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EVEN-ODD EFFECTS IN PROMPT EMISSION IN FISSION INDUCED BY THE CHARGE POLARIZATION

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Abstract. The even-odd effects in prompt emission induced by the charge polarization are investigated. The charge polarization influences the range of fission fragments for which the prompt emission quantities are calculated in the frame of the Point-by-Point model. The way of considering the charge polarization: ΔZ as a function of the fragment mass A or a constant ΔZ value of $|0.5|$ for all fragments affects the fission fragment charge distribution $Y(Z)$. Recent papers focused on proton and neutron even-odd effects in prompt emission showed that the even-odd staggering exhibited by different prompt emission quantities are due to the Z even-odd effect in $Y(Z)$ and $\Delta Z(A)$ and to the N even-odd effect in the average neutron separation energy from fragments. Prompt emission results for even-even and even-odd fissioning nuclei, obtained using different charge polarizations, are given.

Key words: prompt neutron, even-odd effect, charge polarization.

1. INTRODUCTION

The influence of the charge polarization in even-odd effects in fission fragment distributions and in prompt emission in fission is investigated.

Recent papers [1–3] focused on proton and neutron even-odd effect in prompt emission in fission have revealed the following basic features: *a)* the proton (Z) even-odd effect decreases with increasing mass of the fissioning system; *b)* the Z even-odd effect decreases with increasing excitation energy of the fissioning system; *c)* the neutron (N) even-odd effect in the average neutron separation energy from fission fragments (FF) is often acting contrary to the Z even-odd effect; *d)* the charge polarization (ΔZ) and the root-mean-square (*rms*) of the isobaric charge distribution $p(Z,A)$ as a function of FF mass exhibit oscillations with a periodicity of about 5 mass units. The amplitude of these oscillations, reflecting the size of the Z even-odd effect, decreases with increasing mass and excitation energy of the fissioning nucleus. Almost all features of the Z even-odd effect in FF distributions (highlighted in many papers [4–8]) are reflected in the prompt emission.

Prompt emission calculations are done in the frame of the Point-by-Point (PbP) model, even-odd effects being investigated for two types of fissioning systems: even-even $^{235}U(n_{th},f)$ and even-odd $^{234}U(n,f)$.

The charge polarization influences the fission fragments range taken into account in prompt emission calculations. As it was already mentioned in previous papers [9, 10], the range of fragments is chosen taking into account a large range of fragment masses *A* (from symmetric fission up to a very asymmetric split). For each *A*, two up to five charge numbers *Z* are taken as the nearest integers above and below the most probable charge Z_P.

$$Z_p(A) = Z_{UCD}(A) + \Delta Z(A) \quad \text{and} \quad Z_{UCD}(A) = A\frac{Z_0}{A_0}\,, \tag{1}$$

where Z_{UCD} is the unchanged charge distribution and Z_0, A_0 are referring to the fissioning nucleus.

For all this fragmentations, prompt emission calculations are done for total kinetic energies (*TKE*) values covering a convenient range (usually from 100 to 200 MeV with a step of 5 MeV). Thus, the primary results of the PbP model are multi-parametric matrices of different quantities characterizing both the fragments and the prompt emission, generally labeled as *q(A,Z,TKE)*. To obtain different average quantities (needed for comparison with experimental data), *q(A,Z,TKE)* are averaged over the fragment distributions *Y(A,Z,TKE)* in different ways [9,10].

2. EVEN-ODD EFFECTS IN ΔZ*(A)* AND *RMS(A)*

Experimental information about Δ*Z(A)* and *rms(A)* data are available only for a few fissioning systems [11–13]. For those systems for which ΔZ*(A)* and *rms(A)* data are missing, we obtain them by fitting the isobaric charge distribution *p(Z,A)* with Gaussian functions (as it was first described in [2]).

