

Influence of asymmetry and fissility on even-odd effect in fission-fragment yields

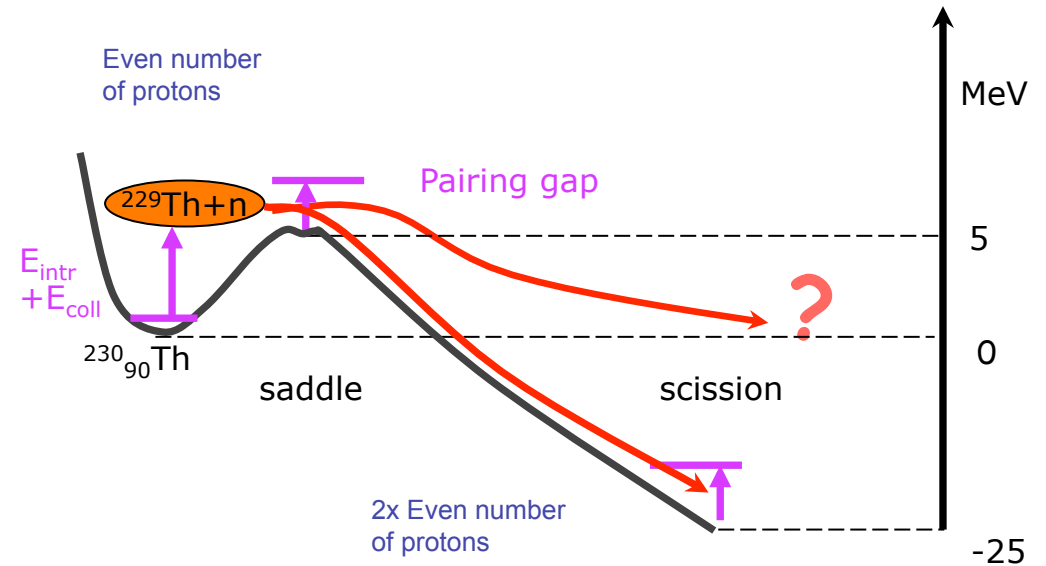
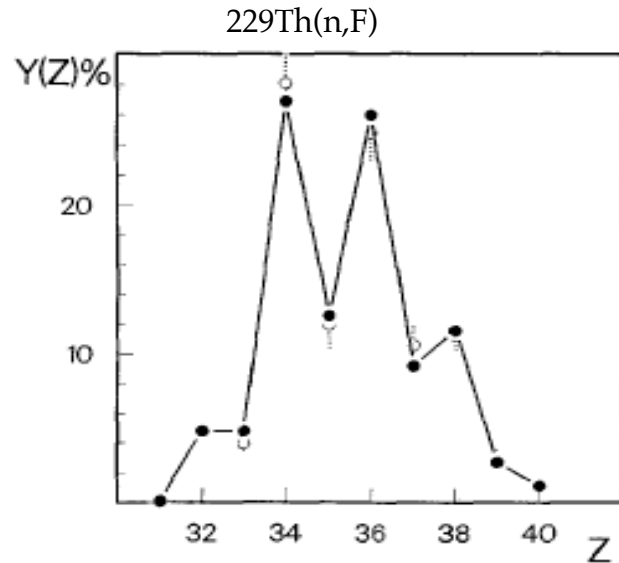
M. Caamaño, F. Rejmund, K.-H. Schmidt

USC, GANIL, GSI

Element yields in n_{therm} induced fission (Lohengrin)
e.m. induced fission in inverse kinematic (GSI)

1. Conventional interpretation of the even-odd effect
2. Asymmetry: the forgotten parameter
3. Consequences of the more complicated picture

Even-odd staggering in fission fragment element yields



J.P. Bocquet et al., Z. Phys A 335(1990)41

Even-odd staggering in Z distribution evidences:

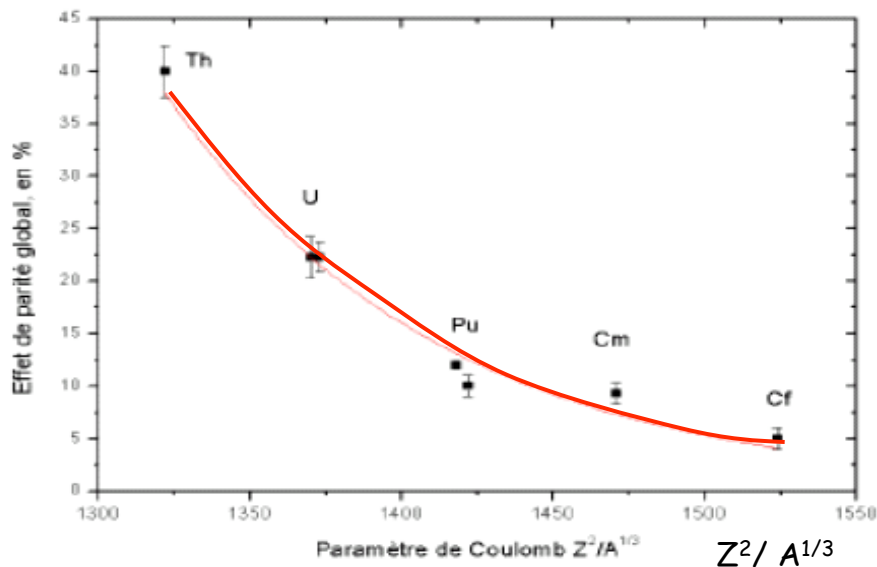
- proton pairs are broken in the descent and may end-up in 2 different fragments
- dissipation in the descent

Challenge to physicists to understand how and how much energy is dissipated

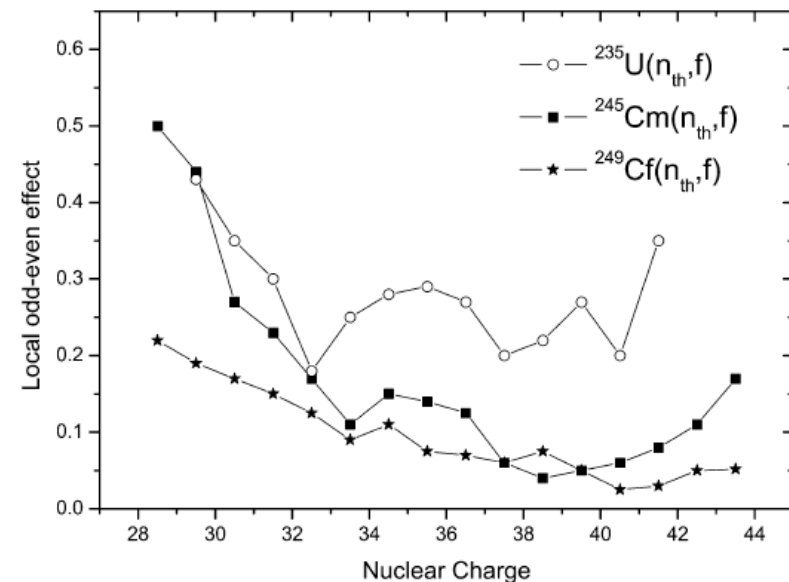
Standard picture of the even-odd effect

- Even-odd effect is understood as a consequence of the dissipated energy during deformation.
- If one pair at least is broken, the even-odd effect is null
- It reflects the probability that the protons remain in a full paired configuration at scission
- Its lower amplitude is associated to a hotter fission (more dissipation) as fissioning system becomes heavier for symmetric fission

