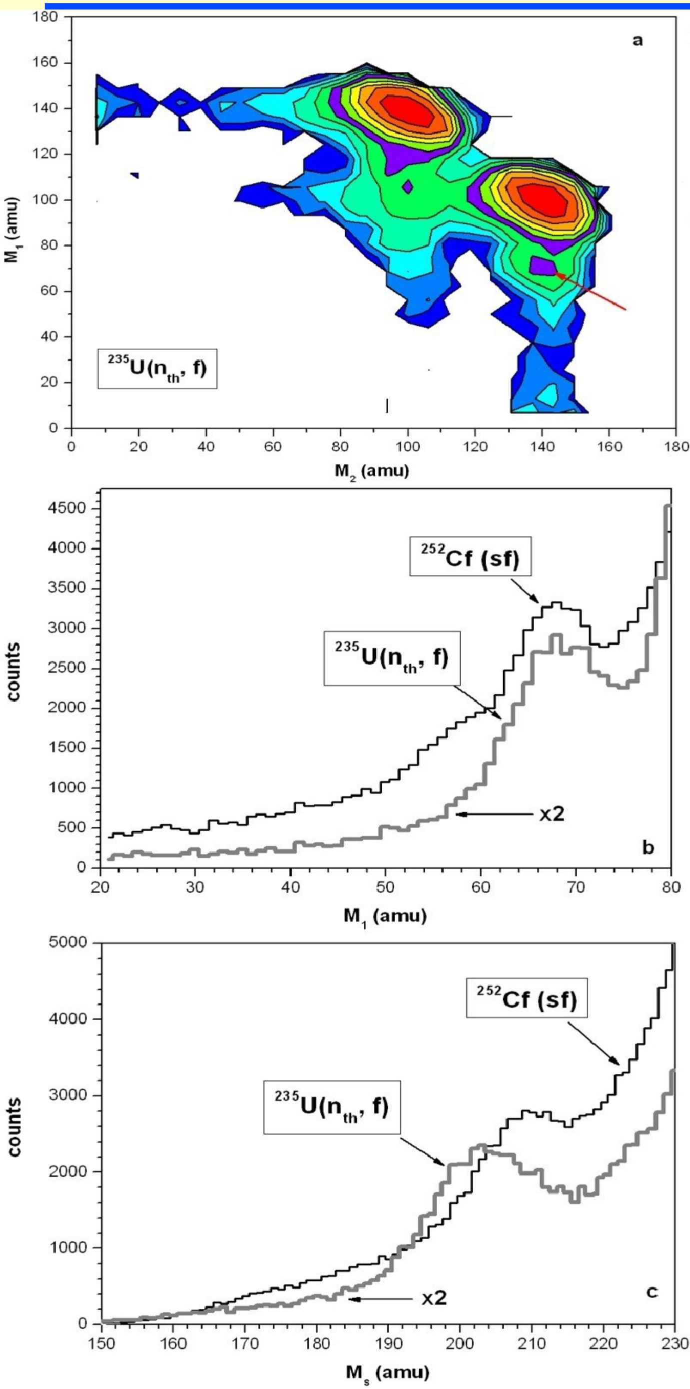
Subtraction: of yield in arm2 (a) from yield in arm1 (b), ^{252}Cf(sf,fff)

Projections: 1) on M1+M2), 2) on M1, M3=(missing mass)



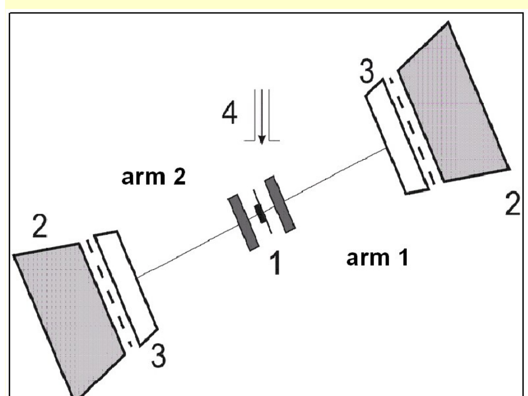
Experiment 2 (Ex2) binary coincidences at 180°,

Test of the new phenomenon with an independent experiment,



Different Nucleus, different detectors!!

^{235}U(n, fff) with ***minifobos***
Correlations of two masses,
M1-- M2,
M1+ M2 => Missing mass
Comparison with previous
^{252}Cf(sf,fff)



1- Target, and TOF

with backing Al2O3, towards arm1!

3 – parallel plate counters (x,y and timing)

4 – neutron beam

2 – ionisation Bragg-chambers, E

Some questions?, e.g. of referees, and answers!

Spontaneous fission [1]

1) ^{252}Cf(fff/ff) = 4.0x10^{-3}, Yield is much to high?! ***Hauser-Feshbach*** approach for statistical decay!

1) **Answer**: because of the larger phase space. Phase space: a)Q-values, b) Kinetic energies, c) number of channels: range of isotope-combinations (30) in the fff-bump, d) Excited (n= 3-6) states of the fragments, e) Spins, *Ter Akopian et al*. (Phys. Rev. C55(1997) spins up to 6(8)+ !! and their multiplicity (2J+1)!!!, *Vijayraghawan et al*, EPJA 48 (2012), 27

2) ***Why only Sn+Ca+Ni?***

2a) **Answer**: Potential energy surface shows deeper valley for Sn+Ca+Ni,!

Compared to Sn+Ni+Ca by 10MeV, *A. Nazirov* et al, *K.R. Vijayaraghavan et al.*

3) ***Collinearity?*** Potential as function of *angle* between Sn-Ca-axis and Ni

3a) **Answer**: Potentials Calculated by *A. Nazirov* et al, *K.R. Vijayaraghavan et al,*

Yields (Potentials) as function of Mass A3, Balasupramanian et al.

Neutron induced fission [1]

4) ^{235}U(*n*, fff) (2xTOF+2x mini-FOBOS) (Reactor, JINR, Dubna) [1]

4a) Similar questions, Differences explained by the Potential energy surfaces, calculated by A. Nazirov, and Balasupramanian

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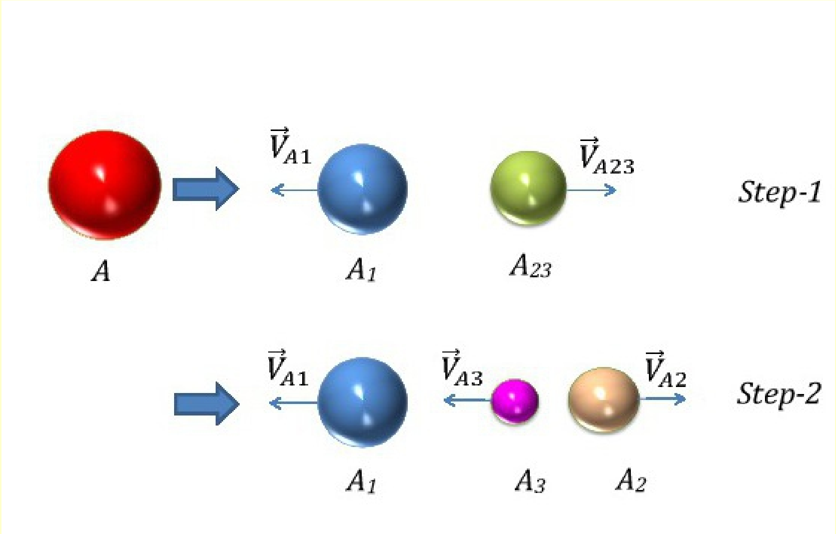
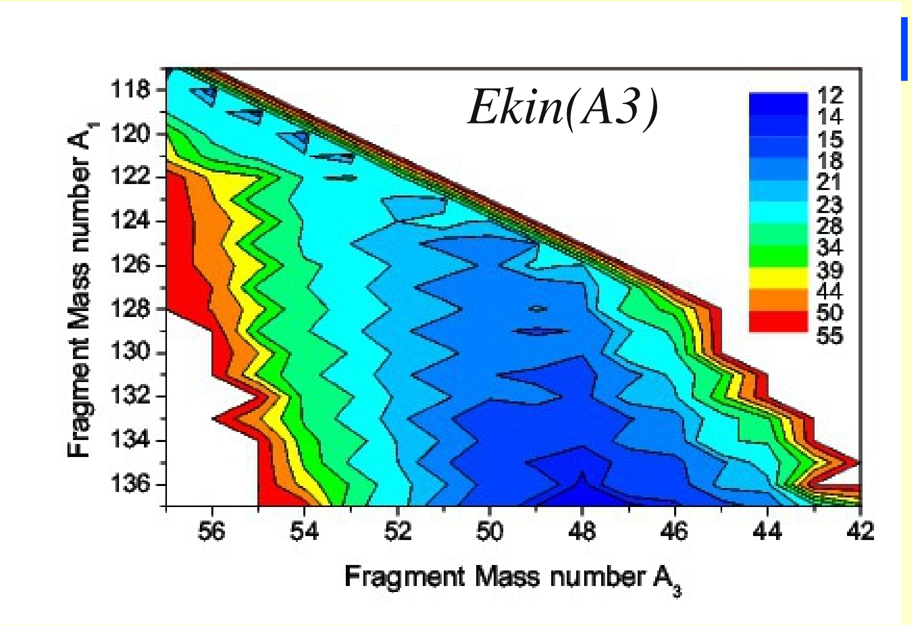
[1] Y. V. Pyatkov, D. Kamanin , W von Oertzen et al. , Eur. Phys. J. A **45** (2010) 29

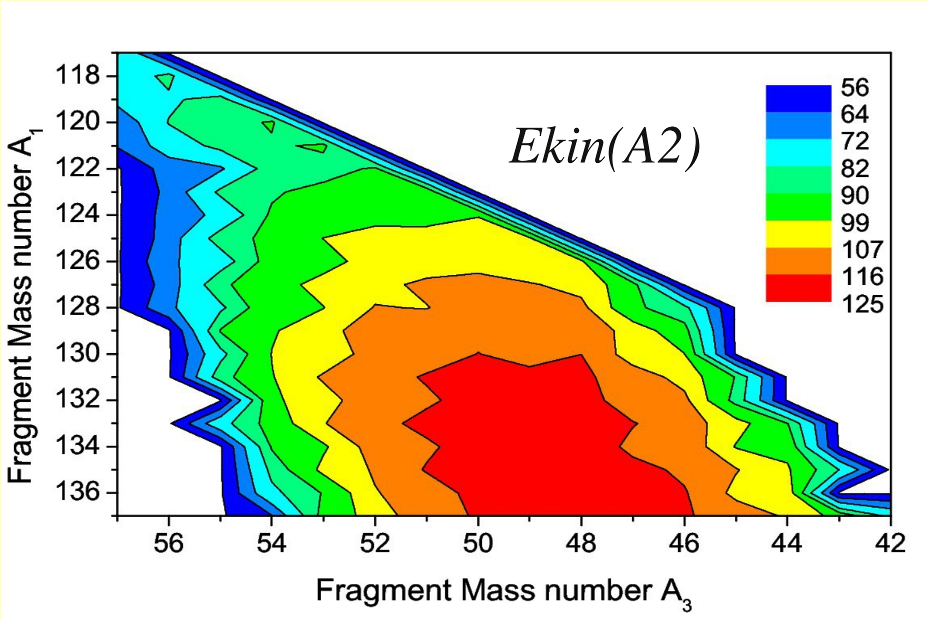
[2] Y.V. Pyatkov et al. , EPJ. A **48** (2012) 94

Kinematics of CCT, Sequential fission process [1], Phase space!!!

