27-th International Seminar
on Interaction of Neutrons with Nuclei
JINR, Dubna, June 10-14, 2018

TRUE QUATERNARY FISSION CHANNEL IN $^{235}U(n_{th}, f)$ REACTION

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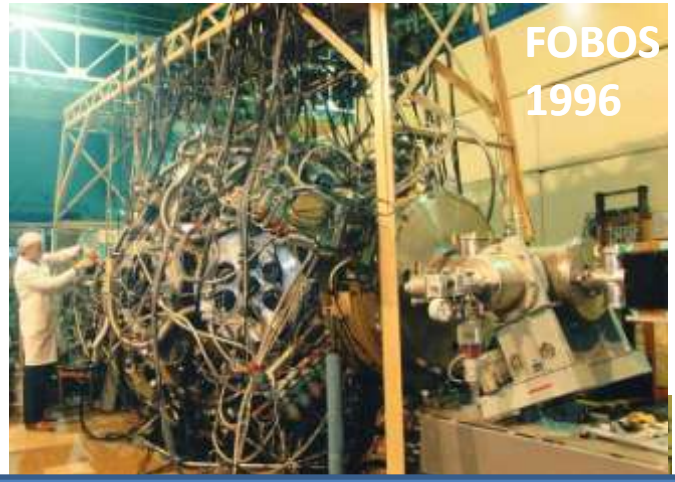
International support

Special thanks to the organizers: Tracking CCT progress from ISINN to ISINN



ISINN #

10 - first neutron-gated data with FOBOS

…..

13 – proposal for the exp @ IBR-2

14 – status of the exp in the cave 6b

15 – preliminary results

16 – detailed report

17 – triple correlations from ^{232}Th+d

18 – COMETA progress report (posters)

19 – first & interesting COMETA data

20 – first CCT physics & Ion Guide proposal

21 – first indications of shape isomers in FF

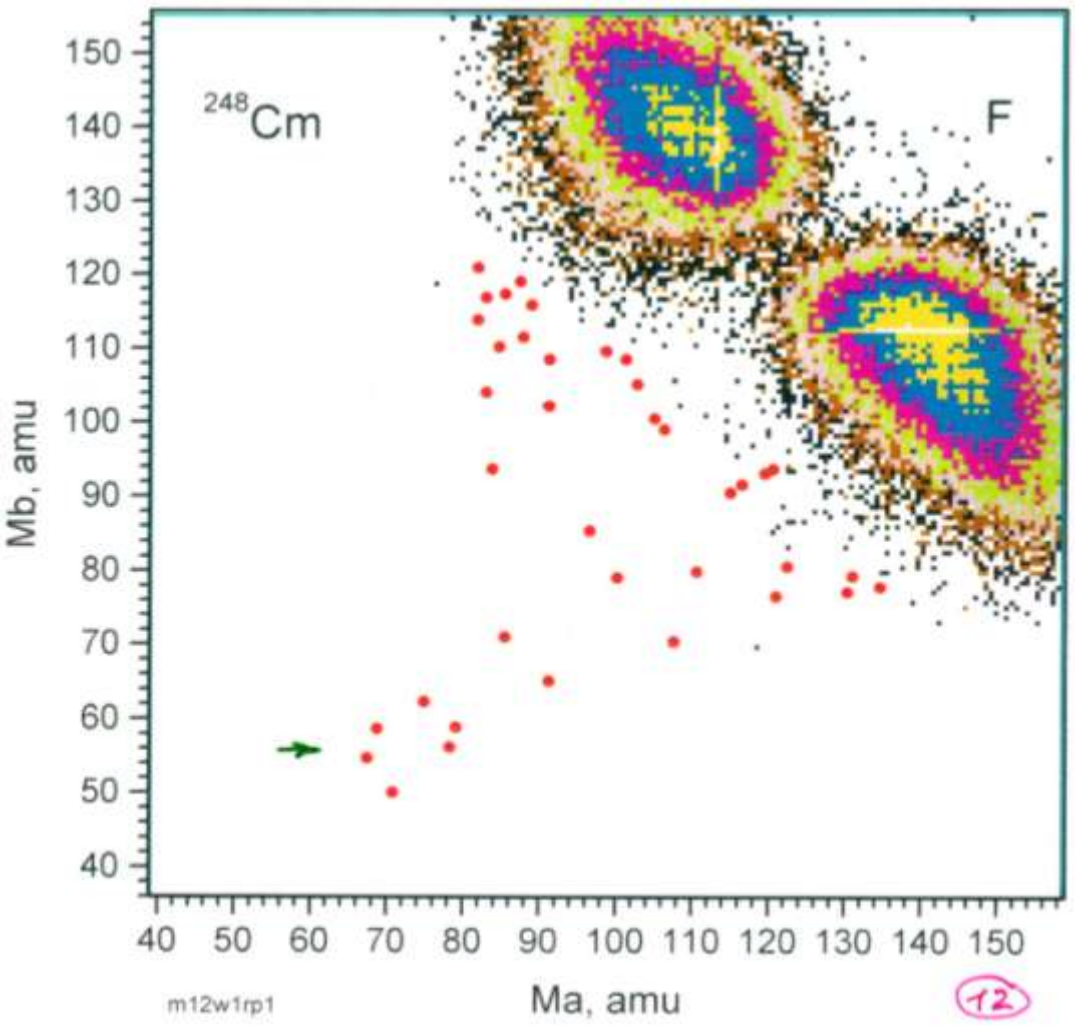
22 – new results on shape isomers in wide range

23 – first “flash”-data

25 – understanding the results and feeding theoretical discussion

26 – behind the Great Chinese Wall

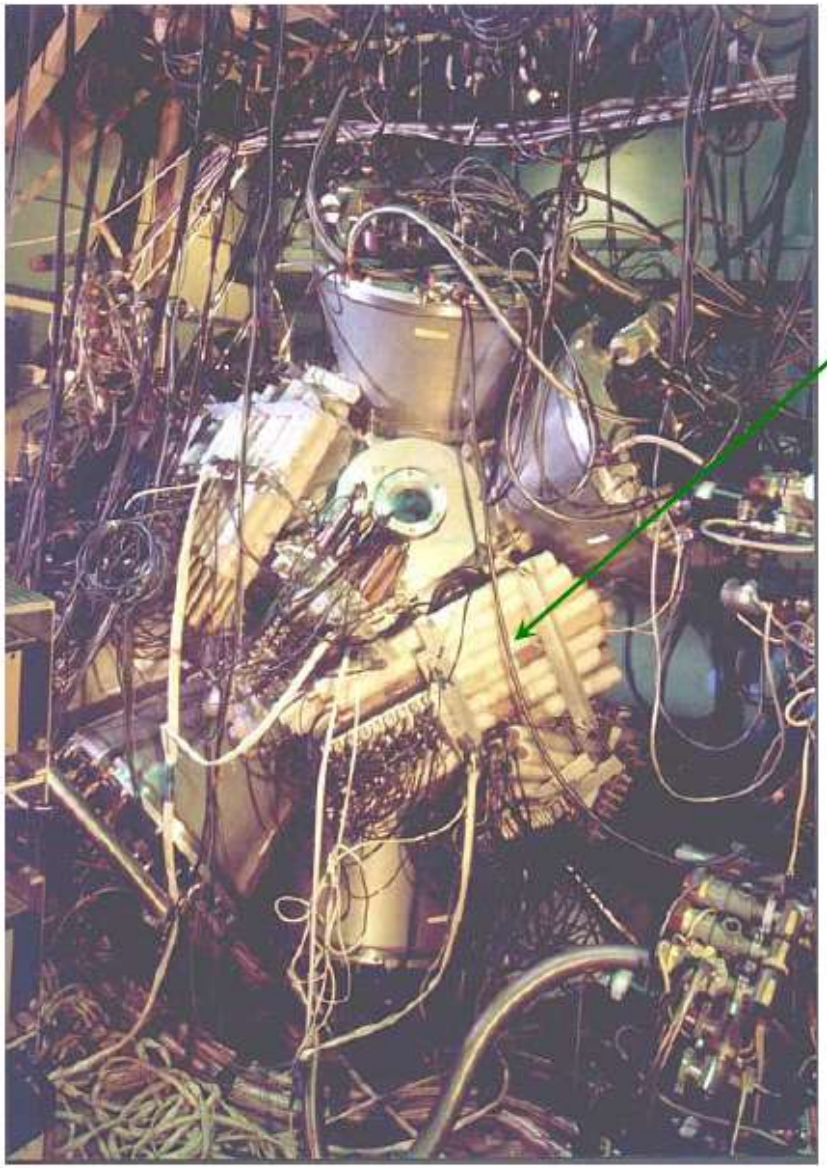
The question at our starting point: $^{246}Cm \rightarrow 3^{82}Ge$?



Experiment was performed in the year of ISINN-4

Modification of experimental setup

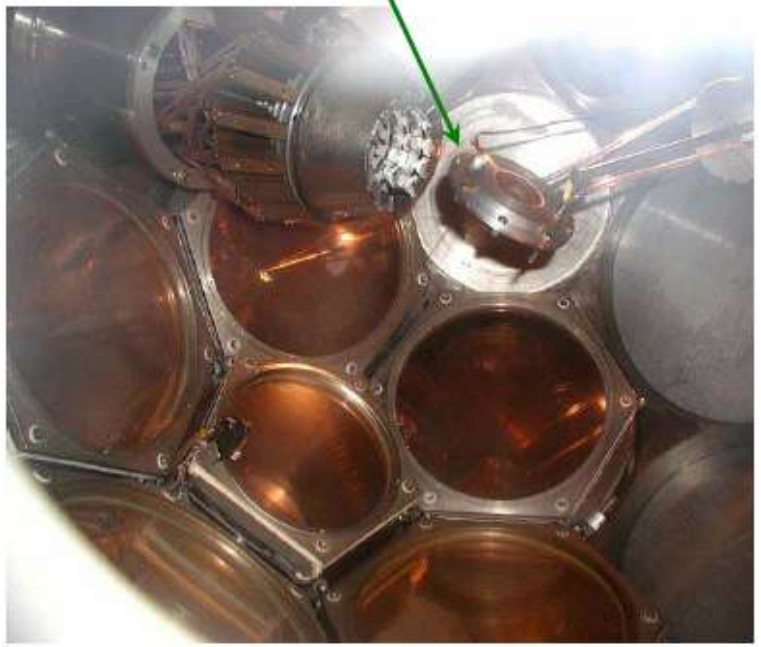
missing mass approach, Z -sensitive variables &
experimental neutron multiplicity ν_{exp} for selection of the CCT events



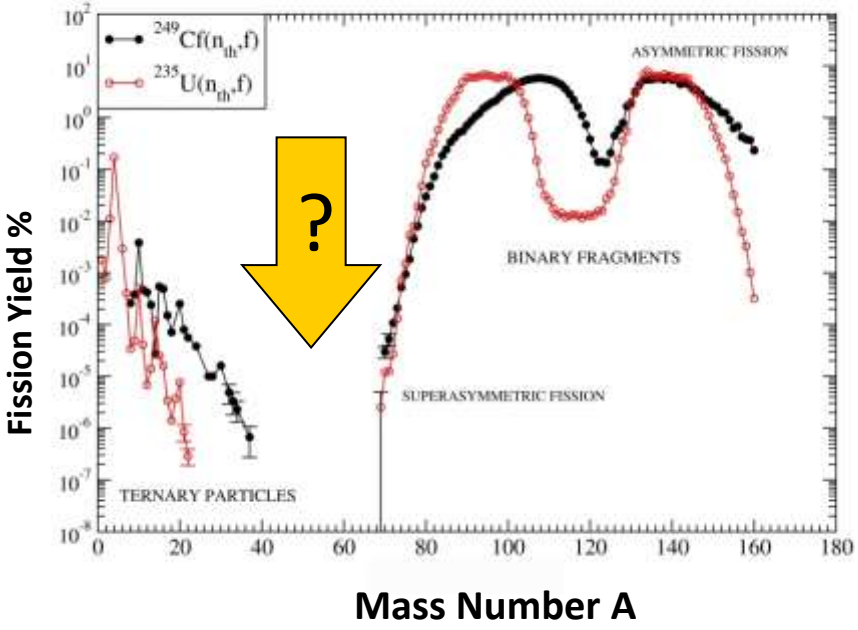
Double arm spectrometer
6+6 modules

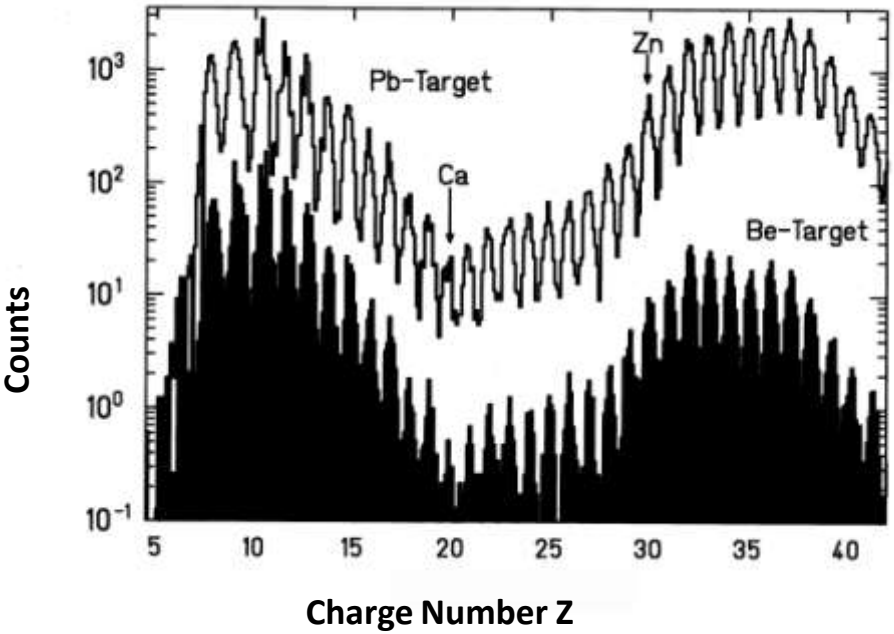
Neutron belt of FOBOS
140 ^{3}He (7 bar) conuters
In PE-moderator

