A new rigorous interpretation of the even-odd structure in fission-fragments yields

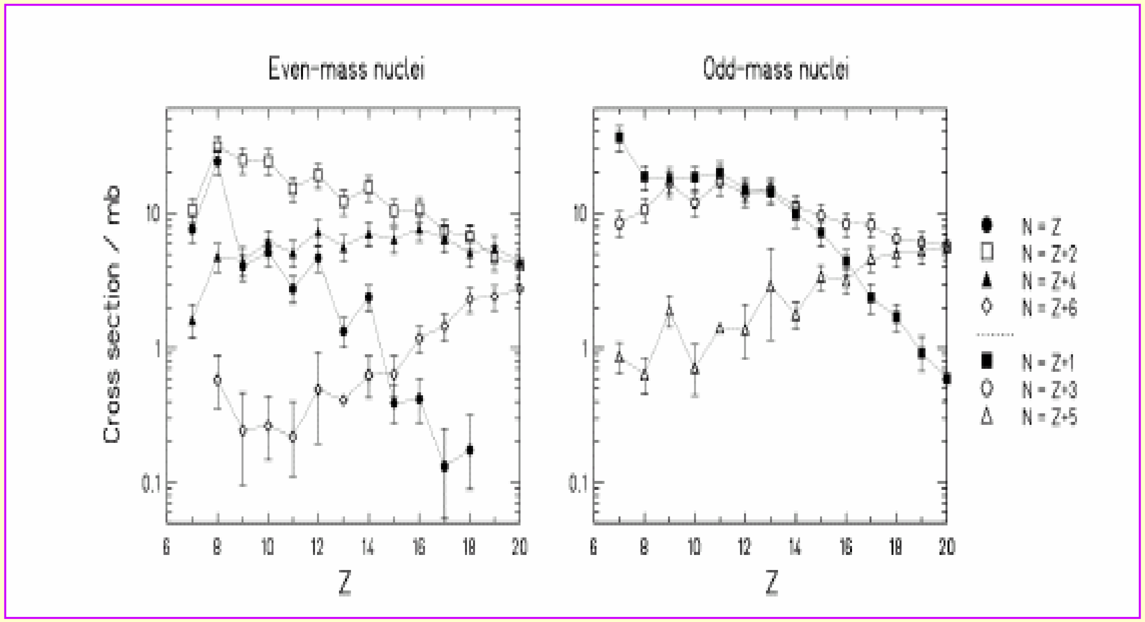
F. Rejmund, A. V. Ignatyuk, A. R. Junghans, K.-H. Schmidt,
Nucl. Phys. A 678 (2000) 215

S. Steinhäuser et al.,
Nucl. Phys. A 634 (1998) 89

- Even-odd structures in nuclear physics and in fission
- Most commonly used models to describe the structures
- Description of the model
- Applications of the model
- conclusions

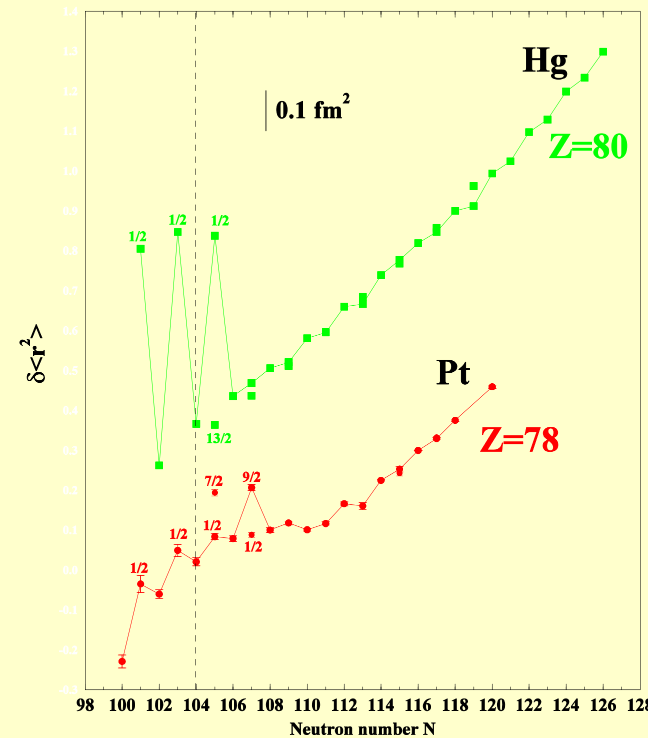
Evidence for even-odd effects in nuclear physics