Kinetic energies E3(A1, A3) A3(A1) and E2 (A1, A3)







[1] K.R. Vijayaraghavan , W. von Oertzen and M. Balasubramanian, EPJ **A 48** (2012), 27

Phase space of CCT for ^{252}Cf(sf)

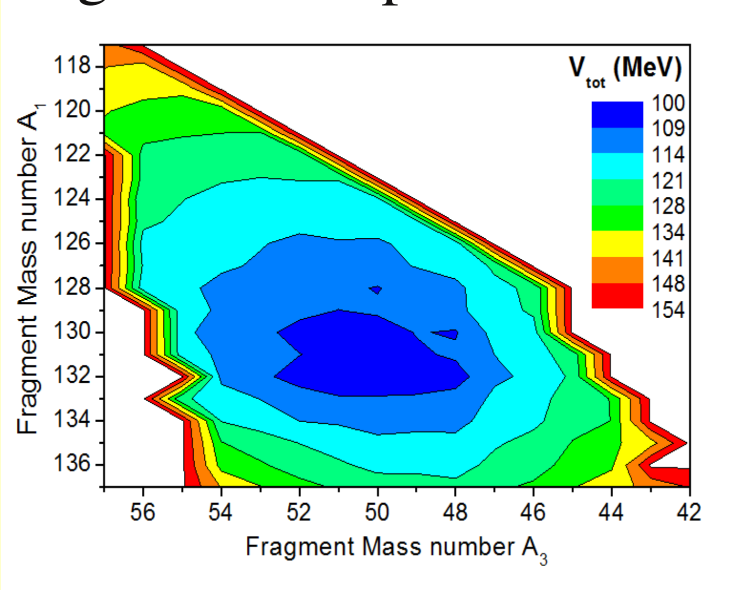
a) 30 mass-mass combinations of isotopes of Ca, Ni and Sn in the shallow region of the potential for ternary fragmentation, N - excited states of fragments (5, more!?) , Pins up to 6+ (TerAkopian

b) for these: Q-values are higher, by 25- 30 MeV, and *momenta are higher*, compared to normal binary fission. (2J+1) factor for the excited states: = <9>

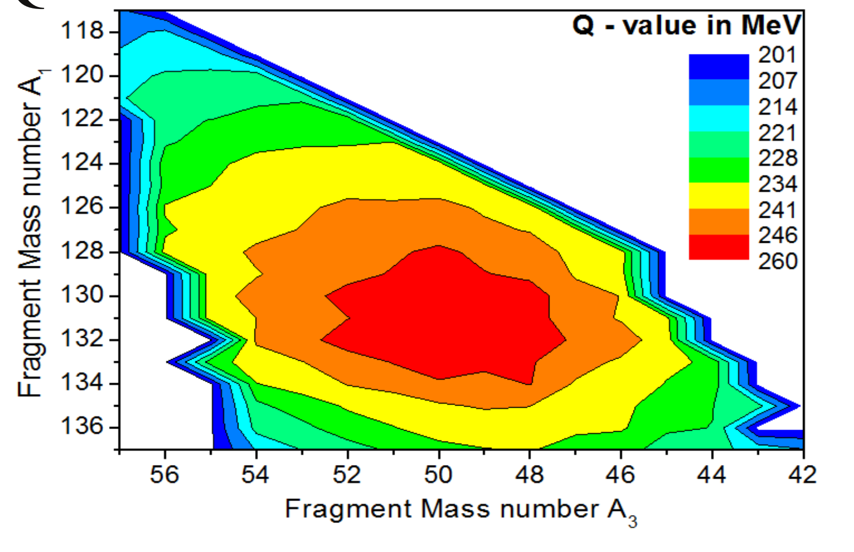
Total Phase space: ~5000-10000 larger, when compared to a Light - *single isotope-particle* ("ternary fission"), perpendicular to ff-axis!

The CCT mode produces a BUMP !! as in binary fission.

Fragmentation potential



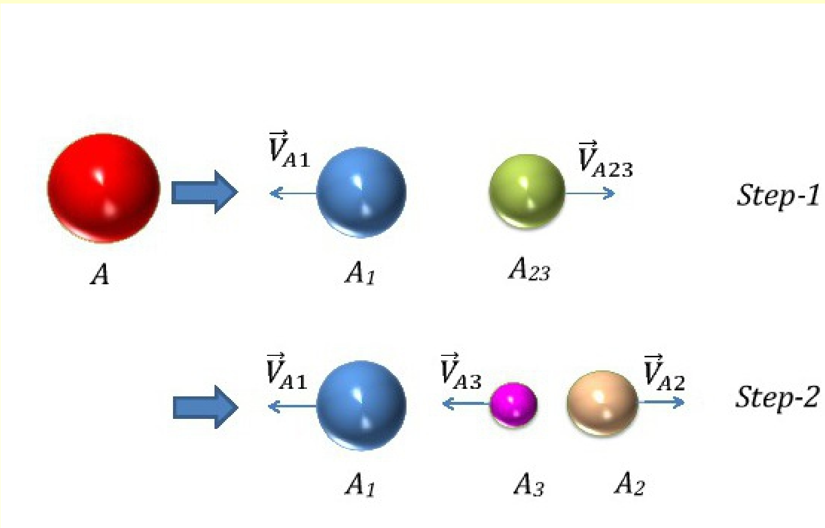
Q-values

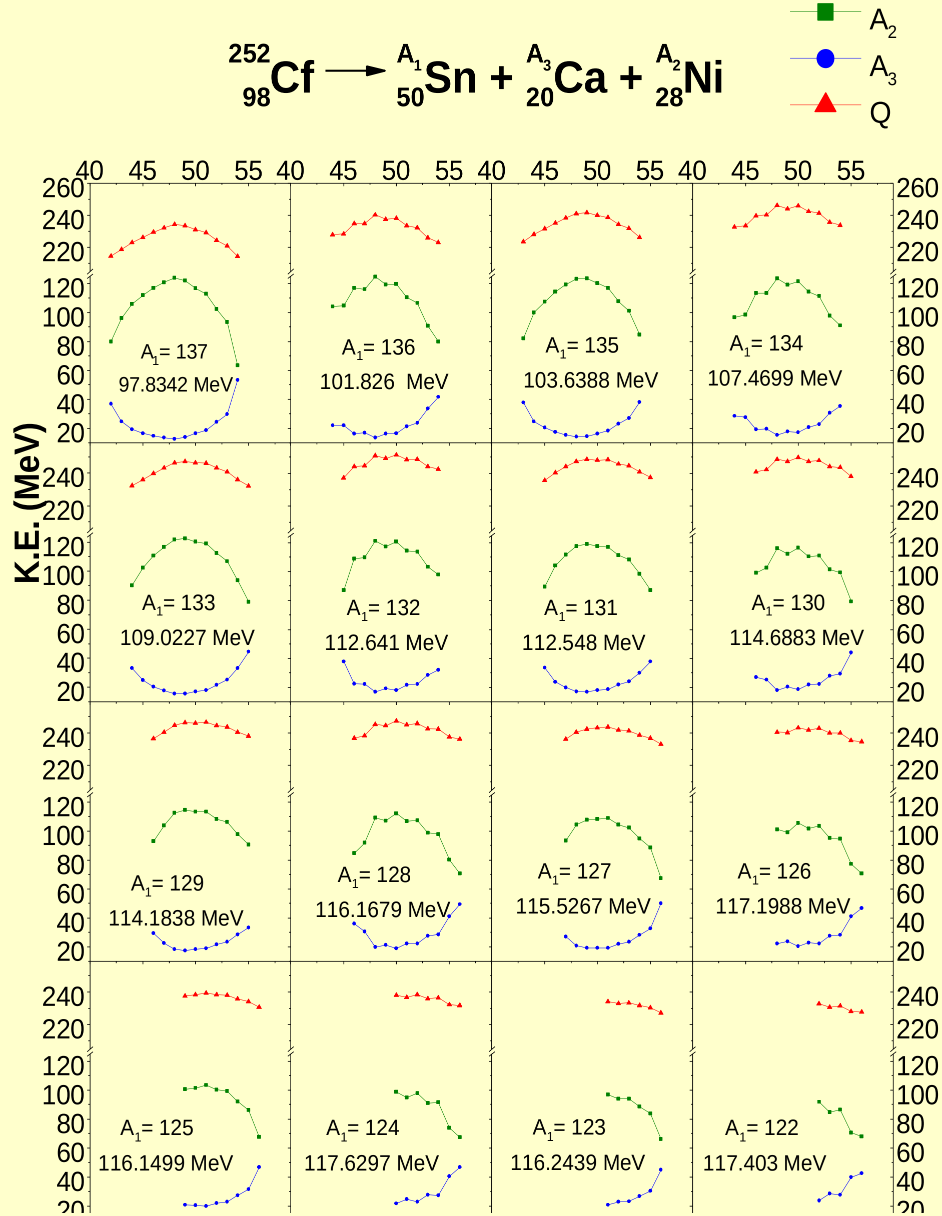


Kinematics of CCT

Sequential fission process [1]

Kinetic energies of A2, A3



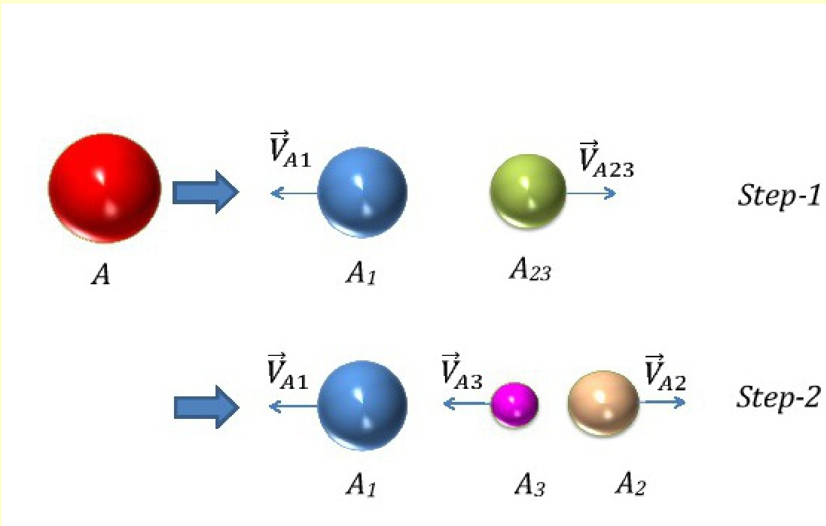


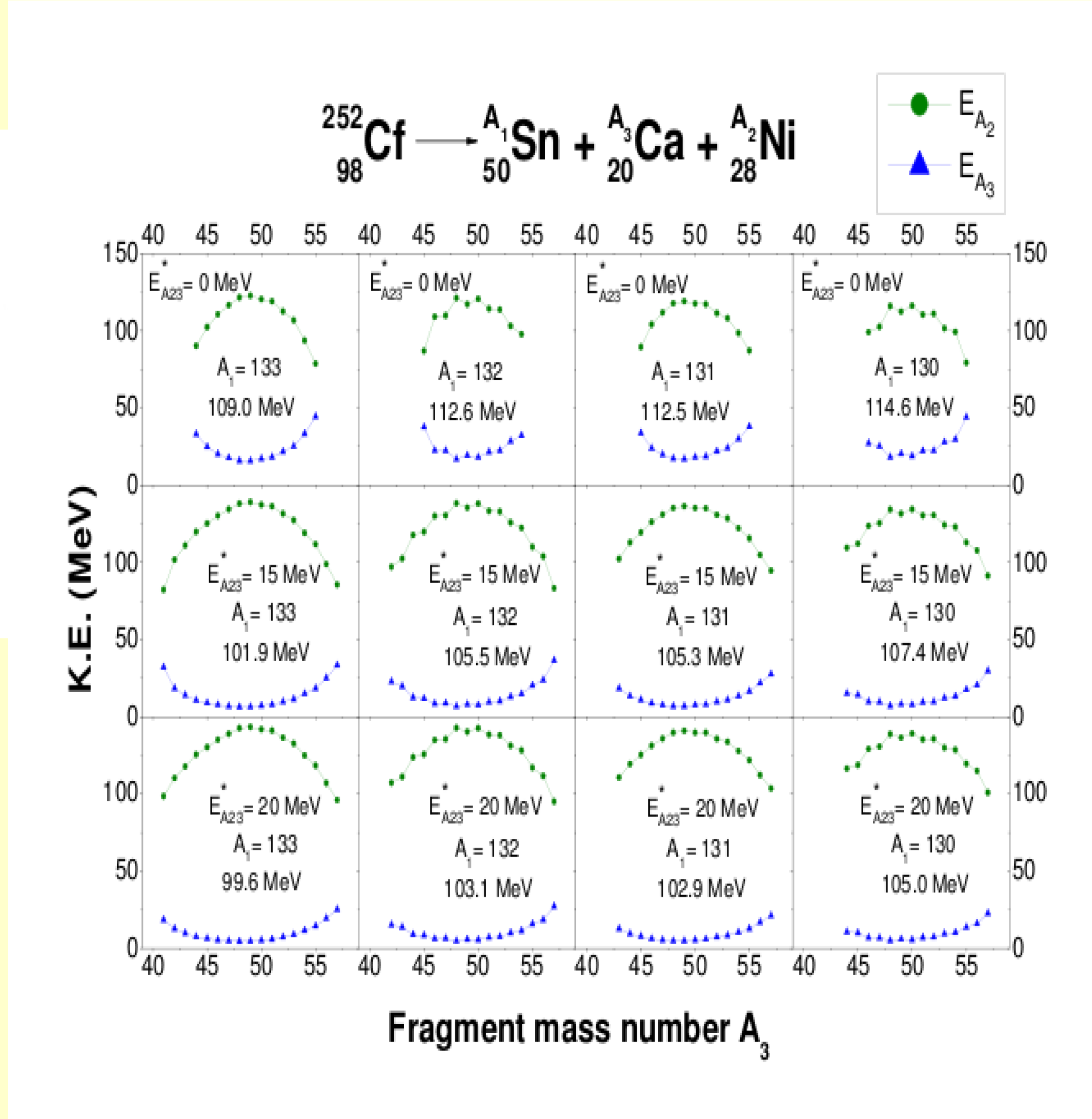
[1] K.R. Vijayaraghavan,
W. von Oertzen and
M. Balasubramanian, EPJ **A 48**
(2012), 27