Start PAC
with internal ^{252}Cf source



Filling the Gap between Ternary and Superasymmetric Fission





ILL Data Grenoble

Thermal neutron induced fission

Lohengrin Separator

F. Gönnenwein, Nucl. Phys. A 734 (2004) 213

GSI Data Darmstadt

750 AMeV ^{238}U beam, FRS separator

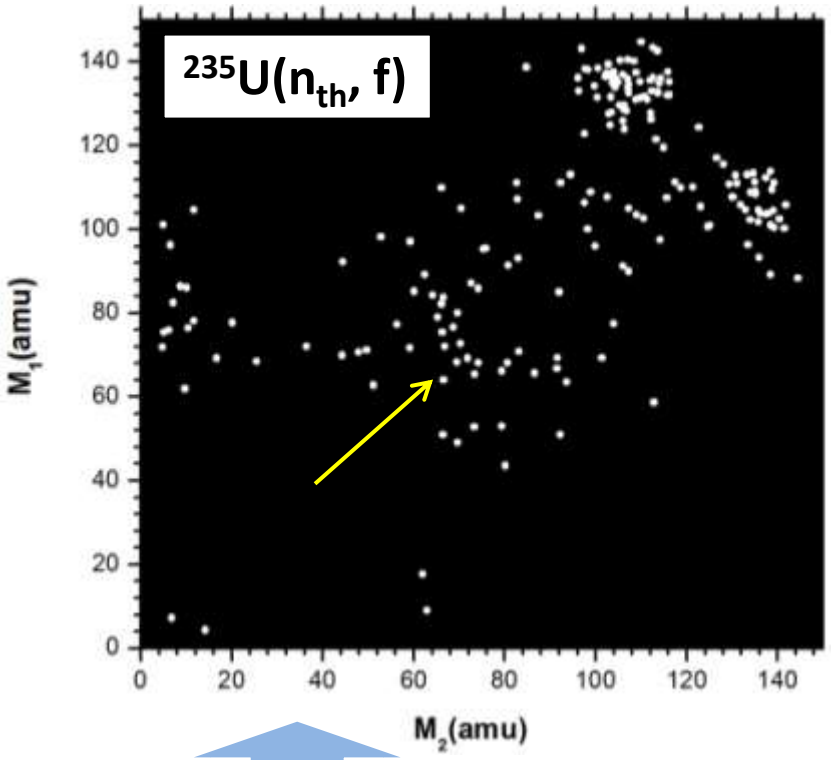
Be-Target: nuclear excitation (≈ 27 MeV)

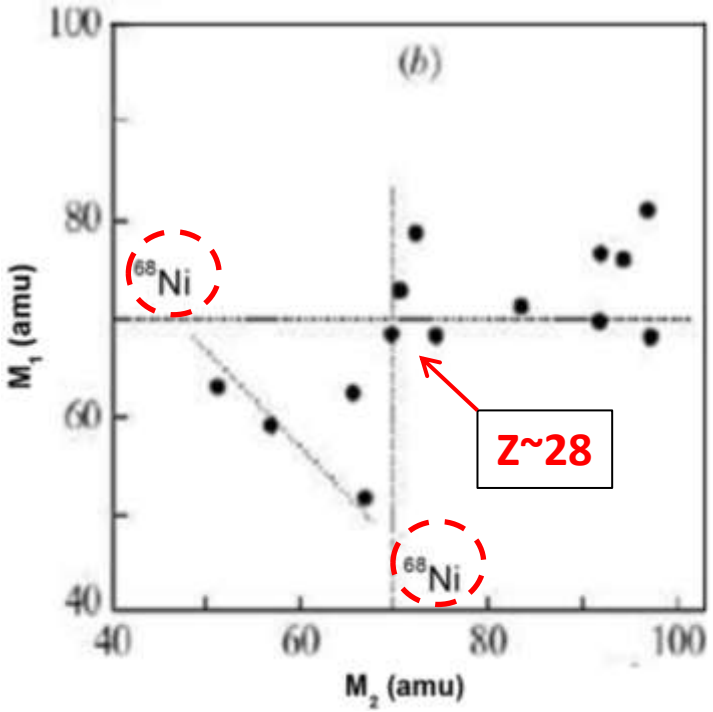
Pb-Target: electromagnetic excitation (≈ 11 MeV)

C. Engelmann, thesis, 1998 (supervisor F. Goennenwein)

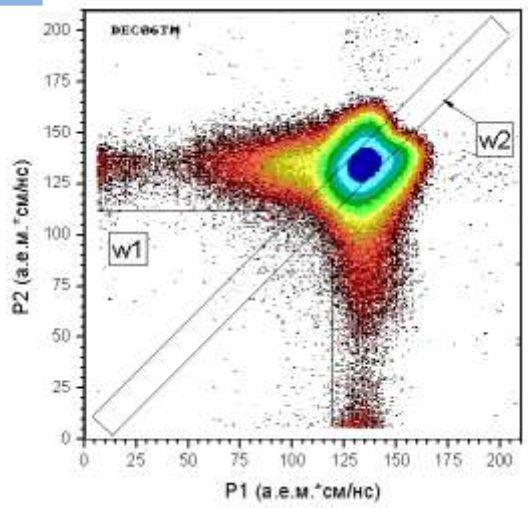
Symmetric Kinematics and charge symmetry in U data

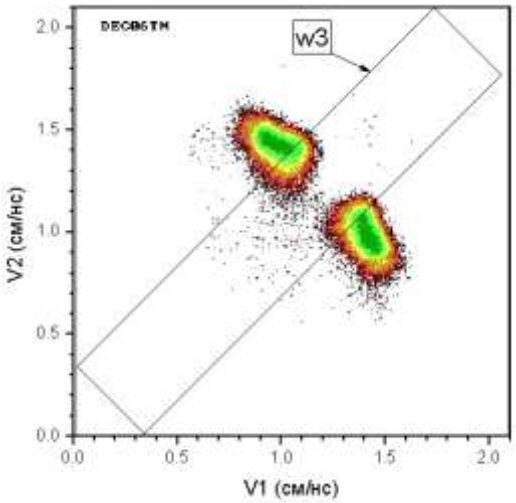
Ex2





P1~ P2
V1~ V2
Z1~Z2

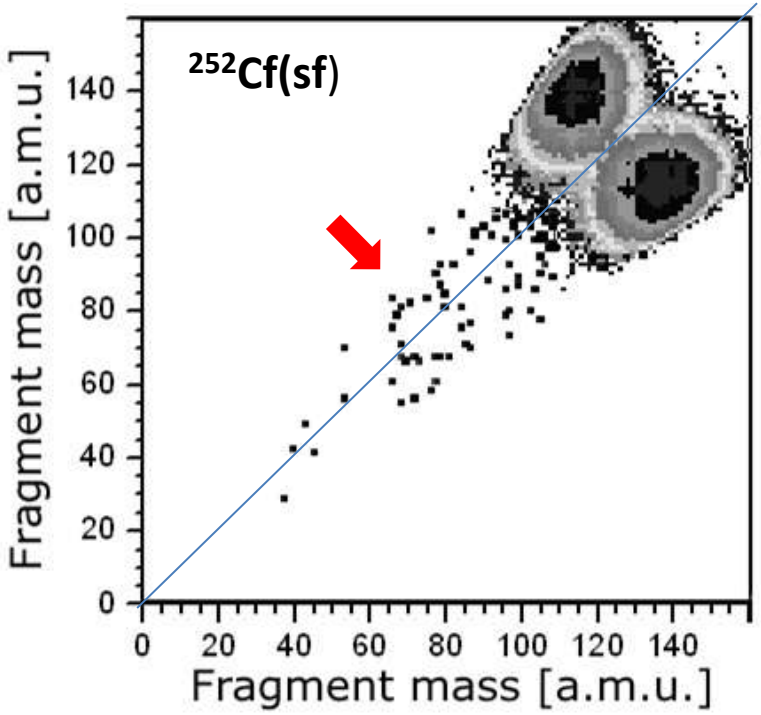


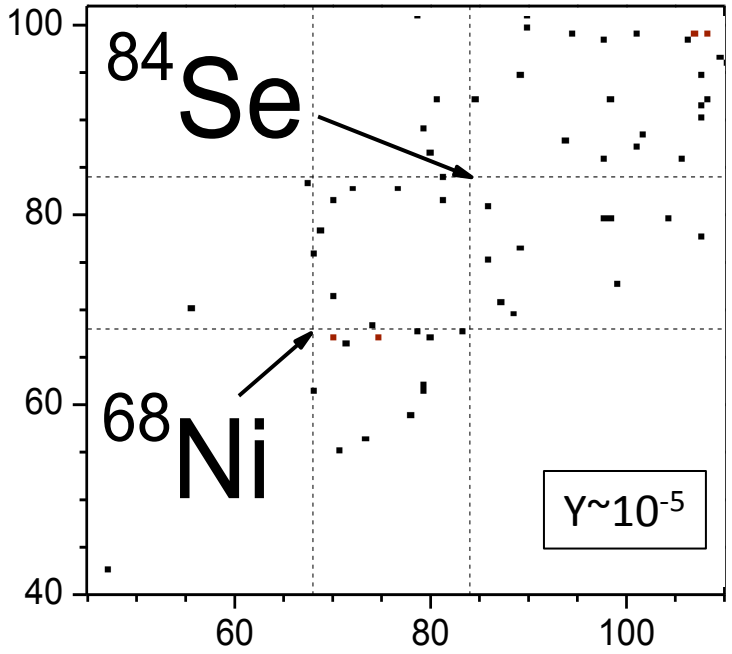


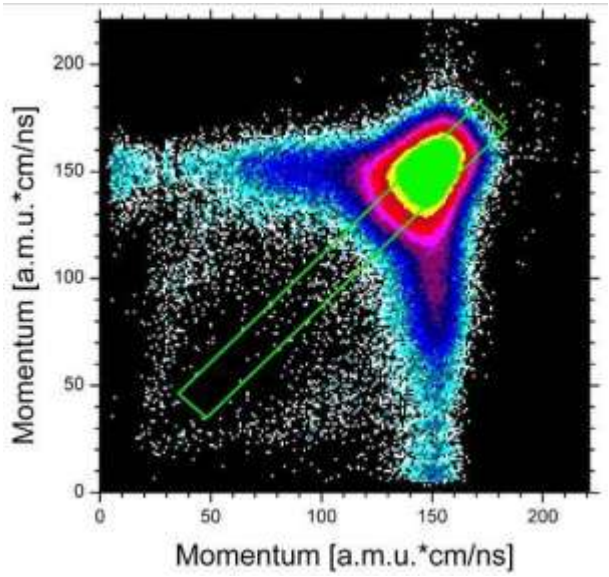
selection windows P1~P2 & V1~V2

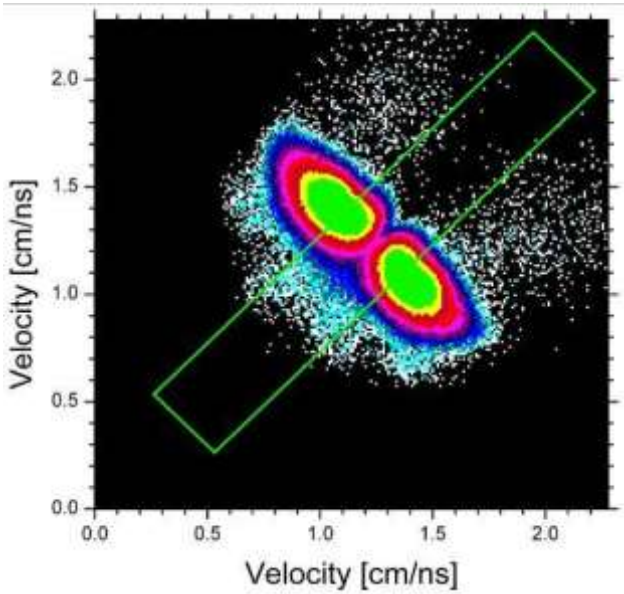
Symmetric Kinematics in Cf data – “Ni square”

