Local and global even-odd effects in prompt emission in fission

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Introduction

- Proton (Z) even-odd effects in prompt emission in fission for even-Z actinides
- Contrary to the extensively studied proton even-odd effects in fragment distributions, the even-odd effects in prompt emission received less attention
- Even-even fissioning nuclei: fissionig spontaneously (^{252}CF(SF), ^{236,238,240,242,244}Pu(SF)) and induced by thermal neutrons (^{233,235}U(n_{th},f), ^{239}Pu(n_{th},f)) and an even-odd system ^{234}U(n,f)- induced by neutrons with En ranging from 0.2 to 5 MeV (14 incident energies)

  A. Tudora, F.-J. Hambsch, G. Giubega, I. Visan, Nucl. Phys. A. **929**, 260-292 (2014)
  A. Tudora, F.-J. Hambsch, G. Giubega, I. Visan, Nucl. Phys. A **933**, 165-188 (2015)
  A. Tudora, F.-J. Hambsch, G. Giubega, EPJA **52**, 182 -193 (2016)

- Prompt emission model Point-by-Point (PbP): the primary results are the multi-parametric matrices of different quantities characterizing the fission fragments and the prompt emission, generally labelled as q(A,Z,TKE) (e.g. ν(A,Z,TKE), Eγ(A,Z,TKE), N(E,A,Z,TKE)).

To obtain different average quantities, <q>(A), <q>(Z), <q>(TKE), <q>, q(A,Z,TKE) are averaged over the fission fragment distributions Y(A,Z,TKE).

➢ Fission fragments range in PbP:

- all mass pairs, from a symmetric fission up to a very asymmetric split are taken in consideration.
- for each mass pair $\{A_L, A_H\}$ 2 up to 5 charge numbers Z are taken at each A, as the nearest integer values above and below the most probable charge Zp. :

$$Zp(A) = Z_{UCD}(A) + \Delta Z(A)$$

$$Z_{UCD}(A) = A_L \frac{Z_0}{A_0} = A_H \frac{Z_0}{A_0}$$

ΔZ(A)- charge polarization (charge deviation, from Z_{UCD})

- for all considered fragments the calculations are done at TKE values covering a convenient range (e.g. from 100 MeV up to 200 MeV) with a step of 5 MeV.

➢ Global Z even-odd effect in prompt emission quantities

$$\delta_{<q>} = \frac{<q>_{even-Z} - <q>_{odd-Z}}{<q>}$$

$$<q>_{even-Z} = \sum_{A,Z_{even},TKE} q(A,Z_{even},TKE)Y(A,Z_{even},TKE) / \sum_{A,Z_{even},TKE} Y(A,Z_{even},TKE)$$

$$<q>_{odd-Z} = \sum_{A,Z_{odd},TKE} q(A,Z_{odd},TKE)Y(A,Z_{odd},TKE) / \sum_{A,Z_{odd},TKE} Y(A,Z_{odd},TKE)$$

$$<q>= \sum_{A,Z,TKE} q(A,Z,TKE)Y(A,Z,TKE) / \sum_{A,Z,TKE} Y(A,Z,TKE)$$

Basic features of the global Z even-odd effect in prompt emission

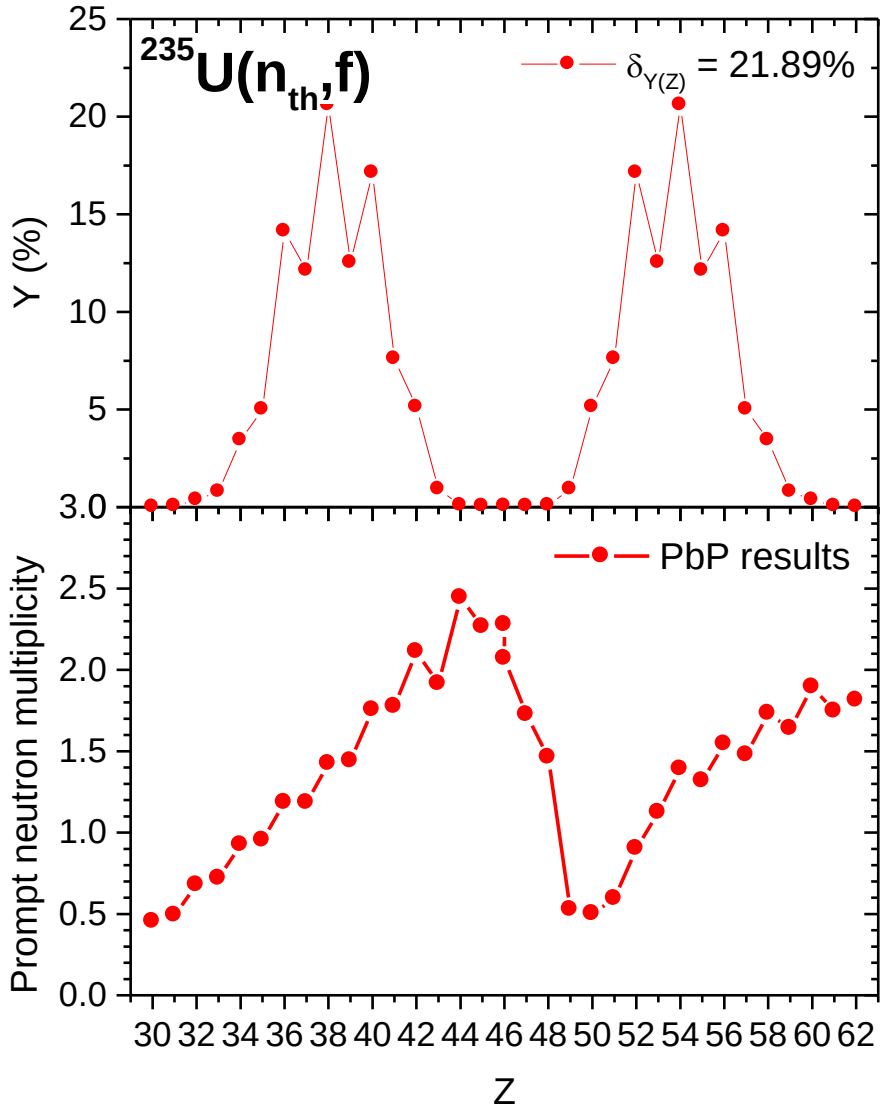
The main features of the global Z even-odd effect in prompt emission[1-3] are similar with those in fission fragment charge yields Y(Z)[4-6]:

- **the global Z even-odd effect in prompt emission decreases with increasing mass of the fissioning nucleus**

	$\delta_{<TXE>}$ (%)	$\delta_{<\nu>}$ (%)	$\delta_{<E\gamma>}$ (%)	$\delta_{Y(Z)}$ (%)
^{235}U(n_{th},f)	**7.68**	**9.07**	**3.88**	**21.89**
^{233}U(n_{th},f)	**8.54**	**8.86**	**3.57**	**21.65**
^{239}Pu(n_{th},f)	7.33	7.75	3.25	12.45
^{236}Pu(SF)	5.77	6.72	2.46	9.5
^{238}Pu(SF)	6.74	7.61	2.84	11
^{240}Pu(SF)	4.91	5.75	2.25	13
^{242}Pu(SF)	7.01	7.59	2.95	13
^{244}Pu(SF)	7.38	8.46	3.46	14
^{252}Cf(SF)	**5.65**	**6**	**2.53**	**4.26**

1. A. Tudora, F.-J. Hambsch, G. Giubega, I. Visan, Nucl. Phys. A. **929**, 260-292 (2014)
2. A. Tudora, F.-J. Hambsch, G. Giubega, I. Visan, Nucl. Phys. A **933**, 165-188 (2015)
3. A. Tudora, F.-J. Hambsch, G. Giubega, EPJA **52**, 182 - 193 (2016)
4. Gonnenwein, F., (1991) in: Wagemans, C. (Ed.), The Nuclear Fission Process, CRC Press, Boca Raton, chapter 8.
5. N.Caamano, F.Rejmund, K.-H.Schmidt, J.Phys.G Nucl.Part.Phys. 38 (2011) 035101
6. F.Gönnenwein, Physics Procedia 47 (2013) 107-114

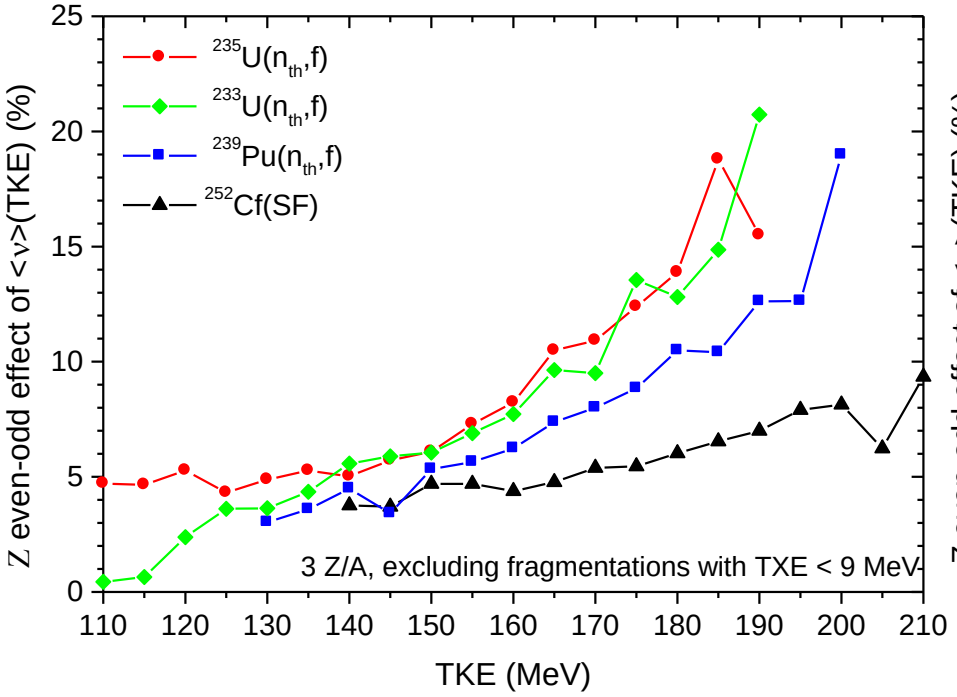
- **prompt neutron multiplicity as a function of Z, ν(Z), exhibit a visible staggering in the asymmetric fission region as Y(Z) does.**