=> Dissipated energy increases with fissility

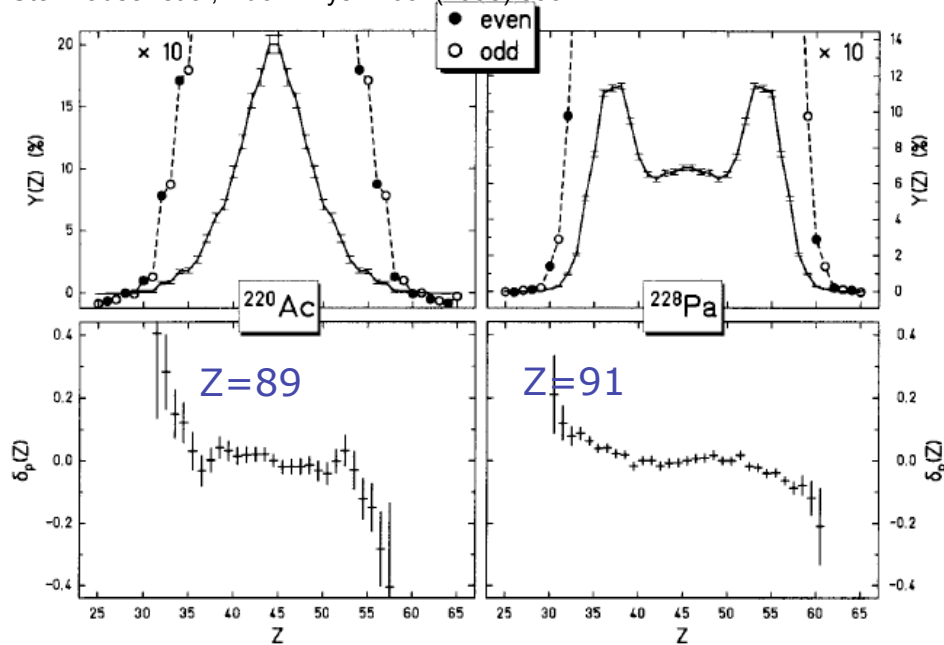


=> Dissipated energy higher at symmetry

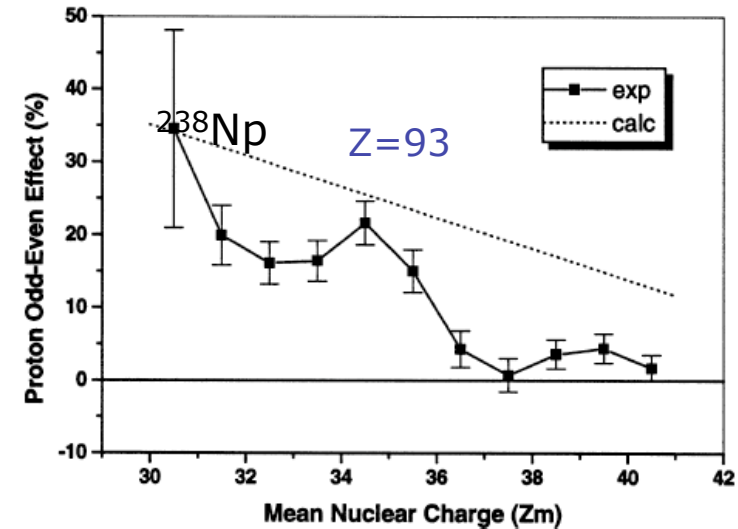


Even-odd effect in odd-Z fissioning nuclei

S. Steinhäuser et al, Nucl. Phys. A 634(1998) 893

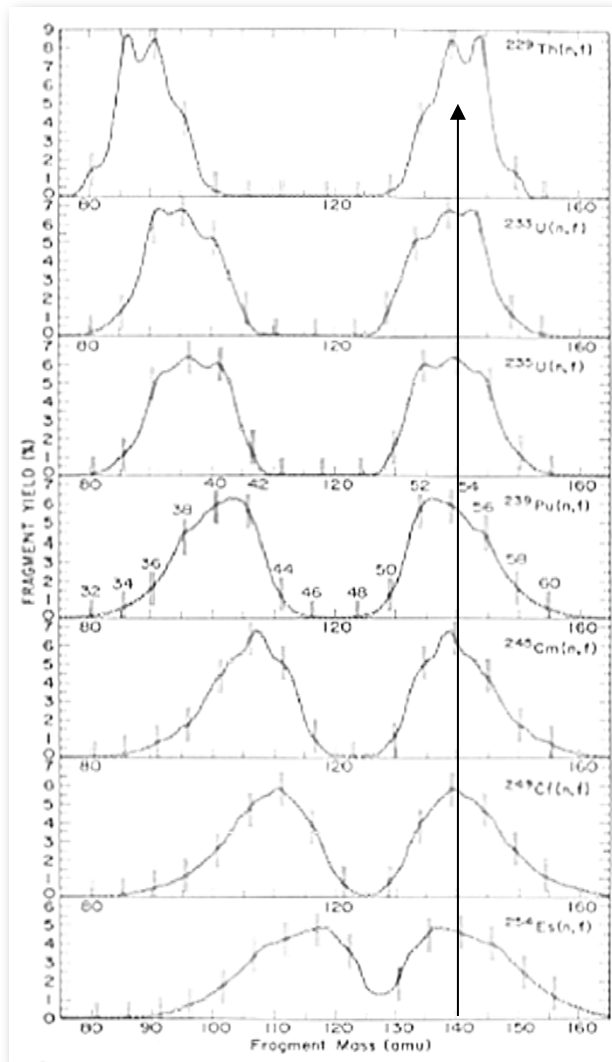


I. Tsekhanovich et al, Nucl. Phys. A 688(2001) 633

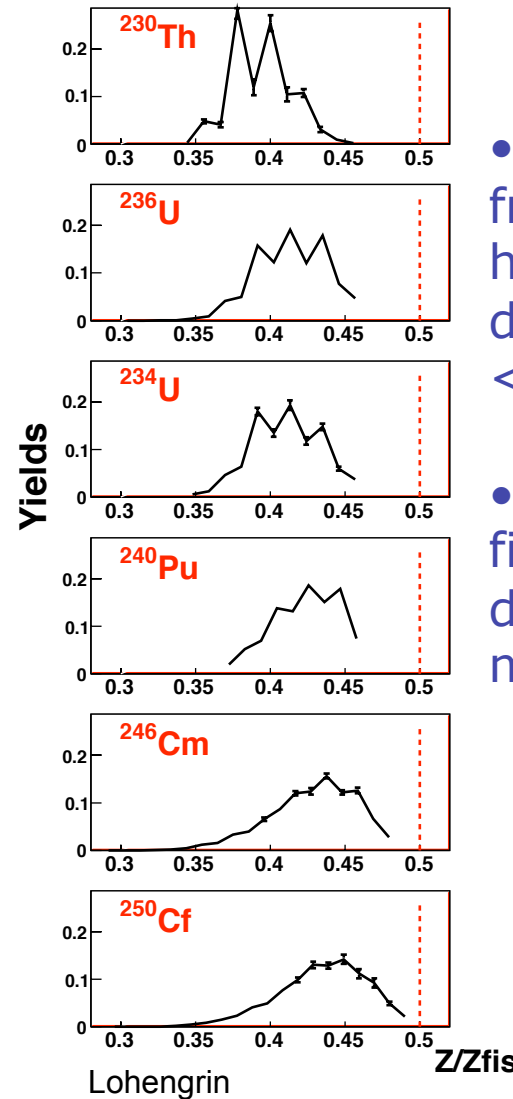


- Scission configuration with at least 1 unpaired proton
 - Large even-odd effects are observed
 - Evidence for the influence of the final fragment phase space
- The presence of one or several unpaired protons does not destroy the even-odd effect
 - ➔ the even-odd effect is not identical to the probability for a completely paired proton configuration at scission

Correlation between fissility and asymmetry



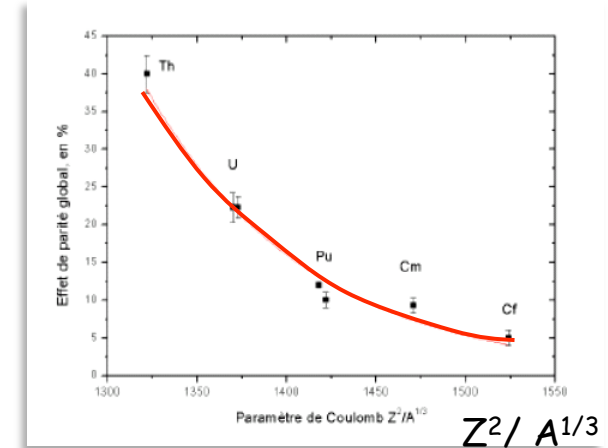
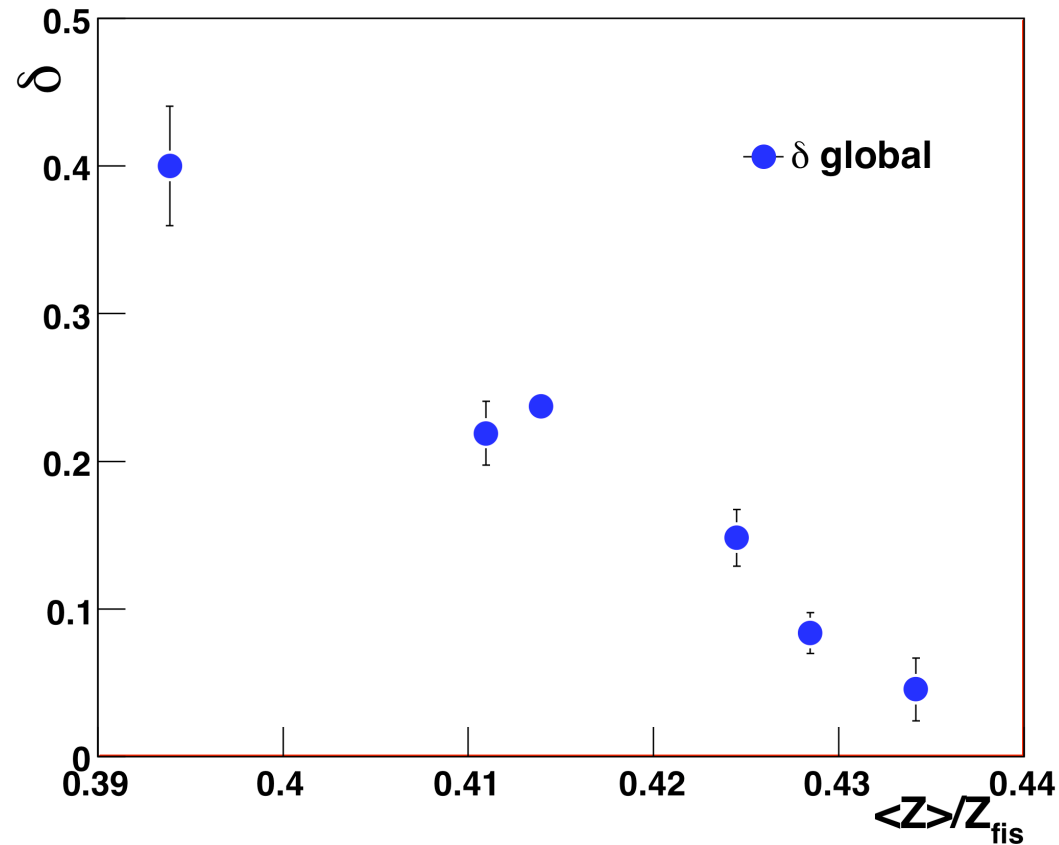
J. P. Unik et al. Symp. on Physics and Chem. of Fission, IAEA Vienna (1974),



