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EVEN-ODD EFFECTS IN THE PROMPT EMISSION OF ^{234}U(n,f) AT INCIDENT NEUTRON ENERGIES FROM 0.2 MeV TO 5 MeV

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Abstract. The even-odd effects in different quantities characterizing the prompt neutron and gamma-ray emission are the result of two contributions: the own even-odd effects of the prompt emission (due to the even-odd character of fragments reflected in their nuclear properties) and the even-odd effect in fragment distributions. The prompt emission of ^{234}U(n,f) at incident energies ranging from 0.2 MeV to 5 MeV offers the possibility to distinguish the role played by each of these contributions.

Key words: prompt emission in fission, even-odd effect in fission fragment distributions, average prompt neutron number, prompt fission neutron spectrum.

1. INTRODUCTION

Among the properties of fission fragment distributions the proton even-odd effect is considered as an interesting feature that was and continue to be extensively studied. Because only the charges and masses of post-neutron fission fragments are known experimentally with sufficient accuracy, only the Z even-odd effect in fragment distributions was investigated. Thus, the study of both Z and N even-odd effects in the prompt neutron and gamma-ray emission is also of interest. Up to now this subject received less attention.

The prompt neutron emission brings an even-odd effect on its own. Consequently the even-odd effects in different prompt emission quantities are the result of two contributions: the intrinsic even-odd effect due to the even-odd nuclear character of fragments reflected in their properties (and consequently in their emitted prompt neutrons and gamma-rays) and the even-odd effect brought by the fragment distribution itself.

In this context our previous work reported in [1, 2] referred to the even-odd effects in the prompt emission of even-even nuclei fissioning spontaneously

(^{252}Cf(SF), $^{236\text{-}244}$Pu(SF)) or induced by thermal neutrons (^{233,235}U(n$_{th}$,f), ^{239}Pu(n$_{th}$,f)) and focused on how the *Z* even-odd effects in the fragment distributions are reflected in the prompt emission.

We extended the investigation of even-odd effects in prompt emission to an even-odd fissioning system ^{234}U(n,f) at incident neutron energies (E_n) ranging from 0.2 MeV to 5 MeV emphasizing the intrinsic even-odd effect of the prompt emission.

As it was mentioned in other papers (see Refs [1, 2] and references therein) our Point-by-Point (PbP) model of prompt emission provides, as primary results, the multi-parametric matrices as a function of *A, Z* and *TKE* (total kinetic energy of complementary fragments) of different quantities characterizing both the fragments and the prompt emission, generically labeled *q(A,Z,TKE)* (*e.g.* total excitation energy of fully-accelerated fragments *TXE(A,Z,TKE)*, average neutron separation energy *<Sn>(A,Z,TKE)*, prompt neutron multiplicity *ν(A,Z,TKE)*, prompt γ-ray energy $E_\gamma(A,Z,TKE)$). By averaging these matrices in different ways over the *Y(A,Z,TKE)* distributions, different average quantities as a function of *A*, of *Z*, of *TKE* and total average quantities are obtained (*q(A), q(Z), q(TKE)* and *<q>*). Consequently the even-odd effect in these average quantities is the combined results of two even-odd effects, one due to the nuclear properties of fragments (correlated with their even-odd character) and another of the *Y(A,Z,TKE)* distribution.

As in previous works the *Y(A,Z,TKE)* distributions are based on the experimental *Y(A,TKE)* data measured at IRMM at 14 incident neutron energies between 0.2 MeV ad 5 MeV [3–5] and the isobaric charge distributions *p(Z,A)* provided by the Z_p model of Wahl [6–8].

In order to see the influence of the *Z* even-odd effect brought by the fragment distributions on the even-odd effects in prompt emission, three *Y(A,Z,TKE)* distributions were used. These are based on the experimental *Y(A,TKE)* data [3–5] and different isobaric charge distributions given by the Z_p model with different F_Z and F_N factors (based on available systematics [7–9]). They lead to different global even-odd effects in *Y(Z)*. The global *Z* even-odd effects in different prompt emission quantities (*e.g.* *<ν>, <TXE>,* $<E_\gamma>$) obtained by averaging the corresponding multi-parametric matrices over these distributions do not differ significantly (the differences being less than the uncertainties induced by the experimental *Y(A,TKE)* data). In all cases a very slow variation with E_n of the global even-odd effects in these quantities was obtained. These facts illustrate that the intrinsic even-odd effects of the prompt emission is the dominant one.