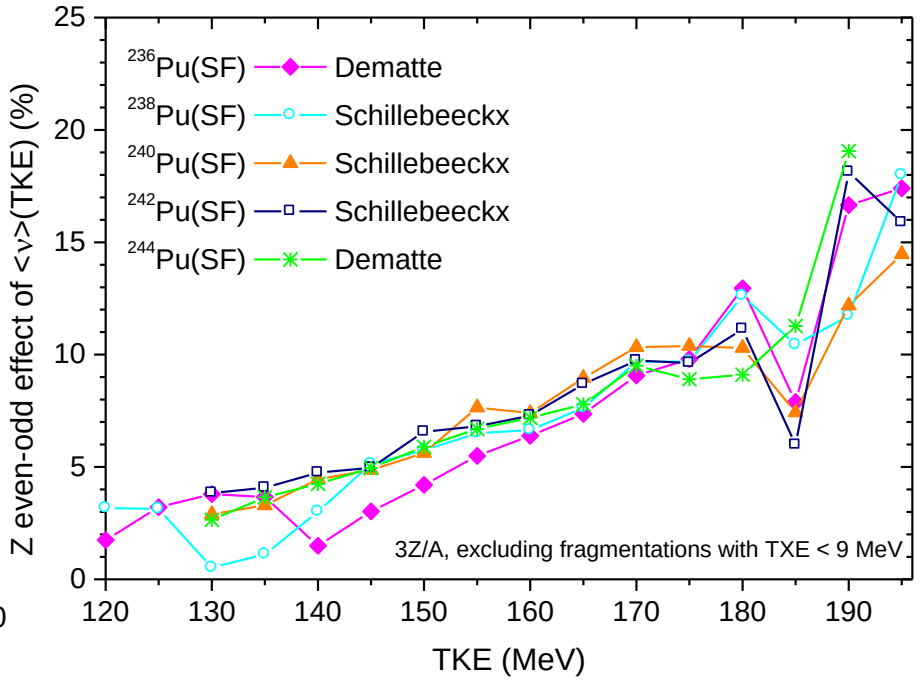


- **the *Z* even-odd effect increases with increasing kinetic energy of the fission fragments**

$$\delta_{<\nu>}(TKE) = \frac{<\nu>_e (TKE) - <\nu>_o (TKE)}{<\nu>(TKE)}$$

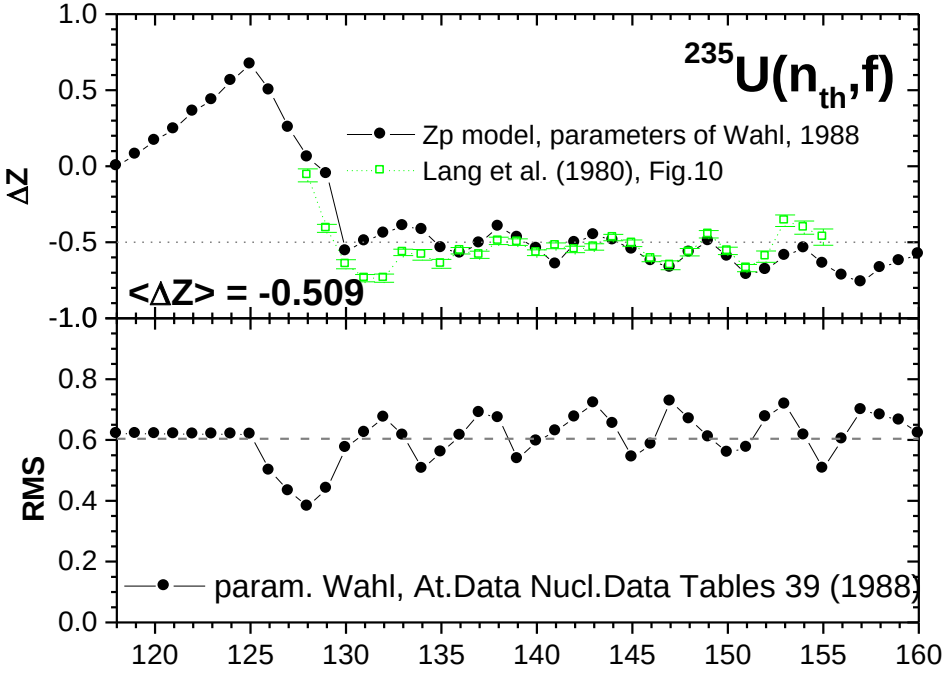
A. Tudora, F.-J. Hambsch, G. Giubega, I. Visan, Nucl. Phys. A. **929**, 260-292 (2014)