- Shell effects in heavy fragment stabilize the heavy fragment distribution around $\langle A \rangle = 140 \Leftrightarrow \langle Z \rangle = 54$
- As fissility increases, the fission fragment distribution becomes more symmetric

- There exists an unavoidable correlation between fissility and symmetry

Even-odd effect variation with average asymmetry

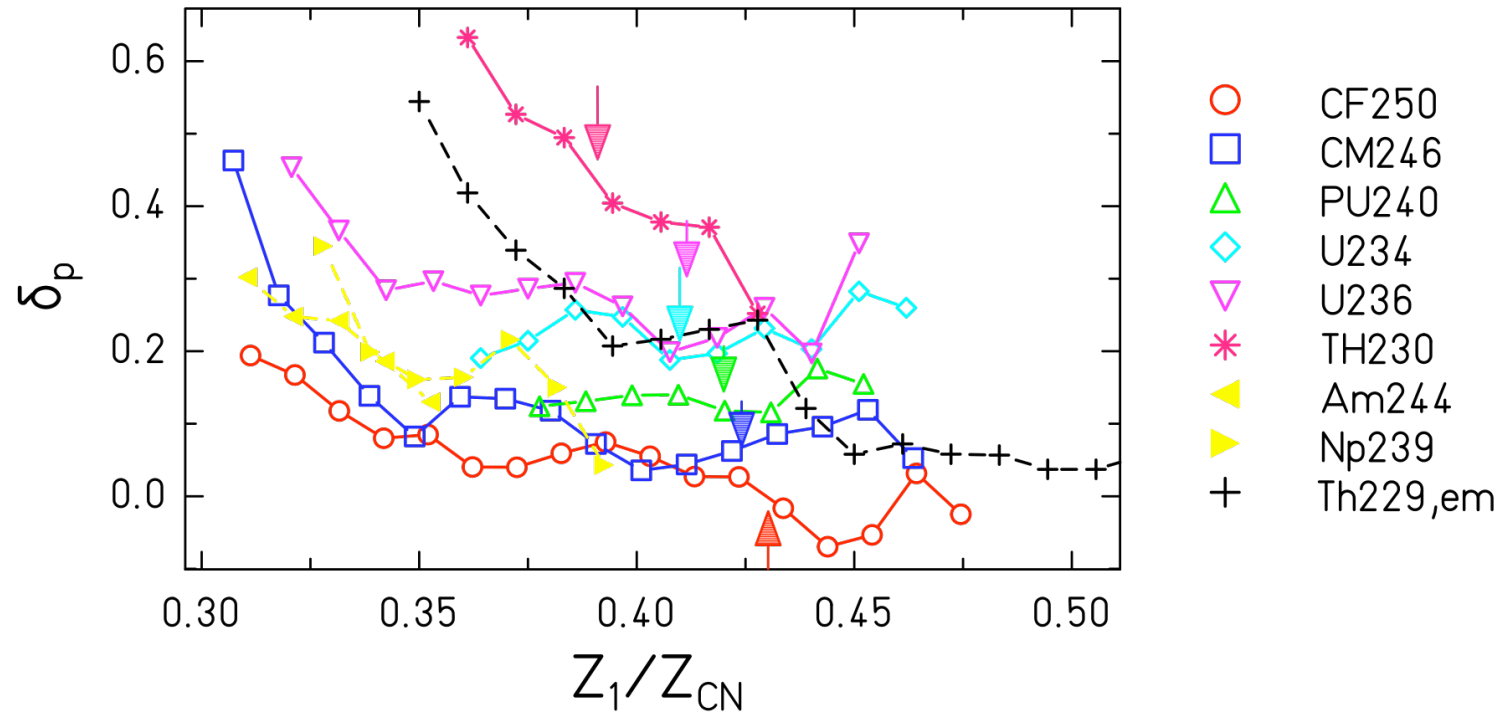


⇒ This systematic variation (hidden in the conventional presentation) complicates the interpretation

All thermal n-induced fission: no influence of the symmetric mode

Local even-odd effect with fissility and asymmetry

Local even-odd effect

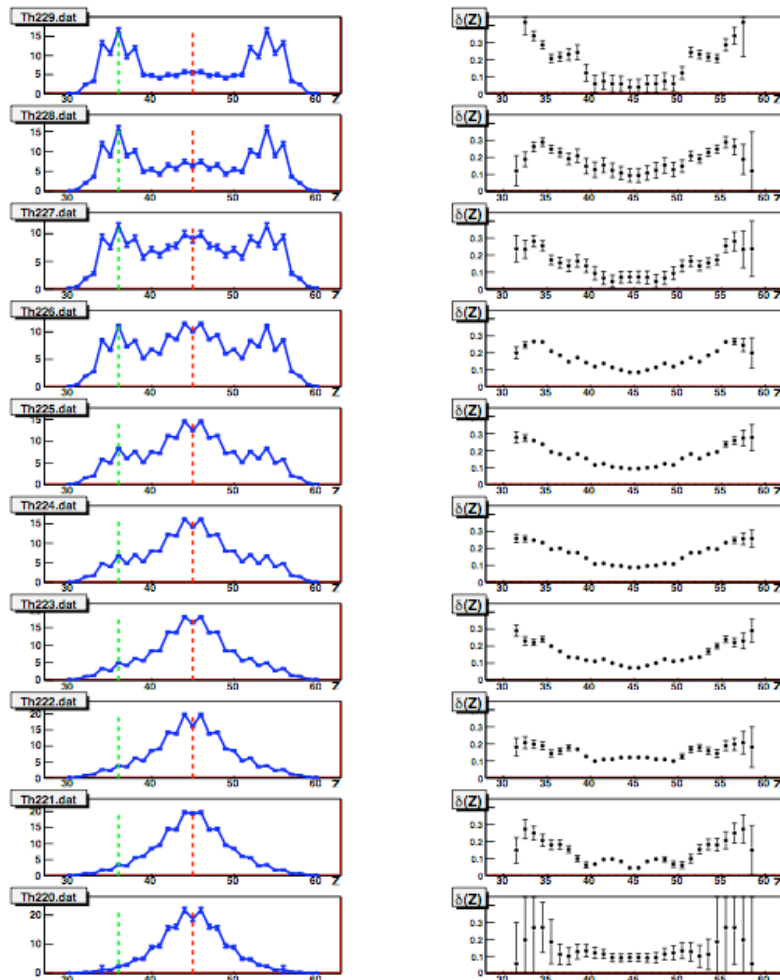


Two contributions to the even-odd effect:

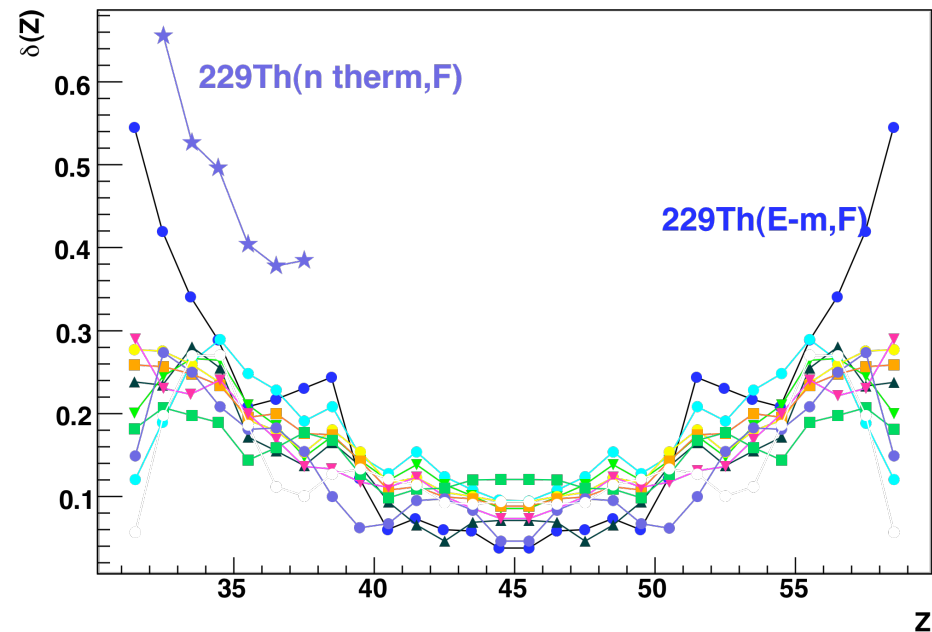
1. Conventional even-odd effect (at symmetry) = result of dissipation in the descent is below 20% for all systems and varies few with the fissility
2. Asymmetry source of even-odd staggering (present for odd Z and even Z systems) grows with asymmetry and is larger for lighter systems

