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on Interaction of Neutrons with Nuclei
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Detailed analysis of the data indicating true quaternary fission of low excited actinides

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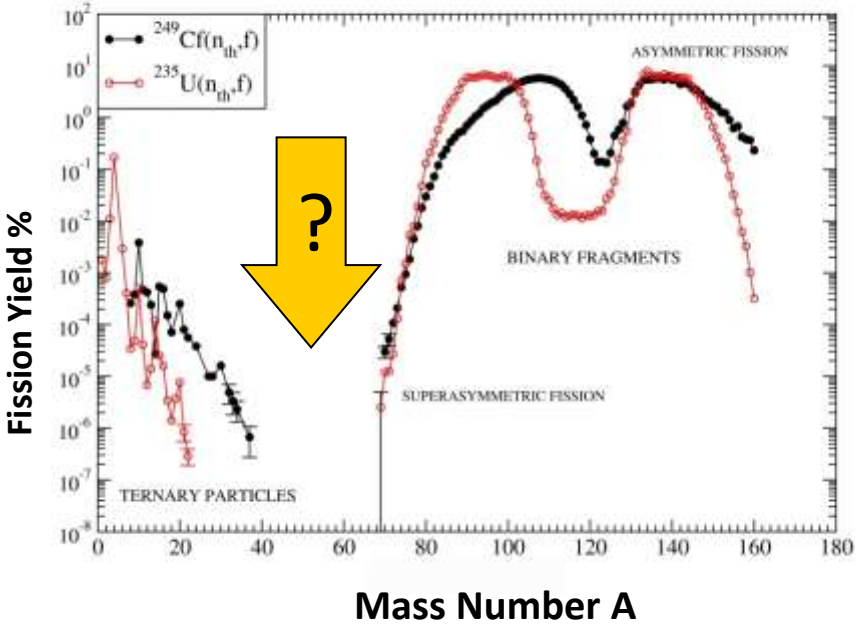
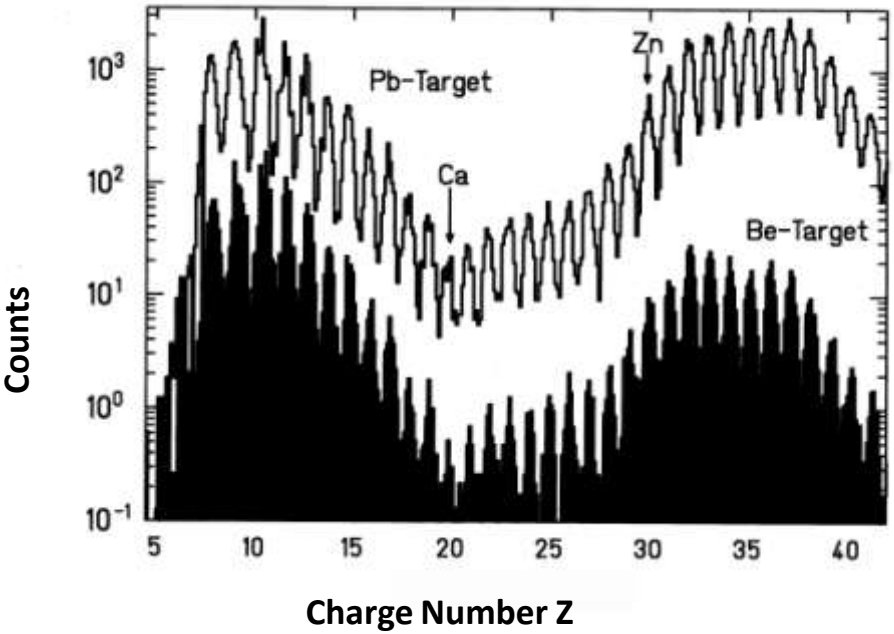
International support

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

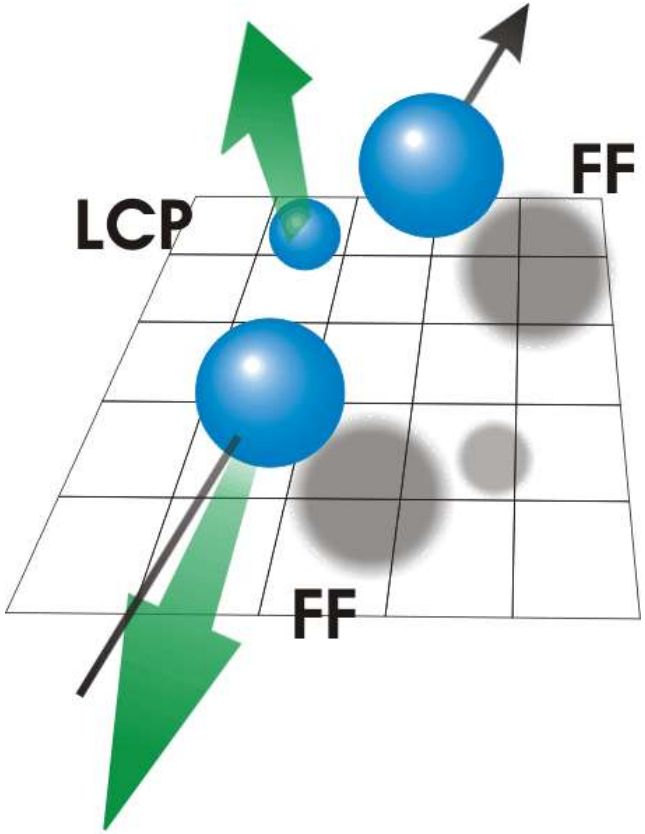
750 AMeV ^{238}U beam, FRS separator

Be-Target: nuclear excitation (≈ 27 MeV)

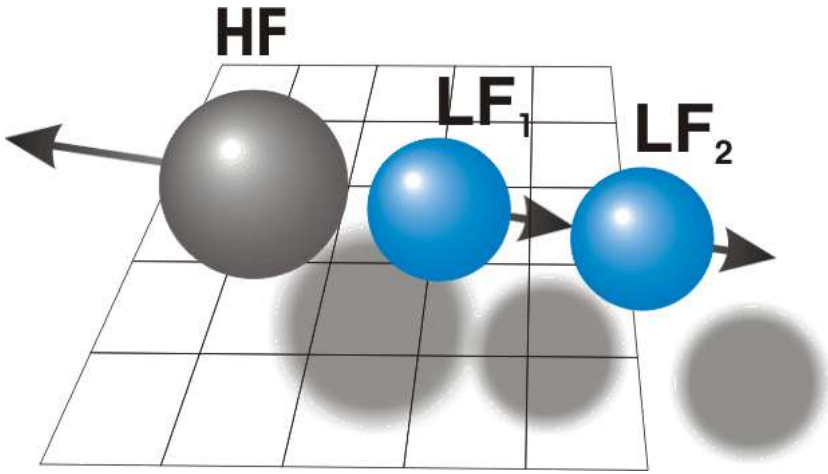
Pb-Target: electromagnetic excitation (≈ 11 MeV)

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

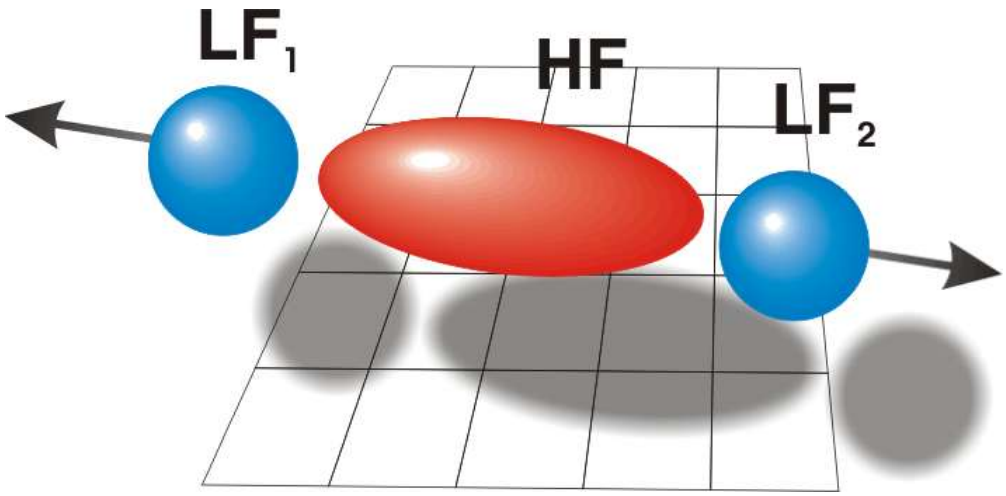
Conventional ternary fission



Collinear Cluster Tripartition



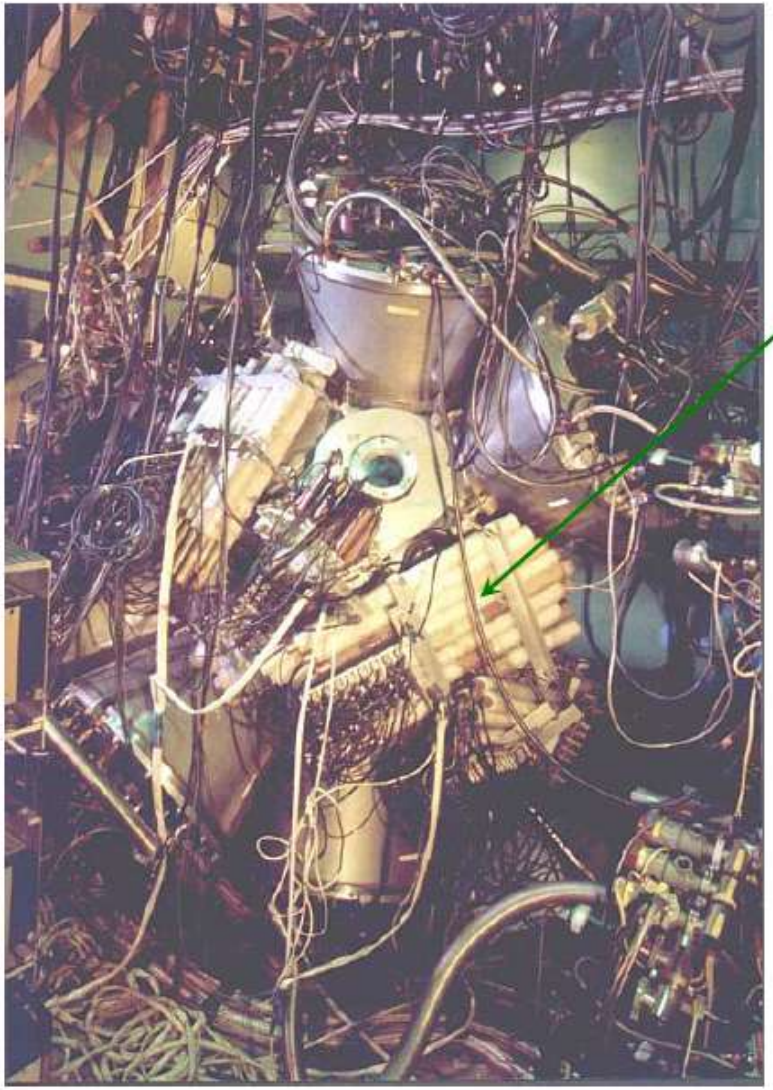
Symmetric Kinematics - this talk



“side fragment” - “core fragment” - “side fragment”