Light fragmentation products U(1A GeV)+Ti



M. V. Ricciardi et al., NPA 2004

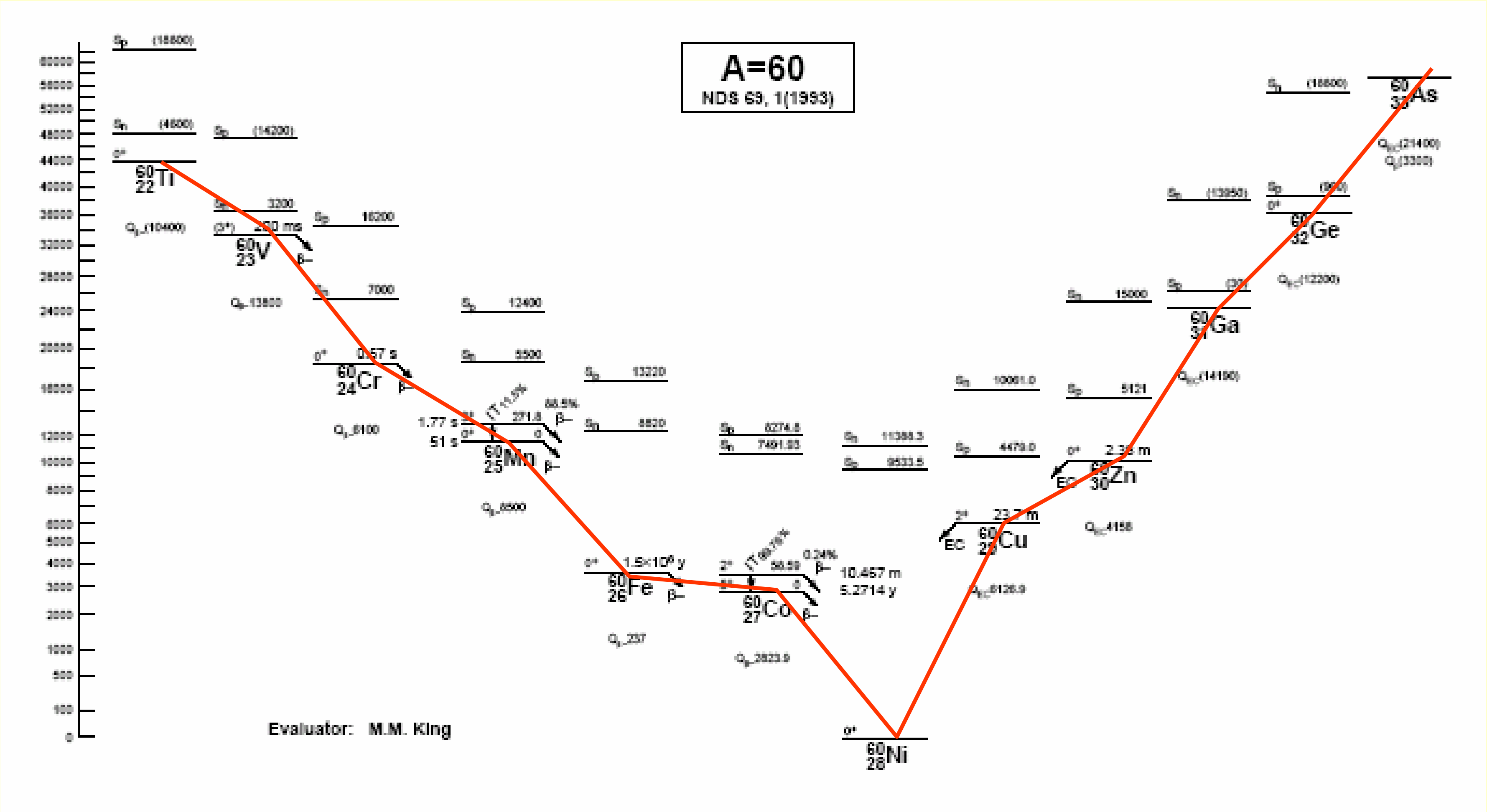
Mean square radii



F. Le Blanc et al., 2000

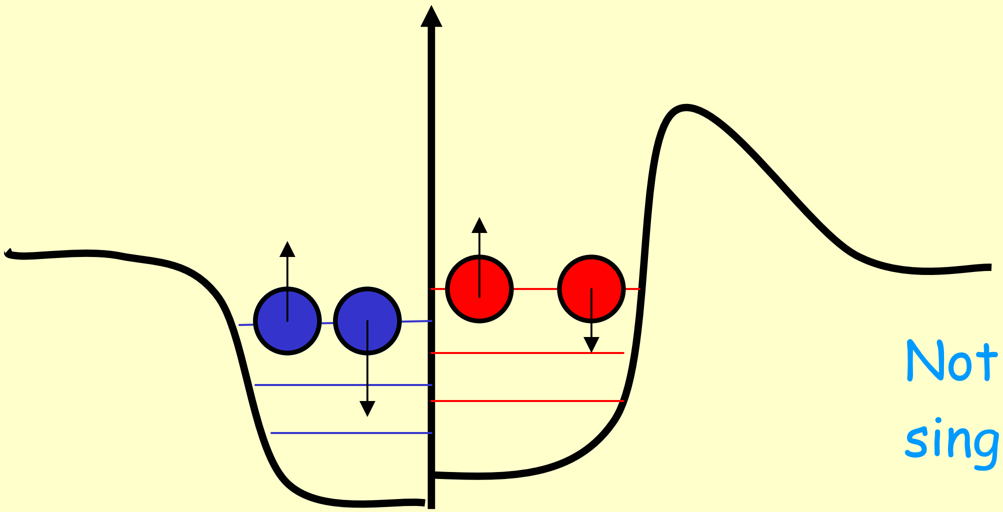
Evidence for even-odd effects in nuclear physics

Nuclear binding energies $B(N,Z)=Nm_n+Zm_p-M(N,Z)$



Even-even nuclei are systematically more bound than the odd-odd nuclei

Nucleons are paired in the nucleus



An extra energy is needed to break a pair

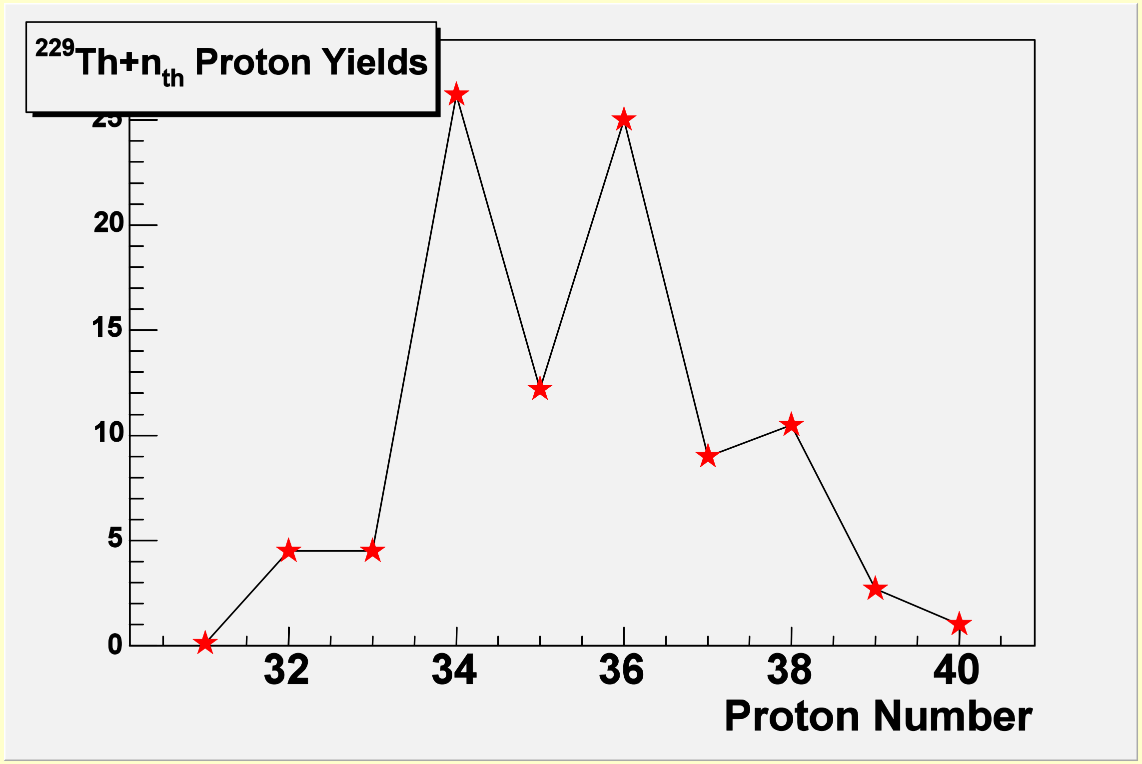
Notion of "pairing gap" below which no single particle excitation is possible

$$\Delta_n = 0.25\{ B(N-2,Z)-3B(N-1,Z)+3\ B(N,Z)-B(N+1,Z) \}$$

$$\Delta_p = 0.25\{B(N,Z-2)-3B(N,Z-1)+3\ B(N,Z)-B(N,Z+1) \}$$

$$\Delta \approx 12/A^{1/2}$$

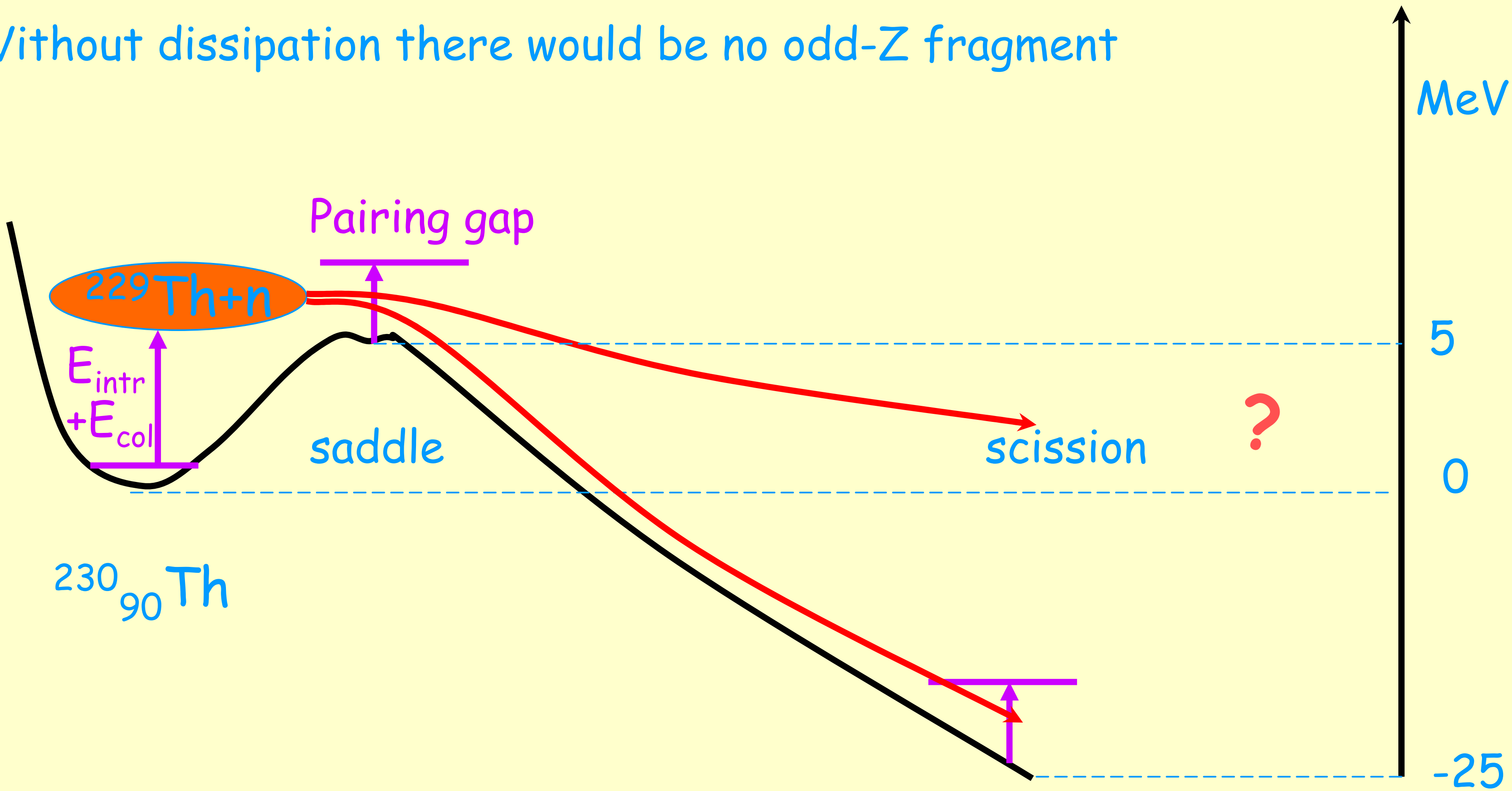
Even-odd structure in fission fragments yields