Kinematics of CCT, Sequential fission process [1]

Ekin(A3, A2) *for different* *Excitation energies* *of A23*

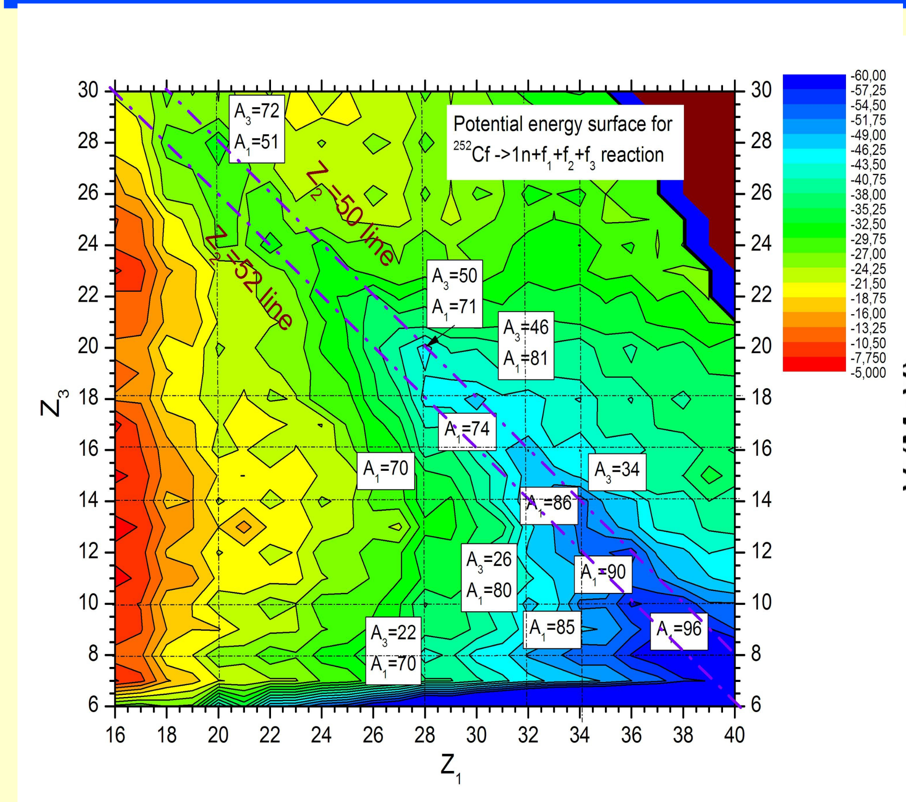
Kinetic energies of A2, A3

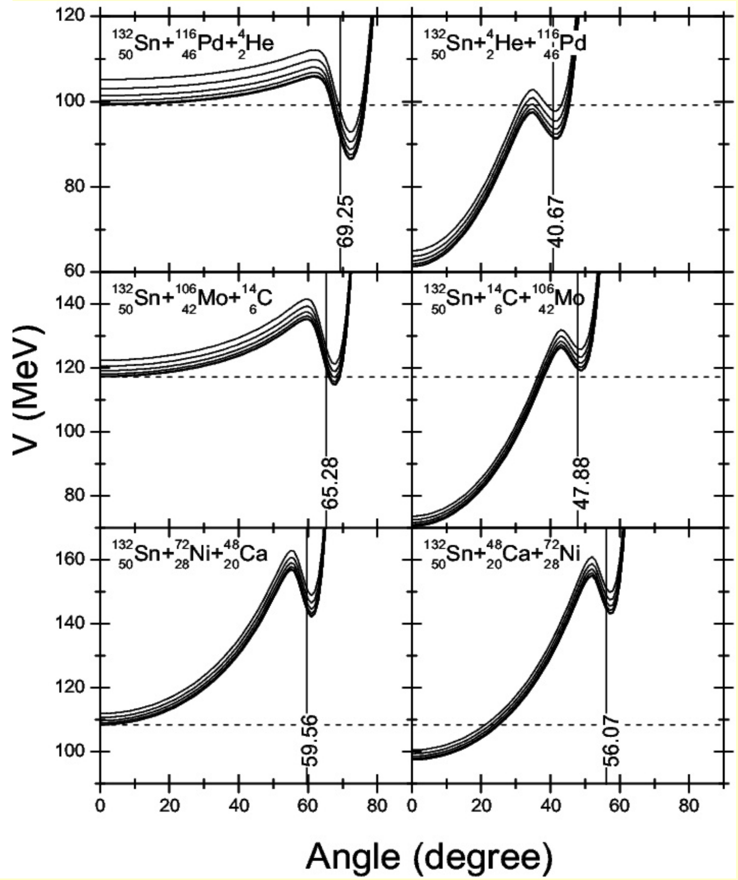


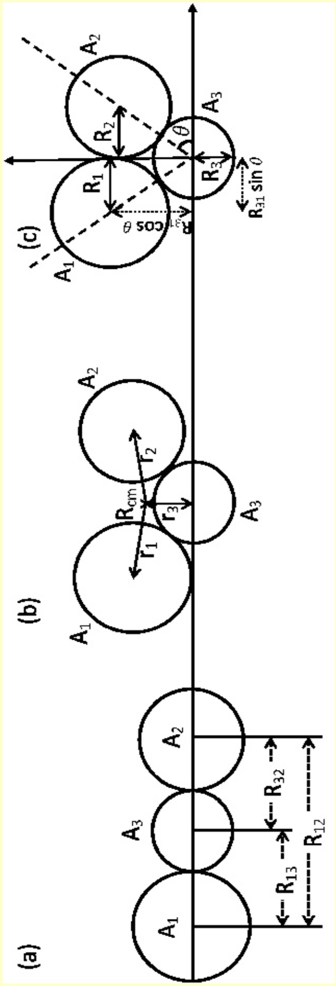


[1] K.R. Vijayaraghavan ,
W. von Oertzen and
M. Balasubramanian,
EPJ **A 48** (2012) 27

Why? (Sn + Ca + Ni) and why not (Sn + Ni + Ca)





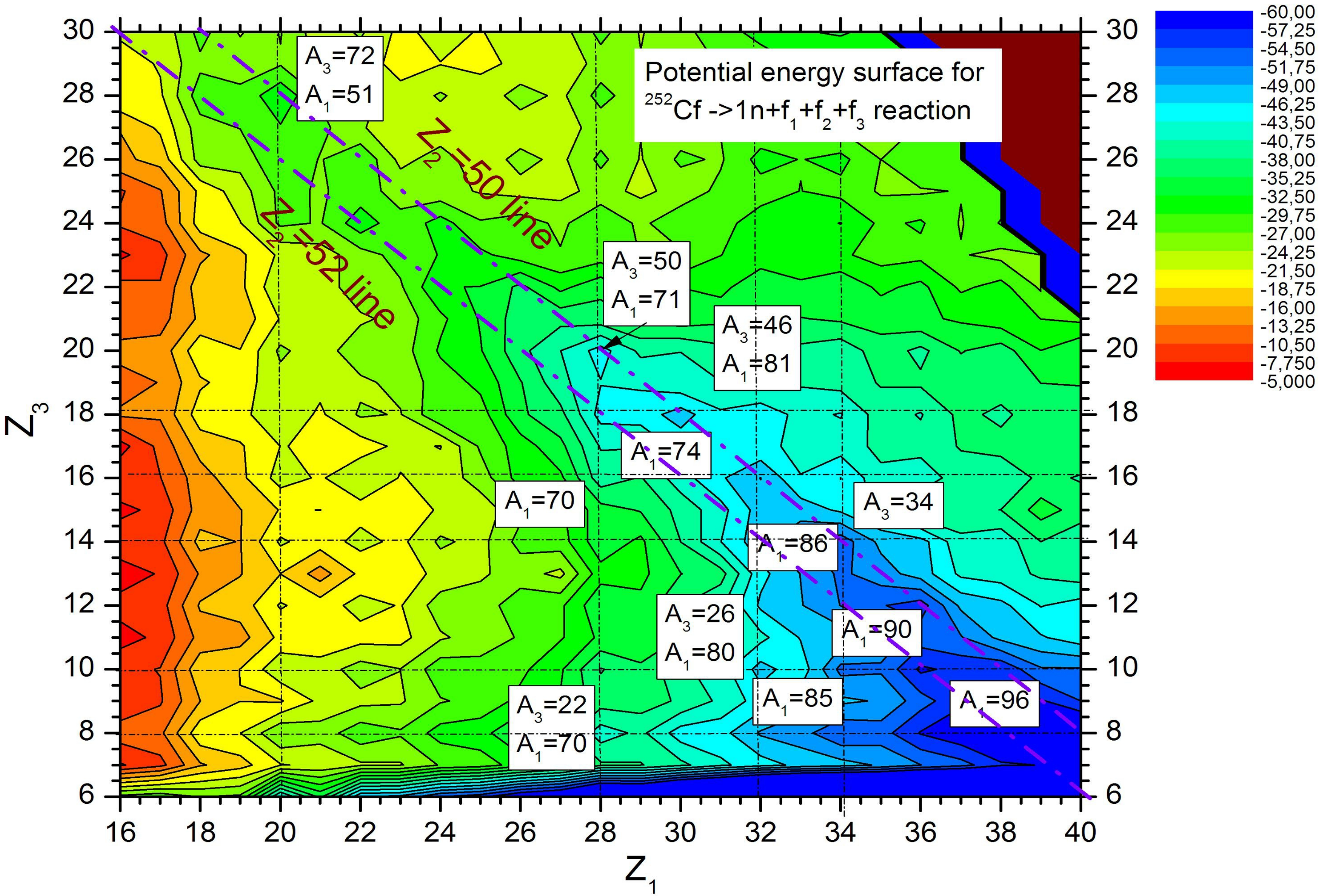


missing Z = 18, 20 (Ca)
or missing Z = 28 (Ni),

Deeper valleys (angle=0) with Ca in the middle

Calculations by Nazirov (JINR) PES, and Balasupramanian (Coimbatore, India)

(Sn + Ca + Ni) and (Sn + Ni + Ca)



Collinearity ? Comparison of Potentials for *Oblate*(Equat.) and *Prolate* geometry

