# Observation of shape isomeric states in fission fragments

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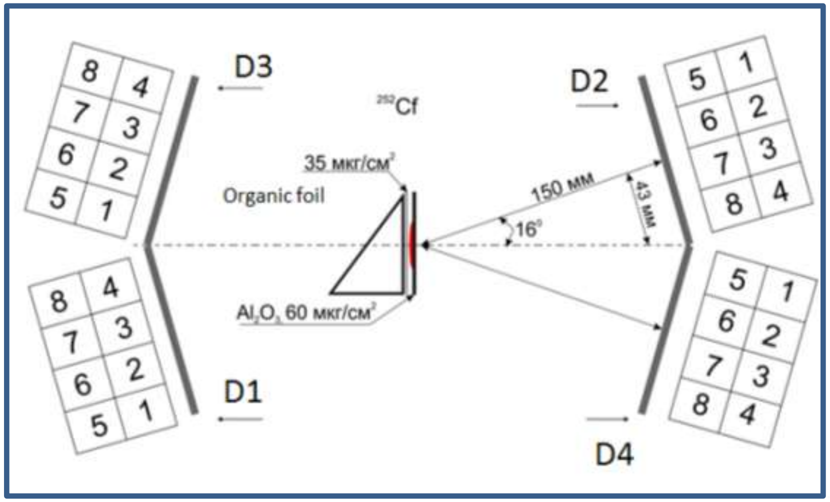
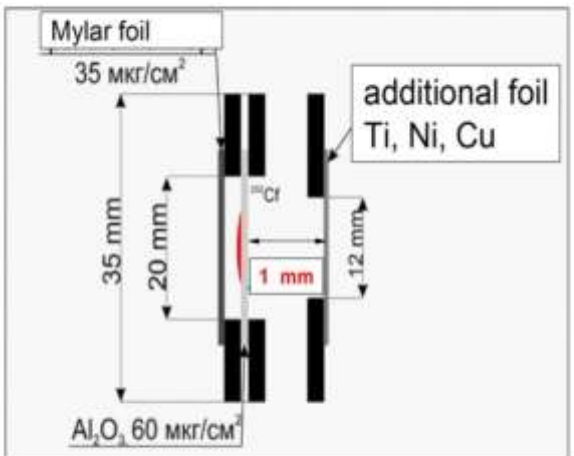
# Just to remind: our previous experimental results

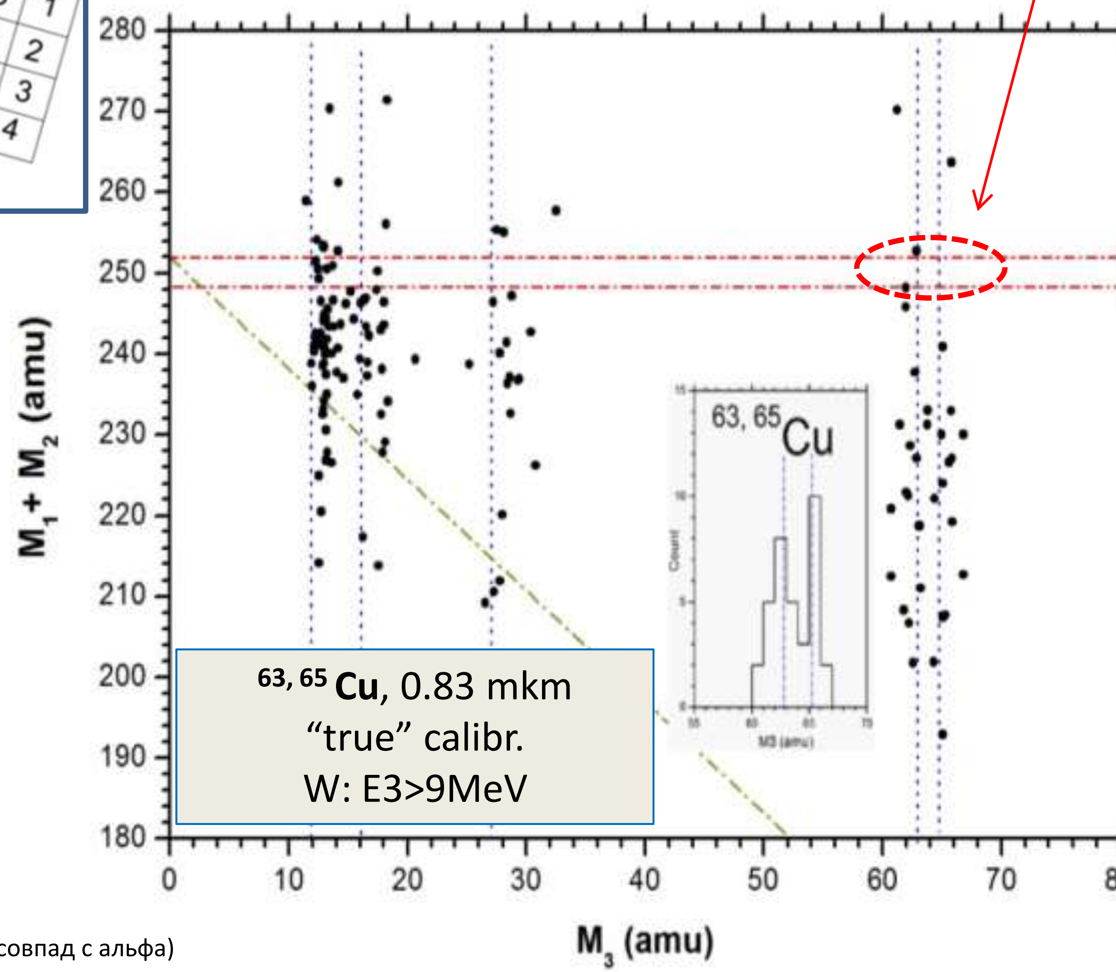



Layout of the source module

In each ternary event: $M_1 > M_2 > M_3$

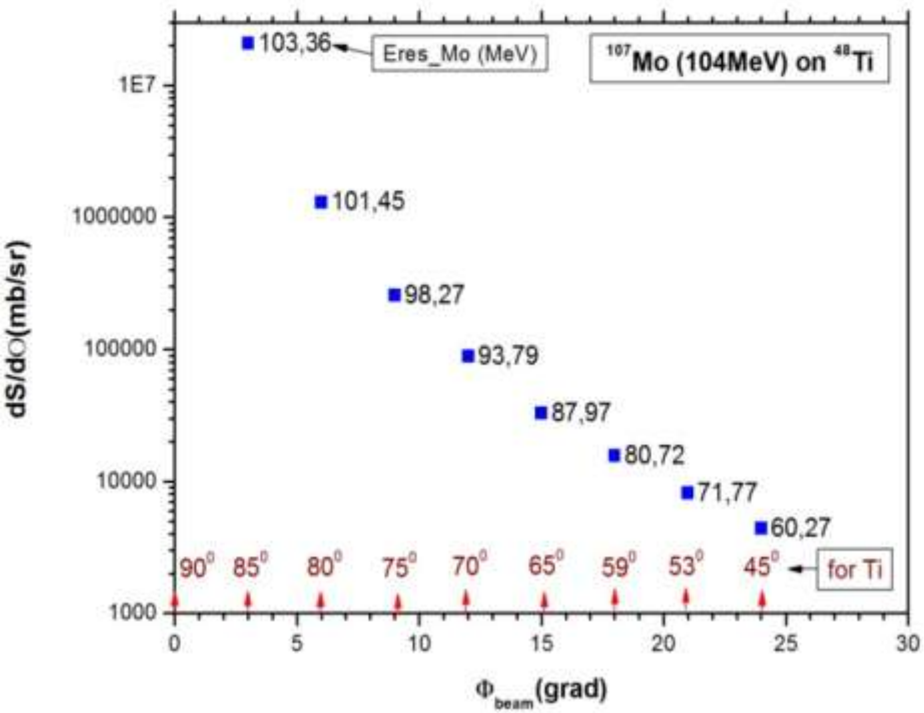
region of elastic FF scattering




From C13_r2_m3_last.opj & w1: E3plz>9MeV (для устранения случ совпад с альфа)

# Rutherford scattering - L_FF/Ti

2 solutions are possible: the same scattering angle at two different impact parameters



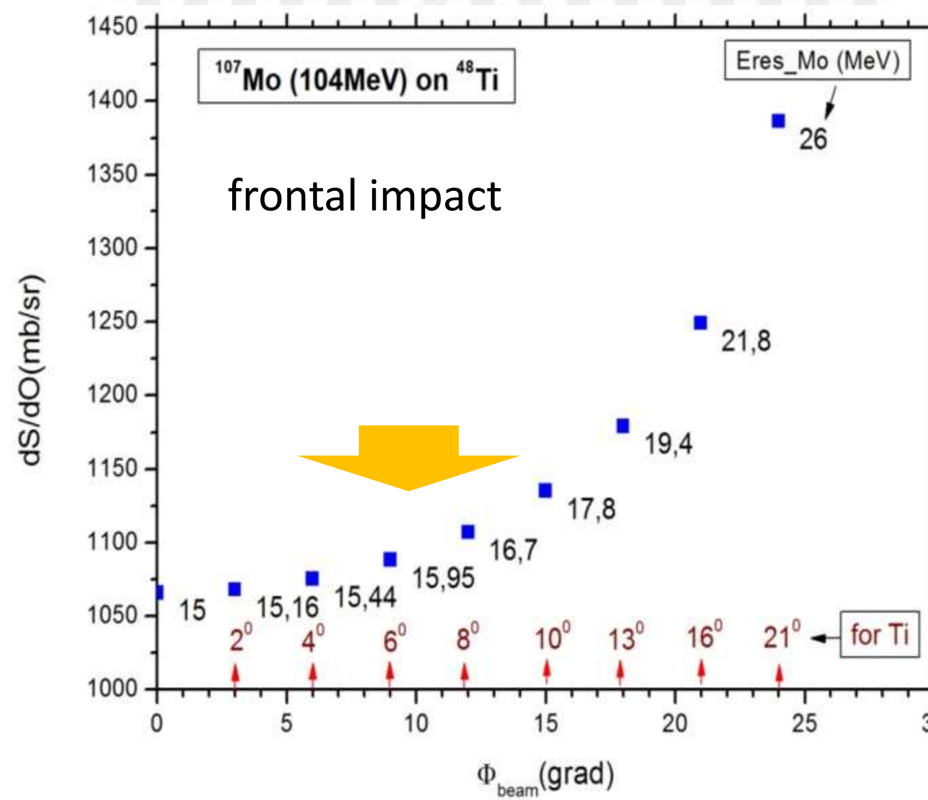

$$\sigma(\theta) = \left(\frac{1}{4\pi\varepsilon_0}\right)^2 \frac{Z^2 e^4}{M^2 v^4} \times \frac{1}{\sin^4(\theta/2)}$$

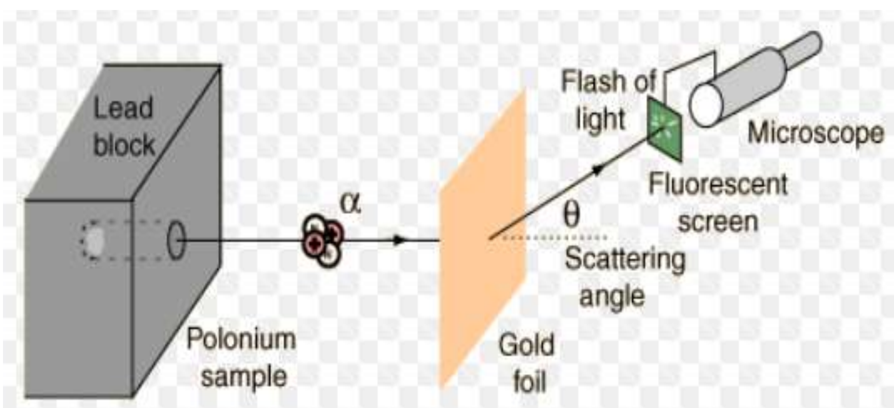
$Ze$ = the positive charge of the target atom,

$M$ = the mass of the $\alpha$ particle,

$v$ = incident speed of the $\alpha$ particle,

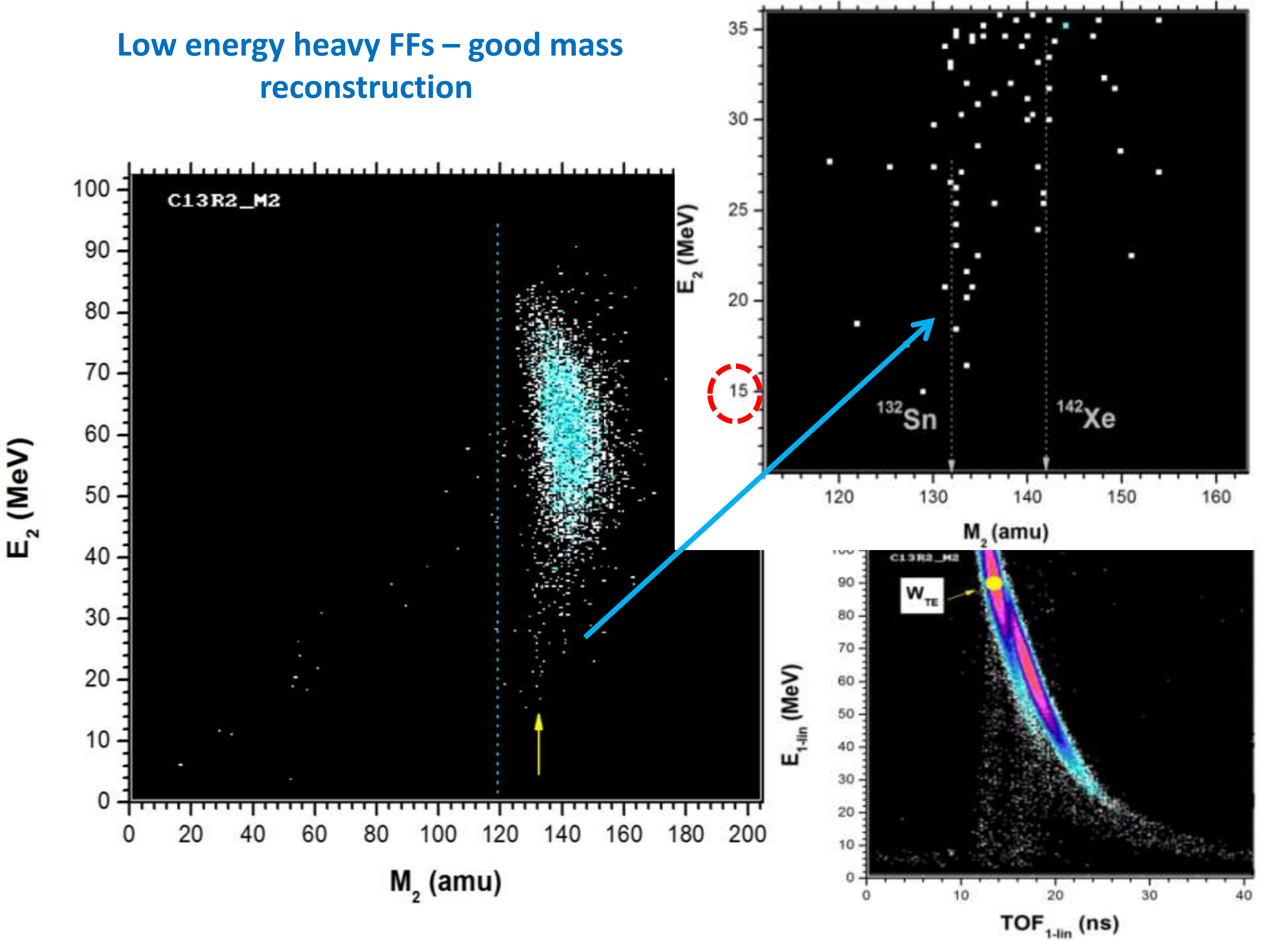
$\theta$ = scattering angle,



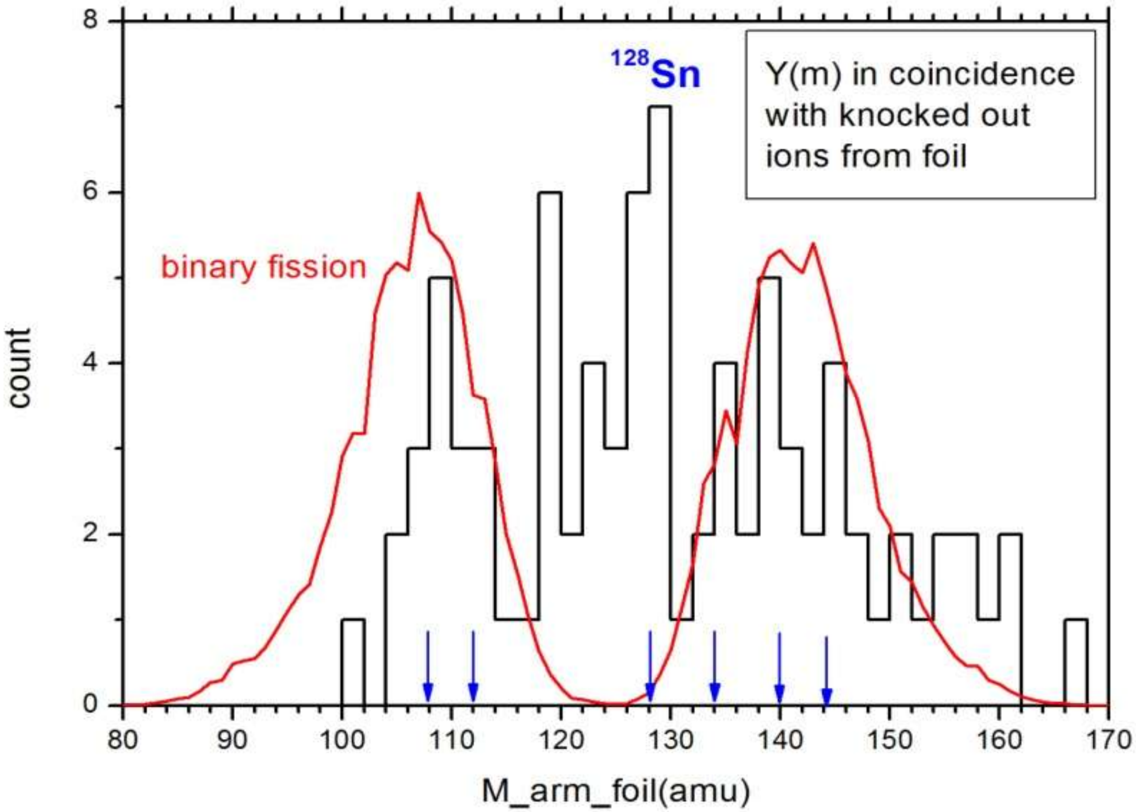

Original Rutherford experiment

# Low energy heavy FFs – good mass reconstruction



# Mass spectrum of the fragments detected in coincidence with the knocked out ions of Ti, Ni, Cu

**Really:**




Hypothesis:
we suppose each FF, at least just after scission, looks like a di-nuclear system "magic cluster + light ion "

Due to the brake-up in the foil both constituents become free. Thus one of them should be magic nucleus.