Bocquet et al., 1990

Qualitative understanding of the even-odd structure

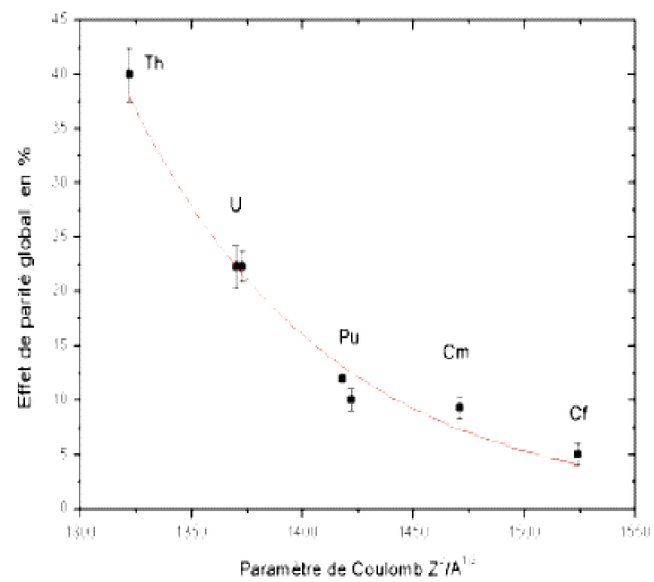
Without dissipation there would be no odd-Z fragment



The even-odd structures in fission-fragments yields are a key to our understanding of dissipation effect in the nucleus

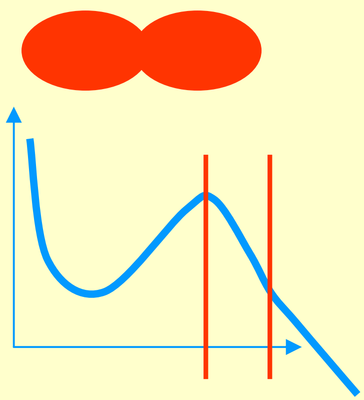
Even-odd structures depend on the fissioning system

Global even-odd effect $\delta_z = \Sigma Y_z^e - \Sigma Y_z^o$

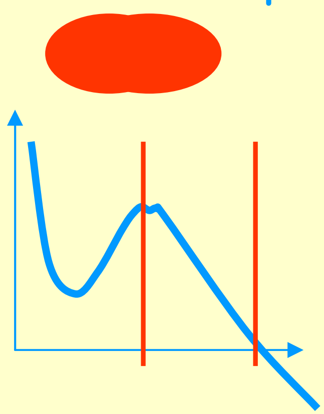


As the Coulomb repulsion inside the nucleus increases, the saddle shape becomes more and more compact

Saddle Ta



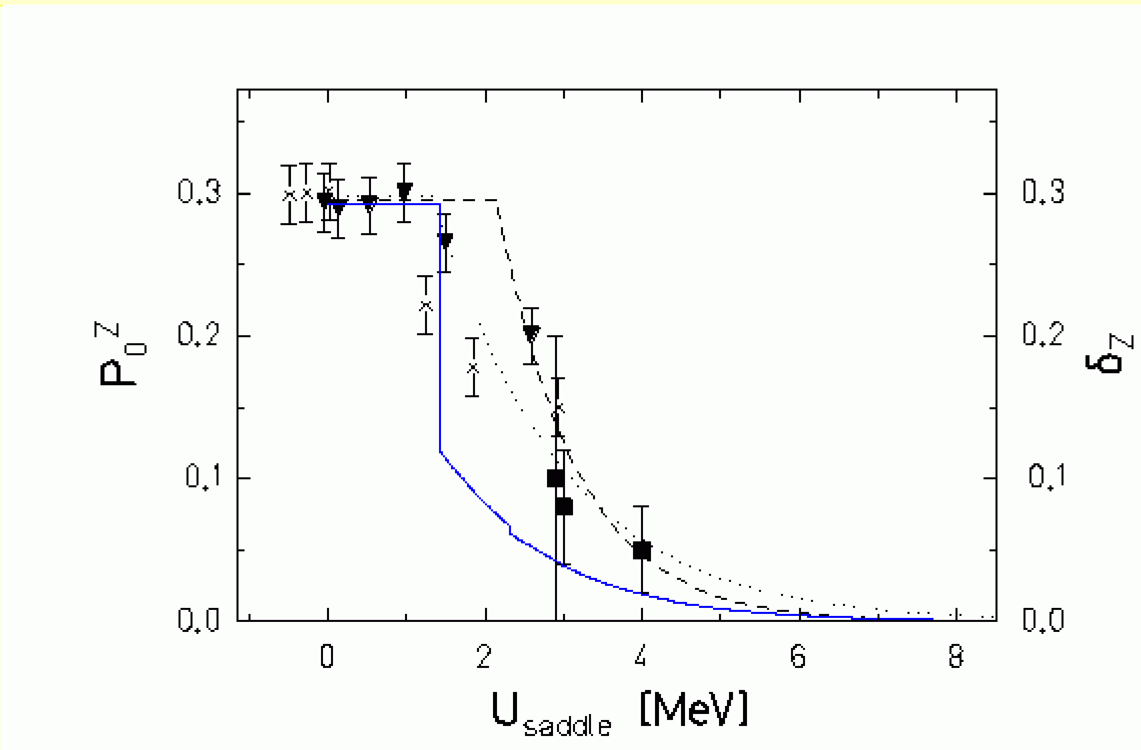
Saddle Np



The descent from saddle to scission increases, as the E_{diss}

Even-odd structures depend on the excitation energy

Influence of the excitation energy at saddle

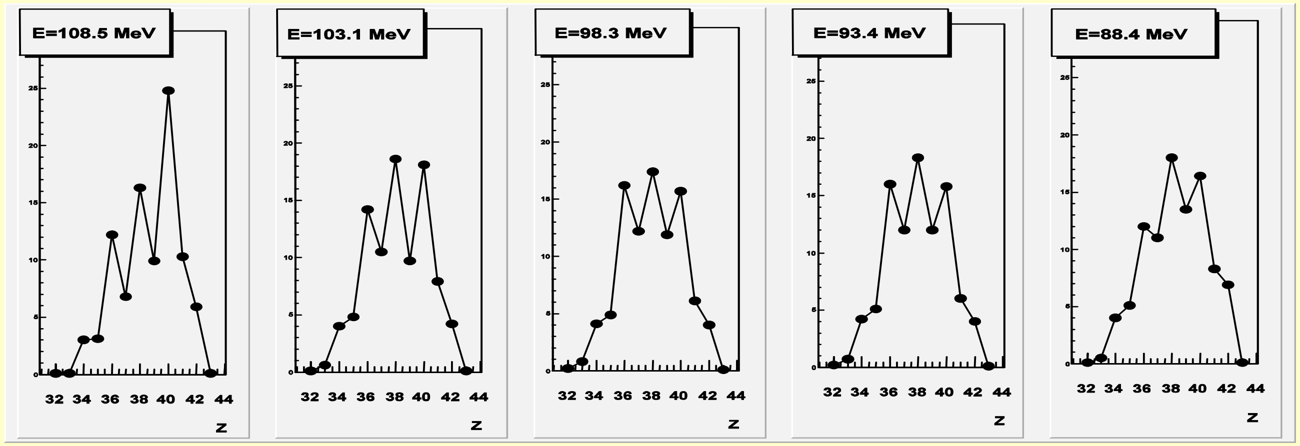


S. Pomme et al. , NPA560(1993), K. Persyn et al., NPA620(1997)

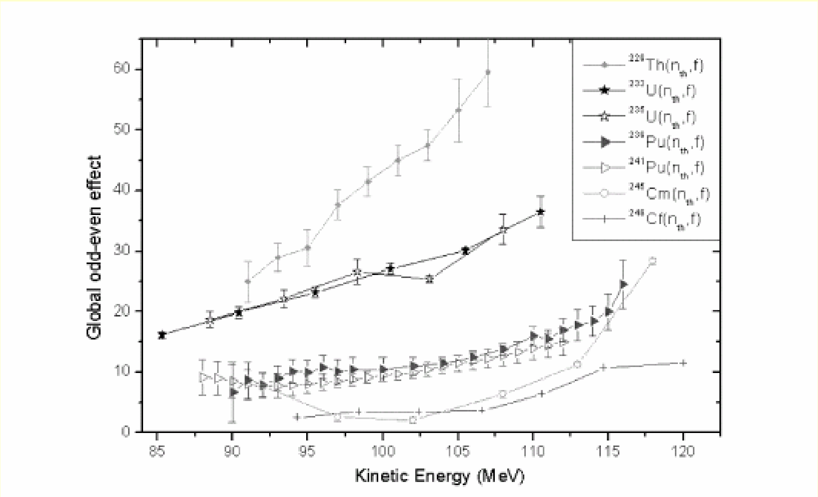
The even-odd effect remains constant below the pairing gap, and then decreases