Hyperdef- and Super-deformed (Collinear) Fission configurations as function of mass A3, in the center (ter. Mass), Cross-over at A3 = 35

PHYSICAL REVIEW C **83**, 034609 (2011)

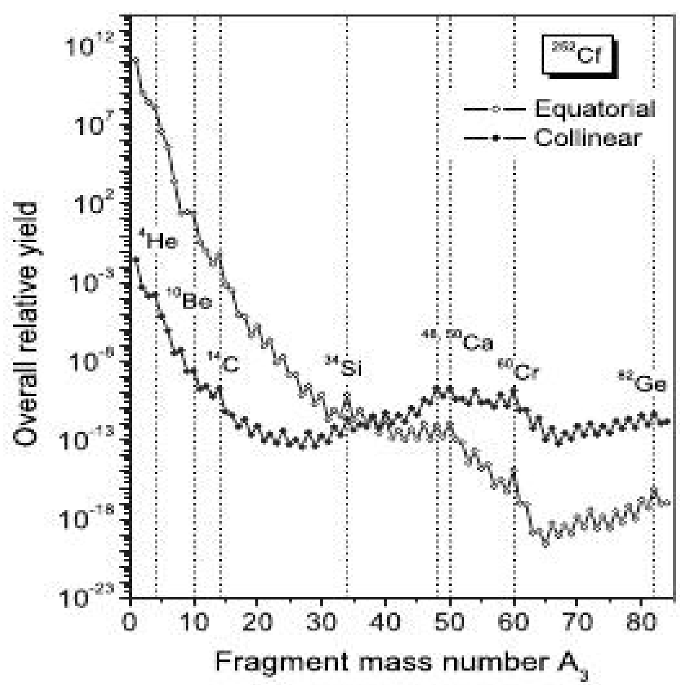
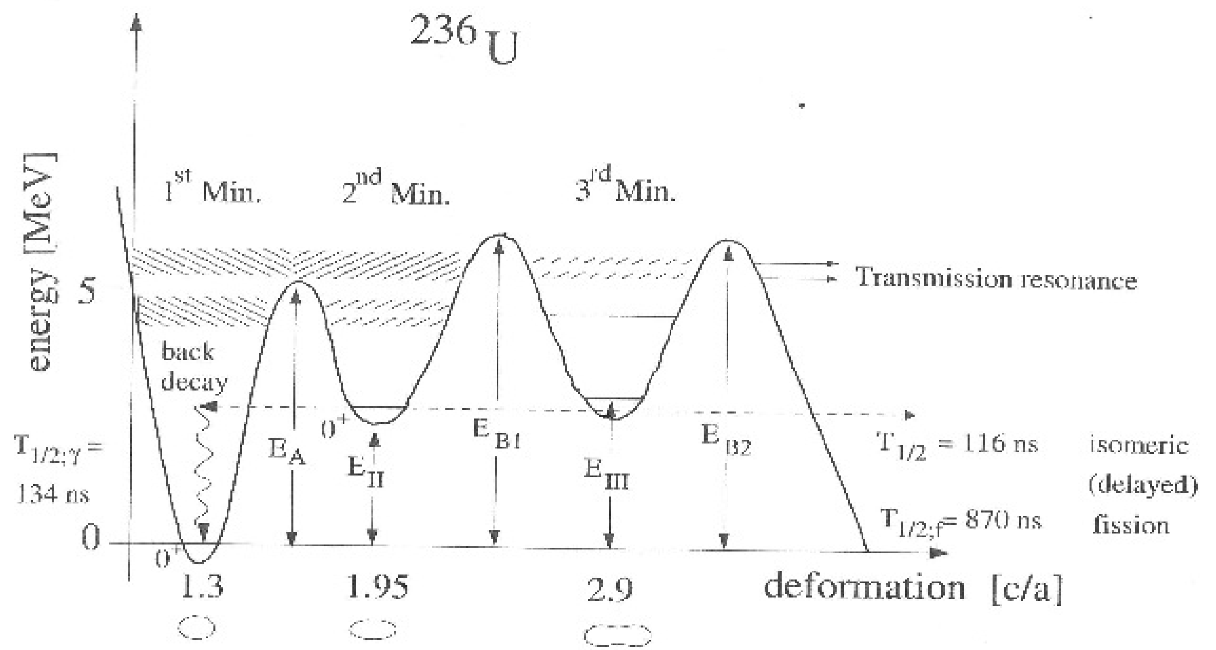
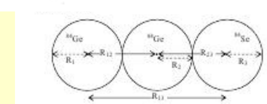
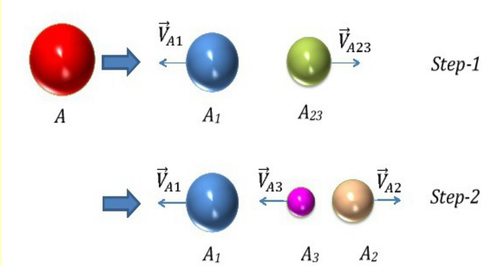


FIG. 11. A comparison between the overall relative yield calculated for equatorial and collinear emission of fragments in ternary fission of ^{252}Cf plotted as a function of third fragment mass number A_3.







K. Manimaran and M. Balasubramanian, Phys.Rev. C **83** (2011) 034609

Multi-Hump Barrier: A. Krasnoharkay et al. Phys. Rev. Letters **80** (1998) 2073

Conclusion:

Collinear Cluster decay has been observed in **four** different experiments

1) ^{252}Cf(sf, fff) (2xTOF+2x FOBOS) JINR

Spontaneous fission [1]

2) ^{235}U(*n*, fff) (2xTOF+2x mini-FOBOS)

Neutron induced fission (Reactor, JINR, Dubna) [1]

Spontaneous fission + neutron coincidences [2]:

3) ^{252}Cf(fff, *n*) (2xTOF+2x5 mini-FOBOS), FLNR

4) ^{252}Cf(fff, *n*) (2xTOF+2xSi-E_Mosaic), FLNR

[1] Y. V. Pyatkov, D. Kamanin , W von Oertzen et al. ,
Eur. Phys. J. A **45** (2010) 29

[2] Y.V. Pyatkov et al. , EPJ. A **48** (2012) 94

Future Experiments

1)Multiple fission decays of heavier nuclei-D. N. Poenaru, R.A. Gherghescu and W. Greiner **Nucl.Phys. A 747(2005) 182** Inverse kimeatics, FRS, fragment separators

2)Compound nuclei with Z = > 100

V. I. Zagrebaev, A.V. Karpov and W. Greiner , "true ternary fission"

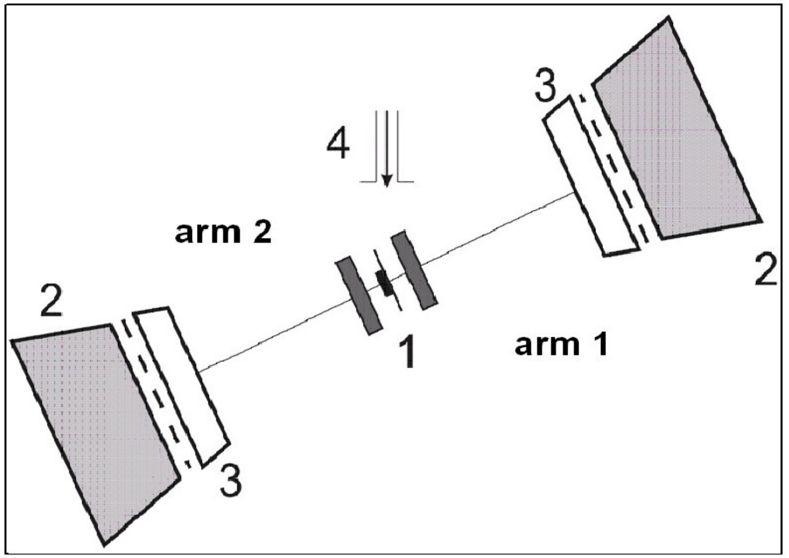
Phys.Rev. C 81(2010) 044608

3) Dedicated experimental set-ups (4 pi- Si-Ball)

Experiment 2 (Ex2) binary coincidences at 180°,

Missing mass approach

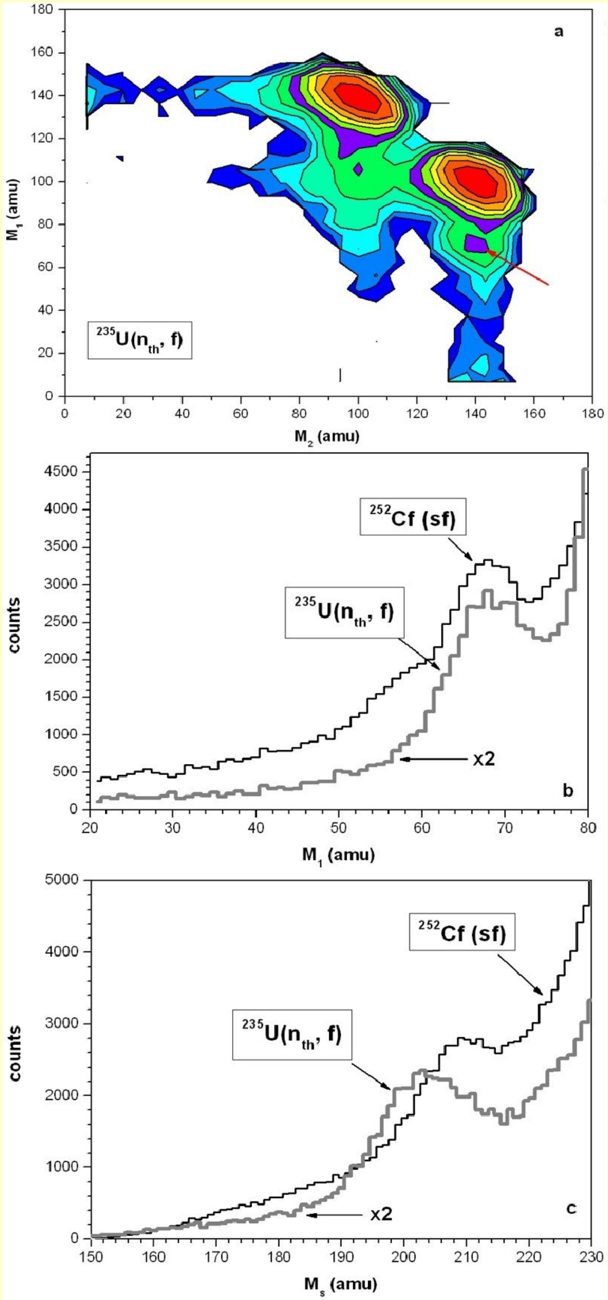
^{235}U(n,fff), (2xTOF+2xFOBOS) (n,ff,fff) JINR Reactor



1 – target + TOF-start, 2 – Bragg-Ionisation chambers
3 – PPAC's, 4 – neutron beam from reactor

1-- backing of source pointing to **arm 1,**
differences in counting rates (**arm1-arm2**)

Experiment 2 (Ex2) binary coincidences at 180°,



^{235}U(n,fff)