## Conclusions presented at the previous ISINN21 meeting in 2013. Presumably:

1. Inelastic impact, at least the frontal one, makes free the constituents of the di-nuclear system (fission fragment) formed in the binary fission .

2. Bearing in mind the distance between the Cf source and the generating foil (~1mm) the lower limit of the life-time of this di-nuclear system (shape isomer) is about 0.1ns.

3. Relative probability of elastic Rutherford scattering of fission fragments i.e. taking place without missing mass is much less then those in the inelastic channel. In other words, **the bulk of the fragments from the conventional binary fission are born as shape-isomers .**

**Principal question to be answered :**

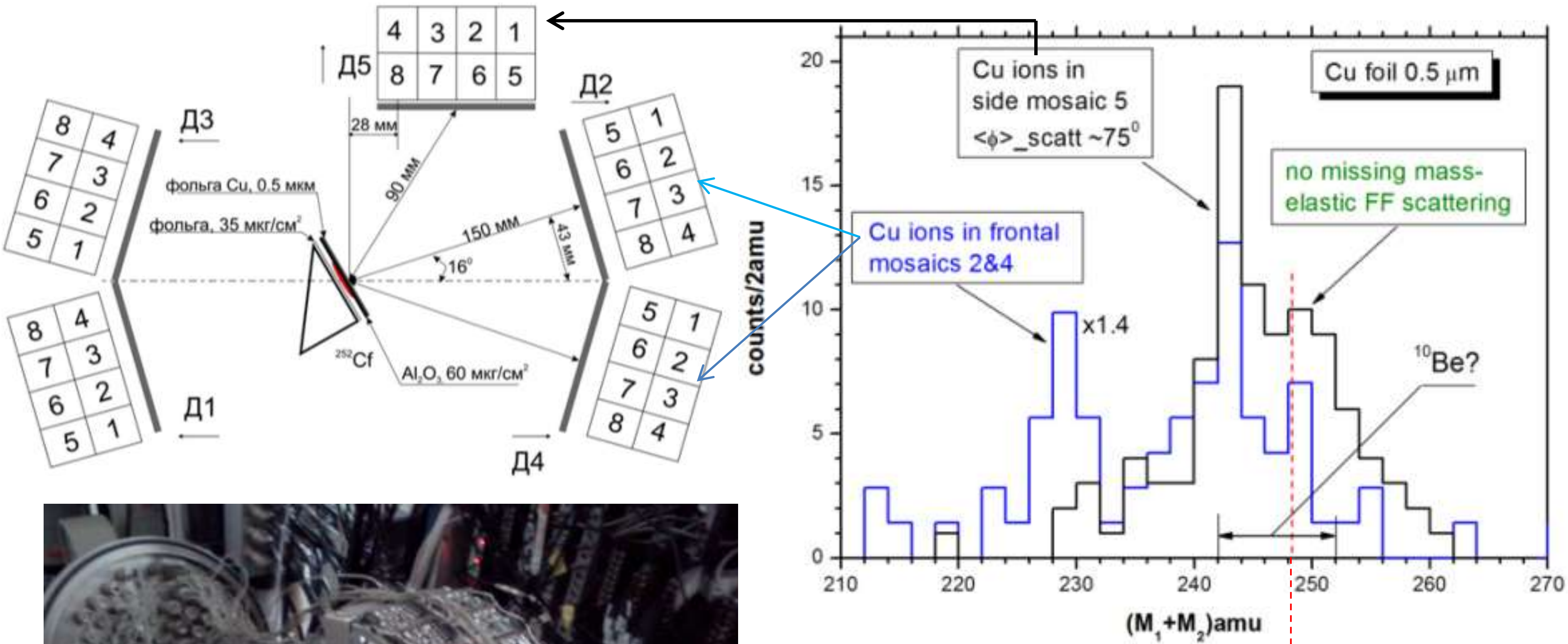
Are there contradictions of the experimental results obtained and model proposed with well known features of the fission process?

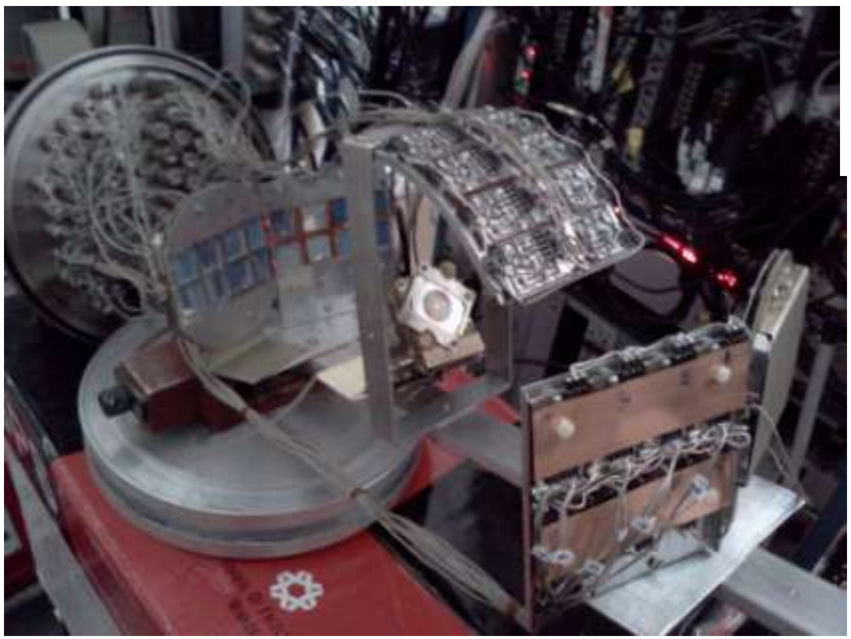
1. We suppose that the bulk of the fragments of conventional binary fission look like di-nuclear systems (are in shape isomeric states) just after scission.

Does it mean that the total yield of the effect is sufficient to change the macroscopical fission constants?

Our answer: **No!** The brake-up of di-nuclear system (FF) appears to occur in almost frontal inelastic collisions which takes place with relatively low probability.

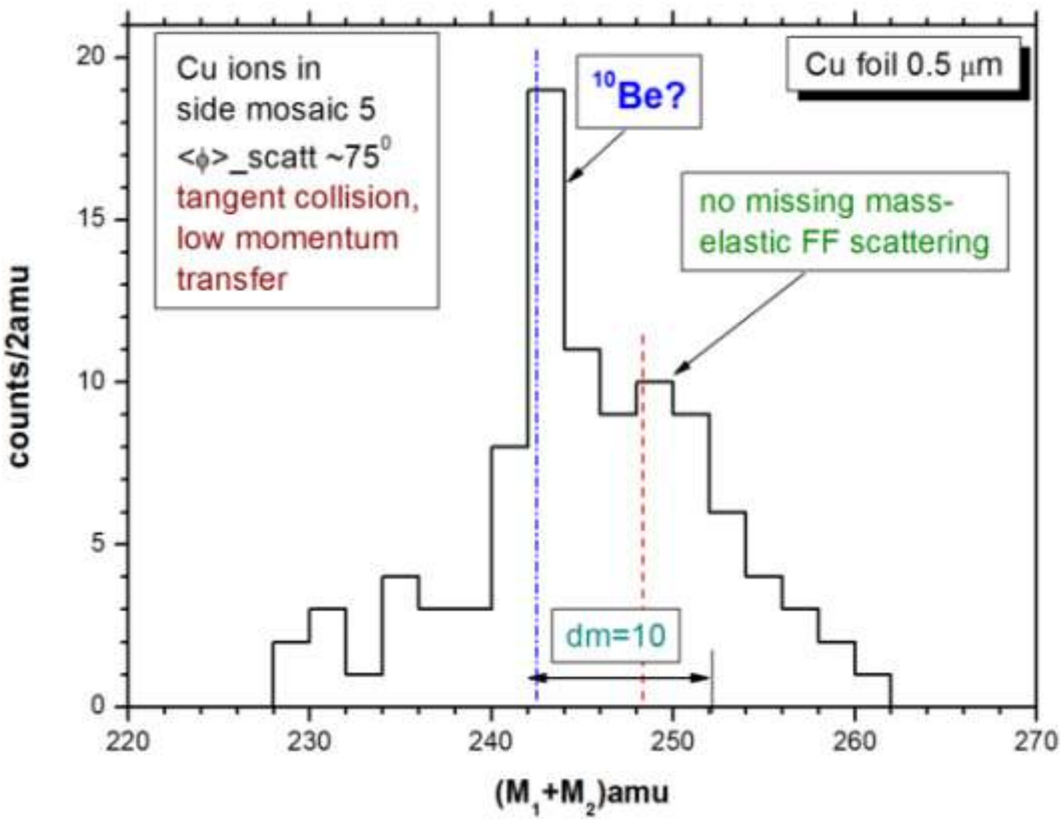
# Angular dependence of the brake-up yield



At the large angles of scattering of the knocked –out ions from the foil conventional elastic Rutherford scattering takes place.

# Manifestation of $^{10}$Be based di-nuclear system




J. Phys. G: Nucl. Part. Phys. **26** (2000) L97–L102
**Nuclear qusi-molecular states in ternary fission**

D N Poenaru†‡§_, B Dobrescu†, W Greiner‡_, J H Hamilton§ andA V Ramayya§

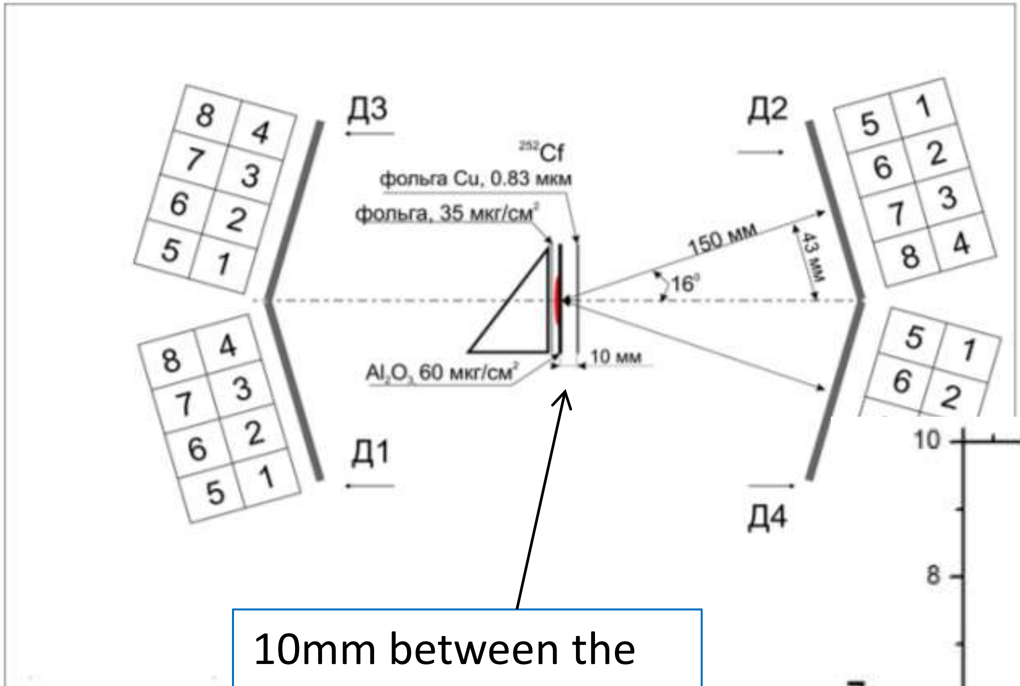
Table 1. Calculated half lives of some quasi-molecular states $^{252}$Cf.

| Particle | Fragments | | $Q_{exp}$ (MeV) | $K$ | log $T$ (s) |
|---|---|---|---|---|---|
| $^{10}$Be | $^{132}$Sn | $^{110}$Ru | 220.183 | 19.96 | −11.87 |
| | $^{138}$Te | $^{104}$Mo | 209.682 | 25.23 | −9.59 |
| | $^{138}$Xe | $^{104}$Zr | 209.882 | 26.04 | −9.23 |
| | $^{146}$Ba | $^{96}$Sr | 201.486 | 22.98 | −10.56 |

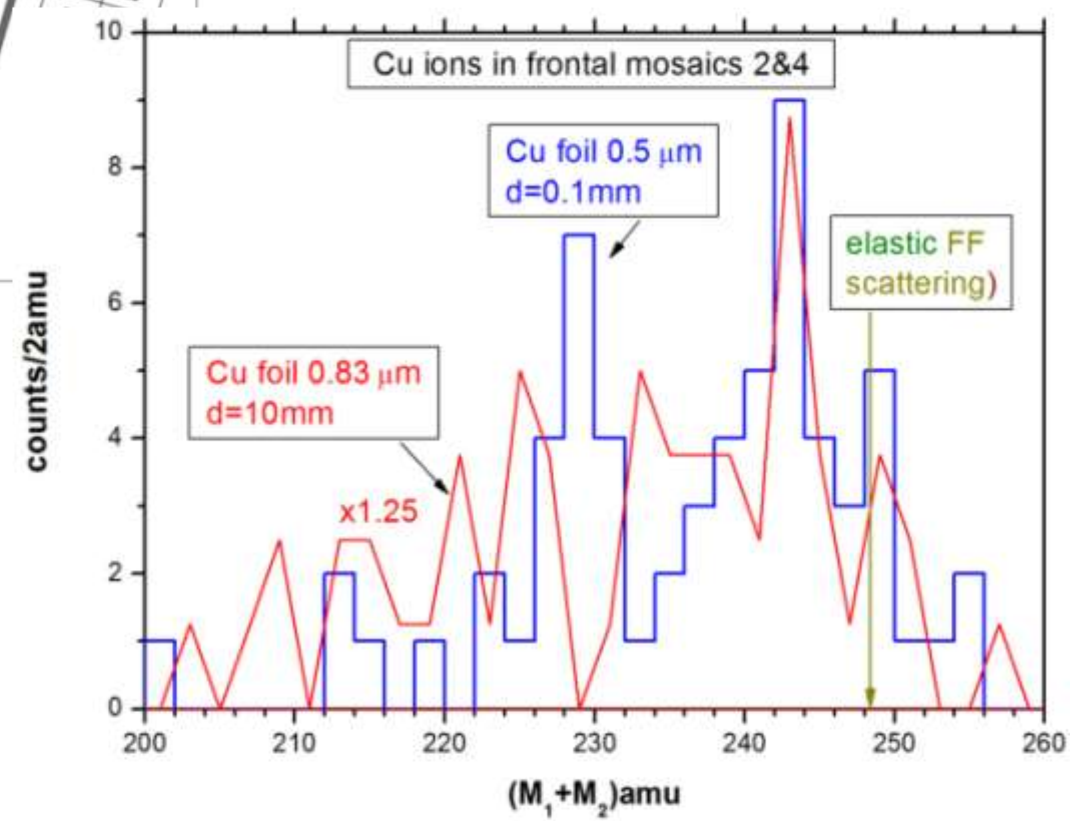
There is no such peak in M1+M2 spectrum FF from conventional binary fission.
Likely loosely coupled (see Poenary predictions)
$^{10}$Be based di-nuclear system experiences a breakdown even in tangent collisions.