Modification of experimental setup

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



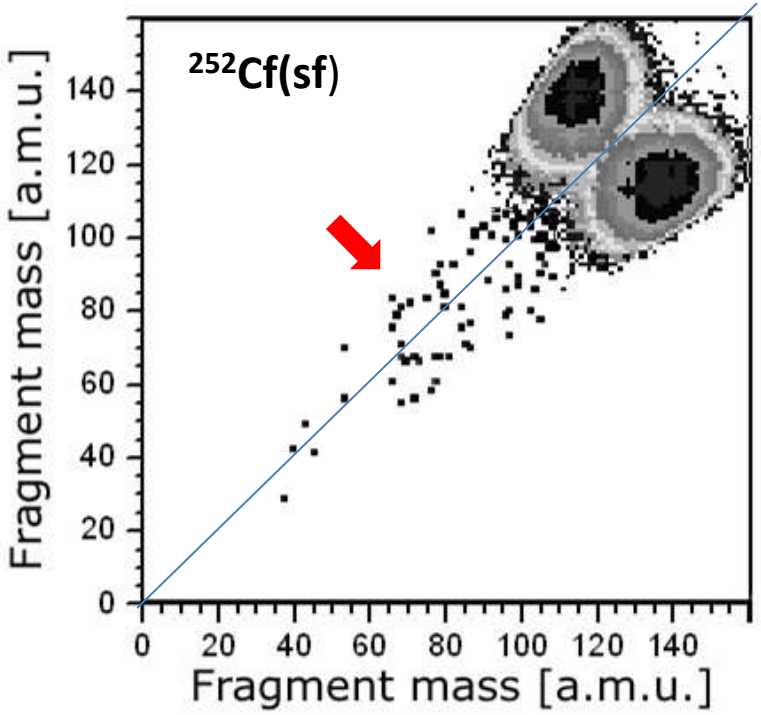
Double arm spectrometer
6+6 modules

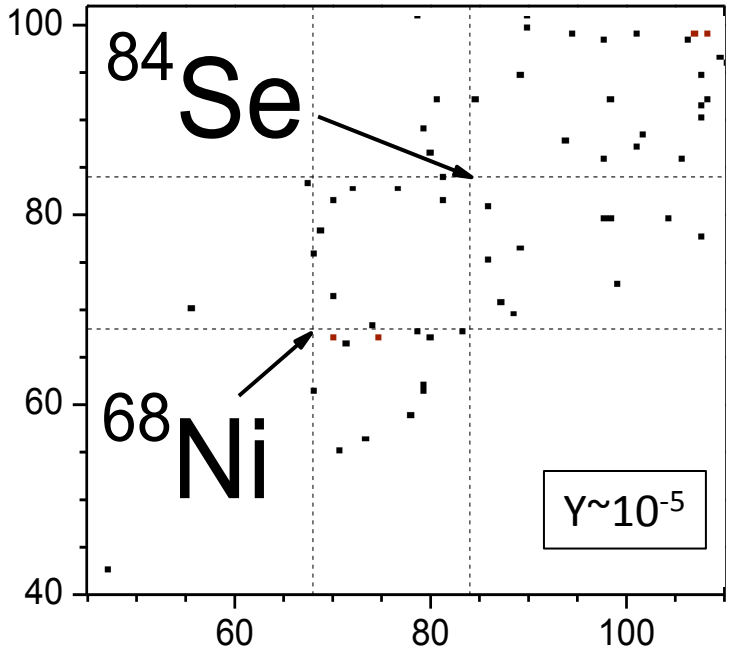
Neutron belt of FOBOS
140 ^{3}He (7 bar) conuters
In PE-moderator

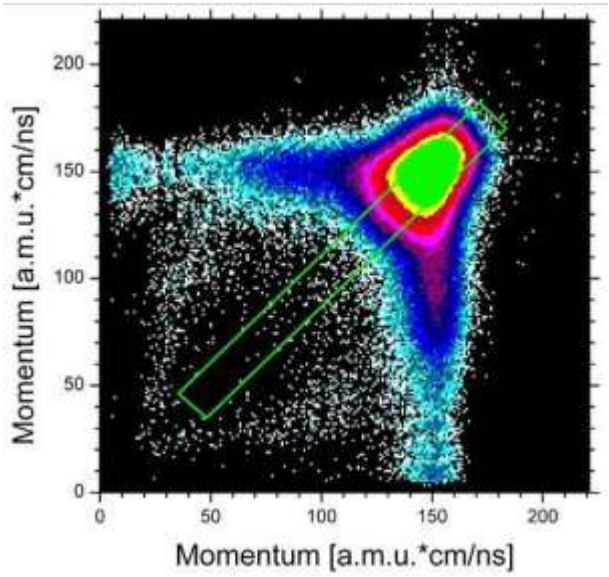
Start PAC
with internal ^{252}Cf source

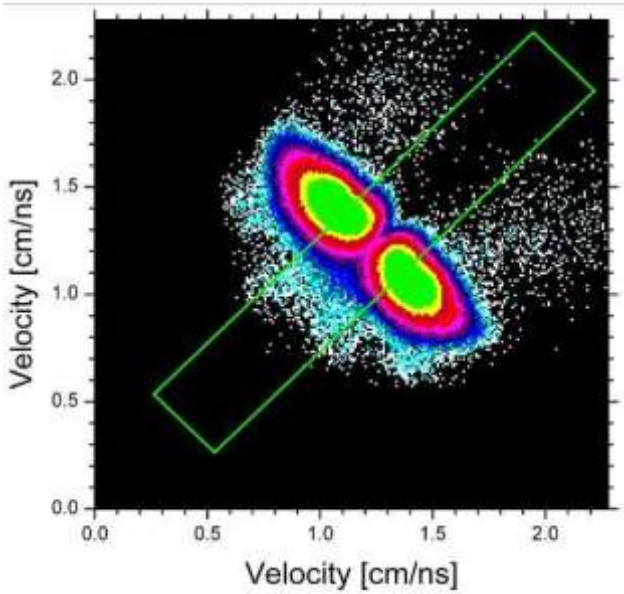
Symmetric Kinematics in Cf data – “Ni square”

Ex1





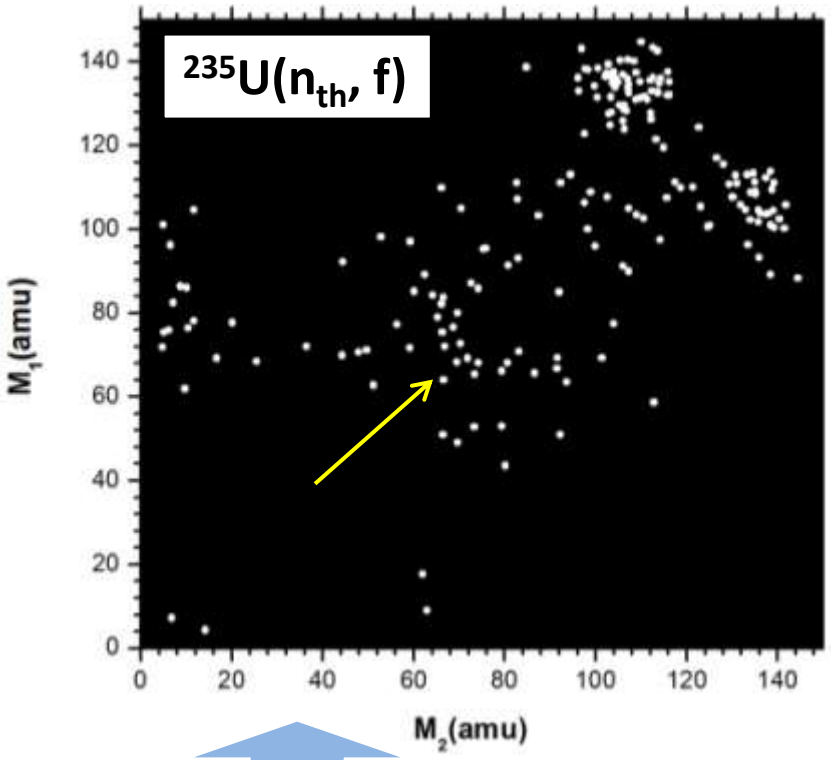


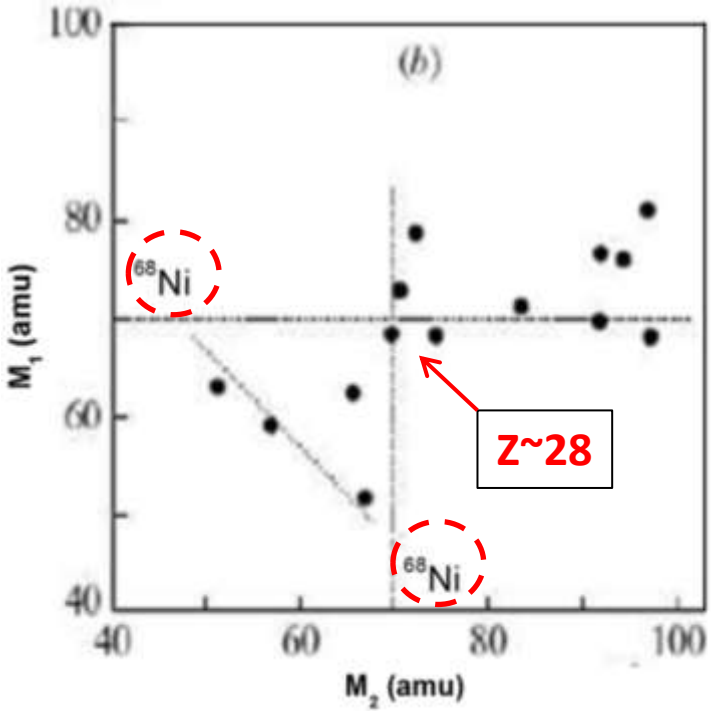


selection windows
P1~P2 & V1~V2

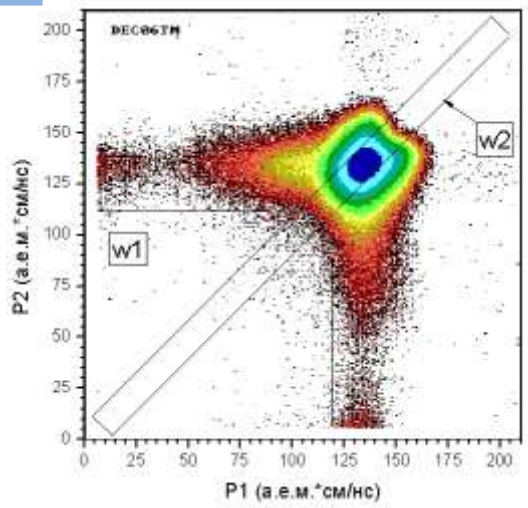
Symmetric Kinematics and charge symmetry in U data