Even-odd structures depend on the kinetic energy of the fragments

- Even-odd structures increase with the kinetic energy of the fragments



Lang et al., 1980



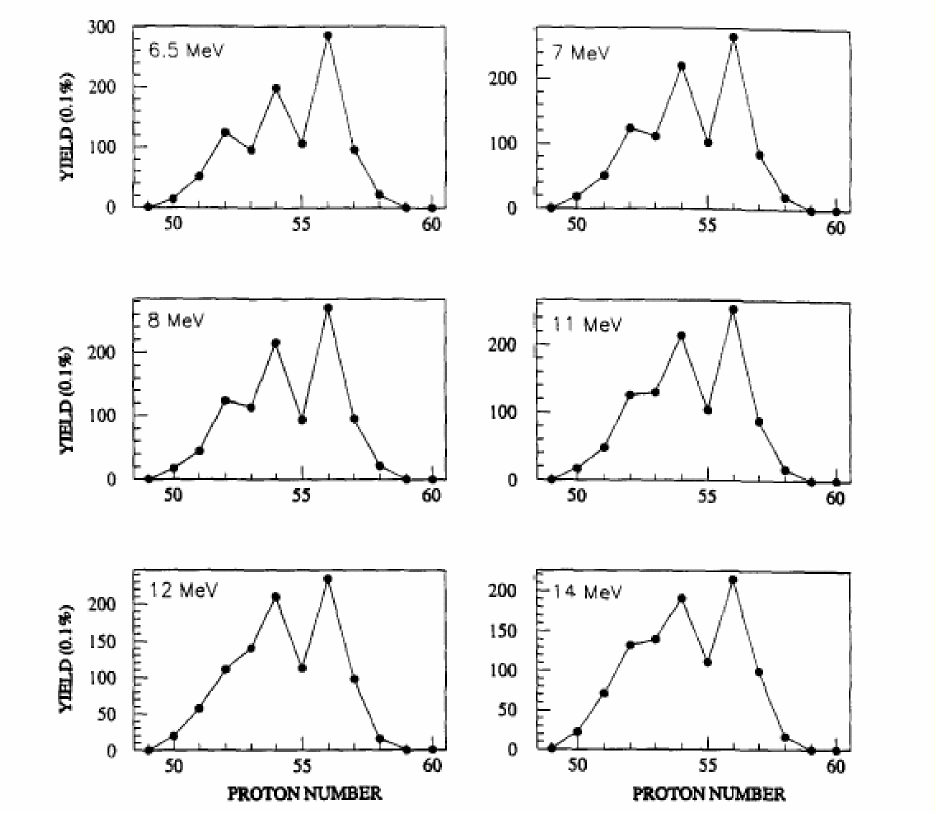
Rochman et al., 2002

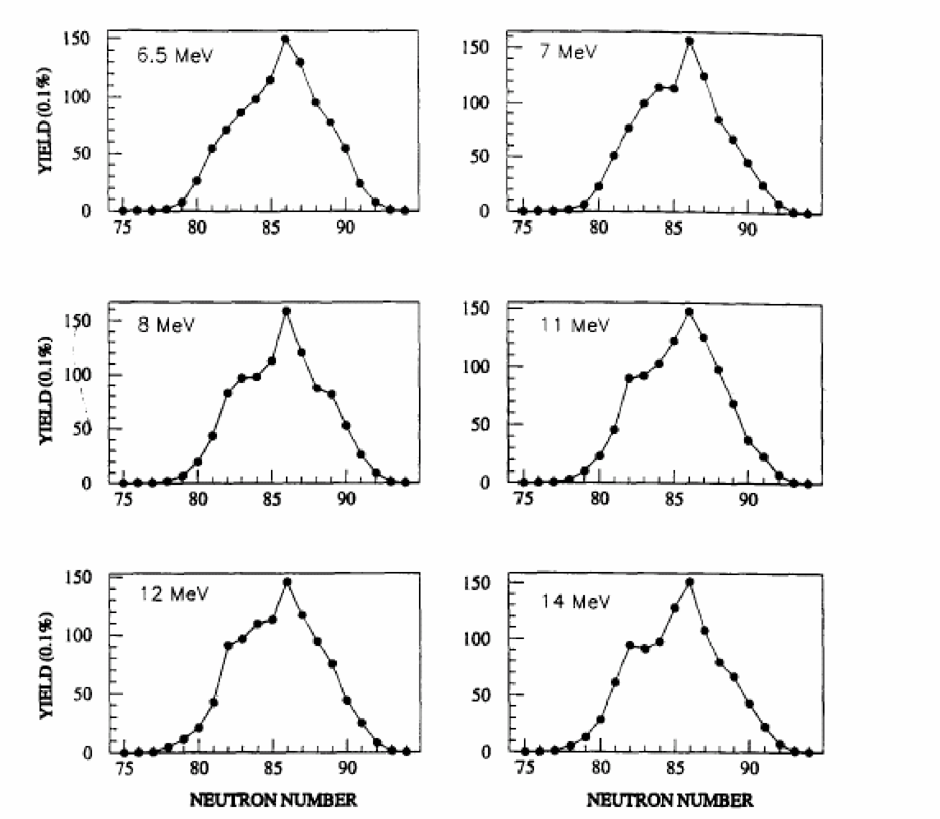
$$Q = M_1 + M_2 - M_f = E_{kin} + \Delta V + E_{diss}$$