p(Z,A) is calculated in the frame of the "Z_P model" of Wahl [11–13], according to the following relations:

$$p(Z,A) = 0.5\,F_{eo}(A)\,N(A)\left(\mathrm{erf}(V) - \mathrm{erf}(W)\right) \tag{2}$$

with

$$V = \frac{Z(A) - Z_p(A) + 0.5}{\sigma_z(A)\sqrt{2}}\,, \quad W = \frac{Z(A) - Z_p(A) - 0.5}{\sigma_z(A)\sqrt{2}} \tag{2.1}$$

and the even-odd factor $F_{eo}(A_p)$

$$F_{eo}(A_p)=\begin{cases}\bar{F}_Z\,\bar{F}_N & \text{even } Z,\ \text{even } N\\ \bar{F}_Z/\bar{F}_N & \text{even } Z,\ \text{odd } N\\ \bar{F}_N/\bar{F}_Z & \text{odd } Z,\ \text{even } N\\ 1/(\bar{F}_Z\,\bar{F}_N) & \text{odd } Z,\ \text{odd } N\end{cases}\quad ,\ \text{with } N=A_p-Z. \tag{2.2}$$

The Gaussian fit of the calculated *p(Z,A)* gives the most probable charge Z_P and the root-mean-square of the distribution, at each mass fragment. Examples of such Gaussian fits are given in Fig. 1 for ^{235}U(n_{th},f).

$\Delta Z(A)$ and *rms(A)* resulted from these fits are exemplified in Fig. 2 a) for ^{235}U(n_{th},f) (red circles) and b) for ^{234}U(n,f) at the incident energy E_n = 0.5 MeV (blue squares) and 5 MeV (red stars). The oscillations with the periodicity of 5 mass units in both $\Delta Z(A)$ and *rms(A)* can be seen in both figures. The decreasing of the oscillation amplitudes with the energy is visible in Fig. 2 b).

As it was reported in [1, 2, 13] the amplitude of the $\Delta Z(A)$ and *rms(A)* oscillations decreases with increasing mass of the fissioning system, reflecting the size of the *Z* even-odd effect. The lack of any *Z* even-odd effect leading to non-oscillating $\Delta Z(A)$ and *rms(A)*.

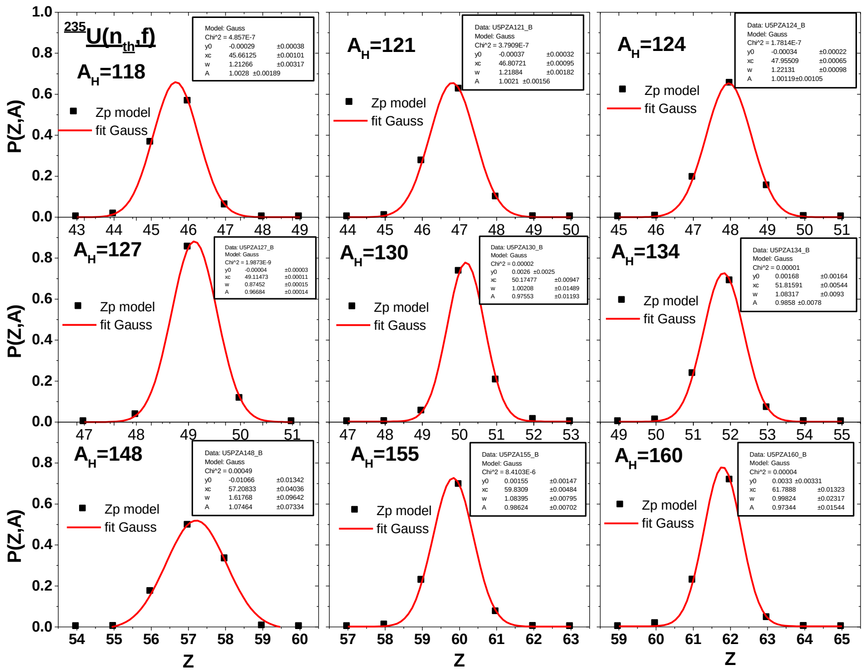
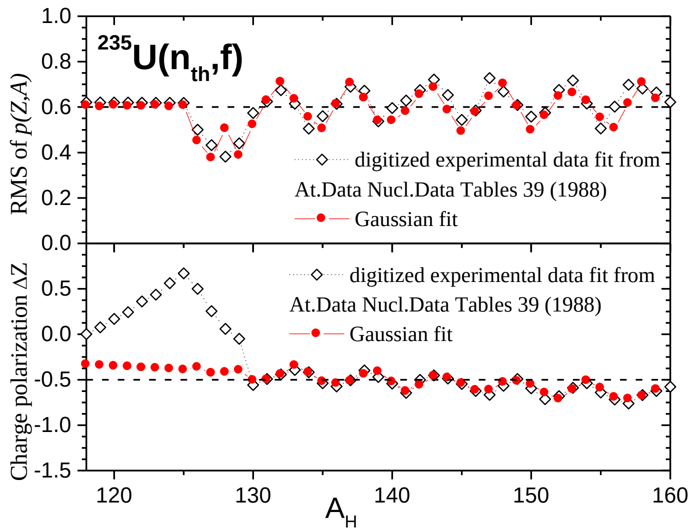