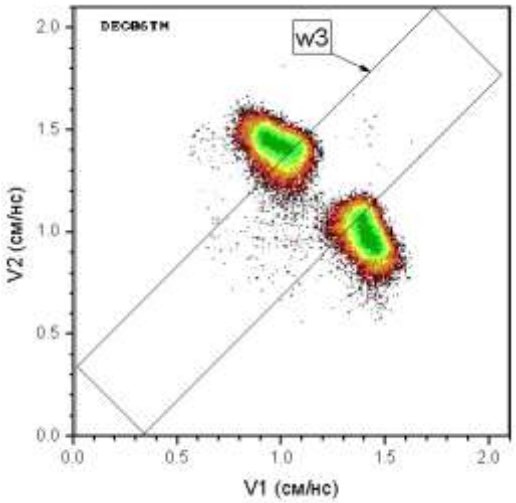
Ex2





P1~ P2
V1~ V2
Z1~Z2

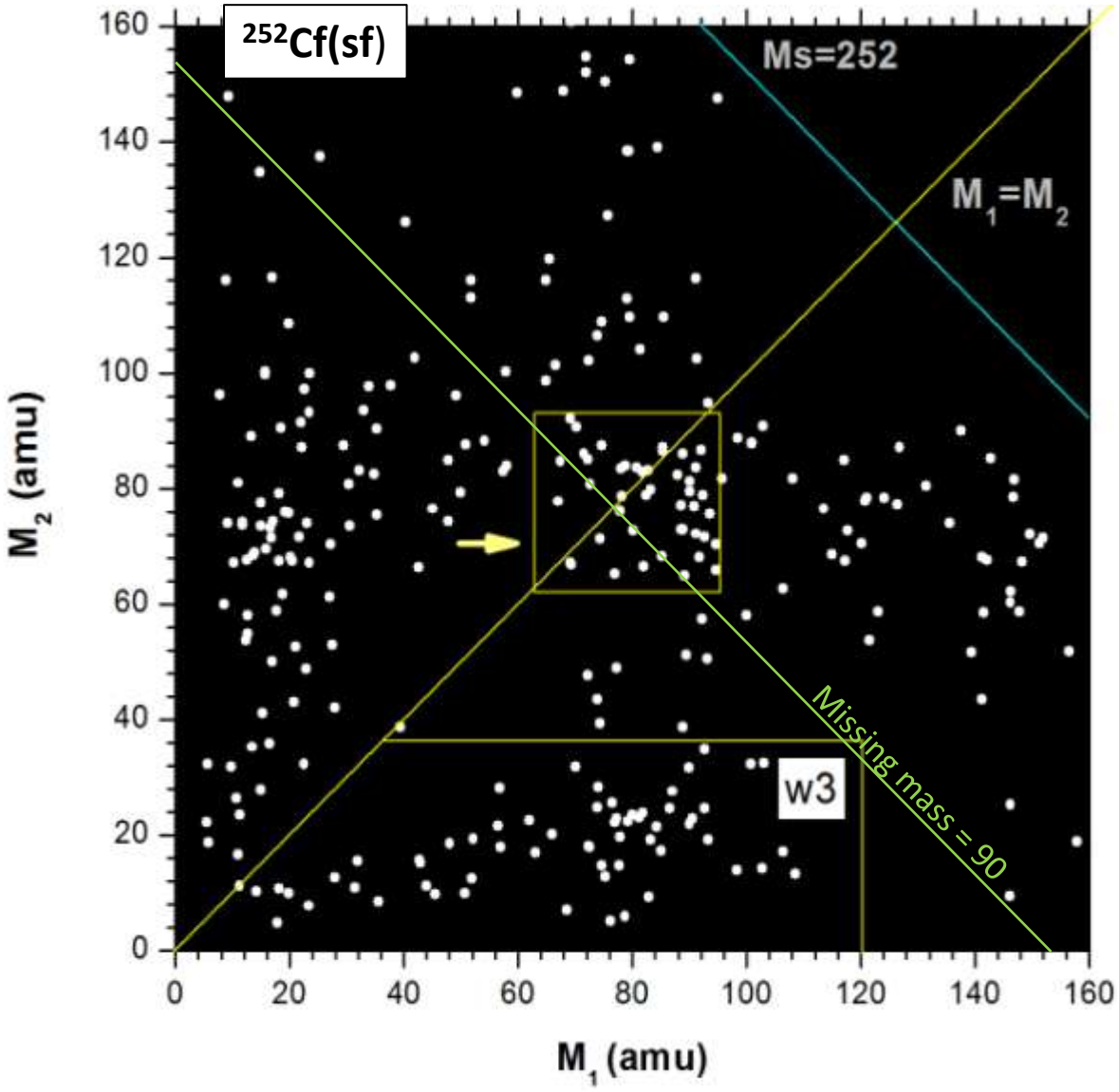




selection windows P1~P2 & V1~V2

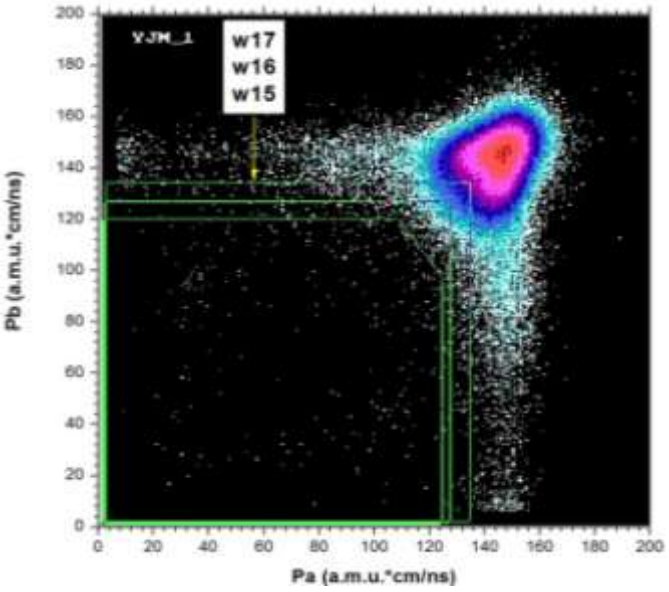
Ex1

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



w15 & n=1
more than 1 neutrons were detected

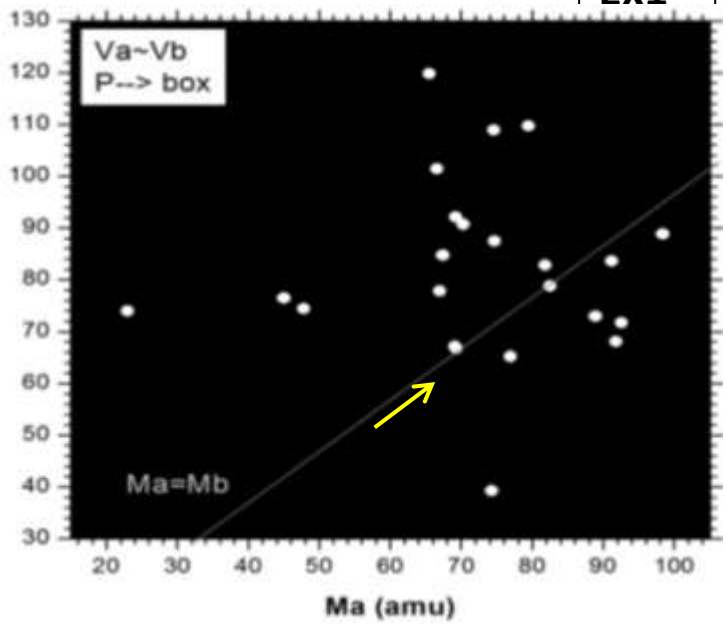
Scattering-free gate

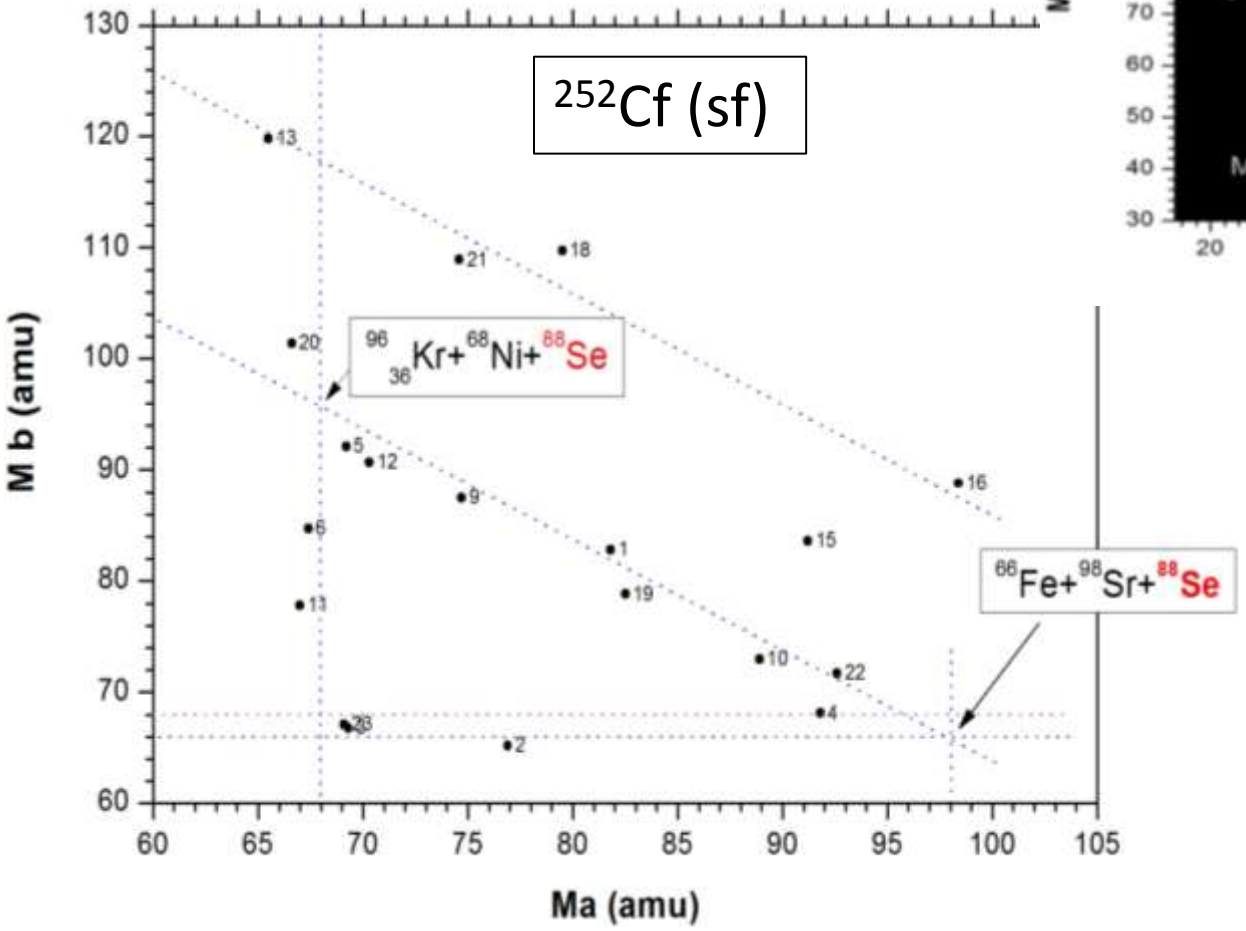


Mystery of missing selenium