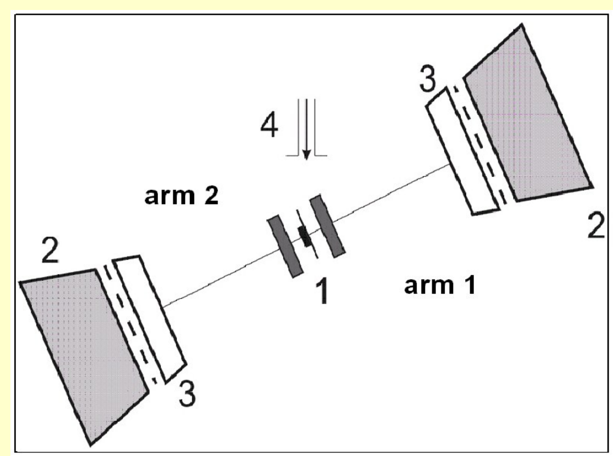
Correlations of two masses,

M1-- M2,

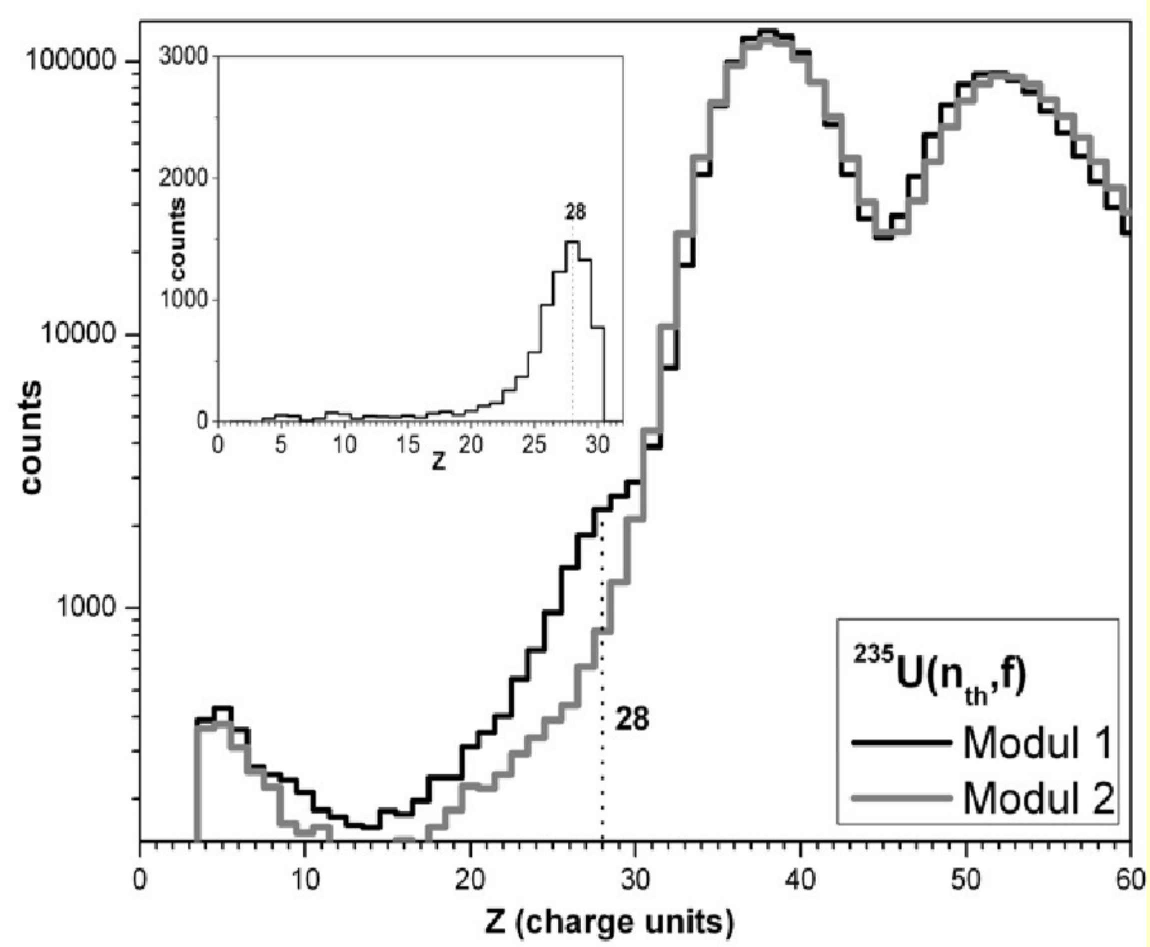
M1+ M2 = Ms

Comparison with

^{252}Cf(sf,fff),



Experiment 2 (Ex2) binary coincidences at 180°,



^{235}U(n,fff)

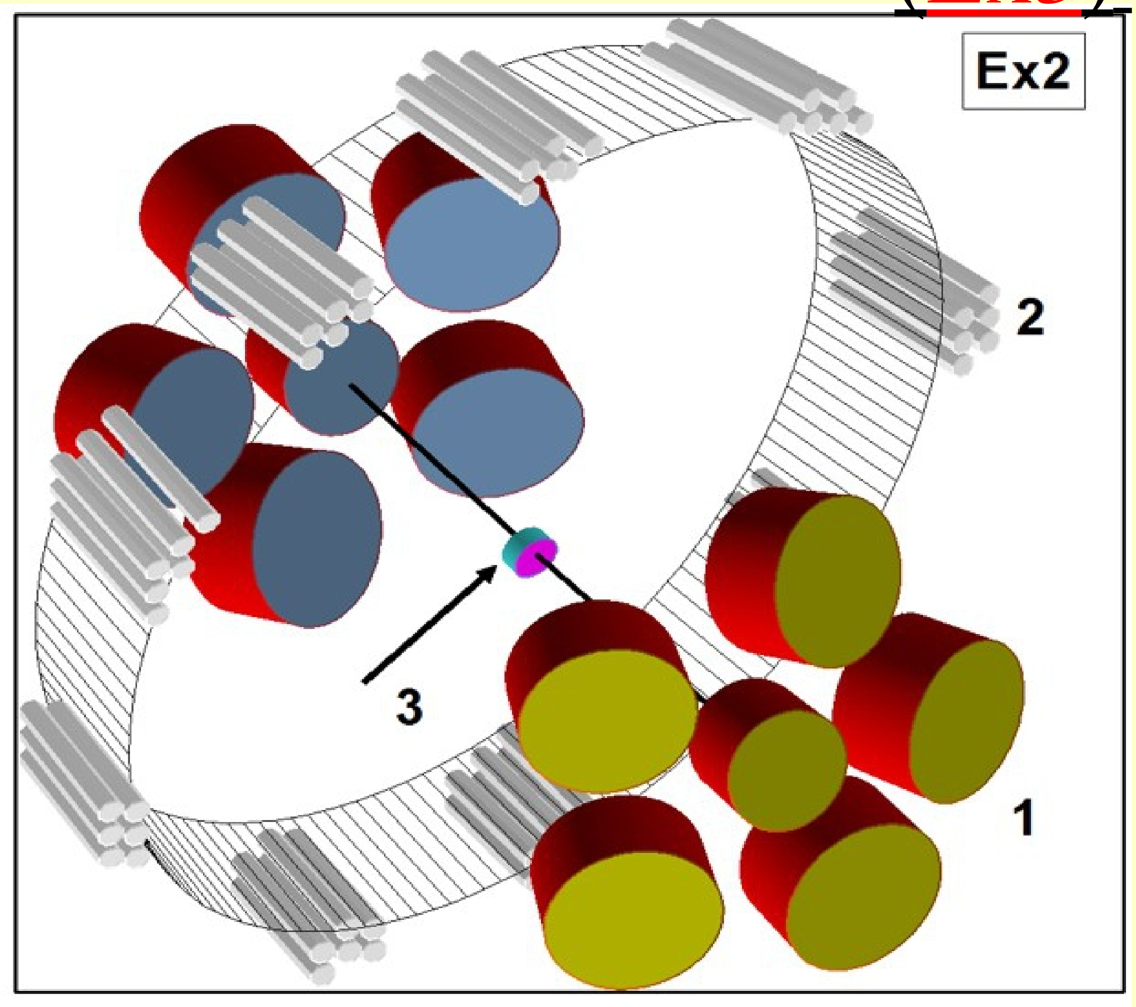
Energy - loss information from
Drift time in two Fobos-ionisation chambers
(Bragg-detectors, give the charge for the “Ni”-bump:

missing Z = 20 (Ca)

Experiment (Ex3), ^{252}Cf(sf,fff, n) neutrons in coincidence, ff at 180°

2x6 Mini-Fobos + Neutron detectors Ring

(Ex3)



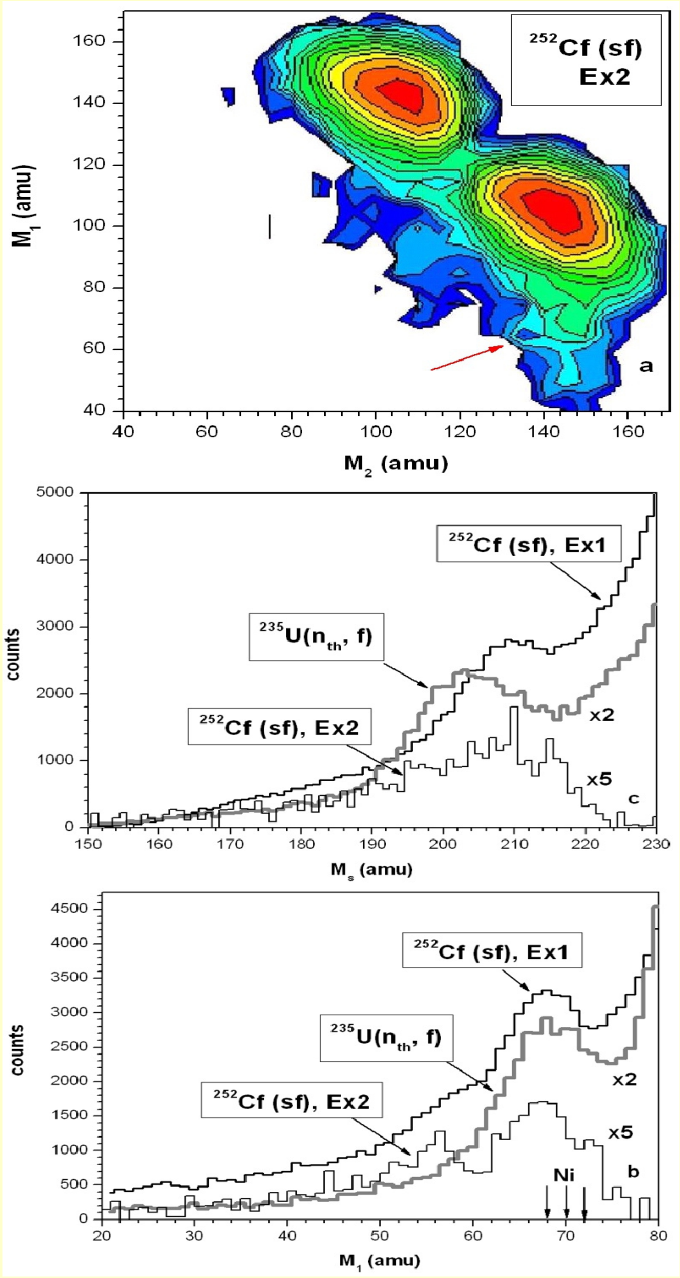
1 –smaller Fobos detectors

2 – Ring ofNeutron-detector chambers

3 – Source (+Start TOF)

^{252}Cf(sf,fff, n)

Experiment (Ex3) binary coincidences at 180°.