**ps** life times are predicted ,
**low barrier**
against the decay

# Estimation of the life time




10mm between the Cu foil and the Cf source, TOF~1ns



Are there contradictions with known features of the fission process?

2. According to our experiments fission fragments in the shape isomeric states show life time at least more than 1ns. What about the neutrons emitted from the fission fragments orders of magnitude faster?

PHYSICAL REVIEW C 86, 054319 (2012)

# Observation of new microsecond isomers among fission products from in-flight fission of 345 MeV/nucleon $^{238}U$

D. Kameda,[1,*] T. Kubo,[1] T. Ohnishi,[1] K. Kusaka,[1] A. Yoshida,[1] K. Yoshida,[1] M. Ohtake,[1] N. Fukuda,[1] H. Takeda,[1] K. Tanaka,[1] N. Inabe,[1] Y. Yanagisawa,[1] Y. Gono,[1] H. Watanabe,[1] H. Otsu,[1] H. Baba,[1] T. Ichihara,[1] Y. Yamaguchi,[1] M. Takechi,[1] S. Nishimura,[1] H. Ueno,[1] A. Yoshimi,[1] H. Sakurai,[1] T. Motobayashi,[1] T. Nakao,[2] Y. Mizoi,[3] M. Matsushita,[4] K. Ieki,[4] N. Kobayashi,[5] K. Tanaka,[5] Y. Kawada,[5] N. Tanaka,[5] S. Deguchi,[5] Y. Satou,[5] Y. Kondo,[5] T. Nakamura,[5] K. Yoshinaga,[6] C. Ishii,[6] H. Yoshii,[6] Y. Miyashita,[6] N. Uematsu,[6] Y. Shiraki,[6] T. Sumikama,[6] J. Chiba,[6] E. Ideguchi,[7] A. Saito,[7] T. Yamaguchi,[8] I. Hachiuma,[8] T. Suzuki,[8] T. Moriguchi,[9] A. Ozawa,[9] T. Ohtsubo,[10] M. A. Famiano,[11] H. Geissel,[12] A. S. Nettleton,[13] O. B. Tarasov,[13] D. Bazin,[13] B. M. Sherrill,[13] S. L. Manikonda,[14] and J. A. Nolen[14]

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## Abstract

A search for isomeric $\gamma$ decays among fission fragments from 345 MeV/nucleon $^{238}U$ has been performed at the RIKEN Nishina Center RI Beam Factory. Fission fragments were selected and identified using the superconducting in-flight separator BigRIPS and were implanted in an aluminum stopper. Delayed $\gamma$ rays were detected using three clover-type high-purity germanium detectors located at the focal plane within a time window of 20 $\mu$s following the implantation. We identified a total of 54 microsecond isomers with half-lives of ~0.1–10 $\mu$s, including the discovery of 18 new isomers in very neutron-rich nuclei: $^{59}Ti^m$, $^{90}As^m$, $^{92}Se^m$, $^{93}Se^m$, $^{94}Br^m$, $^{95}Br^m$, $^{96}Br^m$, $^{97}Rb^m$, $^{108}Nb^m$, $^{109}Mo^m$, $^{117}Ru^m$, $^{119}Ru^m$, $^{120}Rh^m$, $^{122}Rh^m$, $^{121}Pd^m$, $^{124}Pd^m$, $^{124}Ag^m$, and $^{126}Ag^m$, and

The fast isotopic separation and identification of reaction products, which take place in several hundred nanoseconds, allow event-by-event detection of isomeric γ rays at the focal plane of the separator with small decay losses in flight. The γ decays are observed under low-background conditions after ion implantation. …

In-flight fission of a uranium beam have been used as production reactions to populate isomers. In-flight fission is known to be an excellent mechanism for producing neutron-rich exotic nuclei…

Atomic Data and Nuclear Data Tables 98 (2012) 149–300

Contents lists available at SciVerse ScienceDirect

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# Nuclear shape isomers

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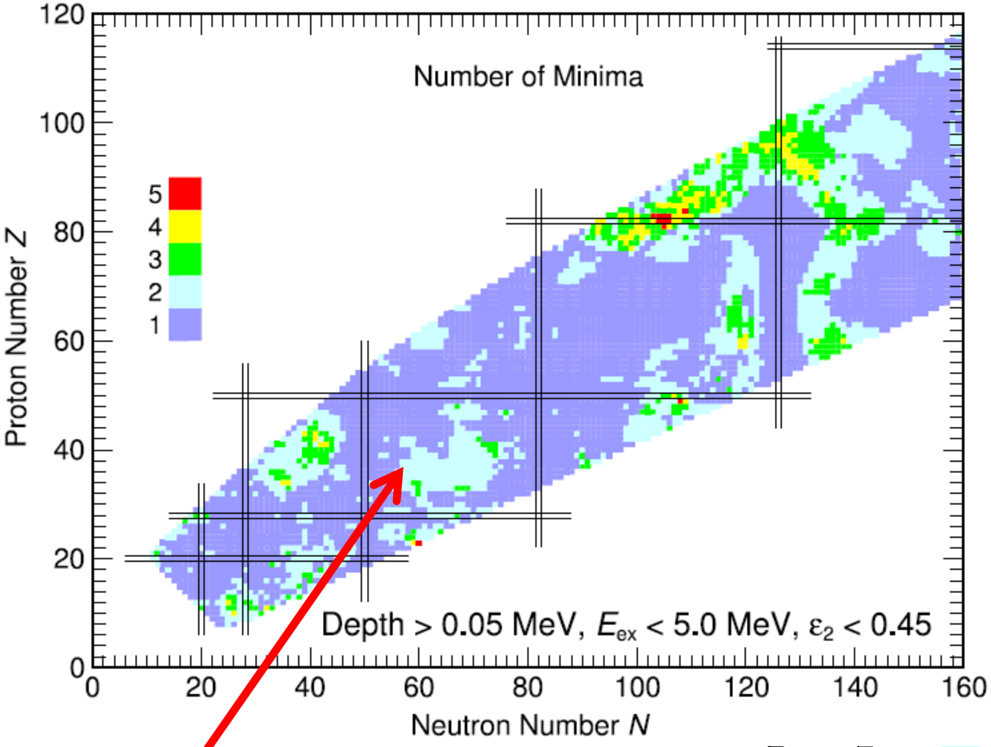
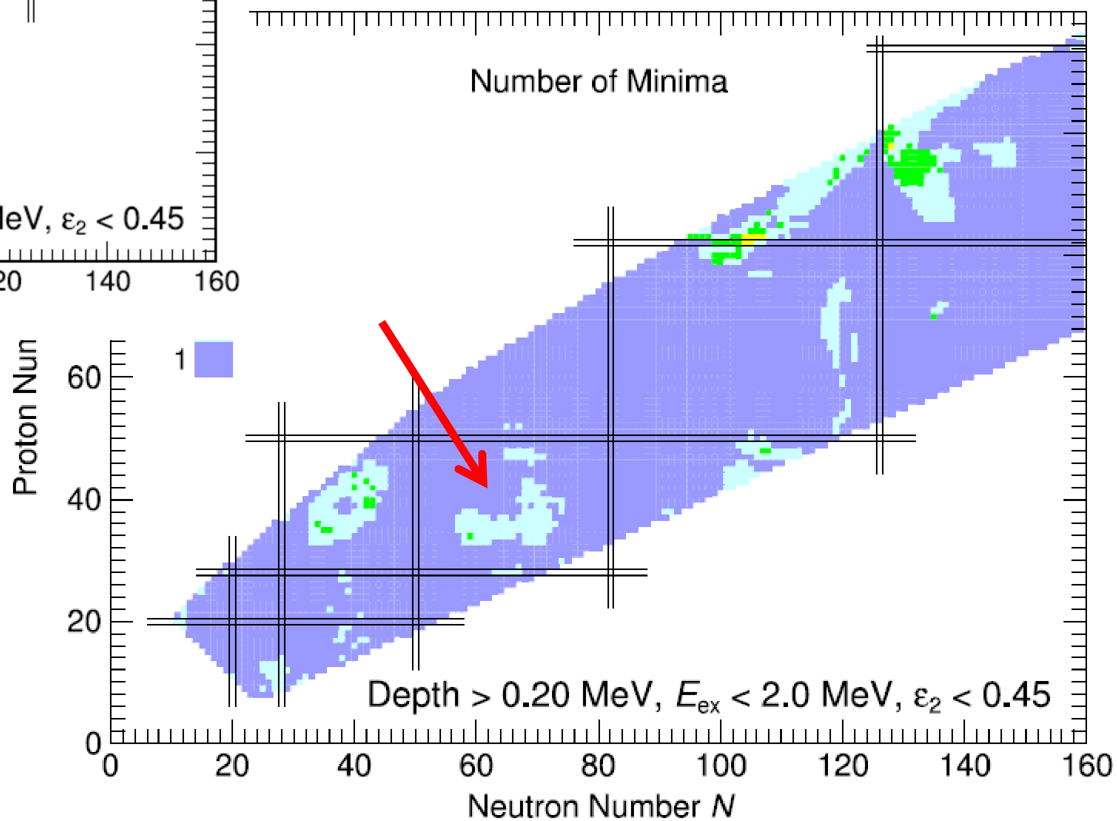
We calculate potential-energy surfaces as functions of spheroidal ($\epsilon 2$), hexadecapole ($\epsilon 4$), and axial asymmetry ($\gamma$) shape coordinates for 7206 nuclei from A = 31 to A = 290. We tabulate the deformations and energies of all minima deeper than 0.2 MeV and of the saddles between all pairs of minima. The tabulation is terminated at N = 160….
We also present potential-energy contour plots versus $\epsilon 2$ and $\gamma$ for 1224 even–even nuclei in the region studied. We can identify nuclei for which a necessary condition for shape isomers occurs, namely multiple minima in the calculated potential-energy surface.




## Some results

Magic numbers




**FF region**

Apparently, we and RIKEN group deal with **the same shape isomers** and they observe the de-excitation of isomeric states by detecting of delayed ɣ-quanta . We fill the presence of di-nuclear system (shape isomer) via brake-up.

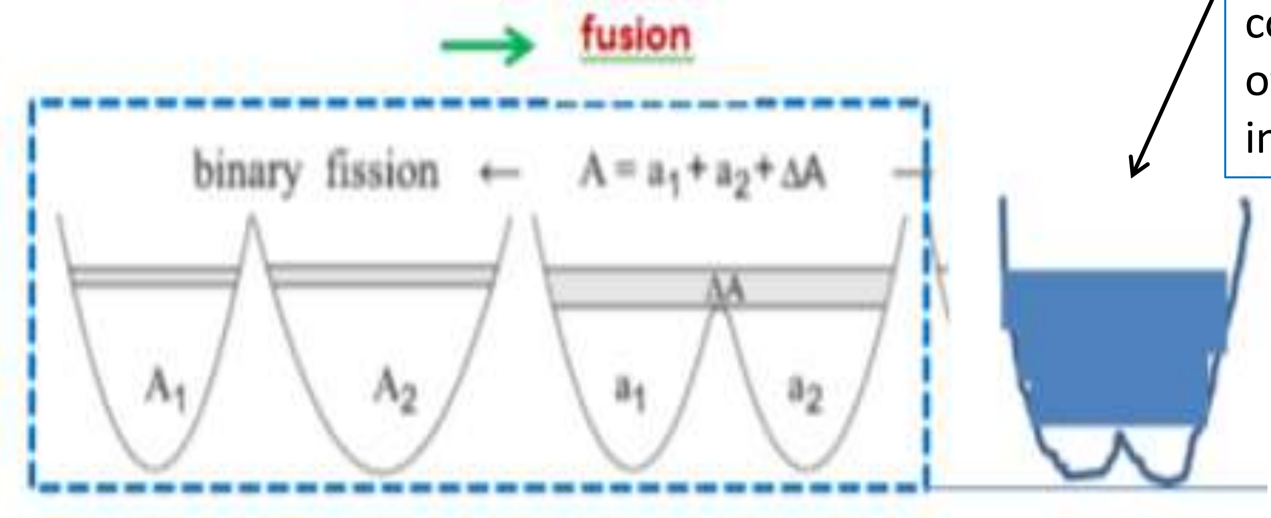
FIG. 5 (color). Number of minima found with deformation $\epsilon_2 < 0.45$. Only the ground-state and isomer minima that are deeper than 0.2 MeV and with energies relative to the ground state of less than 2.0 MeV are counted.

PHYSICAL REVIEW C **81**, 044608 (2010)

# TCSM in description of fission & fusion

**True ternary fission of superheavy nuclei**

V. I. Zagrebaev,[1] A. V. Karpov,[1] and Walter Greiner[2]

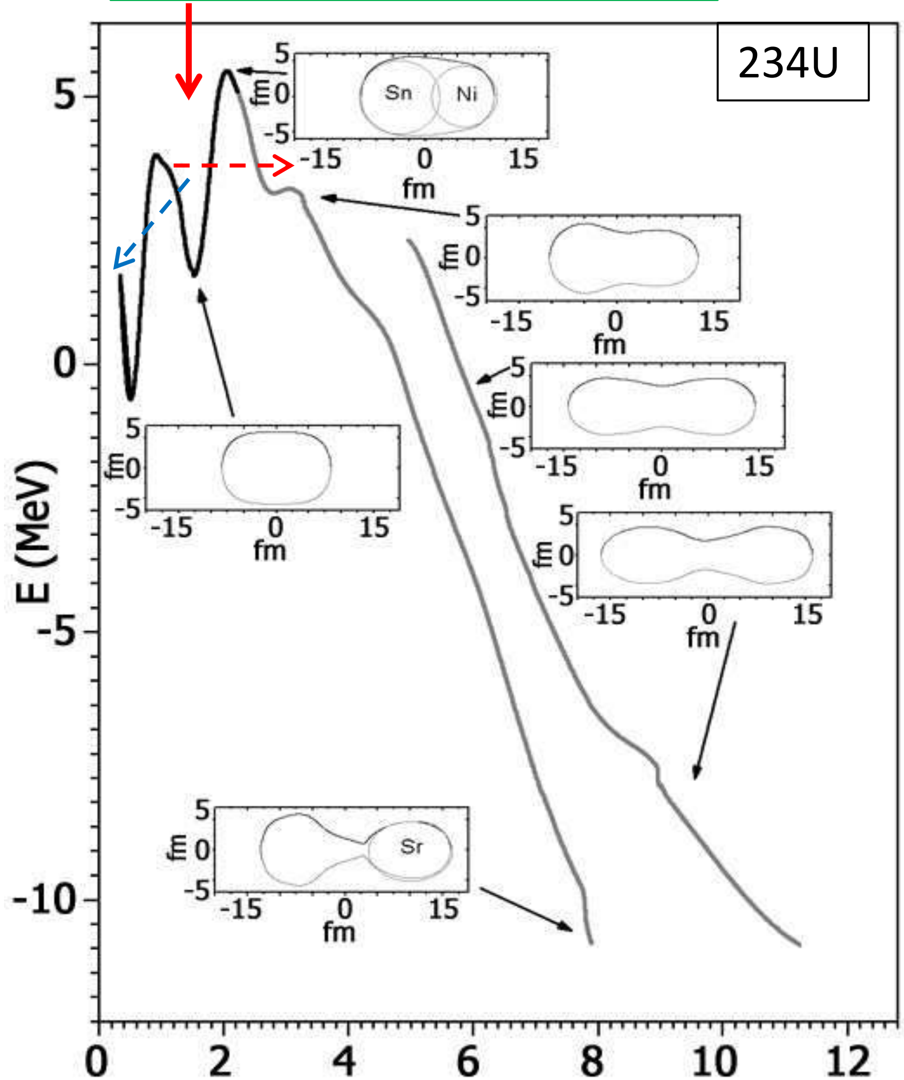



Our case of almost
complete fusion
of two nuclei constituting
initial di-nuclear system

Within the *two-center shell model* (TCSM) for a given nuclear configuration , we may determine the two deformed cores *a*1 and *a*2 surrounded with a certain number of shared nucleons: _*A* = *A*CN − *a*1 − *a*2 During binary fission, these valence nucleons gradually spread between the two cores with the formation of two final fragments,*A*1 and *A*2.