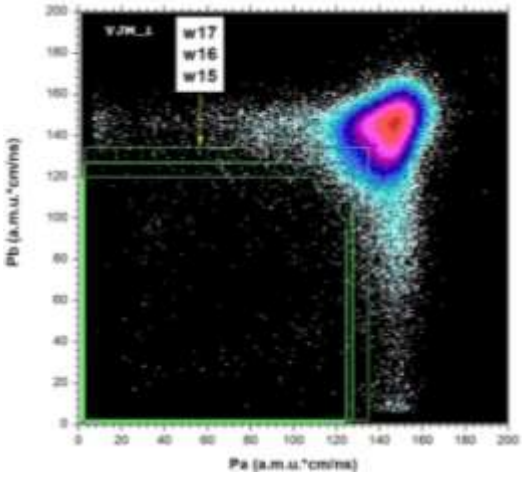
Ex1

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

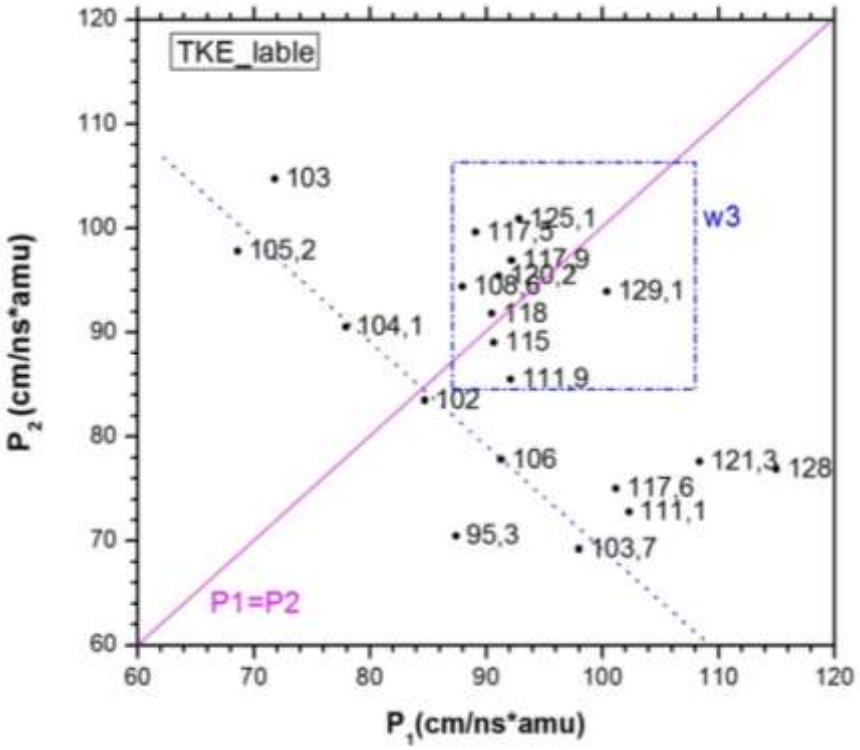


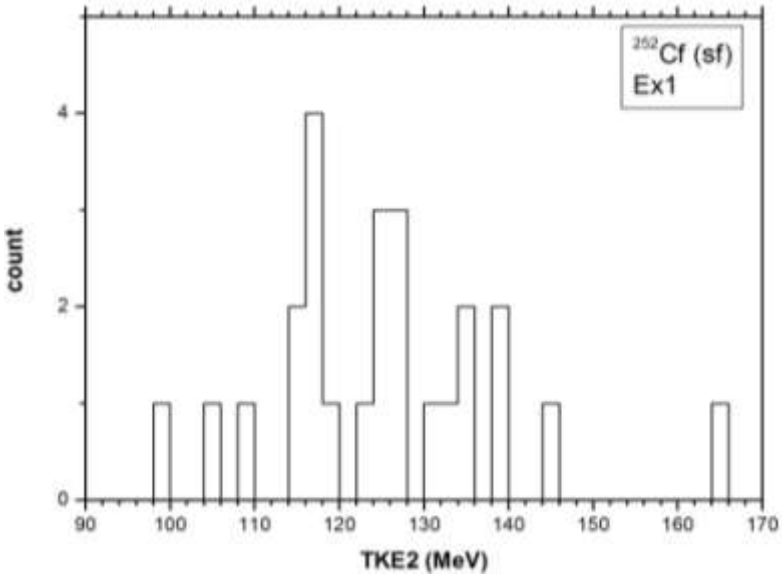


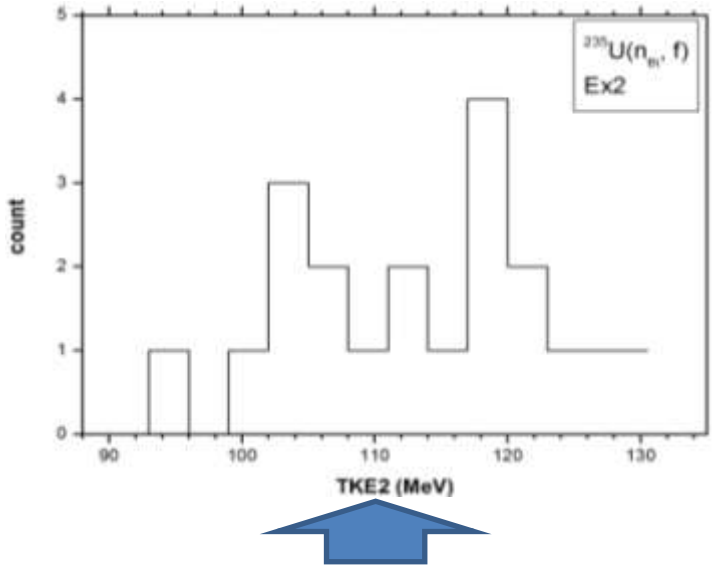
Scattering-free gate



Total kinetic energy of two observed fragments





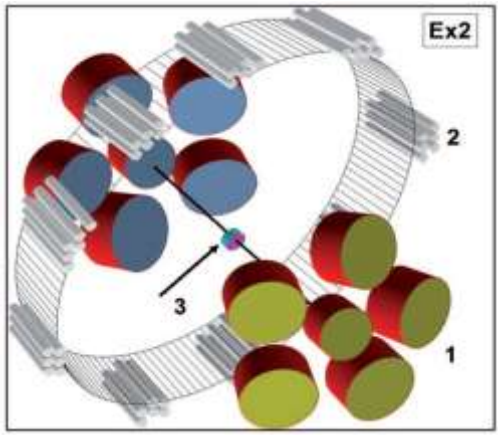


Collinear equal momenta

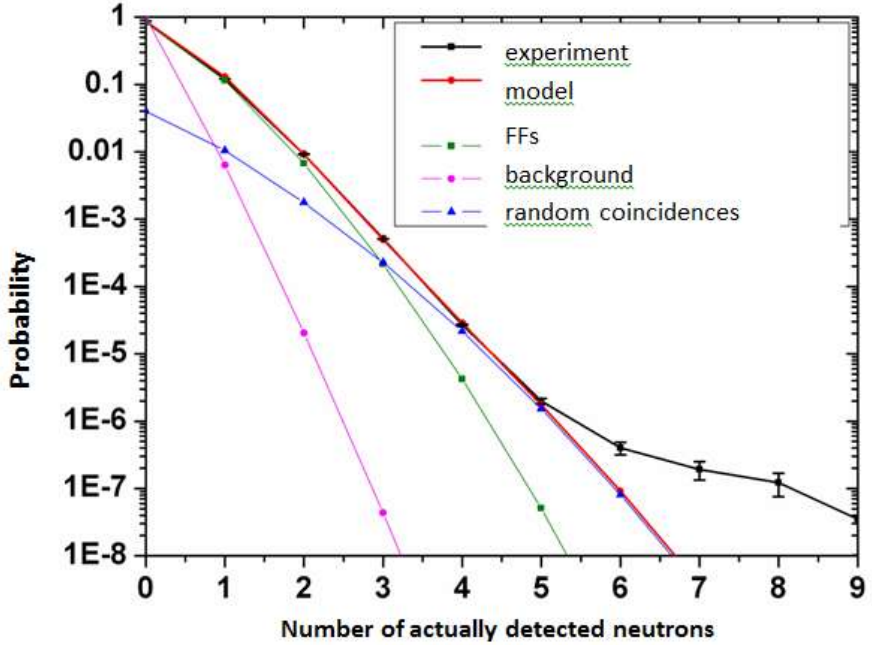
Extremely low TKE !