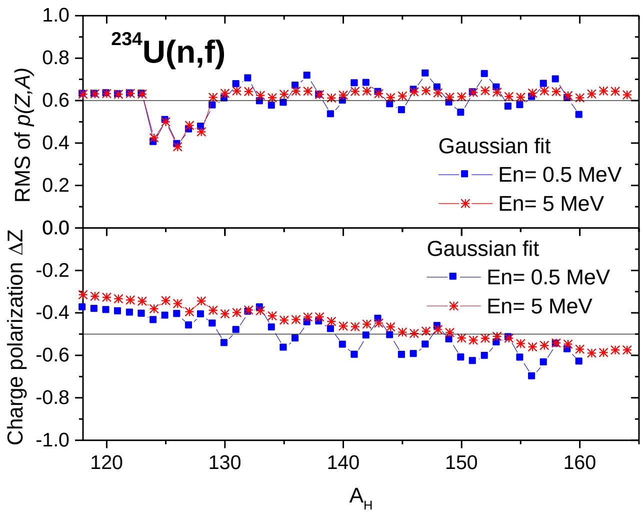
Fig. 1 – The isobaric charge distribution *p(Z,A)* obtained with Z_p model (black squares) and the Gaussian fit (red line).

Averaging the $\Delta Z(A)$ and *rms(A)* data over the fission fragment mass distributions, a value of about 0.5 for ΔZ and 0.6 for *rms* were obtained.

The influence of how the ΔZ and *rms* are considered on even-odd effects in fragment distributions is investigated. Two cases *i)* ΔZ and *rms* as a function of *A* and *ii)* $\Delta Z = |0.5|$ and *rms* = 0.6 for all fragments are analyzed.



a)



b)

Fig. 2 – Root-mean-square of *p(Z,A)* (upper parts) and charge polarization (lower parts) as a function of heavy fragment mass.

3. THE INFLUENCE OF *ΔZ* AND *RMS* IN Z EVEN-ODD EFFECT IN *Y(Z)*

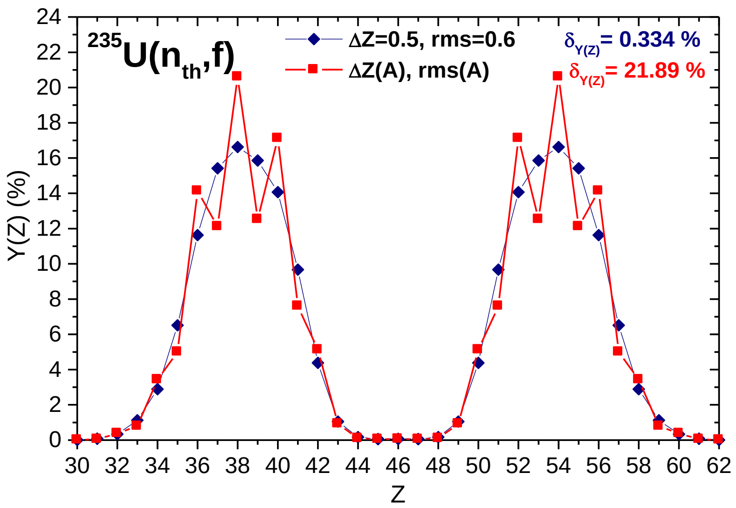
The fission fragment distributions *Y(A,Z,TKE)* needed to obtain different average quantities are constructed as:

$$Y(A,Z,TKE) = Y(A)\frac{1}{\sigma_{TKE}(A)\sqrt{2\pi}}\exp\left(-\frac{(TKE - TKE(A))^2}{2\sigma_{TKE}(A)^2}\right)\times$$
$$\times\frac{1}{rms(A)\sqrt{2\pi}}\exp\left(-\frac{(Z - Zp(A))^2}{2\,rms(A)^2}\right), \tag{3}$$

where *Y(A)*, $\sigma_{TKE}(A)$ and *TKE(A)* are experimental distributions.

