Super-asymmetric Fission

F. Gönnenwein[1)], E. Chernysheva[2)], J.M. Itkis[2)], M.G. Itkis[2)], G. Knyasheva[2)] and E.Kozulin[2)]

1) University of Tübingen/Germany, 2) JINR, Laboratory of Nuclear Problems, Dubna/Russia

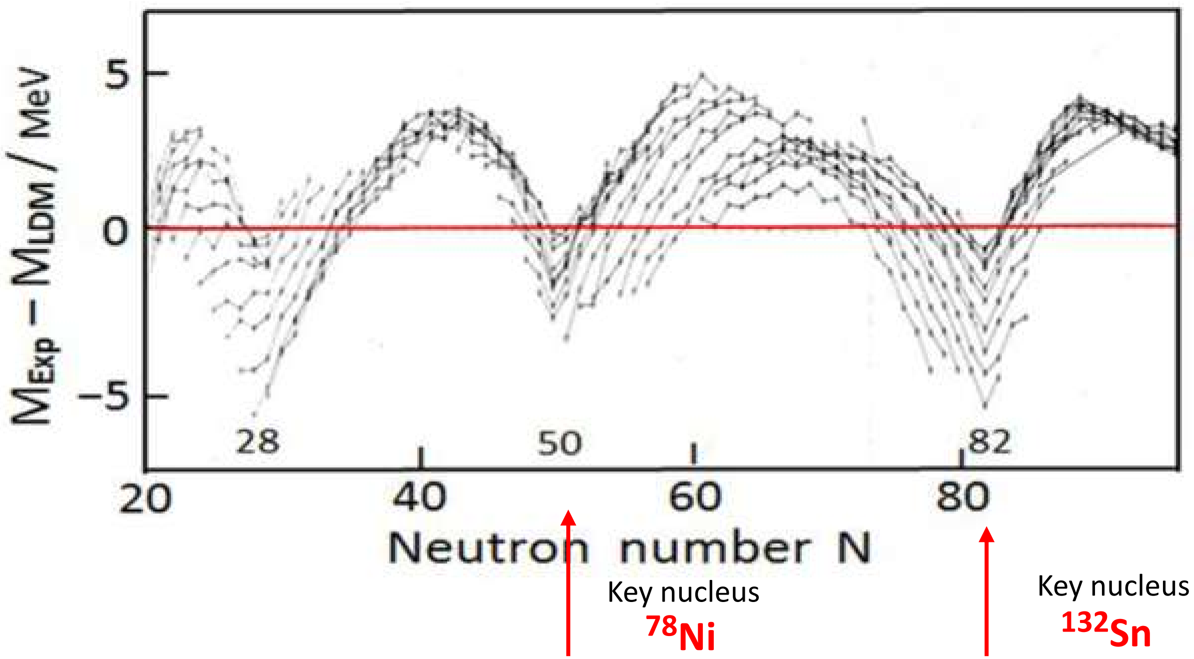
ISINN 27 Dubna June 2019

Shell Effects in Nuclei undergoing Fission

Nuclear masses are described by the Liquid Drop Model (LDM):

$$M(A,Z) = a_V A + a_S A^{2/3} + a_C Z^2/A^{1/3} + a_I (N-Z)^2/A - \delta(A)$$

Volume, Surface, Coulomb, Symmetry, Pairing



Key nucleus ^{78}**Ni**

Key nucleus ^{132}**Sn**

Macroscopic LDM describes average masses.
Microscopic nuclear structure necessitates corrections.

$$\boxed{\delta W = M_{exp} - M_{LDM}}$$

Myers-Swiatecki 1966: neutron and proton ranges with $\delta W < 0$ and $\delta W > 0$ alternate

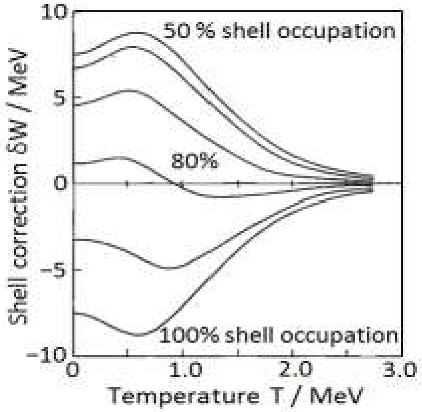
δW < 0: nuclei are more tightly bound than in LDM : **“SHELLS“**

δW > 0: nuclei are less tightly bound than in LDM : **“ANTI-SHELLS“**

Influence of shell effects around fragment masses A = 132 u in fission is dramatic: It explains the prominent asymmetry in the mass distributions of fission fragments in the actinides

Influence of shell effects around fragment masses A = 78 is less spectacular. It becomes only visible in detailed analysis of mass and kinetic energy distributions of fission fragments