Ex1





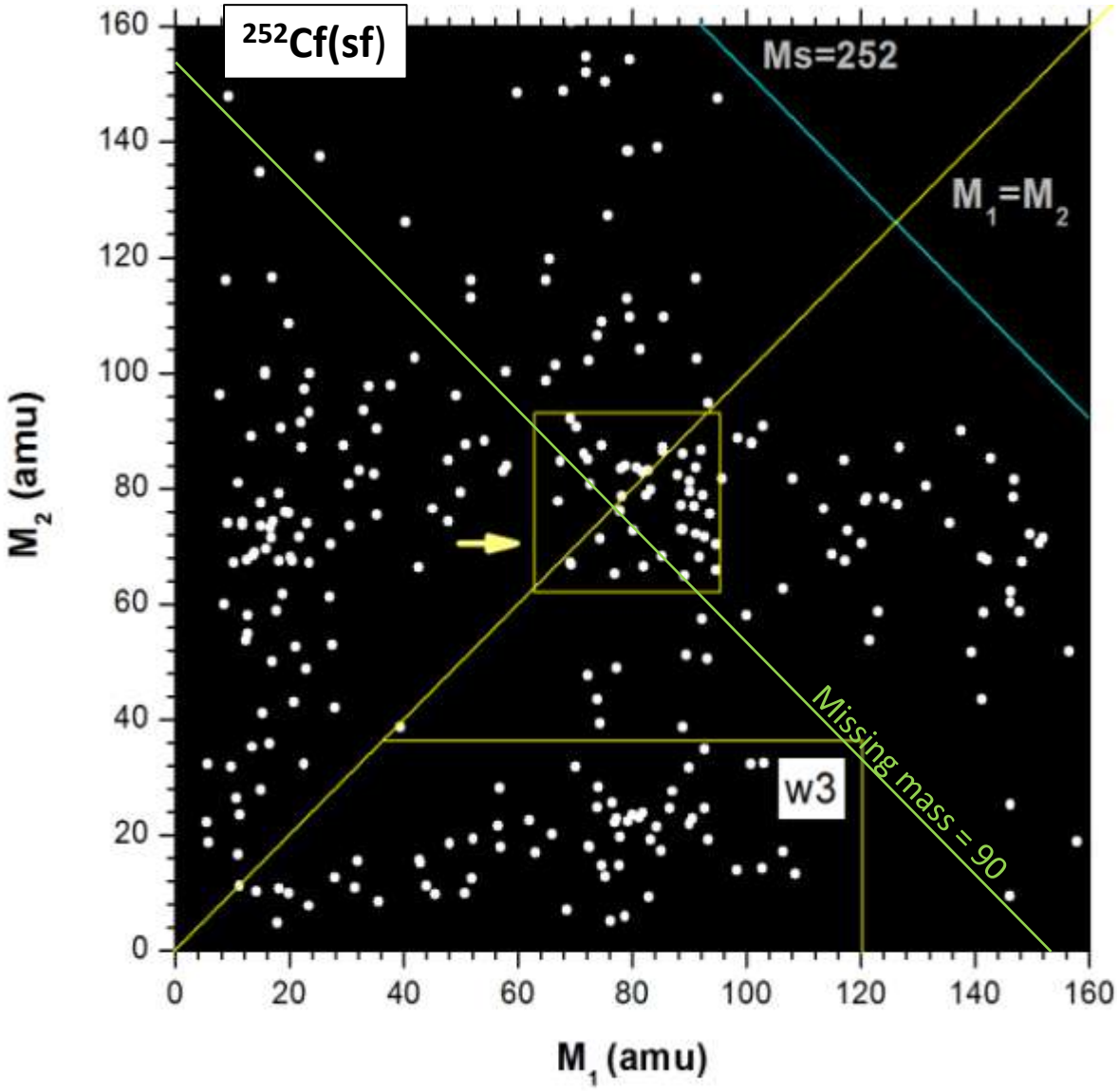




selection windows
P1~P2 & V1~V2

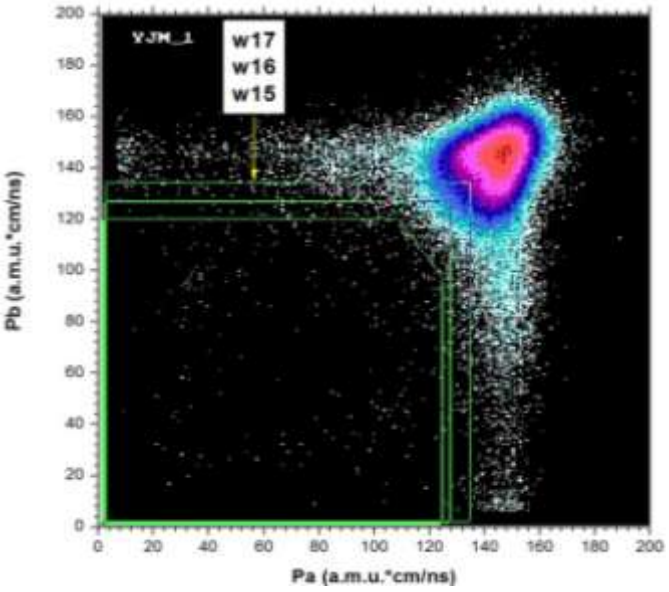
Ex1

Neutron gated data with large missing mass: populated “Ni-square”



w15 & n=1
more than 1 neutrons were detected

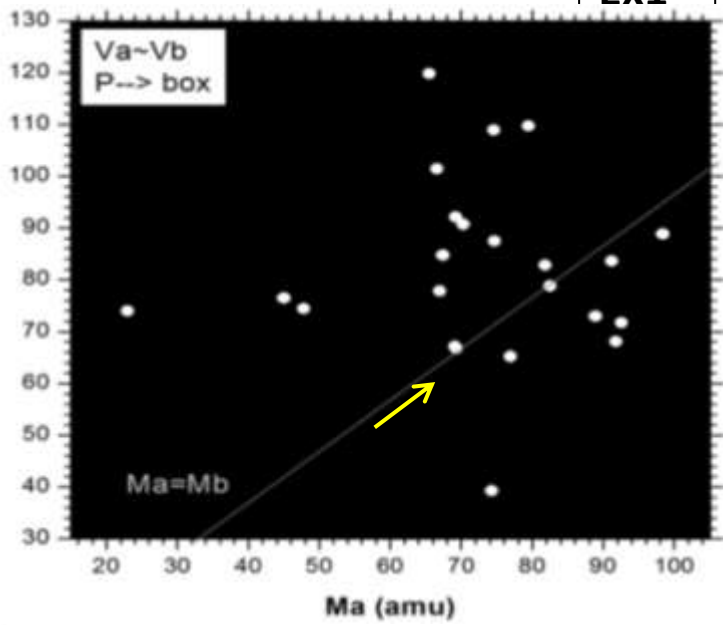
Scattering-free gate

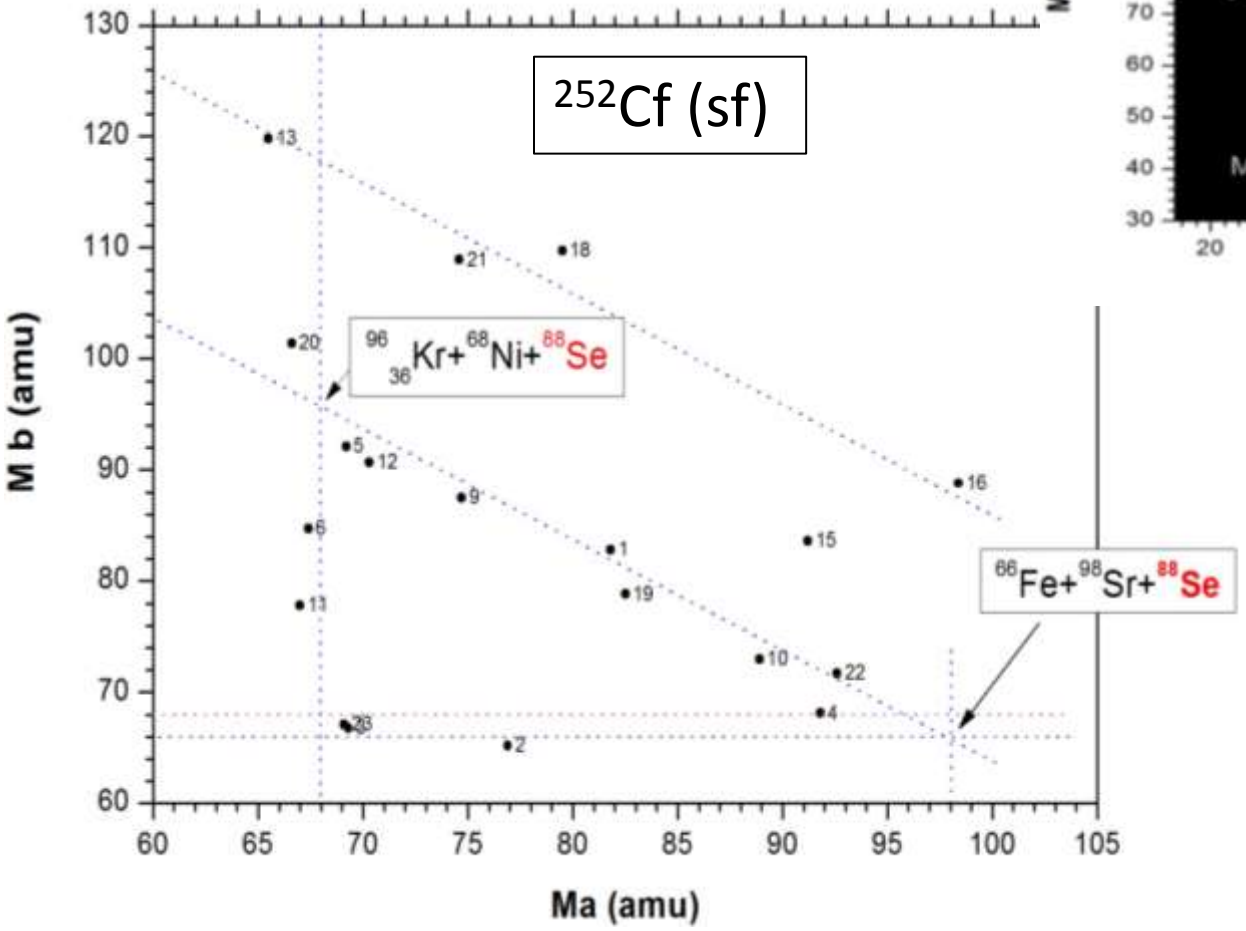


Mystery of missing selenium

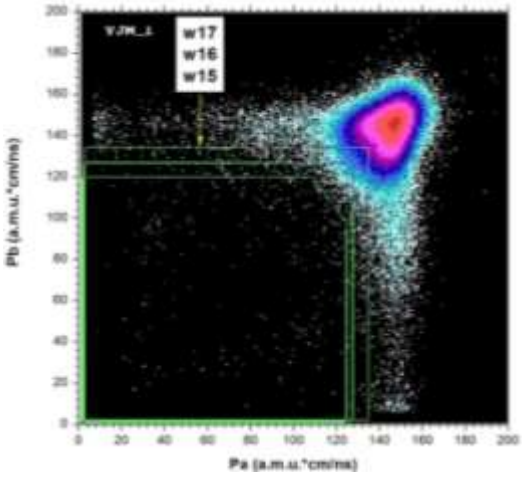
Ex1

Event-by-event analysis of the kinematics does not provide valid ternary configuration . More complicated picture should be assumed – quaternary process

