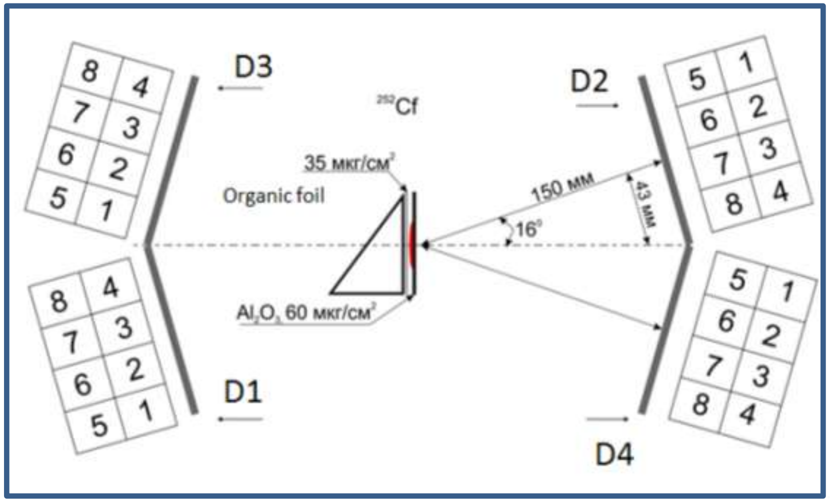
New results in studies of the shape isomer states in fission fragments

Yu. V. Pyatkov[1,2], D.V. Kamanin[2], A.A. Alexandrov[2], I.A. Alexandrova[2], [3]N. Jacobs[3], E.A. Kuznetsova[2], A.O. Strekalovsky[2], O.V. Strekalovsky[2], V.E. Zhuchko[2]

[1]National Nuclear Research University "MEPHI", 115409 Moscow, Russia
[2]Joint Institute for Nuclear Research, 141980 Dubna, Russia
[3]University of Stellenbosch, Faculty of Military Science, Military Academy, Saldanha 7395, South Africa

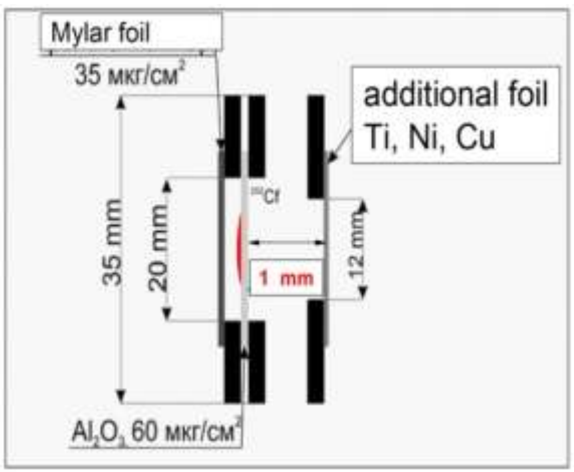
Fission fragments as shape isomers – hot points in treatment

Just to remind: our previous experimental results

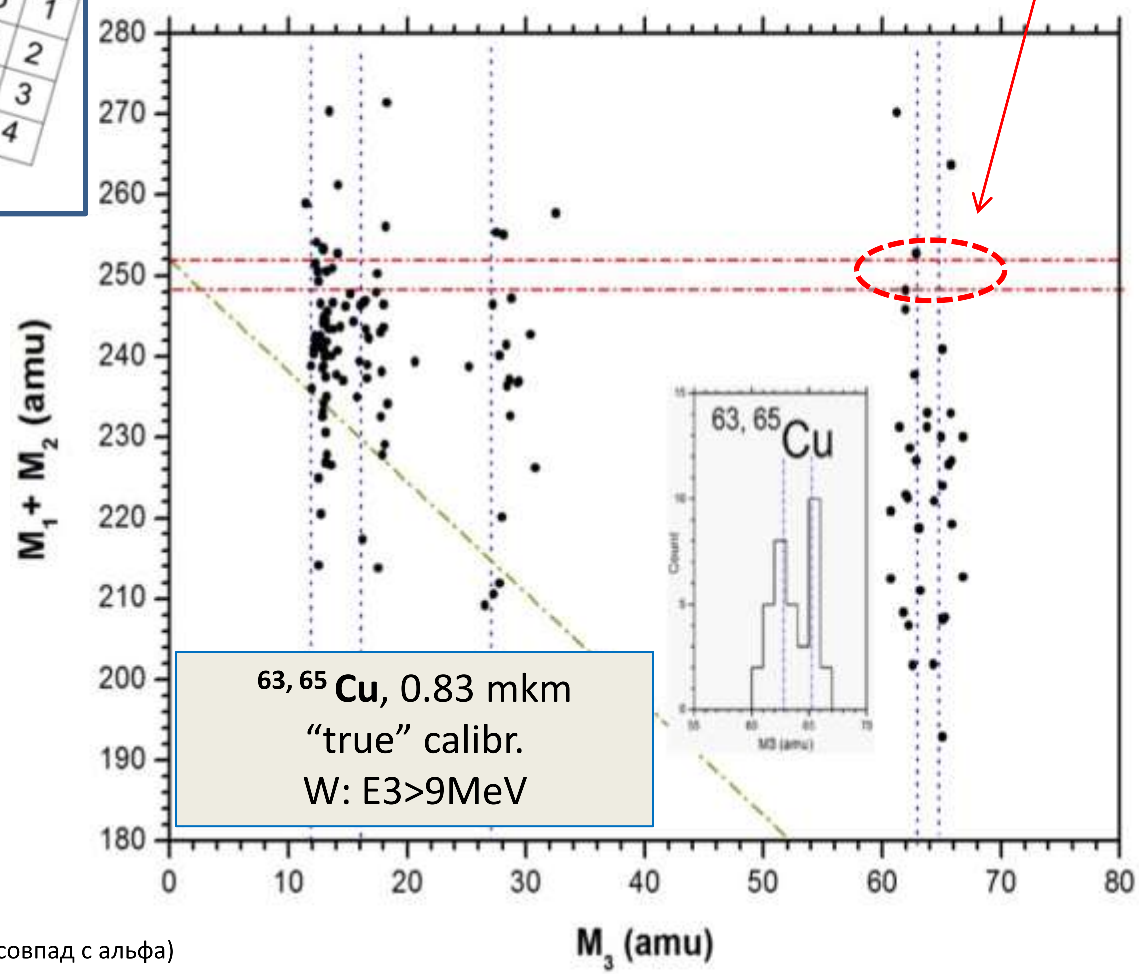


In each ternary event: $M_1 > M_2 > M_3$

region of elastic FF scattering



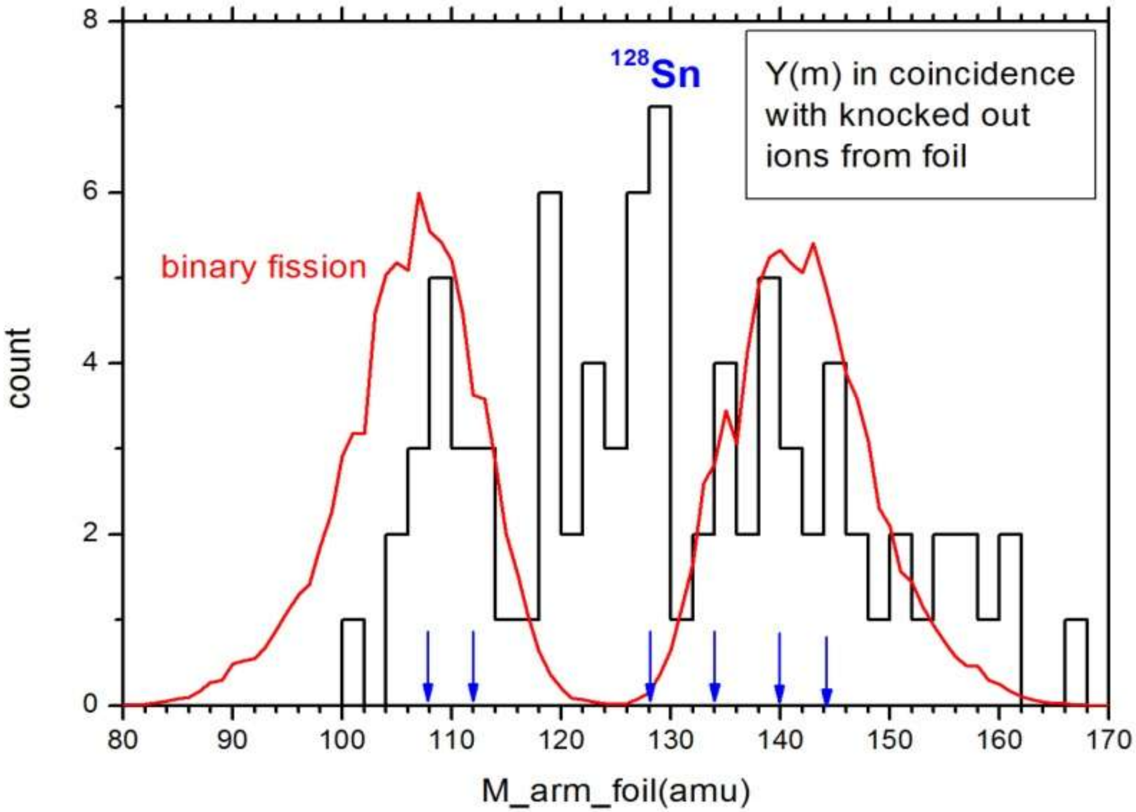
Layout of the source module



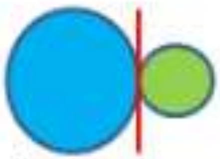
From C13_r2_m3_last.opj & w1: E3plz>9MeV (для устранения случ совпад с альфа)

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

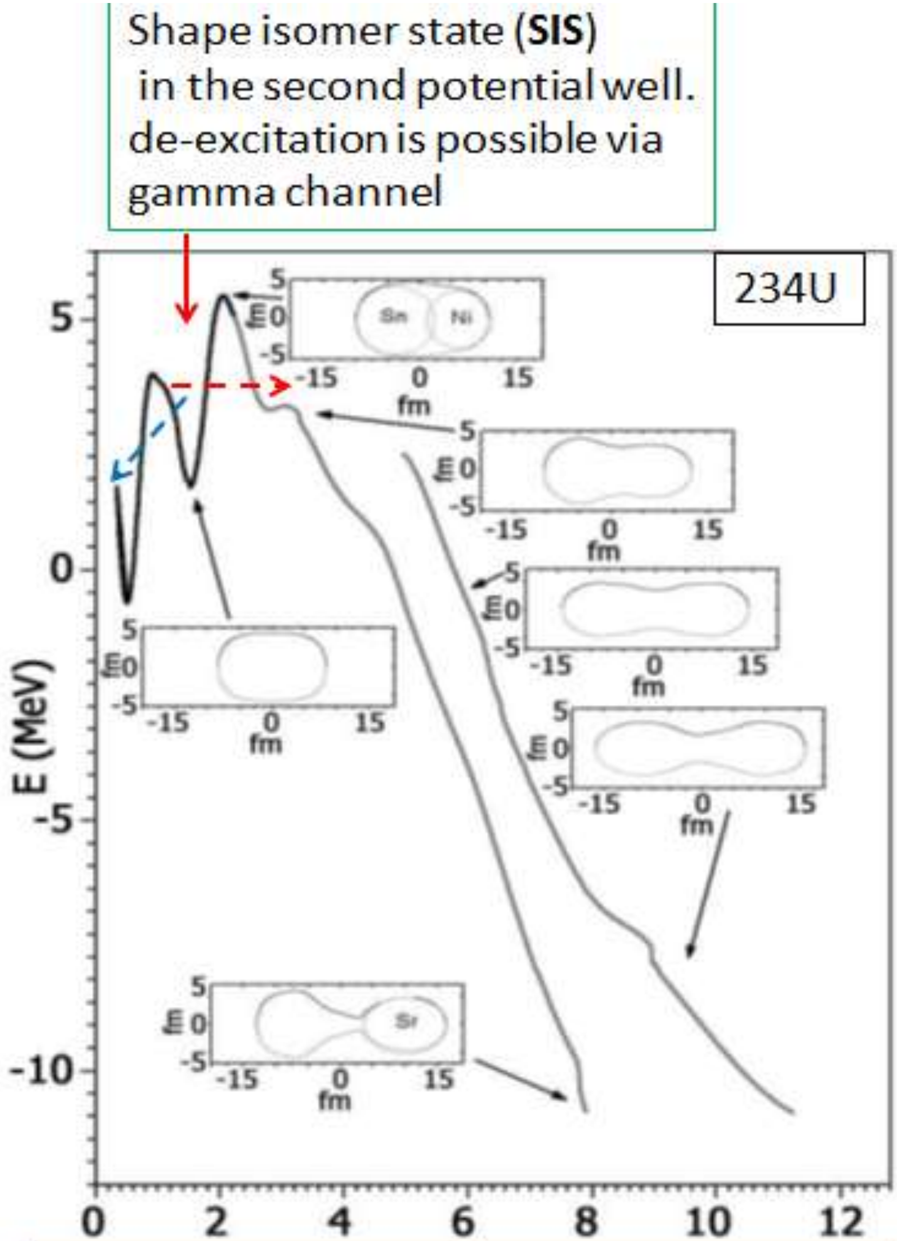
Really:



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.

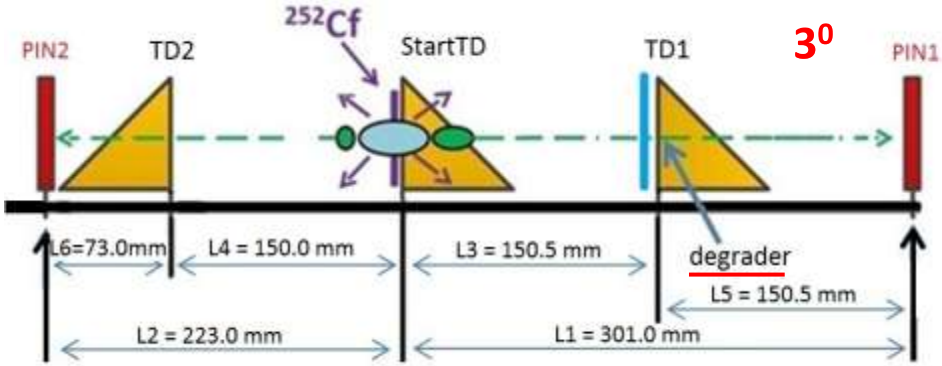


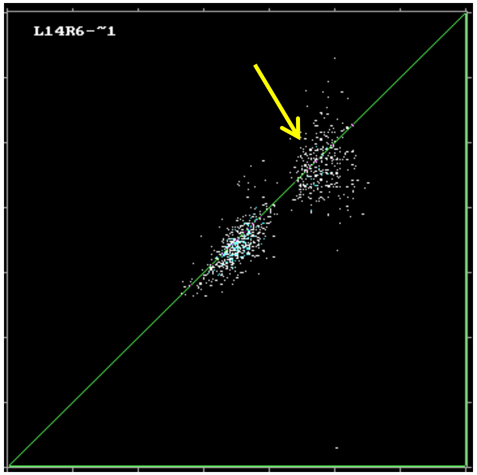
The bottoms of the fission valleys as a function of parameter Q (proportional to the quadrupole moment) for 234U.

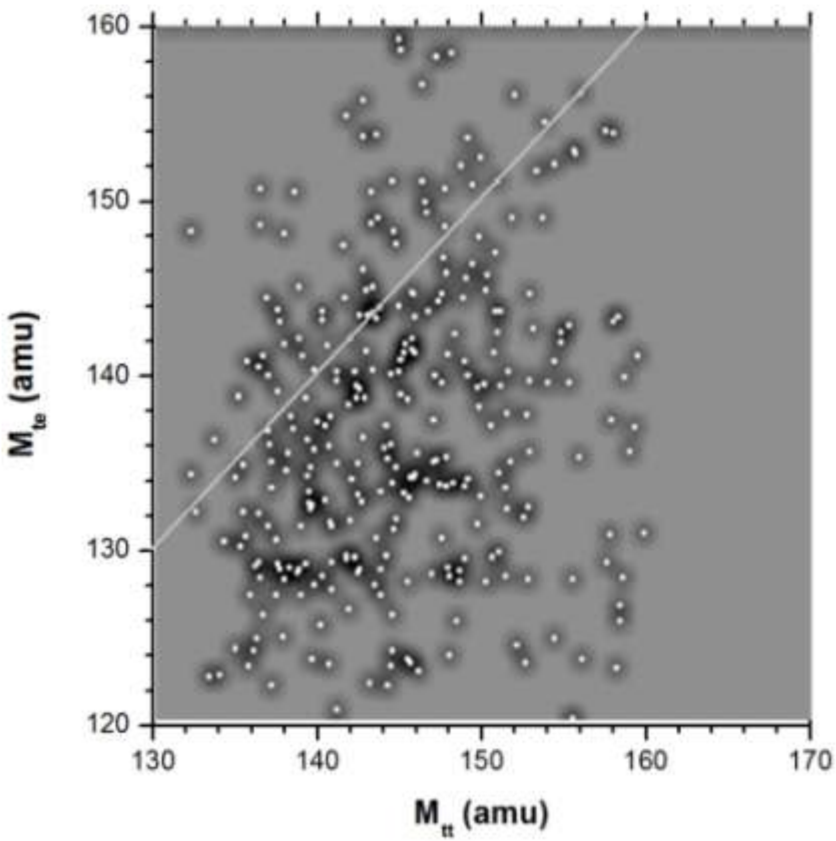
As in the fission isomers we also expect some life-time of the isomer state in FF relative to transition to the ground state.

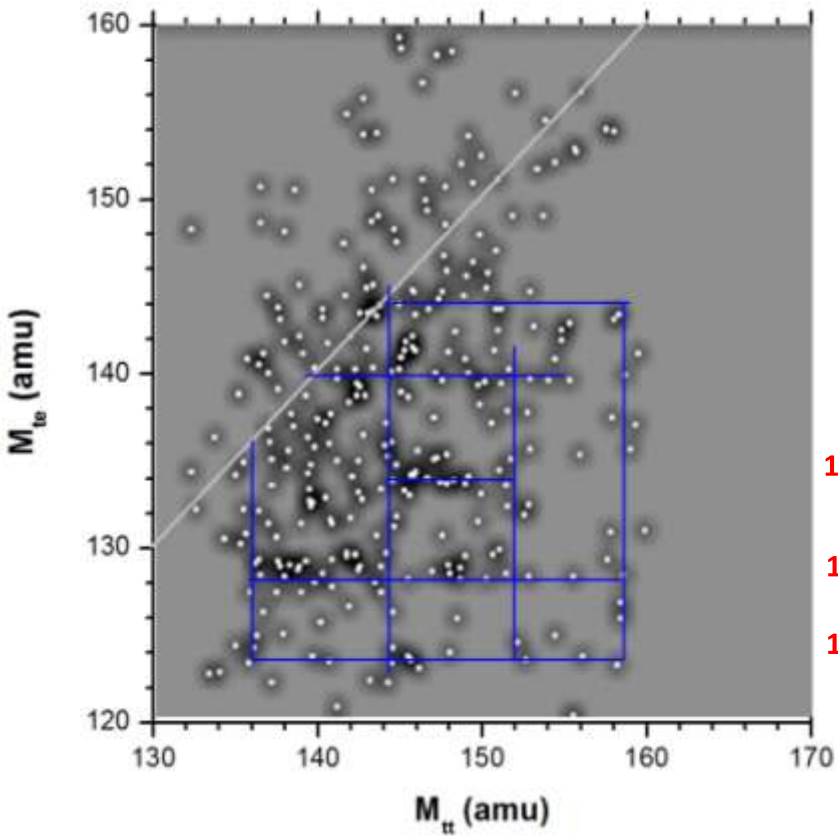
We have estimated experimentally the low limit for this life-time. It exceeds 1 ns.