I'd like to stress once more:
basing on our data
we suppose **each FF** to be
a **di-nuclear system**
at least just after scission

Shape isomer state (**SIS**)
in the second potential well.
de-excitation is possible via
gamma channel




The bottoms of the fission valleys as a function of parameter Q (proportional to the quadrupole moment) for 234U.

## Treating of our case

Some kind of memory about initial configuration: 2 distinct nuclei

Almost complete fusion.

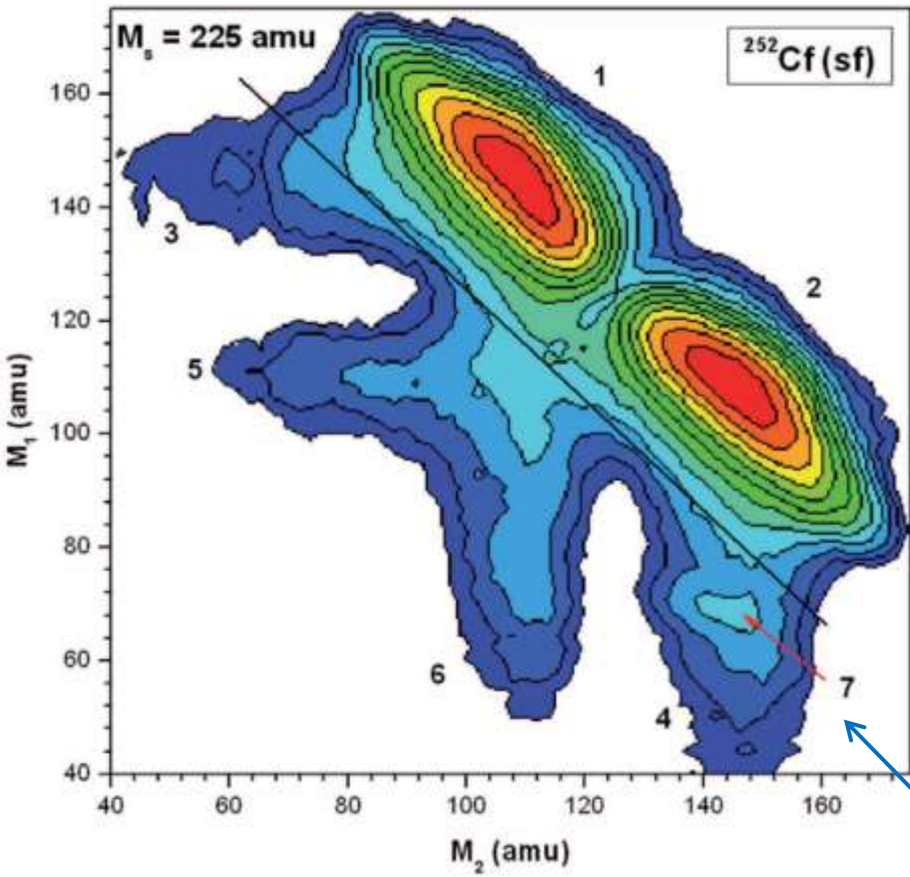
Actually it is a low excited state of the resultant a1+a2 nucleus.
**The main part of the initial E* is *already* exhausted by emitted neutrons.**

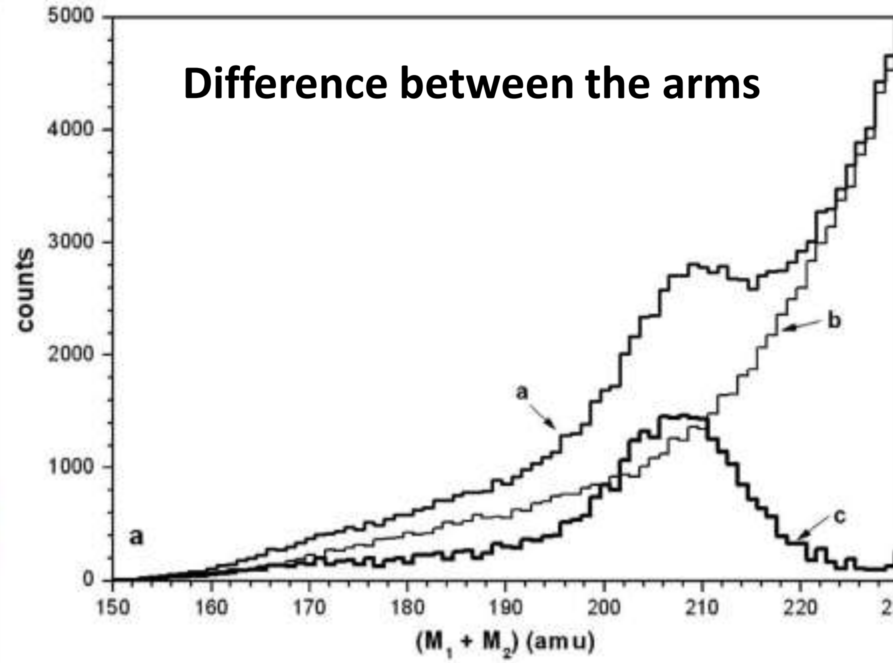
The fusion process is stopped at the final stage reaching gamma-isomeric state. The residual E* will be carry away by gammas through time to be characteristic for this channel of de-excitation.
( some **µs** presumably)

The last intriguing question  to be discussed:

Whether all  structures assigned to the CCT actually  are resulted from the brake-up process discussed above?

# Initial manifestation of the CCT

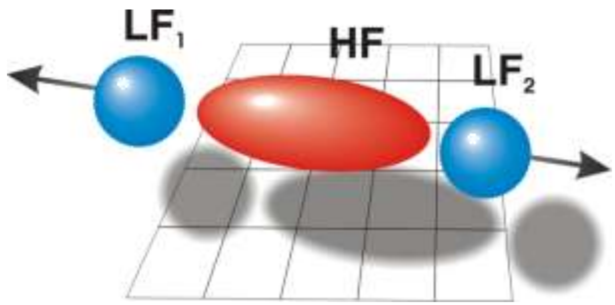


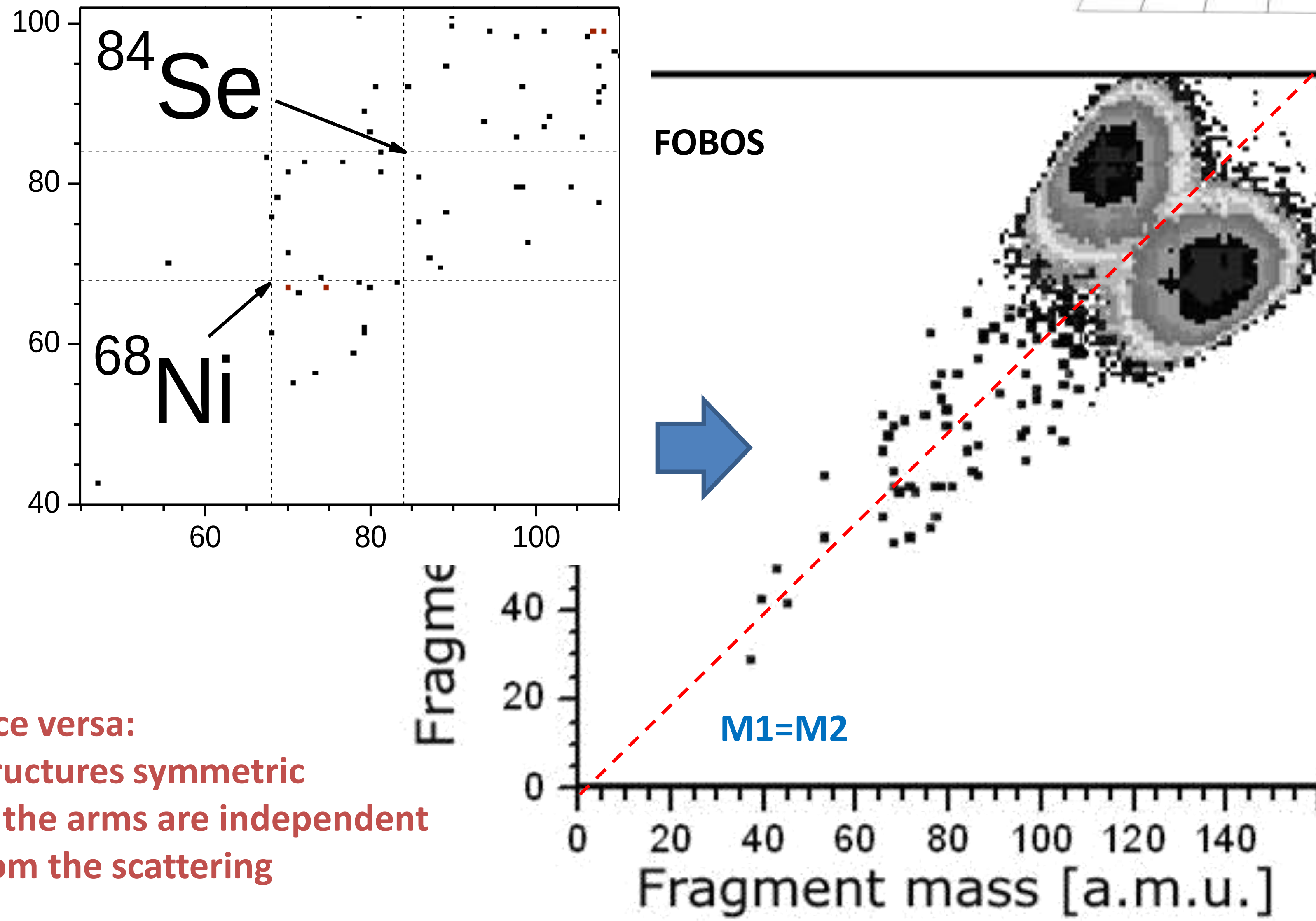

**Effect is seen in the arm from the side of scattering foil only. Thus, it is due to scattering in any cense**

Yu. Pyatkov et al., Eur. Phys. J. A 45, 29–37 (2010)