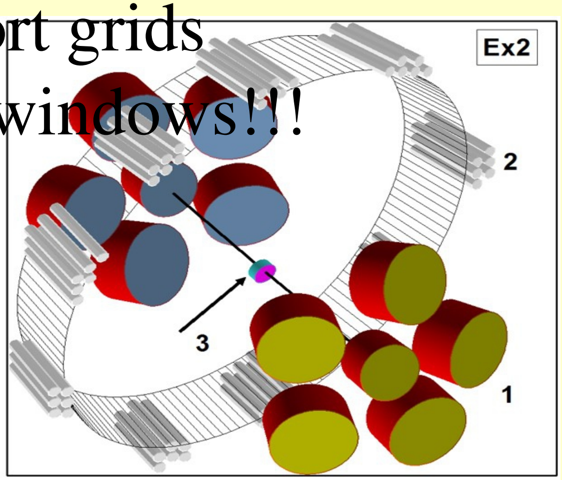


in coincidence with neutrons

^{252}Cf(sf,fff,n)

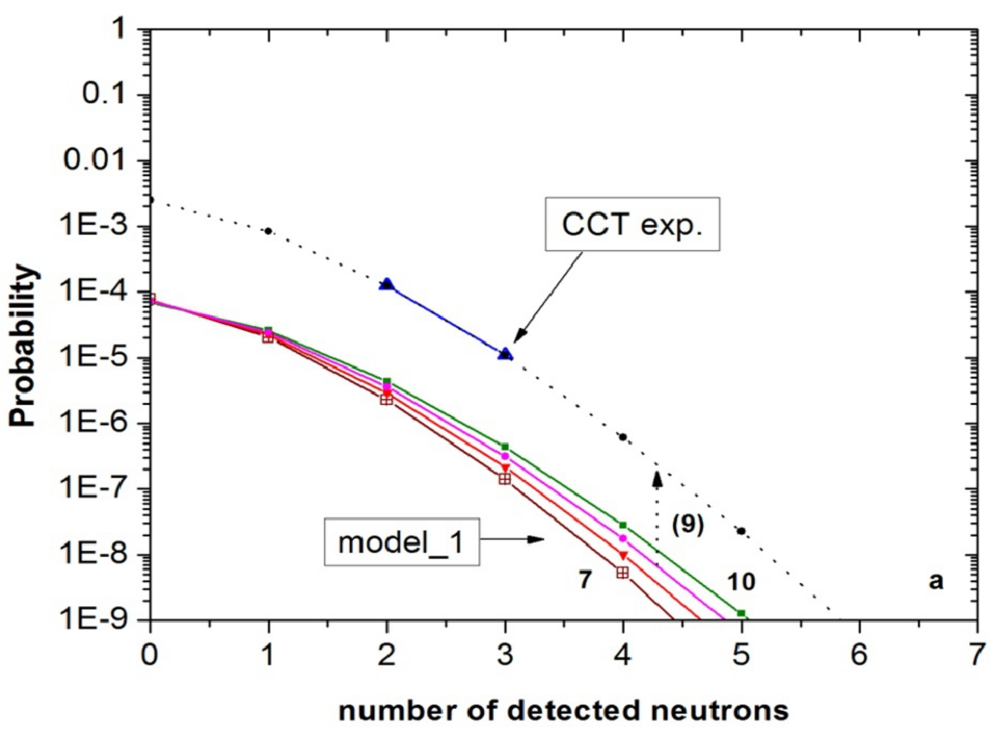
No background (tails), due to
n -coincidences

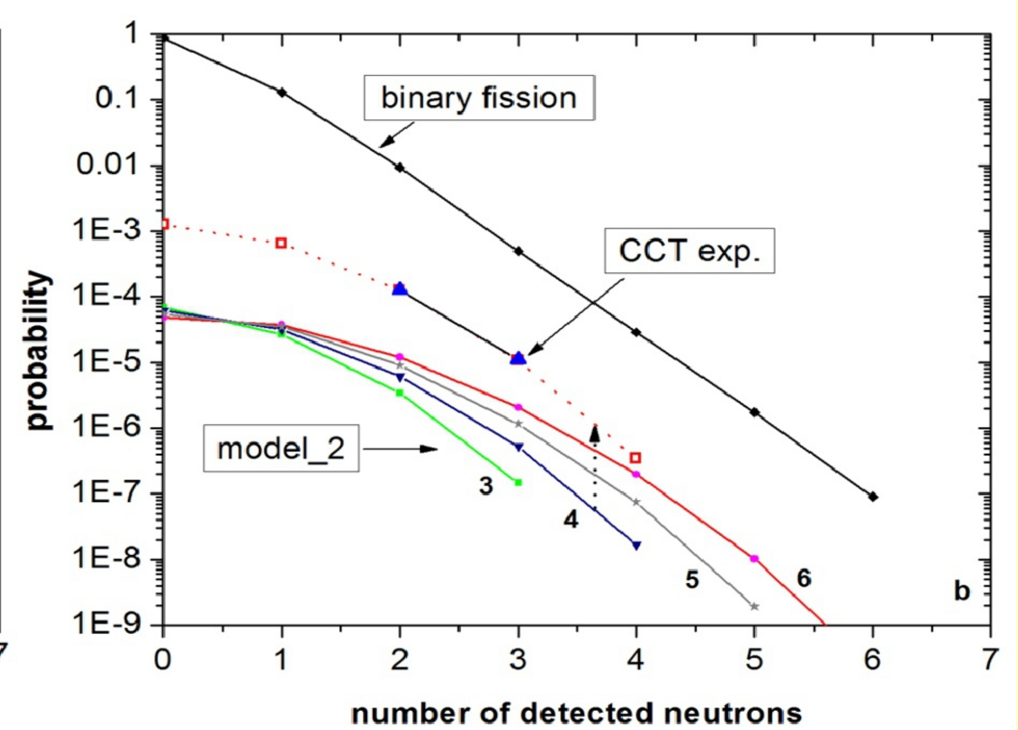
MINI-Fobos ,
smaller support grids
for entrance windows!!!



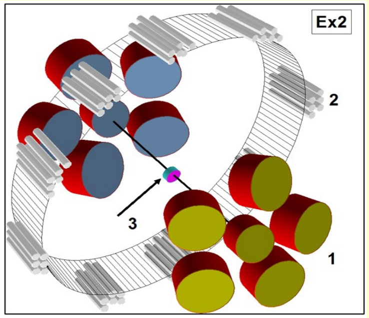
Experiment (Ex3) in coincidence with Neutrons

Neutron multiplicities



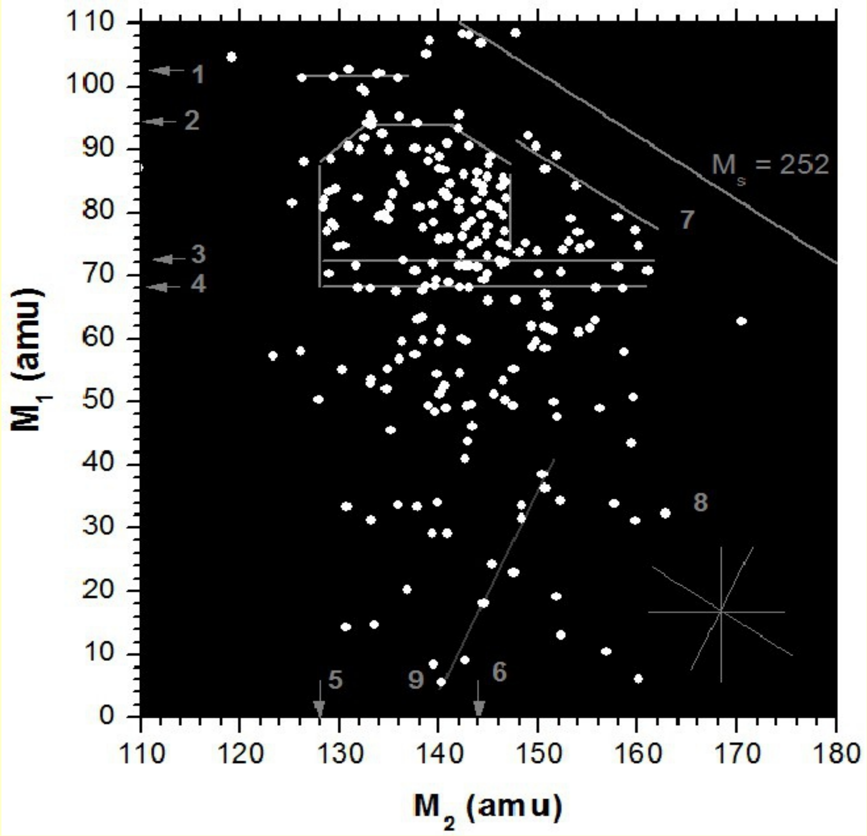


^{252}Cf(sf,fff,n)



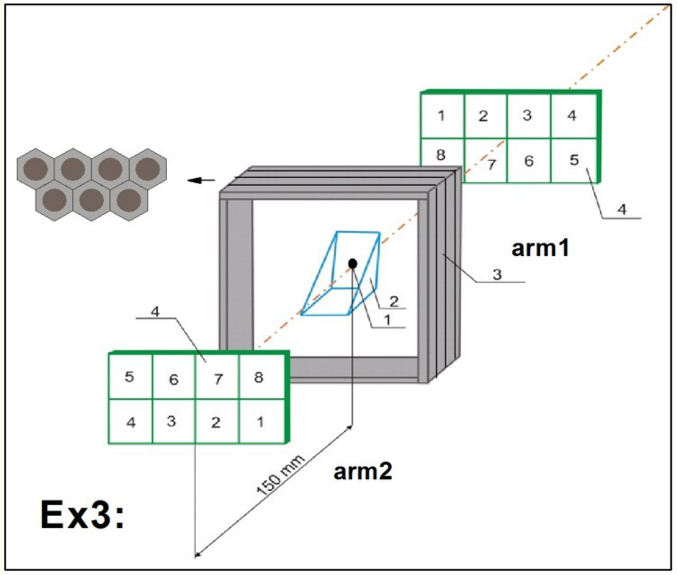
Experiment (Ex4) binary coincidences at 180°,

in coincidence with Neutrons



$^{252}Cf(sf,fff,n)$

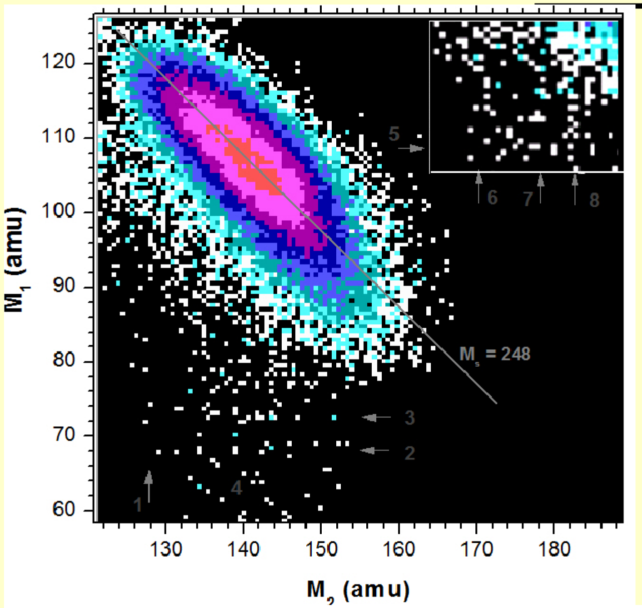
Mosaic of pin diodes, with separating grids



M1-M2 correlations, with Multiplicity Mn = 2

Experiment (Ex4) binary coincidences at 180°,

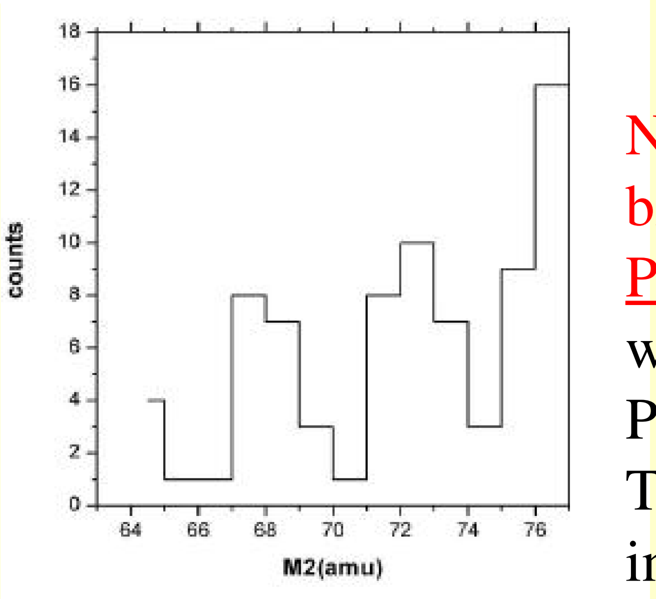
in coincidence with Neutrons



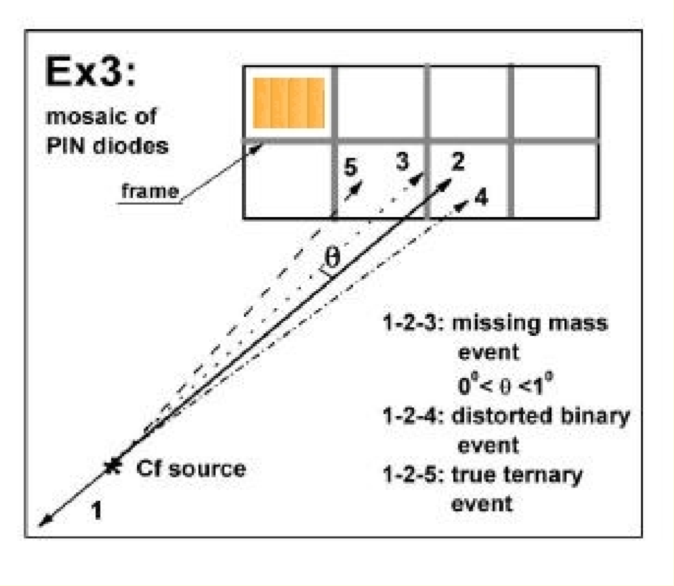
Inclusive data,
No condition on neutron Multiplicity Mn = 1 - 3; horizontal and diagonal lines.