LIS setup : Mtt & Mte & degrader





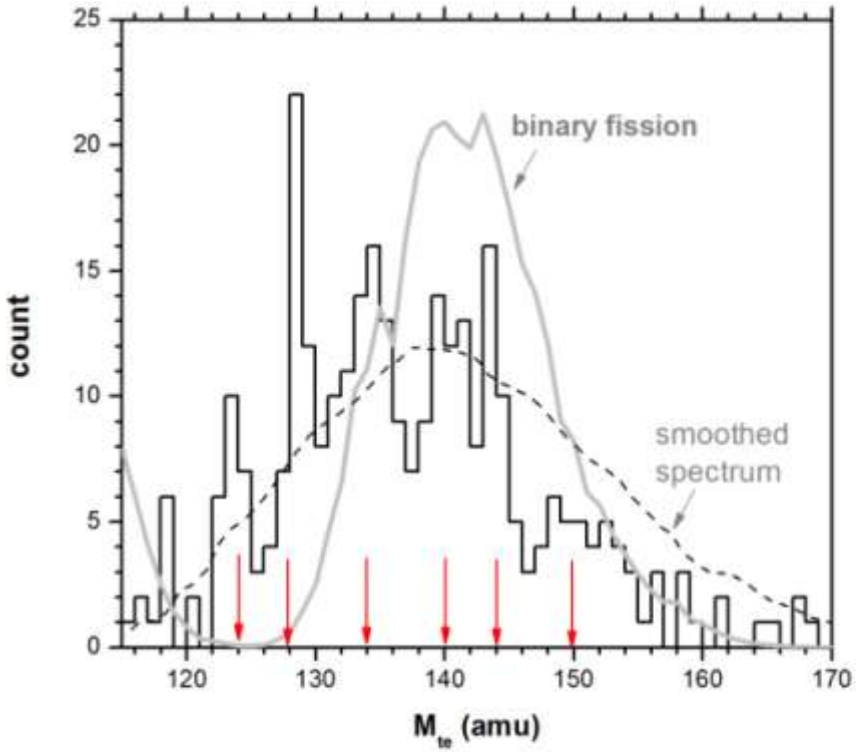




^{144}Ba
^{140}Xe
^{134}Te
^{128}Sn
^{124}Cd

Mass spectra of the FFs crossed the foil

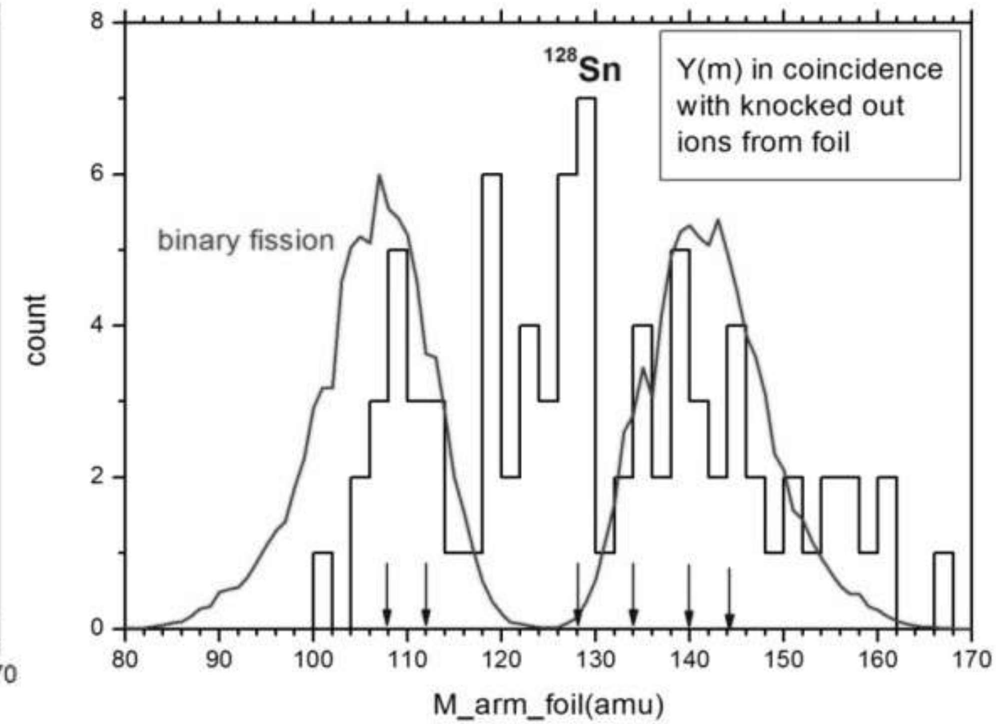
LIS



^{124}Cd ^{128}Sn ^{134}Te ^{140}Xe ^{144}Ba ^{150}Ce

Comparison: Y(M)_lit : $\chi^2/n \sim 30$
Y(128): 3σ=16, S_above_smooth=18

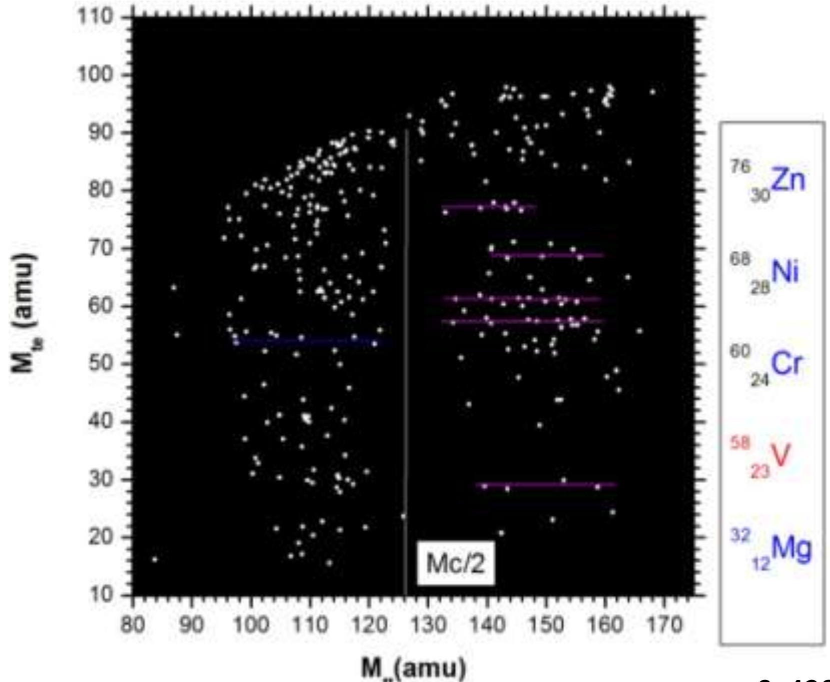
COMETA



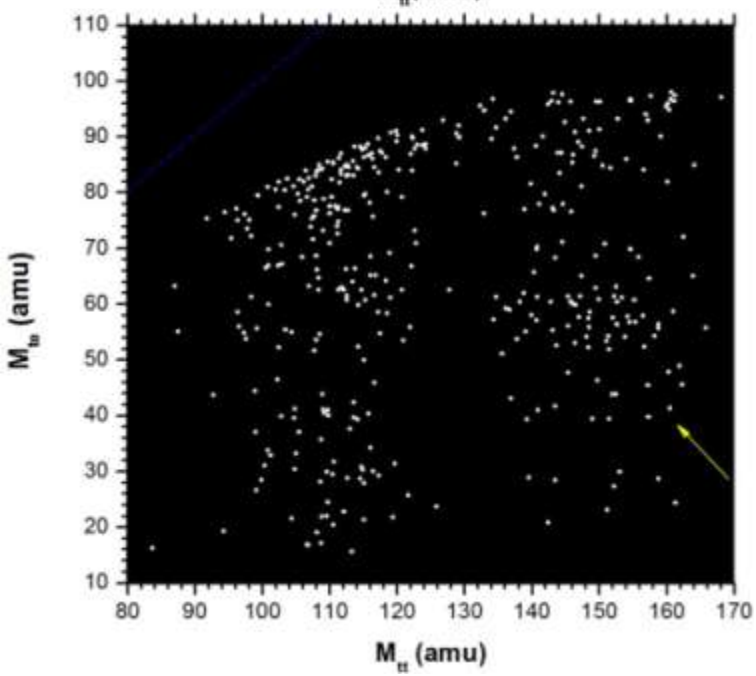
Magic "residuals " only form the mass-spectrum after FF passing through the foil

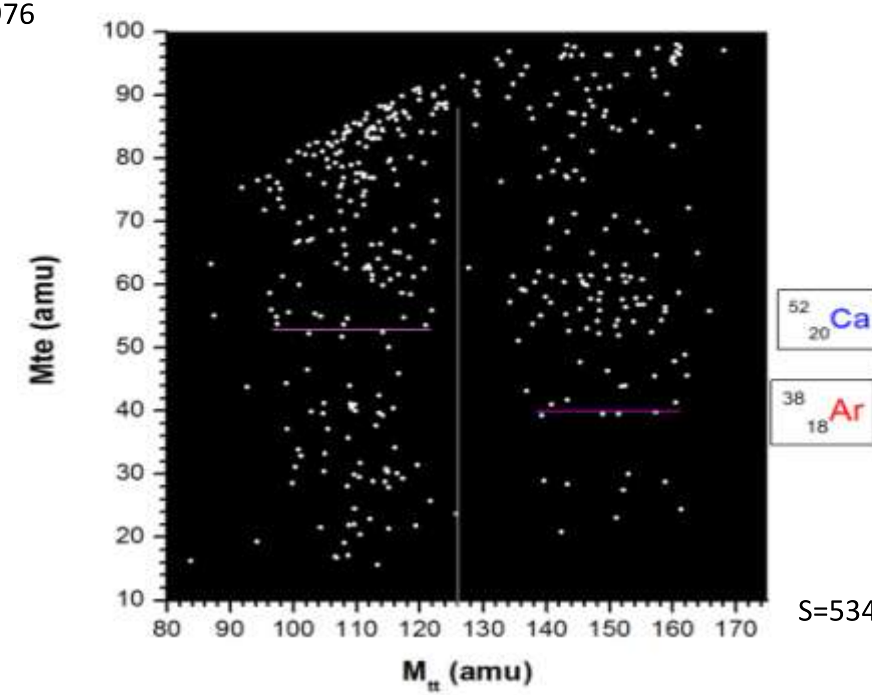
Evidence of a more complicated cluster configurations in heavy fragment

Mass distributions below the loci of binary fission



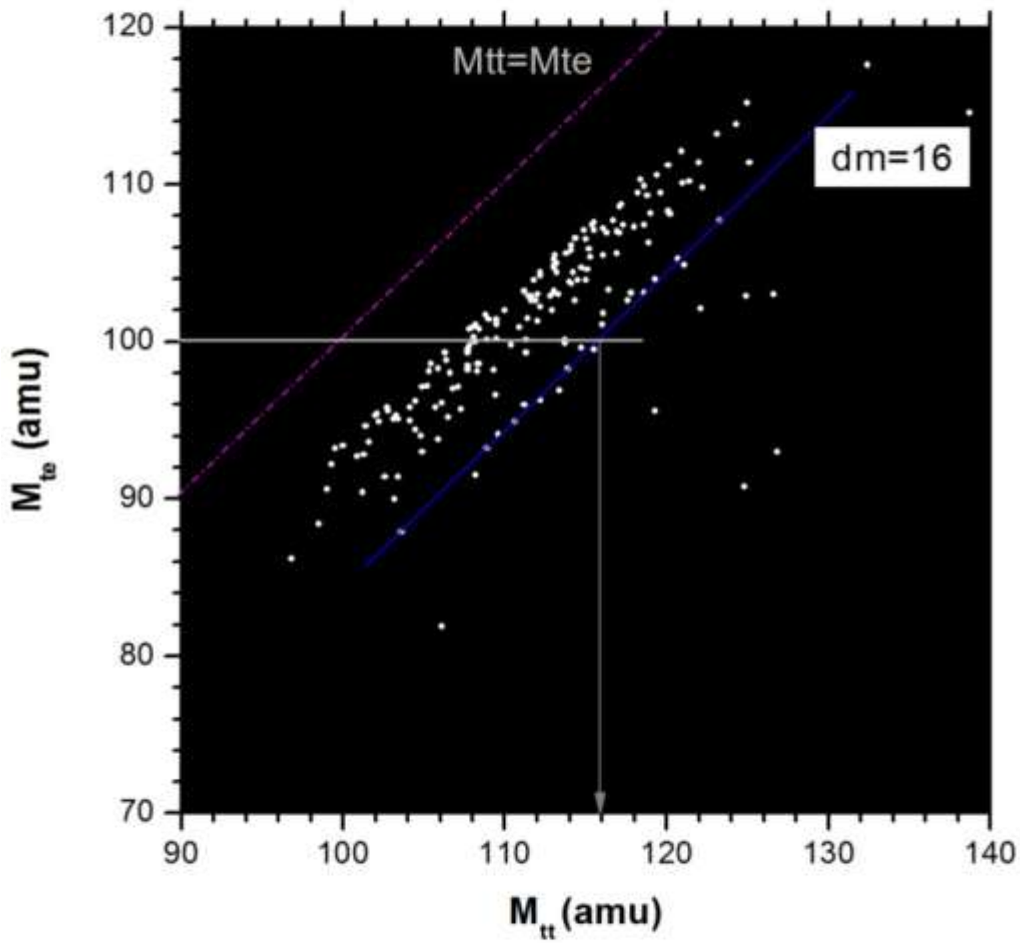
S=428976





S=534773

Evidence of a more complicated cluster configurations in the light fragment

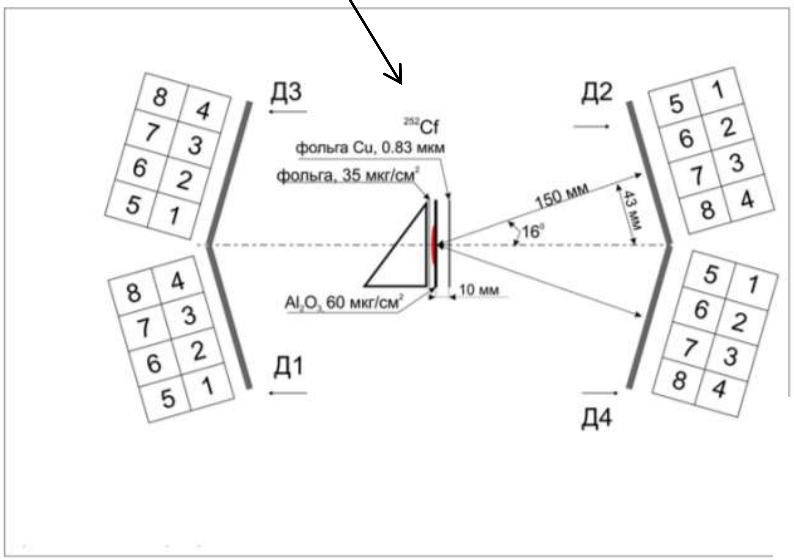


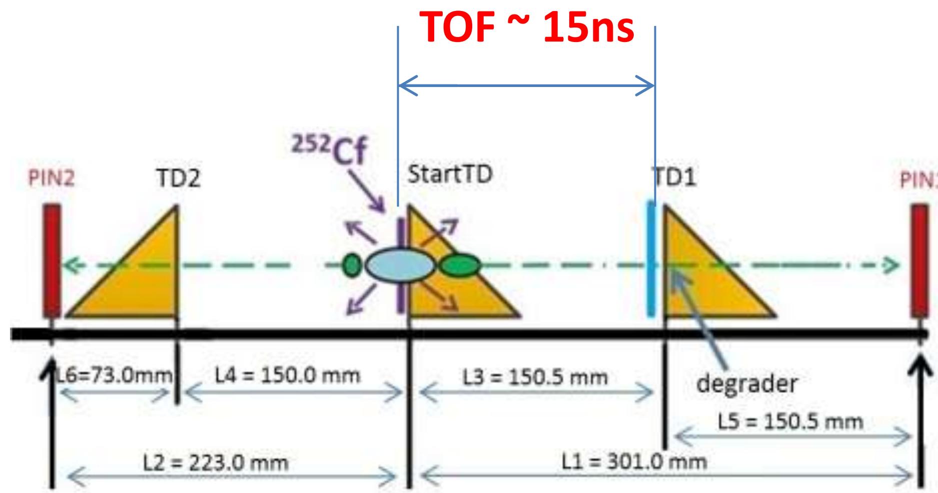
Preformed presumably ^{16}O manifests itself due to inelastic scattering of the FF in the foil

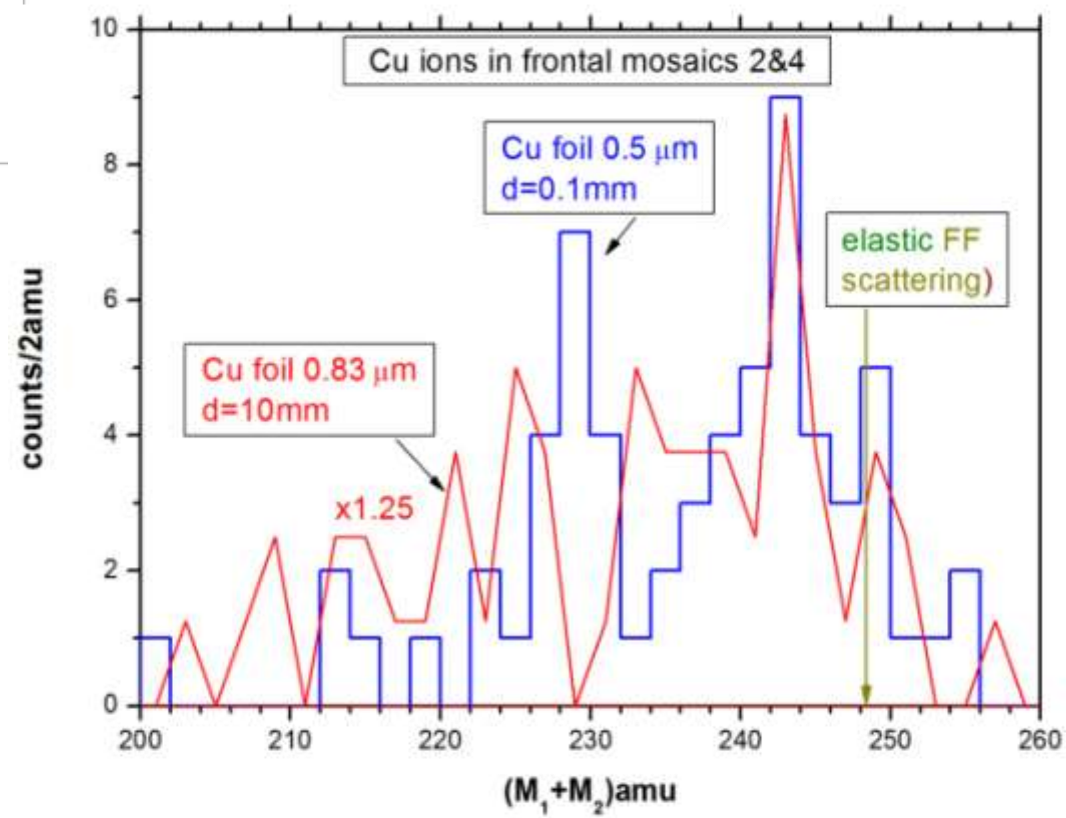
Estimation of the life time of the isomer states in FF

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

Estimation of the life time

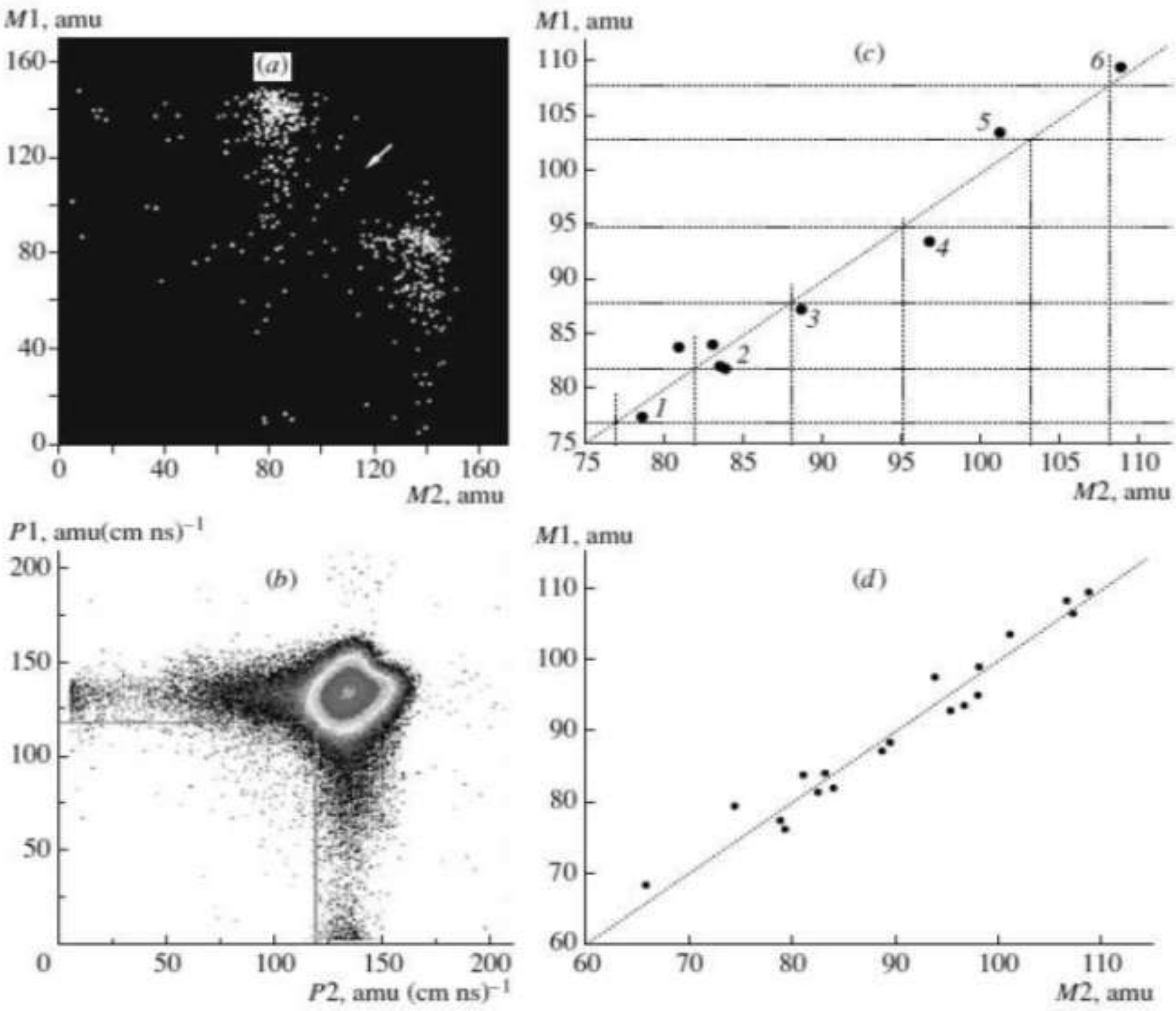




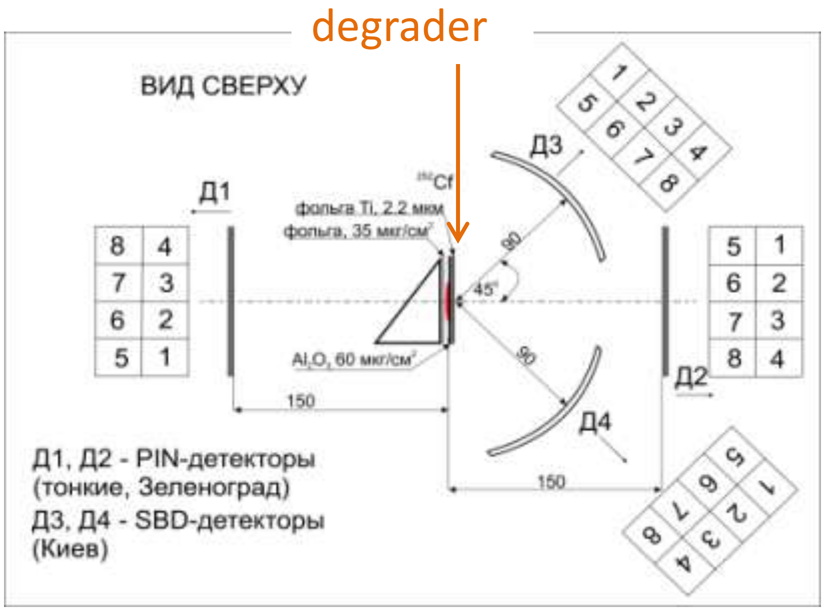


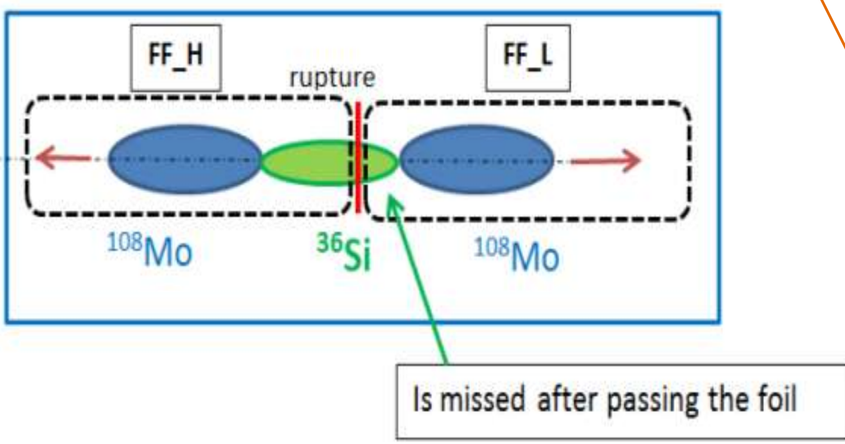
Cluster configurations based on a pair of identic magic clusters