Local even-odd effect with fissility and asymmetry

E-m-induced fission of radioactive beams, inverse kinematics:
Complete charge distribution



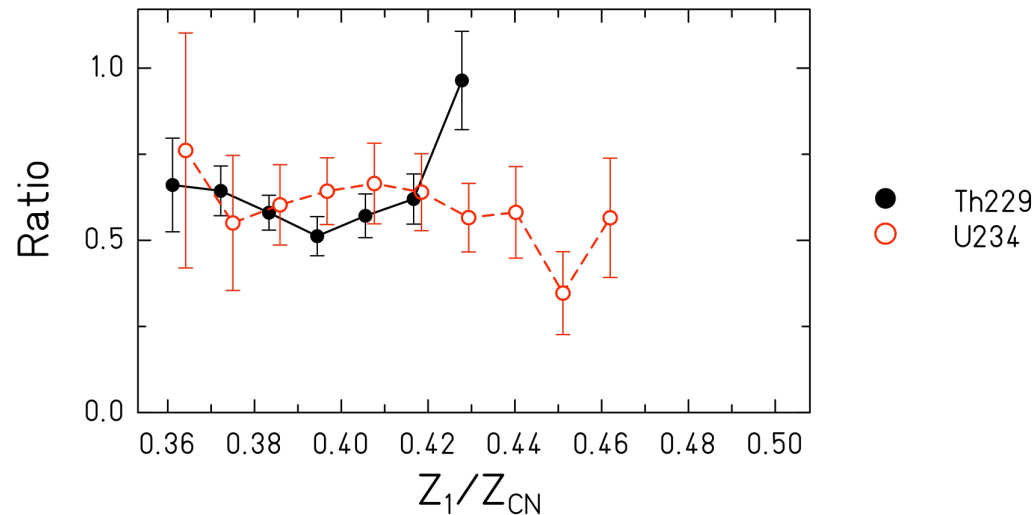
Influence of the fission mode
negligible



Same characteristics as nth-induced fission
with general reduction (higher E^*)

Estimation of the local even-odd effect at symmetry

Ratio $\delta(e-m)/\delta(n-th)$



~Constant ratio

⇒ Estimation of δ at symmetry
for n-th data:

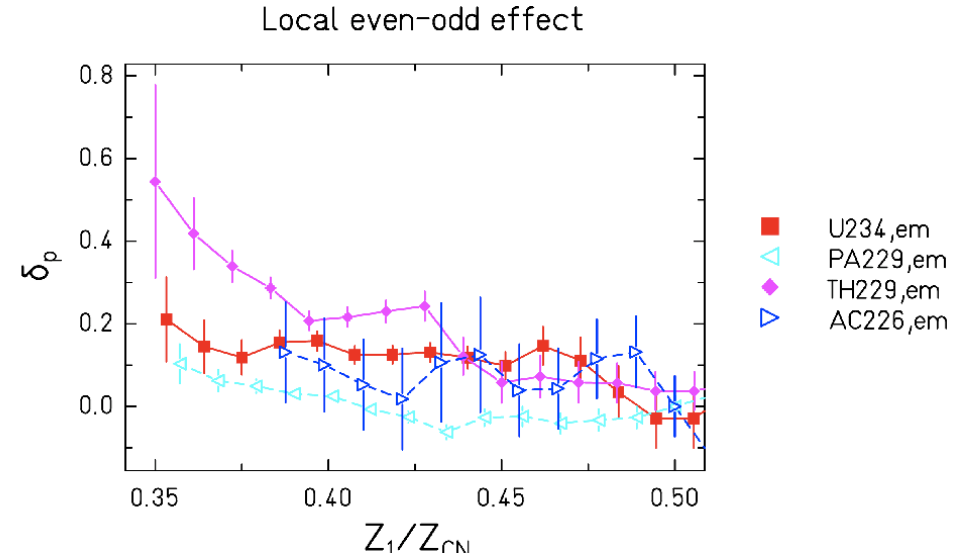
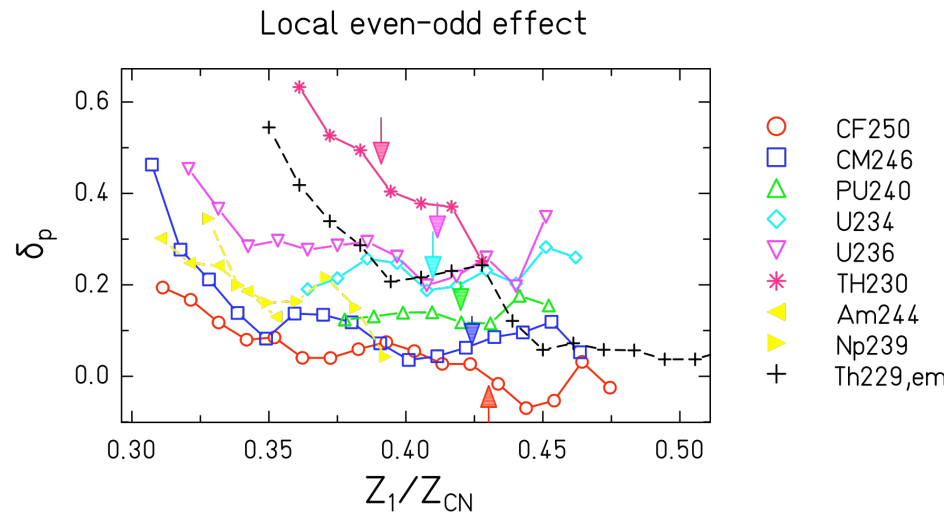
$\delta(\text{sym}) < 10\%$ for ^{230}Th and ^{234}U

⇒ The most important contribution of the even-odd effect is coming from the asymmetry contribution !!

(Estimations of the intrinsic excitation energy from global even-odd effect are wrong)

⇒ The variation at symmetry seems to be weak.

Influence of the excitation energy on the asymmetry contribution to the even-odd effect



n_therm energy:
 Saddle in odd-Z= 0 broken pair +1 p
 δ in odd-Z systems scales with even-Z

E-m energy:
 Saddle in odd-Z= few broken pairs +1 p
 δ in odd-Z systems lower than even-Z

The unpaired proton has more influence when more proton pairs are broken !!

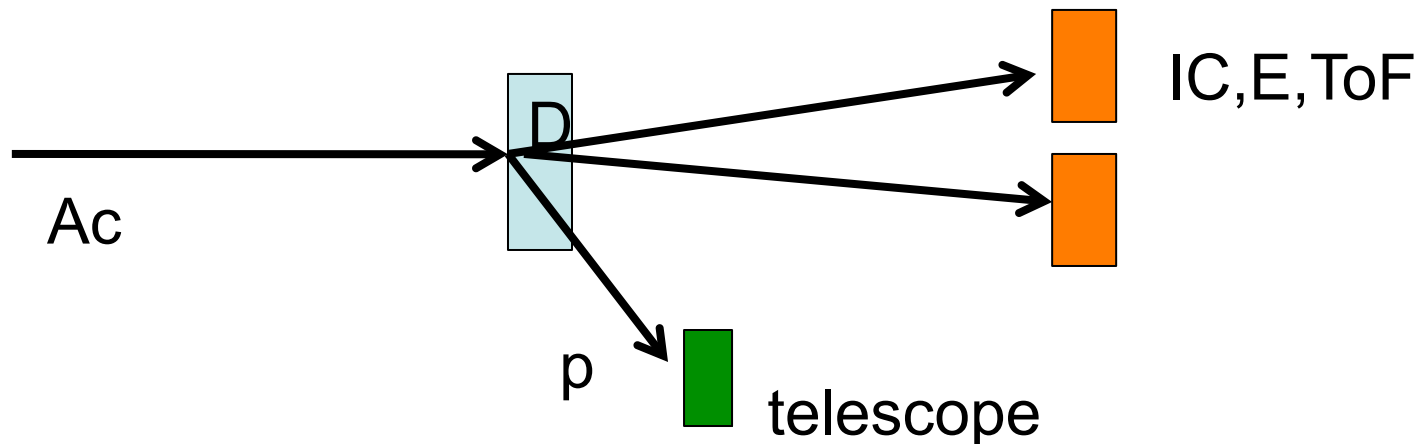
Conclusions

- Global even-odd effect depends on the fissility of the system AND on the average asymmetry of the charge distribution
- As a function of the asymmetry of the charge split :The even-odd effect increases with asymmetry; The increase is larger for lighter systems
- Close to or at symmetry: all systems converge towards lower value which does not seem to vary a lot from one system to the other.
- The asymmetry component is the major component in the total value of the global even-odd effect
- Conclusions on the intrinsic excitation energy cannot be derived from the global even-odd effect. (Conventional interpretation of the even-odd effect is wrong)
- Very scarce amount of data prevents from solid conclusions at symmetry: very few systems, on a limited range in Z and in E^* .
=> New experiments should be performed allowing
 1. Large systematic
 2. Complete element yield measurement→ Inverse kinematics
(GSI-FRS, GANIL-VAMOS, SOFIA@GSI, FYSIK@HiEIsolde, FELISE@FAIR)