As in previous cases of even-even fissioning nuclei [1, 2] different average quantities as a function of *A* (*e.g.* energy release *Q(A), TXE(A), ν(A)*) of even-*Z* fragmentations are higher than those of odd-*Z* fragmentations and they exhibit oscillations with a periodicity of about 5 mass units. These oscillations are the consequence of the periodicity of nuclear properties of fragments, being independent on the existence of even-odd effects in fragment distributions.

2. IMPACT OF THE EVEN-ODD EFFECT BROUGHT BY Y(A,Z,TKE) ON THE EVEN-ODD EFFECT IN PROMPT EMISSION

The fragmentation range of the PbP treatment is obtained as usually: for each mass number A covering a large range (from symmetric fission up to very asymmetric splits for which experimental $Y(A)$ data exist) three charge numbers Z are considered as the nearest integers above and below the most probable charge Z_p taken as unchanged charge distribution corrected with the charge polarization: $Z_p(A) = Z_{ucd}(A) + \Delta Z(A)$. For each fragmentation (Z, A) obtained in this way the PbP calculations are done at *TKE* values covering a large range (*e.g.* from 100 MeV to 200 MeV) usually with a step of 5 MeV.

The charge polarizations $\Delta Z(A)$ at the 14 studied incident neutron energies are obtained as it was described in [2]. The isobaric charge distributions $p(Z,A)$ given by the Z_p model with different F_Z, F_N prescriptions [7–9] are fitted with Gaussian functions. ΔZ are obtained as deviations of the Z_p values on which the Gaussians are centered from Z_{ucd}.

Both $\Delta Z(A)$ and the root-mean-squares $rms(A)$ of $p(Z,A)$ exhibit oscillations with a periodicity of about 5 mass units.

Note, only the amplitudes of these oscillations reflect the magnitude of the even-odd effect (zero amplitudes meaning no oscillations, *i.e.* no even-odd effect).

The multiple distributions $Y(A,Z,TKE)$ are constructed as in previous papers [1, 2] using the experimental $Y(A,TKE)$ data multiplied with the isobaric charge distributions $p(Z,A)$. The use of different Z_p model parameter prescriptions [6–9] lead to different global even-odd effects in the $Y(Z)$ projections, defined by Gönnenwein [10] as:

$$\delta_{Y(Z)} = \left(\sum_{even-Z} Y(Z_{even}) - \sum_{odd-Z} Y(Z_{odd}) \right) \Bigg/ \sum_{allZ} Y(Z) . \qquad (1)$$

$\delta_{Y(Z)}$ of three cases of Z_p model parameter prescriptions (denoted as a) – c)) are plotted in the upper part of Fig. 1. In all cases the global even-odd effect in $Y(Z)$ exhibit a normal decrease with increasing excitation energy of the fissioning nucleus (*i.e.* of *En*).

The decrease of the even-odd effect with increasing energy is also visible in the decreasing amplitudes of $\Delta Z(A)$ oscillations as illustrated in the lower part of Fig. 1 for one of the Z_p model parameter prescriptions at the lowest and highest *En* values of the studied energy range.

The influence of the even-odd effect brought by the $Y(A,Z,TKE)$ distributions on the prompt emission is best proven by the global Z even-odd effects in different prompt emission quantities calculated as [1, 2]:

$$\delta_{Z<q>} = \left(<q>_{even-Z} - <q>_{odd-Z} \right) / <q>_{all-Z} \ , \qquad (2)$$

where q denotes any quantity characterizing the fragments or the prompt emission, which is averaged over $Y(A,Z,TKE)$:

$$<q>=\sum_{Z,A,TKE} q(A,Z,TKE)Y(A,Z,TKE) \Big/ \sum_{Z,A,TKE} Y(A,Z,TKE) \tag{3}$$

by summing over all-Z fragmentations and over even-Z and odd-Z fragmentations individually (see also Refs.[1, 2] for details).

The use of $Y(A,Z,TKE)$ with different even-odd effects induced by three different prescriptions of Z_p model parameters leads to the global Z even-odd effects in $<\nu>$, $<TXE>$ and $<E_\gamma>$ given in Table 1.