Even-odd structures in neutron and proton number yields

- δ_p is always larger than δ_n

^{232}Th(γ,f) Persyn et al., 1997



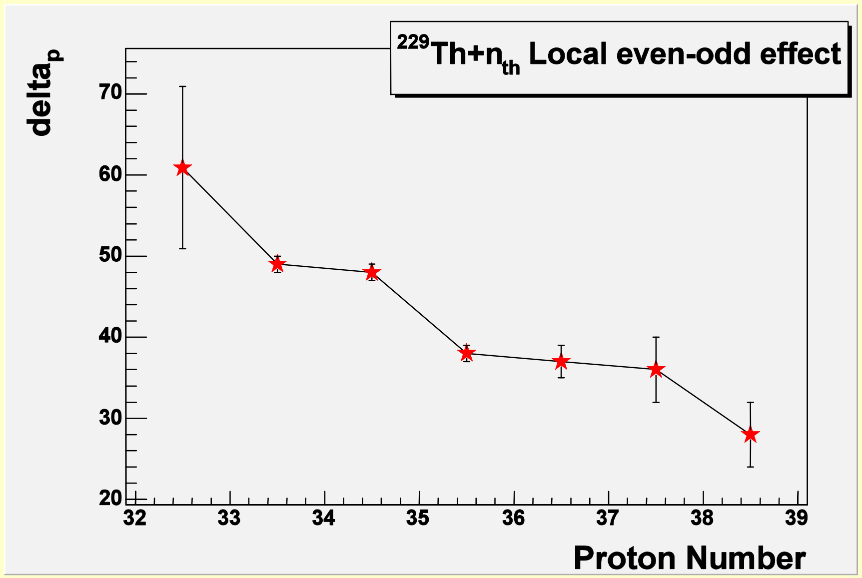


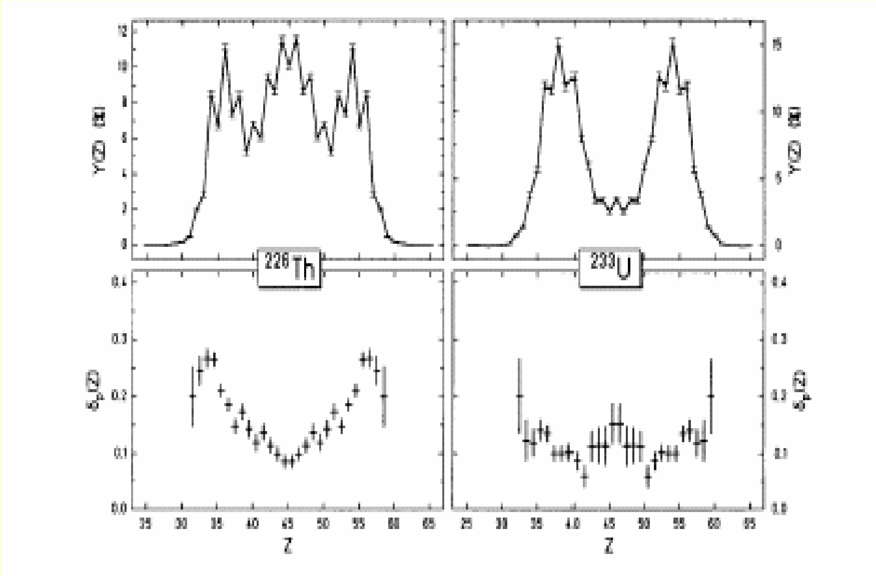
- Neutron evaporation
- Different energy dissipated for protons and neutrons

Local even-odd effects in the fission yields

$$\delta_z(Z+3/2)=1/8(-)^{Z+1}\{\ln Y(Z+3)-\ln Y(Z)-3\ln Y(Z+2)-\ln Y(Z+1)\}$$

- Increases with mass asymmetry

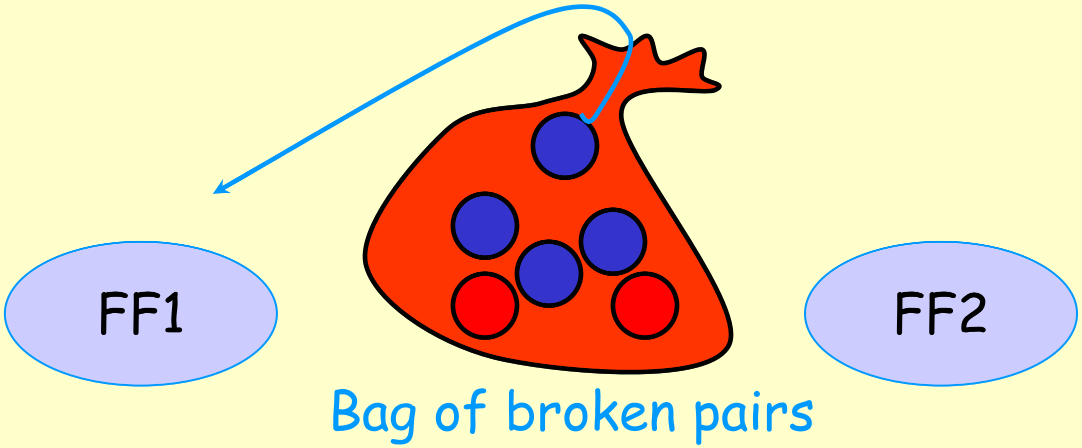




Low E_{diss} configuration for asymmetric splits

Quantitative description of the even-odd structure

A combinatory 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 $Zf/Af \approx 0.4$
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

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

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

Limitations of the combinatory analysis

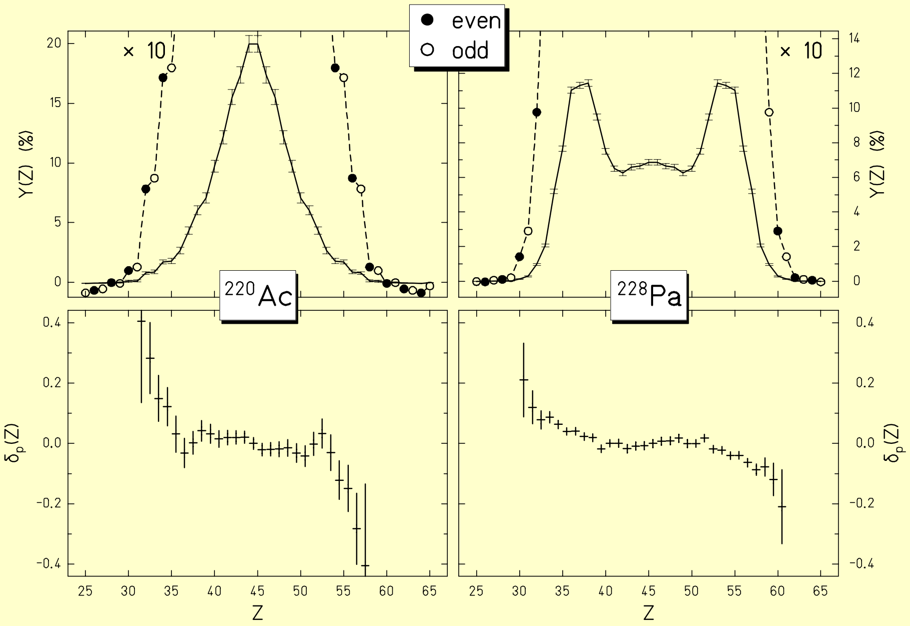
•Model is based on the number of broken pairs and **NOT** on the available phase space

As a consequence the model cannot reproduce

•the variation of δ_z with Z of the fission fragment (p=0.5)

•the amplitude of δ_n ($E_{diss}^n=2*E_{diss}^p$)

•the even-odd structures in odd-Z fissionning systems (q=1)



S. Steinhauser et al., 1998
M. Davi et al., 1998

Temperature-dependent pairing theory

Mantzouranis, Nix, 1982

From an intuitive picture, ……

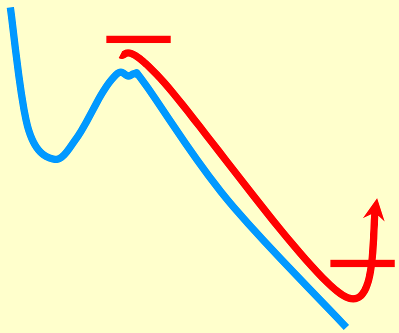
δ_Z = Number of quasi-particles/Number of free nucleon excitations

$$\delta_Z = 2/[1+\exp(\Delta(T)/T)]$$

As pairing decreases with temperature, the consequence is a reduction of the even-odd staggering.

- $\Delta(T)$ is different for protons and neutrons
- $\Delta(T)$ varies with the kinetic energy of fragments

Dynamical analysis of the even-odd structure



Willets 1964, Bouzid et al. 1997

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

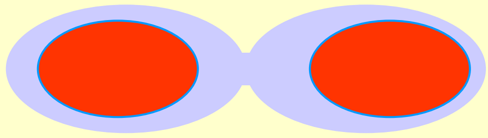
Probability to have odd-odd fragments : $P_{o\text{-}o} = p.\exp(-A/V_c)$

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

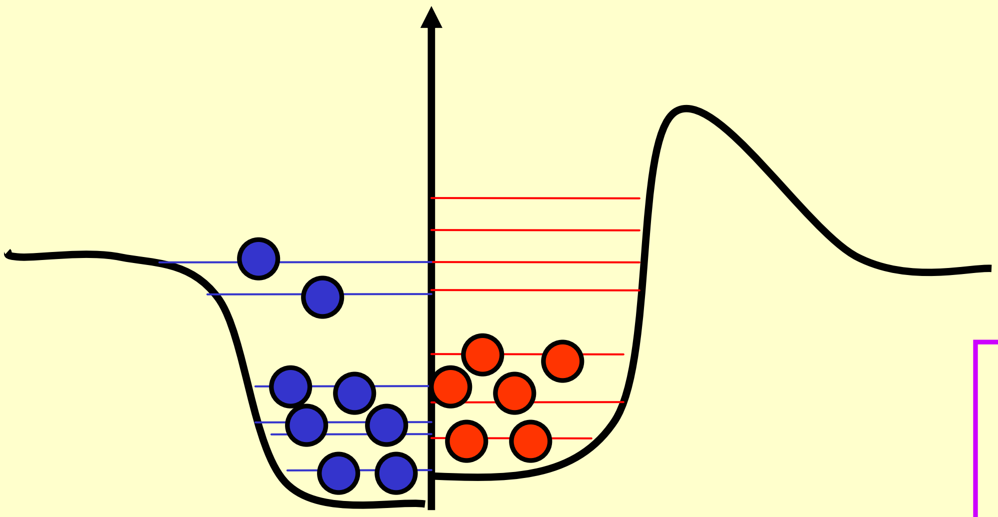


Due to Coulomb repulsion, the neutrons undergo more violent neck rupture and thus show a less pronounced even-odd structure