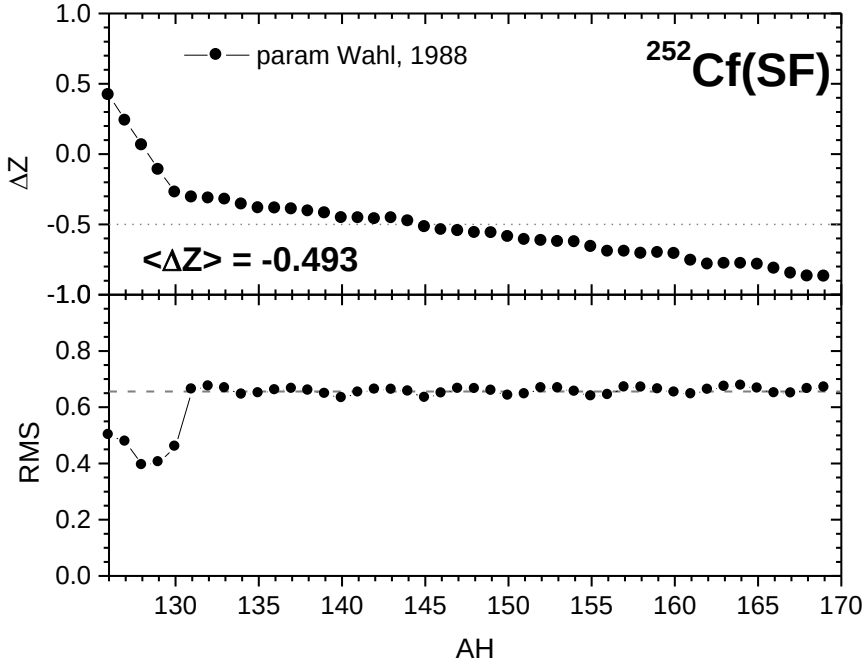




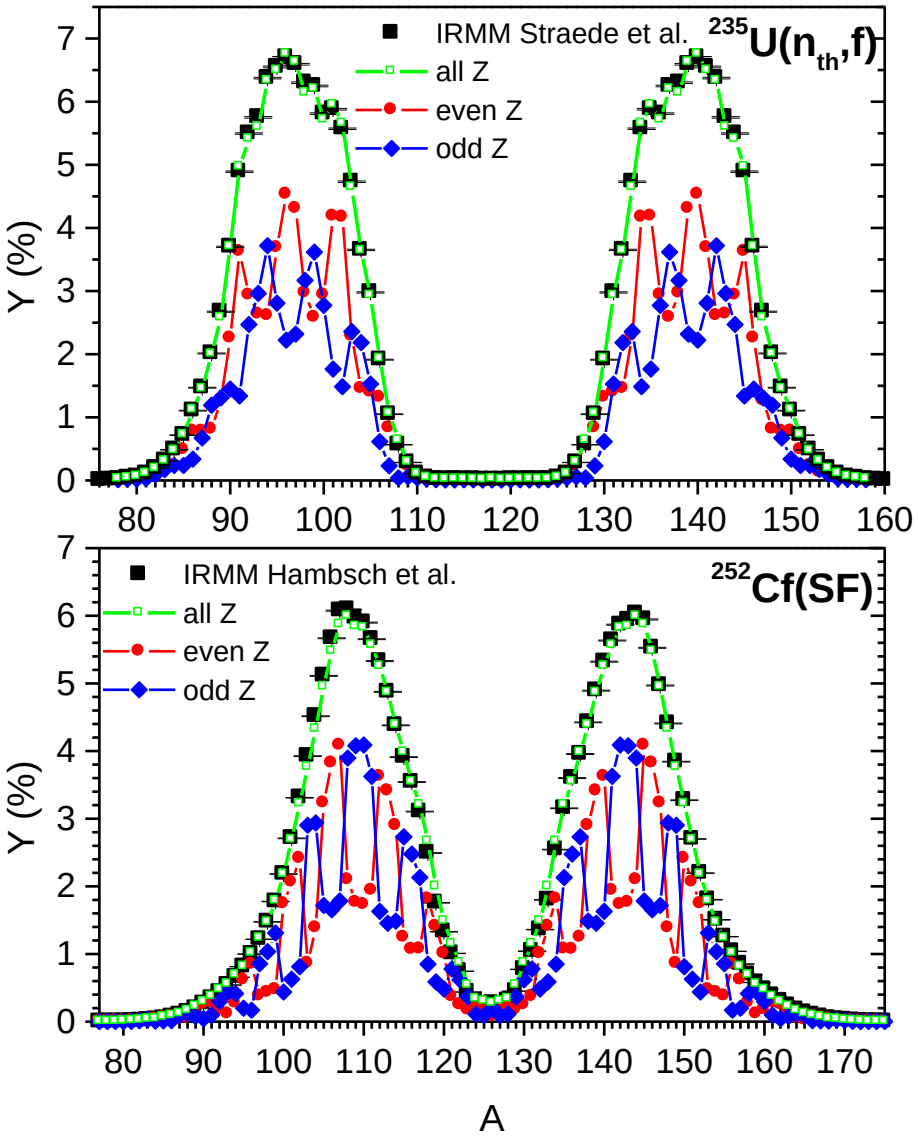
Particular aspects related to even-odd effects in prompt emission

- **Periodicity of ΔA≈5 in quantities as a function of A corresponding to even-Z and odd-Z fragmentations**
  - The same periodicity was seen in experimental ΔZ(A) and rms(A) data





Frament mass distribution

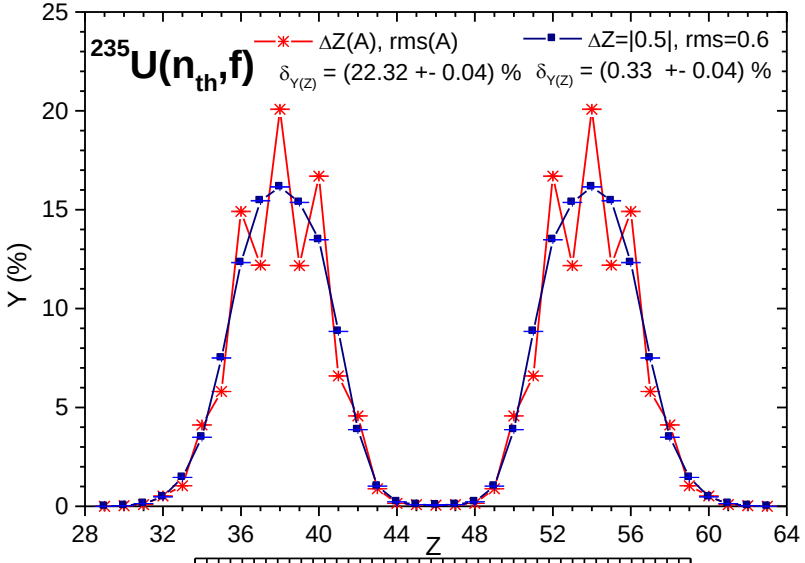


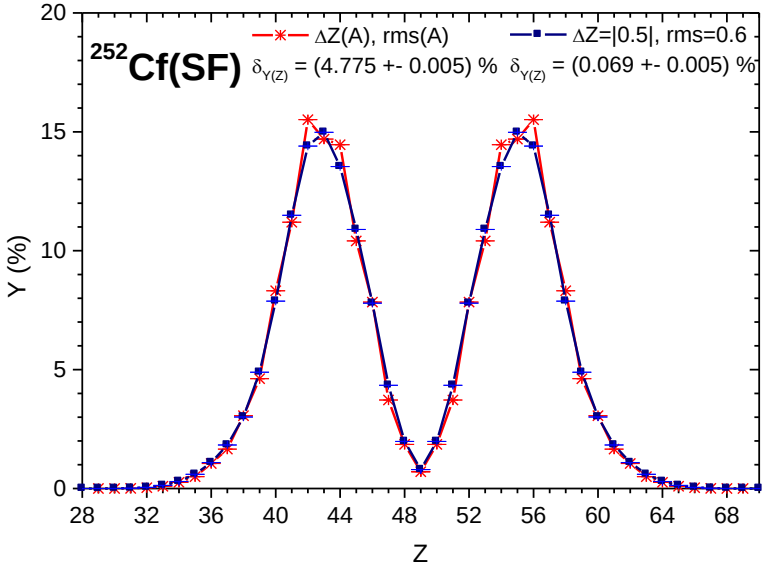
^{235}U(n$_{th}$,f) ($\delta_{Y(Z)}$ = 22 %) : the amplitude of the oscillations is higher for even-Z fragments than for odd-Z fragments