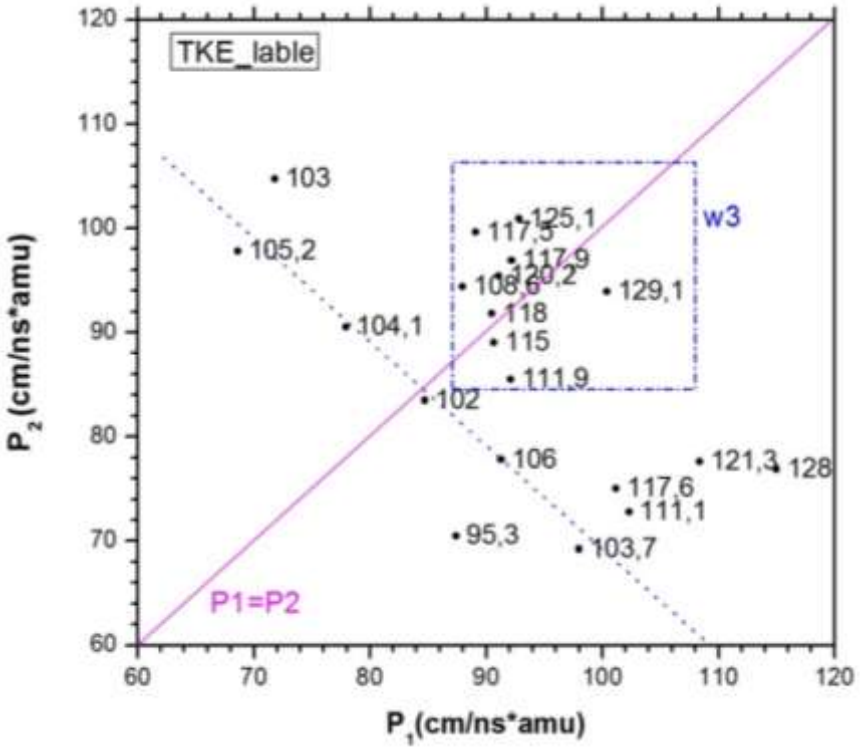


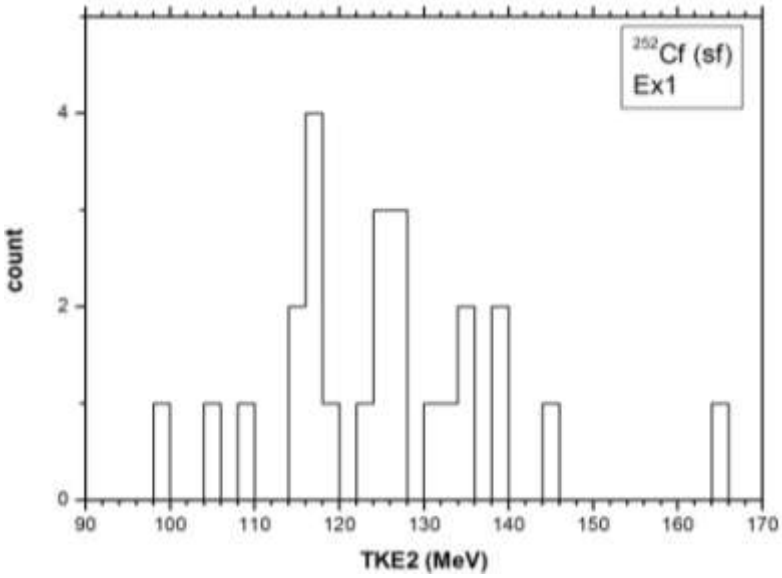


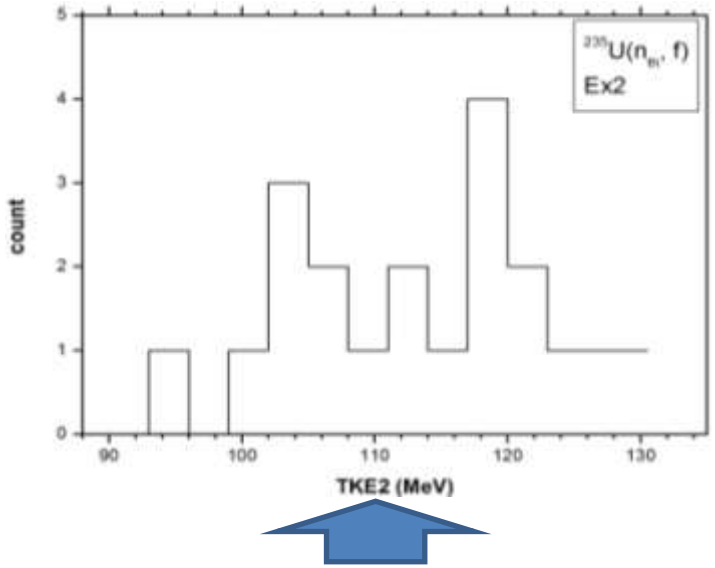
Scattering-free gate



Total kinetic energy of two observed fragments





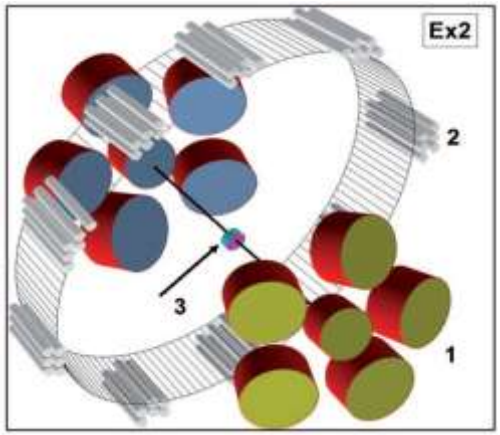


Collinear equal momenta

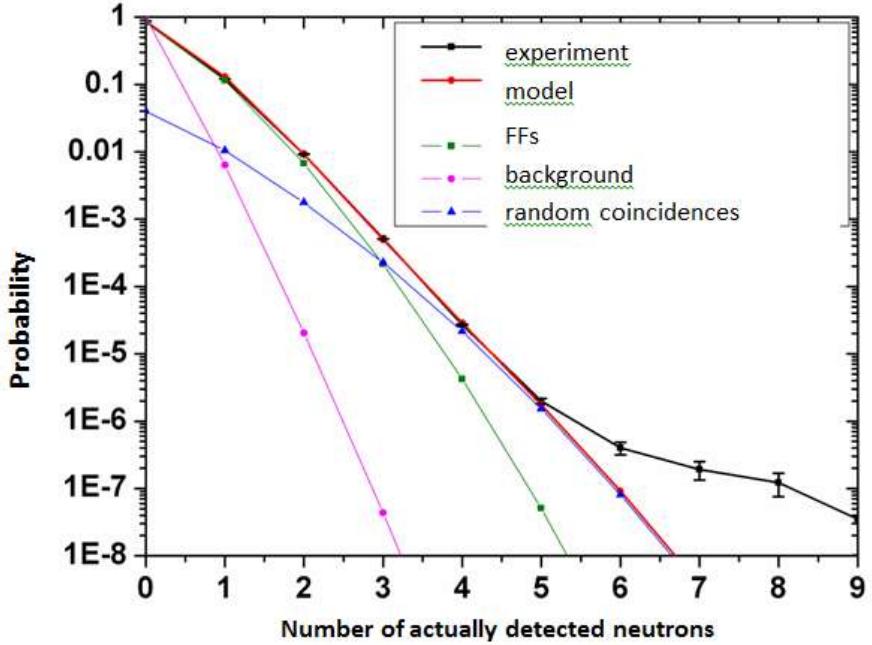
Extremely low TKE !

Estimation of the real neutron multiplicity

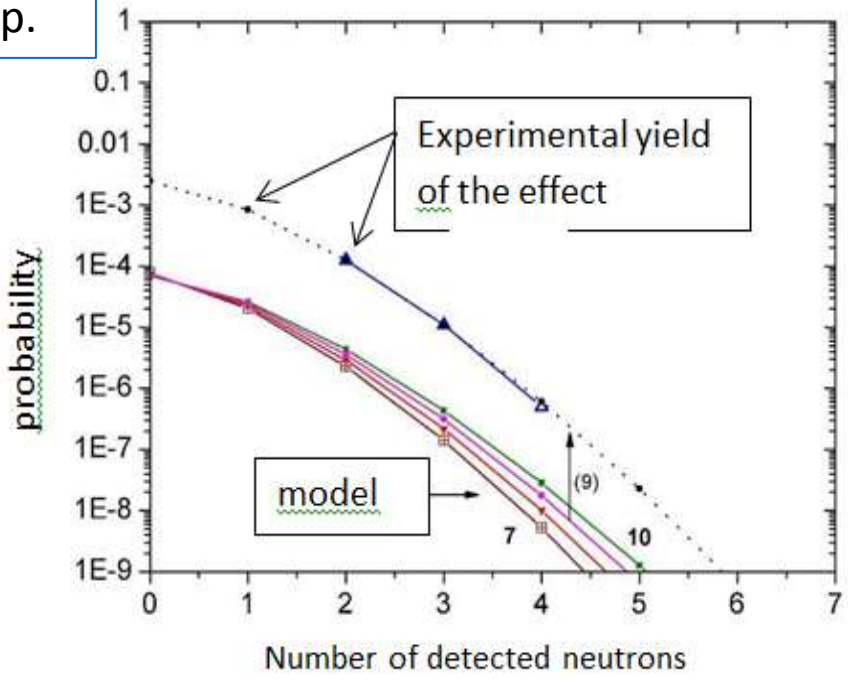
Ex1



~ 16% of the hemisphere;
registration efficiency for neutrons:
~4% in binary fission
~12% isotrope comp.

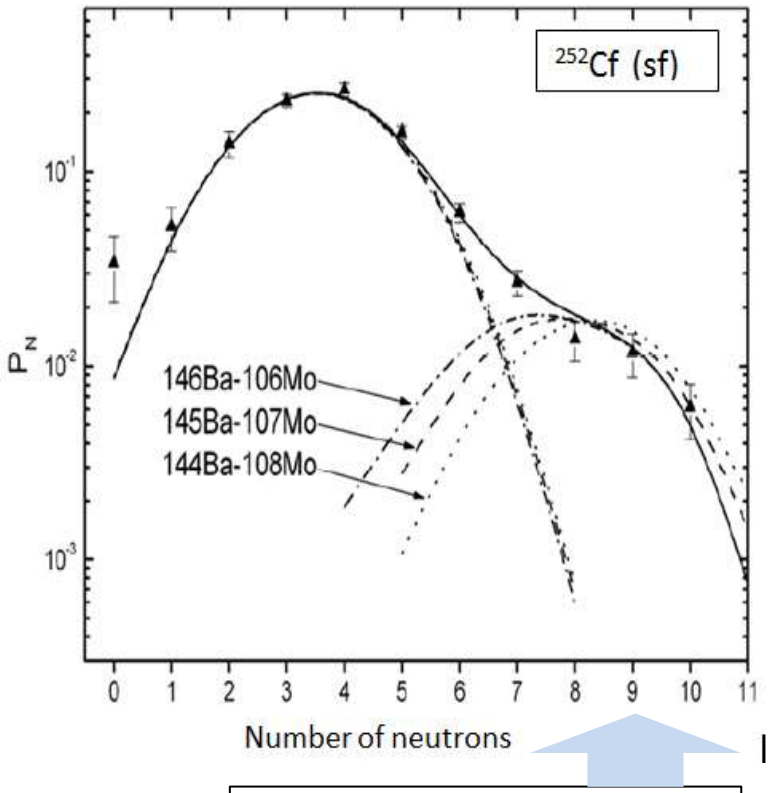


Adequate math. model of the mosaic neutron detector used ("neutron belt")

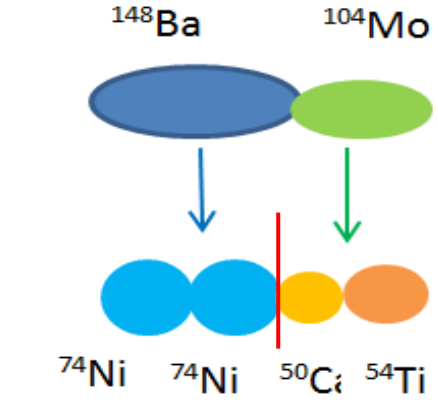


Yn=1~1.3*10-4/bin fission
Yn=2 ~1.3*10-5/bin fission
Due to the slope it could be:
- isotrop. **n~2**
- acc.FFs **n~7**

Is mass-symmetric quaternary pre-configuration not a fantasy? Treatment of two modes in Ba/Mo partitions



Mode_2 : TKE~154MeV, 7-10 neutrons



Edef~20MeV

Edef~15MeV

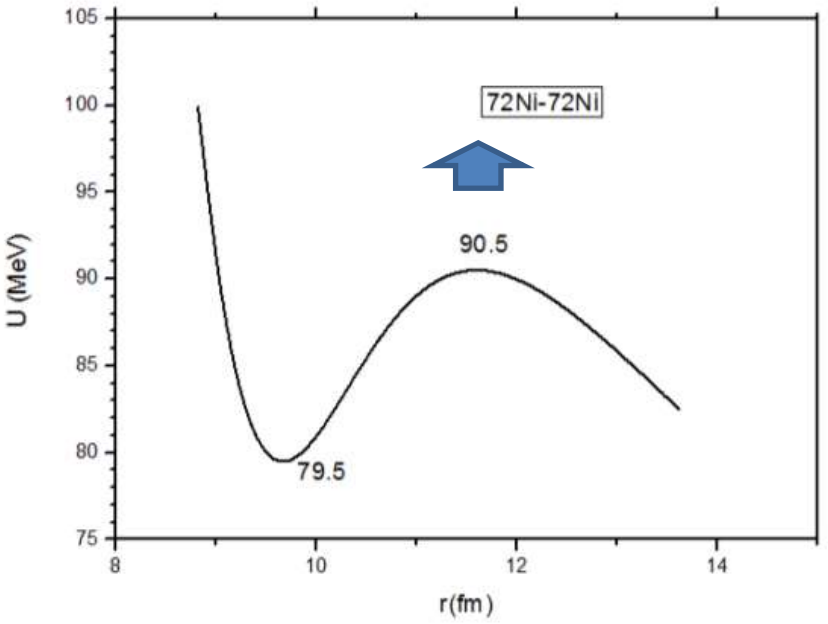
TKE~TKEexp=154MeV, all clusters in 2^+ state

T.M. Shneidman, G. G. Adamian, N.V. Antonenko et al., Phys. Rev. C 65 064302

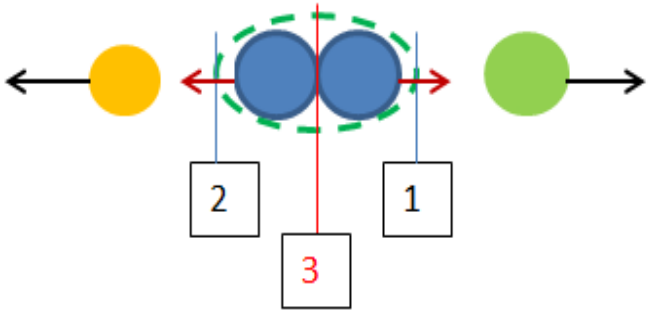
Wu, S. C., Donangelo, R., Rasmussen, J. O., Daniel, A. V., Hwang, J. K., Ramayya, A. V., Hamilton, J. H. New determination of the Ba-Mo yield matrix for ^{252}Cf // Physical Review C - 2000. - Vol. 62, No. 8. - P. 041601-4.