Estimation of the real neutron multiplicity

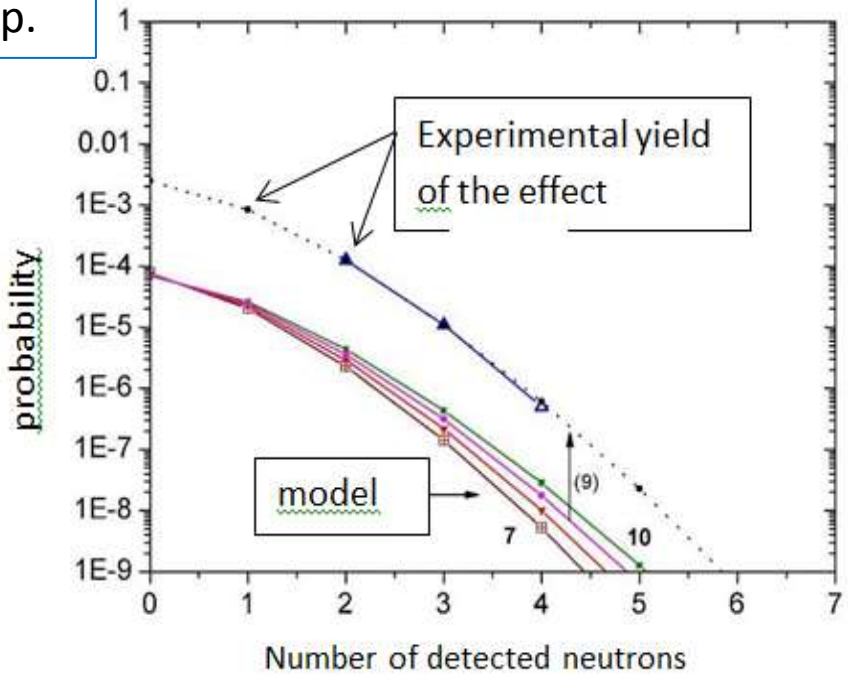
Ex1



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

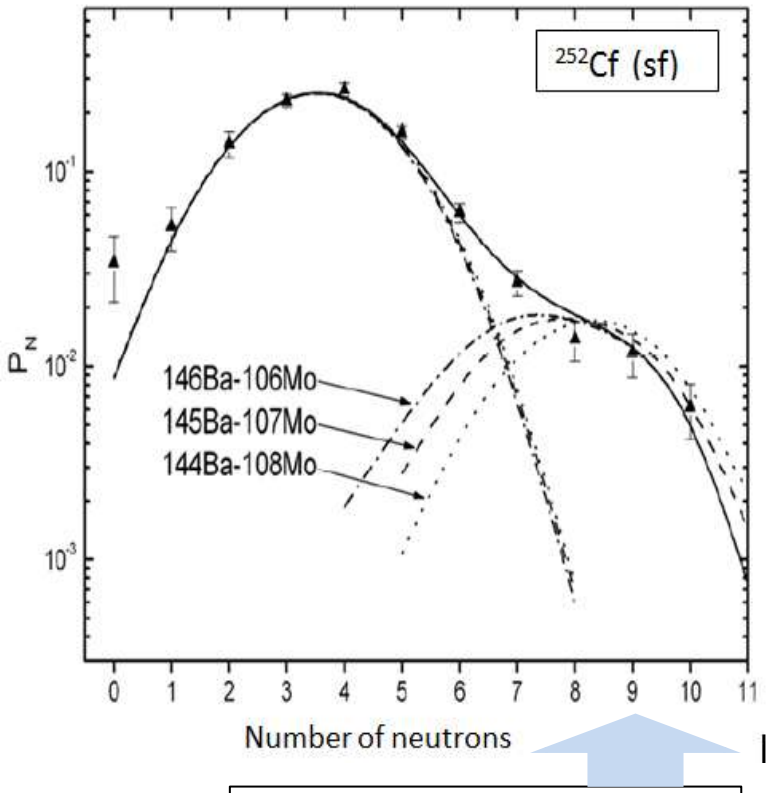


Adequate math. model of the mosaic neutron detector used ("neutron belt")

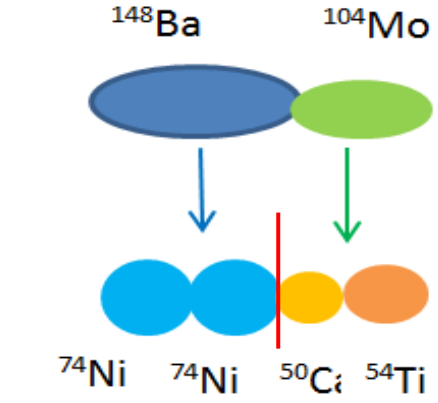


Yn=1~1.3*10-4/bin fission
Yn=2 ~1.3*10-5/bin fission
Due to the slope it could be:
- isotrop. **n~2**
- acc.FFs **n~7**

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

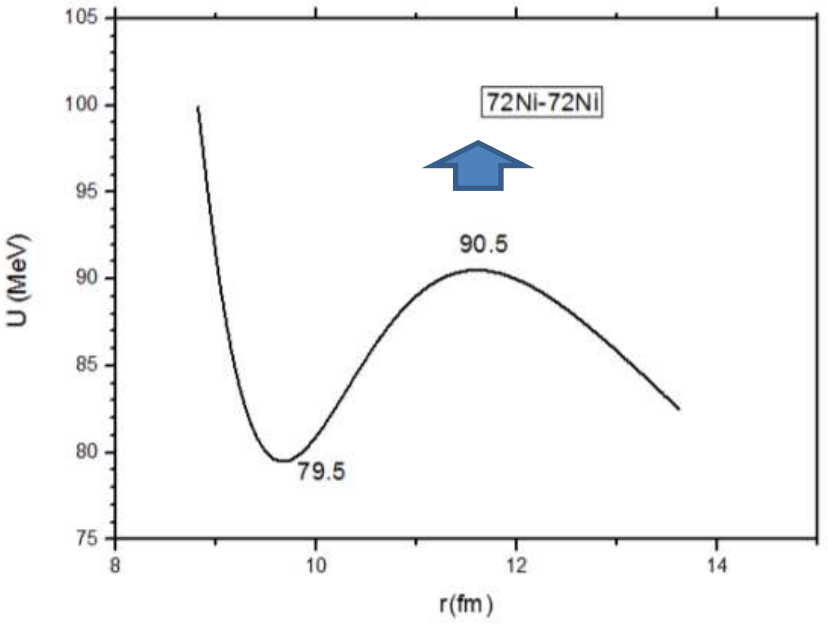
TKE~TKEexp=154MeV, all clusters in 2^+ state

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

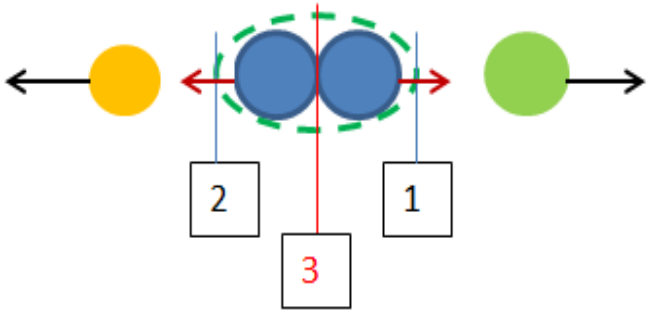
Wu, S. C., Donangelo, R., Rasmussen, J. O., Daniel, A. V., Hwang, J. K., Ramayya, A. V., Hamilton, J. H. New determination of the Ba-Mo yield matrix for ^{252}Cf // Physical Review C - 2000. - Vol. 62, No. 8. - P. 041601-4.

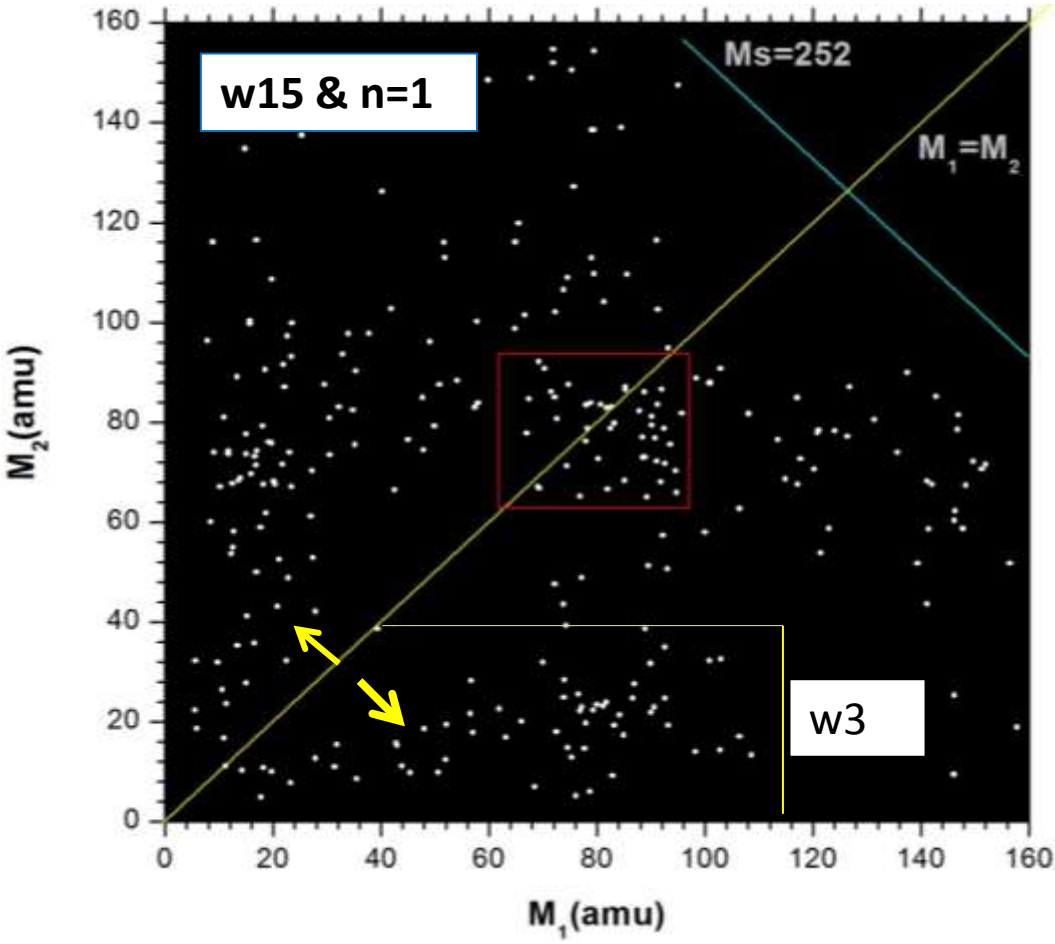
4-body clustering but binary fission

Testing the hypothesis of Ni-Ni core



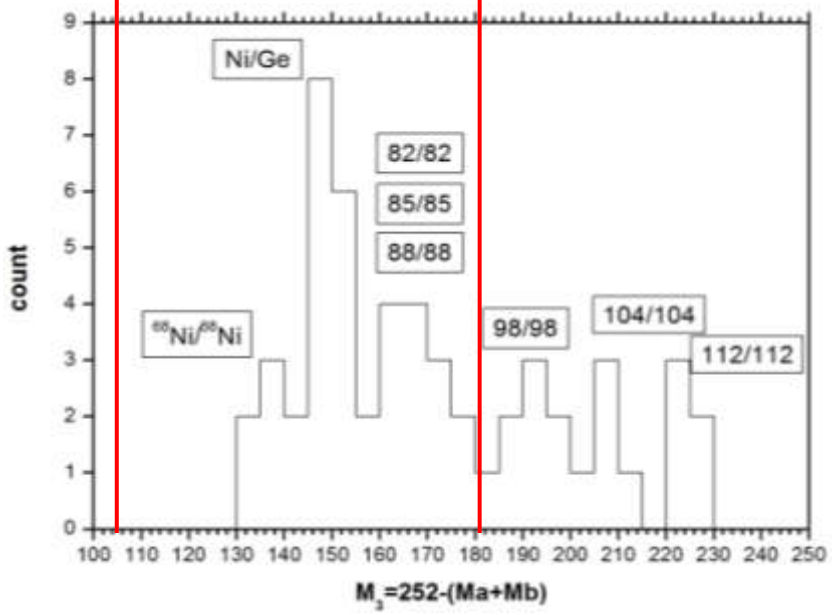
Ni/Ni partition: TKEexp ~ Eb → fission of 144Ba to be at rest?!