## Structures symmetric to the arms

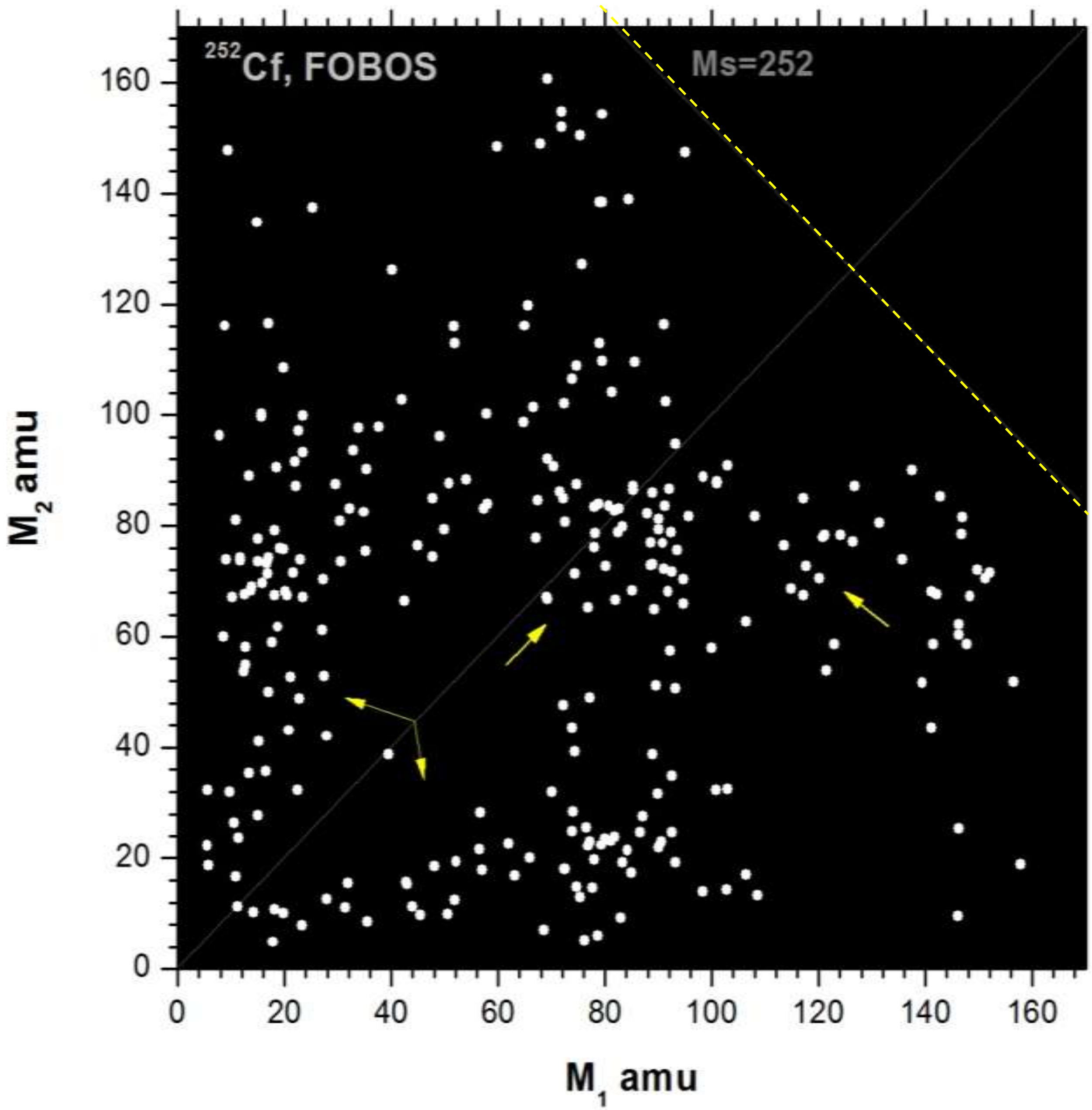



Individual modes / structures
**with equal velocity/momentum window**



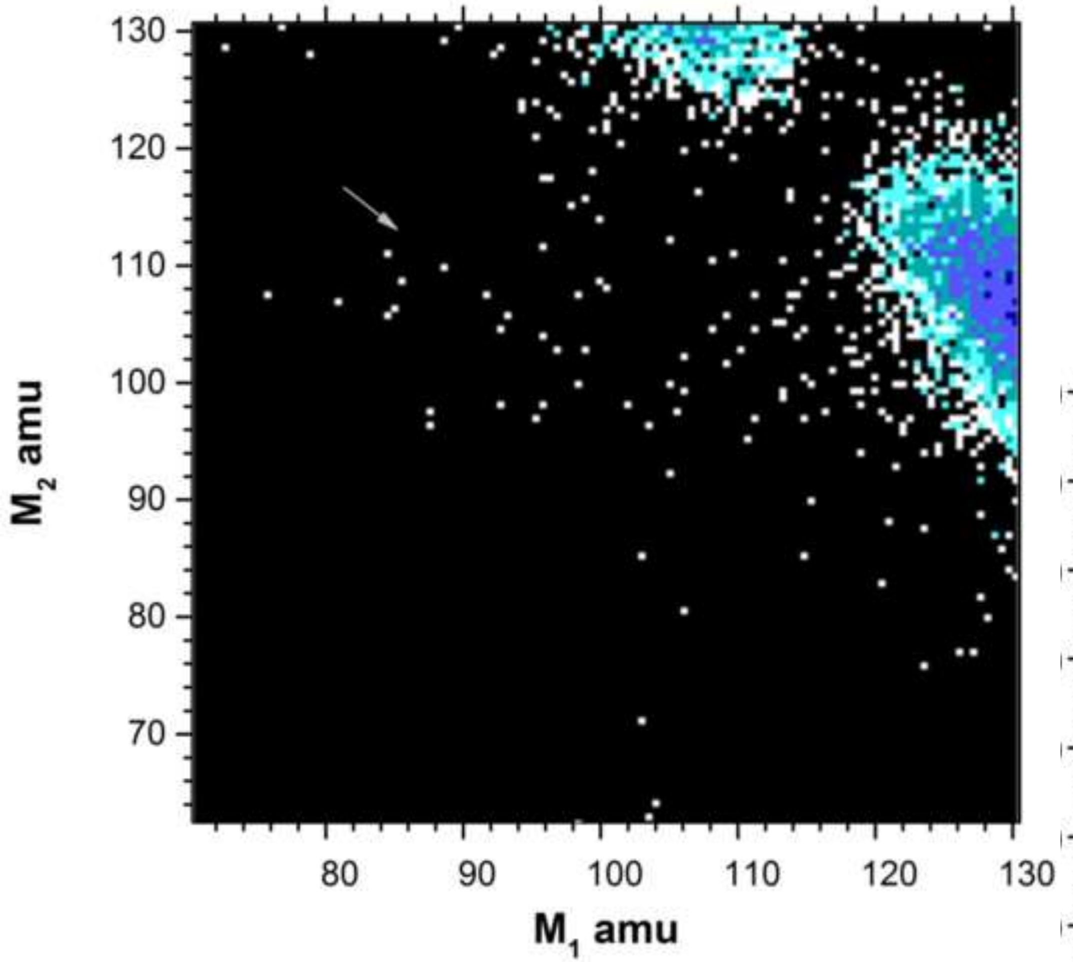

**Vice versa:**
**structures symmetric**
**to the arms are independent**
**from the scattering**

# Structures symmetric to the arms

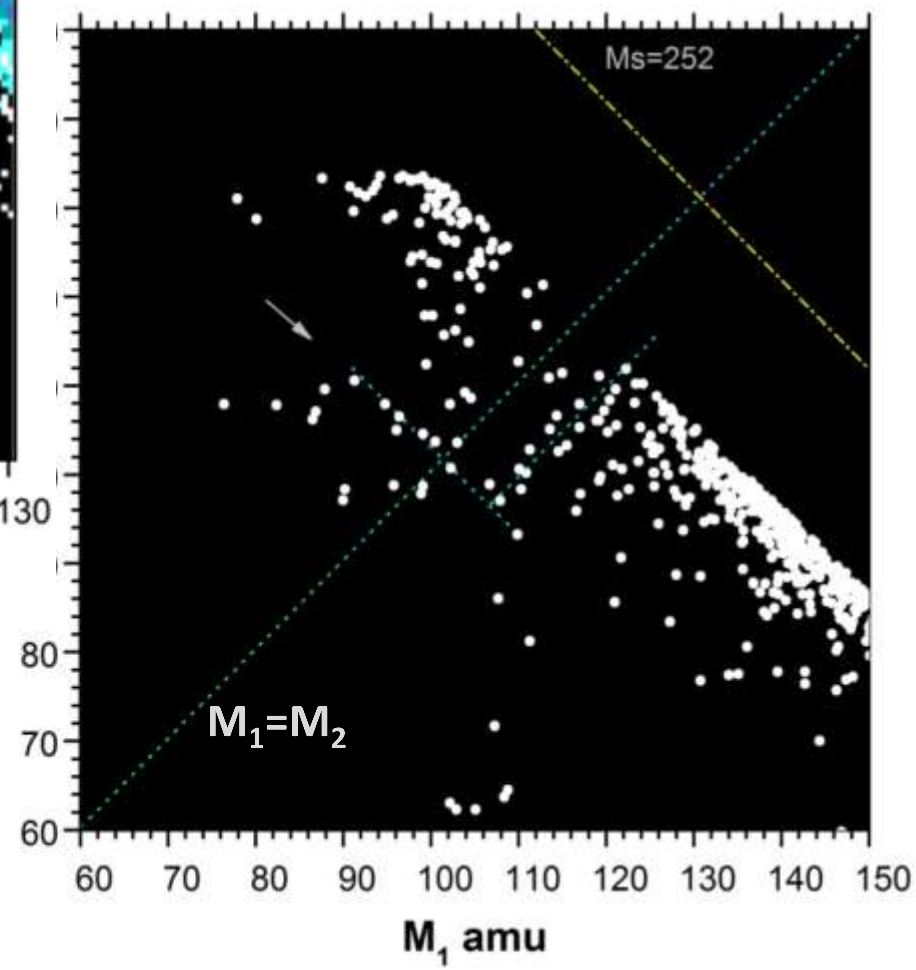



**FOBOS**
**n=1**
**&**
**momentum**
**box**

## Structures symmetric to the arms




COMETA, Cu foil, n=1




Missing mass ~50amu

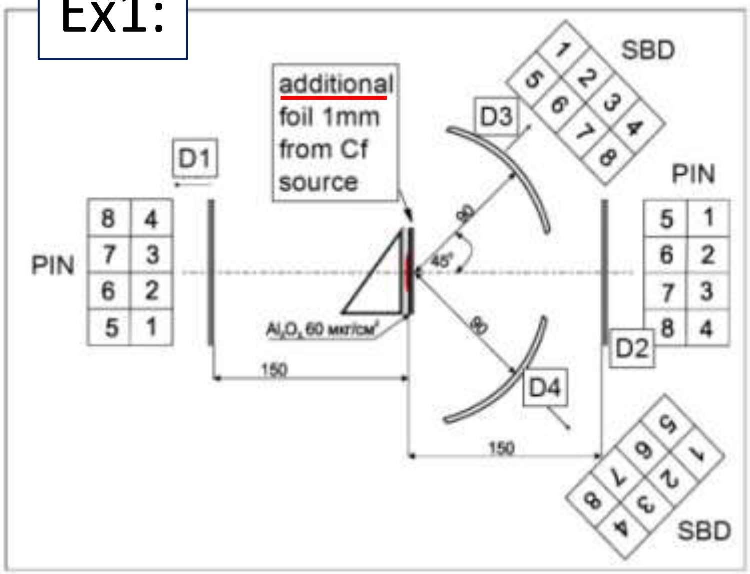
## Conclusions

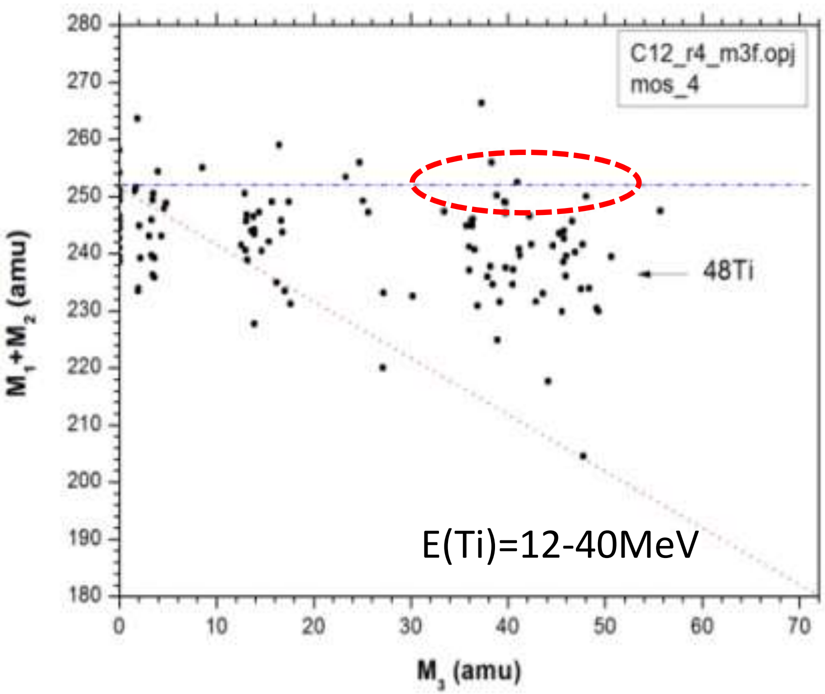
1.Now we have not find any contradictions between all our experimental data obtained and known features of conventional fission process.

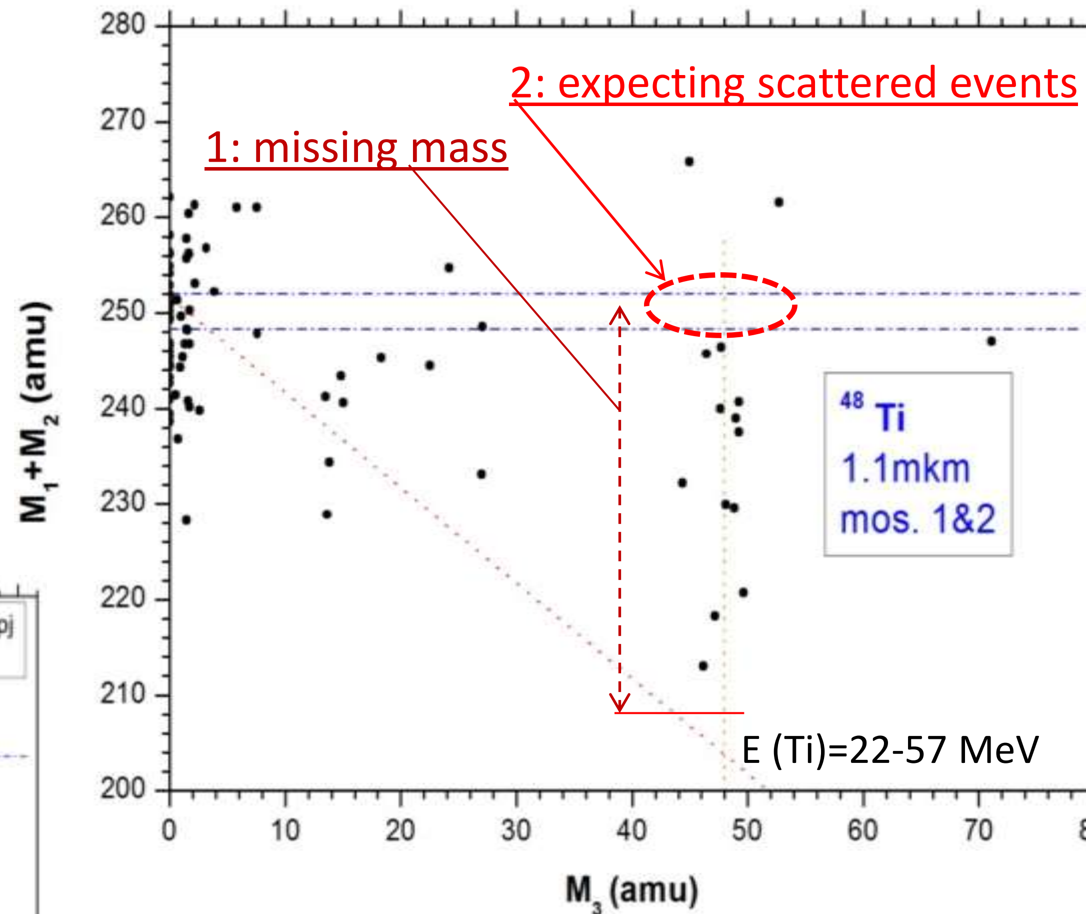
2. Studying of rare multi-body decays flashes up fundamental properties of the main process of “conventional” binary fission.

# Experimental results_1

Ex1:

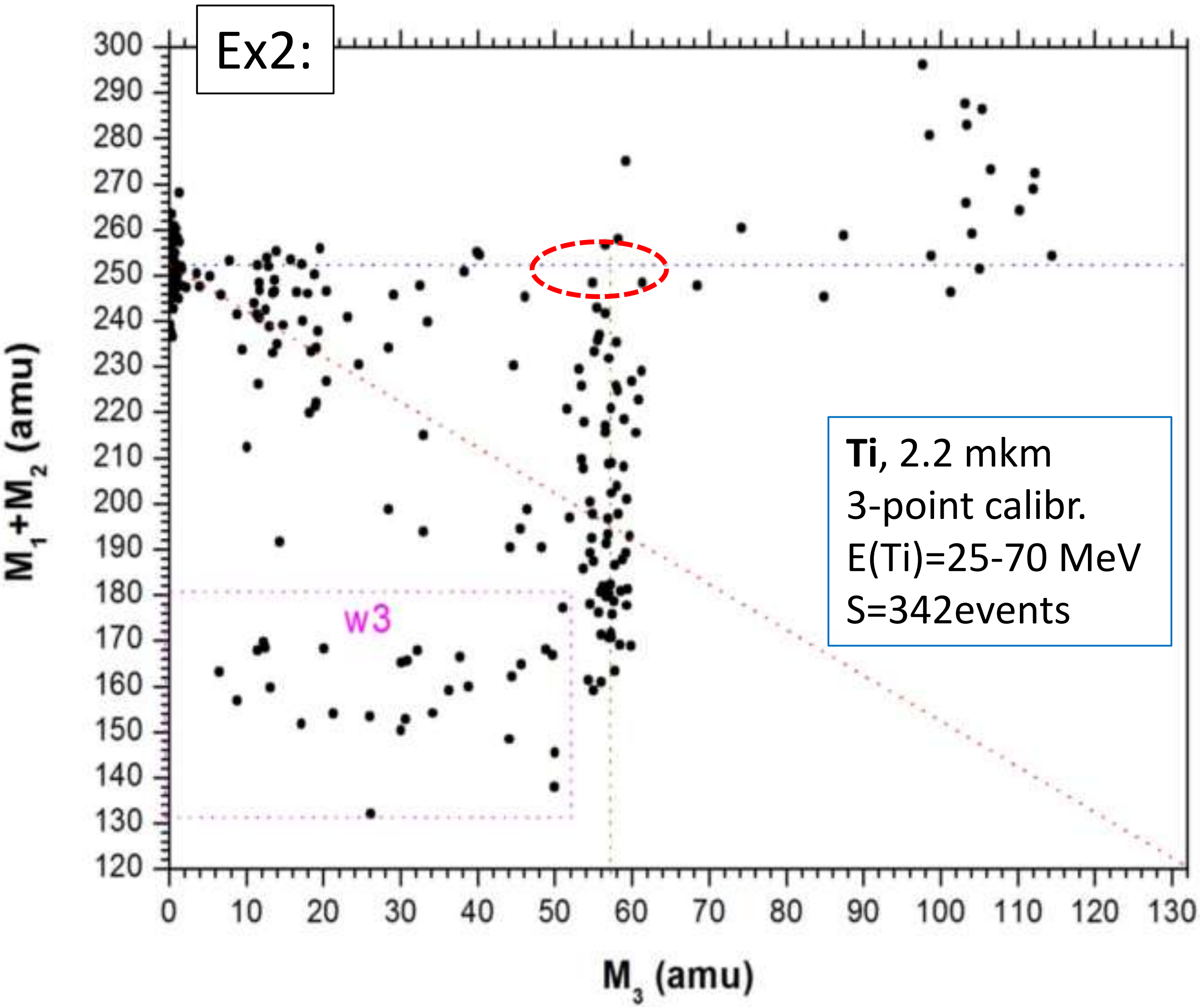



**In each ternary event:**
**$M_1>M_2>M_3$**

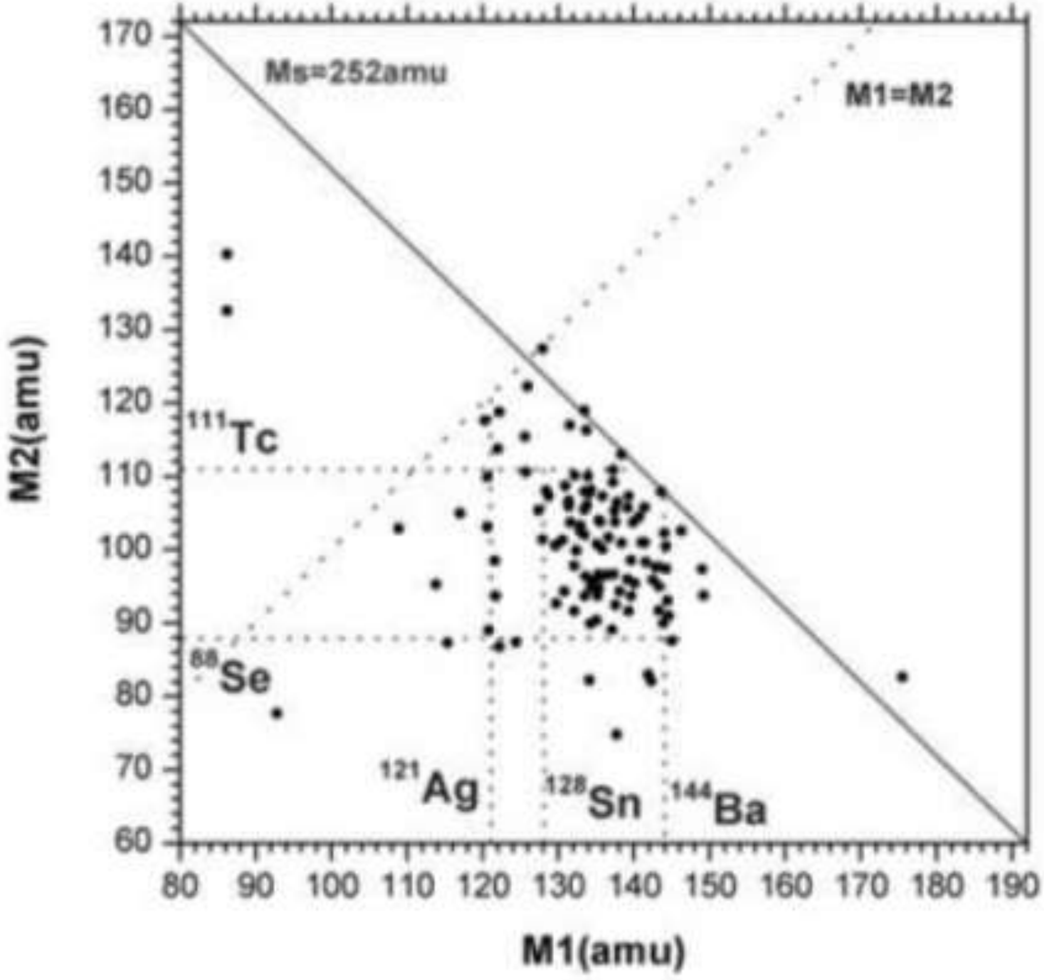
# Experimental results_2




rand. coinc.
α-FF

C12_r5 w1: n3_p3<30 (t.e. M3_3p in mos1&2) s=342 3p_calibr

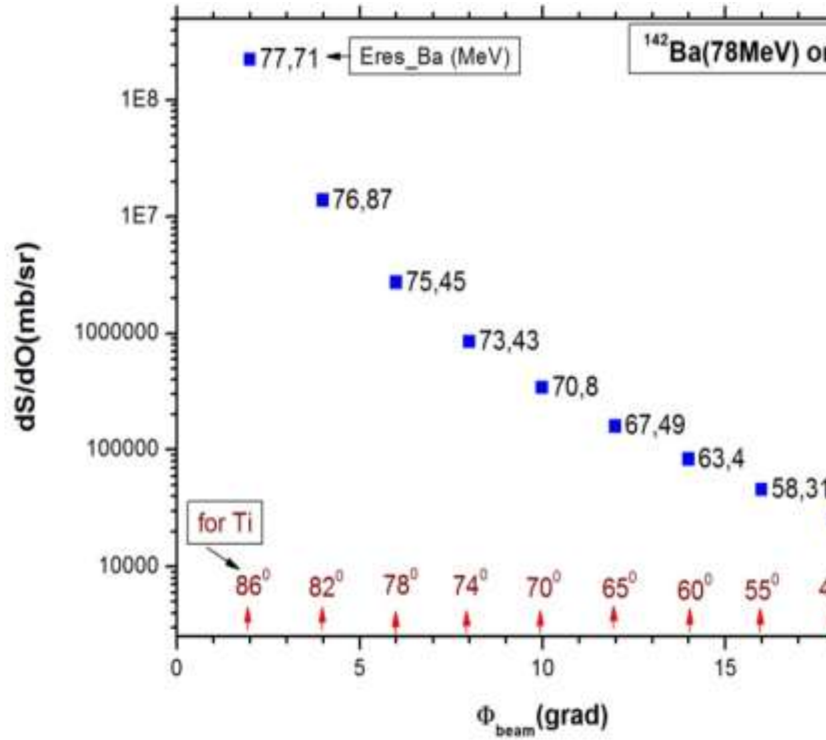
# Previous experiments at the COMETA setup - only thin $AL_2O_3$ backing was in game