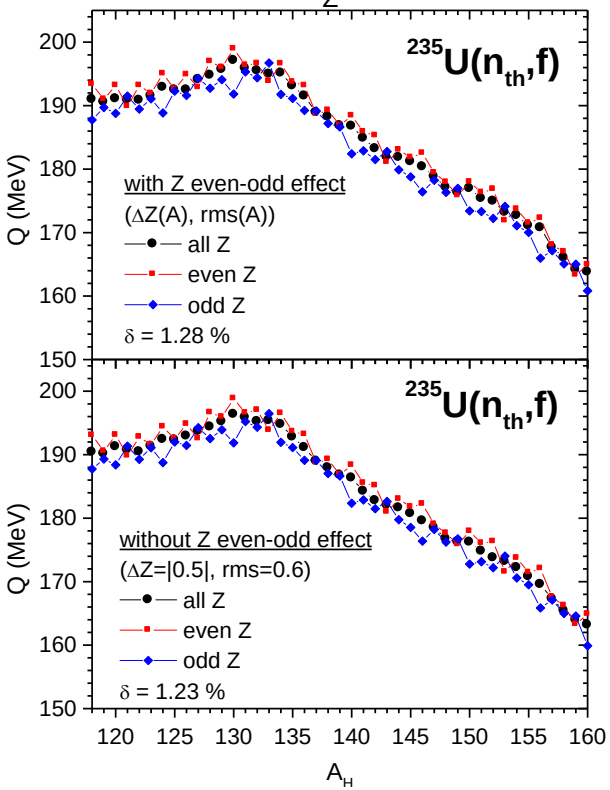
^{252}Cf(SF) ($\delta_{Y(Z)}$ aprox. 4 %) the amplitude of the oscillations are almost equal

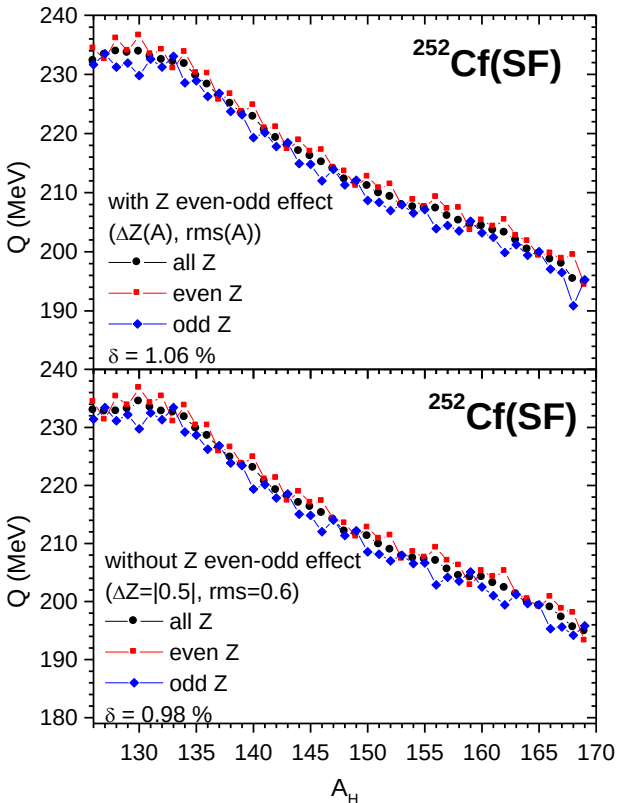
- Y(A) of even-Z and odd-Z fragments oscillate in anti-phase: ampl. of Y(A) of Z par > Y(A) of odd-Z means the presence of the Z even-odd effect in Y(Z). Equal amplitudes → canceled effect.