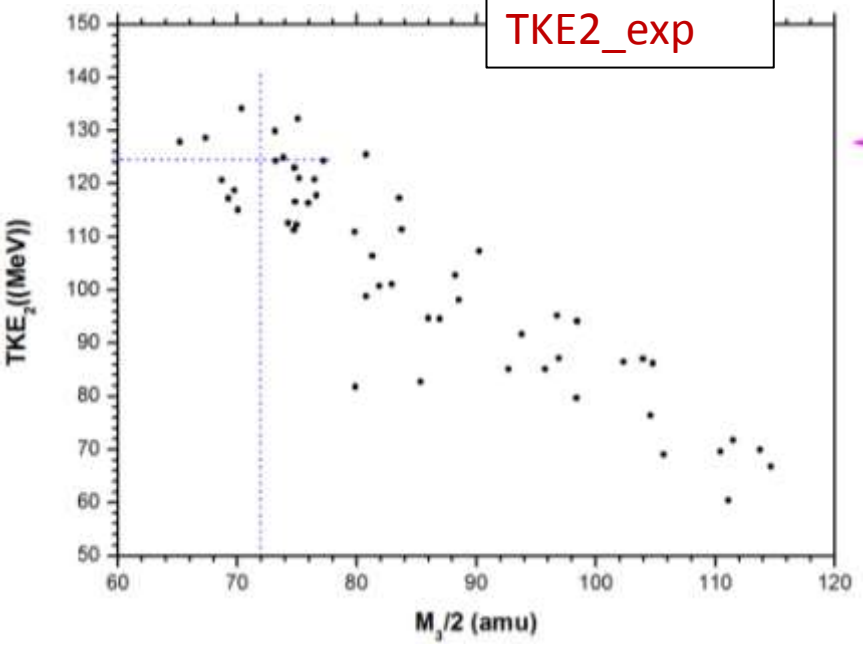


Testing w3-wing to "Ni-square" correspondence

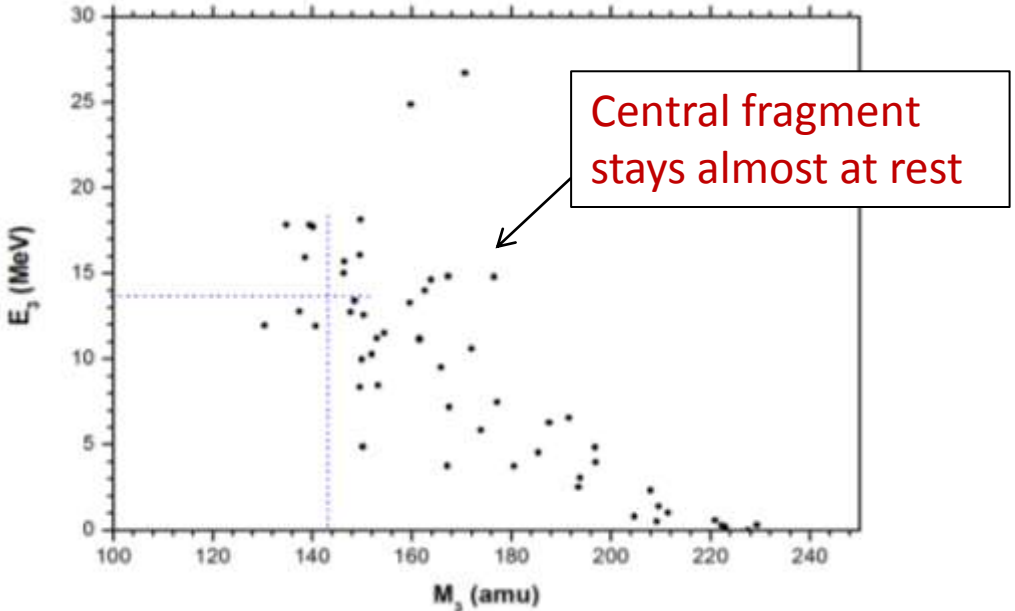
partitions from the rectangle



TKE2_exp



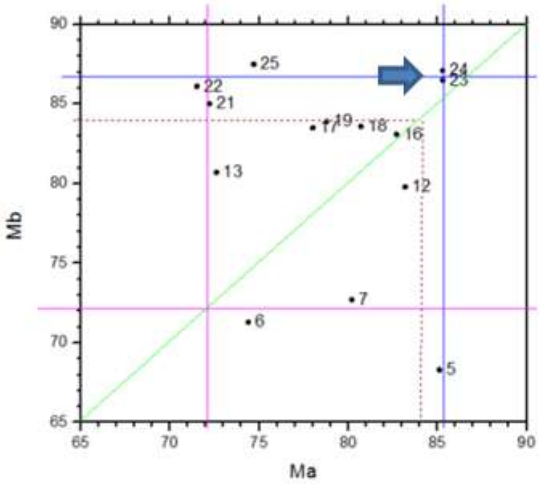
Central fragment stays almost at rest



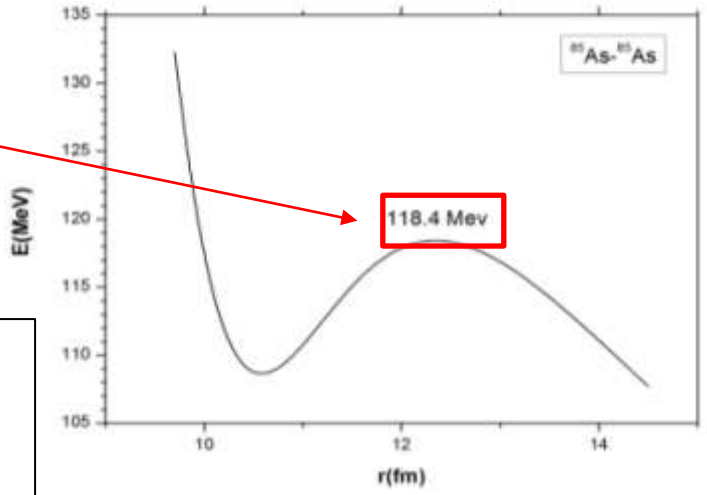
TKE4exp=125+14+90 =229MeV

26Ne-72Ni-72Ni-82Ge
Q4=253MeV
E*=Q4-TKE4exp=24MeV
emitting of ~3neutrons
Good agreement

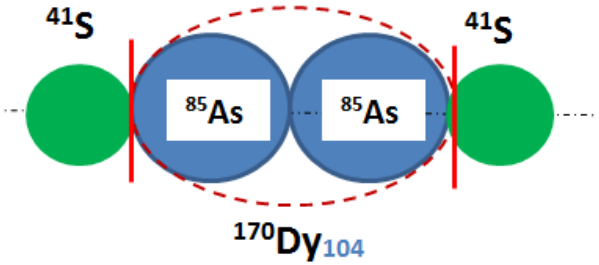
Scission scenario in fully symmetric point: 85As-85As core

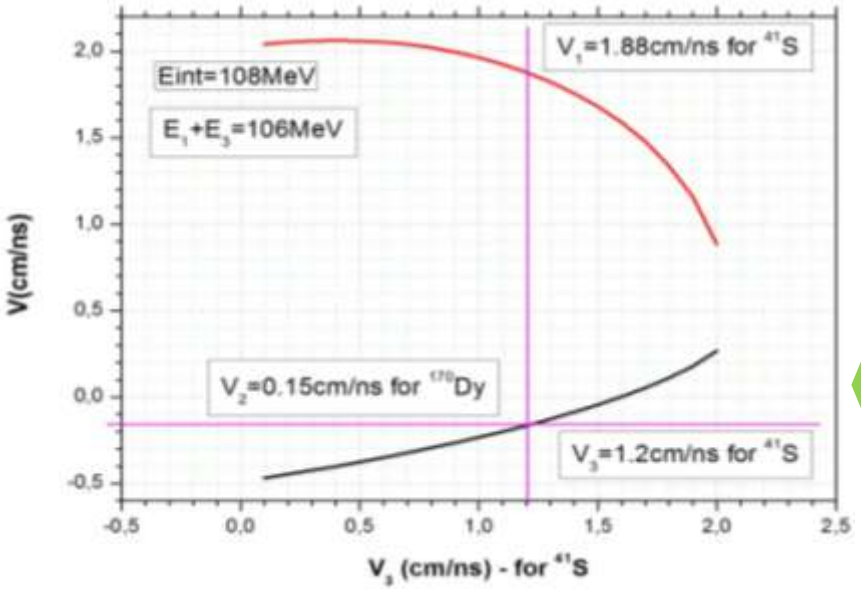


85As/85As (170Dy)
TKE2exp=118MeV
Va_exp=1.3cm/ns
Vb_exp=1.068cm/ns



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

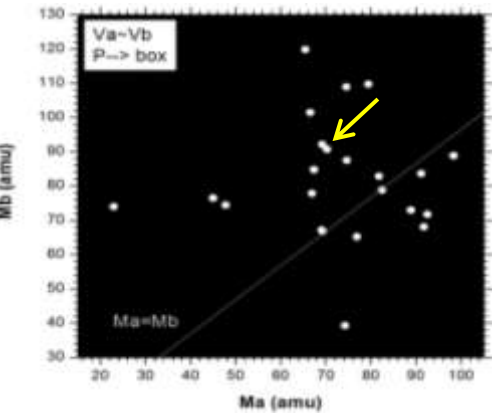


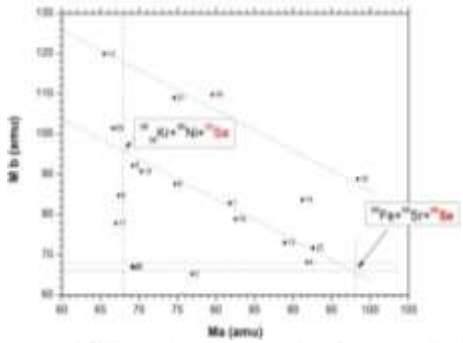


Q3(Cf→S/Dy/S)=165MeV
Q4 (Cf→ S/As/As/S)=235MeV
Q2(Dy→2 85As)=+71MeV
Expected: E*(Dy)=TKE2exp-Q2+Bn=55MeV
Eint (S/Dy/S)=Q3- E* (Dy)- Etr=108MeV