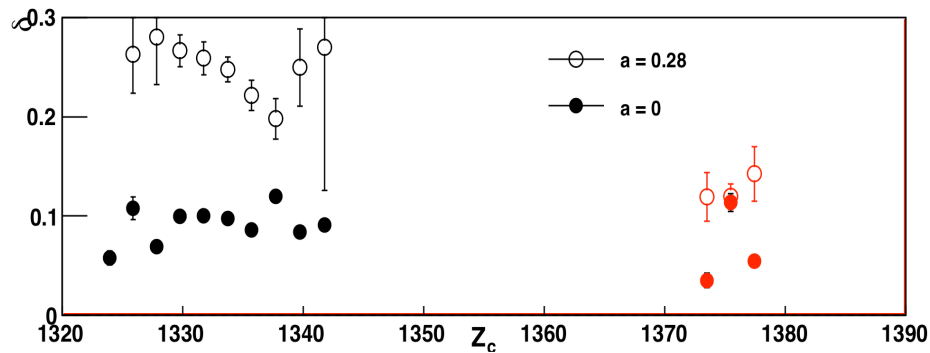
HiE ISOLDE: an opportunity for fissionists



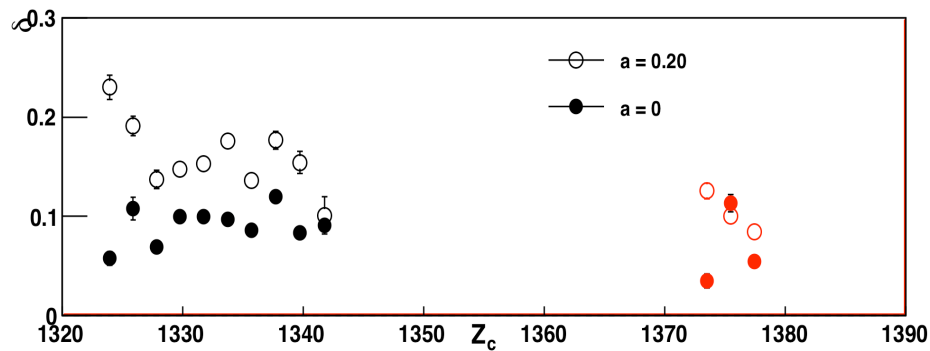
- 10 MeV/u actinide beams
- Already available: $^{200-228}\text{Rn}$, 10^3-10^8 pps
 - » $^{203-230}\text{Fr}$, 10^5-10^9 pps
 - » $^{208-230}\text{Ra}$ 10^4-10^8 pps
- Possibility to extend to other actinides (Th,U,...)
- Simple set-up to measure precisely element yields as a function of excitation energy



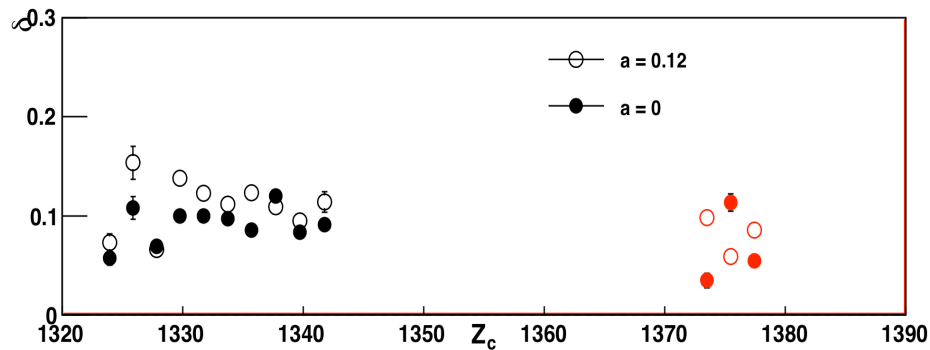
Evolution of the even-odd effect with fissility AND asymmetry



Even-odd effect at symmetry constant with (C_b parameter)



Even-odd effect amplitude varies for asymmetric split ONLY



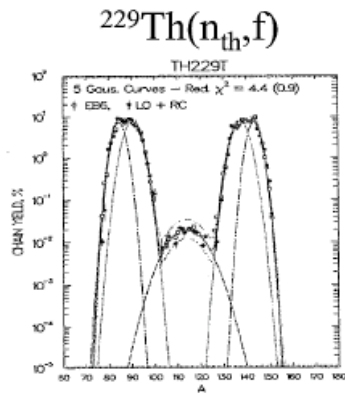
Th

U

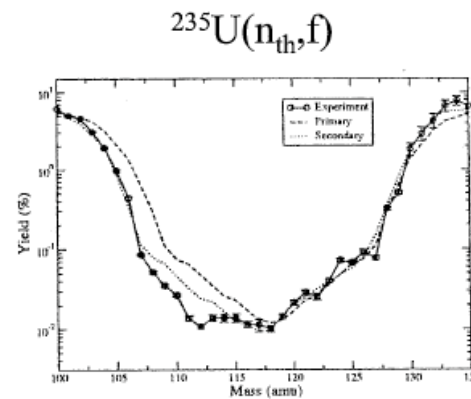
E-m induced fission

E-o effect in mass distributions

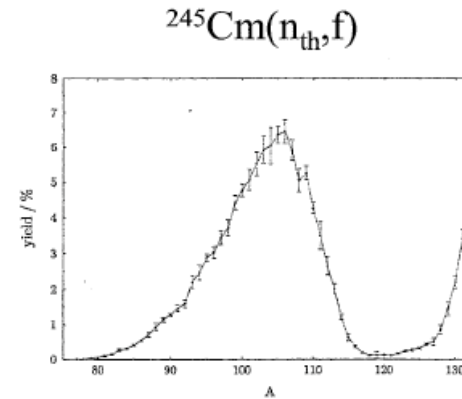
Even-odd effects in near-symmetric fission of fissile nuclei