Prompt emission quantities









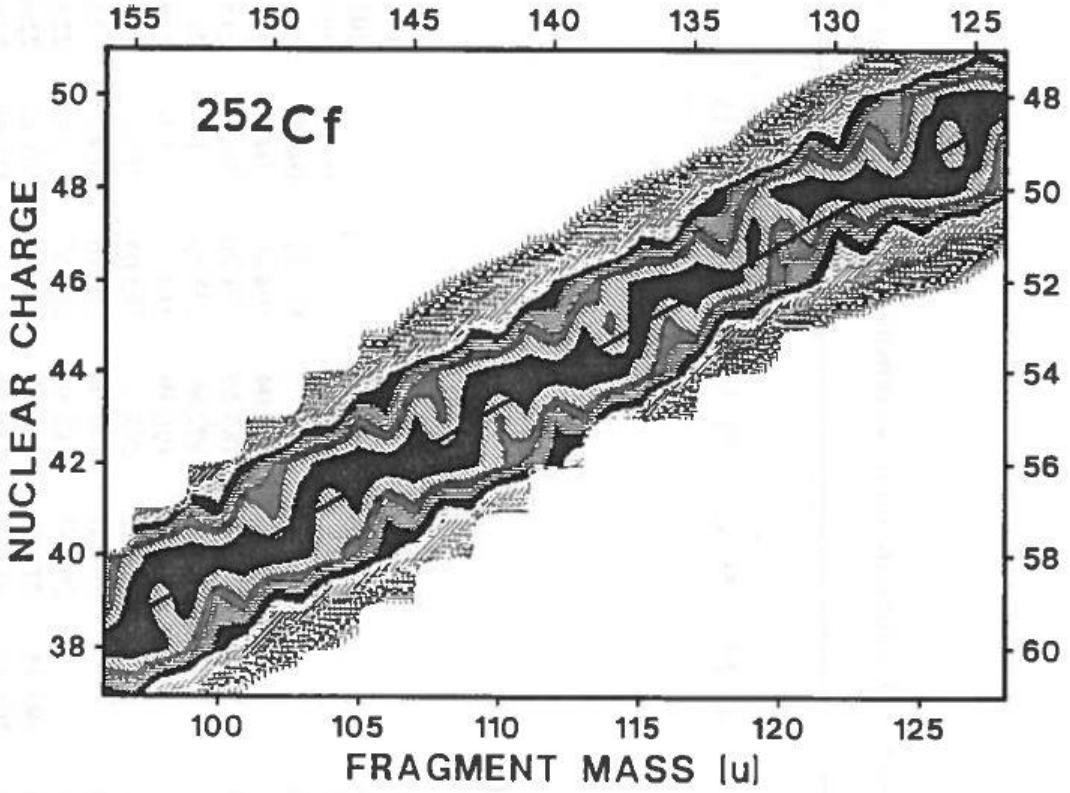
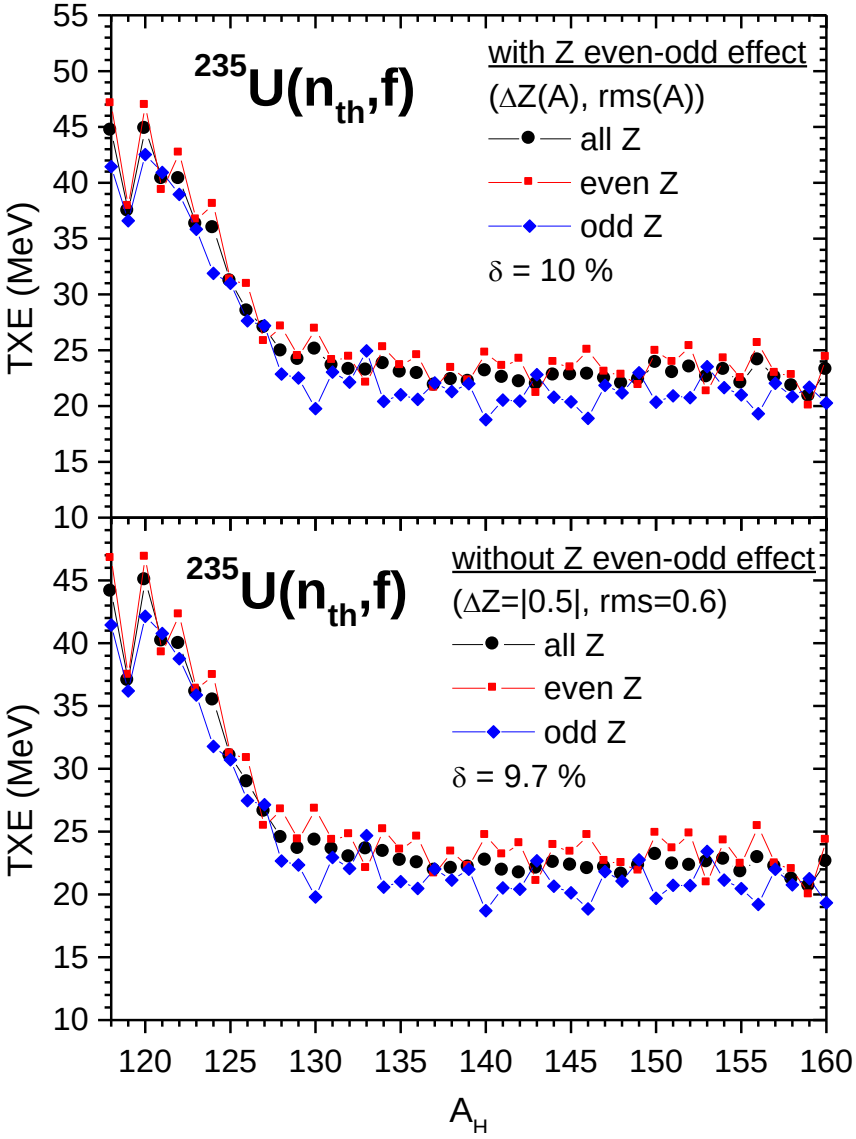
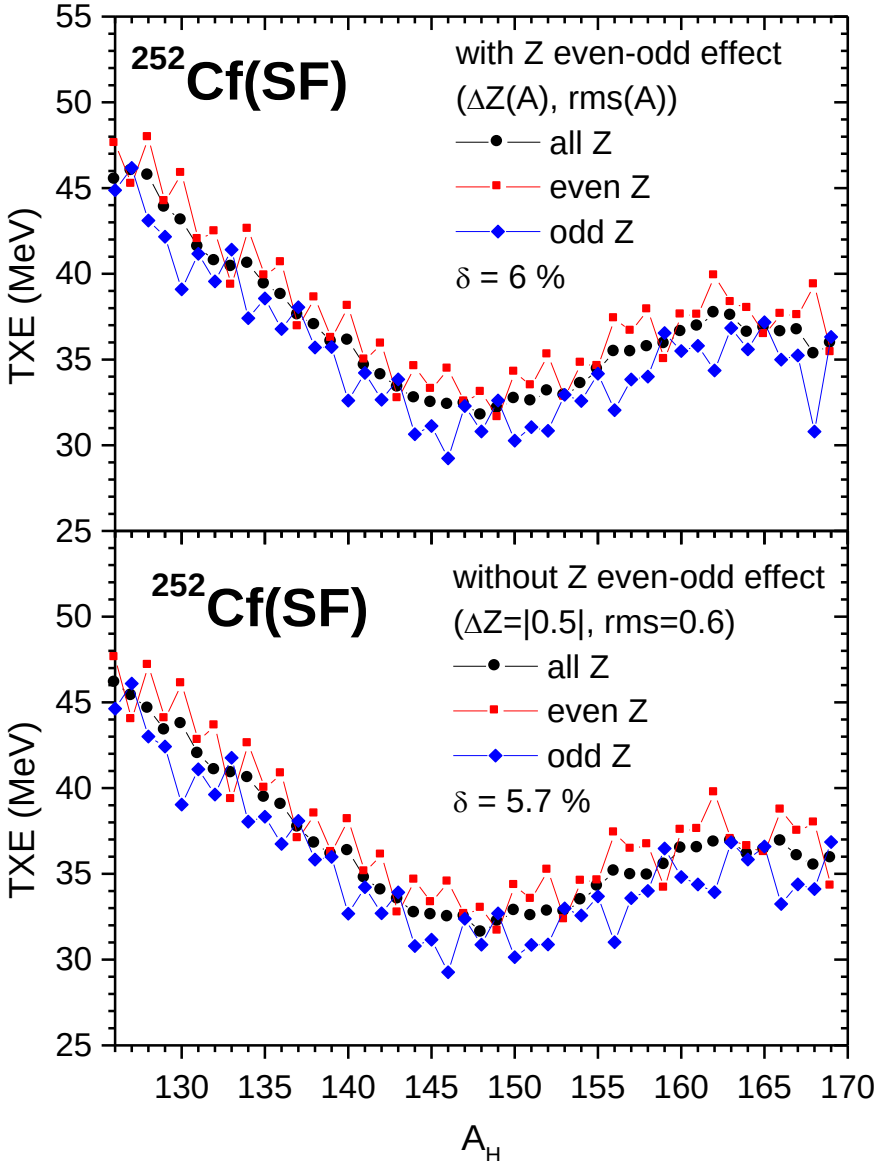