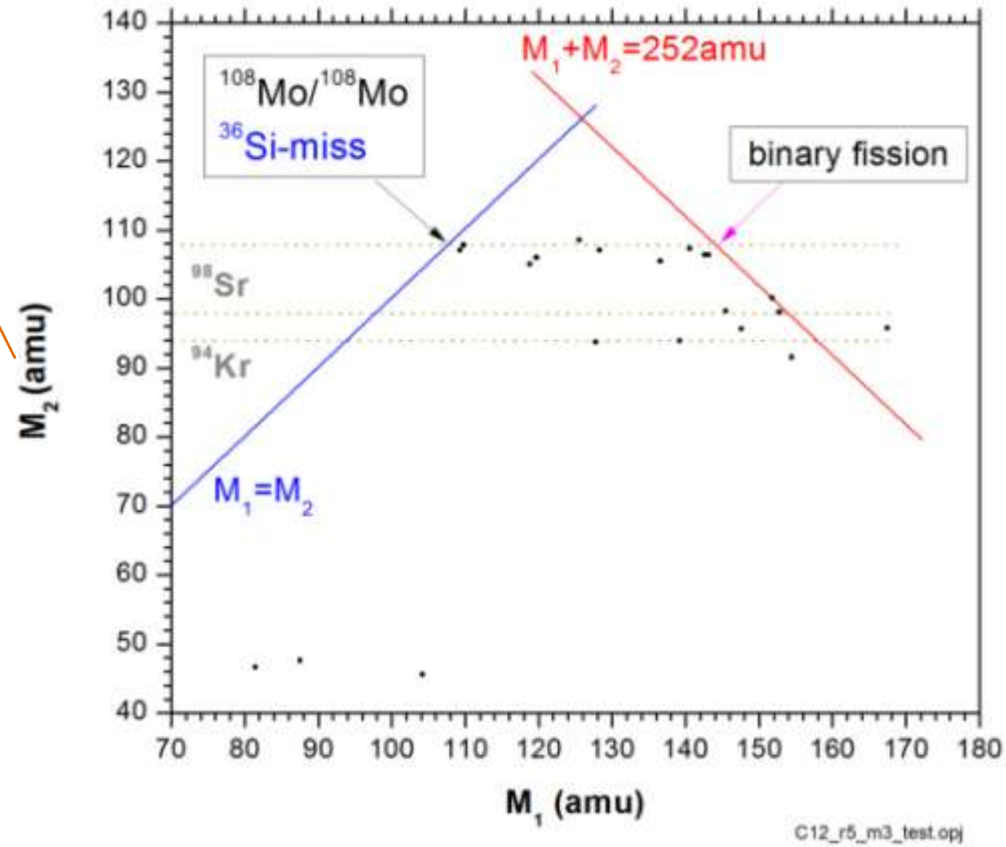
Observation of the “symmetric” CCT mode in $^{235}U(n_{th}, f)$ (IBR-2, mini-FOBOS)



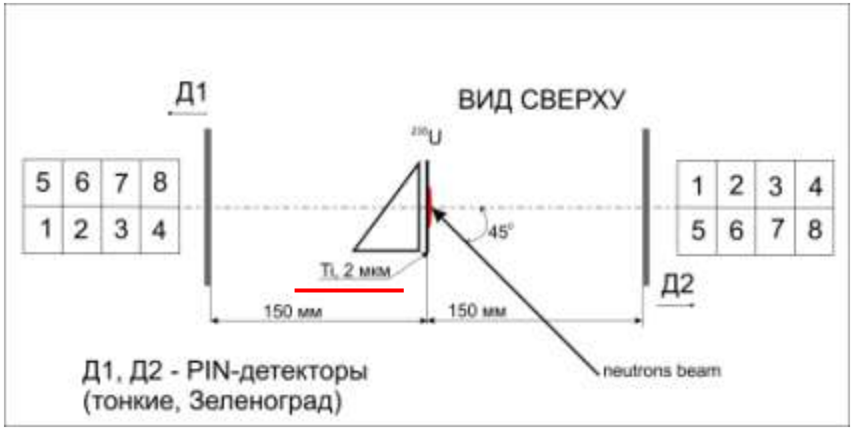
Cluster configurations based on a pair of identic magic clusters

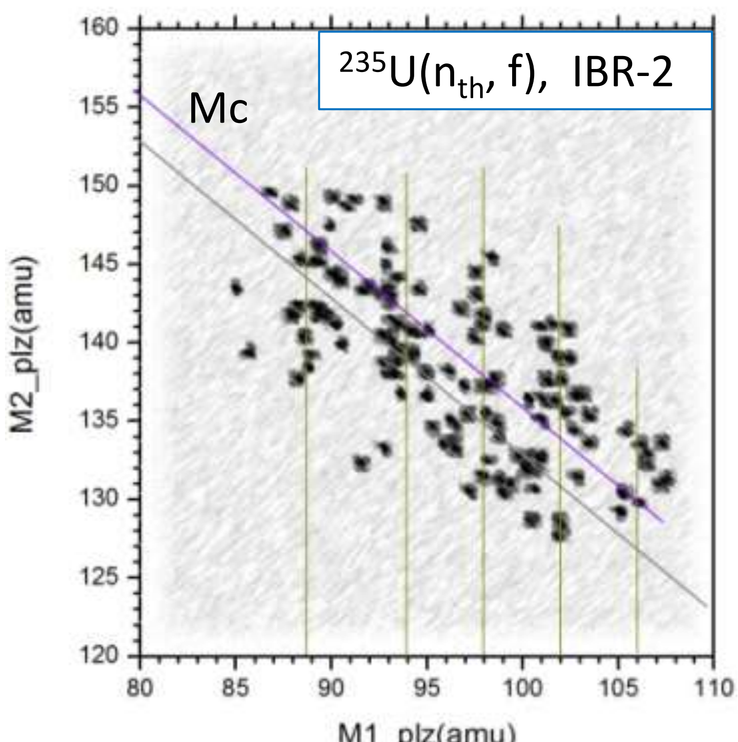




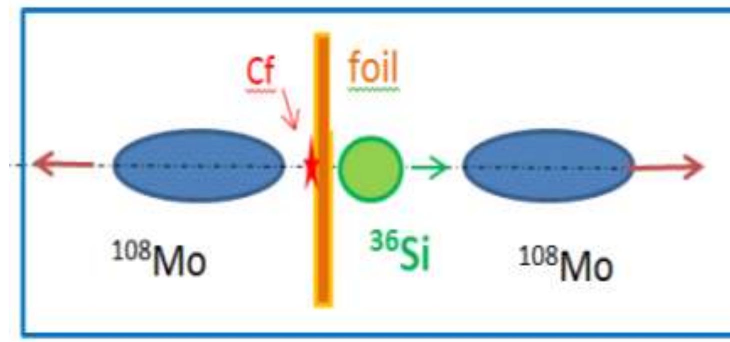


Cluster configurations based on a pair of identic magic clusters





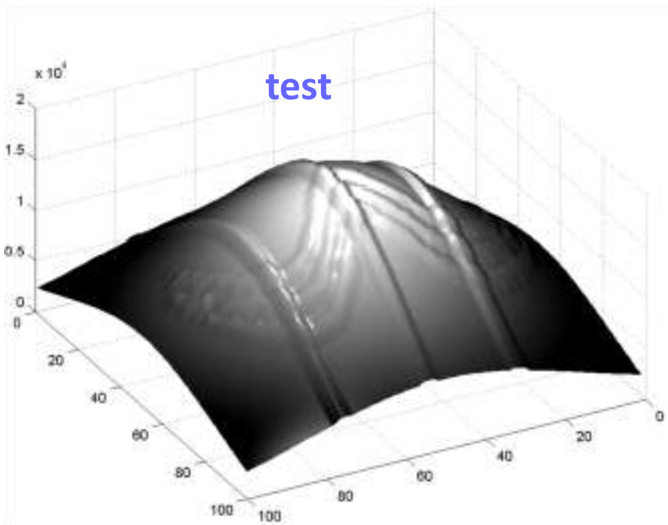
^{88}Se, ^{94}Kr. ^{98}Sr, ^{106}Nb

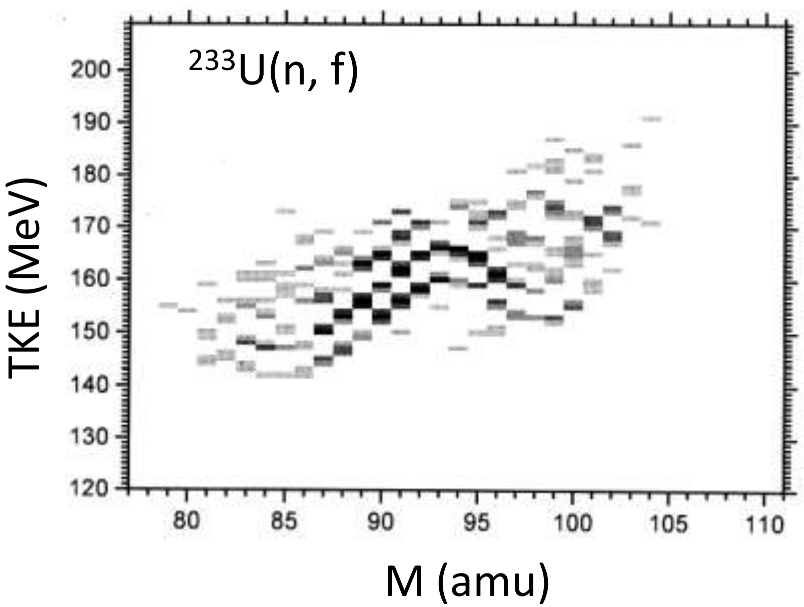


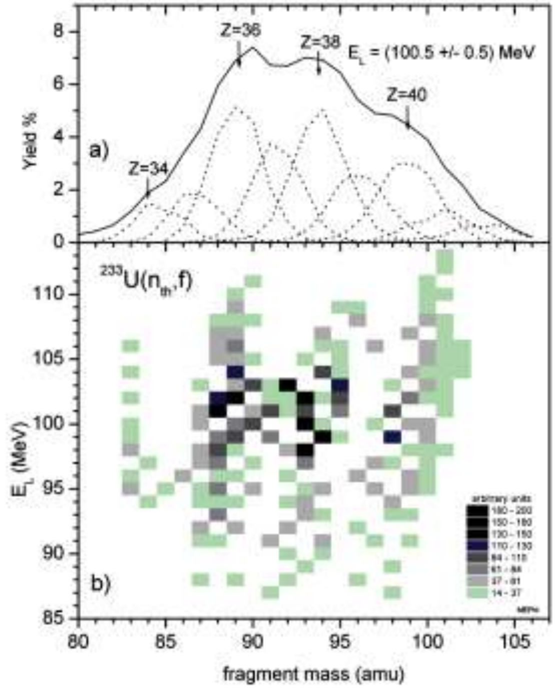
Energies are summed up → unrealistic big MH

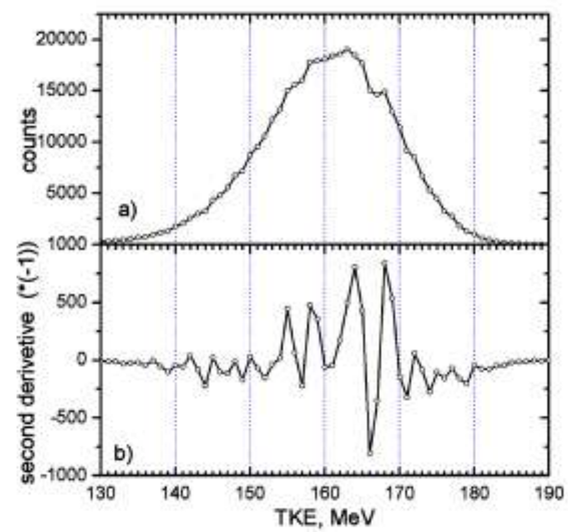
Now cross-talk with our results linked with the topic under discussion but obtained by an absolutely different way.

Revealing of the fine structures (FS) in the M-TKE distributions





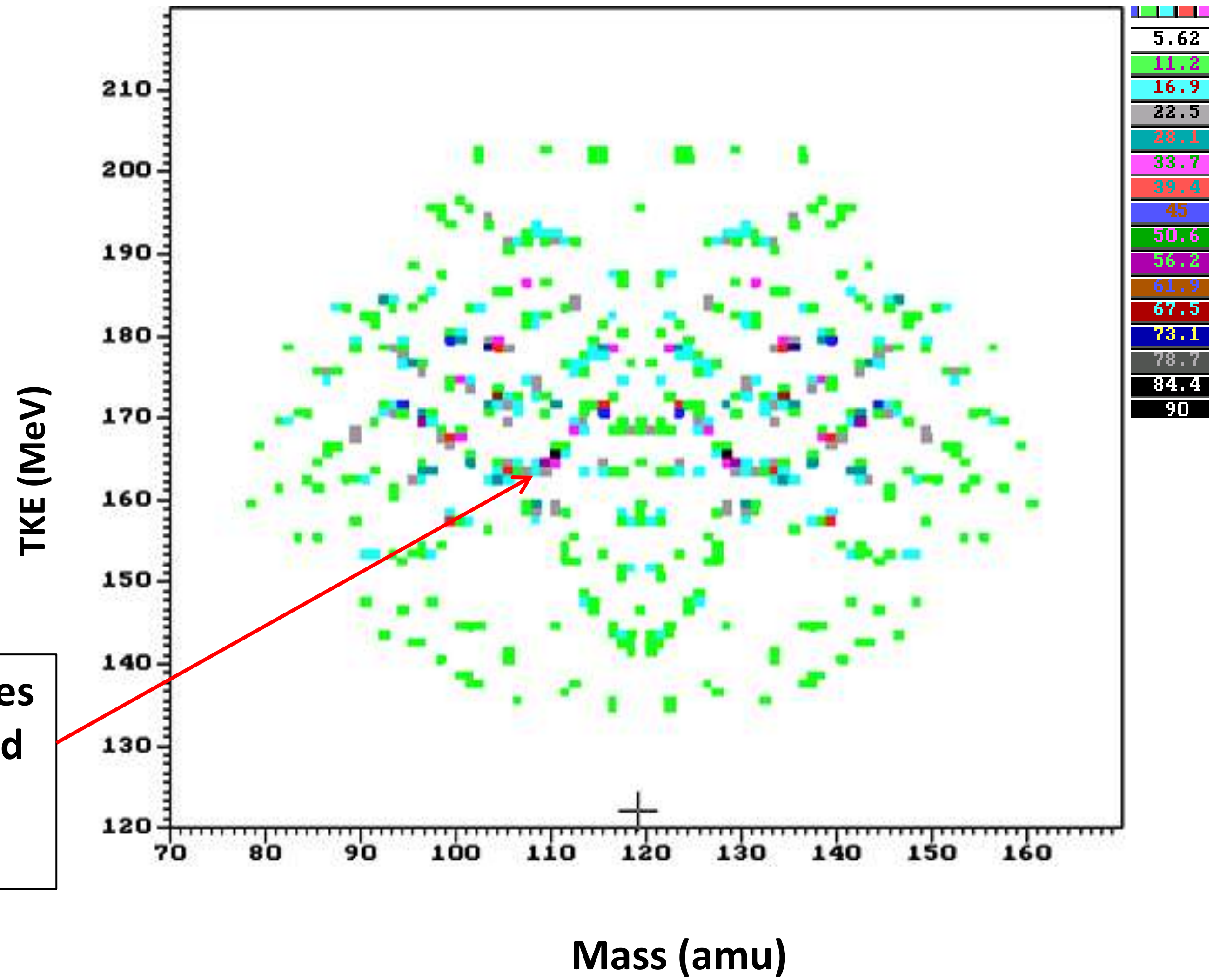




We assume that a trajectory in the deformation space as a continuous sequence of nuclear states in the fission valley is mapped to continuous trajectories (smooth curves) in the plane of experimentally observed variables.
Thus, the fine structure under discussion is a unique image of separate fission trajectories passed by a system.

Yu. V. Pyatkov et al., Pattern Recognition and Image Analysis, v. 21, №16 (2011) 82

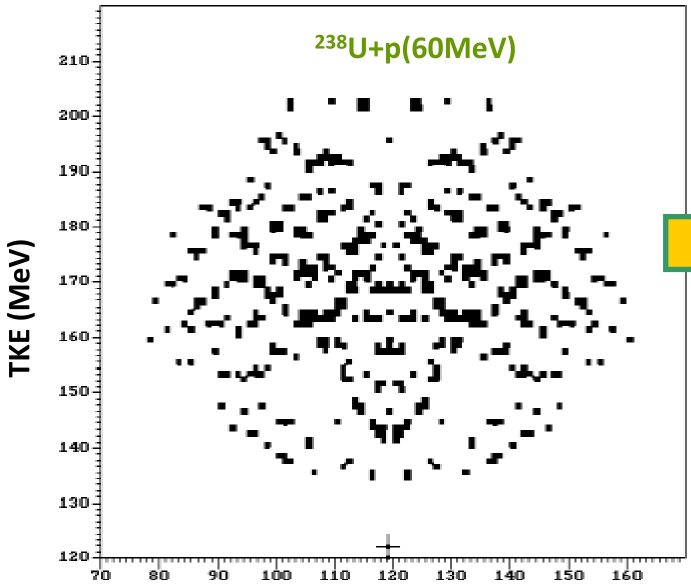
^{238}U+p (60MeV), TOF-TOF, HENDES setup

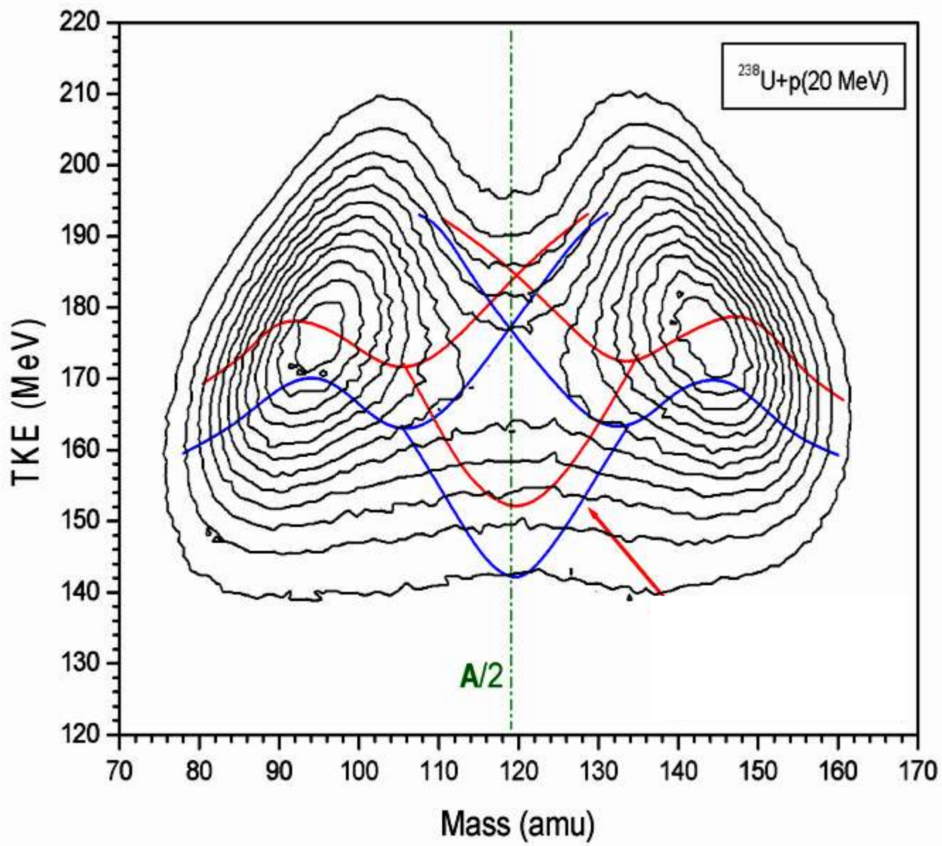


“Symmetric” modes based on deformed magic clusters of ^{108}Mo & ^{112}Ru

- Fine structure revealed by the “symmetry” filter;a – using M=120amu as an axis of symmetry;
- b – the same for the M=121amu.The most pronounced structures are marked to guide the eye.