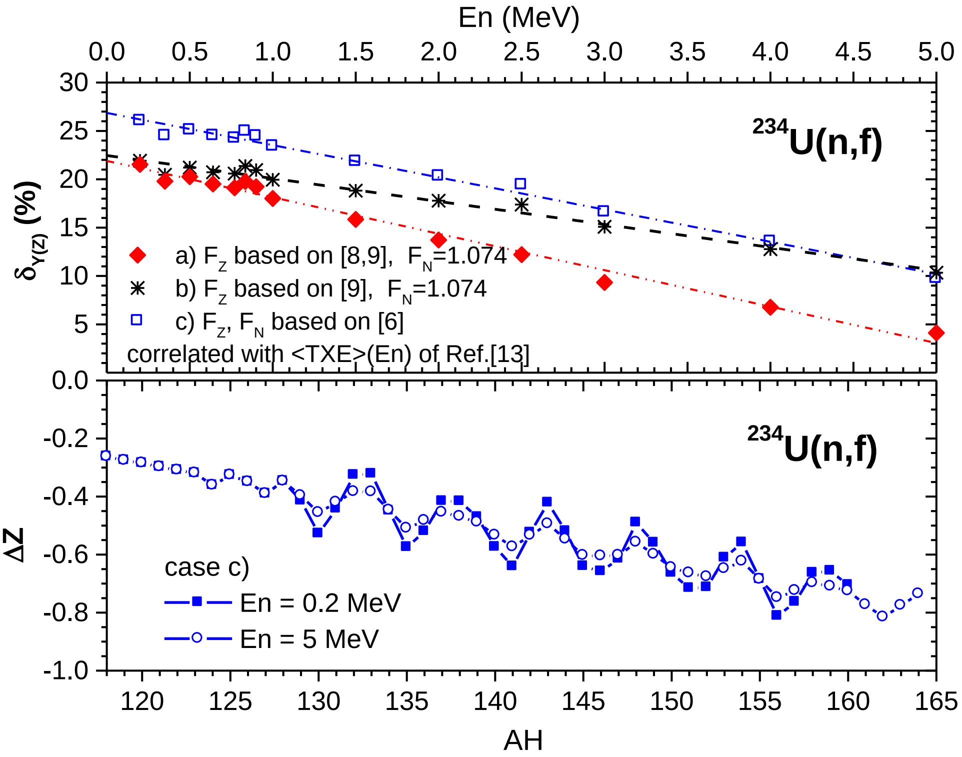

Fig. 1 – Upper part: the global even-odd effect in $Y(Z)$ as a function of En obtained with different prescriptions of Z_p model parameters F_Z and F_N. The uncertainties in $\delta_{Y(Z)}$ resulting from the propagation of uncertainties in the experimental $Y(A,TKE)$ distributions are included in the size of symbols. Lower part: the charge polarizations $\Delta Z(A)$ at the lowest and highest values of the studied incident energy range illustrated for case c). The decrease of oscillation amplitudes with increasing En is visible.

Table 1

Global Z even-odd effect in $<\nu>$, $<TXE>$ and $<E_\gamma>$ at 14 incident energies using three $Y(A,Z,TKE)$ resulted from different Z_p model parameter prescriptions

En [MeV]	δ in $<\nu>$ [%]*			δ in $<TXE>$ [%]*			δ in $<E_\gamma>$ [%]*		
0.2	8.91	8.92	8.86	8.24	8.24	8.24	3.70	3.70	3.68
0.35	8.85	8.86	8.85	8.17	8.18	8.23	3.71	3.71	3.71
0.5	8.86	8.86	8.80	8.25	8.26	8.34	3.69	3.69	3.68
0.64	8.40	8.40	8.31	7.82	7.82	7.68	3.52	3.52	3.49
0.77	8.46	8.46	8.41	7.92	7.92	7.93	3.55	3.55	3.54
0.835	8.42	8.42	8.35	7.87	7.87	7.84	3.53	3.53	3.50
0.9	8.66	8.66	8.57	8.09	8.10	8.05	3.63	3.63	3.60
1.	8.31	8.31	8.21	7.85	7.85	7.79	3.51	3.51	3.48
1.5	8.73	8.73	8.67	8.25	8.25	8.22	3.73	3.73	3.71
2.	8.93	8.94	8.90	8.09	8.09	8.08	3.85	3.86	3.85
2.5	8.77	8.78	8.77	7.83	7.82	7.83	3.81	3.82	3.82
3.	8.23	8.23	8.20	7.71	7.70	7.71	3.65	3.65	3.65
4.	8.23	8.28	8.22	7.56	7.59	7.55	3.72	3.75	3.73
5.	8.07	8.16	8.00	7.71	7.78	7.61	3.72	3.76	3.70

* The uncertainties in the global even-odd effects are less than 10%. The results of the three cases do not differ significantly (the differences being less than the uncertainties).