Fig. 18. The fission energy valley ($Q_{max}(A_L) - Q(A_L, Z_L)$) is shown in a grey tone picture versus the light fragment mass and the nuclear charge. The energy steps of the grey tone are 1.25 MeV.

- The $\Delta A \approx 5$ periodicity in Q was observed in the experimental results obtained by Hambsch and Knitter- Knitter et al. NPA 536 (1992) 221

Average total excitation energy TXE





The closed values of δ in TXE demonstrates that the prompt emission has an intrinsic even-odd effect due to the nuclear properties of fission fragments.

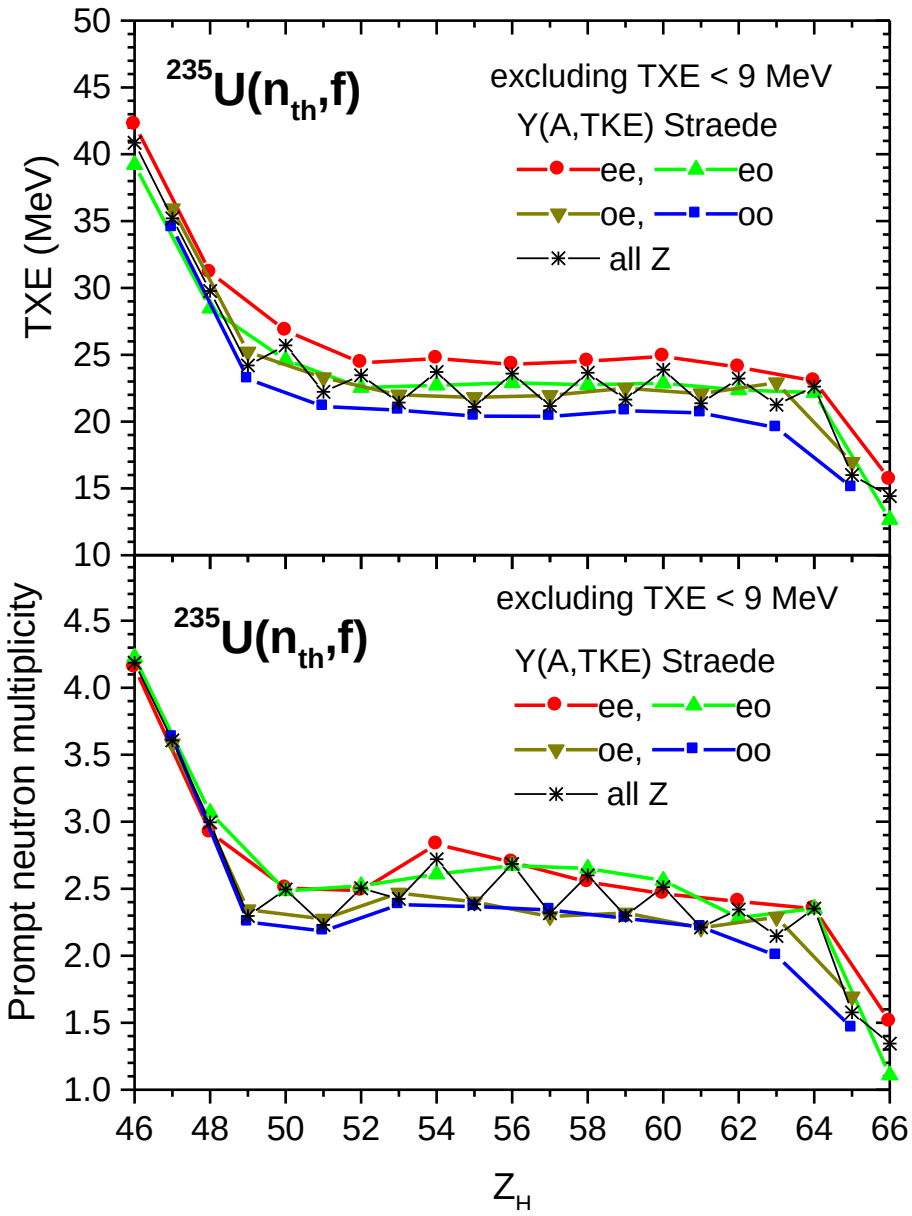
^{234}U(n,f) at 14 incident energies ranging from 0.2 MeV to 5 MeV