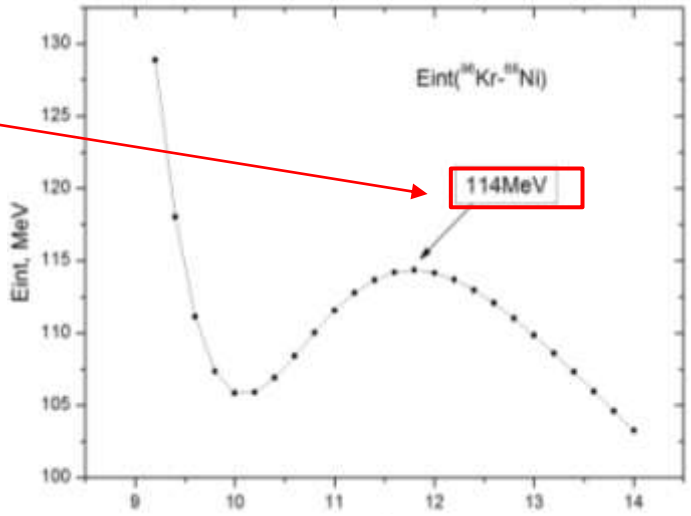
Q4-Q4exp(TKE_2As&2S)=235-232=3MeV
good agreement

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

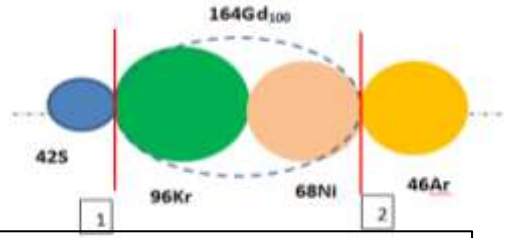


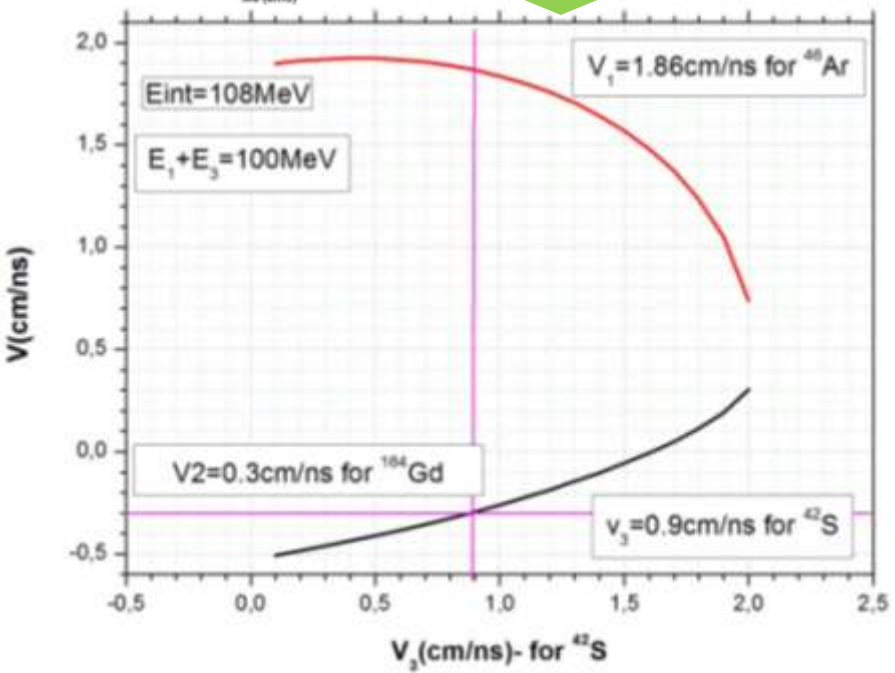


96Kr/68Ni ($164Gd_{100}$)
TKE2exp=116MeV
V(Kr)_exp=1.247cm/ns
V (Ni)_exp=1.101cm/ns



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

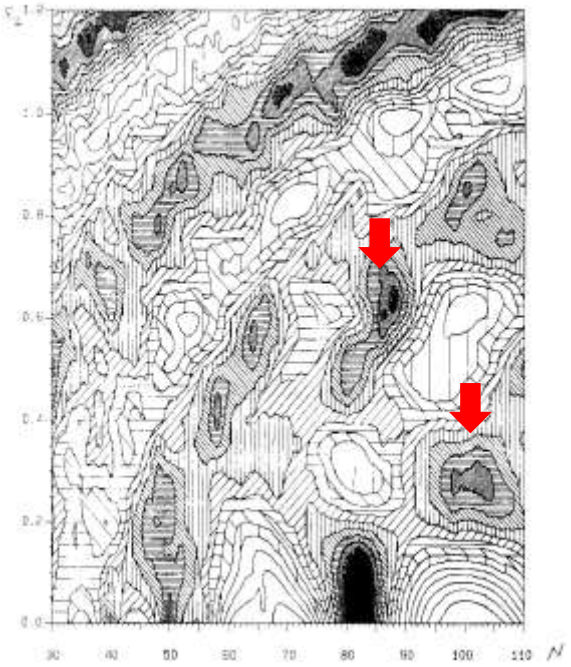


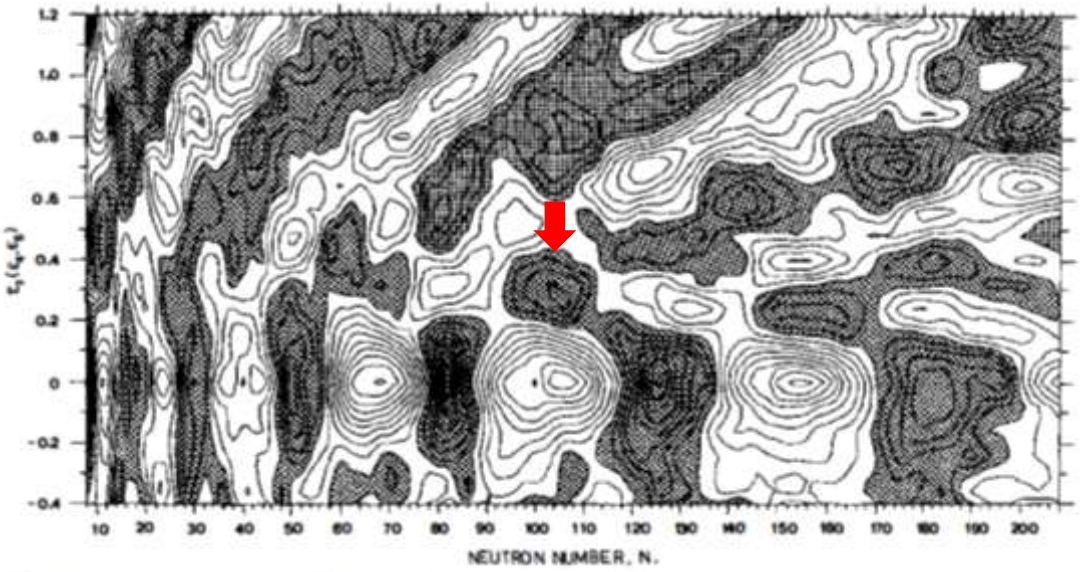


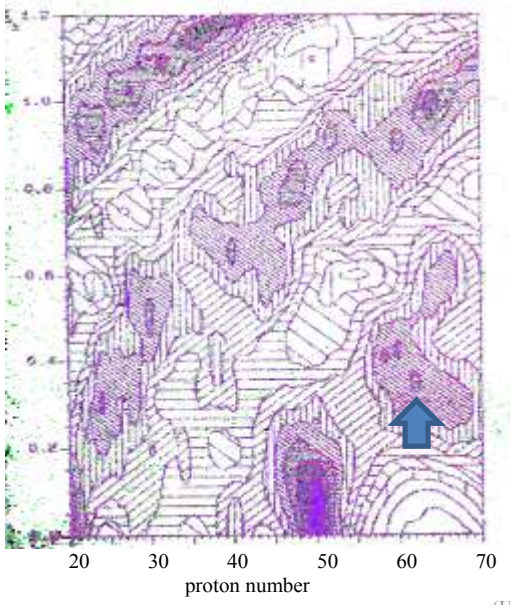
Q3(Cf→S/Gd/Ar)=181MeV
Q4 (Cf→ S/Kr/Ni/Ar)=237MeV
Q2(Gd→Kr/Ni)=+56MeV
Expected: E*(Gd)=TKE2exp-Q2+Bn=66MeV
Eint (S/Gd/Kr)=Q3- E* (Gd)- Etr=108MeV