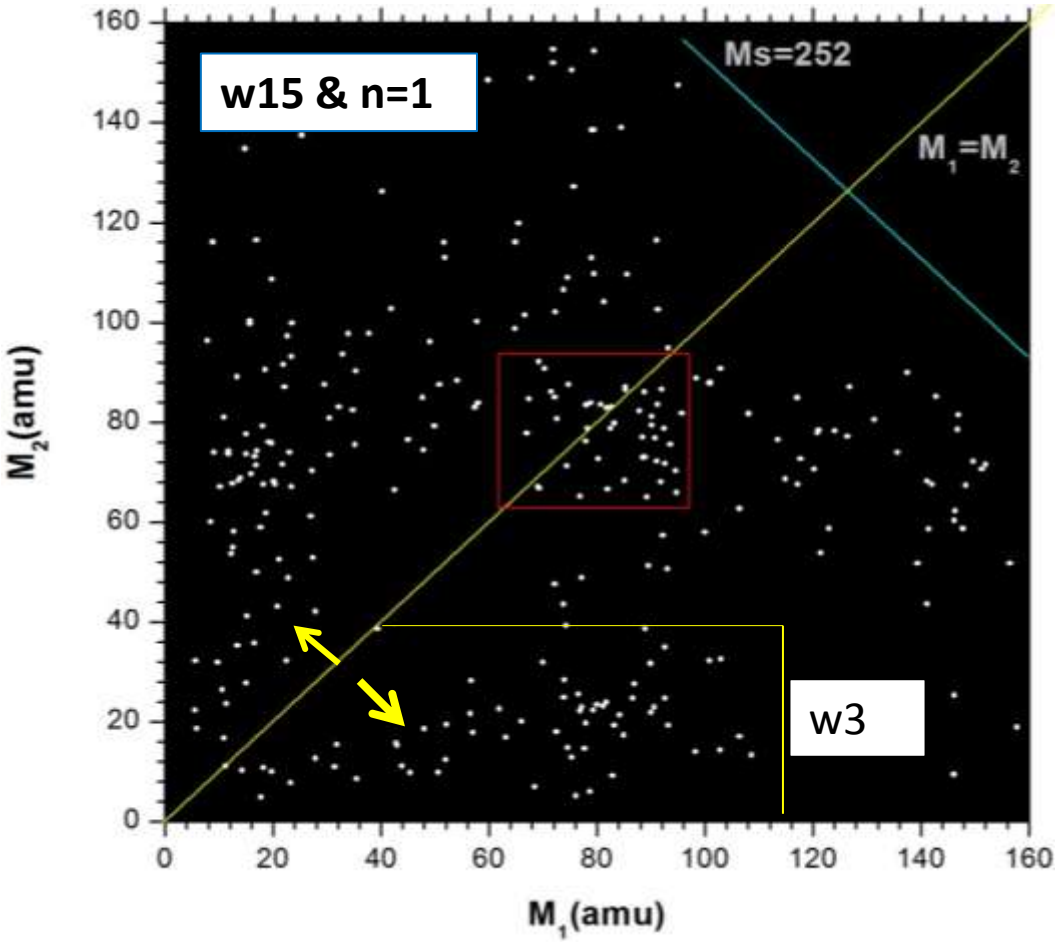
4-body clustering but binary fission

Testing the hypothesis of Ni-Ni core

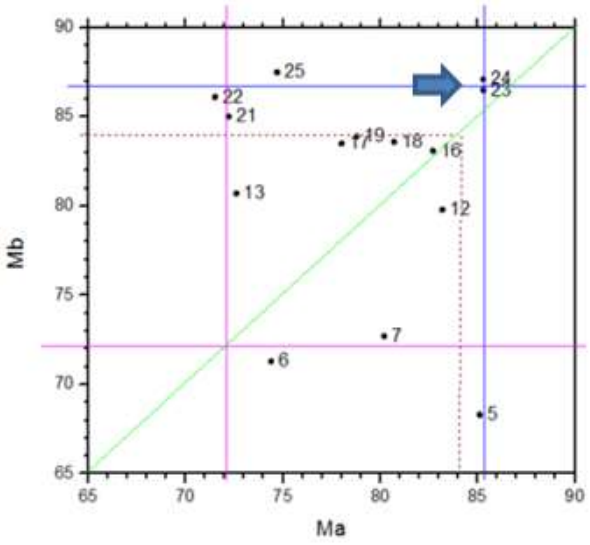


Ni/Ni partition: TKEexp ~ Eb → fission of 144Ba to be at rest?!



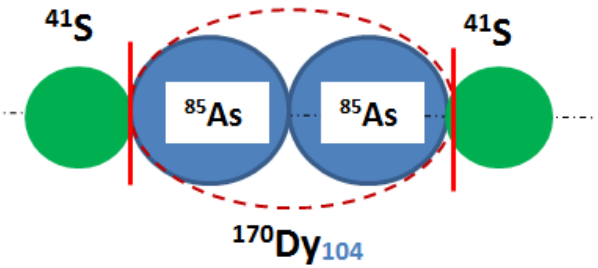


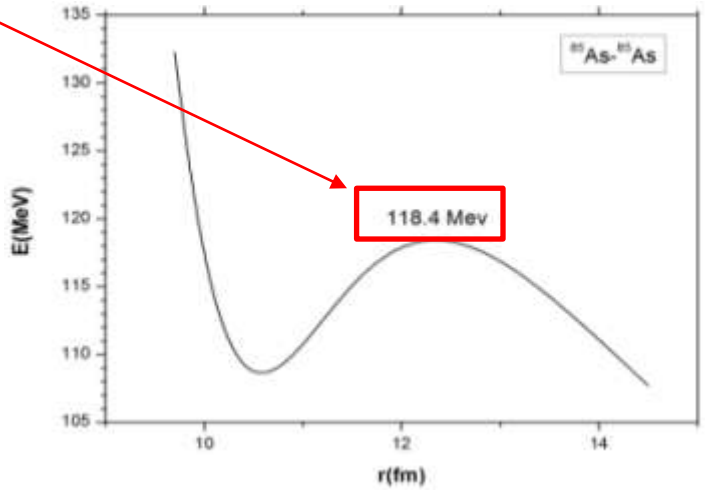
Scission scenario in fully symmetric point: 85As-85As core

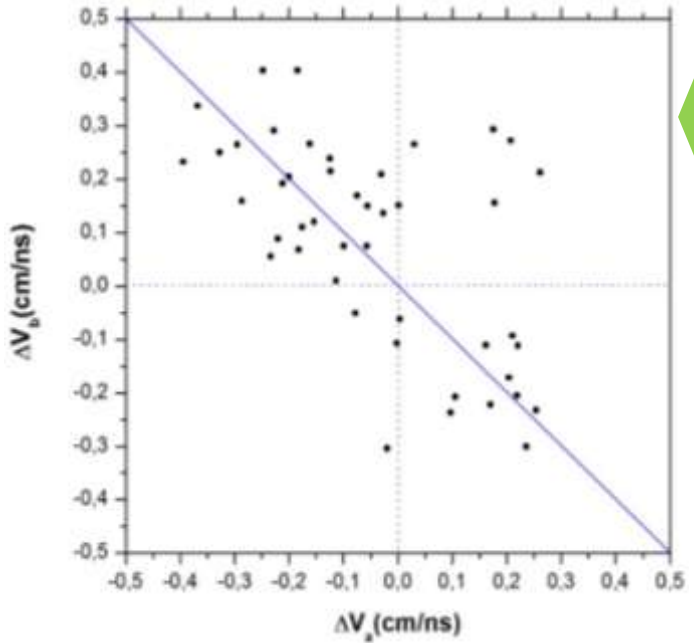


85As/85As (170Dy)
TKE2exp=118MeV
Va_exp=1.3cm/ns
Vb_exp=1.068cm/ns

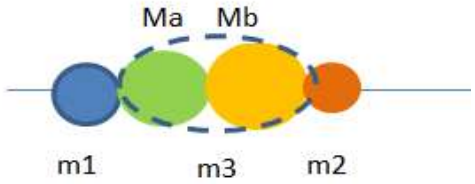
Fission of Dy **in rest** →
V_0(As)=1.15cm/ns;
dVexp=Va, b - V_0
=±0.15cm/ns -→
it is Vtr (Dy); Etr~2MeV



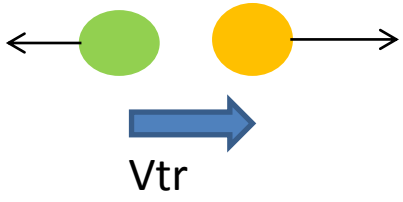




Results of the similar calculations for all 45 experimental points
Bright correlation seen above shows that really at the moment of the scission of the central fragment m3 it flown as a whole body .
Two decay partners (Ma, Mb) were at the Coulomb barrier at scission.

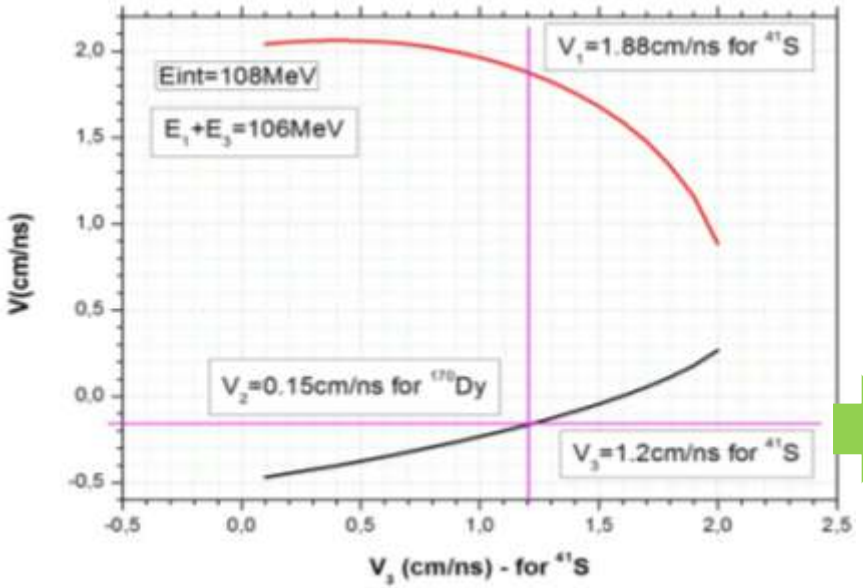


Prescission configuration



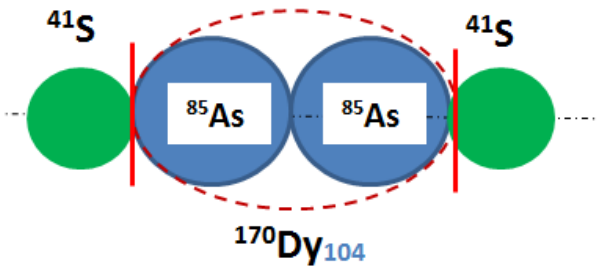
After fission of m3

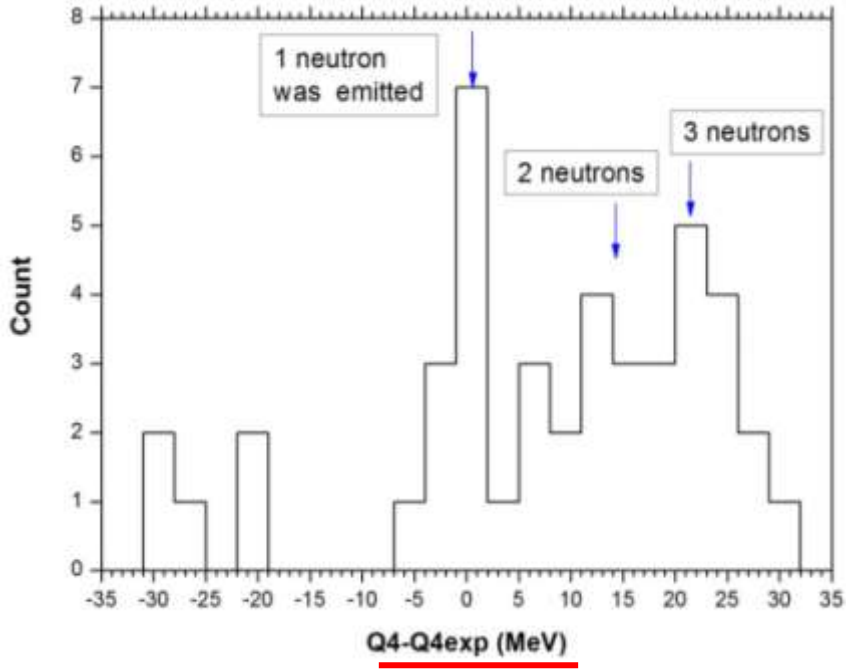
Scission scenario in fully symmetric point: 85As-85As core



Q3(Cf→S/Dy/S)=165MeV
Q4 (Cf→ S/As/As/S)=235MeV
Q2(Dy→2 85As)=+71MeV
Expected: E*(Dy)=TKE2-Q2+Bn=55MeV
Eint (S/Dy/S)=Q3- E* (Dy)- Etr=108MeV

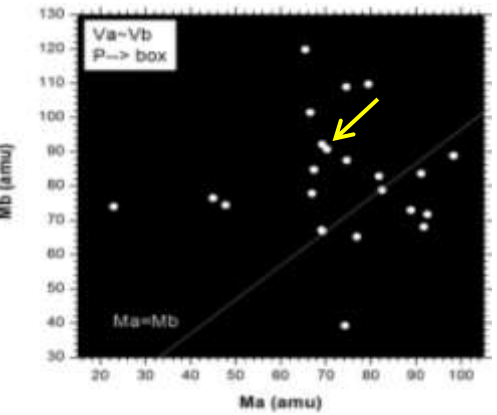
Q4-Q4exp(TKE_2As&2S)=235-232=3MeV
good agreement