- **the global Z even-odd effect δ in Y(Z) is decreasing from 20-25 % (0.2 MeV) up to 5-7 % (5 MeV)**
- **δ in <ν> is slightly decreasing with En, from about 9 % at 0.2 MeV to 8 % at 5 MeV**
- **δ in < TXE> decreases from about 8.3 % at 0.2 MeV to 7.6 at 5 MeV**
- **δ in <Eγ> decreases from 3.9 % at 0.2 MeV to 3.5 % at 5 MeV**

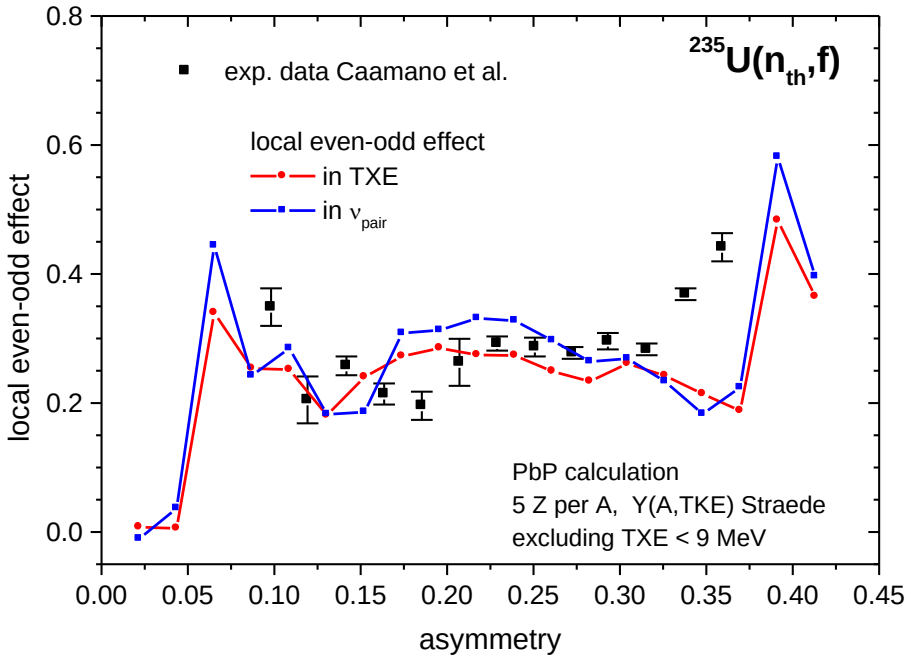
➢ **The even-odd effects in prompt emission are the result of two contributions**:

- a dominant intrinsic even-odd effect due to the even-odd nuclear character of fragments reflected in their properties (and consequently in the emitted prompt neutrons and γ-rays)
- a weak even-odd effect caused by the fragment distributions on which the multi-parametric matrices are averaged

Local even-odd effect in prompt emission quantities



$$\delta_{p<q>} = \frac{1}{2}\frac{<q>_{even-Z} - <q>_{odd-Z}}{<q>_{even-Z} + <q>_{odd-Z}}$$



- δ_p in TXE and ν exhibit a similar behavior as experimental δ_p referring to fragment yields
- pronounced increase at asymmetry values $a_s = (Z_H - Z_L)/Z_0$ of: 0.07 → N_H=82
  0.4 → Z_L=28

Conclusions

- **The basic features of the even-odd effect in fragment yields and prompt emission quantities are the same, *e.g.* the staggering of *Y(Z)* and *v(Z)* in the asymmetric fission region, the decrease of the effect with increasing mass of the fissioning nucleus.**
- **The periodicity *ΔA ≈ 5* of the oscillations in *ΔZ(A)*, *rms(A)*, *Y(A)* and different quantities related to the prompt emission corresponding to even-*Z* and odd-*Z* fragmentations are due to the periodicity of nuclear properties of fragments being independent of the presence or not of the even-odd effect in the charge yield *Y(Z)*.**
- **In the case of the fragment yields, not the periodicity but the amplitude of the oscillations in *ΔZ(A)*, *rms(A)*, *Y(A)* is the one which is correlated with the even-odd effect in two different ways:**
  - The magnitude of the amplitude oscillation of *ΔZ(A)*, *rms(A)* is proportional with the size of the even-odd effect in *Y(Z)*
  - *Y(A)* of even-*Z* and odd-*Z* fragments oscillate in anti-phase. Higher amplitudes of even-*Z* than of odd-*Z* fragments means the presence of the even-odd effect. At limit, equal amplitudes in anti-phase cancel the even-odd effect in *Y(Z).*

Conclusions (2)

- **The even-odd effect in prompt emission quantities is the result of two contributions**:
  - a dominant intrinsic even-odd effect due to the nuclear properties of fragments and
  - a weaker even-odd effect brought by the fragment distributions (over which the multi-parametric matrices are averaged).

For this reason the oscillations with the period $\Delta A \approx 5$ are present in different prompt emission quantities corresponding to even-*Z* and odd-*Z* fragmentations independent on the size of the even-odd effect in *Y(Z)*.

For the first time, a local even-odd effect in prompt emission was determined

- **The local even-odd effect in *TXE* and prompt neutron multiplicity exhibits the same behaviour as the local even-odd effect in fragment yields: the pronounced increase at asymmetry values corresponding to fragmentations in which the heavy fragment (*Z*=50 and/or *N*=82) or the light one (*Z*=28) is magic**

Thank you for your attention!