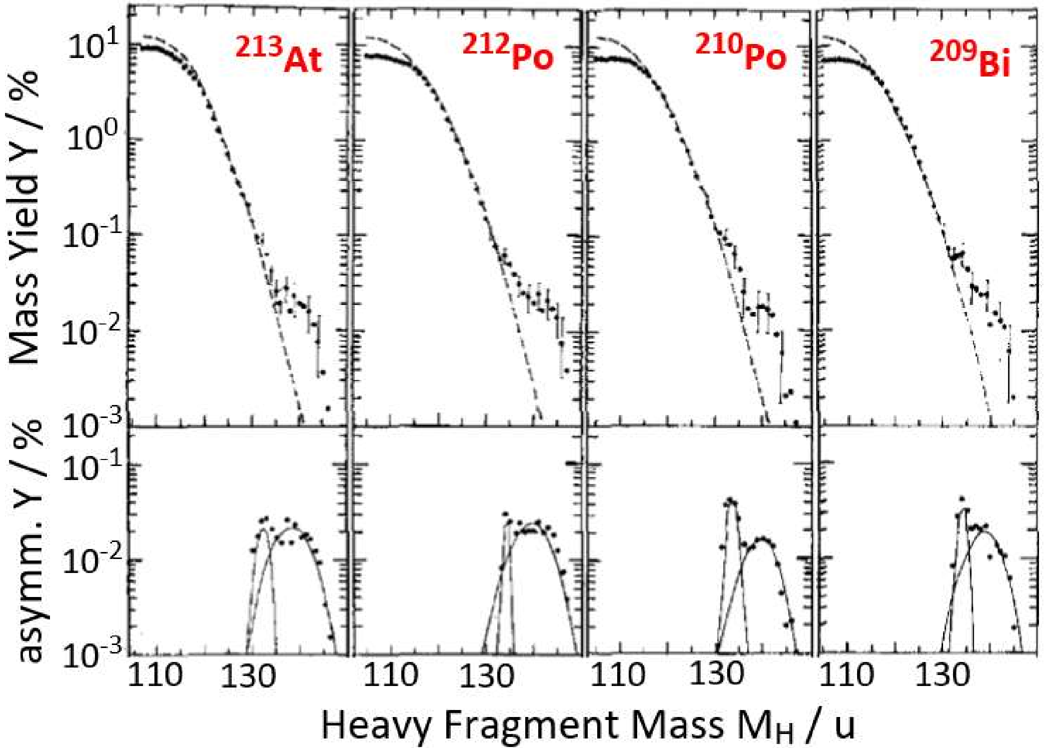
Characteristic property of shells:



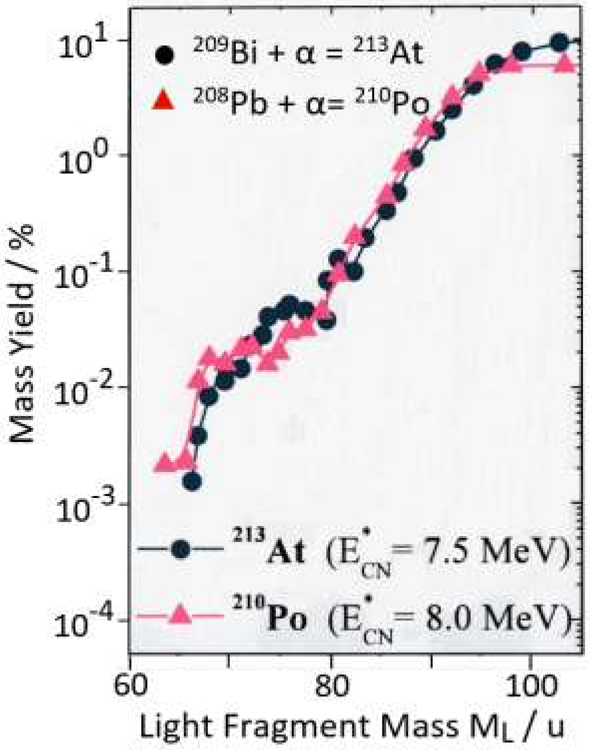
Shell effects disappear when excitation energy is increased

Superasymmetric fission in the preactinides

α-induced reactions leading to



Itkis 1988



Itkis 1988

Mass distribution is symmetric but in tails appears at large masses shell structure (Brosa modes):
Standard I at $\langle A_{ST\ I} \rangle$ = 134 u
Standard II at $\langle A_{ST\ II} \rangle$ = 139 u

KEY NUCLEUS
^{132}Sn

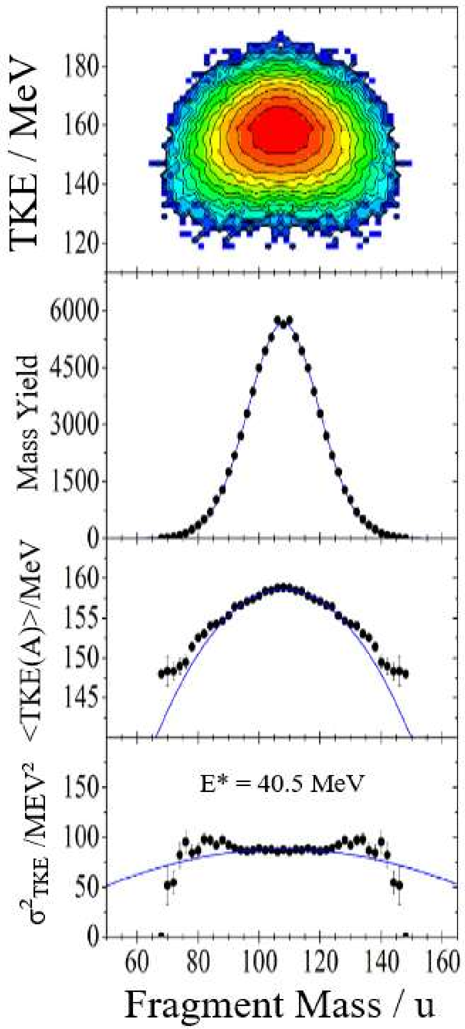
At small fragment masses structure
Standard III at $\langle A_{ST\ III} \rangle$ = 78 u