^{252}Cf(sf,fff,n)

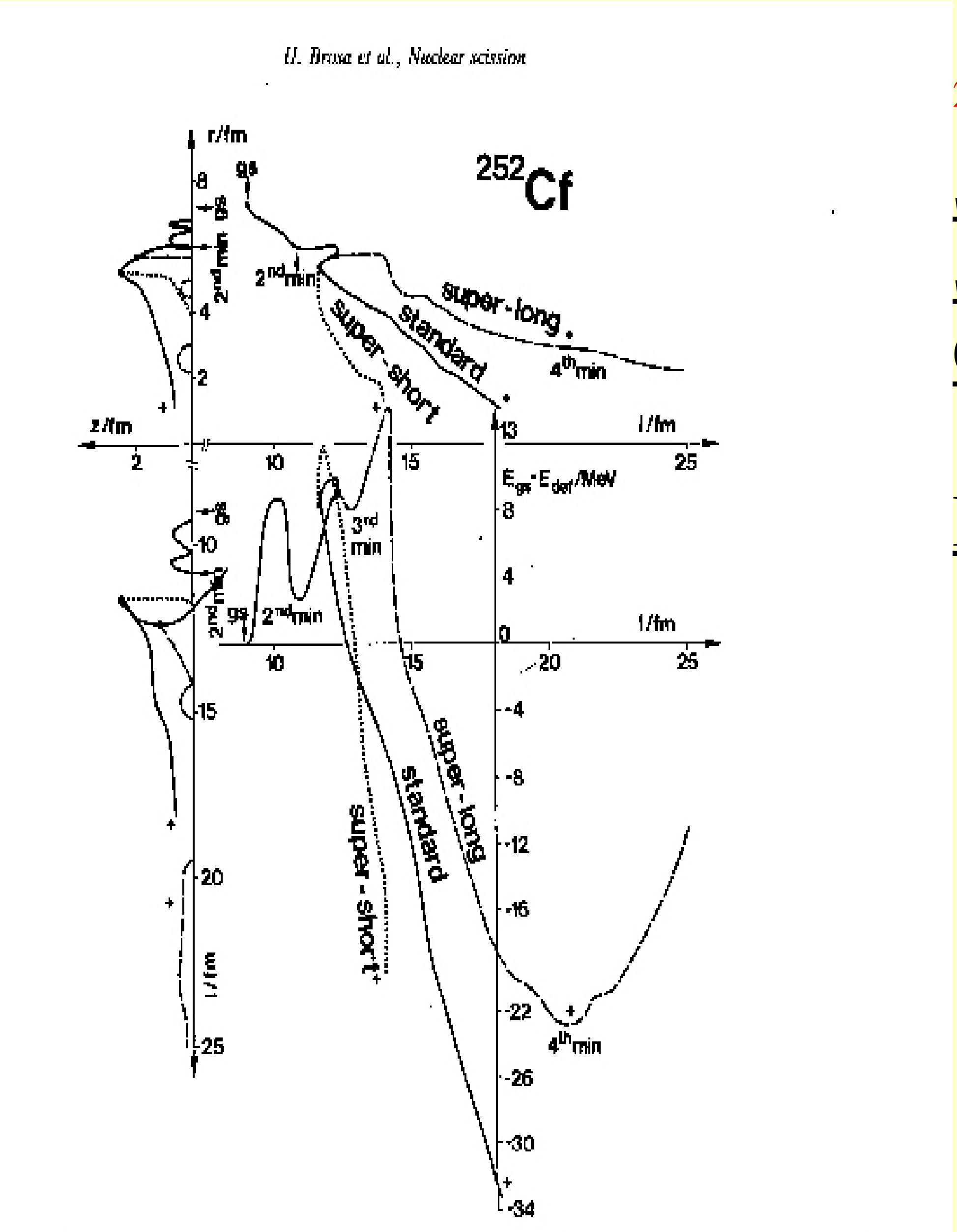
Mosaic of pin diodes, with separating grids



No background close to binary bump.
Projections: of "Ni"-lines with M2 = 68, 72,
PES of Nazirov show,
That other charges are involved:, Z = 26, 28, 30



Different fission paths as function of *prolate* deformation



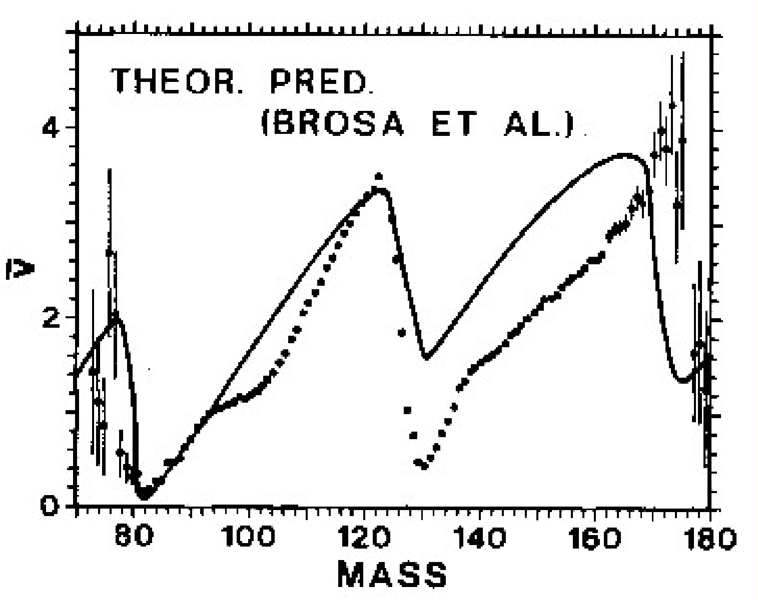
^{252}Cf(sf,ff), Fission-modes of Brosa et al.

SuperLong (Hyperdef), fff?

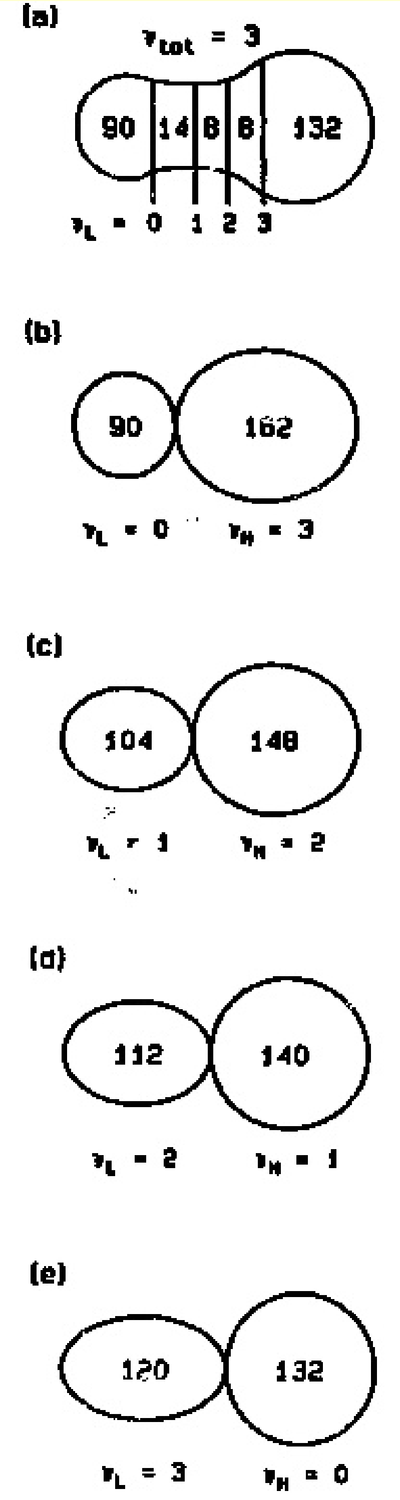
Standard (Superdef)

Compact(supershort, all Clusters,
realized in, fff.

Neutron multiplicities:



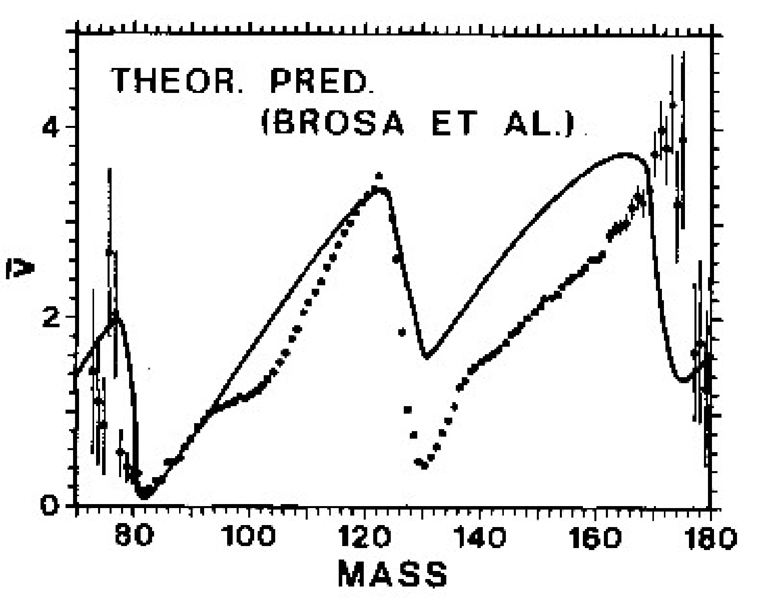
Neutron multiplicities as function of prolate deformation