As it can be seen in Table 1 the differences between the global Z even-odd effects obtained in three different cases of $Y(A,Z,TKE)$ are insignificant (being less than the uncertainties resulted from the propagation of uncertainties in experimental distributions).

The global Z even-odd effect in prompt neutron multiplicity varies between 8 % and 9 % being at the same level of of magnitude as in the case of neighbouring even-even nuclei fissioning by thermal neutrons (of about 9 % for ^{235}U(n$_{\mathrm{th}}$,f) and 8.8 % for ^{233}U(n$_{\mathrm{th}}$,f) [1]). The Z even-odd effect in $<TXE>$ is slightly lower than the effect in prompt neutron multiplicity, varying between 7.6 % and 8.3 %. As in the case of other studied even-even fissioning nuclei the global Z even-odd effect in $<E_\gamma>$ is almost three times lower than the effect in prompt neutron multiplicity and practically does not vary with *En*. The Z even-odd effects in $<\nu>$ and $<TXE>$ show only a slowly decreasing trend, compared to the pronounced decrease of the even-odd effect in the $Y(Z)$ distributions (Fig. 1).

The global N even-odd effect in the average neutron separation energy from fission fragments $<Sn>$ (resulted from the sequential emission, for details see [11] and references therein), calculated as:

$$\delta_{N<Sn>} = \left(<Sn>_{even-N} - <Sn>_{odd-N}\right) / <Sn>_{all-N} \tag{4}$$

is plotted as a function of incident neutron energy in Fig. 2.

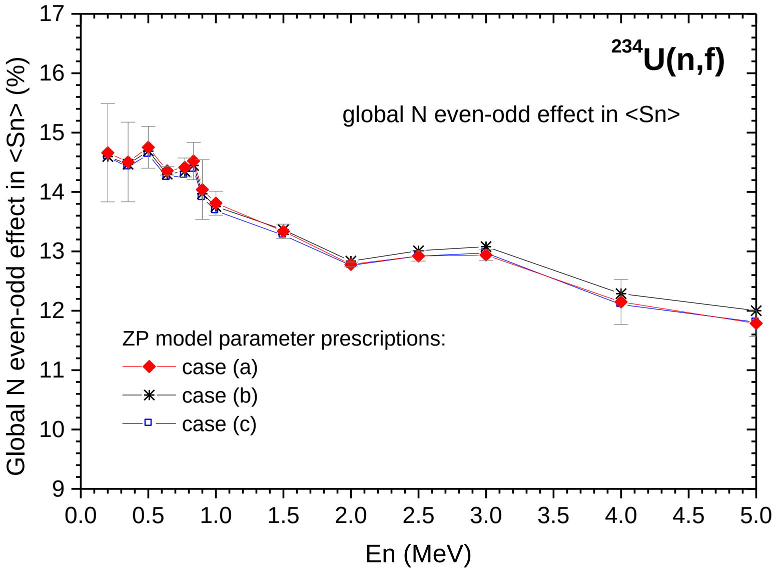

Fig. 2 – Global *N* even-odd effect in the average neutron separation energy as a function of *En*.

As it can be seen $\delta_{<Sn>}$ is clearly decreasing with increasing *En* and the differences between the results of different Z_p model parameter prescriptions (giving different even-odd effects in fragment distributions) are insignificant.

The insignificant differences between the *Z* global even-odd effects in $<\nu>$, $<TXE>$, $<E_\gamma>$ and between the *N* global even-odd effects in $<\rho_n>$ resulting from the use of different *Y(A,Z,TKE)* (with different even-odd effects in *Y(Z)*) as well as their slow variation with the incident energy, compared to the pronounced decrease of $\delta_{Y(Z)}$, demonstrate that the intrinsic even-odd effect of the prompt emission (due to the nuclear properties of fragments) plays a much more important role than the even-odd effect in fragment distributions.

3. EVEN-ODD EFFECTS IN DIFFERENT AVERAGED QUANTITIES RELATED TO PROMPT EMISSION

Taking into account the insignificant differences between the global even-odd effects in different prompt emission quantities induced by fragment distributions with different even-odd effects, the following results are exemplified for one of these distributions randomly chosen.