A new interpretation of the even-odd structure

If $E_{intr} > \Delta$

- there exists a probability that one pair is broken
- there exists a probability that one of the two subsystems of the nucleus remains completely paired P_{surv}



The statistical description of the properties of the nucleus allow us to quantify rigorously these probabilities

Probability that one pair is broken

Proportional to the number of available single particle states

Level density accessible to n particle-holes:

$\rho_n(U) = g^n(U-n\Delta)^{n-1}/(n/2)!^2(n-1)\,!$ Strutinski, 1958

g level density at the Fermi level

Δ pairing gap

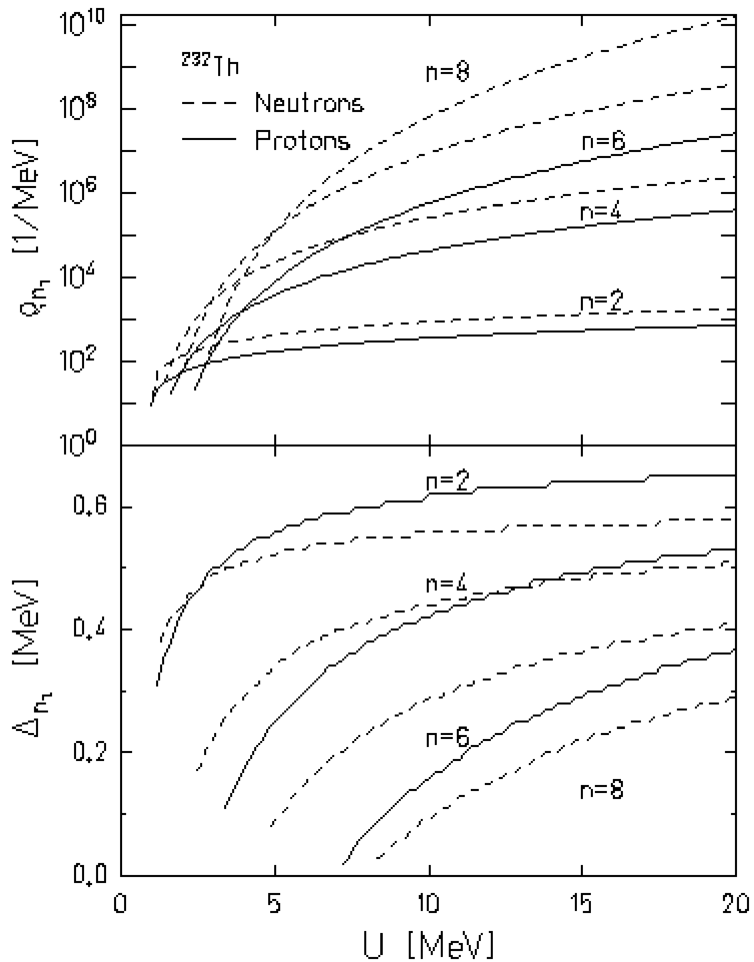
$\rho_n(U)=g^n(U_{eff})^{n-1}/(n/2)!^2(n-1)$ Ignatyuk, Sokolov, 1973

$U_{eff}=U - 1/4\, g(\Delta_0^2 - \Delta_n^2) - \Pi_n$

- Pauli exclusion reduces the number of excitations
- Energy-and n- dependence of the pairing-gap:

$$\Delta_n = \Delta_0(0.996-2.36(n/n_c)^{1.57})/(U/C)^{0.76}$$

Level density of n quasi-particles



$\rho_{n\tau}(U)=g^n(U_{eff})^{n-1}/(n/2)!^2(n-1)$

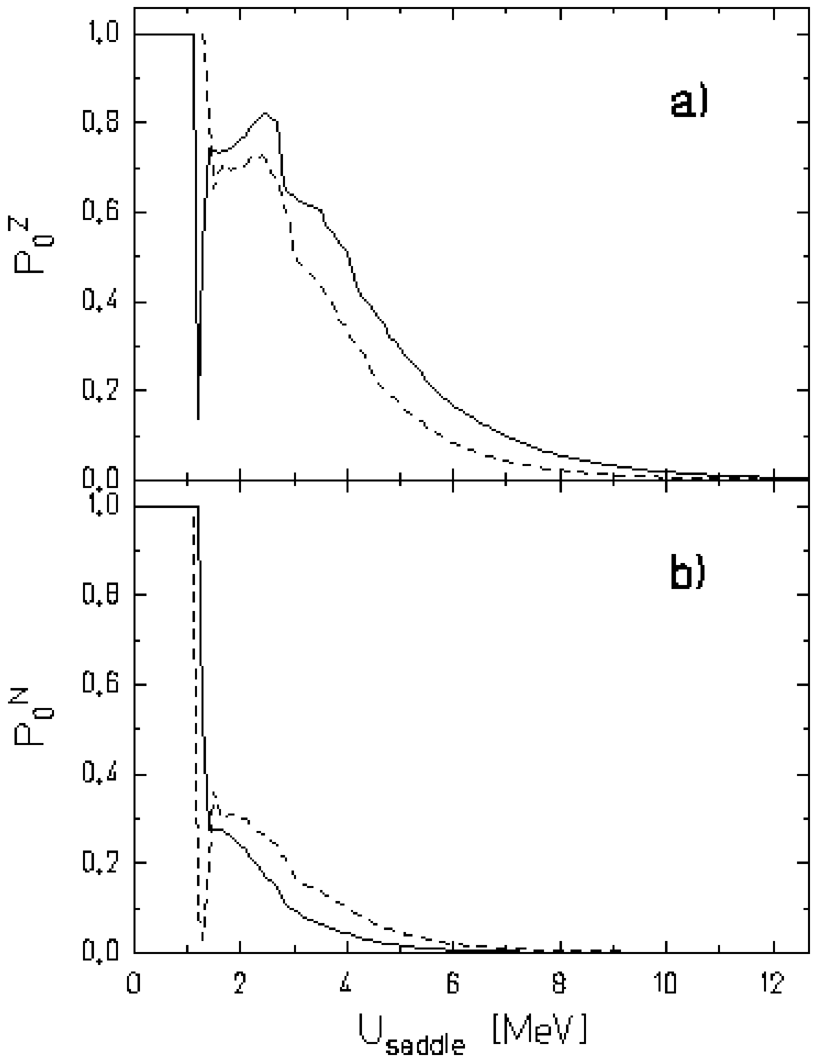
$g_\tau = N_\tau / 15$ MeV^{-1}

$g_\tau = N_\tau A^{2/3} / 2^{2/3}\ 15$ MeV^{-1}

$\Delta_{0\,\tau} = 3.2 / N_\tau^{1/3}$ MeV

Nix and Moeller, 1995

Survival probability of completely paired subsystem



Probability that protons remain paired:

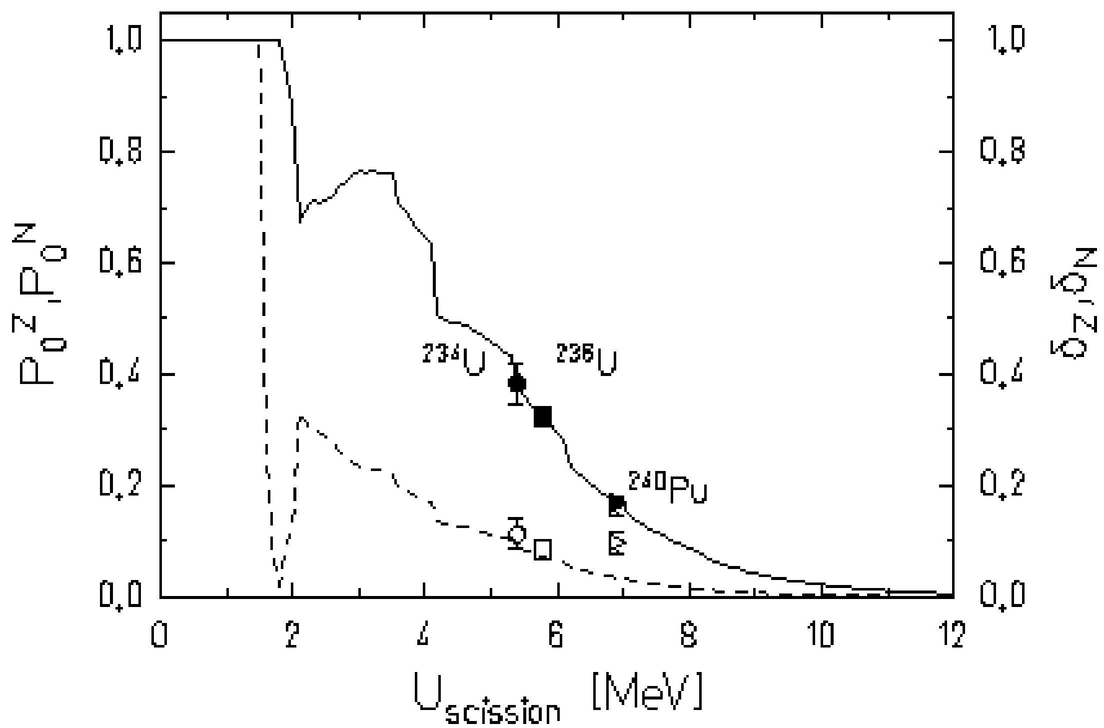
$$P_0^Z(U) = \sum_{n_N} \rho_{n_Z=0,n_N}(U) \Big/ \sum_{n_Z\,n_N} \rho_{n_Z,n_N}(U)$$