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

Central core: deformed magic cluster

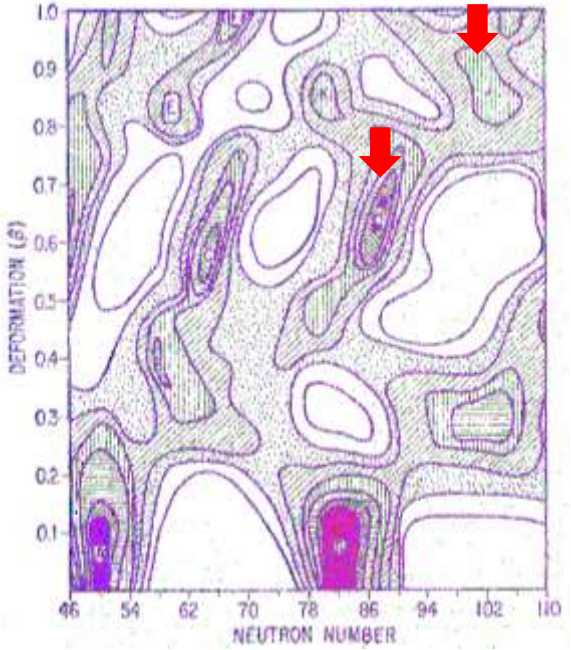






(H.Mä

$\varepsilon_2=0.95\beta_2$

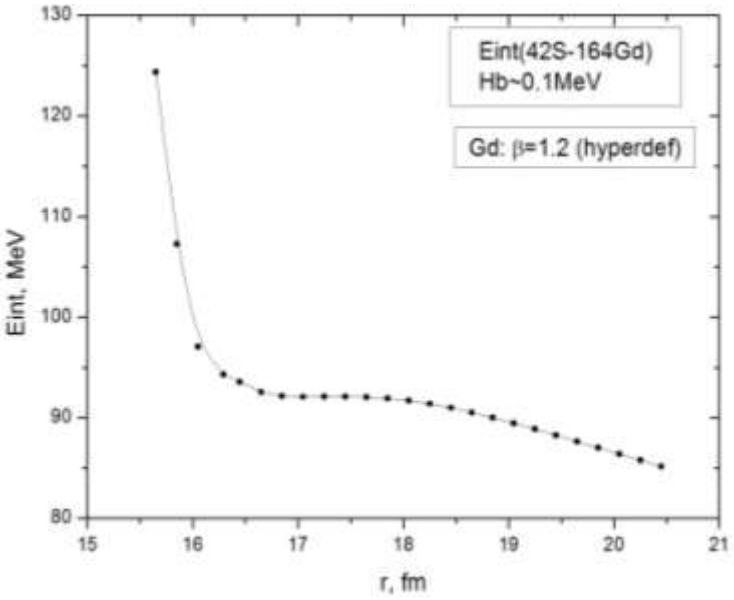


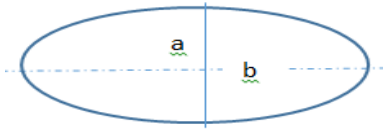
B.D. Wilkins et al., C 14 (1976) 1832

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

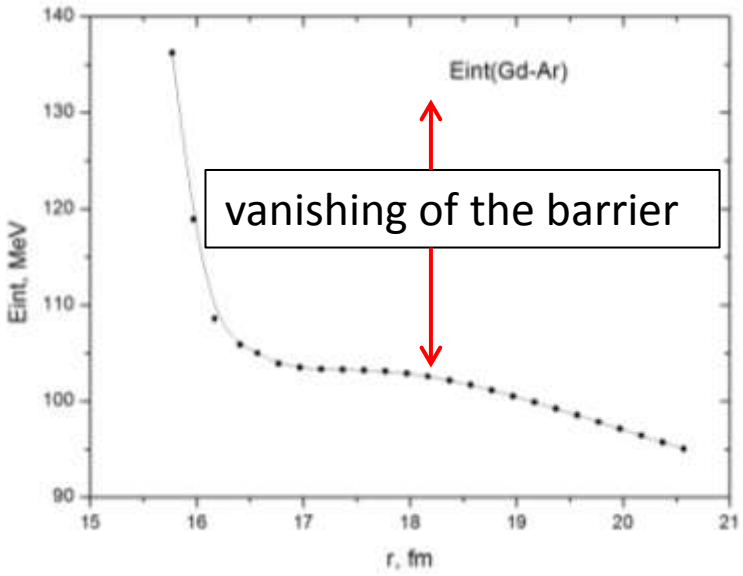
Strong shell minima
at **N~88, 100, Z~ 60**

Almost simultaneous separation of side fragments





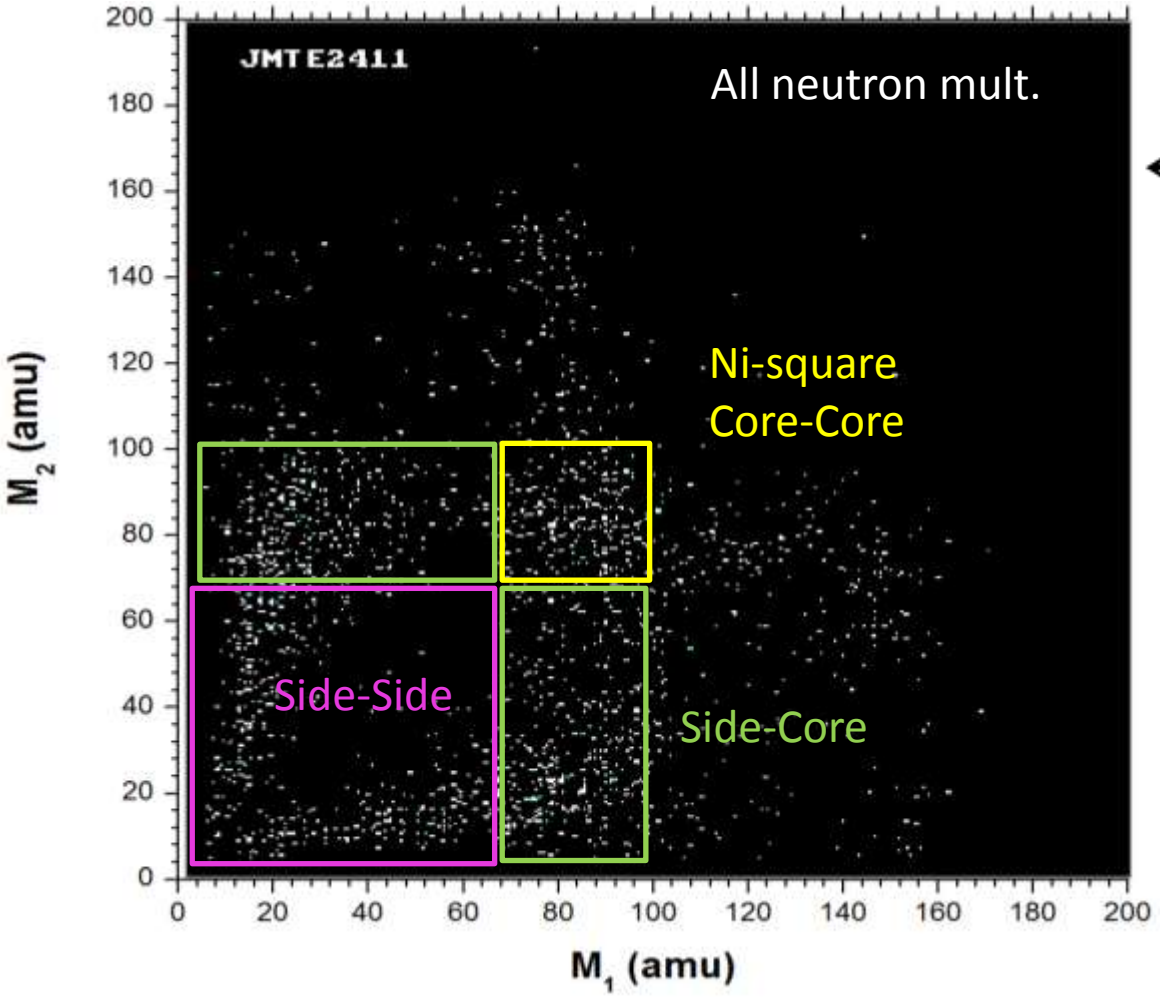
Parameters	Ground state of ^{164}Gd	Hyper-deformed state of ^{164}Gd
β	0,298	1,2
a, фм	5.77	4,40
b, фм	7.68	13,20

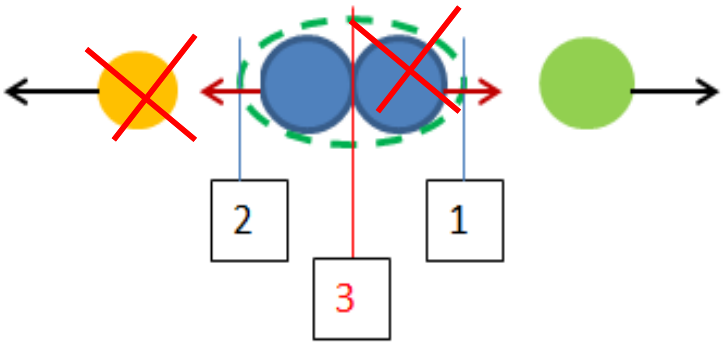


Eint (^{42}S/^{164}Gd$_{def}$/^{46}Ar) =211МэВ;
Q3=181.03 MeV;
30 MeV deficit , fission is interdicted → prescission configuration should be more elongated up to the moment Eint ≤ Q3;

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

Consistency test: side-core coincidences





Limits of decay times:

$\tau_{1\text{-}2} \sim 10^{-21}$ s

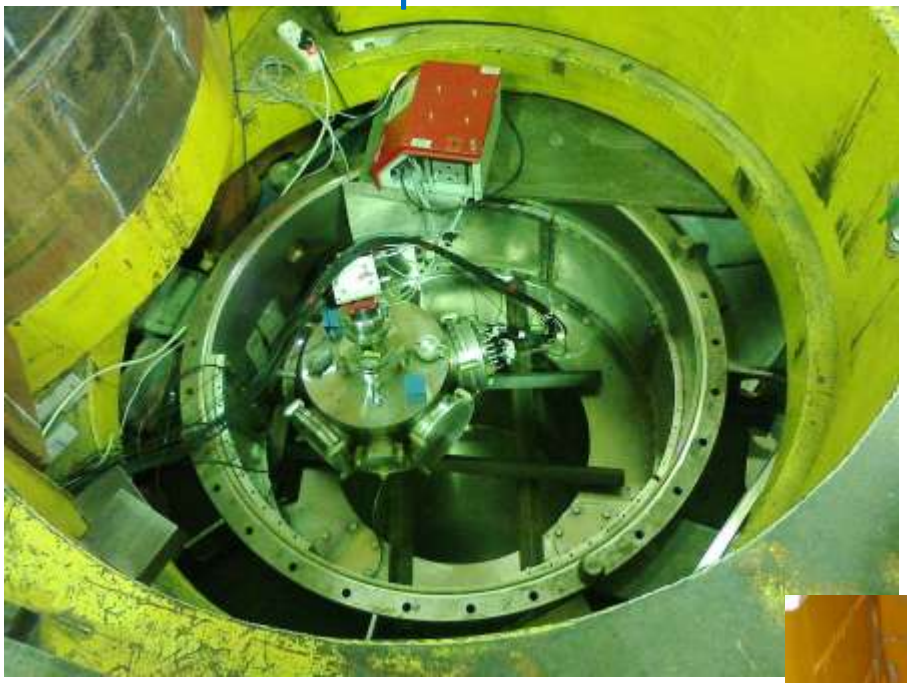
$\tau_{2\text{-}3} << 1$ ns

Conclusion

Strong experimental indication of the **Mass-symmetric (true?) quaternary decay** of heavy low excited nucleus is obtained for the first time.

Our plan to the next ISINN

Current experiment at IBR-2



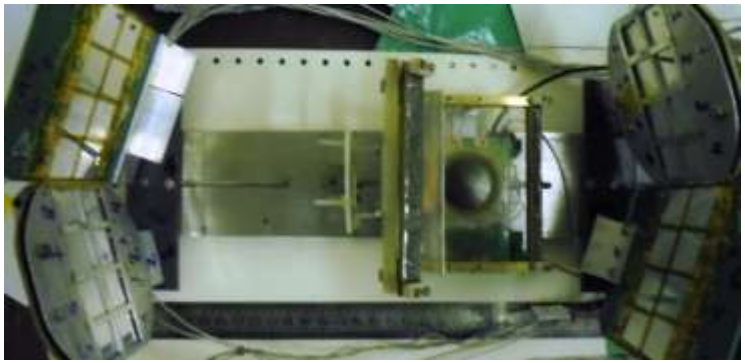


Photo-fission experiment at MT-25