KEY NUCLEUS
^{78}Ni

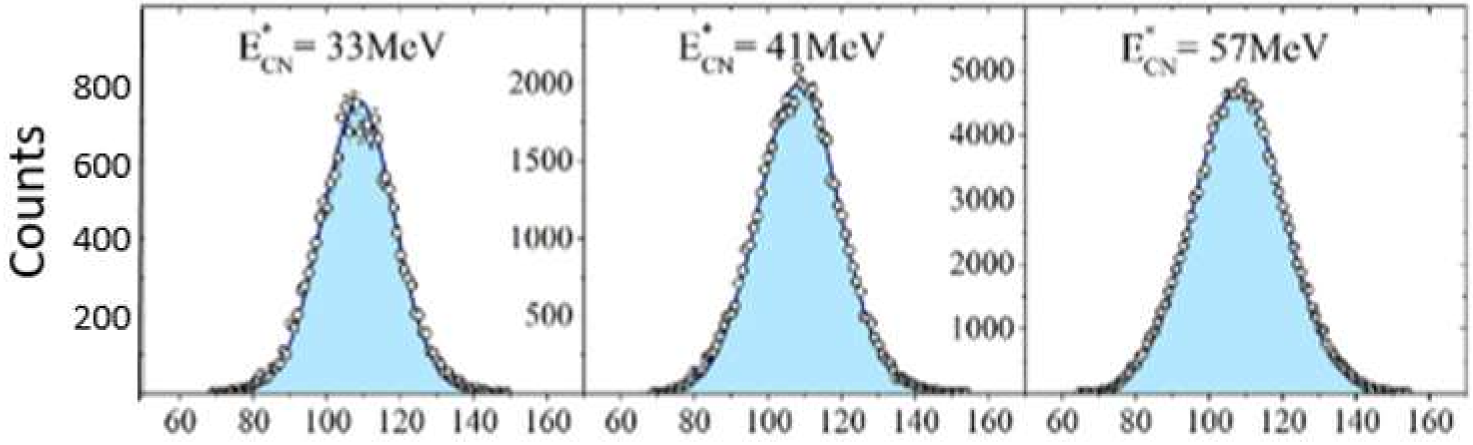
Super-asymmetric Fission

Super-asymmetric Fission of ^{214}Ra

$^{12}C + ^{204}Pb \rightarrow ^{214}Ra^*$



$^{12}C + ^{204}Pb \longrightarrow ^{216}Ra$



Surprisingly, in the fragment mass distribution of $^{12}C + ^{204}Pb \rightarrow ^{214}Ra$ there is no indication for shell structure in the restricted mass range $A_{CN}/2 \pm 25$ u. By this restriction in mass the ST III mode is cut away. However, in the TKE(A) and the $\sigma^2_{TKE}(A)$ plots the mode St III is clearly present.

Noteworthy : St III stronger than St I and St II

Fragment Mass / u

Chizov 2003

Super Asymmetric Fission in the standard Actinides

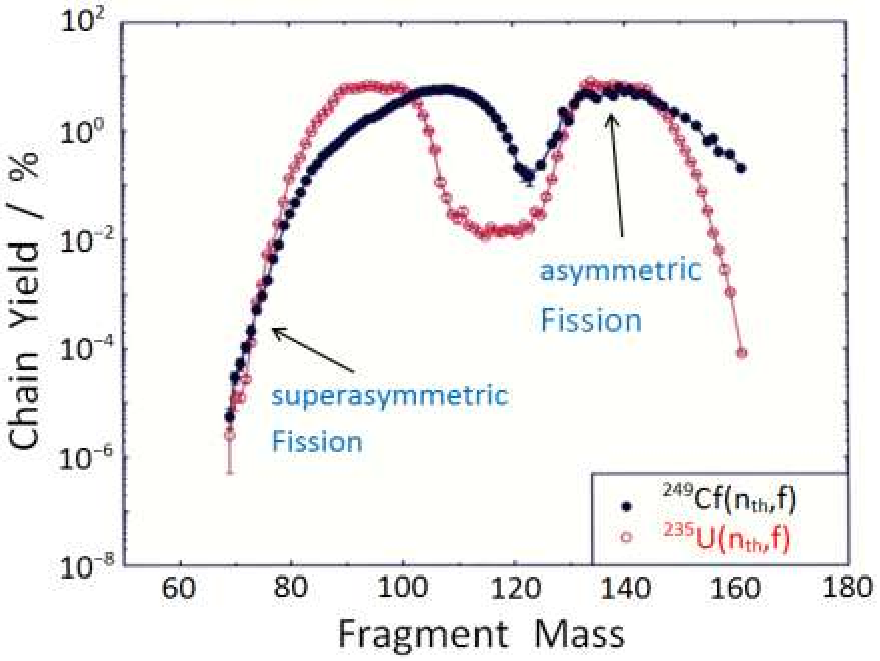
thermal Neutron induced

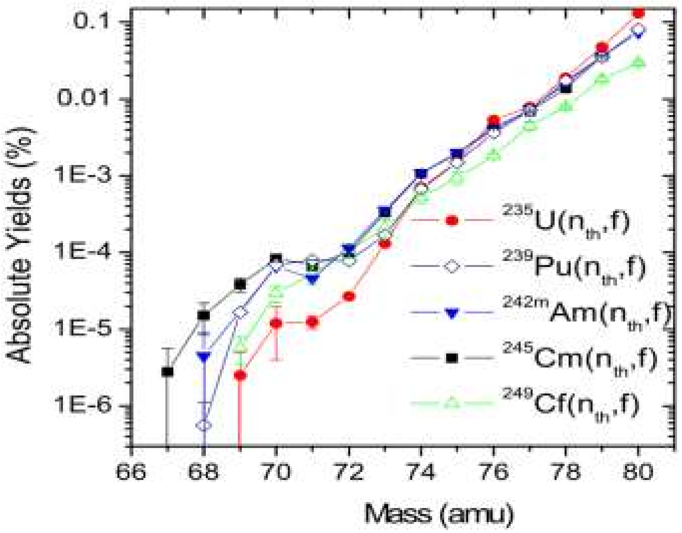
Shell modes St I and St II fix asymmetric fission.