Level density of only broken neutron pairs

Level density of all possible excitations

Survival probability at scission of a fully paired configuration

Due to the higher level density in the neutron subsystem, the probability to break a neutron pair is much higher



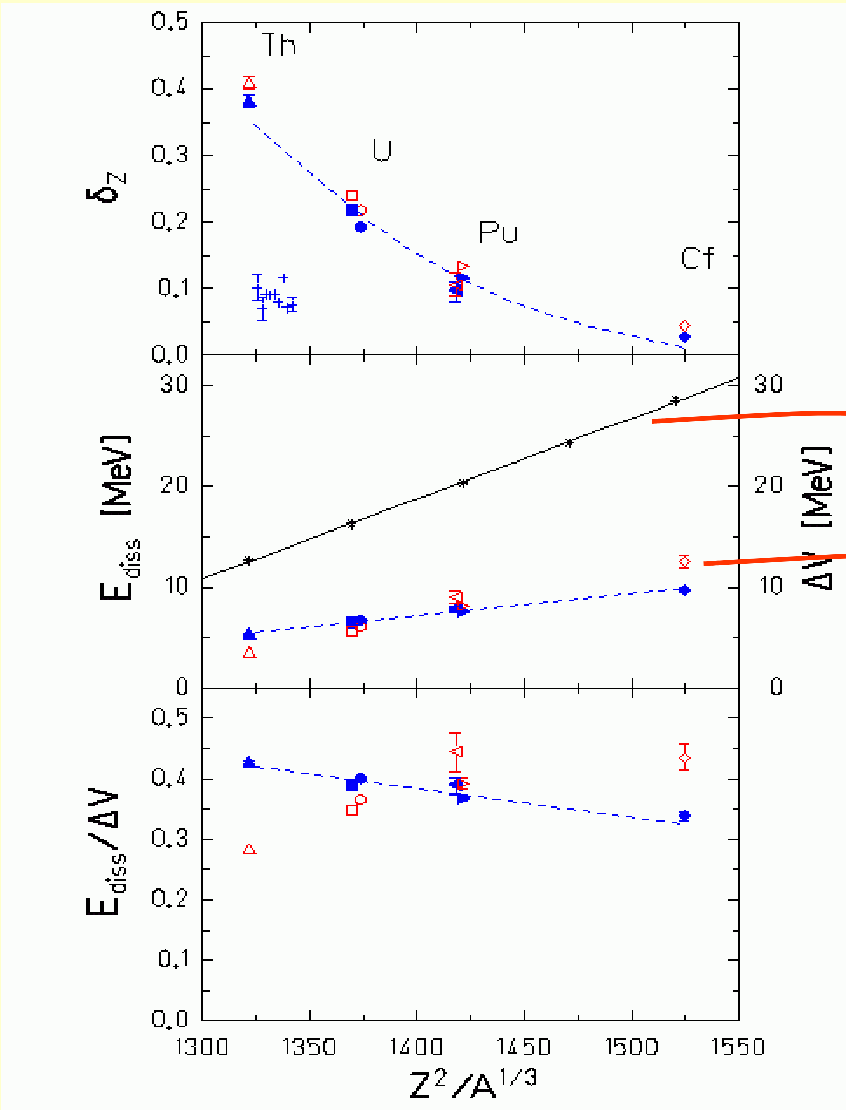
$$\Delta_{0\,\tau}^{scis} = \sqrt{2}\,\Delta_{0\,\tau}^{sad}\ \text{MeV}$$

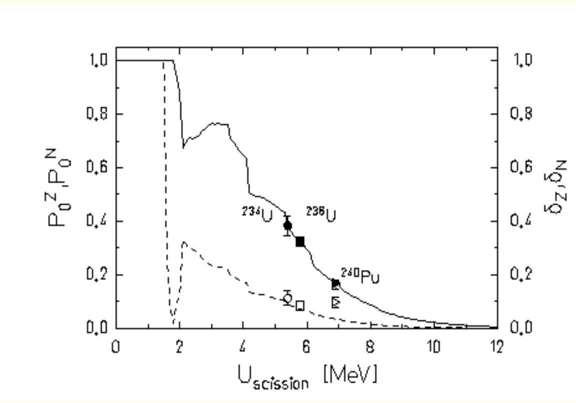
Zeldes, 1967

The model reproduces the experimental difference between proton and neutron even-odd structures

δ_p, δ_n measured for the highest kinetic energies

Determination of the dissipated energy





$\Delta V = 0.0796 Z_c - 92.65$ MeV

Asghar et al.

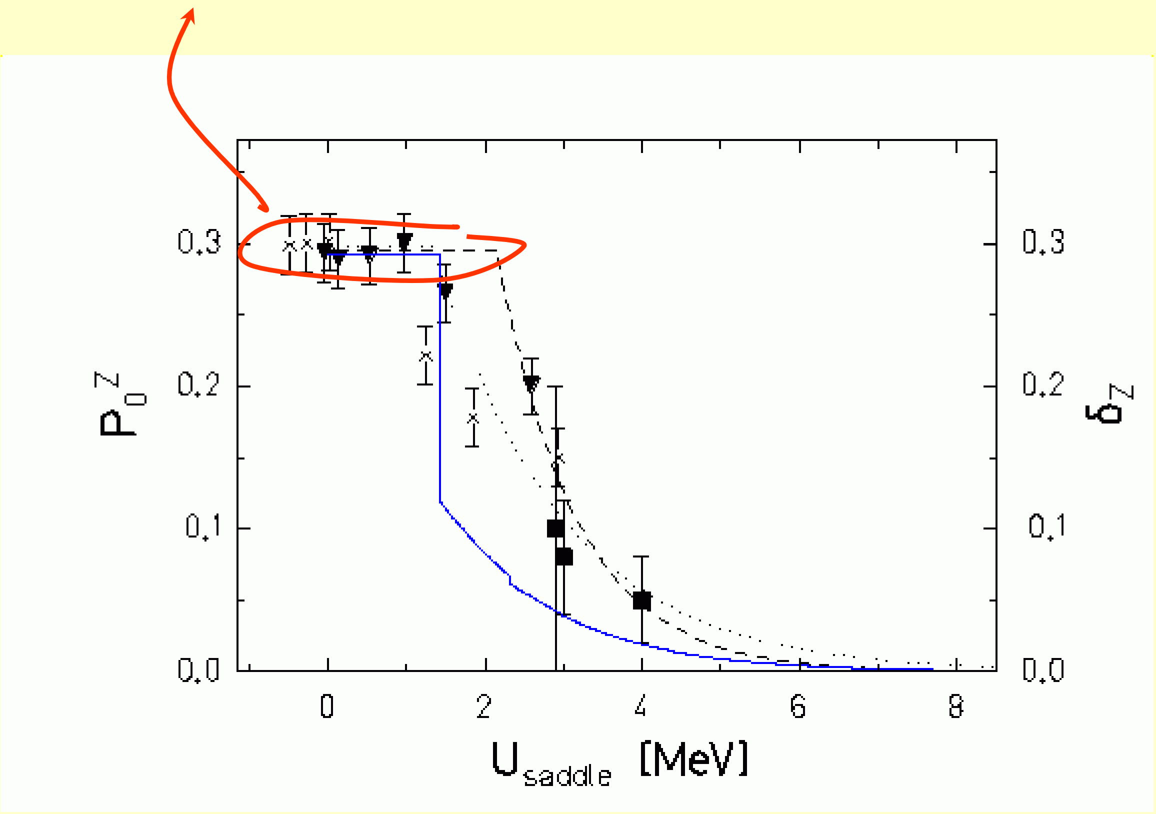
$E_{diss} = -4\ln(\delta_Z)$

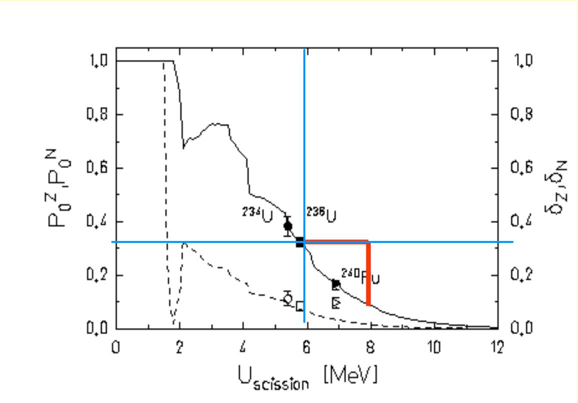
Nifenecker et al.