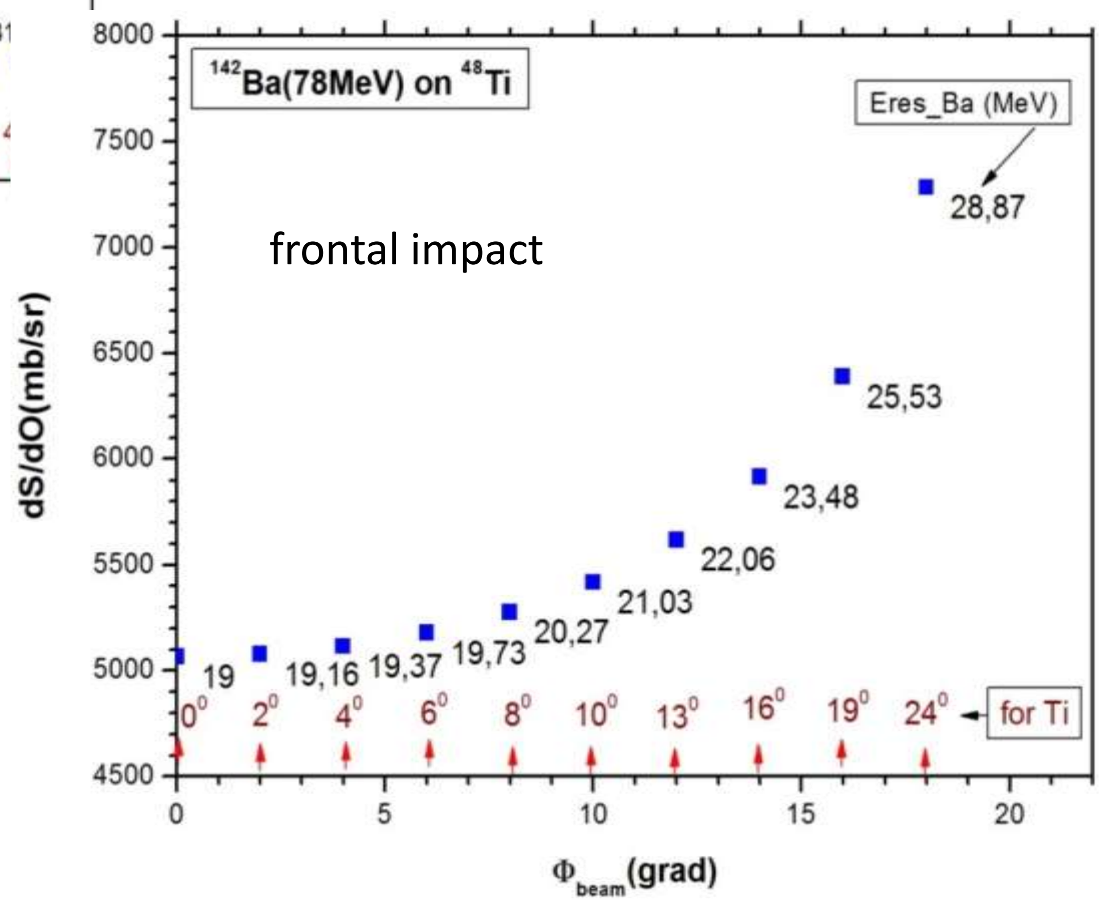

Similar structure of the $M_1$-$M_2$ plot for ternary events

Такое получилось в C10_r3_m3f.opj (folder: st_all –c big TOF3 – до этого Ж их резал) на COMETA – просто две мозаики с PINs (впервые использовался новый источник)

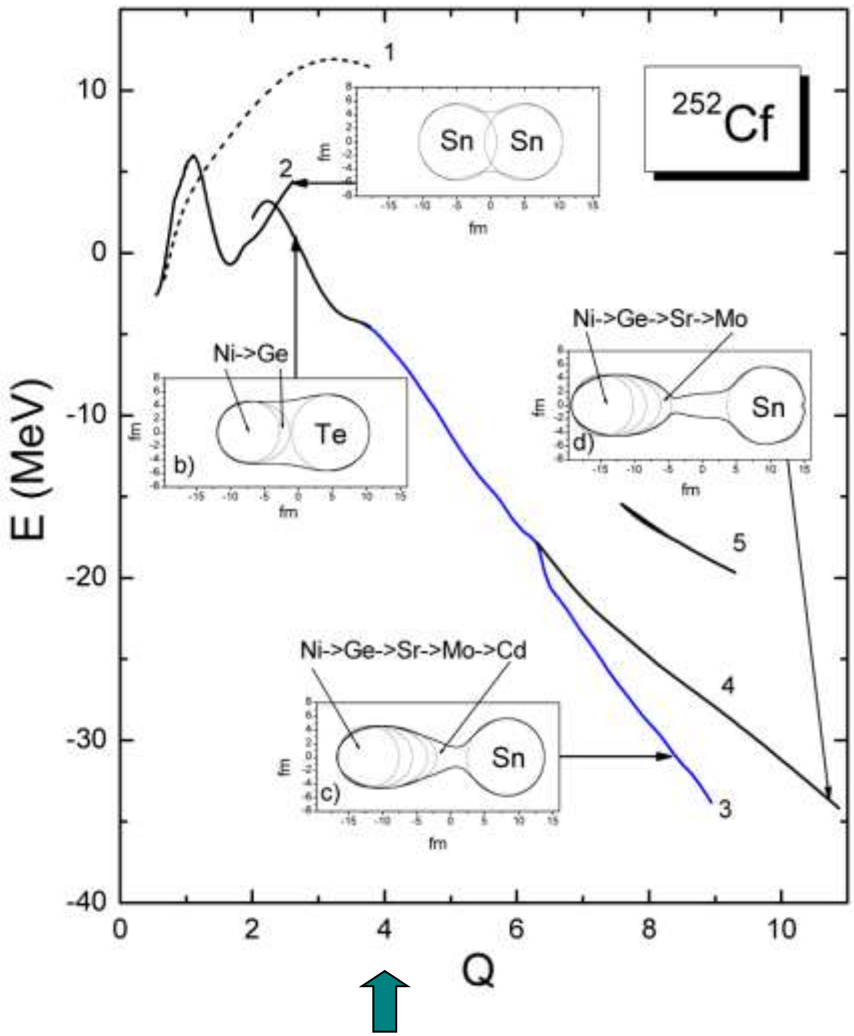
# Rutherford scattering – H_FF/Ti




Both the experimental geometry and energies of the knocked –out Ions give evidence that we deal with this brunch of the scattering process



# FF as a di-nuclear system – possible scenario of forming




Yu.V. Pyatkov, V.V. Pashkevich, Yu.E. Penionzhkevich et al.,
Nucl. Phys. A 624 (1997) 140

**Double- magic- cluster structure of the fissioning system:**

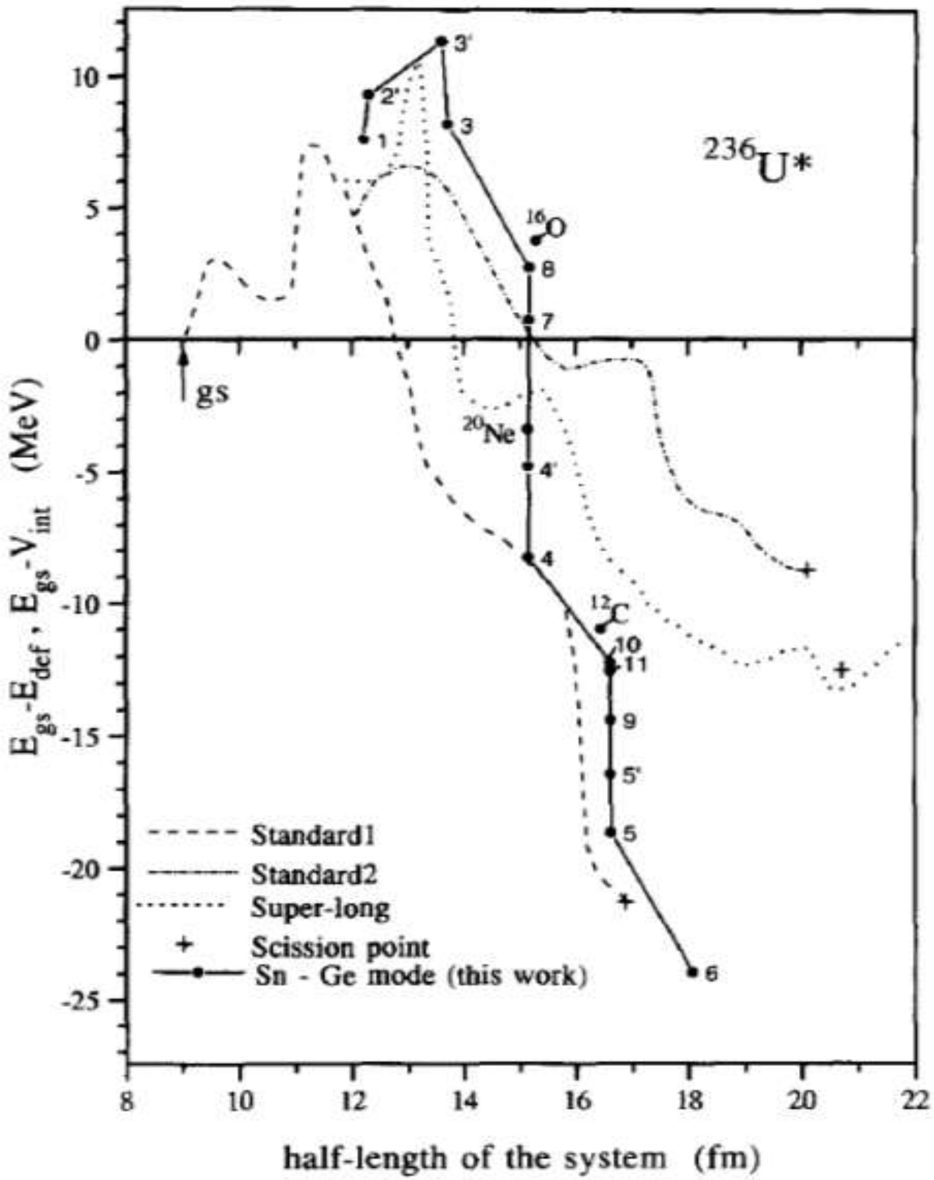
V.V. Vladimirski, JETP (USSR) 5 (1957) 673

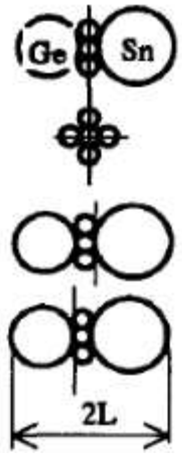
S.L. Whetstone, Phys. Rev. 114 (1959) 581

. . .

I.Tsekanovich,
H.-O.Denschlag, M.Davi,
Z. Büyükmumcu,
F. Gönnenwein, S Oberstedt,
H.R. Faust
Nucl. Phys. A 688 (2001) 633

# FF as a di-nuclear system – possible scenario of forming




Initial configuration
Of the fission mode
Based on Sn & Ge clusters

Two magic clusters namely, light & heavy give rise to fission mode while the neck is also clusterised consisting of LCP

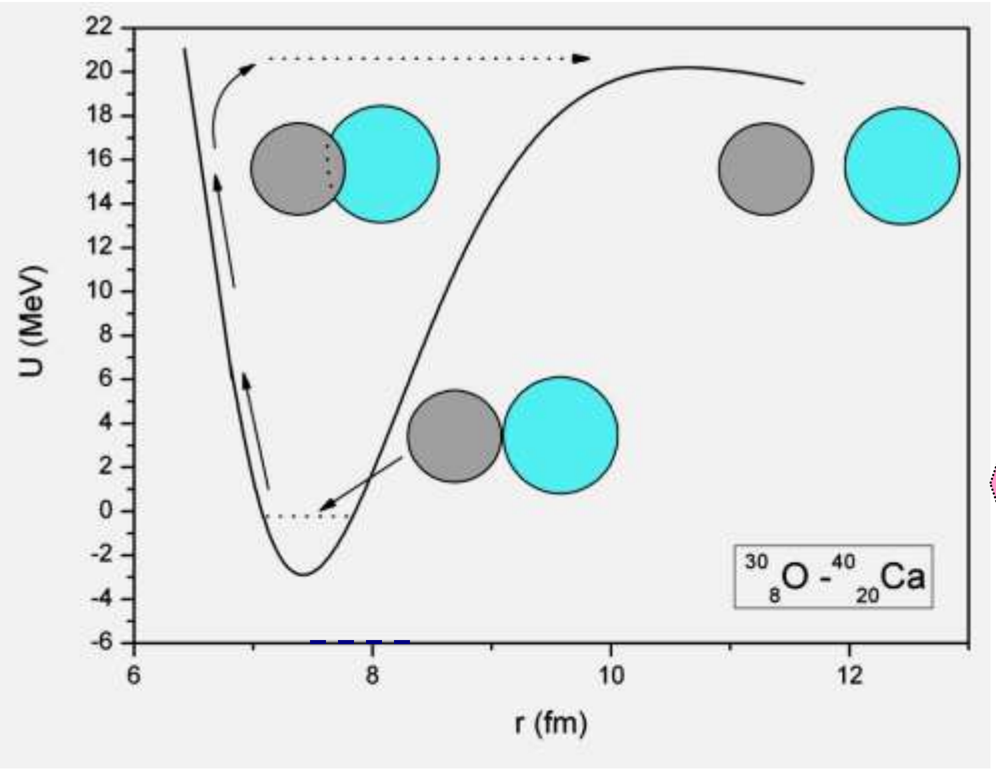
Yu.V. Pyatkov, G.G. Adamian,
N.V. Antonenko et al.,
Nucl. Phys. A 611 (1996) 355

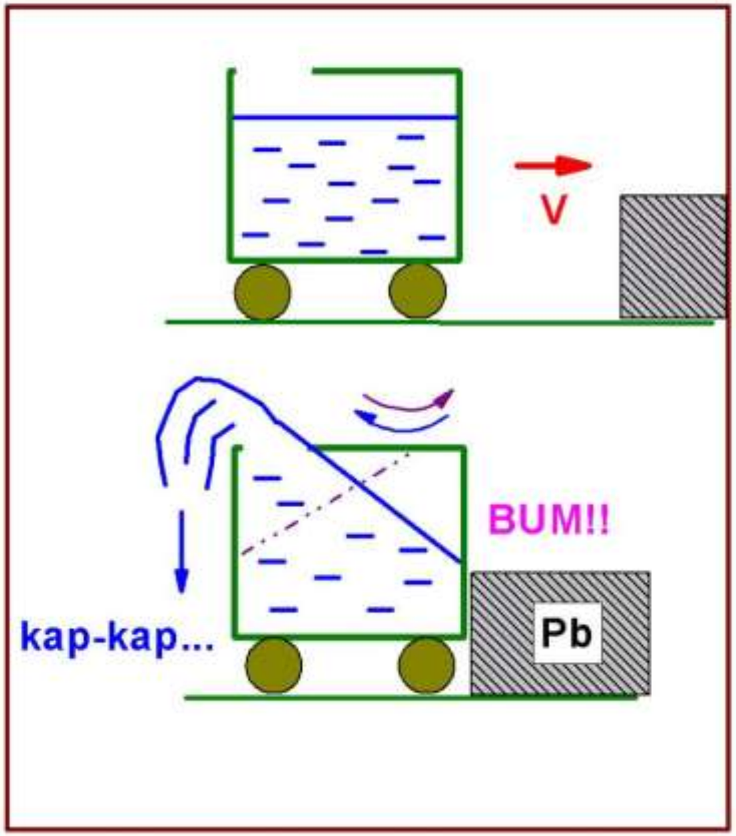
## Discussion

**CCT mechanism in the light of the results presented above:**

**inelastic impact is not exclusive channel of producing ternary events!**

# A possible way of decaying of di-nuclear system




Different inertia of the partners in the frontal impact could be the reason of their scission.