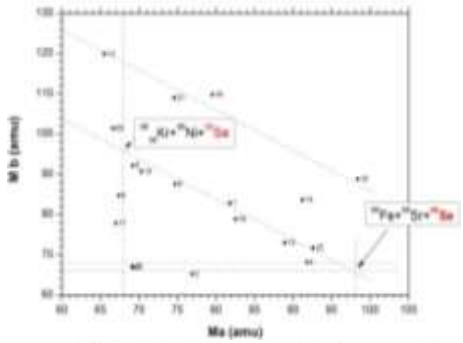




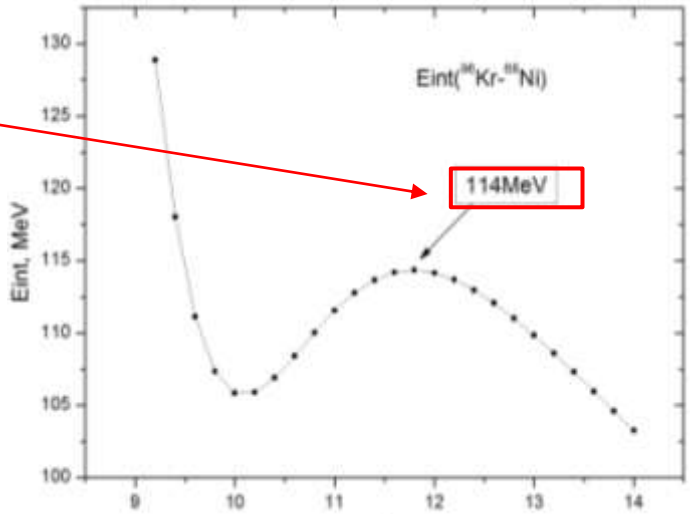
good agreement

Scission scenario for ^{164}Gd core - “missing ^{88}Se”

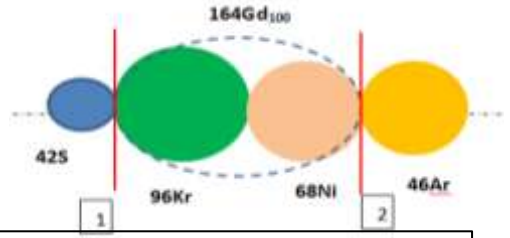


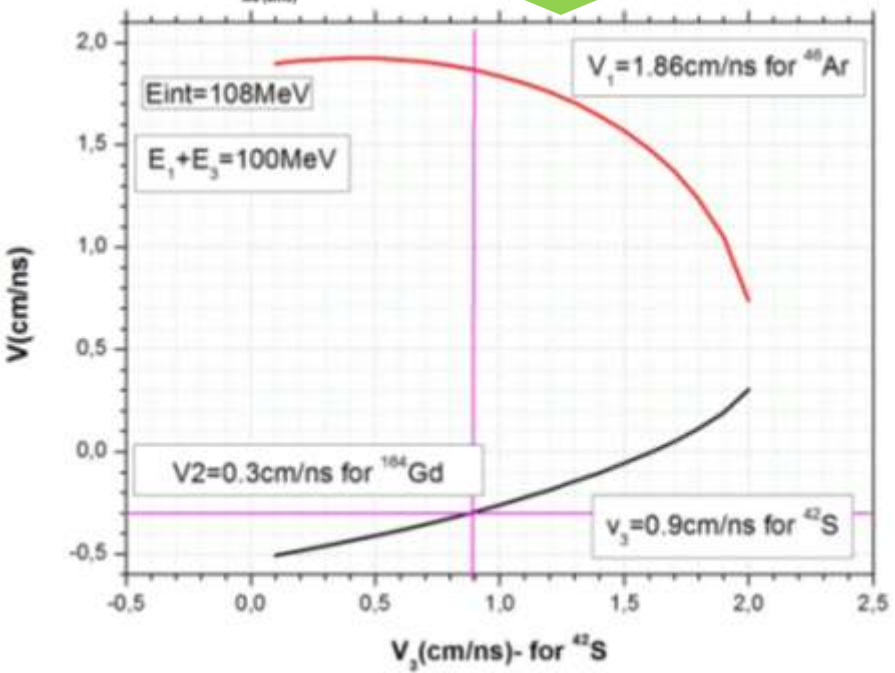


96Kr/68Ni ($164Gd_{100}$)
TKE2exp=116MeV
V(Kr)_exp=1.247cm/ns
V (Ni)_exp=1.101cm/ns



Fission of Gd **in rest** →
V_0(Kr)=0.987cm/ns;
V_0(Ni)=1.39cm/ns
dVexp=Va, b - V_0
≈±0.3cm/ns -→
it is Vtr (Gd); Etr~7MeV

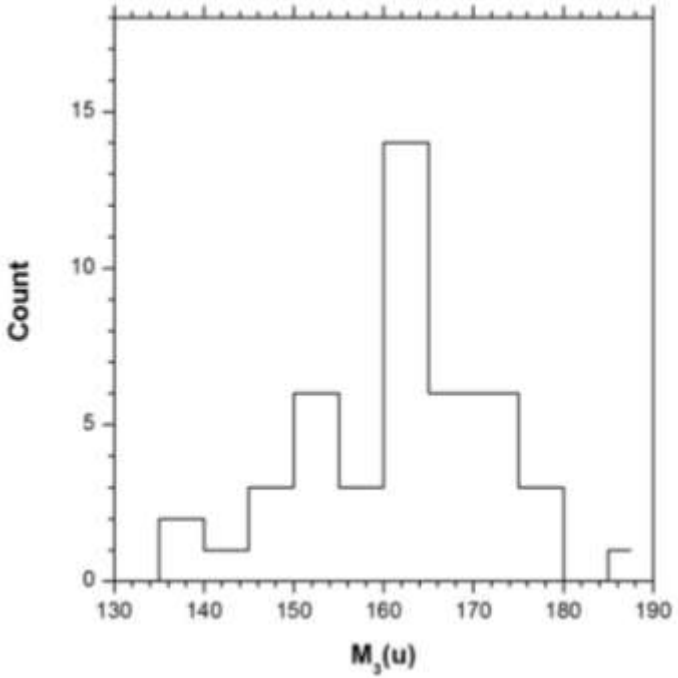


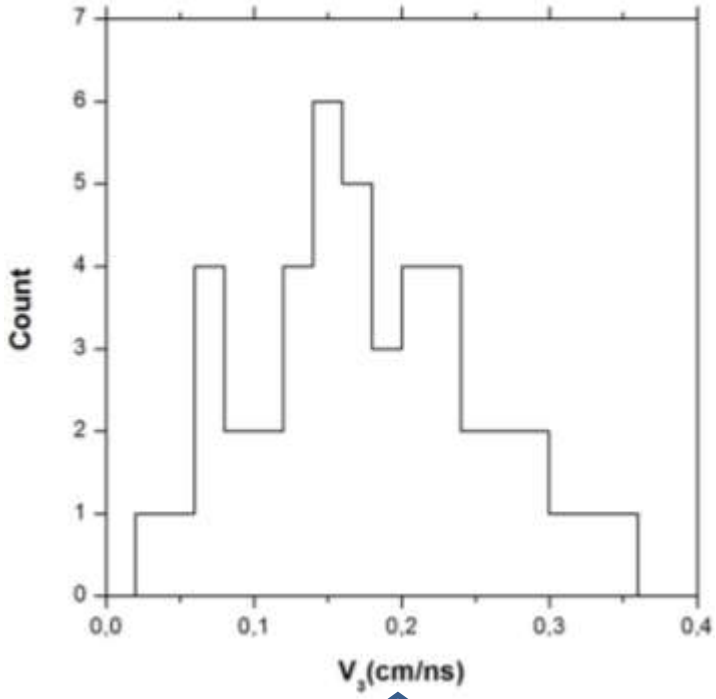


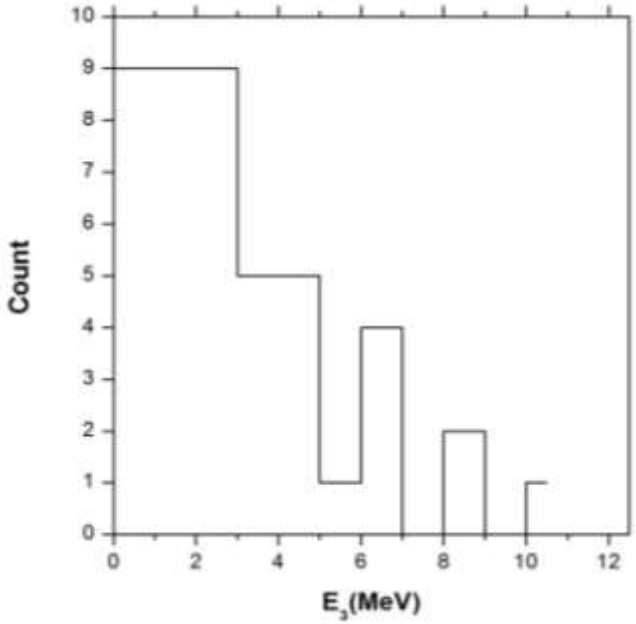
Q3(Cf→S/Gd/Ar)=181MeV
Q4 (Cf→ S/Kr/Ni/Ar)=237MeV
Q2(Gd→Kr/Ni)=+56MeV
Expected: E*(Gd)=TKE2-Q2+Bn=66MeV
Eint (S/Gd/Kr)=Q3- E* (Gd)- Etr=108MeV

Q4-Q4exp(TKE_2As&2S+n)=237-224=13MeV
-→ all in all **2** neutrons could be emitted
good agreement

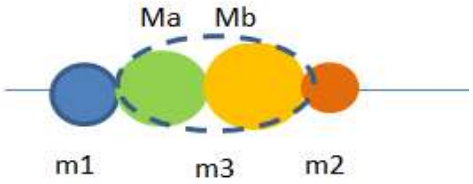
Results: important details

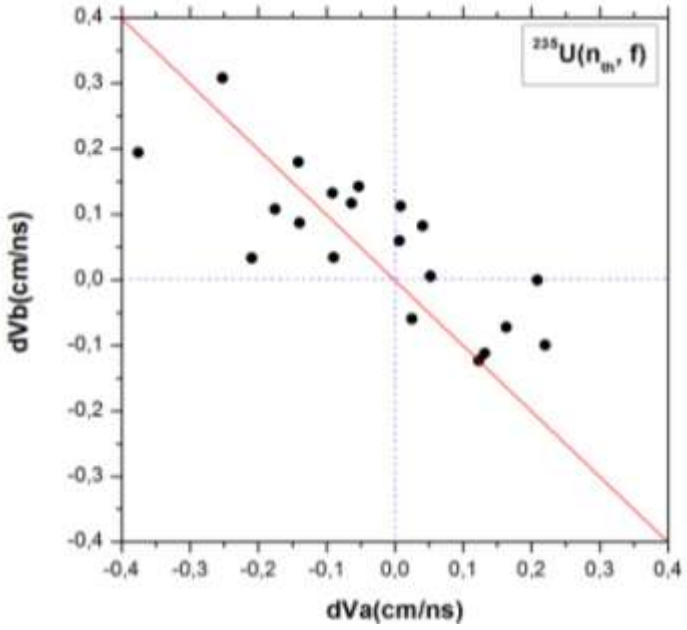


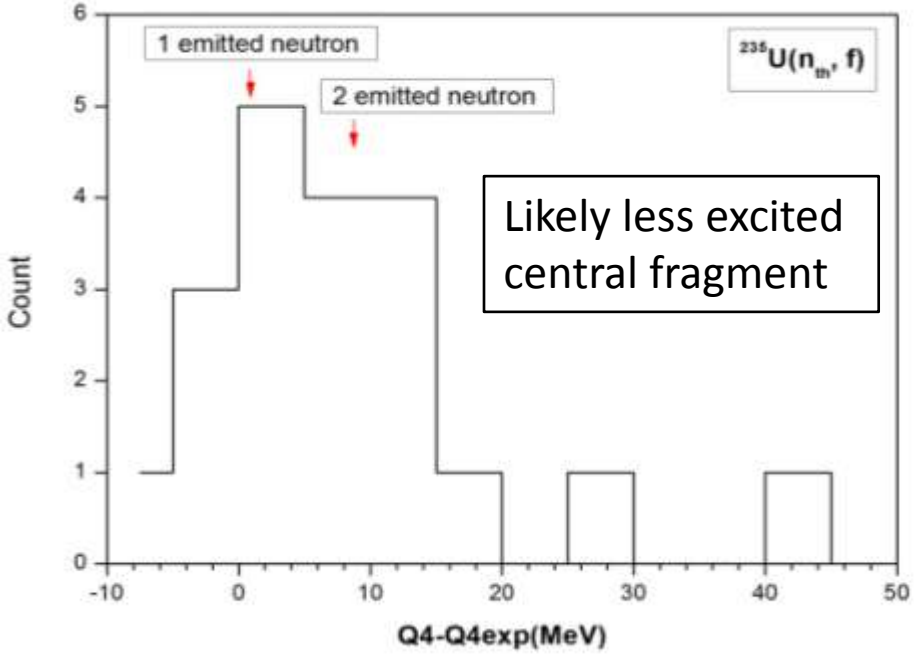




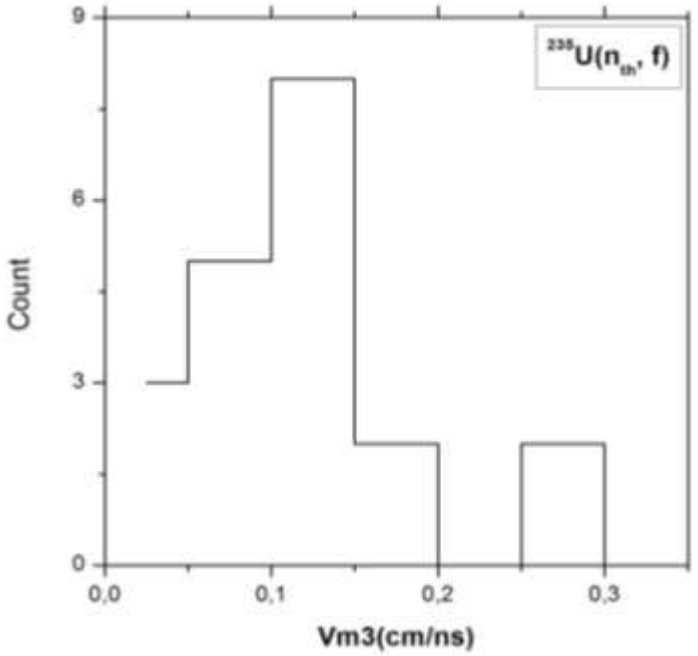
Really, the central fragment m3 undergoes fission (m3 ➡Ma+Mb) being almost at rest