Origin of the symmetric fission mode





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

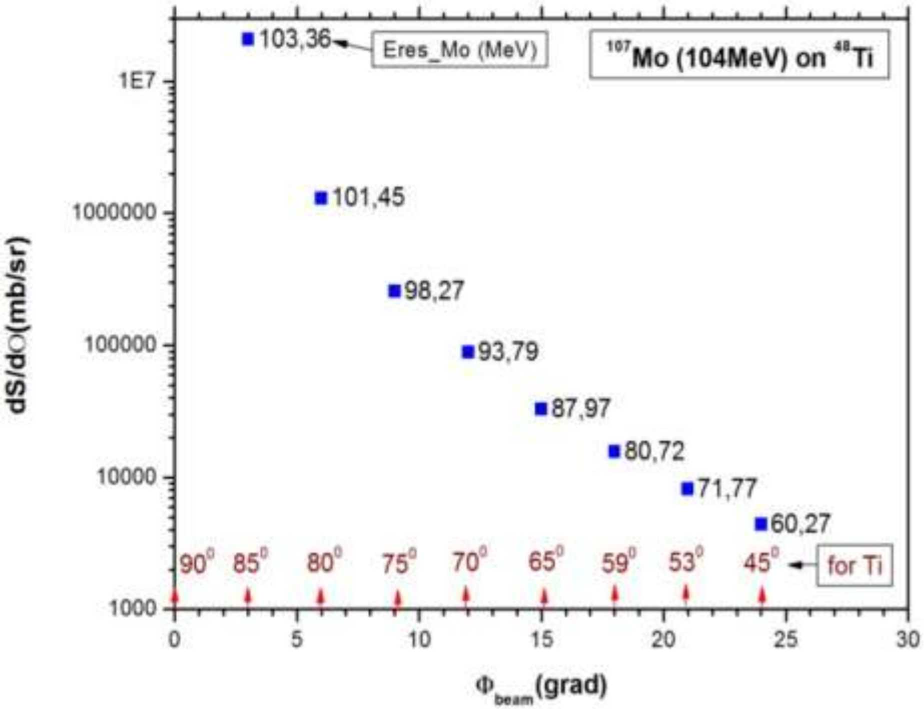
The shape of the distinct path gives an idea concerning the origin of so called "symmetric fission mode"

Conclusions

1. In the frame of the new methodic approach some basic results concerning the shape isomer states in the FF were confirmed.
2. New cluster effects linked with “symmetric” CCT mode are revealed.
3. The low limit of the FF isomer states life time was re-estimated to be more than 15ns.

Rutherford scattering - L_FF/Ti

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



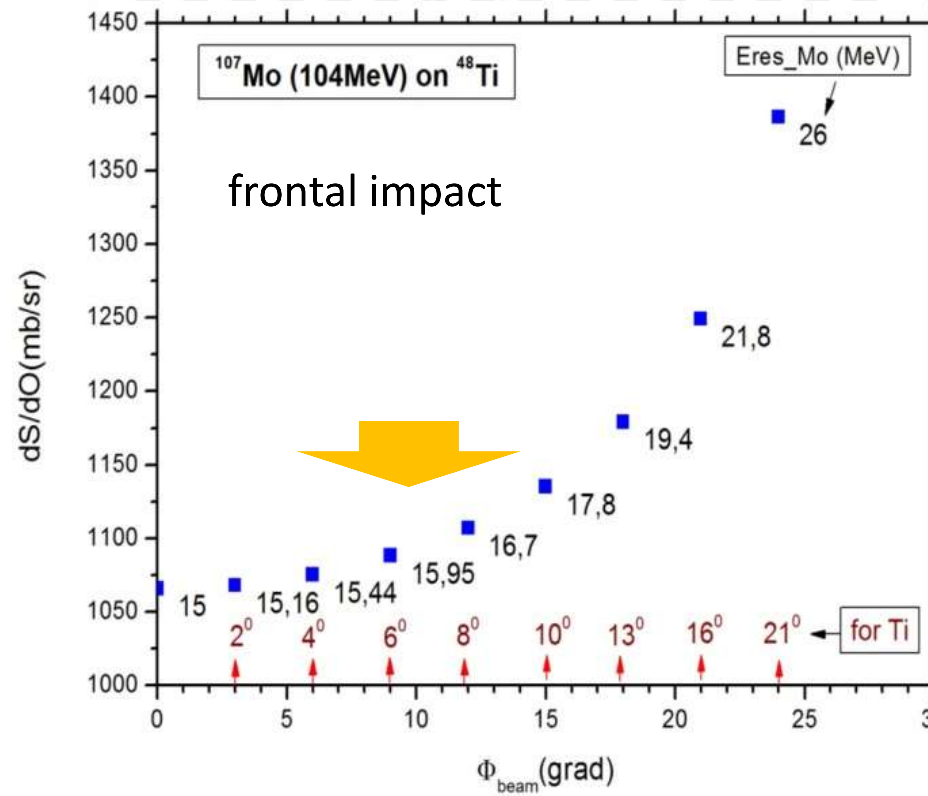
$$\sigma(\theta) = \left(\frac{1}{4\pi\varepsilon_0}\right)^2 \frac{Z^2 e^4}{M^2 v^4} \times \frac{1}{\sin^4(\theta/2)}$$

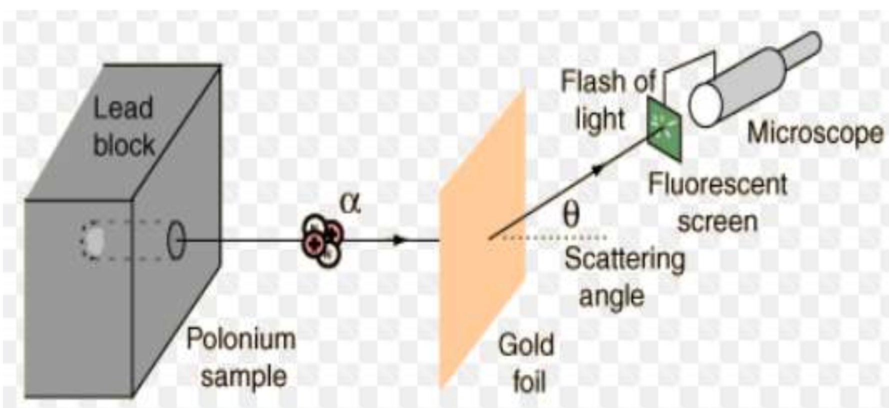
Ze = the positive charge of the target atom,

M = the mass of the α particle,

v = incident speed of the α particle,

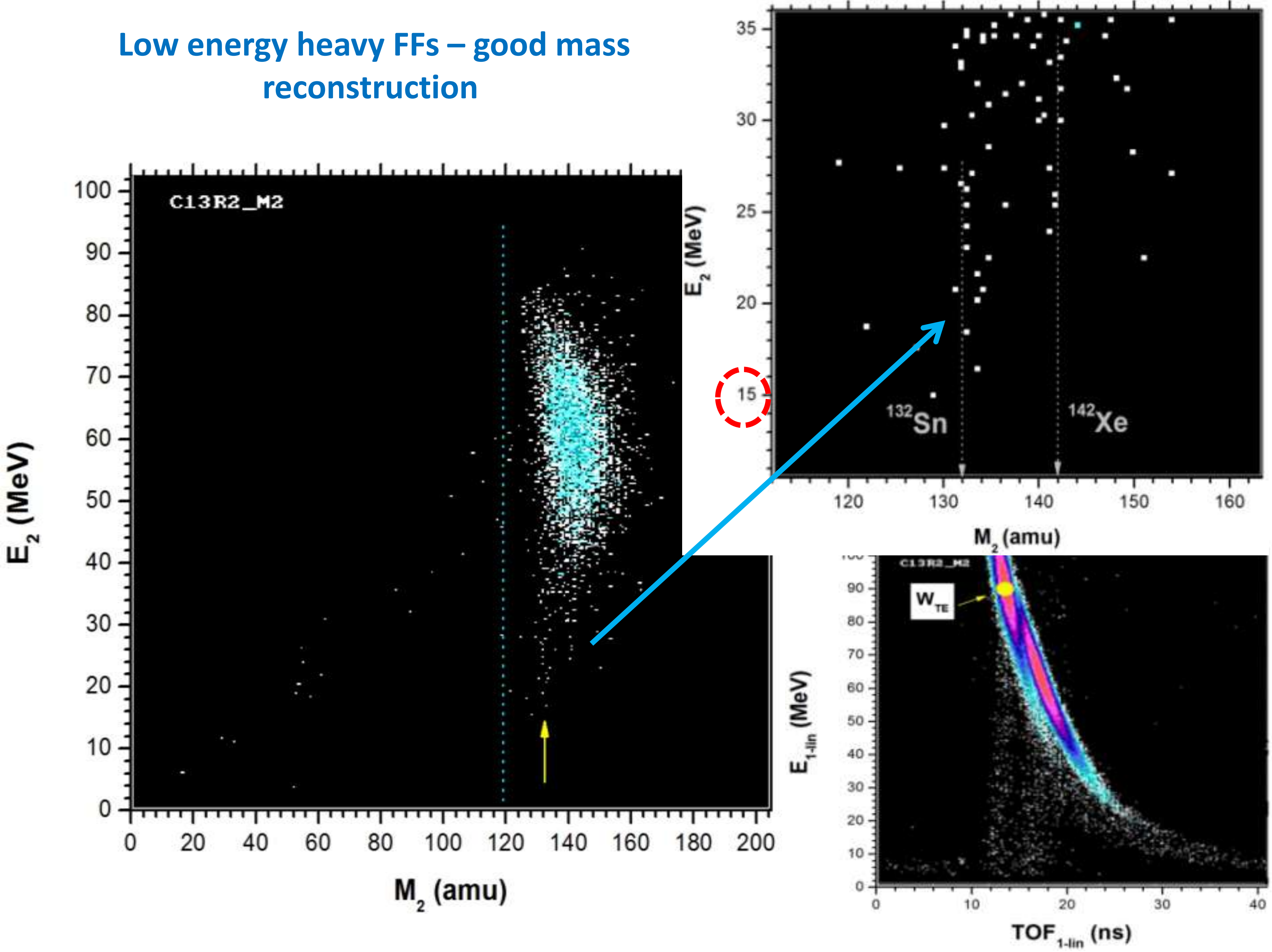
θ = scattering angle,





Original Rutherford experiment

Low energy heavy FFs – good mass reconstruction



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 :

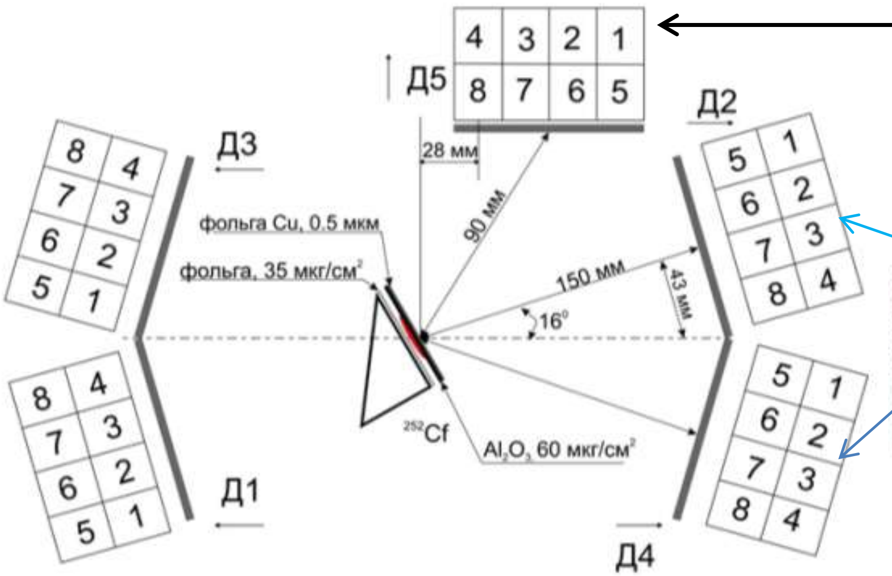
Are there contradictions of the experimental results obtained and model proposed with well known features of the fission process?

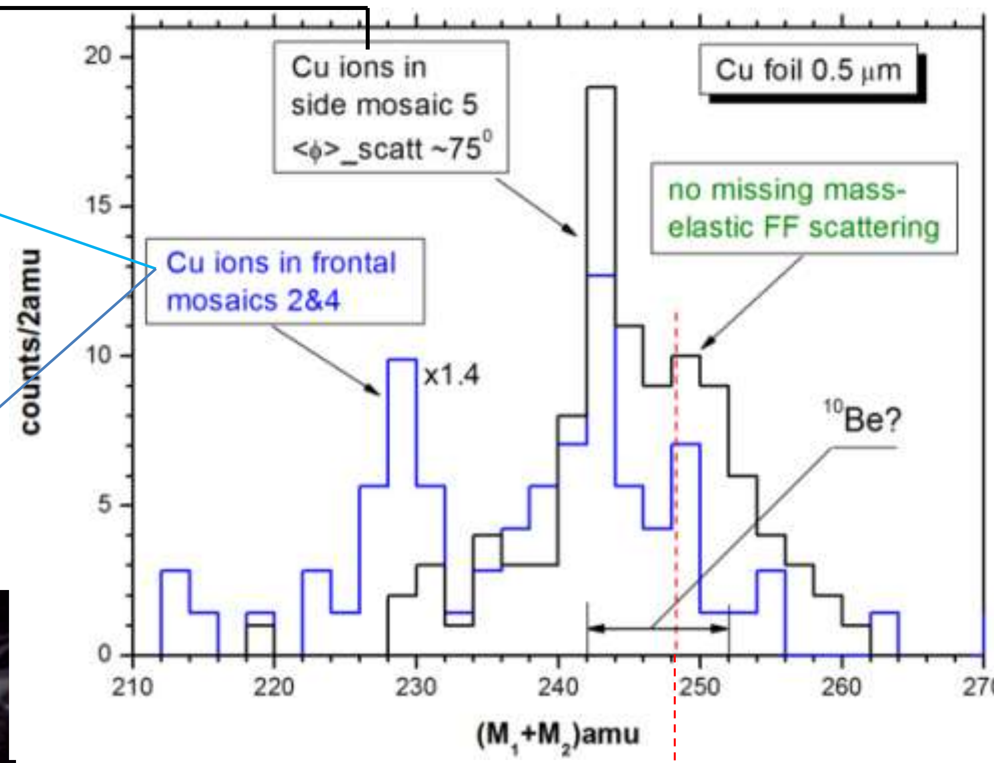
1. We suppose that the bulk of the fragments of conventional binary fission look like di-nuclear systems (are in shape isomeric states) just after scission.

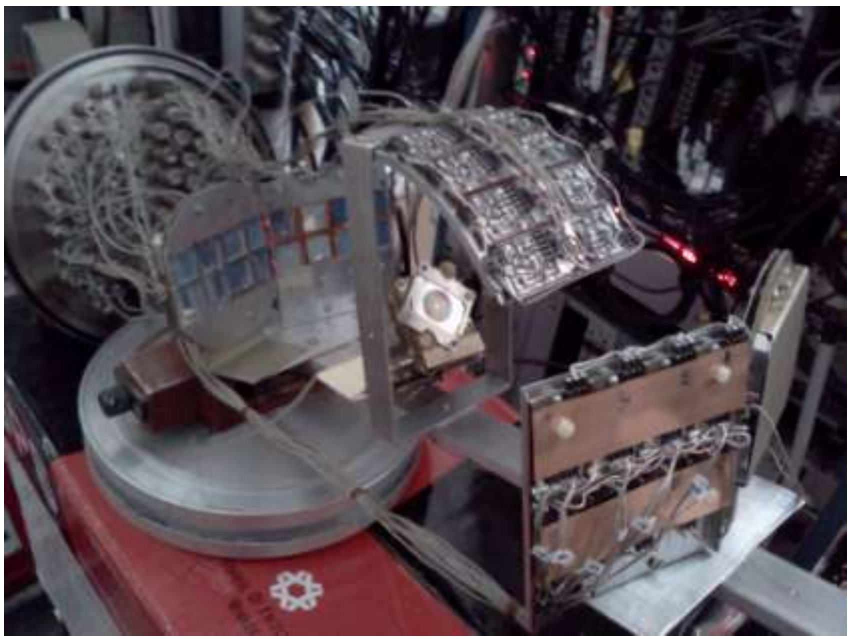
Does it mean that the total yield of the effect is sufficient to change the macroscopical fission constants?

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

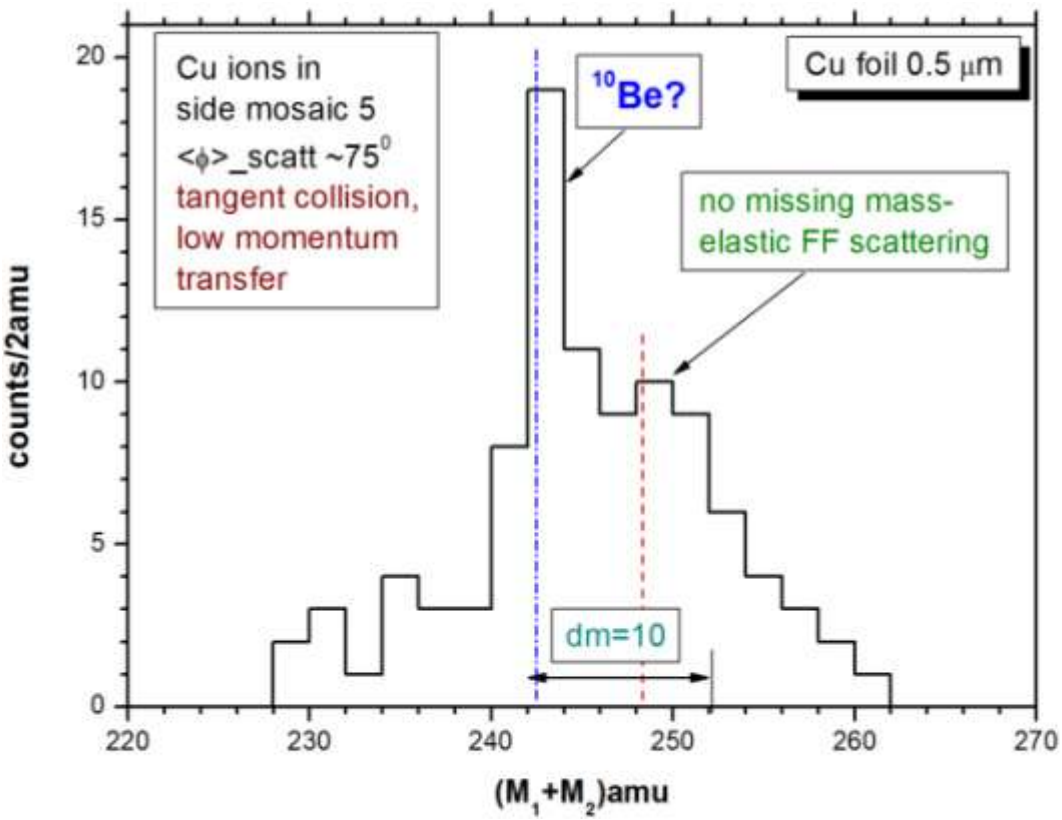






At the large angles of scattering of the knocked –out ions from the foil conventional elastic Rutherford scattering takes place.

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§

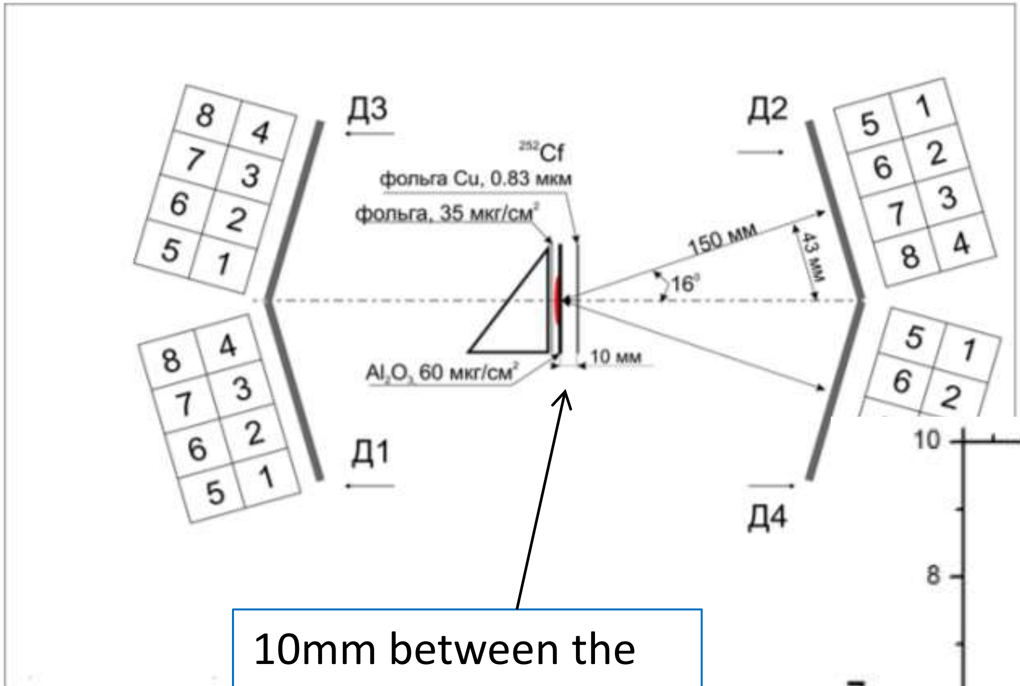
Table 1. Calculated half lives of some quasi-molecular states ^{252}Cf.