**naive illustration of an inertial effect**

**likely to be decisive for decaying of a nuclear molecule**

S. Ċwiok et al.,
Phys. Lett. B 322 (1994) 304

**SIS in heavy nuclei**

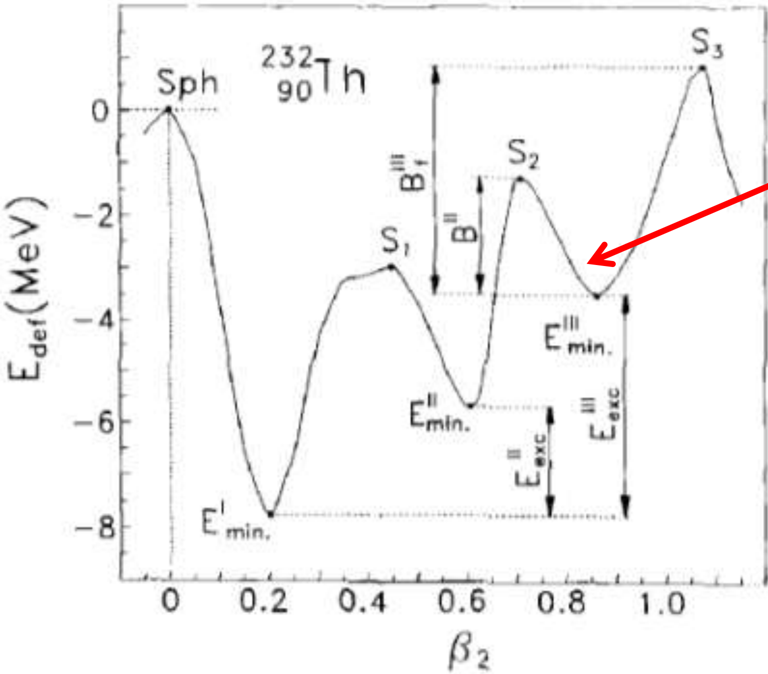
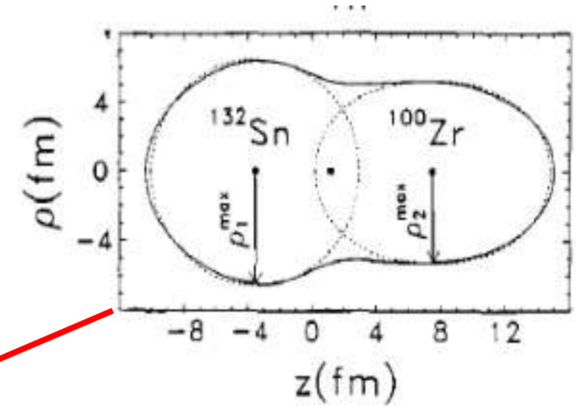



Fig. 1. Potential energy curve for $^{232}$Th as a function of quadrupole deformation $\beta_2$ along the shorter static fission path of fig. 2.



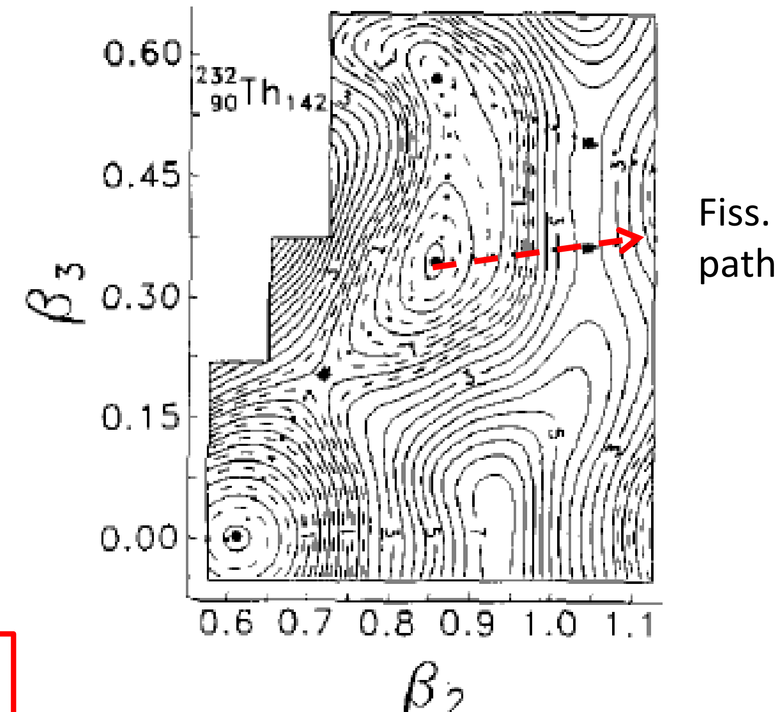
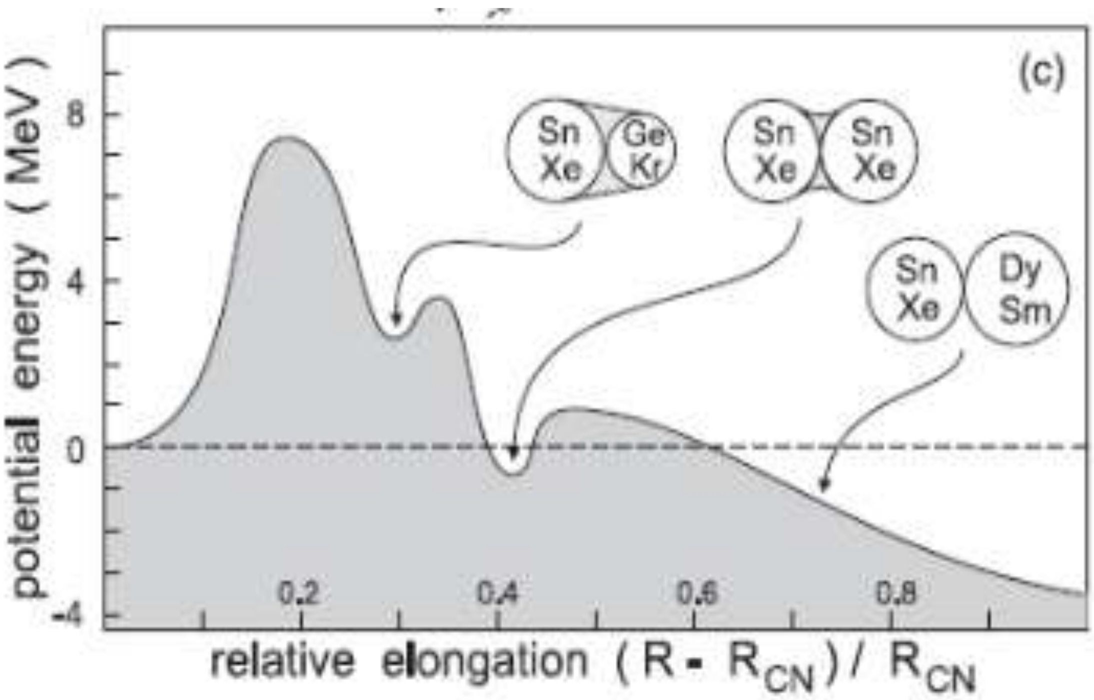




Fig. 2. The Woods–Saxon–Strutinsky total potential energy (relative to the spherical macroscopic energy) for $^{220}$Rn, $^{222}$Ra, $^{232}$Th, and $^{234}$U, as a function of $\beta_2$ and $\beta_3$. At each ($\beta_2$, $\beta_3$) point the energy was minimized with respect to $\beta_4$–$\beta_7$. The distance between the solid contour lines is 0.5

density distribution at the third minimum looks like a di-nucleus consisting of a nearly-spherical heavier fragment (around doubly-magic $^{132}$Sn) and a well-deformed lighter fragment (from the neutron-rich $A \sim 100$ region).




# SIS in super-heavy nuclei

Three-humped barrier calculated along the fission path of $^{296}_{116}Lv$ (Livermorium).

V. ZAGREBAEV, W. GREINER

Proc. Int. Symp. on Atomic Cluster Collisions (ISACC07), GSI
Darmstadt, 2007, (Imperial College Press, London, 2008), Eds. J.-P.
Connerade and A. V. Solov'yov, p. 23

"These intermediate minima correspond to the <u>shape isomer states.</u>
From analysis of the driving potential we may definitely conclude that these <u>isomeric states</u> are nothing else but <u>the two-cluster configurations with magic or semi-magic cores</u> surrounded with a certain amount of shared nucleons."

## Shape isomers at high spin

**SIS at high spin**

Sven Åberg et al., Z. Phys. A 358 (1997) 269

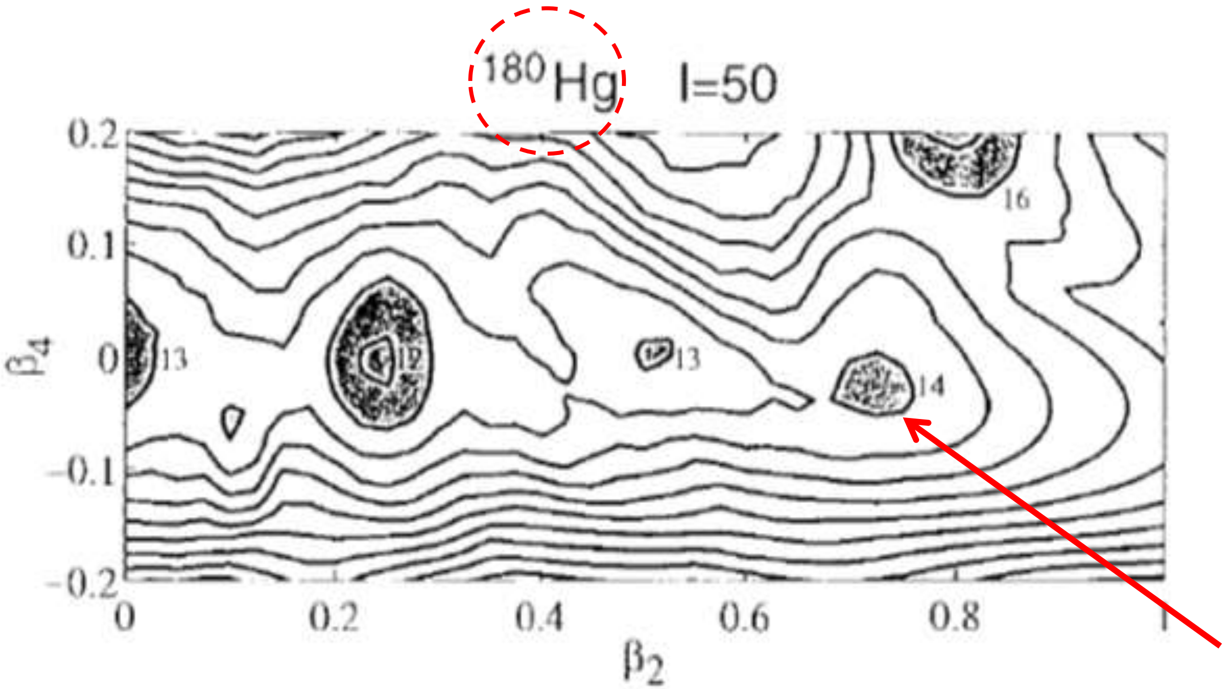



**Fig. 5.** Potential-energy surface valid for $^{180}$Hg at $I$=50. The calculation has been performed within the cranked Nilsson-Strutinsky formalism using the Woods-Saxon potential. Local minima are shaded, and the line separartion is 1 MeV. Notice the minimum at $\beta_2$=0.75, $\beta_4$=0 that corresponds to a necked-in superdeformed shape

"Superdeformed (or hyperdeformed) nuclei with necking was calculated to exist, e.g. in 180Hg. The exotic configuration was similar in shape as well as in single-particle structure to **two partly overlapping spherical 90Zr nuclei.**"

SIS of light nuclei

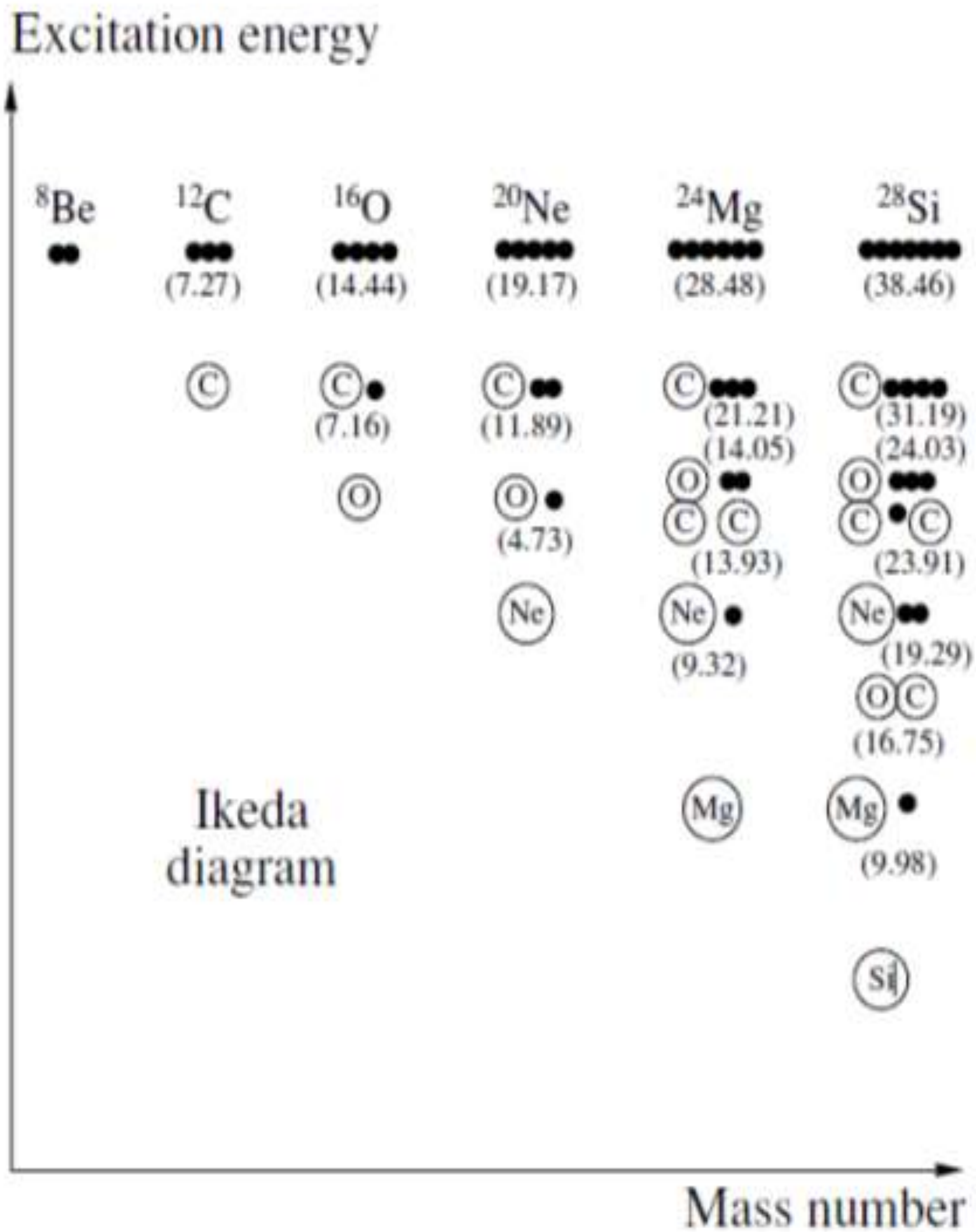
The *cluster states of light nuclei* and the possible existence of the *necked-in shaped nuclei* were considered in:


Cseh, J., Scheid, W.  J.: Phys. G 18 (1992) 1478
Cseh, J. et al.,:  Phys. Rev.C 48 (1993) 1724
Sanders S.J. et al.,: Phys. Rep. 311 (1999) 487
Freer, M : Prog. Phys. 70 (2007) 2149
Sciani, W et al., : Phys. Rev. C80 (2009) 034319
Cseh, J. et al.,:  Phys. Re v. C 80 (2009) 034320
Beck, C. et al.,:  Phys. Rev. C 80 (2009) 034604
Von Oertzen W.  et al.,;  Phys. Rev. C 78 (2008) 044615


**We likely deal with shape-isomers in the new mass rang typical for the fission fragments of the conventional binary fission**

# Conclusions.

1. **New mechanism of ternary decay based presumably on the Rutherford break-up of the fragment in the shape-isomeric state is observed.**
2. **Break-up is only one of the different ways leading to the CCT.**
3. **The results obtained let us to suppose that the bulk of the fragments from the conventional binary fission are born in the shape-isomeric states.**
4. **The conclusions above can be regarded as the preliminary ones till further estimation of the life times of the shape isomers under discussion will be obtained.**

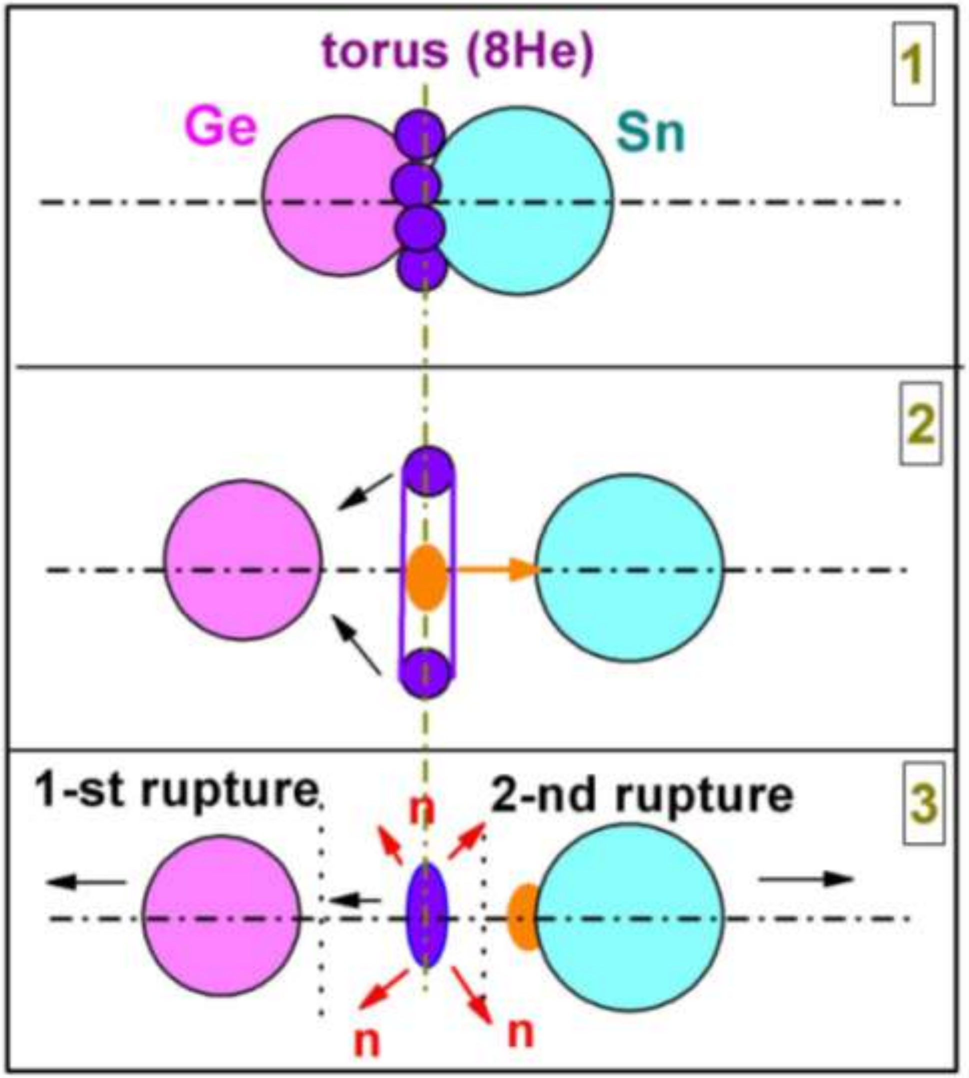


Excitation energy
$^{8}Be$
$^{12}C$
$^{16}O$
$^{20}Ne$
$^{24}Mg$
$^{28}Si$
(7.27)
(14.44)
(19.17)
(28.48)
(38.46)
C
(7.16)
(11.89)
(21.21)
(31.19)
(14.05)
(24.03)
O
(4.73)
(13.93)
(23.91)
Ne
(9.32)
(19.29)
(16.75)
Mg
(9.98)
Si
Ikeda diagram
Mass number

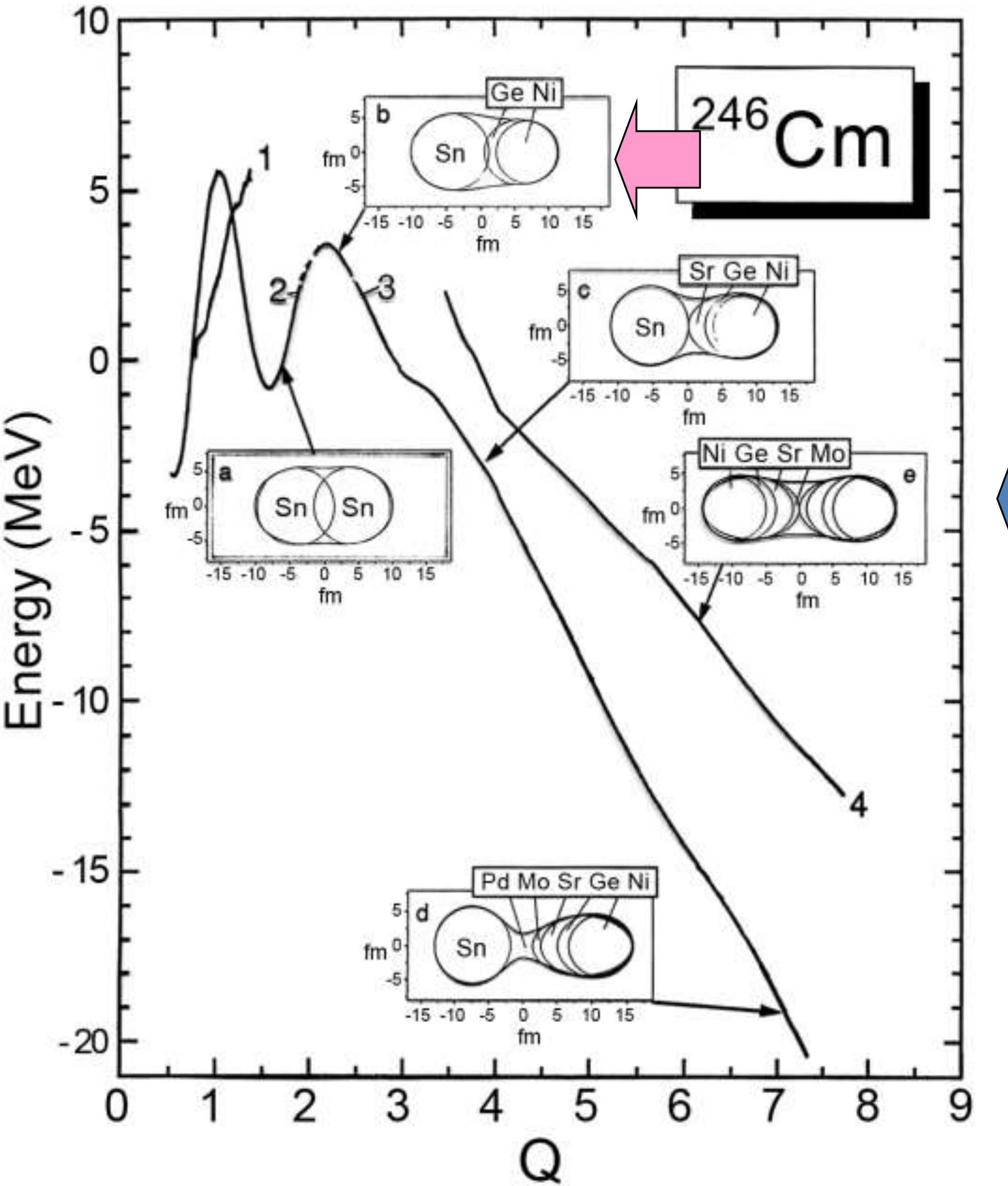
## Scenario of the collinear cluster tripartition

Discovery of fission (shape) isomers: FLNR (JINR ) 1961
242Am, τ =0.014sec

More then 30 fission isomers of heavy nuclei, namely,
isotopes of
U, Np, Pu, Am, Cm, Bk
are known including short lived in the ns range.
(Flerov, Polikanov)



# Calculated Fission Valleys ($^{246}$Cm)



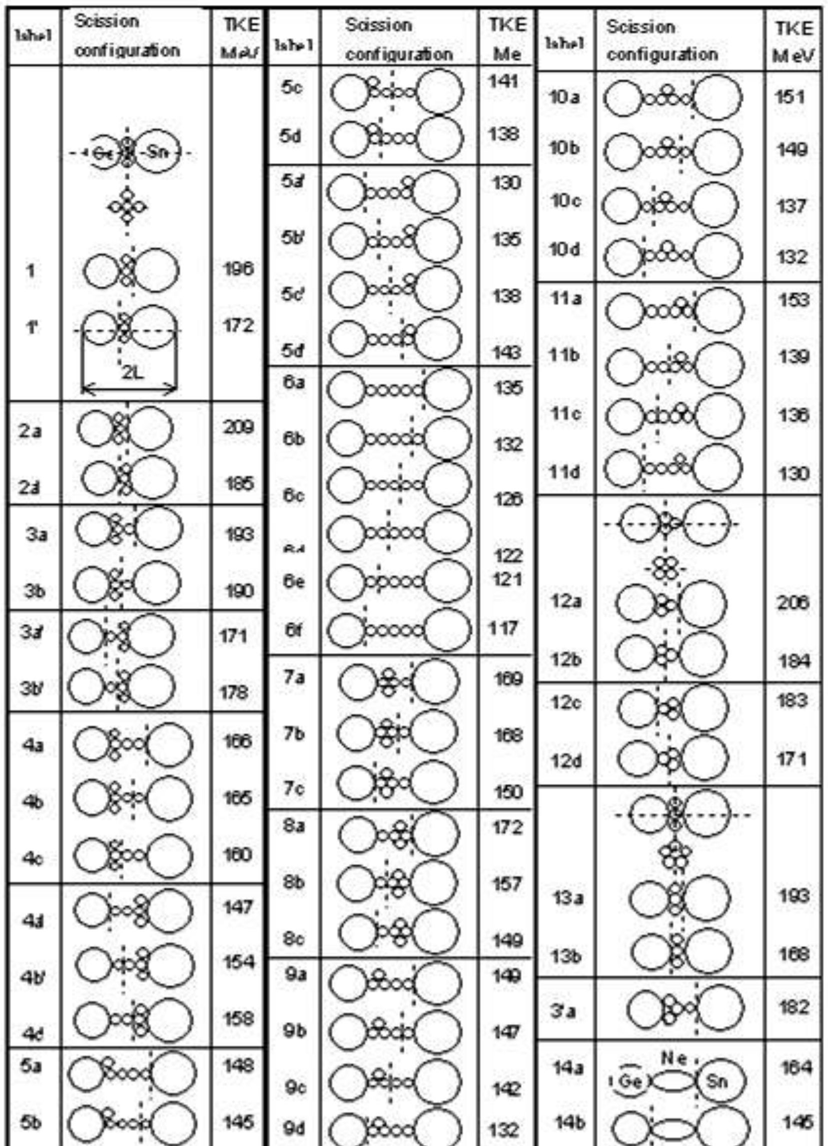

Valley of the mass-asymmetrical shapes

Valley of the mass-symmetrical shapes

V. V. Pashkevich et al.

# Known calculations

Table1: TKE for some configurations of the fissioning system $^{236}U^{*}$




α-cluster configurations analyzed in:

Yu.V. Pyatkov, G.G. Adamian,

N.V. Antonenko, V.G. Tishchenko

Nucl. Phys. A 611 (1996) 355

Thus pre-formation of light clusters in the neck region and just forming of two and three-neck shapes are energetically possible. At the same time nothing is known from theory about probability of the decay modes discussed here.

# Known calculations

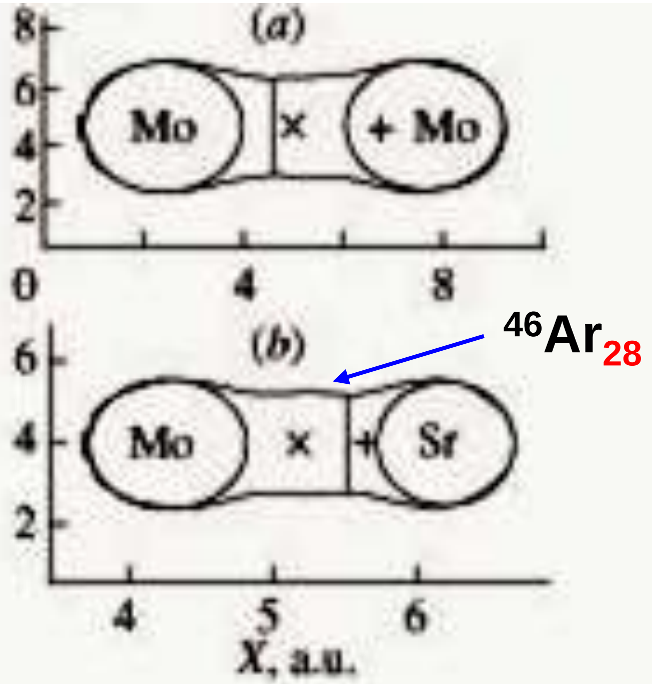
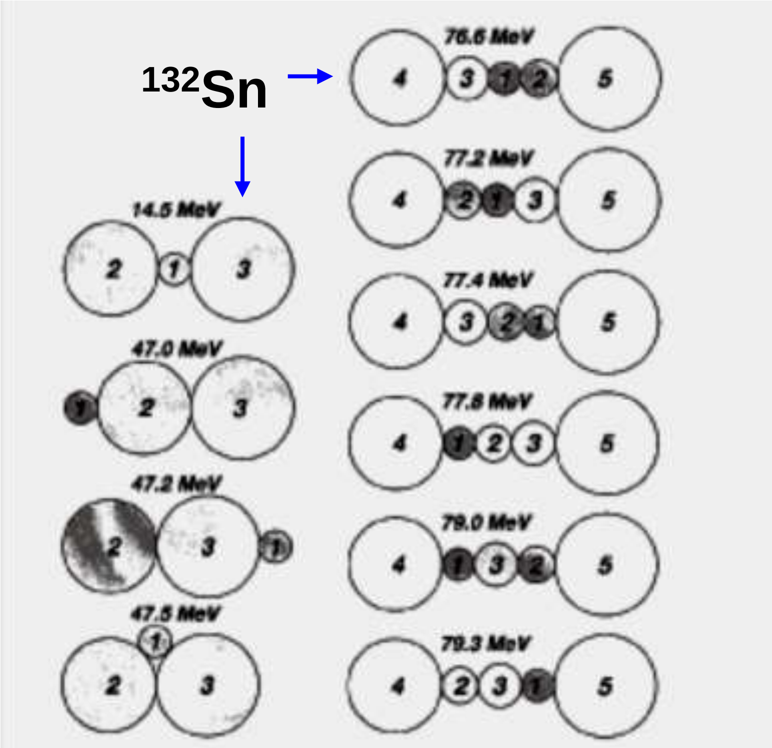



Fig. 7. The shape of the nucleus at the bottom of the "symmetric" valley ($Q_2$ – 7.52 a.u., $\eta$ – 0.074) (a); the same system at the point $Q_2$ – 7.52 a.u., $\eta$ – –0.208 (b).

Yu.V. Pyatkov, V.V. Pashkevich, A.V. Unzhakova et al., Physics of Atomic Nuclei 66 (2003) 1631




**Aligned and compact configurations for α-accompanied and α+$^{6}$He+$^{10}$Be accompanied cold fission of $^{252}$Cf**

D.N. Poenaru et al., Phys. Rev. C 59 (1999) 3457