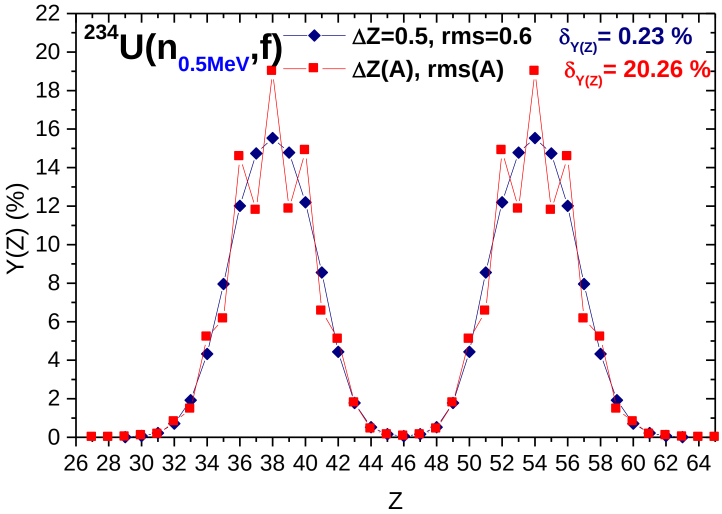
In Fig. 3 a–b are given examples of *Y(Z)* projections for ^{235}U(n$_{th}$,f) (a) and ^{234}U(n,f) at E_n = 0.5 MeV (b) for the two cases of considering ΔZ and *rms* in choosing fragments and in *Y(A,Z,TKE)* construction. The presence of the even-odd effect, exhibited by the staggering in *Y(Z)* when Δ*Z(A)* and *rms(A)* are used (red squares) is visible. When constant values ΔZ = |0.5| and *rms* = 0.6 for all fragments are used (navy diamonds) the even-odd effect disappears, the staggering being vanished.

This fact is reflected by the size of the global even-odd effect [5] calculated as: $\delta_{Y(Z)} = \left(\sum Y(Ze) - \sum Y(Zo)\right) / \sum Y(Z)$ and given in the legend of Fig. 3. The $\delta_{Y(Z)}$ is almost 0 at constant ΔZ and *rms* and 21.89 % (^{235}U(n$_{th}$,f)), reported in [1], 20.26 % (^{234}U(n,f) at E_n = 0.5 MeV) for Δ*Z(A)* and *rms(A)*.



a)

Fig. 3



b)

Fig. 3 (continued) – Charge distribution *Y(Z)* obtained using: Δ*Z(A)* and *rms(A)* (red squares), Δ*Z* = 0.5, *rms* = 0.6 (navy diamonds): a) ^{235}U(n$_{th}$,f), b) ^{234}U(n,f) at E_n = 0.5 MeV.

4. THE INFLUENCE OF *ΔZ* AND *RMS* IN EVEN-ODD EFFECTS IN PROMPT EMISSION QUANTITIES

To obtain different average quantities, the multi-parametric matrices *q(A,Z,TKE)* are averaged over the *Y(A,Z,TKE)* distribution in different ways [1, 2, 9, 10]:

– average quantities corresponding to all fragments:

$$\bar{q}(A) = \frac{\sum_{Z,TKE} q(A,Z,TKE)Y(A,Z,TKE)}{\sum_{Z,TKE} Y(A,Z,TKE)} \quad . \tag{4}$$

$\bar{q}(Z)$ is obtained using a similar relation, by summing over *A* and *TKE*; $\bar{q}(TKE)$ by summing over *A* and *Z*, total averaged <*q*> by summing over *A*, *Z* and *TKE*.

– average quantities corresponding to even-*Z* (or even-*N*) fragments:

$$< q >_{evenZ/N} = \frac{\sum_{A,Ze/Ne,TKE} q(A,Ze/Ne,TKE)Y(A,Ze/Ne,TKE)}{\sum_{A,Ze/Ne,TKE} Y(A,Ze/Ne,TKE)} \quad . \tag{5}$$

Average quantities corresponding to odd-*Z* (or odd-*N*) fragments are obtained in a similar way, by summing over *A*, odd-*Z* (or odd-*N*) and *TKE*.