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

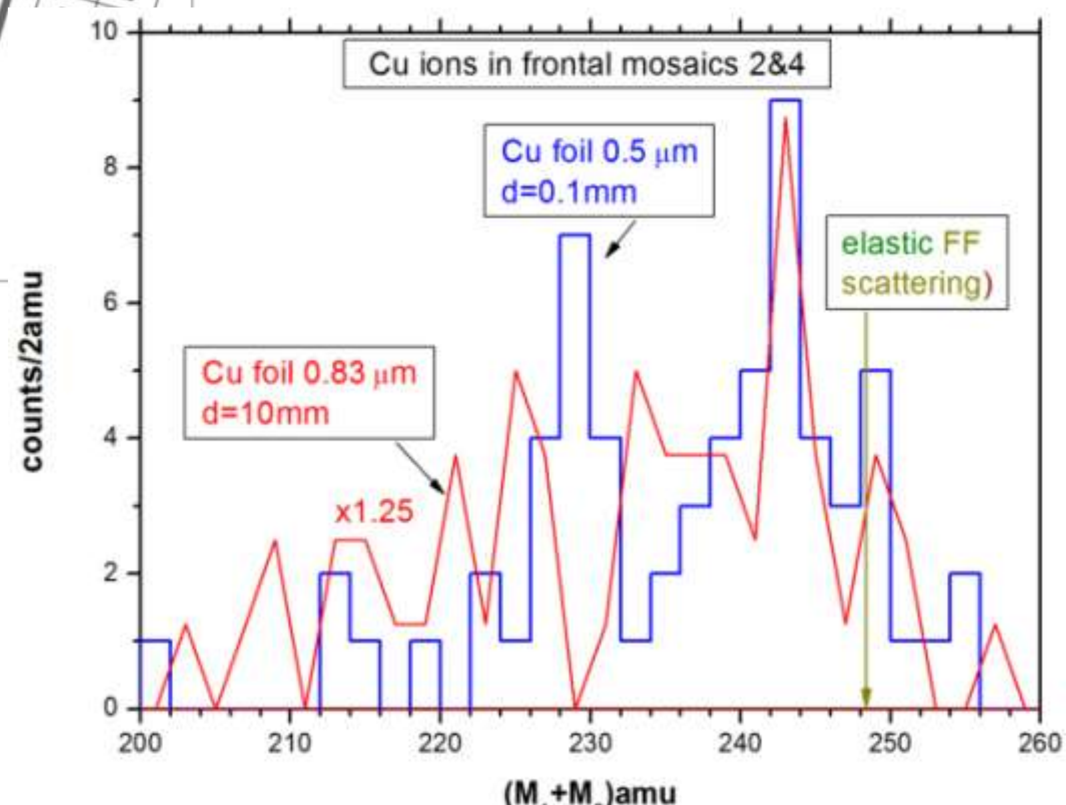
There is no such peak in M1+M2 spectrum FF from conventional binary fission.
Likely loosely coupled (see Poenary predictions)
^{10}Be based di-nuclear system experiences a breakdown even in tangent collisions.

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]

[1]*RIKEN Nishina Center, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[2]*Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[3]*Department of Engineering Science, Osaka Electro-Communication University, 18-8 Hatsucho, Neyagawa, Osaka 572-8530, Japan*
[4]*Department of Physics, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima-ku, Tokyo 171-8501, Japan*
[5]*Department of Physics, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan*
[6]*Faculty of Science and Technology, Tokyo University of Science, 2461 Yamazaki, Noda, Chiba 278-8510, Japan*
[7]*Center for Nuclear Study, University of Tokyo, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[8]*Department of Physics, Saitama University, 255 Shimo-Okubo, Sakura-ku, Saitama City, Saitama 338-8570, Japan*
[9]*Institute of Physics, University of Tsukuba, 1-1-1 Ten'noudai, Tsukuba, Ibaraki 305-8571, Japan*
[10]*Institute of Physics, Niigata University, 8050 Ikarashi 2-no-cho, Nishi-ku, Niigata 950-2181, Japan*
[11]*Department of Physics, Western Michigan University (WMU), 1903 W. Michigan Avenue, Kalamazoo, Michigan 49008-5252, USA*
[12]*Gesellschaft fuer Schwerionenforshung (GSI) mbH, 1 Planckstraße, Darmstadt 64291, Germany*
[13]*National Superconducting Cyclotron Laboratory (NSCL), Michigan State University (MSU), 640 South Shaw Lane, East Lansing, Michigan 48824-1321, USA*
[14]*Argonne National Laboratory (ANL), 9700 S. Cass Avenue, Argonne, Illinois 60439, USA*

(Received 10 August 2012; revised manuscript received 17 October 2012; published 27 November 2012)

Abstract

A search for isomeric γ 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 γ rays were detected using three clover-type high-purity germanium detectors located at the focal plane within a time window of 20 μs following the implantation. We identified a total of 54 microsecond isomers with half-lives of ~0.1–10 μs, 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

Atomic Data and Nuclear Data Tables

journal homepage: www.elsevier.com/locate/adt

Nuclear shape isomers

P. Möller[a,*], A.J. Sierk[a], R. Bengtsson[b], H. Sagawa[c], T. Ichikawa[d]

[a] *Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545, United States*

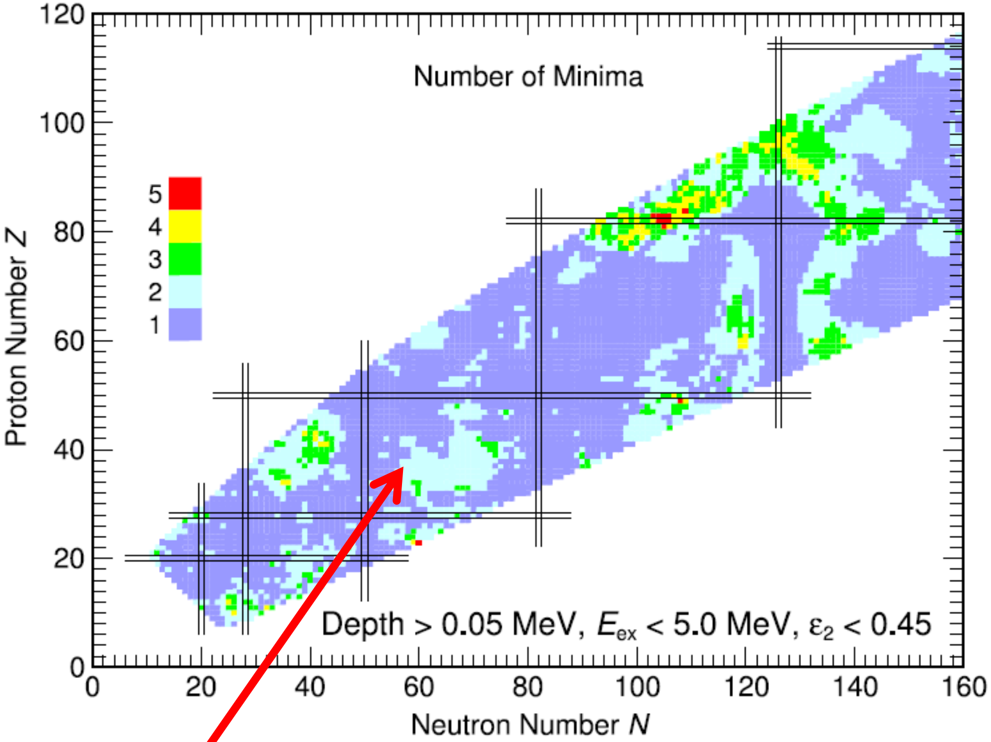
[b] *Department of Mathematical Physics, Lund Institute of Technology, P.O. Box 118, SE-22100 Lund, Sweden*

[c] *Center for Mathematical Sciences, University of Aizu, Aizu-Wakamatsu, Fukushima 965-80, Japan*

[d] *Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan*

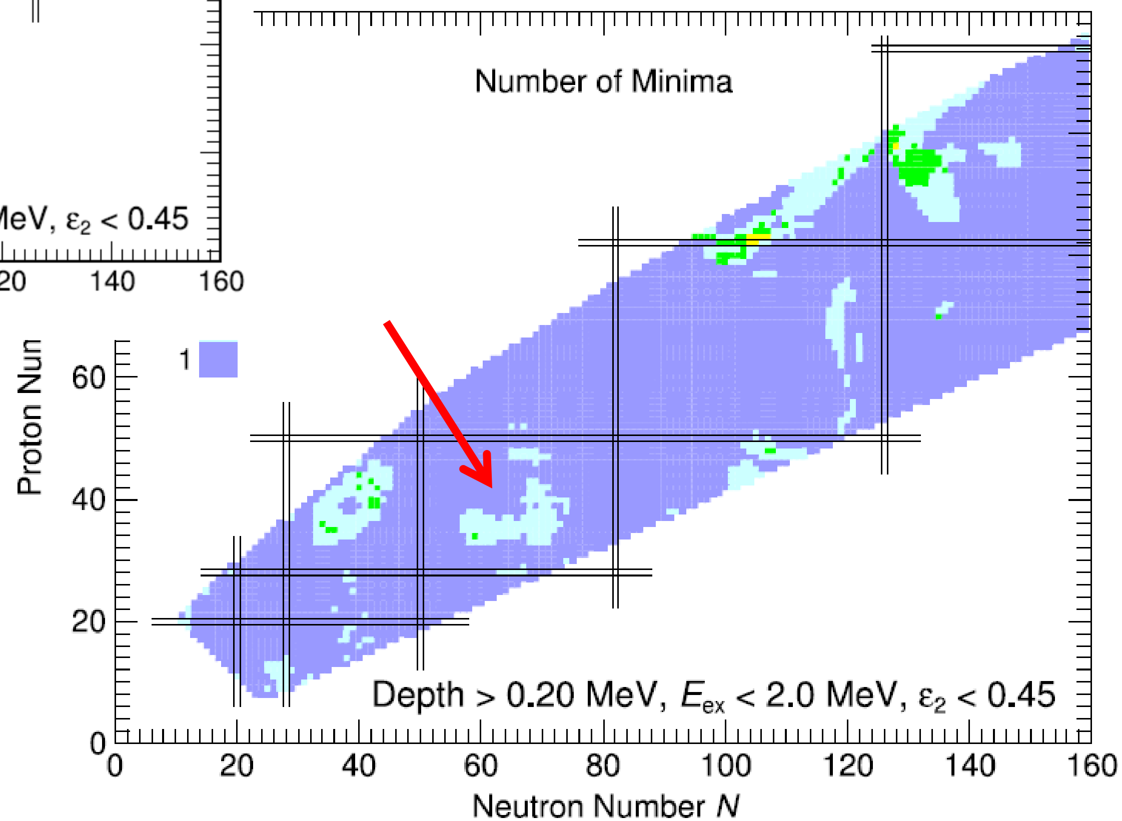
We calculate potential-energy surfaces as functions of spheroidal ($\epsilon 2$), hexadecapole ($\epsilon 4$), and axial asymmetry (γ) shape coordinates for 7206 nuclei from A = 31 to A = 290. We tabulate the deformations and energies of all minima deeper than 0.2 MeV and of the saddles between all pairs of minima. The tabulation is terminated at N = 160….
We also present potential-energy contour plots versus $\epsilon 2$ and γ 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



FF region

Magic numbers



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.

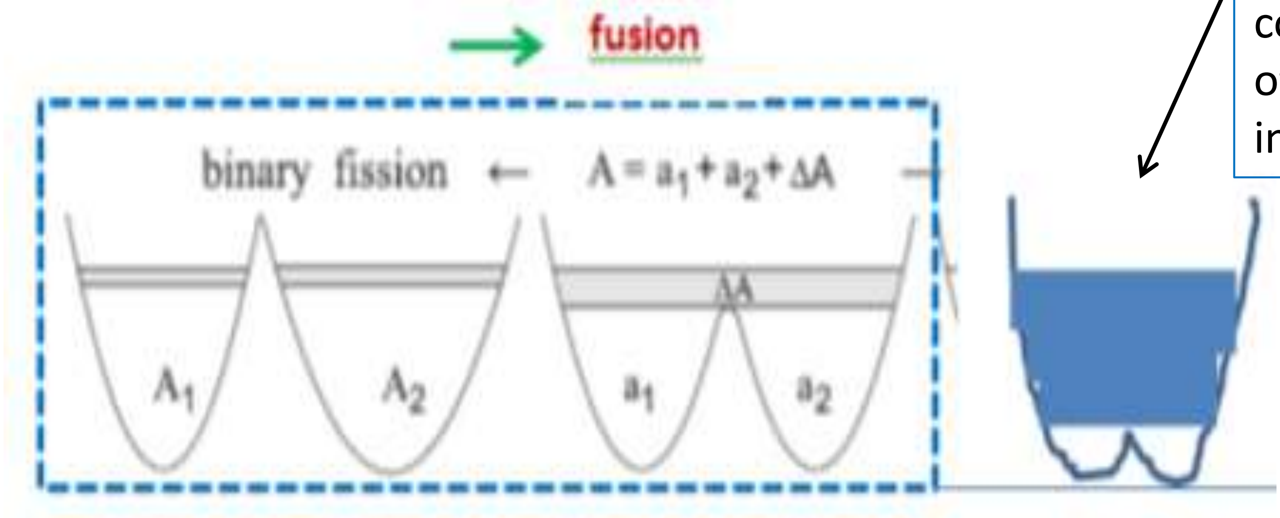
FIG. 5 (color). Number of minima found with deformation $\epsilon_2 < 0.45$. Only the ground-state and isomer minima that are deeper than 0.2 MeV and with energies relative to the ground state of less than 2.0 MeV are counted.

TCSM in description of fission & fusion

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

True ternary fission of superheavy nuclei

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

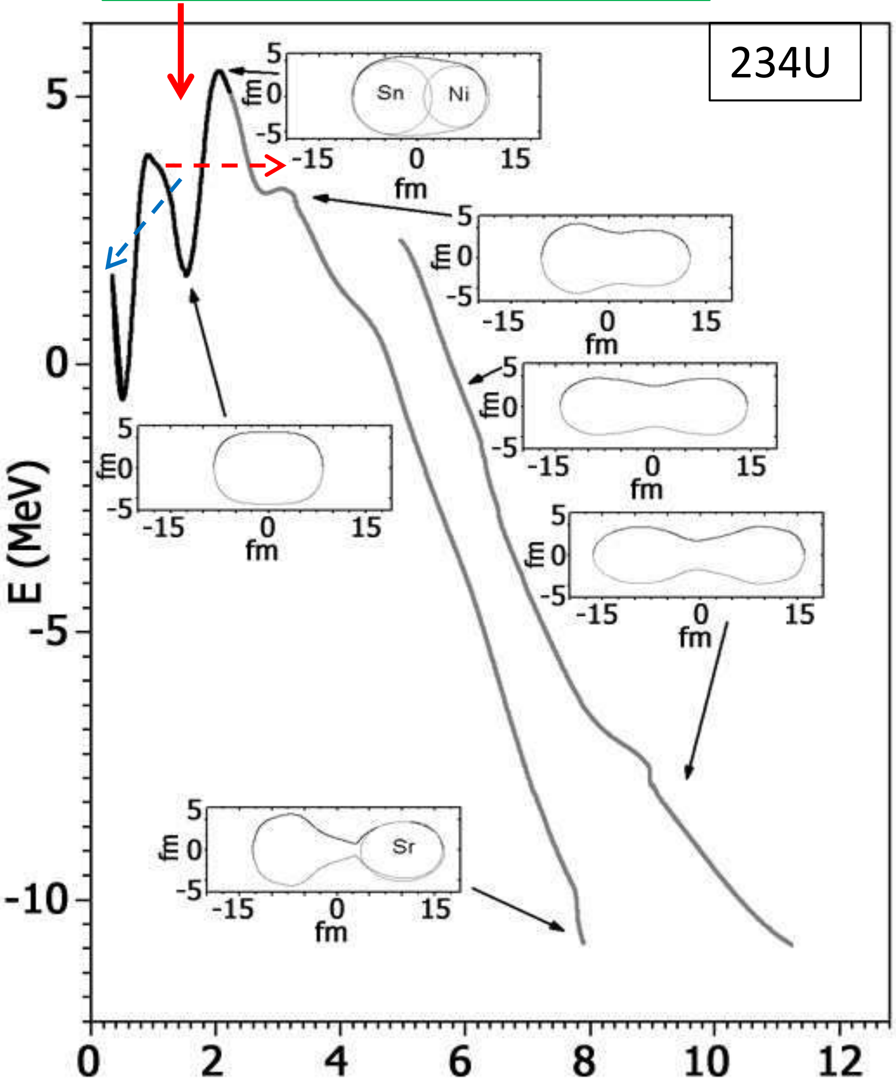


Our case of almost complete fusion of two nuclei constituting initial di-nuclear system

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.

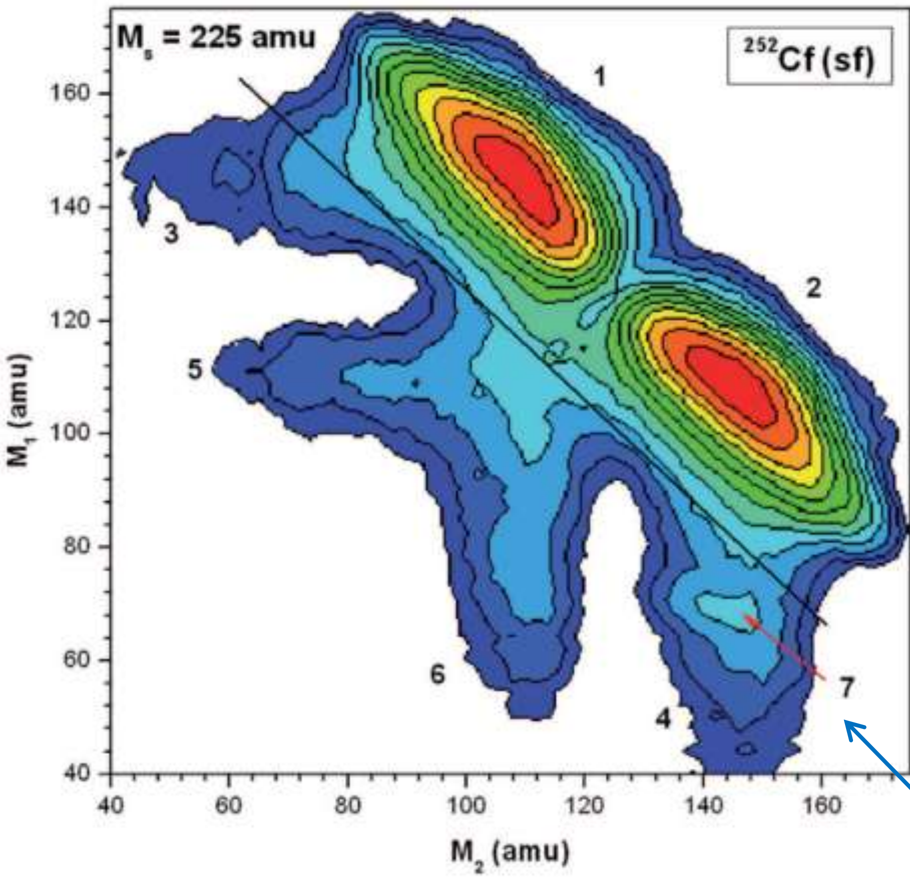
Actually it is a low excited state of the resultant a1+a2 nucleus.
The main part of the initial E* is *already* exhausted by emitted neutrons.