KEY ^{132}Sn

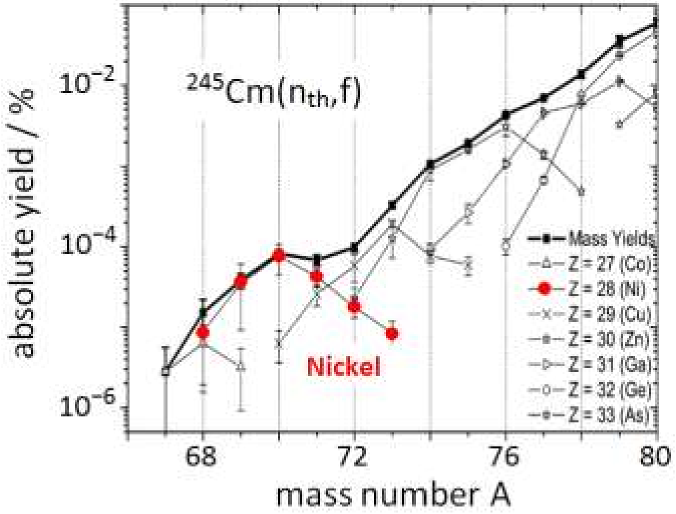
Shell mode St III fixes Super-asymmetric fission

KEY ^{78}Ni





Standard III is present in all (n$_{th}$, f) reactions



The key nucleus ^{78}Ni
Is not observed.
But the element Ni is prominent

ILL Lohengrin collaboration

Super-asymmetric Fission in electromagnetic Fission ?

●

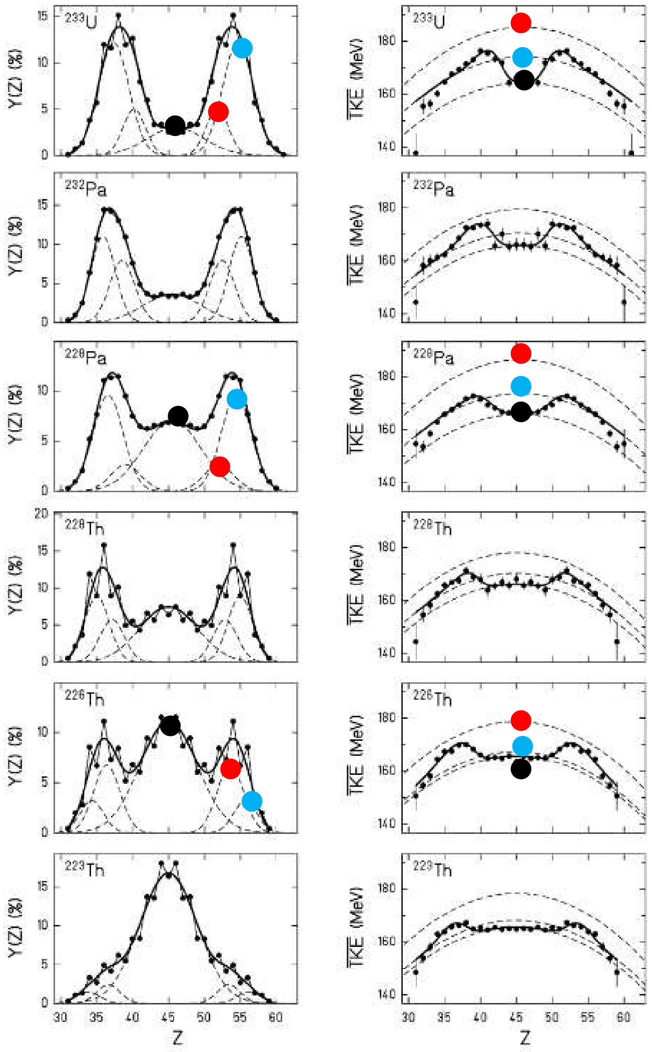
Liquid Drop Model

●

Standard I

●

Standard II



No super-asymmetric St III
In electromagnetic Fission

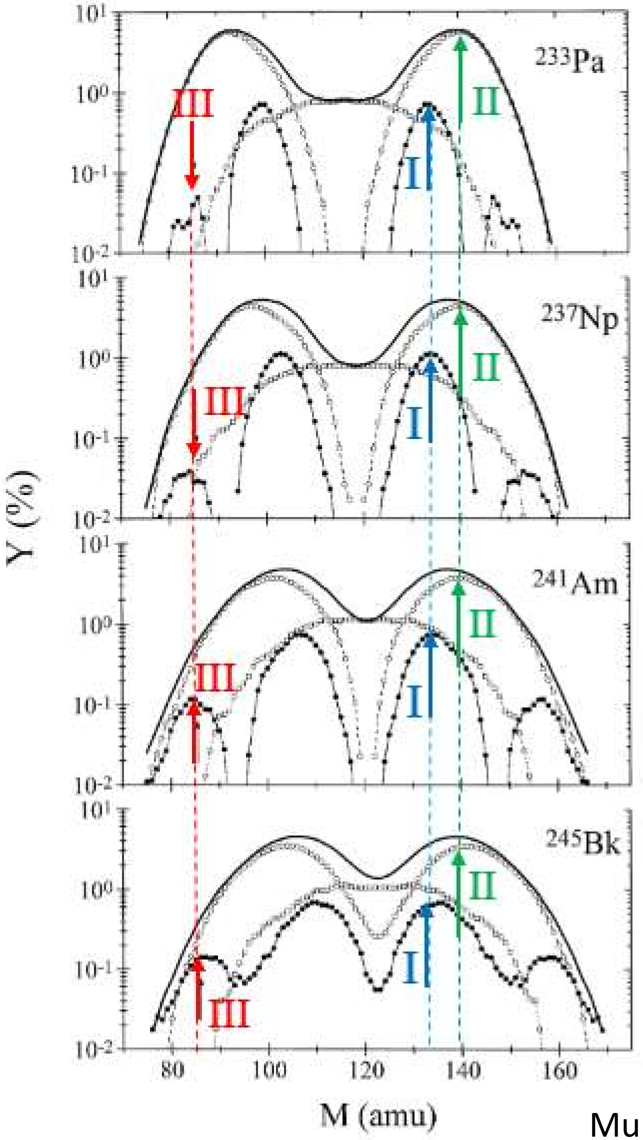
Average excitation energy $E^* \approx 11$ MeV