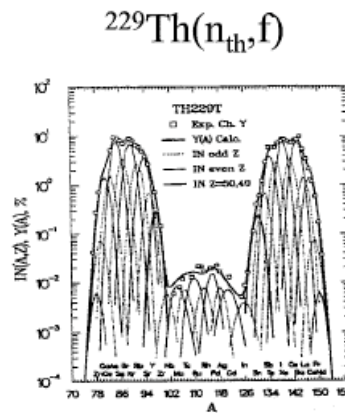
A. Wahl 2000



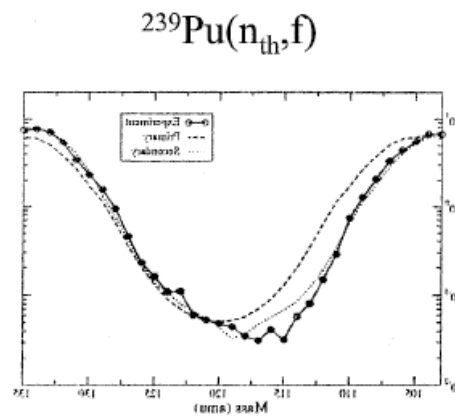
I. Tsekhanovich 2004



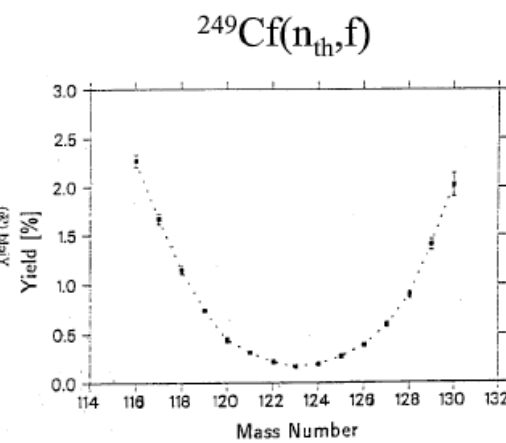
T. Friedrichs 1998



A. Wahl 2000

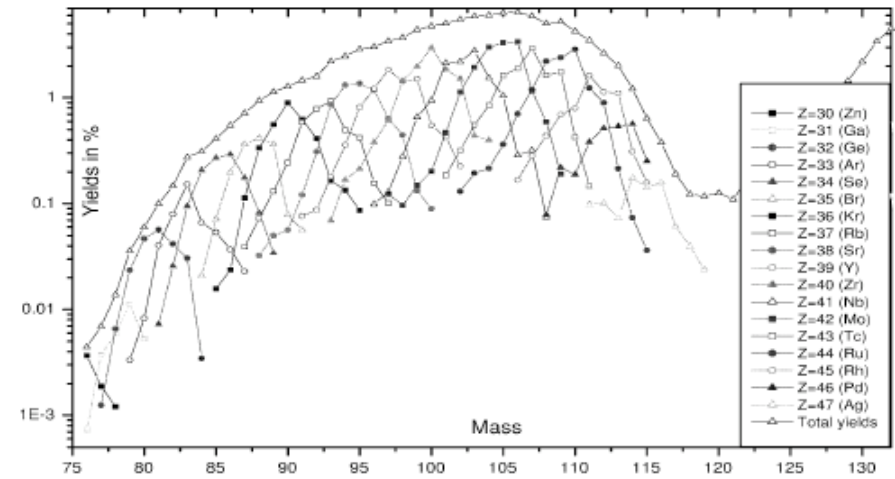
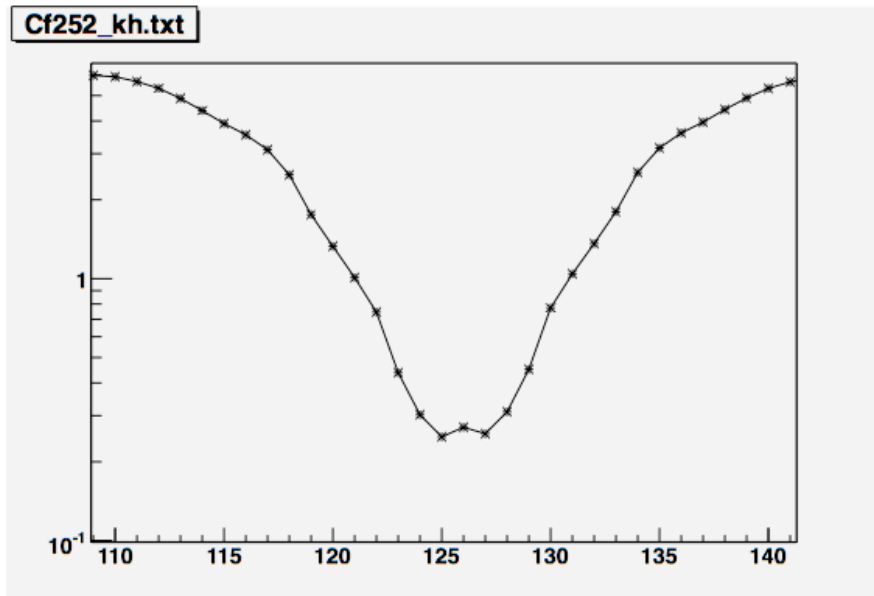


I. Tsekhanovich 2004



W. Ditz et al. 1991

E-o effect in mass distributions

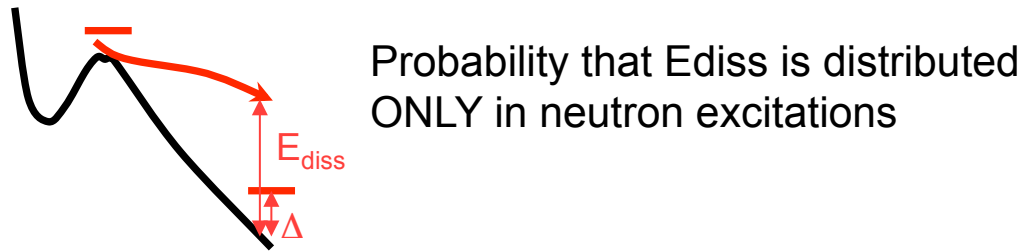


References

- $^{229}\text{Th}(n,\text{F})$ J.-P. Bocquet et al, ZP; Djebara et al, Nuc. Phys. A 425 (1984) 120
 $^{235}\text{U}(n,\text{F})$ Lang et al, NPA 345 (1980) 34; Siegert et al, PRC 14(1976) 1873
 $^{233}\text{U}(n,\text{F})$ Quade et al, NPA 487 (1988) 1
 $^{239}\text{Pu}(n,\text{F})$ C. Schmitt et al., NPA 430 (1984) 21
 $^{245}\text{Cm}(n,\text{F})$ Rochman et al, NPA710 (2002) 3; NPA735
 $^{249}\text{Cf}(n,\text{F})$ Djebarra et al, NPA 496 (1989) 346; Hentzschel et al, NPA 571
S. Steinhäuser et al,

Quantitative description of the even-odd structure (3)

Statistical description of the nuclear level density, F. Rejmund et al., 2001

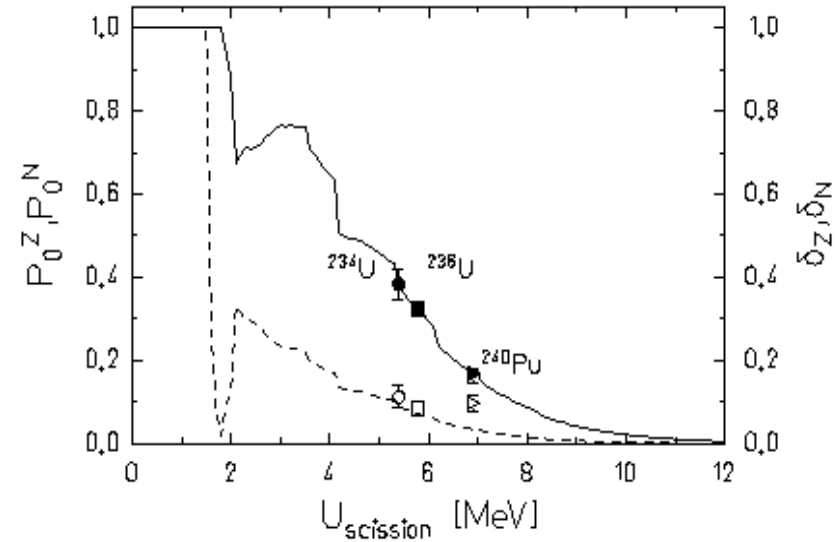


Level density of **only** broken neutron pairs

$$\rho_0^Z(U) = \frac{\sum \rho_{n_Z=0, n_N(U)}}{\sum \rho_{n_Z=0, n_N(U)}}$$

Level density of all possible excitations

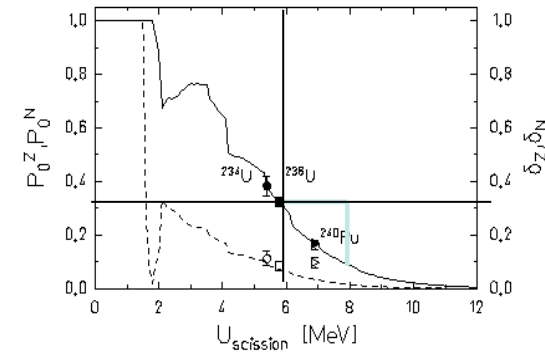
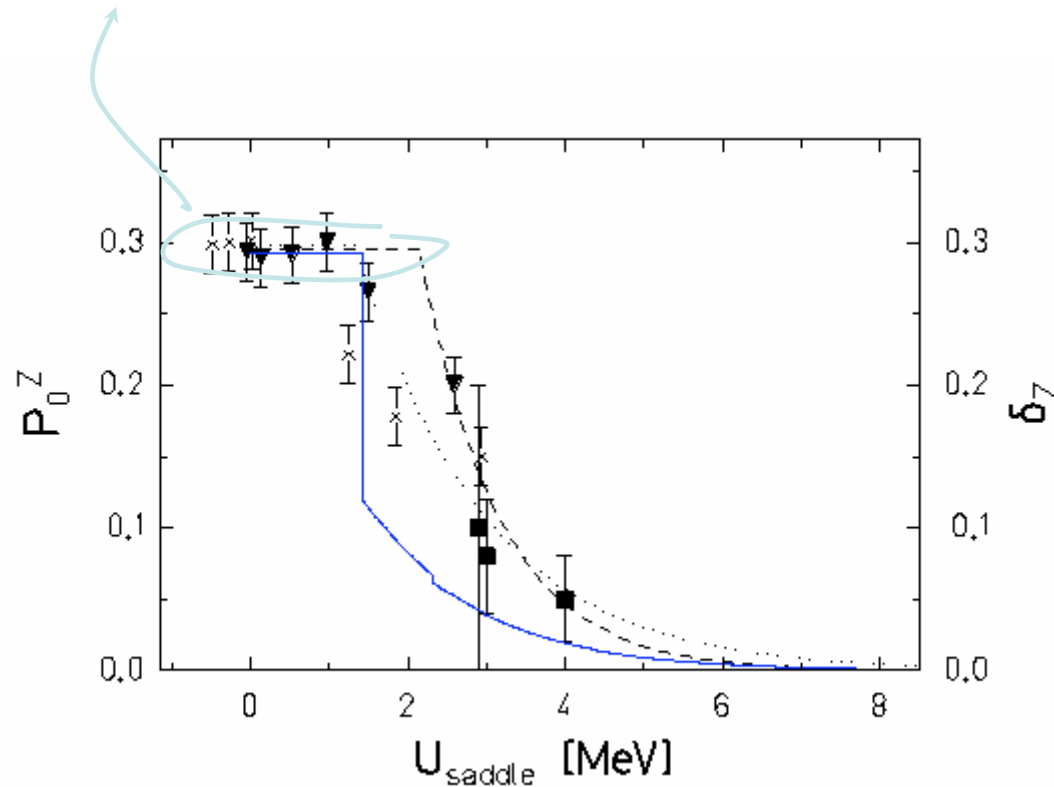
$$\rho_n = \frac{g^n (E - n\Delta)^{n-1}}{(n/2)!^2 (n-1)!}$$



For the first time the difference between proton and neutron number yields is reproduced without further assumption

Influence of the excitation energy at saddle

No pair breaking at saddle \rightarrow estimation of $E_{\text{diss}} = 6 \text{ MeV}$