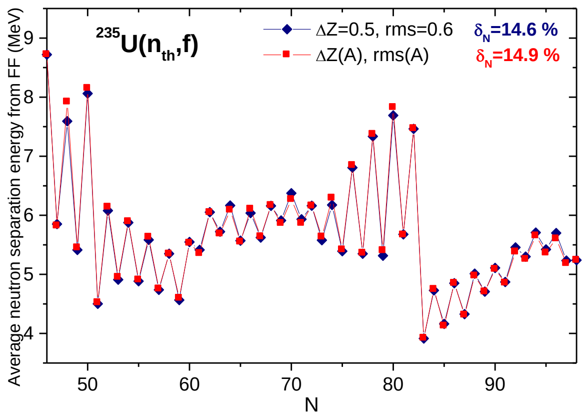
The global Z or N even-odd effect in different quantities [1, 2] can be calculated as:

$$\delta_q = \frac{<q>_{evenZ/N} - <q>_{oddZ/N}}{<q>}. \tag{6}$$

The even-odd effects in prompt emission quantities are the result of a “Z and N even-odd effect mixture” due to the Z even-odd effect in $Y(Z)$ and ΔZ and to the contrary acting N even-odd effect in average neutron separation energy from FF.

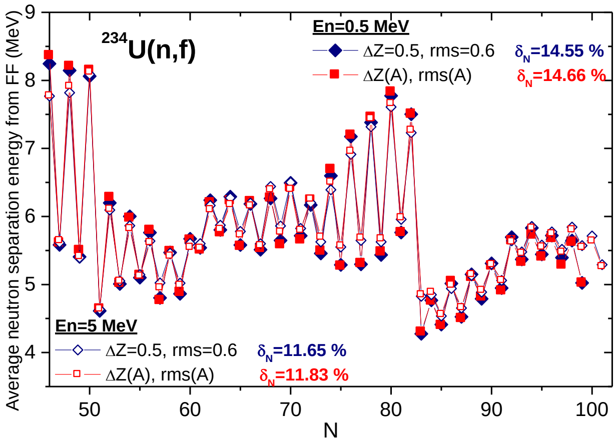
The average neutron separation energy from FF ($<S_n>(N)$), calculated in the two cases of considering the ΔZ and *rms*, is plotted in Fig. 4 a–b as a function of N, for the two studied fissioning systems (^{235}U(n_{th},f) (a), ^{234}U(n,f) at two incident energies E_n = 0.5 and 5 MeV (b)). In both figures, the stagger of $<S_n>(N)$ is visible (fragments with even-N having a higher S_n than the neighboring fragments with odd-N). Small differences between the two sets of results come from different fragments that can show up in the two cases of considering the ΔZ and *rms*. Both sets of results lead to very close N global even-odd effect (δ_N) calculated according to Eq. (6) and given in the legend of Fig. 4. In Fig. 4b, we can see that δ_N decreases with increasing E_n (from about 14.6 % at E_n = 0.5 MeV to 11.7–11.8 % at E_n = 5 MeV).

As it was mentioned in previous studies [1, 2, 3] the most pronounced even-odd effect is in prompt neutron multiplicity, best seen being in the average prompt neutron multiplicity as a function of Z, $\bar{\nu}(Z)$. Examples of PbP results of $\bar{\nu}(Z)$ are given in Fig. 5 a–b for ^{235}U(n_{th},f) and ^{234}U(n,f), for the two cases of considering the ΔZ and *rms*. As it can be seen, both sets of results are very close to each other, differences being visible only in the symmetric region. The even-odd structure of $\bar{\nu}(Z)$ in the asymmetric region, visible in both cases of considering the ΔZ and *rms*, is due to the N even-odd effects.



a)

Fig. 4

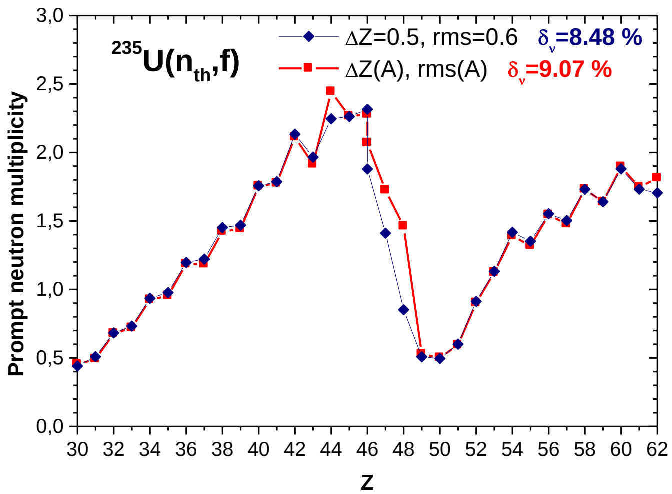


b)