An example of average prompt neutron multiplicity as a function of *Z* is given in Fig. 3 for two incident energies (*En* = 0.835 MeV with open symbols and 5 MeV with full symbols).

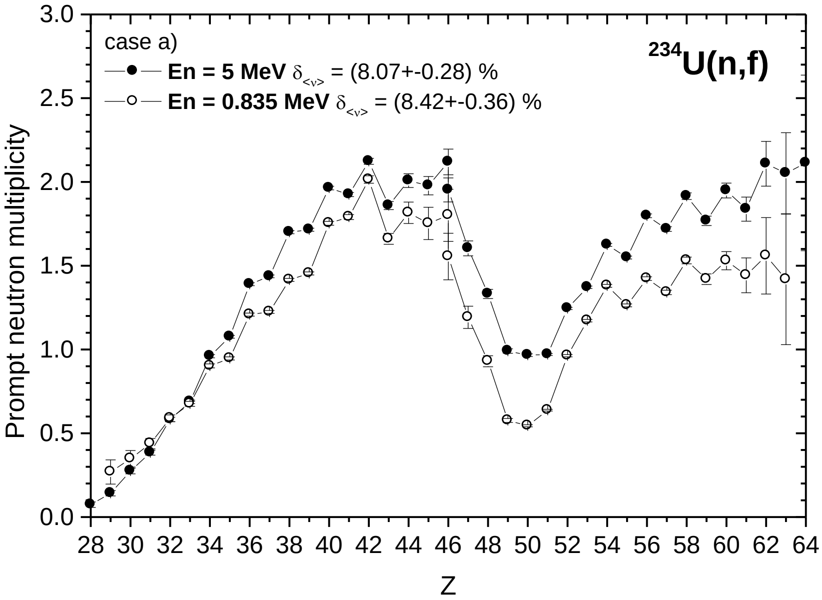

Fig. 3 – *ν(Z)* results exemplified for two incident energies *En* = 0.835 MeV (open circles) and *En* = 5 MeV (full circles).

As in the case of even-even fissioning nuclei previously studied [1, 2], *ν(Z)* exhibit a sawtooth shape. The *ν(Z)* staggering is due to the intrinsic even-odd effect of the prompt emission (as consequence of even-odd character of fragments reflected in their nuclear properties). The interesting behaviour experimentally observed in the case of *ν(A)*, consisting in the multiplicity increase with *En* mainly for heavy fragments and described by the PbP results (see *e.g.* Refs.[11–14]), is seen for *ν(Z)*, too. This multiplicity increase is due to the energy partition at scission (see details in [14, 15]).

As for even-even fissioning nuclei [1, 2], also in the case of ^{234}U(n,f) different average quantities as a function of *A*, corresponding of even-*Z* fragmentations are higher than those of odd-*Z* fragmentations, for all *En* between 0.3 MeV and 5 MeV. Two examples are given in Fig. 4 (*TXE(A)* in the upper part and $\nu_{pair}(A)$ in the lower part) with black circles for all *Z* fragmentations, red squares for even-*Z* fragmentations and blue diamonds for odd-*Z* fragmentations.

The oscillations with a periodicity of about 5 mass units of *TXE(A)* and $\nu_{pair}(A)$ of even-*Z* and odd-*Z* fragmentations are visible. These oscillations are due to the energy release entering the *TXE* expression. *Q(A)* of even-*Z* and odd-*Z* fragmentations oscillate with a periodicity of about 5 mass units as a consequence of the even-odd character of nuclei forming the fragmentations range, reflected in their nuclear properties (*i.e.* mass excesses).