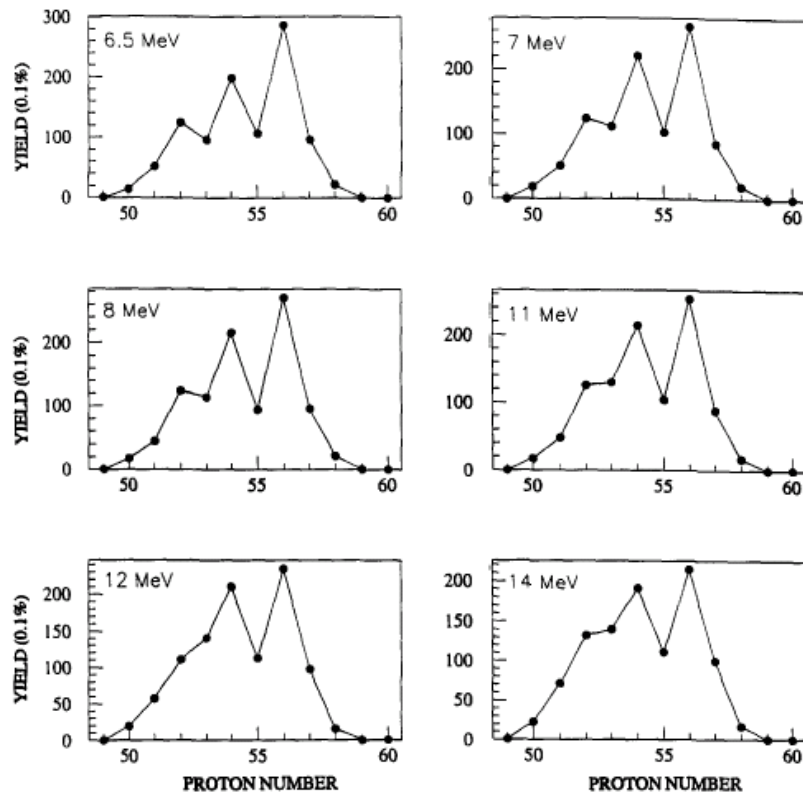


At scission the survival probability is constant for 2Δ and decreases sharply to reach the regular slope

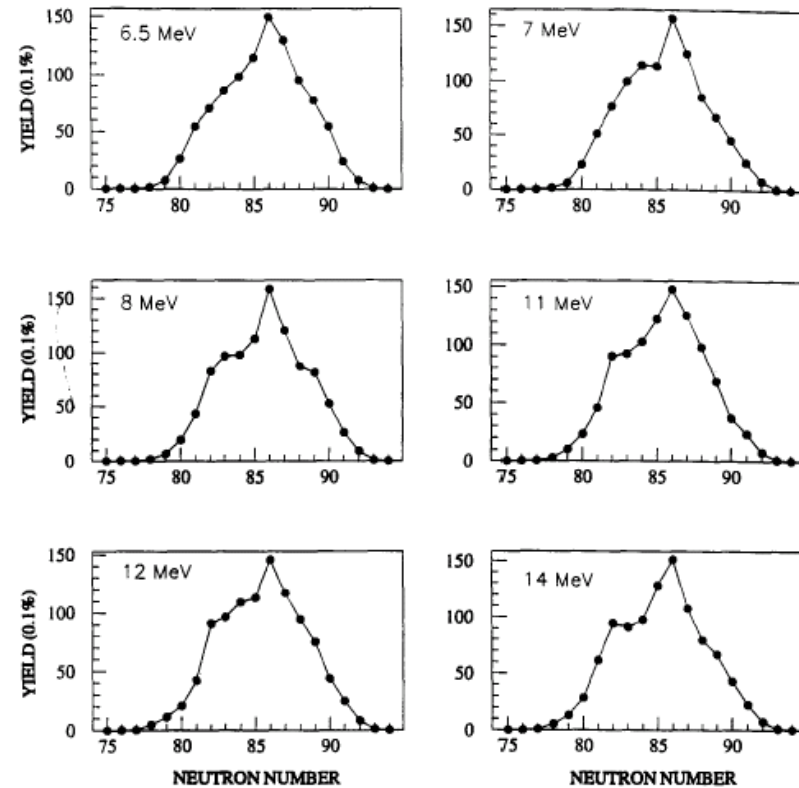
Brehmstrahlung experiments = large uncertainty in the energy determination

Even-odd structures in neutron and proton number yields

- δ_p is always larger than δ_n

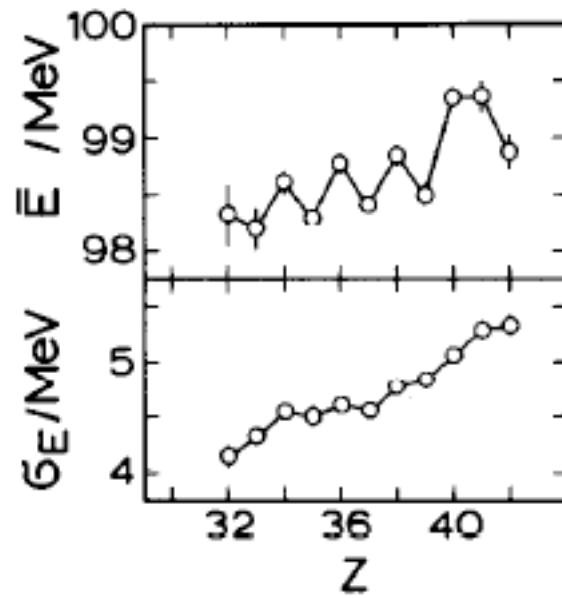


$^{232}\text{Th}(\gamma, f)$ Persyn et al., 1997



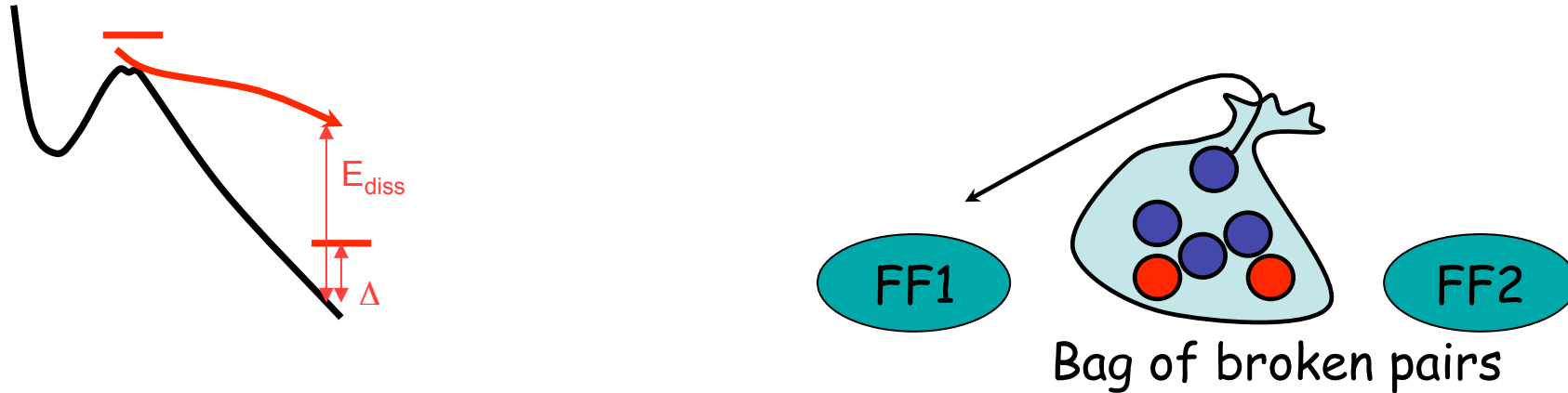
- Neutron evaporation
- Different energy dissipated for protons and neutrons

Even-odd effect in TKE



Quantitative description of the even-odd structure (1)

A combinatorial analysis, H. Nifenecker et al., 1982



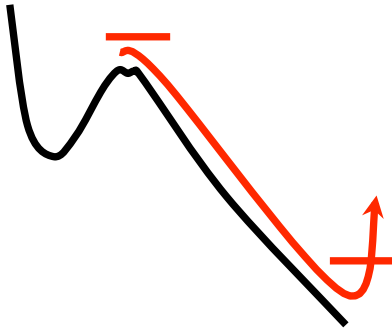
- N** the maximum possible number of broken pairs $N = E_{diss}/\Delta$
- ϵ** the broken pair is a proton pair $Z_f/A_f \sim 0.4$
- q** break a pair when the required energy is available **0.5**
- p** the 2 protons of a given pair to end up into 2 different fragments **0.5**

$$\delta_Z = (1 - 2pq\epsilon)^N$$

$$E_{diss} = -4 \ln(\delta_Z)$$

Quantitative description of the even-odd structure (2)

Dynamical analysis, Willets 1964, Bouzid et al. 1997



- Adiabatic descent to scission
- Heating produced by the breaking of the neck between the 2 nascent fragments

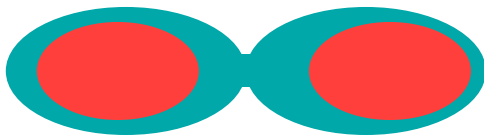
Probability to have odd-odd fragments : $P_{o-o} = p \cdot \exp(-A/V_c)$