Böckstiegel 2008

Super Asymmetric Fission in the standard Actinides

at intermediate excitation

10.3 MeV proton induced Fission



Mulgin 1999

Constant mass position
for St I and St II
in <u>heavy</u> mass group

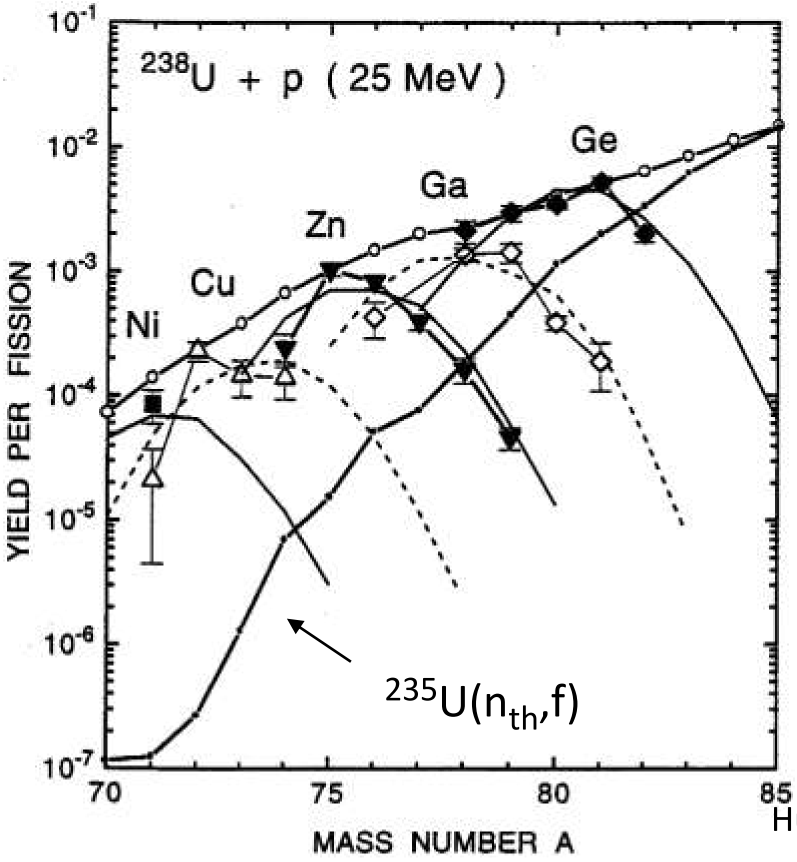
Constant mass position
for St III
in <u>light</u> mass group

Element by element zoom for St III in
p + ^{238}U → ^{239}Np

Yield of St III increases dramatically with T.

Yet also in Liquid Drop Model $\sigma^2_M \sim T$

This increase has to be taken into account



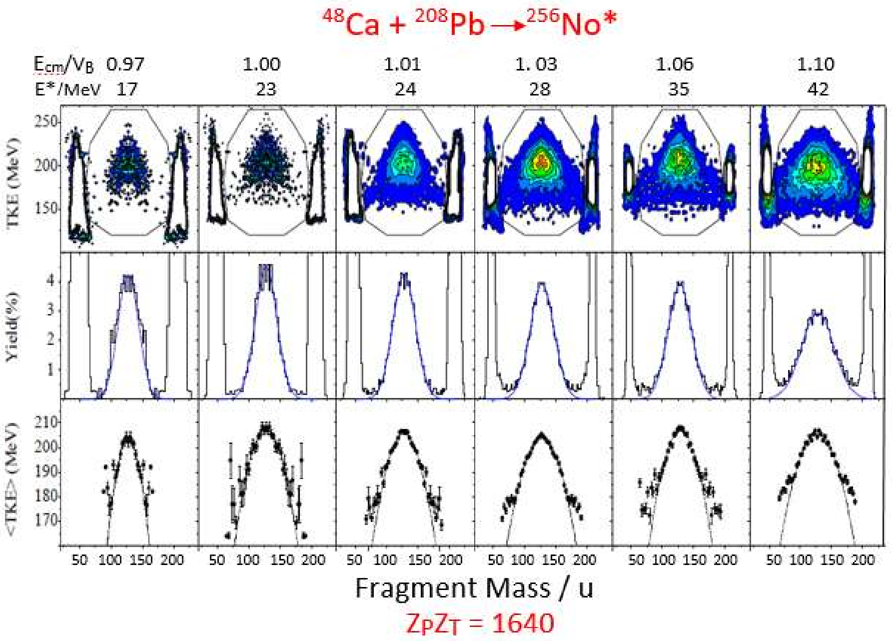
^{235}U(n_{th},f)

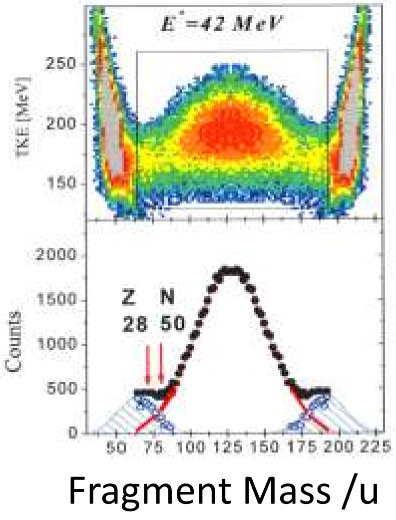
Huhta 1997

PLB 405,230 (1997)