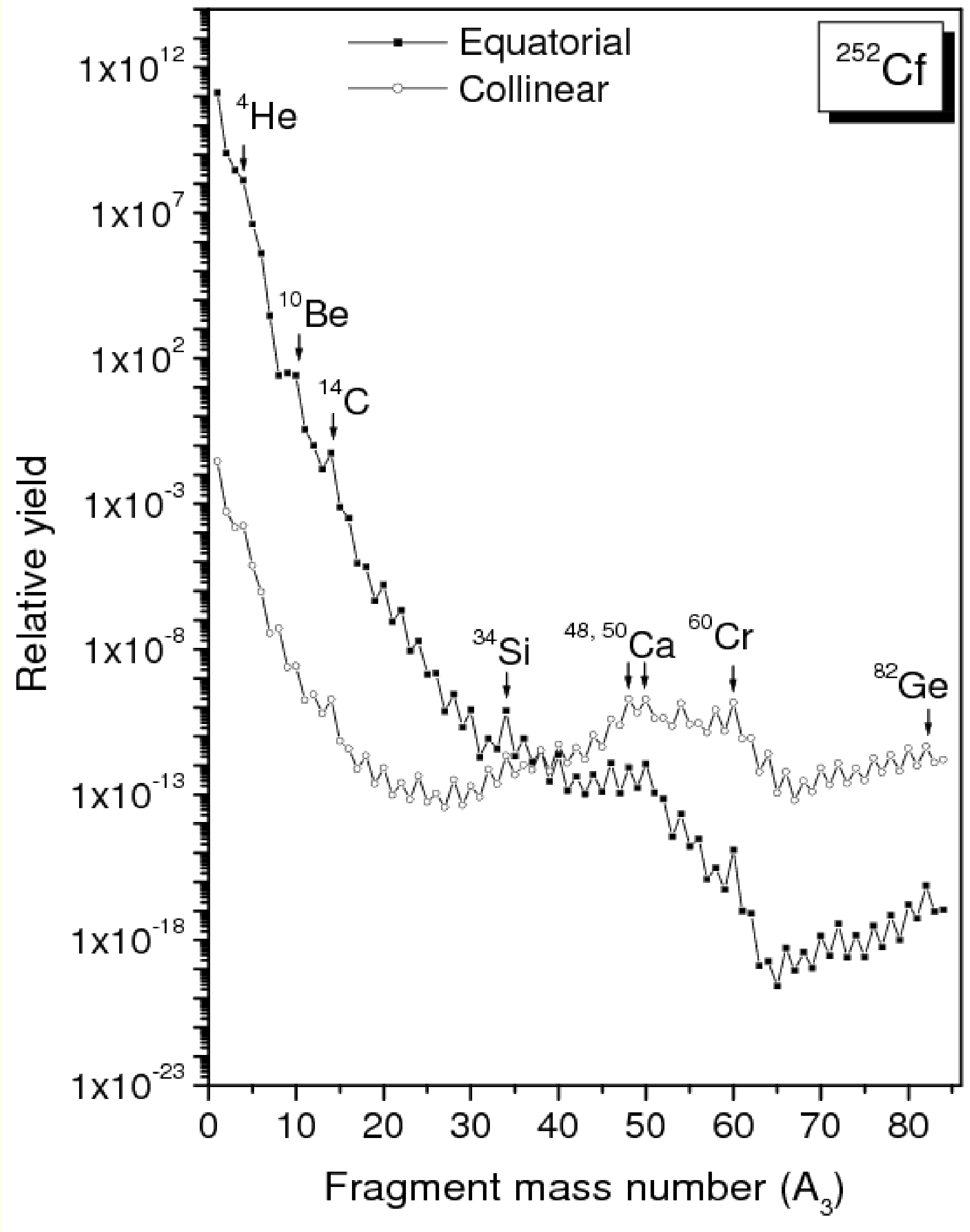
^{252}Cf(sf,ff) Fission-modes of Brosa et al.

SuperLong (Hyperdef), fff different CCT?
Standard (Superdef)
SuperShort (all Clusters, also realized in CCT)

Neutron multiplicities have a minimum for clusters, e.g. 132Sn



Perspectives of true ternary fission



- -- Other Heavy and **super-heavy** nuclei, Zagrebaev, Karpov, Greiner: Phys.Rev. C 81(2010)
- – Kinetic energies of fragments.
- -- Experiments with 3 clusters in coincidence: INVERSE KINEMATICS. Fission in fligth (FRS – GSI, FAIR)
- -- Higher mass resolution
- -- Definition of fission modes (BROSA): Hyper-deformation!

- -- At high spins, fission from super —and hyper-deformation will occur as CCT

Future:

studies with inverse kinematics, FRS-mode: K.H. Schmidt

N-H
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Nuclear Physics A 665 (2000) 221–267

NUCLEAR PHYSICS A

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Relativistic radioactive beams: A new access to nuclear-fission studies ☆

K.-H. Schmidt [a], S. Steinhäuser [b], C. Böckstiegel [b], A. Grewe [b], A. Heinz [b], A.R. Junghans [a], J. Benlliure [c], H.-G. Clerc [b], M. de Jong [b], J. Müller [b], M. Pfützner [d], B. Voss [a]

[a] *Gesellschaft für Schwerionenforschung, Planckstraße 1, D-64291 Darmstadt, Germany*
[b] *Institut für Kernphysik, Technische Universität Darmstadt, Schloßgartenstraße 9, D-64289 Darmstadt, Germany*
[c] *Facultad de Fisica, Universidad de Santiago de Compostela, E-15706 Santiago de Compostela, Spain*
[d] *Instytut Fizyki Doswiadczalnej, Uniwersytet Warszowski, ul Hoza 69, 00-381 Warszawa, Poland*

Received 28 June 1999; accepted 20 August 1999

Abstract

The secondary-beam facility of GSI Darmstadt was used to study the fission properties of 70 short-lived radioactive nuclei. Most of them have not been accessible so far in conventional fission experiments. Relativistic secondary projectiles were produced by fragmentation of a 1 A GeV ^{238}U primary beam and identified in nuclear charge and mass number. Using these reaction products as secondary beams, the giant resonances, mostly the giant dipole resonance, were excited by electromagnetic interactions in a secondary lead target, and fission from excitation energies around 11 MeV was induced. The fission fragments were identified in nuclear charge, and their velocity vectors were determined. Elemental yields and total kinetic energies have been obtained for a number of neutron-deficient actinides and preactinides. The characteristics of multimodal fission of nuclei around ^{227}Th were systematically investigated. The proton even–odd effect was determined for all systems.

PACS: 24.30.Cz; 24.75.+i; 25.20.-x; 25.60.-t; 25.70.Mn; 25.85.-w; 25.85.Jg; 27.80.+w; 27.90.+b; 29.30.Aj; 29.40.-n; 29.40.Mc
Keywords: Nuclear reaction; Radioactive beams; Nuclear fission; Measured fission-fragment elemental yields for ^{205,206}At, $^{204-209}$Rn, $^{206-212,217,218}$Fr, $^{209-219}$Ra, $^{212-226}$Ac, $^{217-229}$Th, $^{224-232}$Pa, $^{230-234}$U and total kinetic energies for $^{210-215,217-219}$Ra, $^{215-225}$Ac, $^{221-229}$Th, $^{226-232}$Pa, $^{232-234}$U; Transition from symmetric to asymmetric fission; Deduced even–odd effect

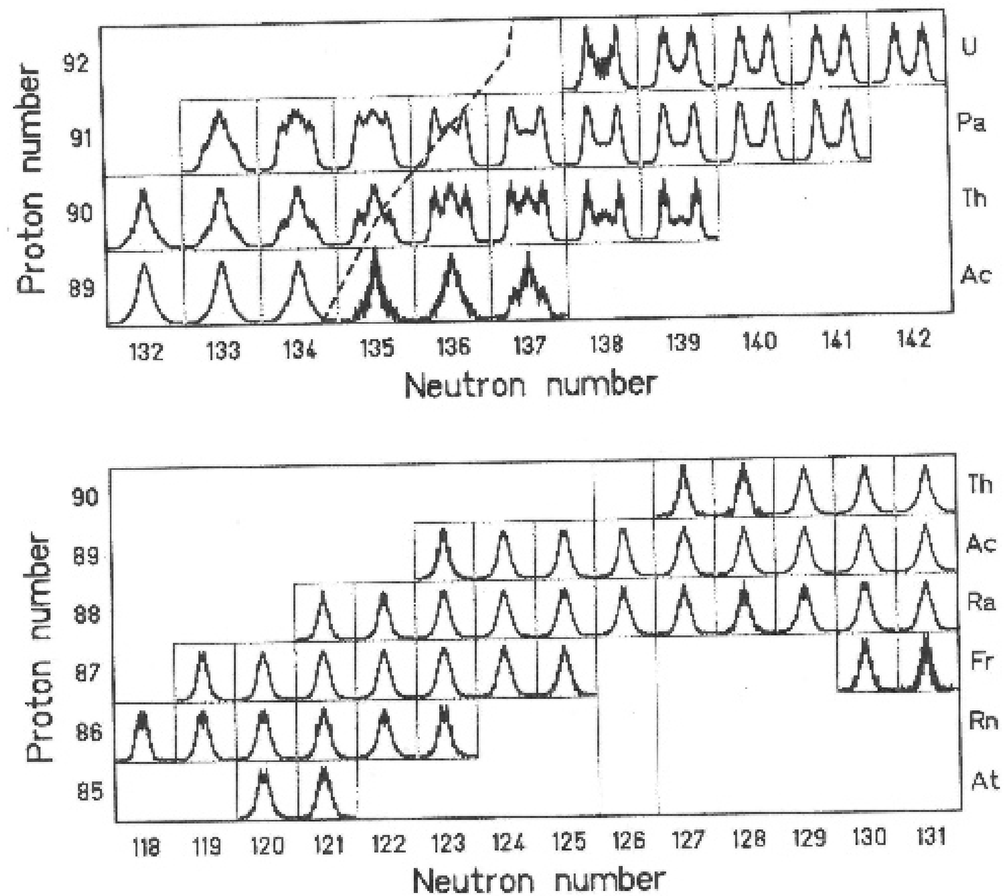

Fig. 20. Measured fission-fragment nuclear-charge distributions in the range $Z = 24$ to $Z = 65$ from ^{221}Ac to ^{234}U (upper part) and from ^{205}At to ^{221}Th (lower part) in electromagnetic-induced fission are shown on a chart of the nuclides. The dashed line in the upper part indicates the transition from symmetric to asymmetric fission as predicted by Möller [103] who calculated the stability of the saddle-point configuration against mass-asymmetric deformations. Nuclei on the right-hand side of this line were expected to predominantly show asymmetric fission, while nuclei on the left hand side were expected to show symmetric fission with higher probability.

Fragmentation of 1 GeV, ^{238}U

$^{232-234}$U(ff), and many other nuclei

Multimodal Fission-modes

Future:

studies with inverse kinematics, FRS-mode

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Nuclear Physics A 665 (2000) 221–267

NUCLEAR PHYSICS A

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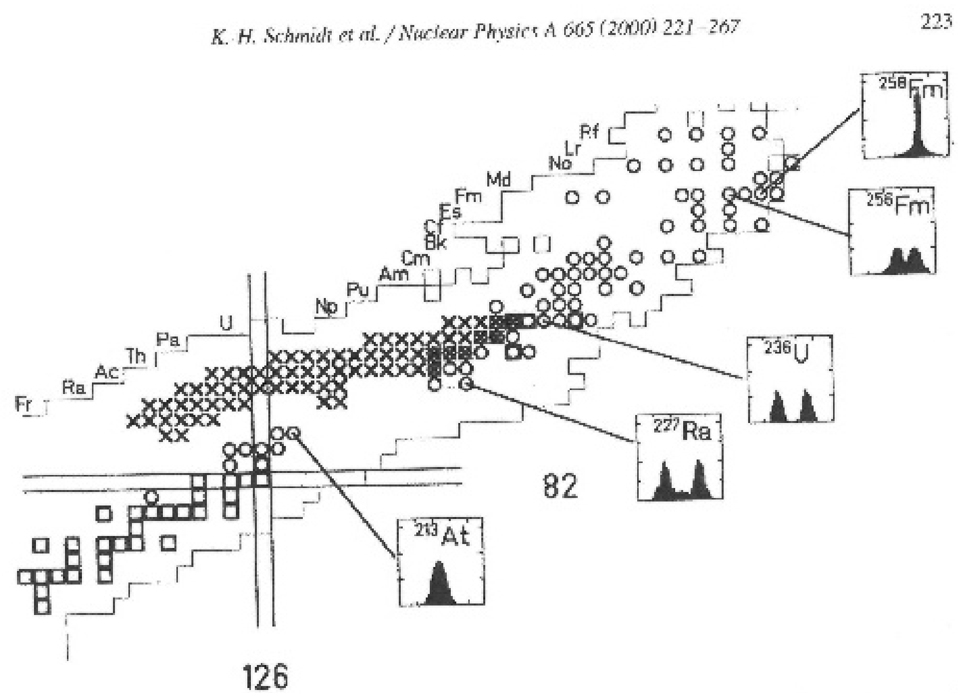

Fig. 1. Isotopes investigated in low-energy fission. Circles: Mass distributions measured in previous experiments for excitation energies less than 10 MeV above the fission barrier. Crosses: Systems investigated in the present experiment. Additionally, examples of previously measured fission-fragment mass distributions are shown (data from Refs. [20,30,38,52]). For orientation, the primordial isotopes are indicated by squares.

Fragmentation of 1 GeV, ^{238}U

$^{232-234}U$(ff), and many other nuclei

Multimodal Fission-modes