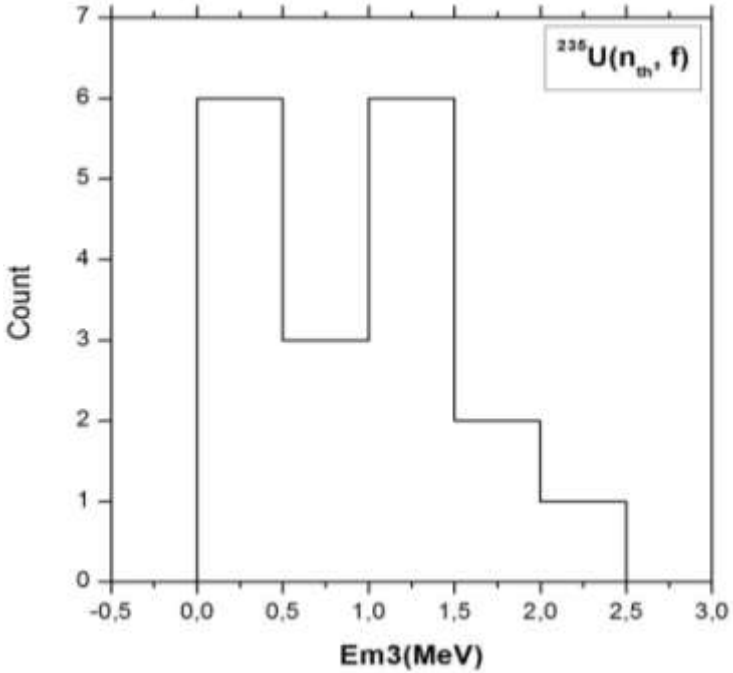


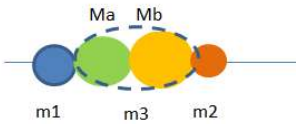




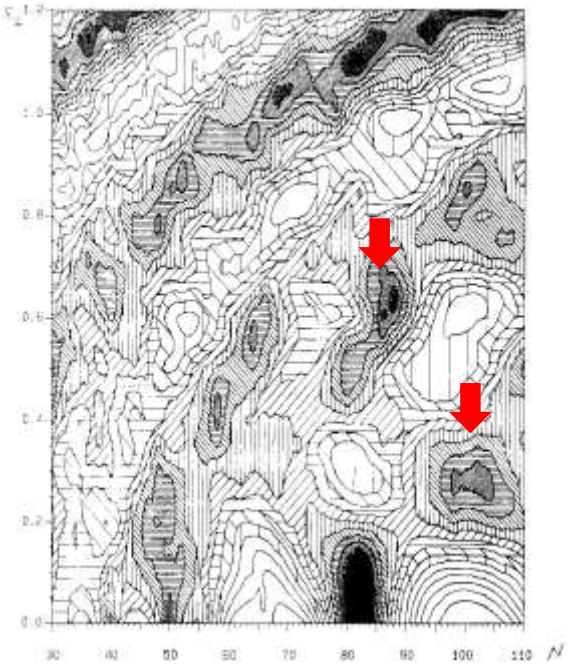
Likely less excited central fragment

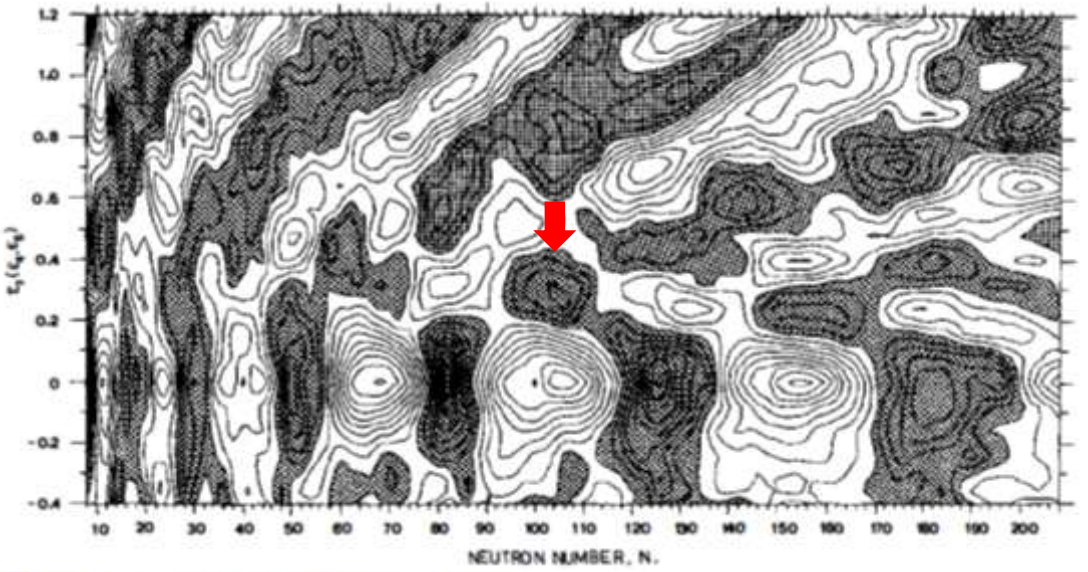


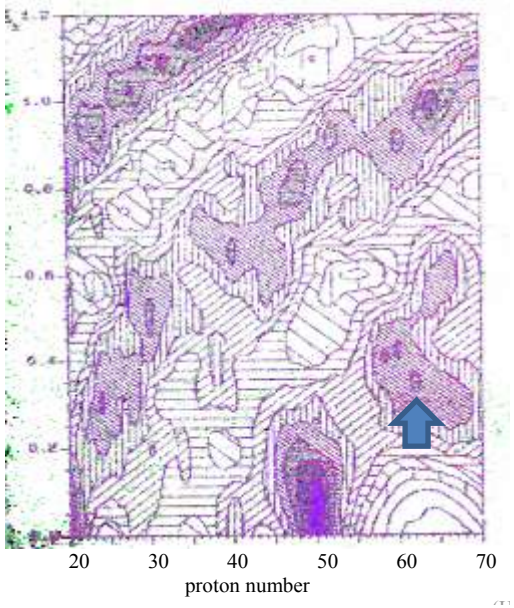




Central core: deformed magic cluster

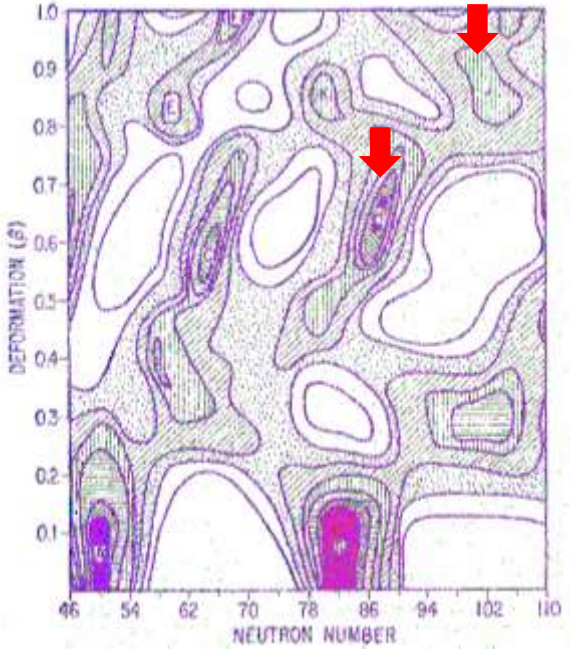






(H.Mä

$\varepsilon_2=0.95\beta_2$

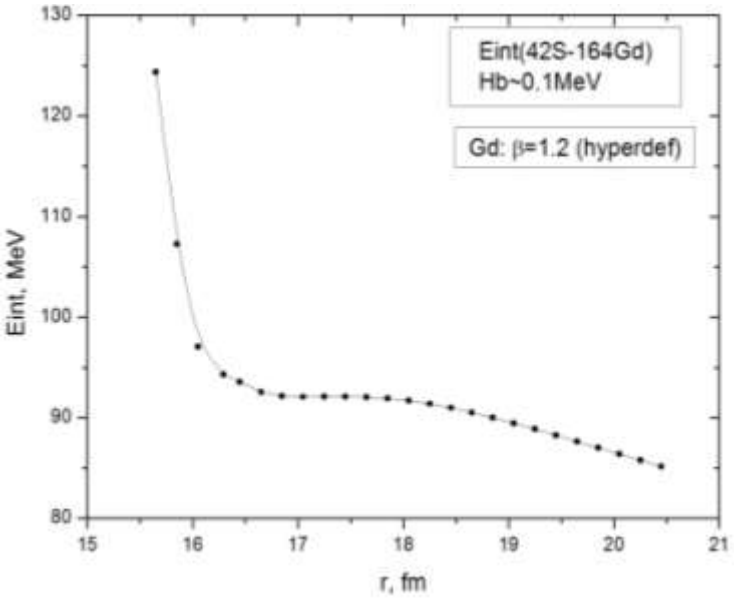


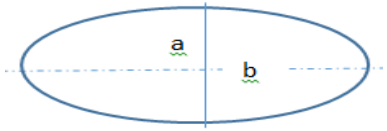
B.D. Wilkins et al., C 14 (1976) 1832

S. Aberg, H. Flacard, W. Nazarewicz,
Annu. Rev. Nucl. Part. Sci.
1990.40: 439

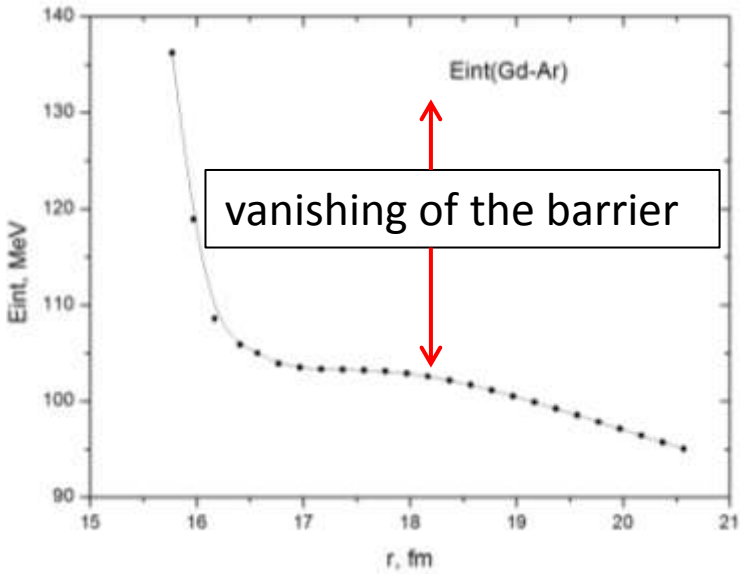
Strong shell minima
at **N~88, 100, Z~ 60**