Super-asymmetric Fission in ^{256}No

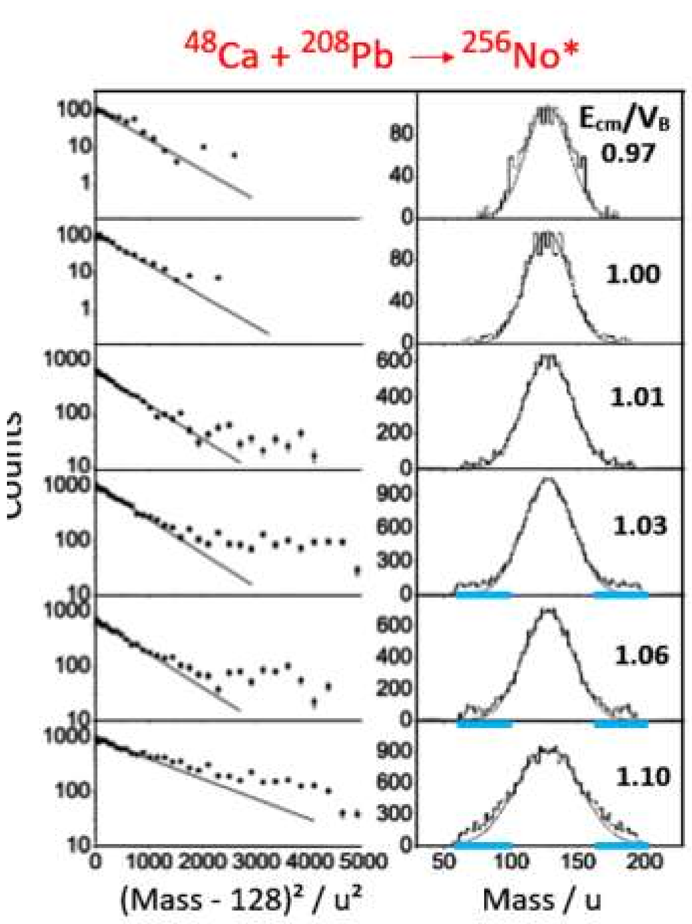
Sup.asym. Fission at high excitation





Zoom of MED
at highest E*

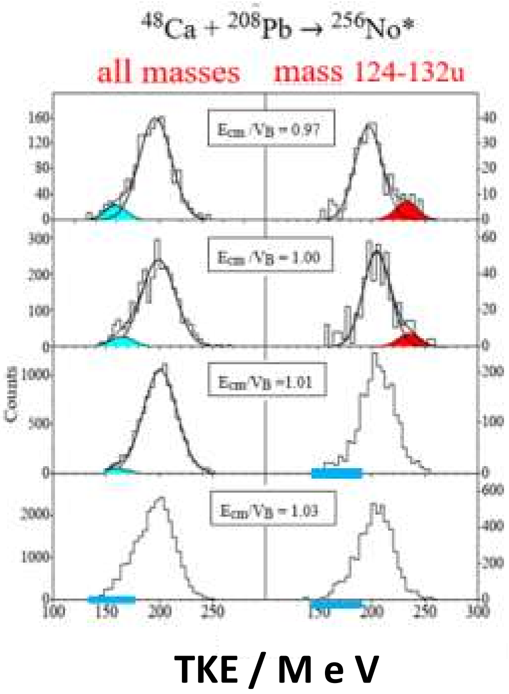
Structure (in blue)
attributed to
Super-asymmetric fission
Key nucleus ^{78}Ni