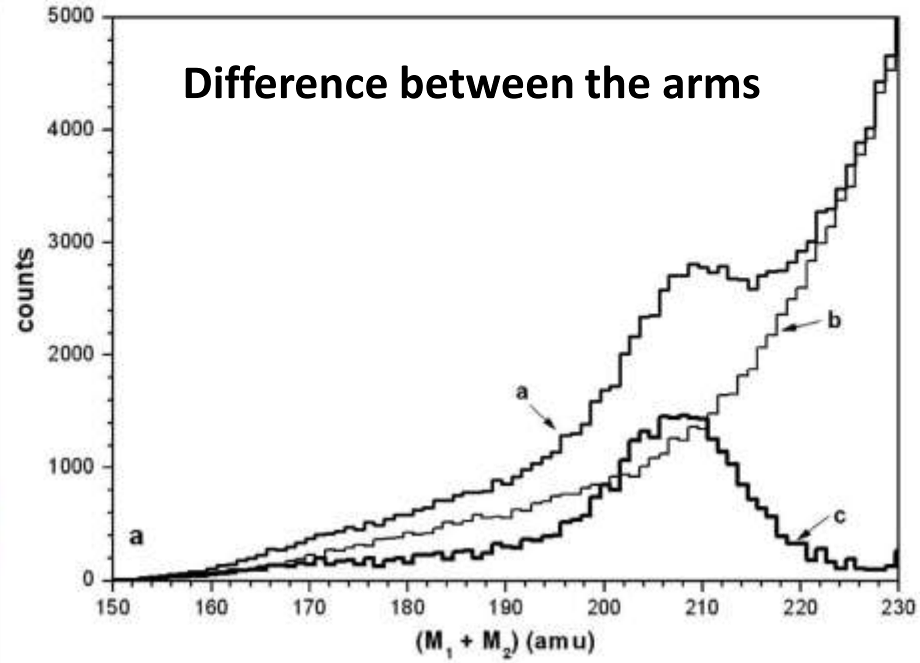
The fusion process is stopped at the final stage reaching gamma-isomeric state. The residual E* will be carry away by gammas through time to be characteristic for this channel of de-excitation. (some **μs** presumably)

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

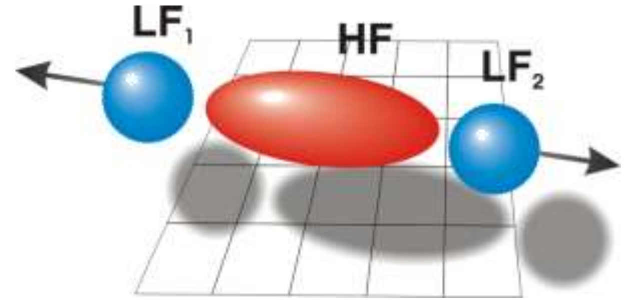




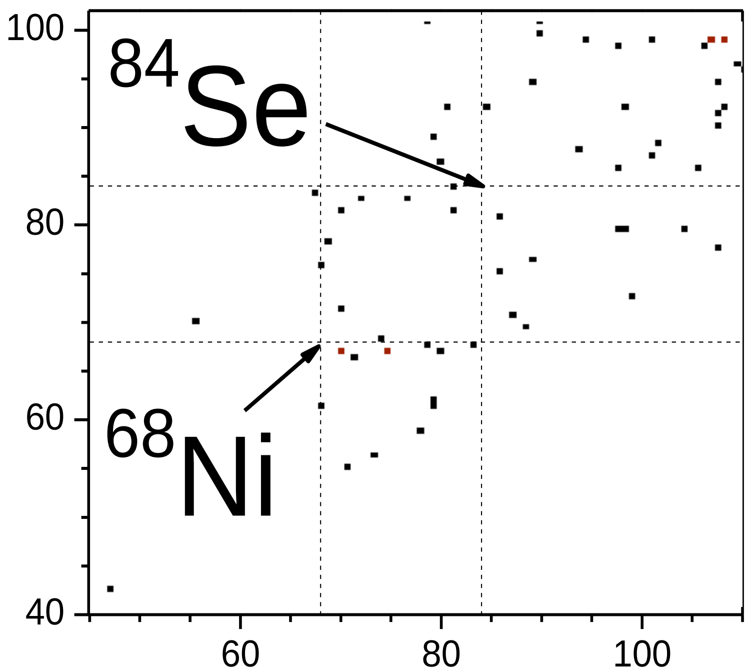
Effect is seen
in the arm from
the side of scattering
foil only.
Thus, it is due to
scattering in any cense

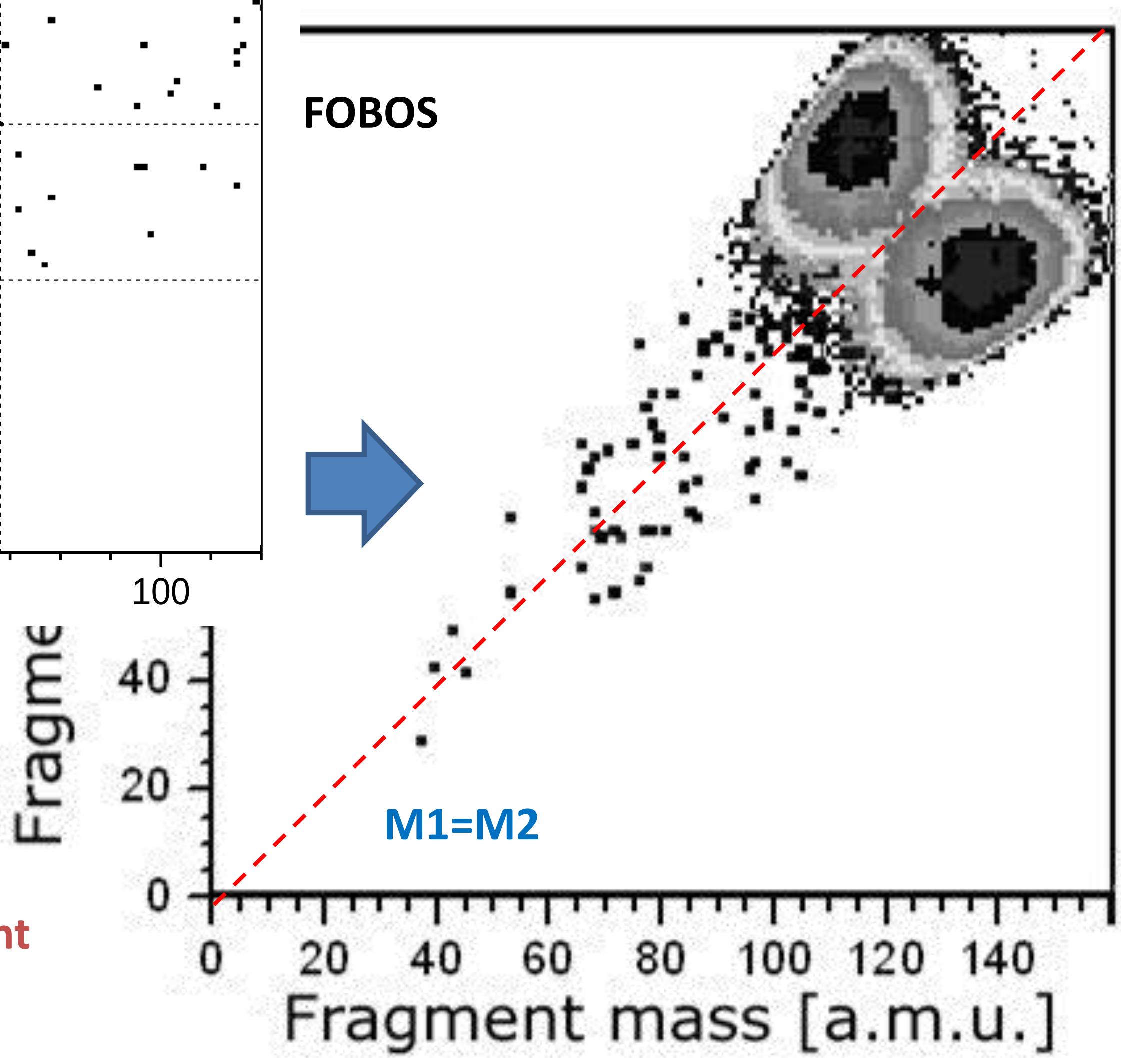
Yu. Pyatkov et al., Eur. Phys. J. A
45, 29–37 (2010)

Structures symmetric to the arms



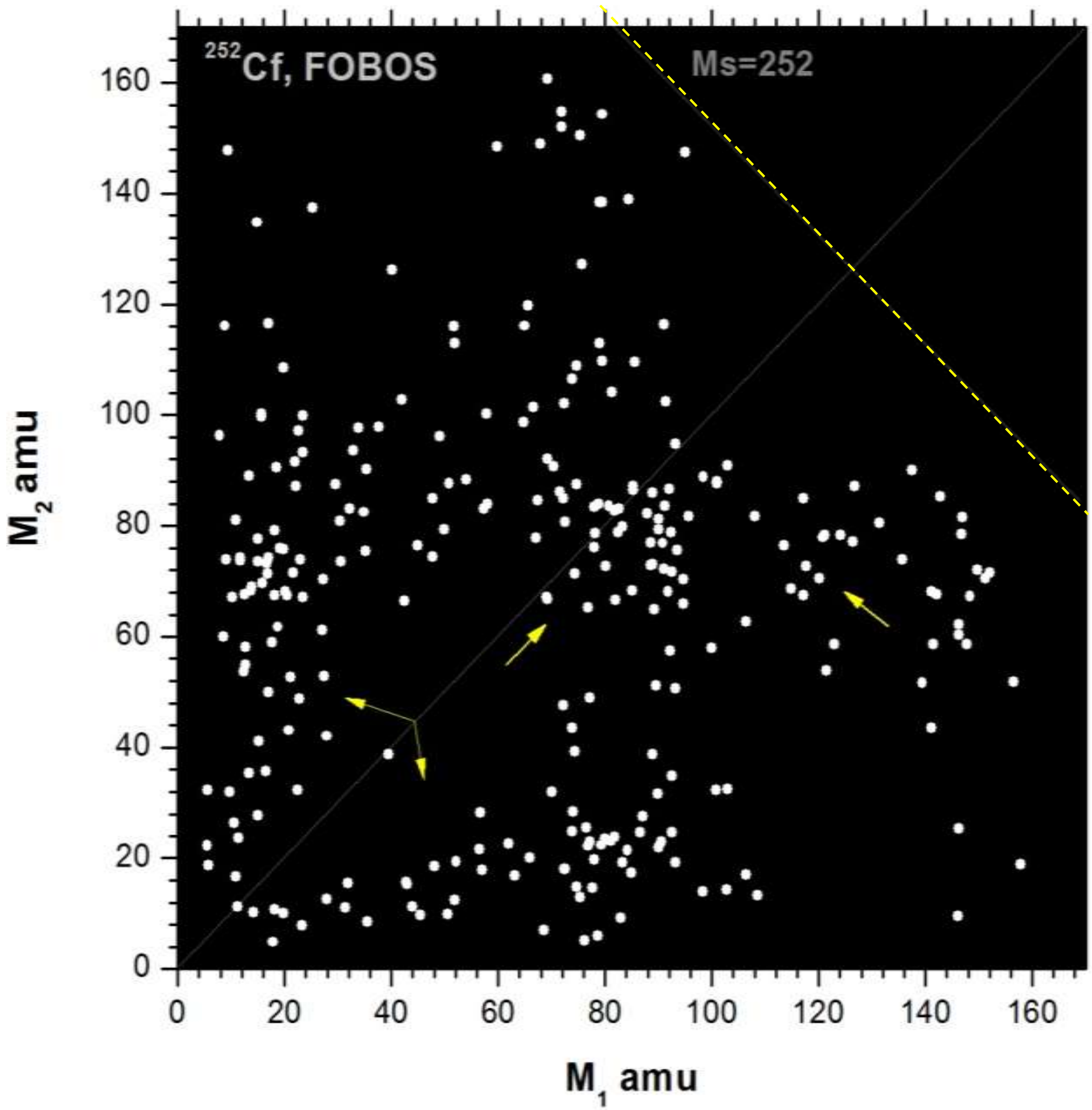
Individual modes / structures
with equal velocity/momentum window





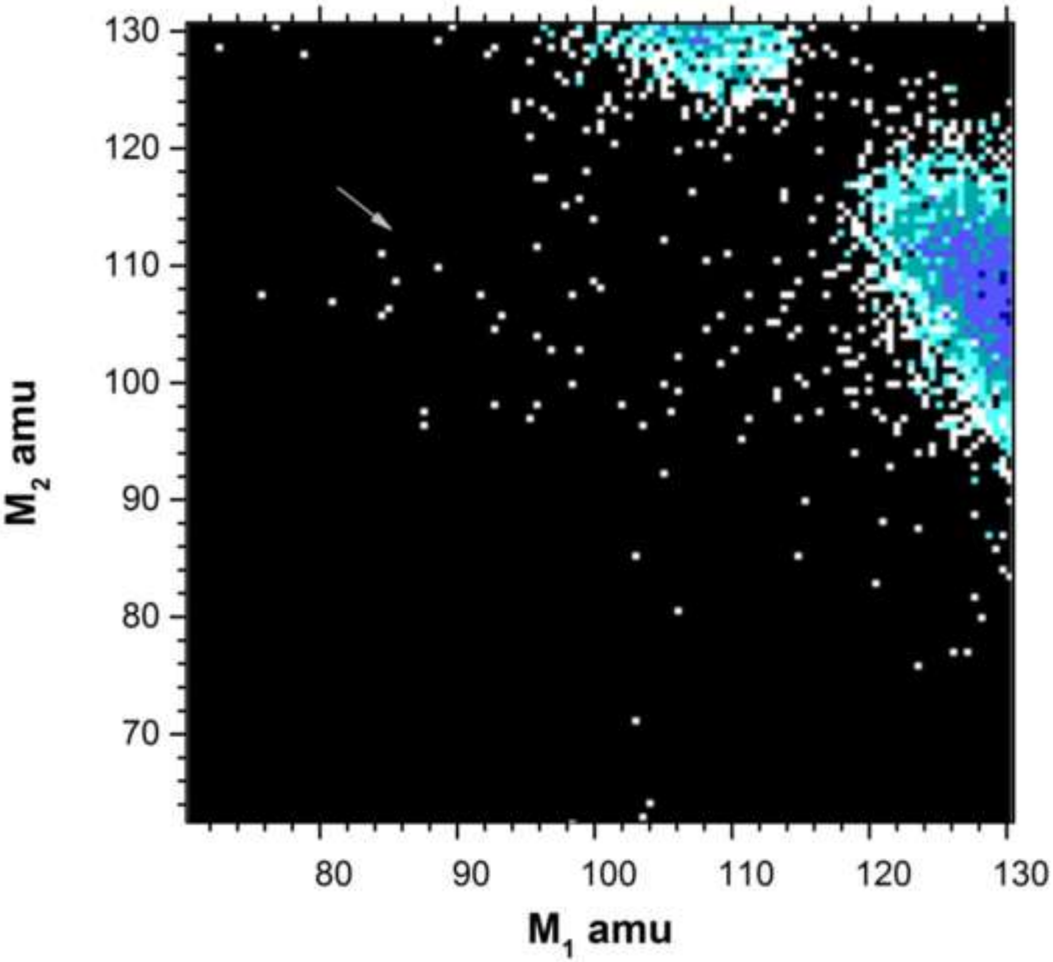
Vice versa:
structures symmetric
to the arms are independent
from the scattering

Structures symmetric to the arms

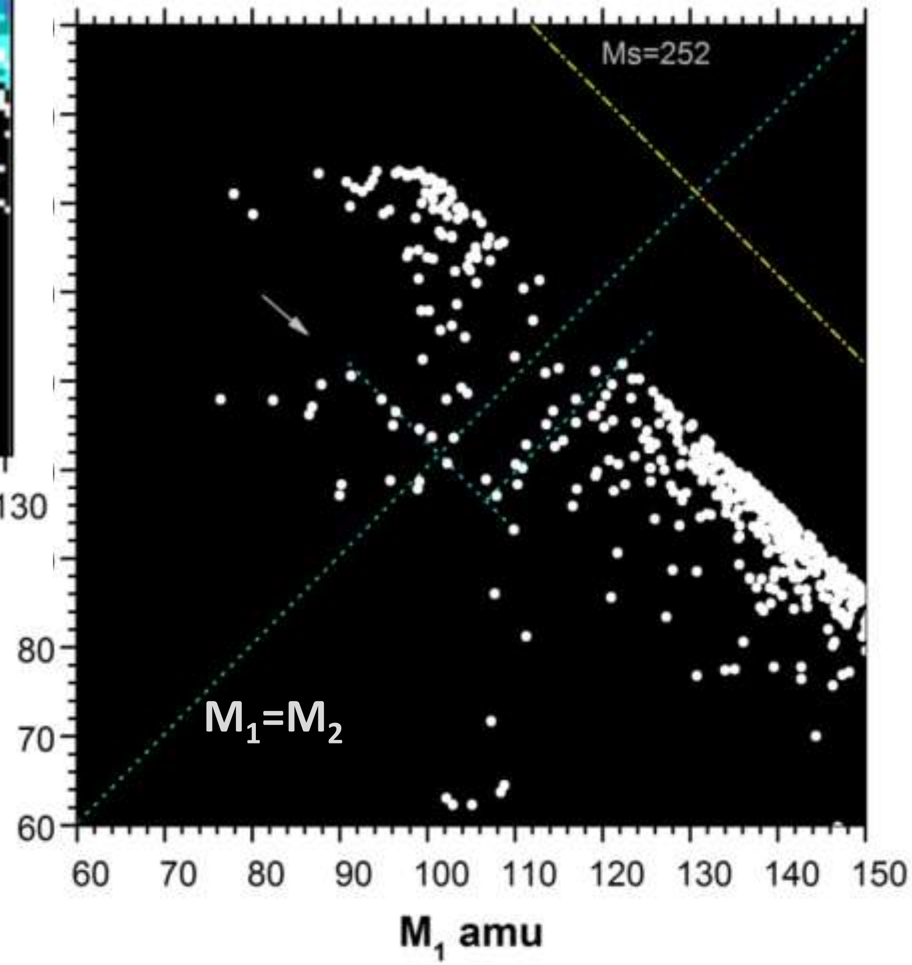


FOBOS
n=1
&
momentum
box

Structures symmetric to the arms



COMETA, Cu foil, n=1



Missing mass ~50amu

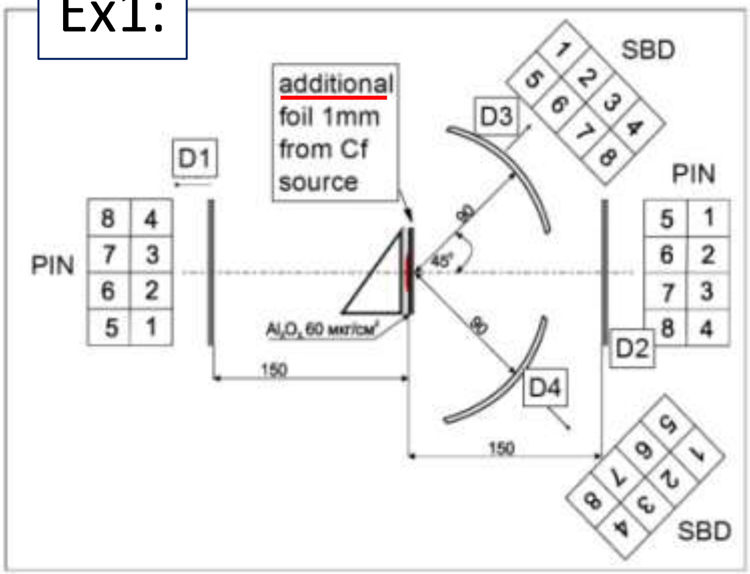
Conclusions

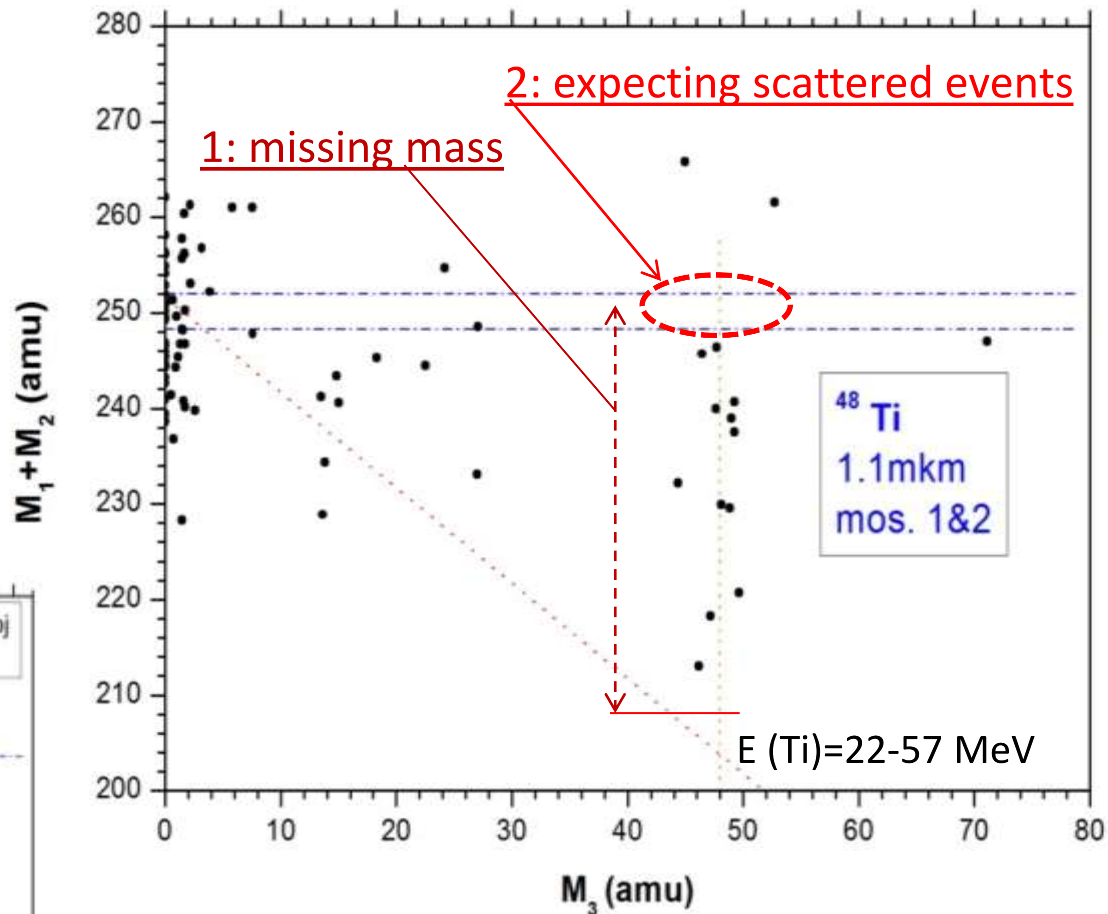
1.Now we have not find any contradictions between all our experimental data obtained and known features of conventional fission process.