Fig. 4 (continued) – Average neutron separation energy from FF as a function of *N* for two cases of considering the Δ*Z* and *rms*: navy diamonds when constant Δ*Z* and *rms* are used, red squares when Δ*Z(A)* and *rms(A)*

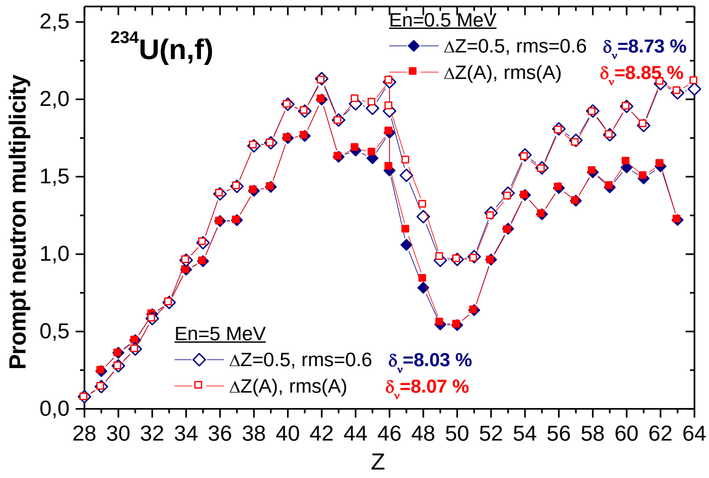
The global *Z* even-odd effect (δ_ν), given in the insert, is slightly decreasing from 9.07 % (Δ*Z(A)*, *rms(A)*) to 8.5 % (Δ*Z*=|0.5|, *rms* = 0.6) for ^{235}U(n$_{th}$,f) while for ^{234}U(n,f) the differences are even smaller. Also, the δ_ν slightly decreases from 8.7–8.9 % (E_n = 0.5 MeV) to 8–8.1 % (E_n = 5 MeV) for ^{234}U(n,f).

Examples of average prompt neutron multiplicity of fragment pair as a function of heavy fragment mass ($<\nu_{pair}>(A_H)$) are given in Fig. 6 a–b.with full symbols for the case Δ*Z(A)*, *rms(A)* and open symbols for constant Δ*Z* and *rms*.



a)

Fig. 5

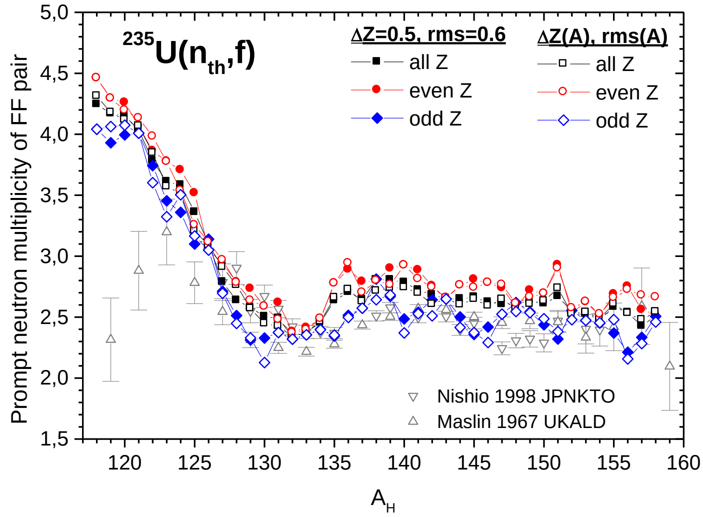


b)

Fig. 5 (continued) – Average prompt neutron multiplicity as a function of Z: navy diamonds when $\Delta Z=|0.5|$ and rms = 0.6, red squares when $\Delta Z(A)$ and $rms(A)$ are used.