Flattening of Gaussian fit: $\sigma^2_M \sim T$ LDM

Super-asymmetric Fission ↗ excitation energy E*

SAF is Quasi-Fission



TKE / M e V

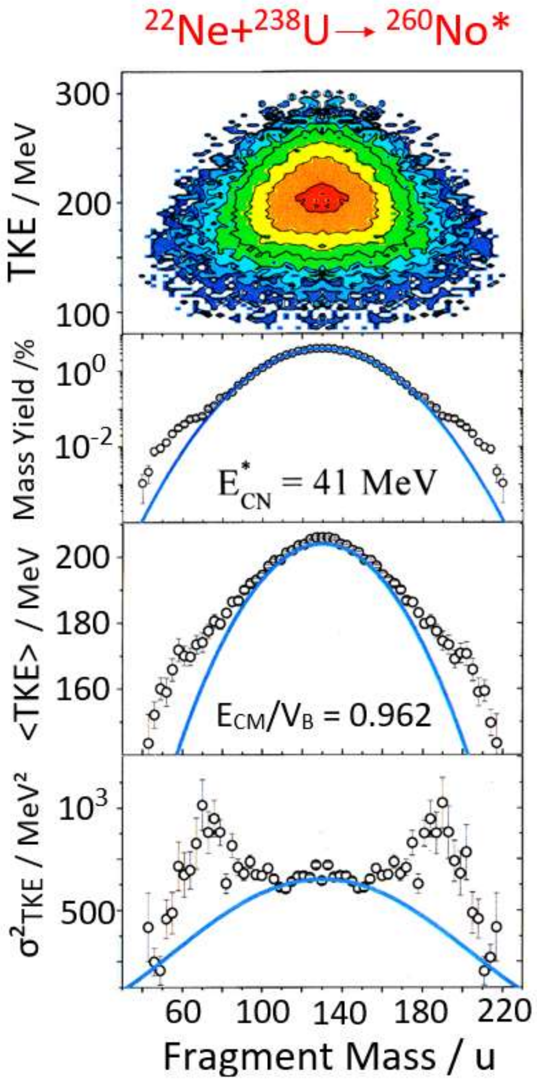
St I and St II at high TKE

St III and SAF at low TKE

E. Chernysheva 2019

Super-asymmetric Fission in ^{260}No*

Sup.asym. Fission is dominant

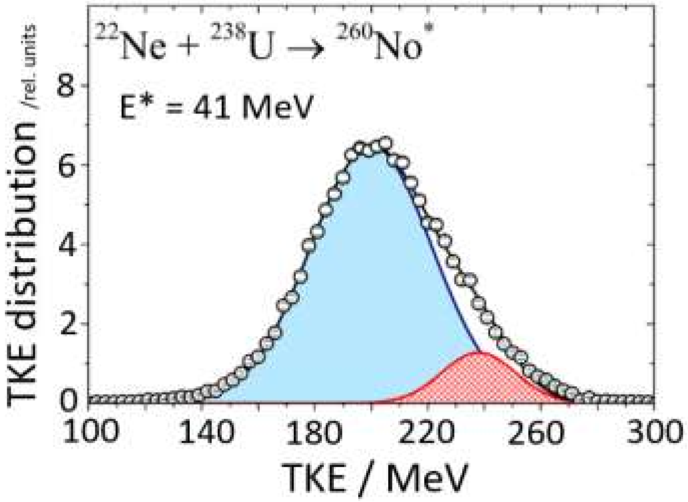


MED plot at
$E_{cm}/V_B = 0.962$
shows no asym.
Quasi-Fission

Pronounced structure in far asymmetric fission

Structure traced to **St III** super-asym. Fission

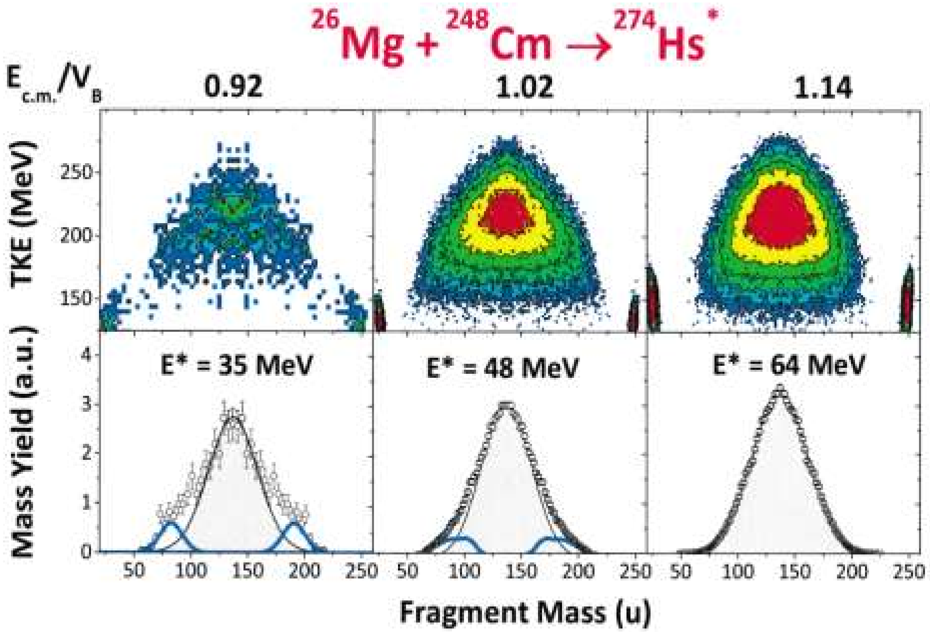
Structure best evidenced by $\sigma^2_{TKE}(M)$ with peaks near **^{78}Ni**

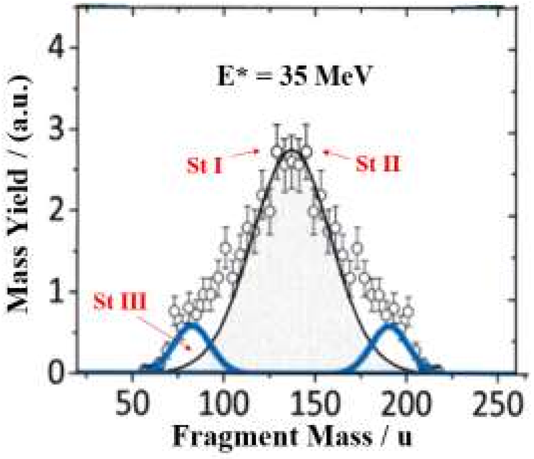


In heavy Ion induced fission of the heavy Actinide ^{260}No the mode St III is dominant. A trace of the more common modes St I and St II is only visible in the TKE distribution at high TKE energies for fragments near the KEY nucleus ^{132}Sn

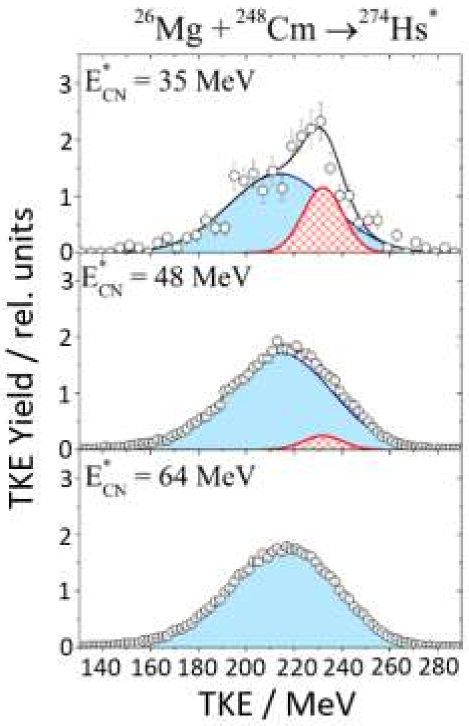
J.M. Itkis 2018

Super-asymmetric Fission in Super-heavy Nuclei





Zoom of mass yield
Strongly pronounced St III
In CN reaction



St I and St II best seen in TKE distribution near symmetry $A_{CN}/2 \pm 20$ u

One of the few examples of Heavy Ion reactions where MED is not overwhelmed by Quasi-Fission. Only for this type of reactions it is possible to start a shell effect analysis of Compound Nucleus Fission.