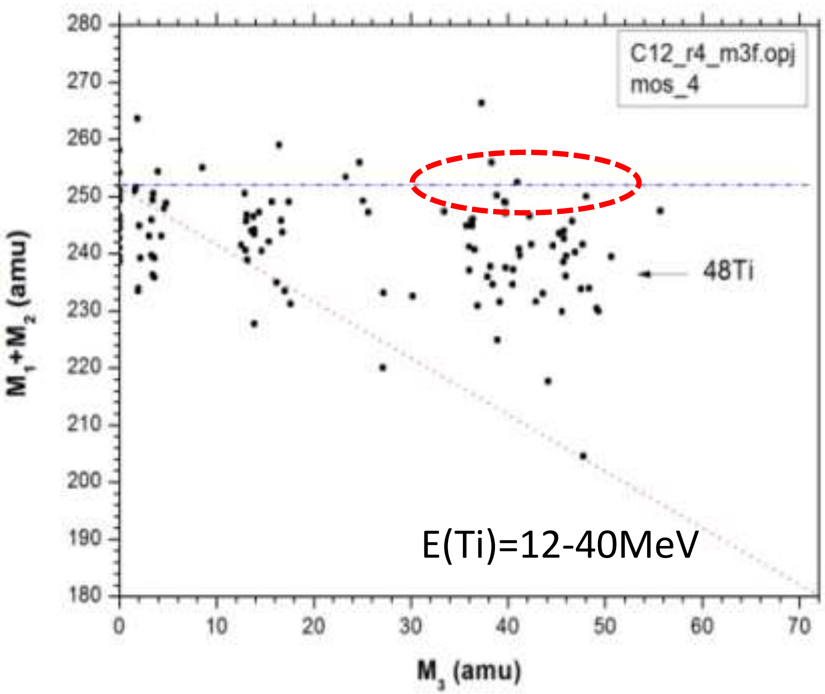
2. Studying of rare multi-body decays flashes up fundamental properties of the main process of “conventional” binary fission.

Experimental results_1

Ex1:

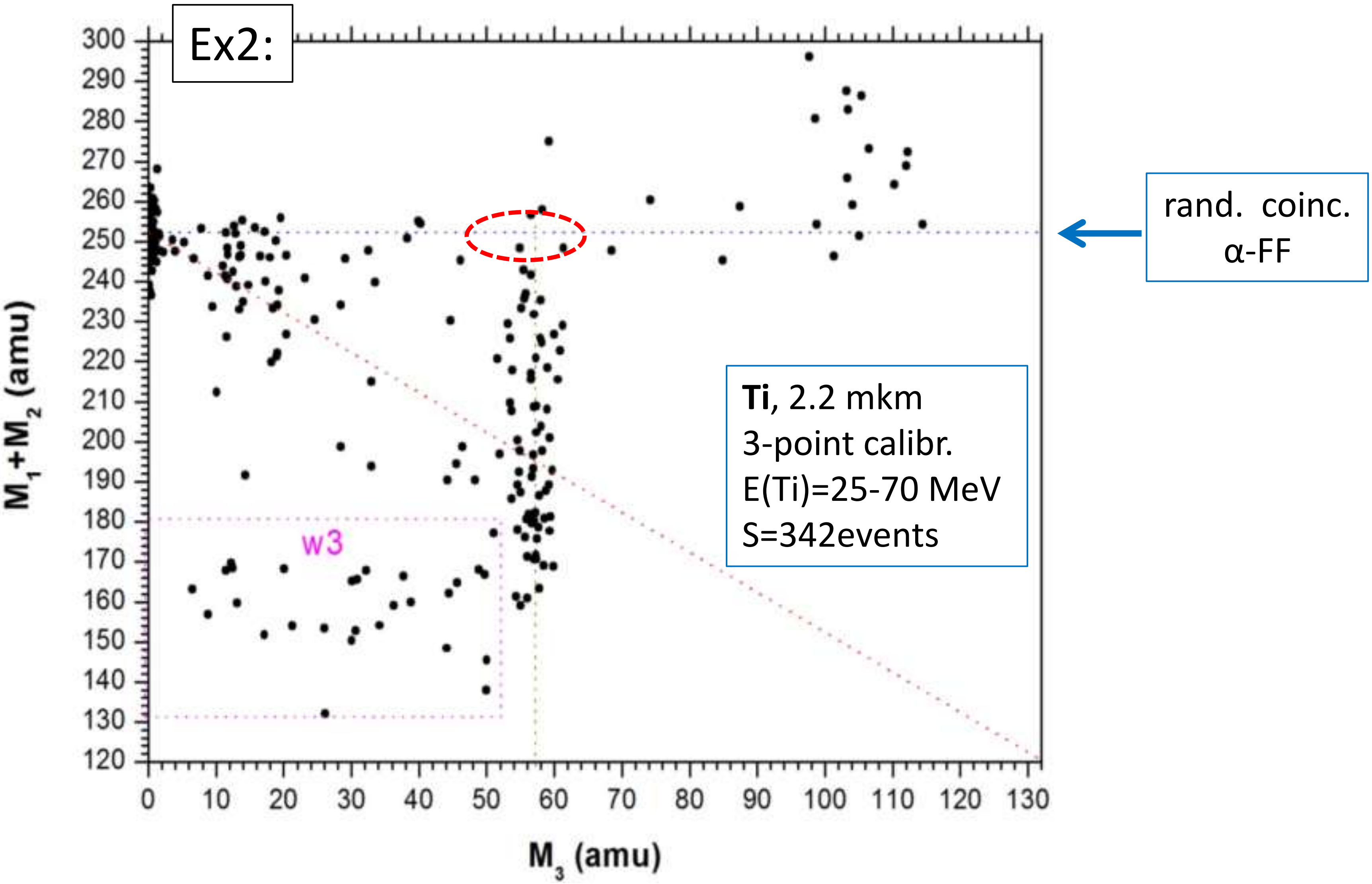






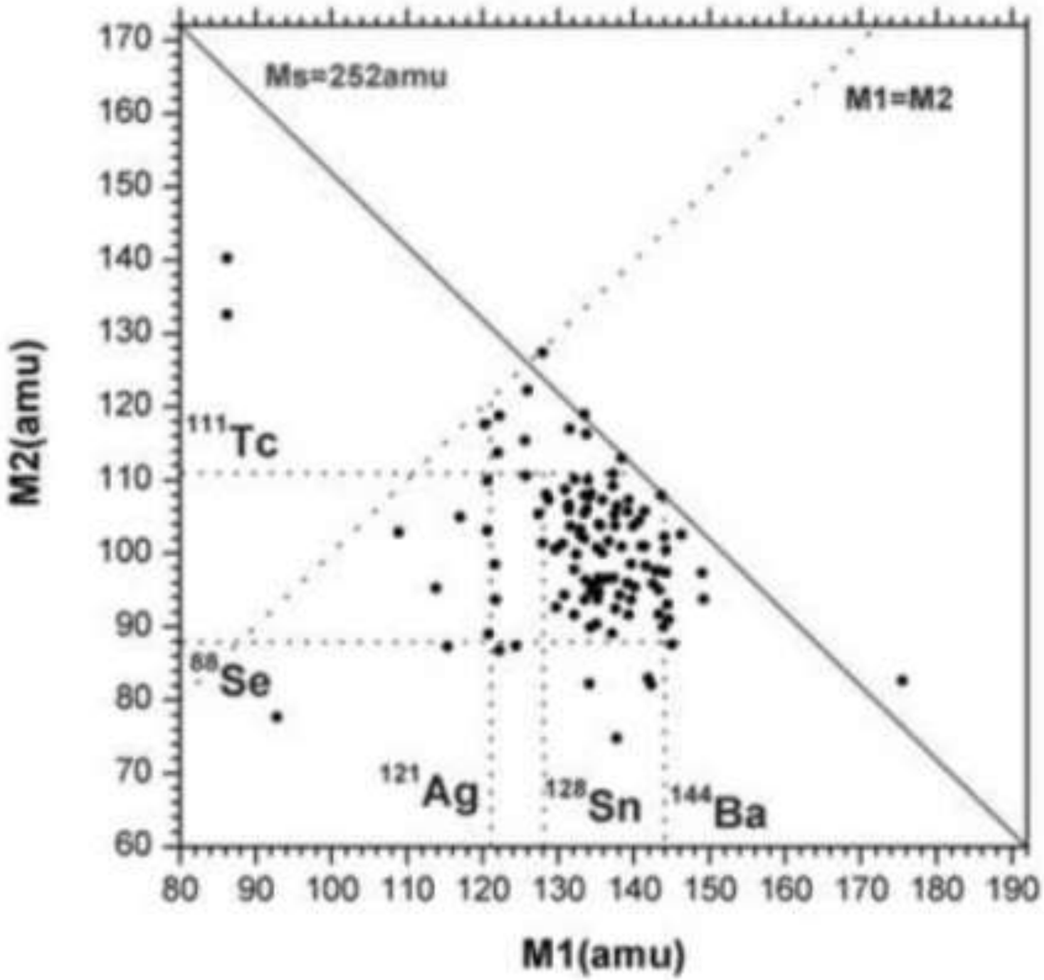
In each ternary event:
$M_1>M_2>M_3$

Experimental results_2



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

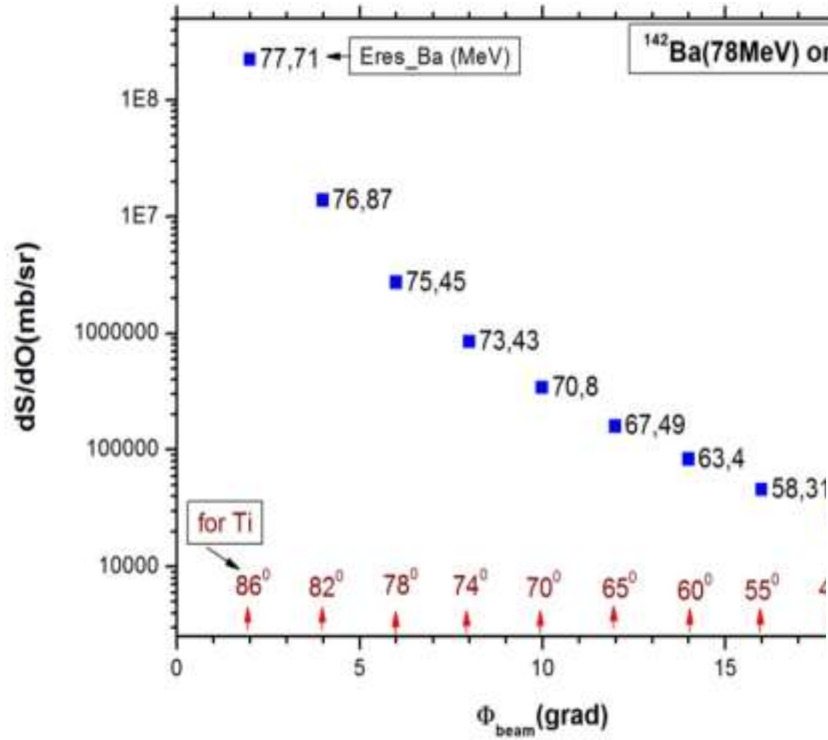
Previous experiments at the COMETA setup - only thin AL_2O_3 backing was in game

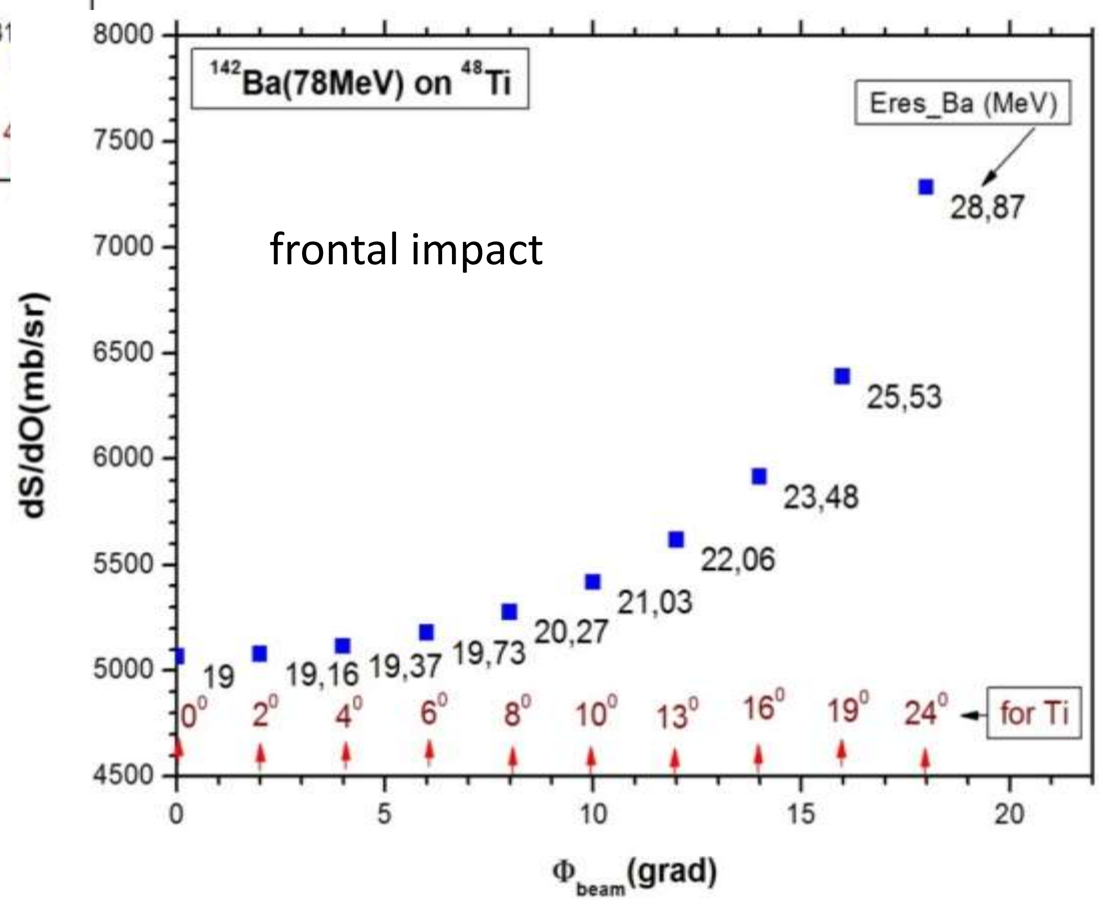


Similar structure of the M_1-M_2 plot for ternary events

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)

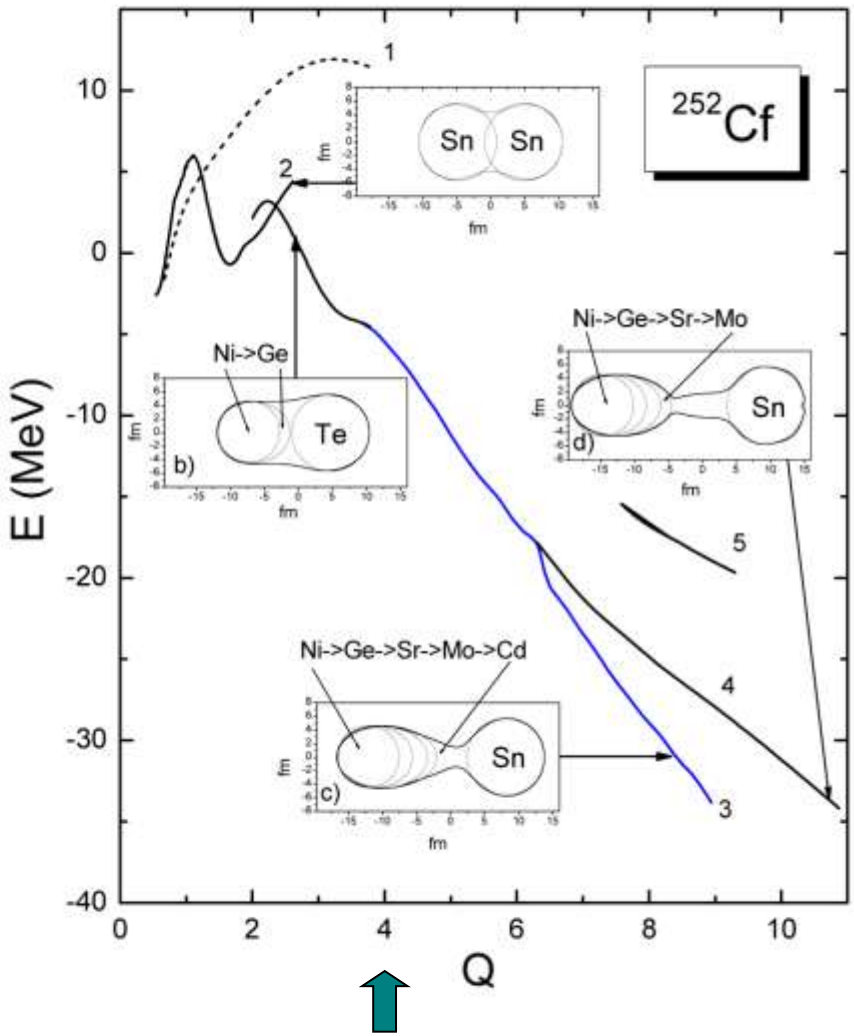
Rutherford scattering – H_FF/Ti





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:

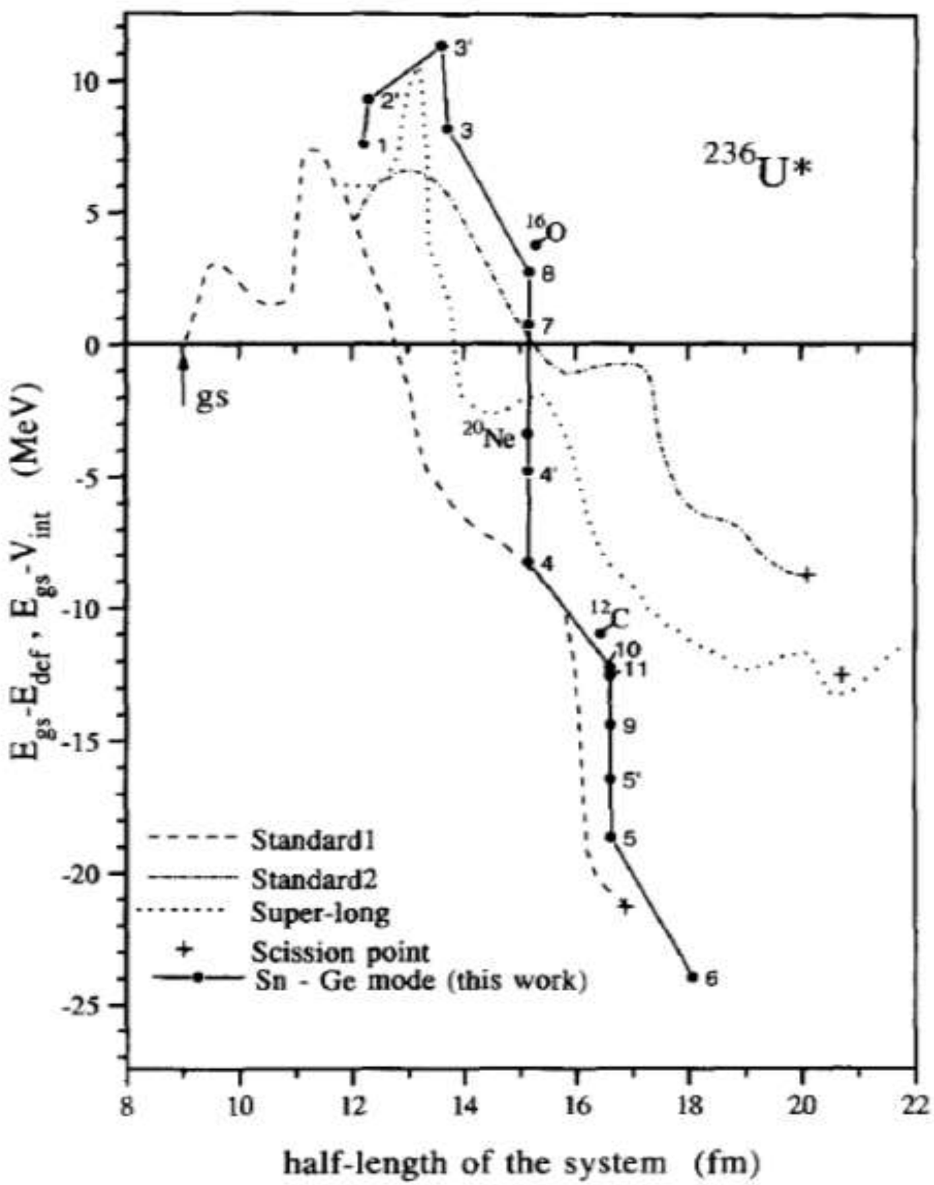
V.V. Vladimirski, JETP (USSR) 5 (1957) 673

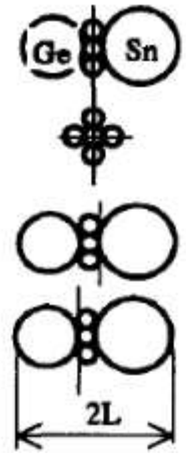
S.L. Whetstone, Phys. Rev. 114 (1959) 581

. . .