$p = 0.5$

A strength of coupling between the ind. part. states

V_c = velocity of neck rupture

As Z_c increases, the velocity of neck rupture increases and thus δ_p decreases

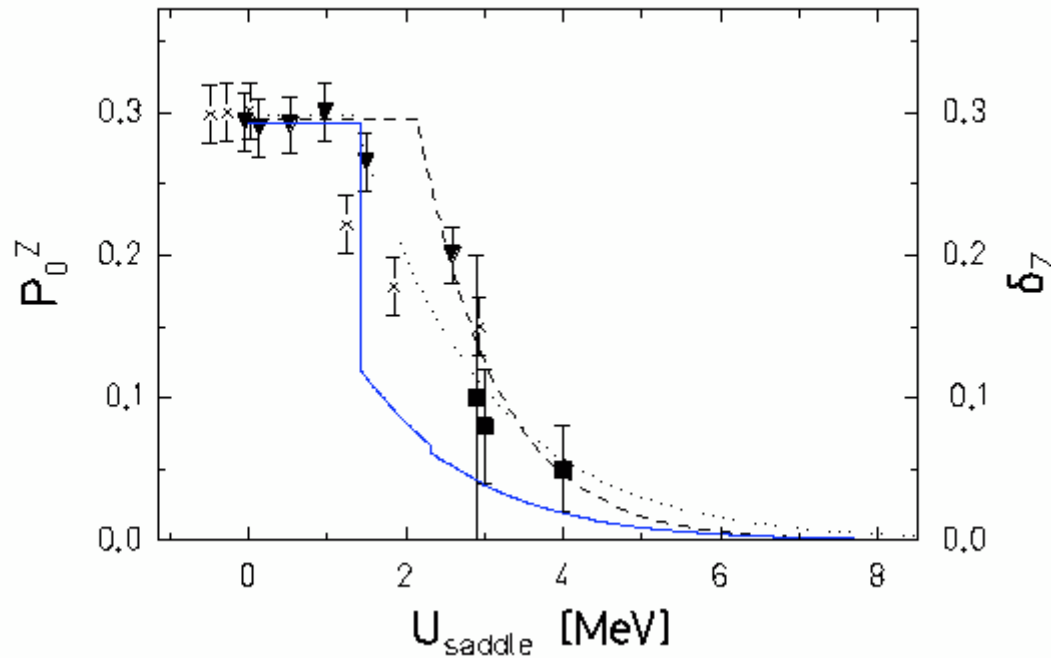


Due to Coulomb repulsion, the neutrons undergo more violent neck rupture and thus show a less pronounced even-odd structure

Even-odd structures depend on the excitation energy

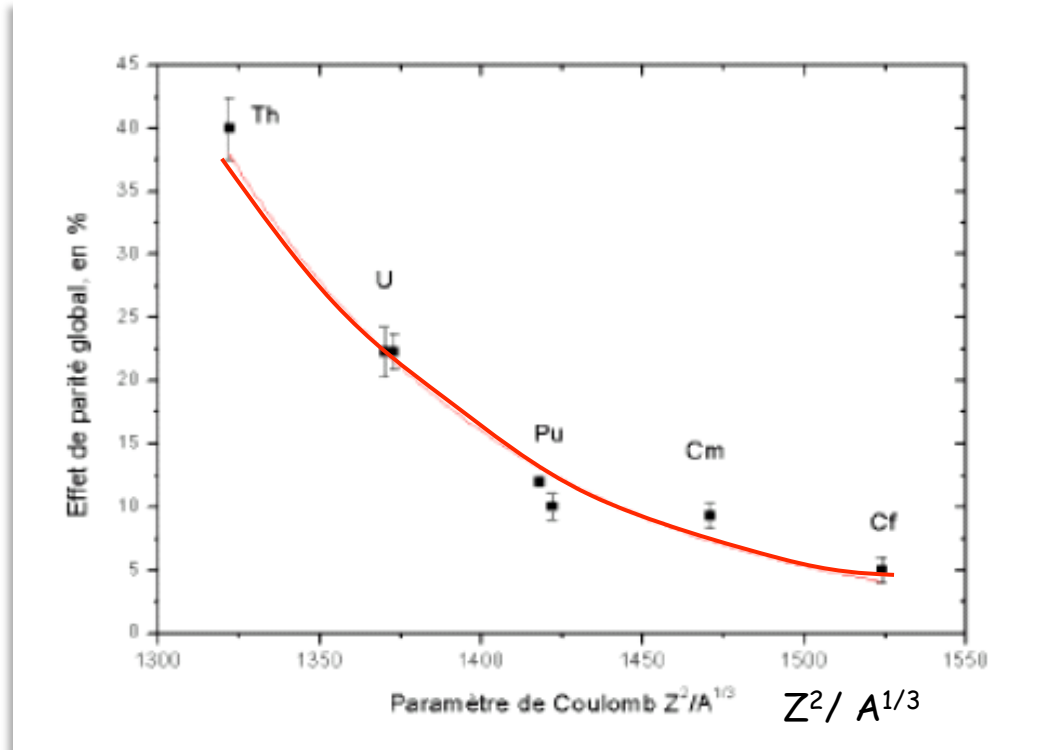
Global even-odd effect $\delta_z = \frac{\sum Y_z^{e-} - \sum Y_z^{o}}{\sum Y_z^{e+} + \sum Y_z^{o}}$

Influence of the excitation energy at saddle



The even-odd effect remains constant below the pairing gap, and then decreases

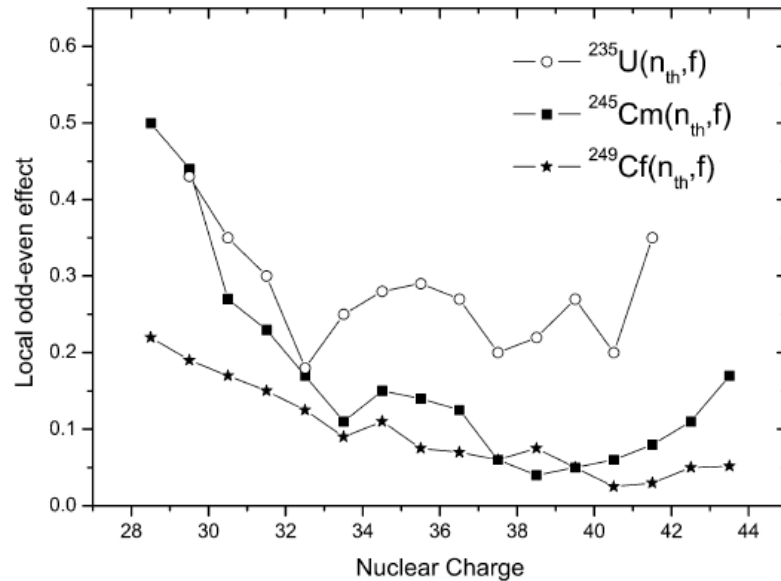
Even-odd effect depends on fissility of the system



δ_p shrinks drastically with fissility of the fissioning nucleus
 δ_p related to the intrinsic excitation energy at scission
→ Dissipated energy increases with fissility

Local even-odd effect depends on asymmetry

Local even-odd effects: deviation from a Gaussian distribution



$$Y_G(Z) \approx Y_G(Z)(1 \pm \delta_Z(Z))$$

$$\delta_Z\left(Z + \frac{3}{2}\right) = \frac{1}{8} (-1)^{Z+1} \ln Y(Z+3) - \ln Y(Z) - 3 \ln Y(Z+2) - \ln Y(Z+1)$$

Energetic balance:

$$Q = \text{TKE} + \text{TXE}$$

$$\text{TXE} = Q - \text{TKE} = E_{\text{def}} + E_{\text{intr}}$$

D. Rochman et al., NPA735(2004) 3

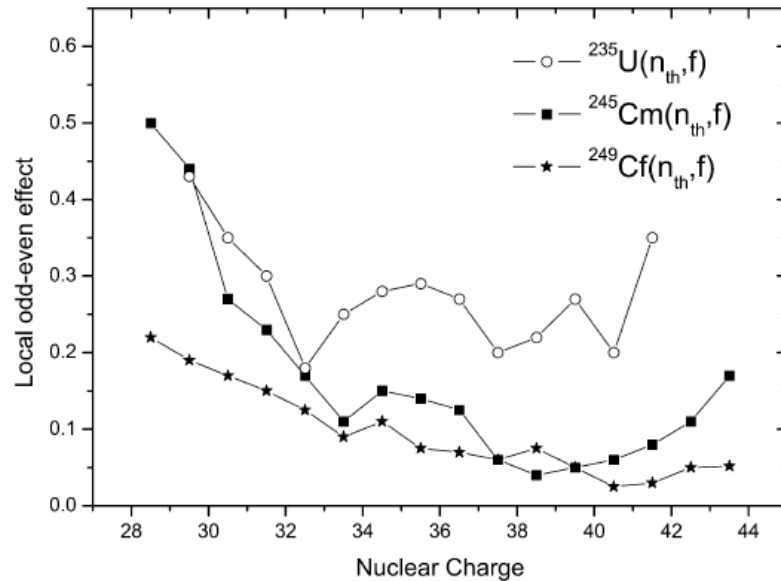
Notions of:

- cold asymmetric fission \Leftrightarrow extreme deformation
- hot symmetric fission (though linked to large deformation)

E-o effect not measured at symmetry

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