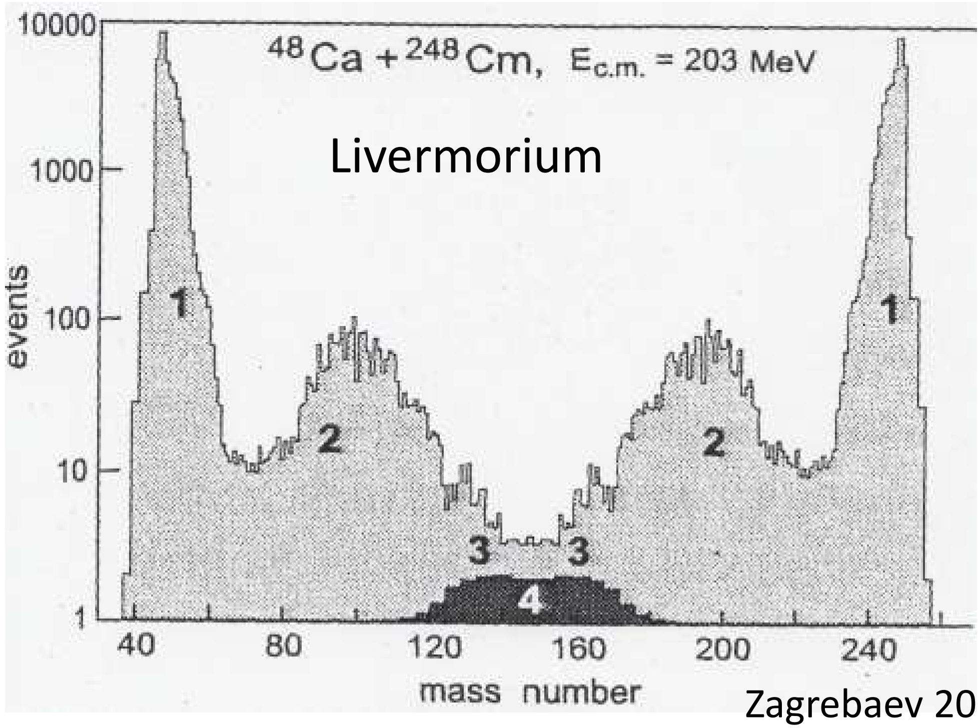
In CNF all shell effects fade away at higher excitation

J.M. Itkis 2011

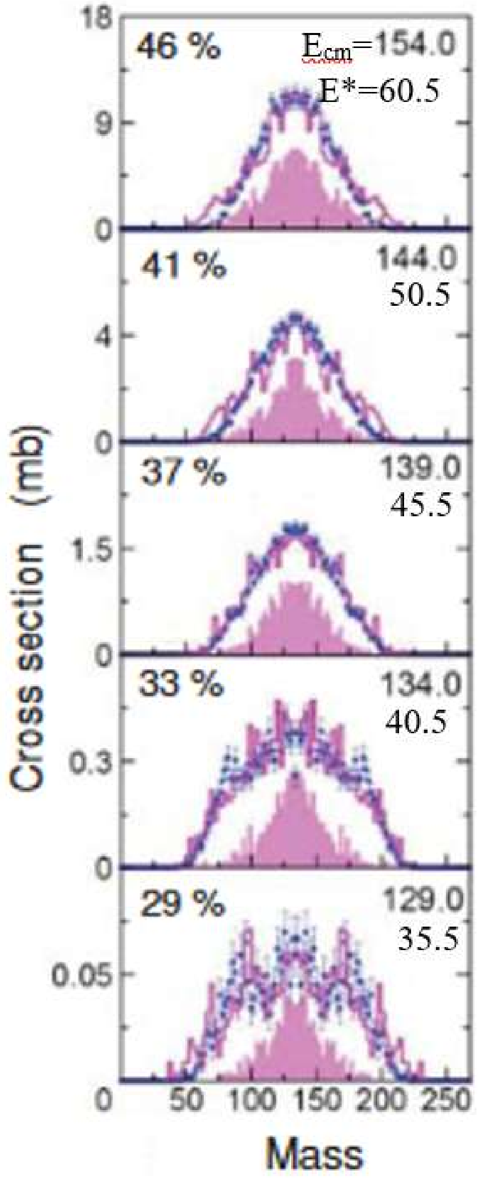
Theory of Mass Distributions for FF + QF

Theory of Heavy Ion Reactions identifies the different sources of fission.

Mass distribution Y(A) for Livermorium (Z = 116)
1= Deep Inelastic Scattering
2= Fast asymmetric QF I
3= Slow QF II near to symmetry (not going through CN)
4= Compound Nucleus Fission with symmetric Y(A)



Zagrebaev 2008



Remarkable:
Theory predicts QF near symmetry with ≈ constant contribution up to high excitation energies E*.

From experiment it is tentatively conjectured that the QF is mainly SAMF.

Super-Asymmetric Mass Distribution

Aritomo-Nishio 2008