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

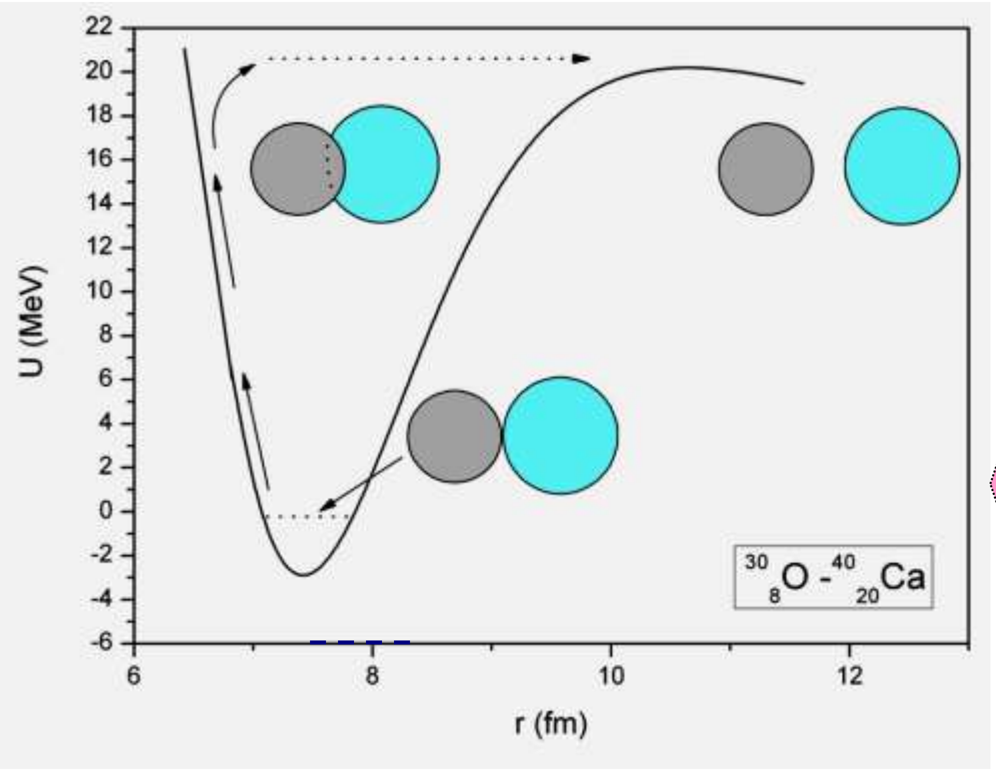
Two magic clusters namely, light & heavy give rise to fission mode while the neck is also clusterised consisting of LCP

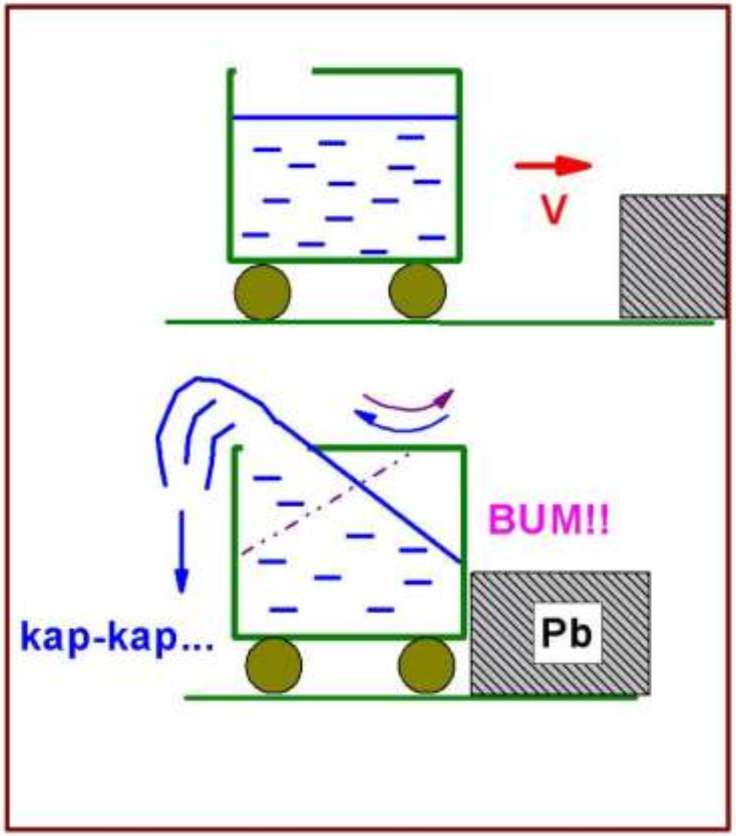
Yu.V. Pyatkov, G.G. Adamian,

N.V. Antonenko et al.,

Nucl. Phys. A 611 (1996) 355

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

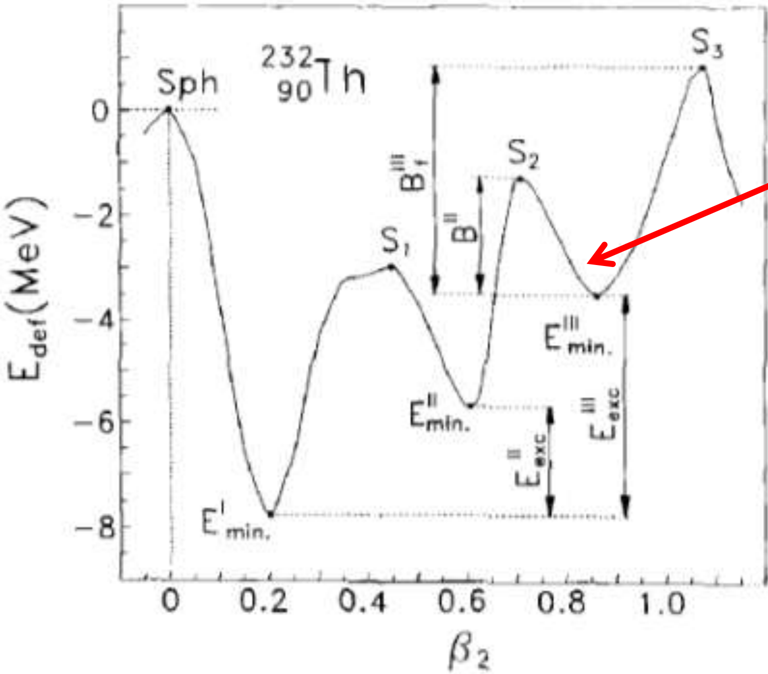
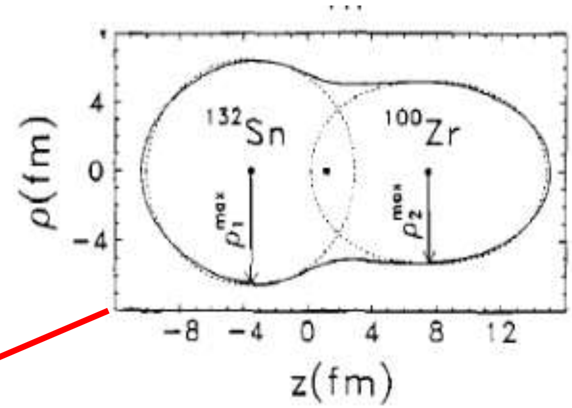


Fig. 1. Potential energy curve for ^{232}Th as a function of quadrupole deformation β_2 along the shorter static fission path of fig. 2.



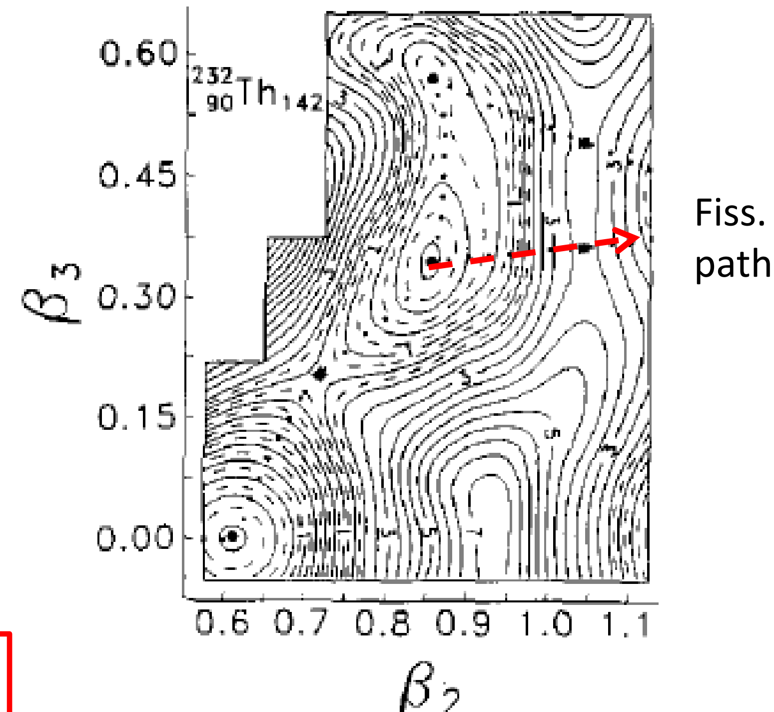
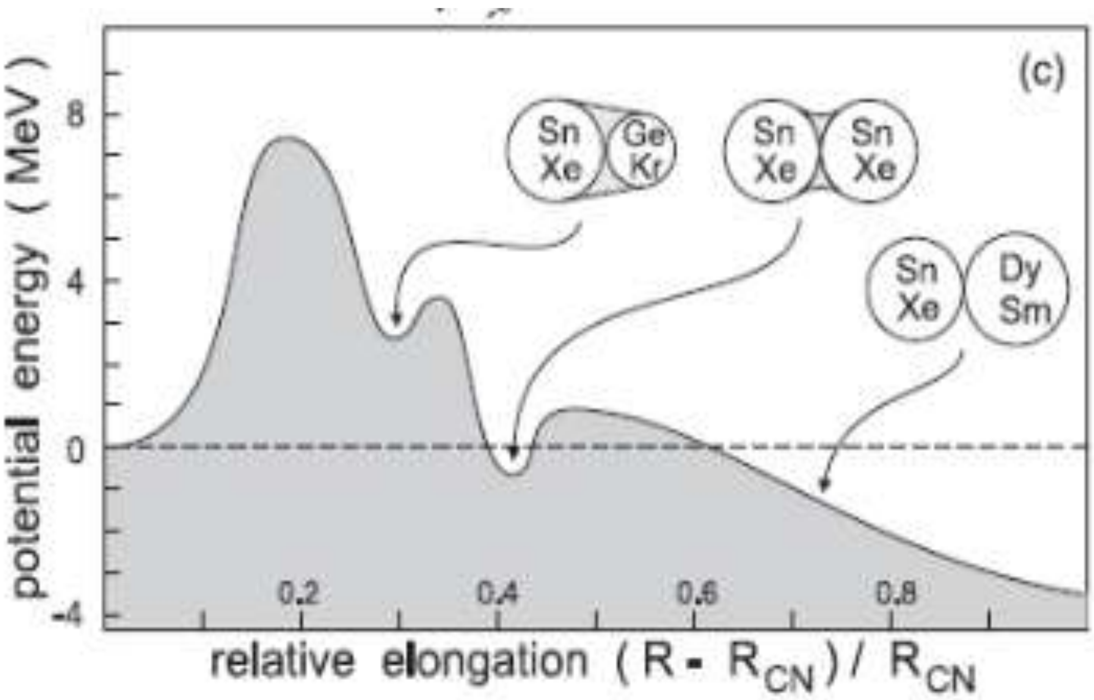


Fig. 2. The Woods–Saxon–Strutinsky total potential energy (relative to the spherical macroscopic energy) for ^{220}Rn, ^{222}Ra, ^{232}Th, and ^{234}U, as a function of β_2 and β_3. At each (β_2, β_3) point the energy was minimized with respect to β_4–β_7. The distance between the solid contour lines 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).



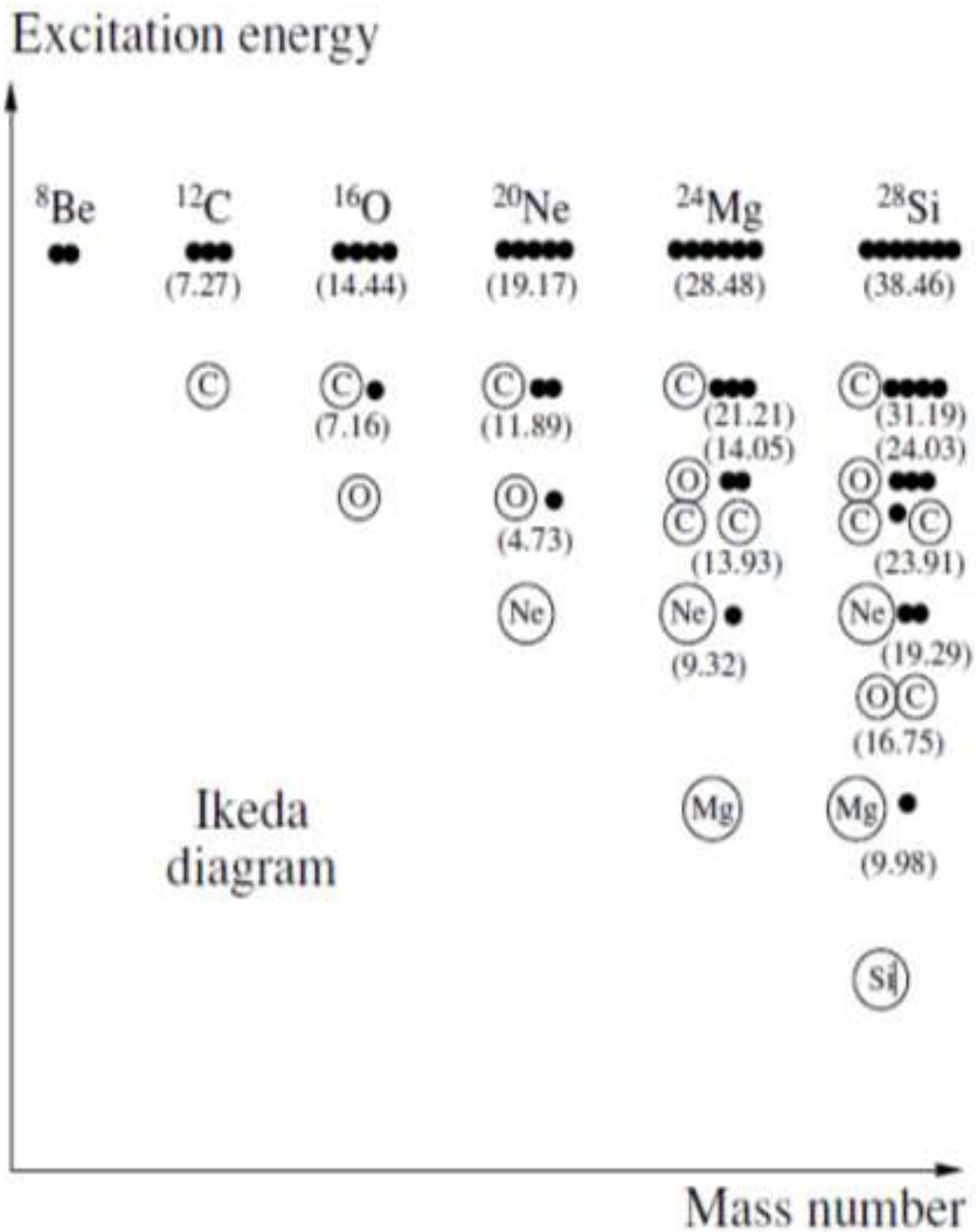
Three-humped barrier calculated along the fission path of $^{296}{}_{116}Lv$ (Livermorium).

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

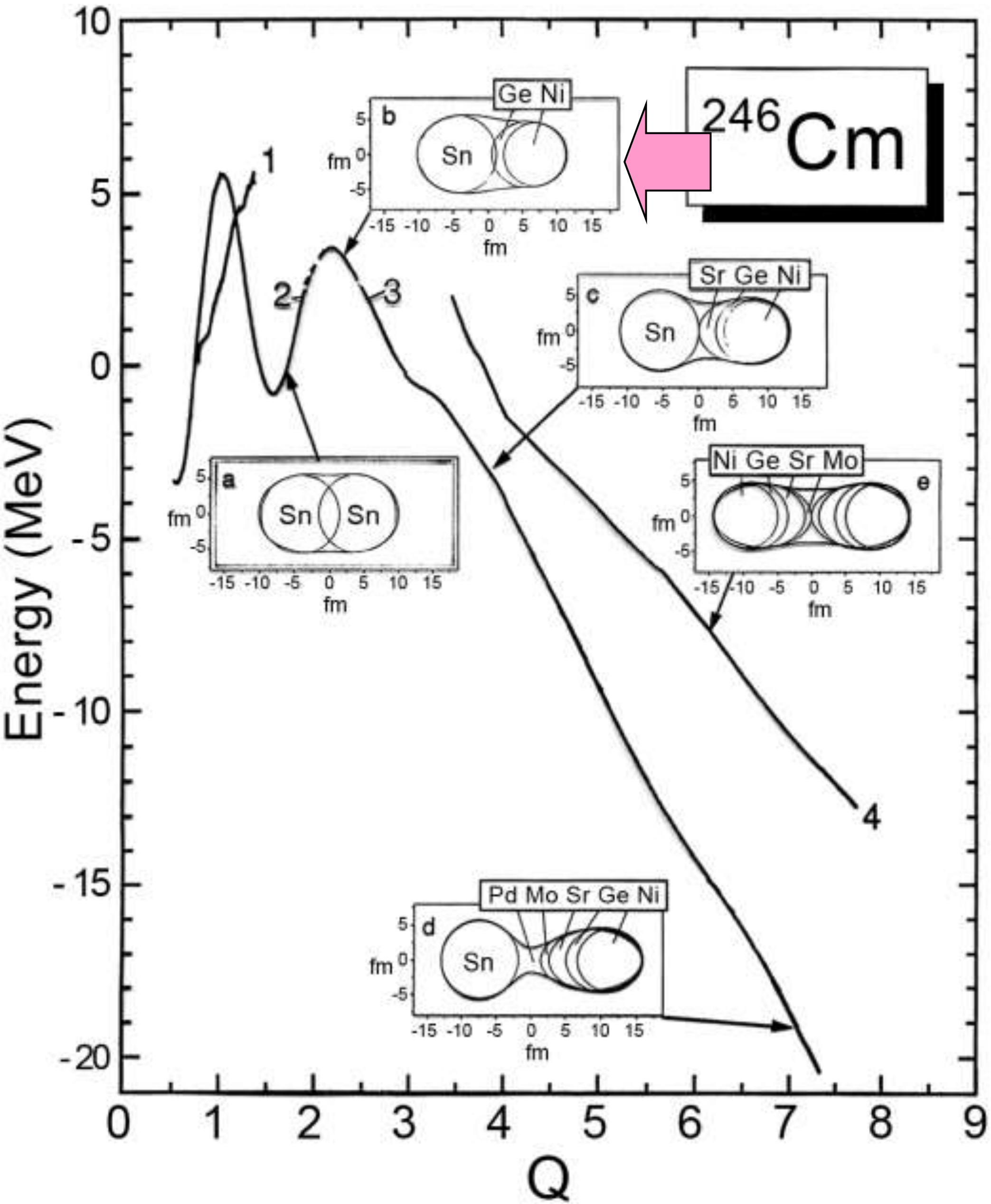
SIS in super-heavy nuclei

"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."



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

Calculated Fission Valleys (^{246}Cm)



Valley of the mass-asymmetrical shapes

Valley of the mass-symmetrical shapes

V. V. Pashkevich et al.

Known calculations

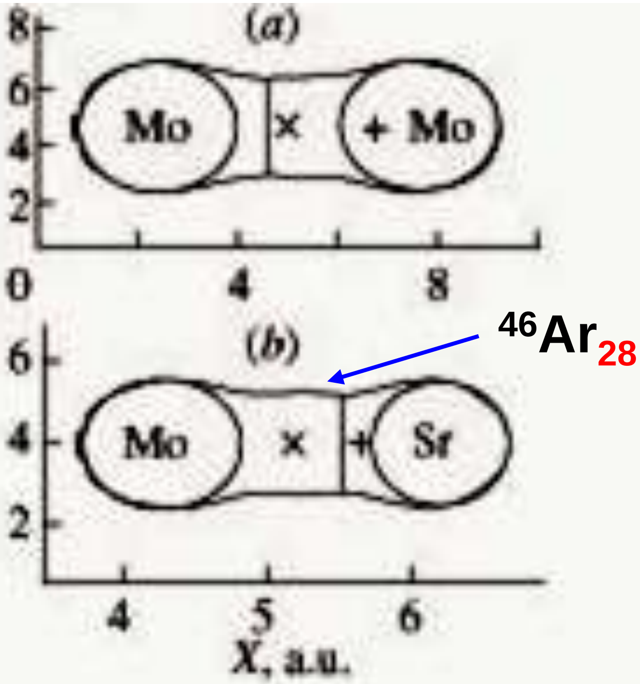
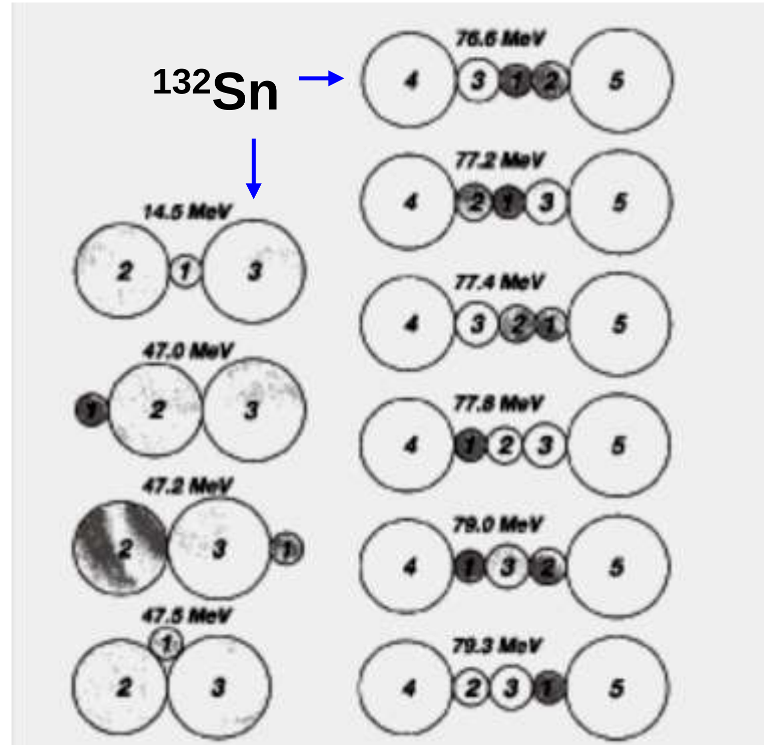


Fig. 7. The shape of the nucleus at the bottom of the "symmetric" valley ($Q_2 = 7.52$ a.u., $\eta = 0.074$) (a); the same system at the point $Q_2 = 7.52$ a.u., $\eta = -0.208$ (b).

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