About 40 to 30 % of the energy release between saddle and scission is dissipated into intrinsic excitation.

Influence of the excitation energy at saddle

No pair breaking at saddle -> estimation of E_{diss}= 6 MeV



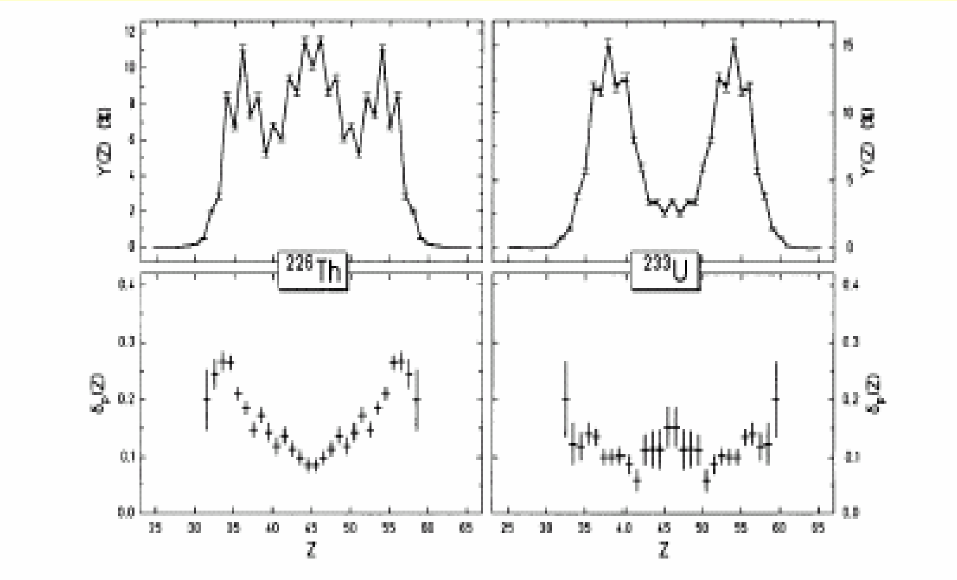


At scission the survival probability is constant for 2Δ and decreases sharply to reach the regular slope

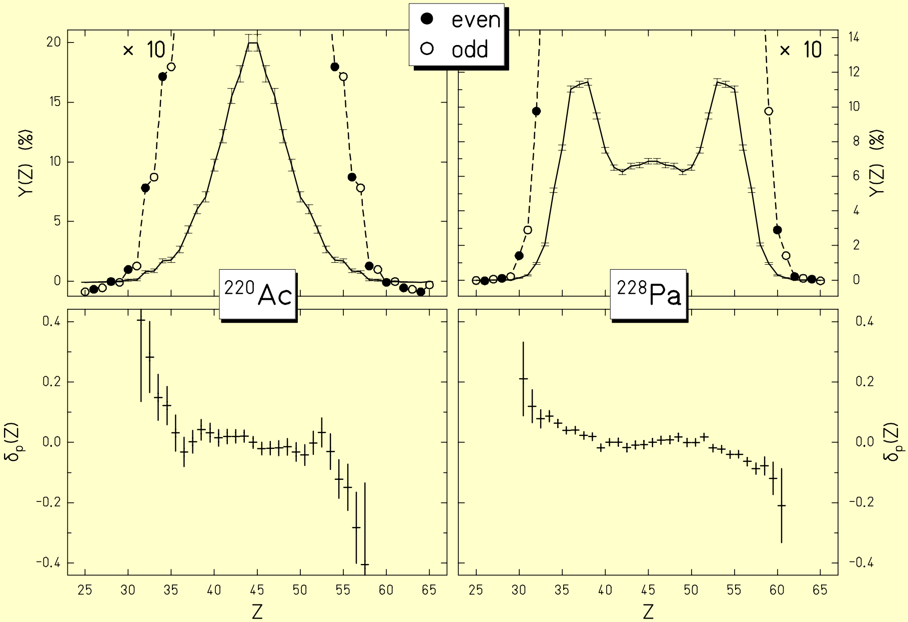
Brehmstrahlung experiments = large uncertainty in the energy determination

Local even-odd effect in the frame of the statistical model

Even-odd effect increases with asymmetry



Even-odd effect exists for odd-Z fissioning system



Negative even-odd effect for heavy Z fragments:
The particle sticks to the heavier fragment !!

Local even-odd effect in the frame of the statistical model

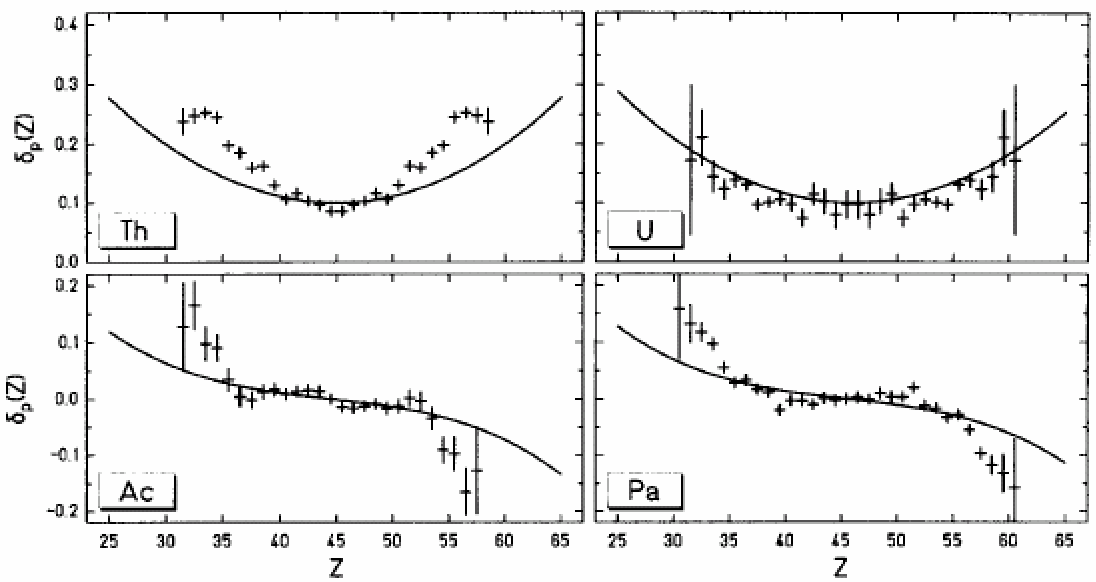
Level density in the fission fragment :

$$\rho(Z) = g(Z) \qquad g(Z) \propto Z$$

The relative statistical weight of 1 nucleon in fragment (Z) is :

$$p(Z) = (Z/Z_{cn})$$

$$\delta_p = (1-p(Z))^n \qquad \delta_p = (1-Z/Z_{cn})^n$$



S. Steinhauser et al., NPA634(1998)89

Conclusions

- A model based on the statistical properties of the nucleus is able to describe many features of experimental data relative to the even-odd effect in fission :
    - Amplitude in neutron and proton number
    - Decrease with the excitation energy
    - Increase with the mass asymmetry of the fission
- No fitted parameter has been used to reproduce the data
- The success of the predictions revitalizes the discussion between dynamical and statistical interpretation of the fission process.
- New experimental data to sign the dynamical features are requested.