Almost simultaneous separation of side fragments





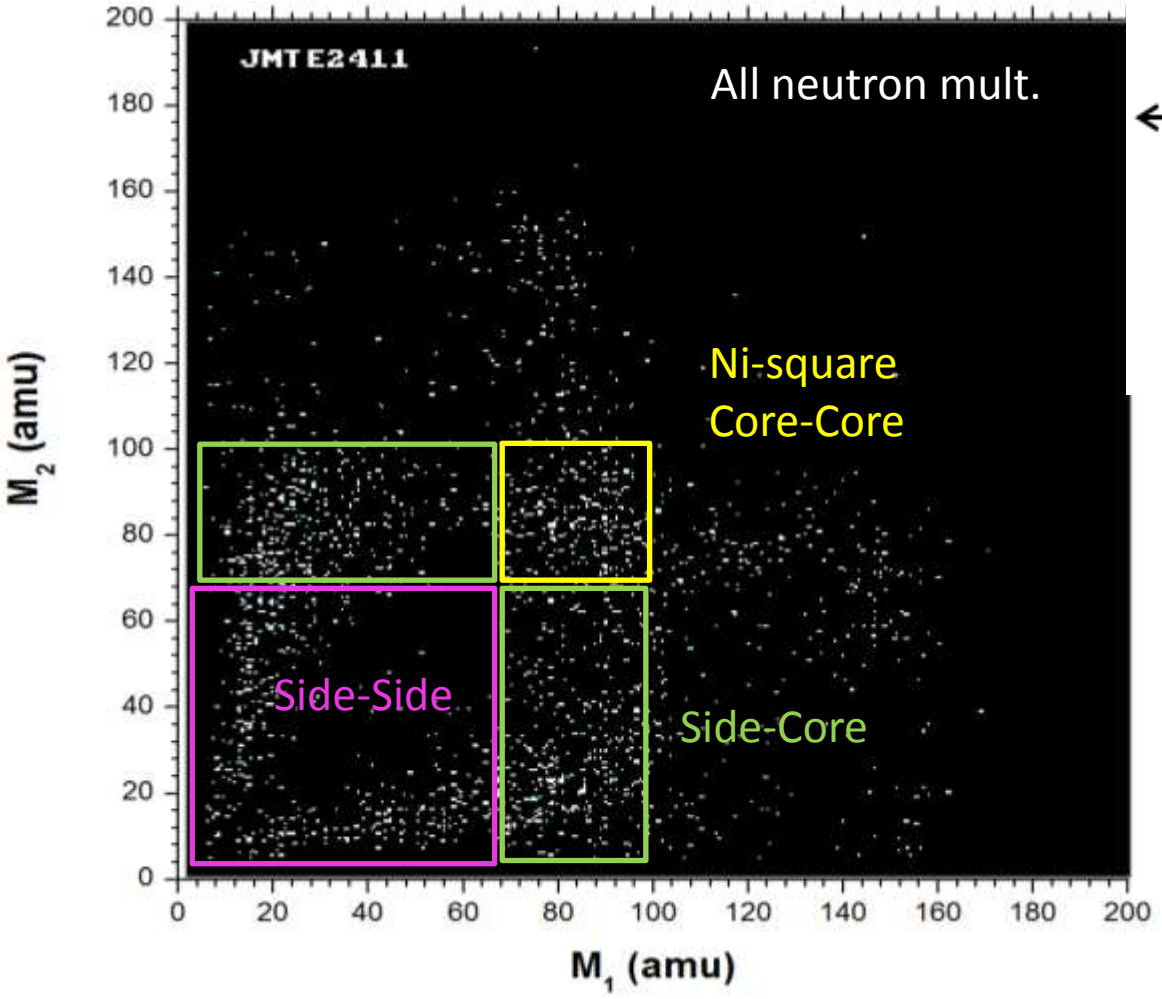
Parameters	Ground state of ^{164}Gd	Hyper-deformed state of ^{164}Gd
β	0,298	1,2
a, фм	5.77	4,40
b, фм	7.68	13,20

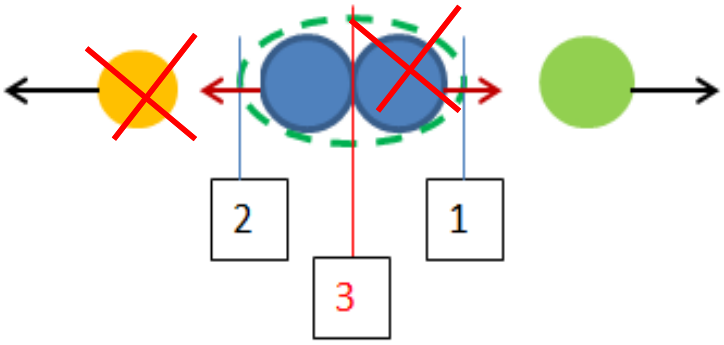


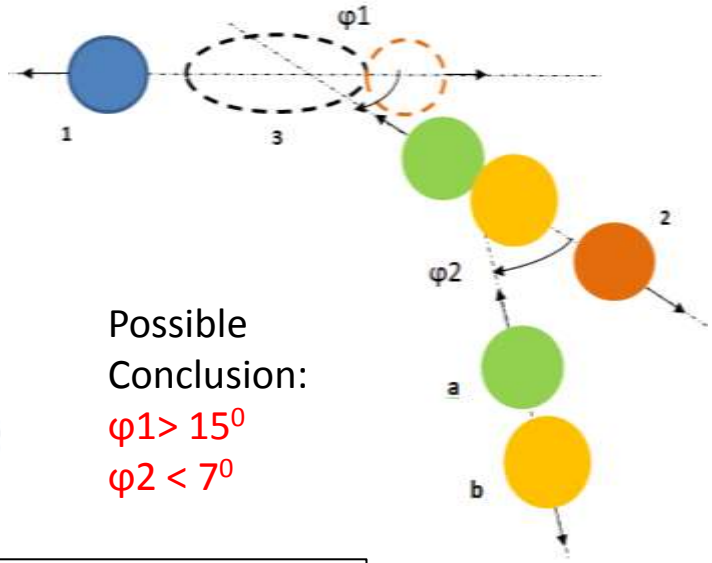
Eint (^{42}S/^{164}Gd$_{def}$/^{46}Ar) =211МэВ;
Q3=181.03 MeV;
30 MeV deficit , fission is interdicted → prescission configuration should be more elongated up to the moment Eint ≤ Q3;

Two reasons for system elongation:
- interaction energy Eint must be ≤ Q3
- vanishing of the barrier for the side fragments

Consistency test: hypothesis of side-core coincidences







Possible Conclusion:

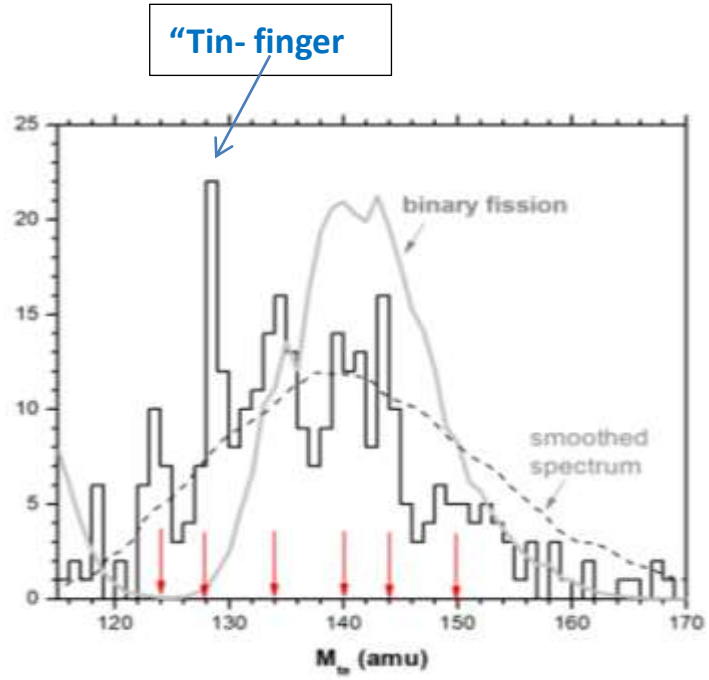
$\varphi 1 > 15^0$

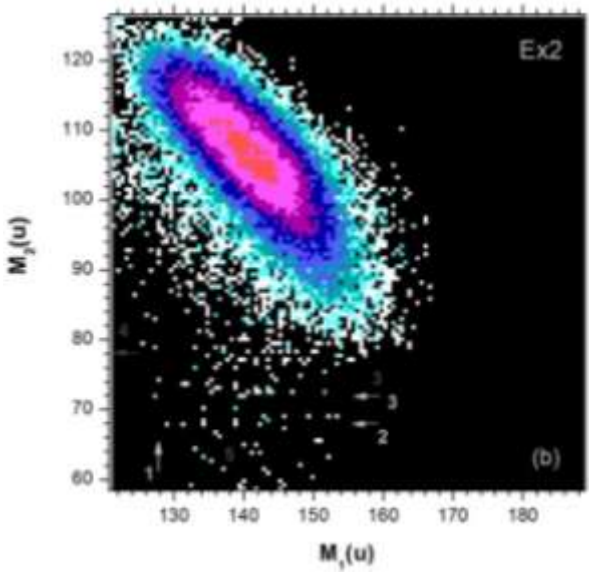
$\varphi 2 < 7^0$

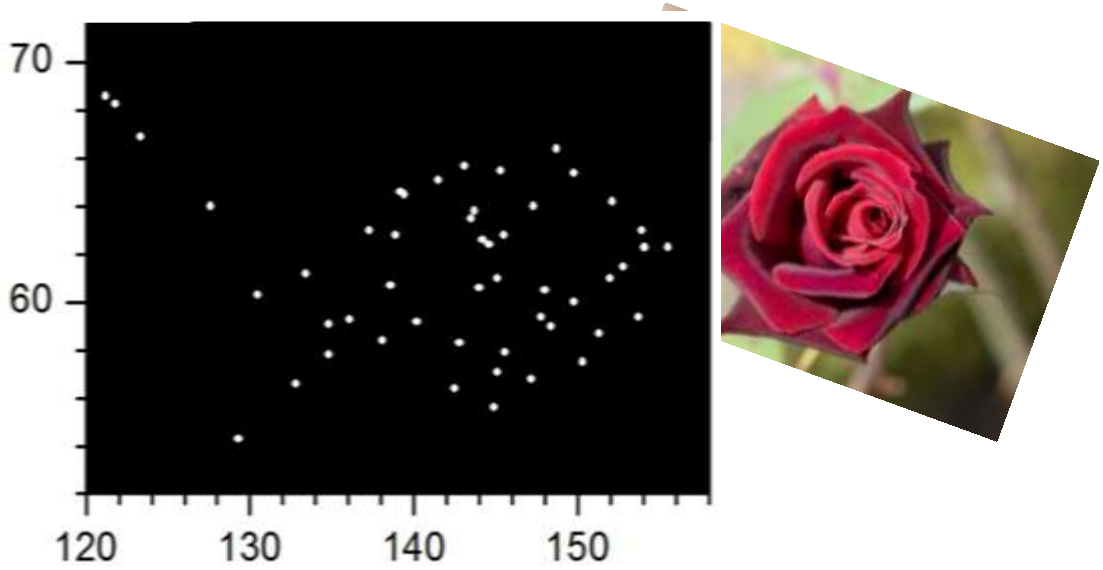
Conclusion

Strong indications of the **true quaternary decay** of heavy low excited nucleus $^{252}Cf(sf)$ and $^{235}U(n_{th}, f)$ are obtained for the first time.

System behind the structures?







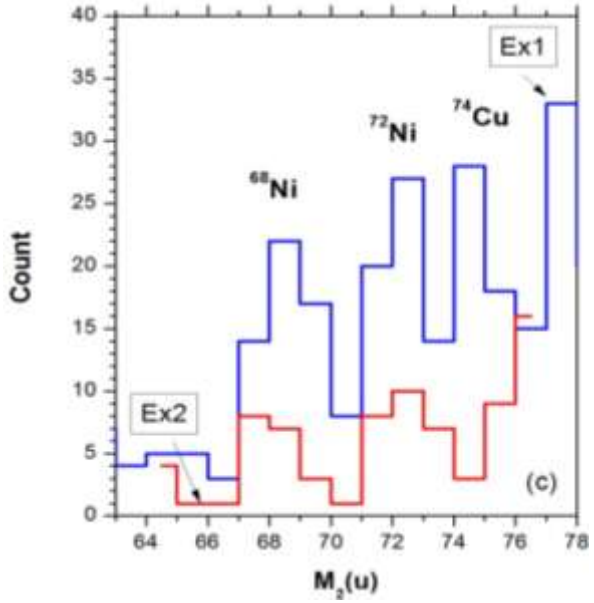


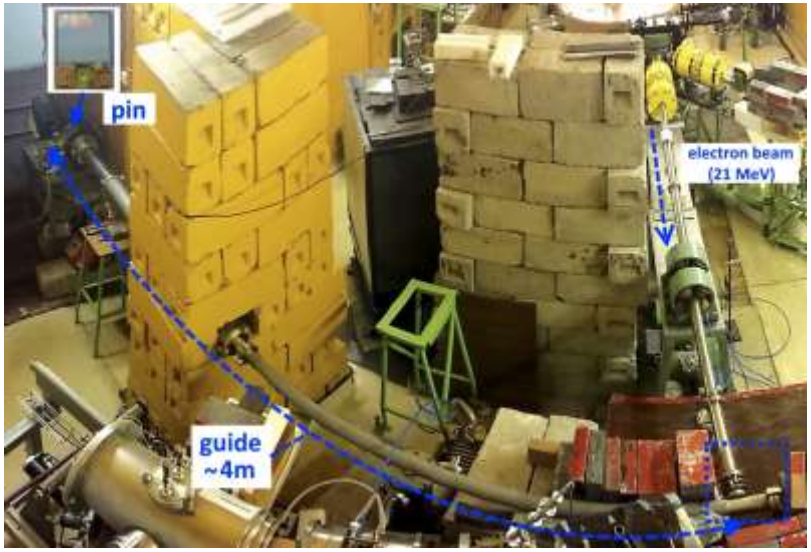
Photo-fission experiment at MT-25 (VEGA)

Three families of our experimental setups

COMETA – family

LIS-family

VEGA- family



Current experiment at IBR-2 (COMETA-R)

Continue to produce experimental data permanently

The sources : ^{252}Cf, U(n_{th}, f), U(γ, f)