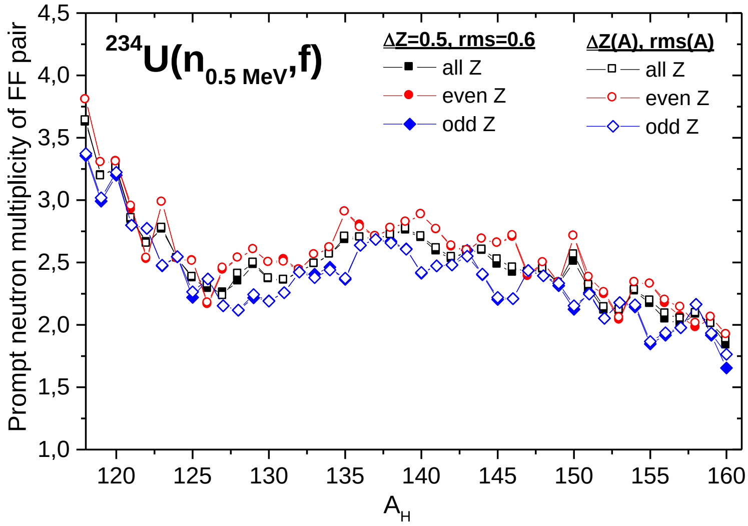
The $<\nu_{pair}>(A_H)$ results obtained by summing over even-Z and odd-Z (Eq. (5)) are given with red circles and blue diamonds, respectively, and those obtained by summing over all Z (Eq. (4)) with black squares.

As it can be seen, $<\nu_{pair}>(A_H)$ corresponding to even-Z fragments is higher than that of odd-Z fragments. In both cases of using ΔZ and rms, the oscillations with the periodicity of 5 mass units are visible.



a)

Fig. 6



b)

Fig. 6 (continued) – $<\nu_{pair}>(A_H)$ of all Z (squares), of even-Z (circles), of odd-Z (diamonds). Full symbols for constant $\Delta Z = |0.5|$, $rms = 0.6$ and open symbols for $\Delta Z(A)$ and $rms(A)$. Experimental data are plotted with open gray symbols.

The even-odd effects in prompt emission are related to the different types of fragmentations appearing in even-even and even-odd fissioning systems. In the case of an even-even fissioning nucleus, *e.g.* ^{235}U(n$_{th}$,f), pairs with {(e-e)$_L$, (e-e)$_H$}, {(e-o)$_L$, (e-o)$_H$}, {(o-e)$_L$, (o-e)$_H$}, {(o-o)$_L$, (o-o)$_H$} complementary fragments are formed. For an even-odd fissioning nucleus, *e.g.* ^{234}U(n,f), other types of fragmentations are possible: {(e-e)$_L$, (e-o)$_H$}, {(e-o)$_L$, (e-e)$_H$}, {(o-e)$_L$, (o-o)$_H$}, {(o-o)$_L$, (o-e)$_H$}. The subscripts L and H come from the light and heavy fragments.

The even-Z fragments are favored (due to higher probability of occurrence) and the odd-N fragments are favored from the prompt neutron emission point of view (due to lower neutron separation energy). Looking at ^{234}U(n,f), we see that every type of fragmentation has one odd-N fragment, favoring the prompt neutron emission. In the case of ^{235}U(n$_{th}$,f) only 2 types of fragmentations (those in even-odd and those in odd-odd complementary fragments) favors the prompt neutron emission, but from the fragmentation probabilities (fragment distributions) point of view only one type (even-odd) of fragmentation is favored.

In the case of neighboring fissioning systems with the same Z, the competition between different types of fragmentations favored from the Z and N point of view, leads to even-odd effects in prompt emission at the same level of magnitude.

5. CONCLUSIONS

The charge polarization influences the range of fragments for which prompt emission quantities are calculated.

The proton even-odd effect in the fragment charge distribution *Y(Z)* is vanished when ΔZ and *rms* are |0.5| and 0.6 for all fragments.

Although the *Z* even-odd effect in *Y(Z)* disappears when ΔZ and *rms* are taken constant, the two cases considered for the charge polarization and root-mean-square lead to close values of the even-odd effect in prompt emission quantities. This fact is due to the neutron emission which brings an even-odd effect on its own (being favored for odd-*N* fragments).

The study of two fissioning systems with the same $Z = 92$, and close mass number A_0, one even-even and another even-odd, showed insignificant differences in the global size of the *Z* even-odd effect in prompt multiplicity.

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