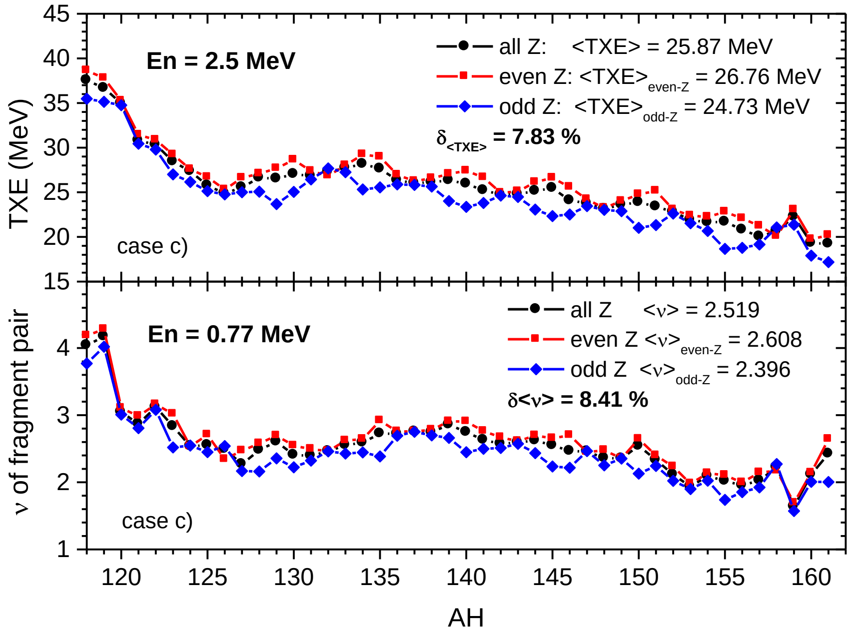

Fig. 4 – Examples of *TXE(A)* (upper part) and $\nu_{pair}(A)$ (lower part) of even-*Z* (red squares), odd-*Z* (blue diamonds) and all *Z* fragmentations (black circles).

The *Z* even-odd effect in different quantities as a function of *TKE* can be emphasized by the following function

$$\delta_q(TKE) = \left(< q >_{even-Z} (TKE) - < q >_{odd-Z} (TKE) \right) / < q >_{all-Z} (TKE) \,. \quad (5)$$

The function of Eq. (5) is exemplified in Fig. 5 for the average prompt neutron multiplicity *ν(TKE)* at five incident energies covering the studied range. An increase of $\delta_\nu(TKE)$ with increasing *TKE* is visible.

The very low *Z* even-odd effect at low *TKE* values (already observed for even-even fissioning nuclei [1, 2]) can be explained by the behaviour of the experimental *Y(A,TKE)* distributions. See Fig. 6 where *Y(A,TKE)* as a function of *A* are exemplified at two incident energies for two low *TKE* values (upper part), two medium *TKE* values (middle part) and two high *TKE* values (lower part). As it can be seen, at low *TKE* values the distributions are mainly populated in the mass region of symmetric fission where the even-odd effect in *Z* is very small [1, 10, 16]. In other words in the symmetric fission region, where the *Z* even-odd effect is almost inexistent, the super-long fission mode *SL*, having the lowest weight, is the dominant one. At medium and high *TKE* values the yields are high in the asymmetric fission region where the *Z* even-odd effects are pronounced [1, 10, 16]. The standard asymmetric fission mode *S*2 (with the highest weight) is the dominant one at medium *TKE* values and the standard asymmetric fission mode *S*1 (with the weight placed between *S*2 and *S*L) is dominant at high *TKE*.

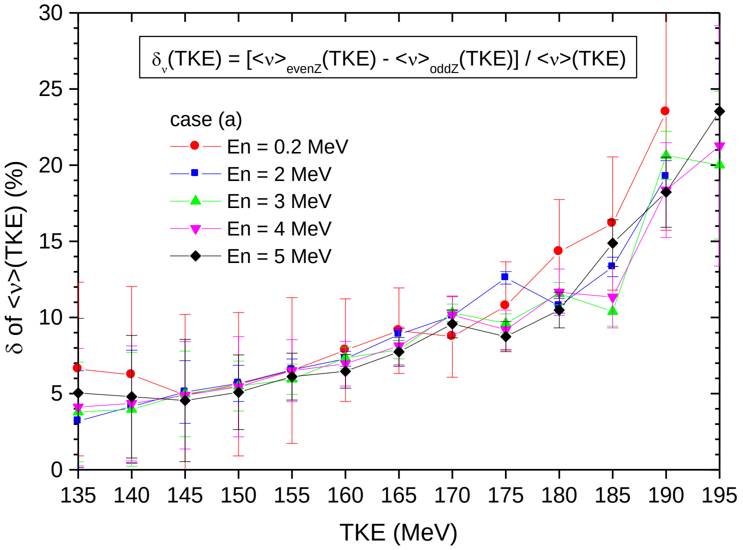

Fig. 5 – The function of Eq.(5) exemplified for *ν (TKE)* at five incident neutron energies.

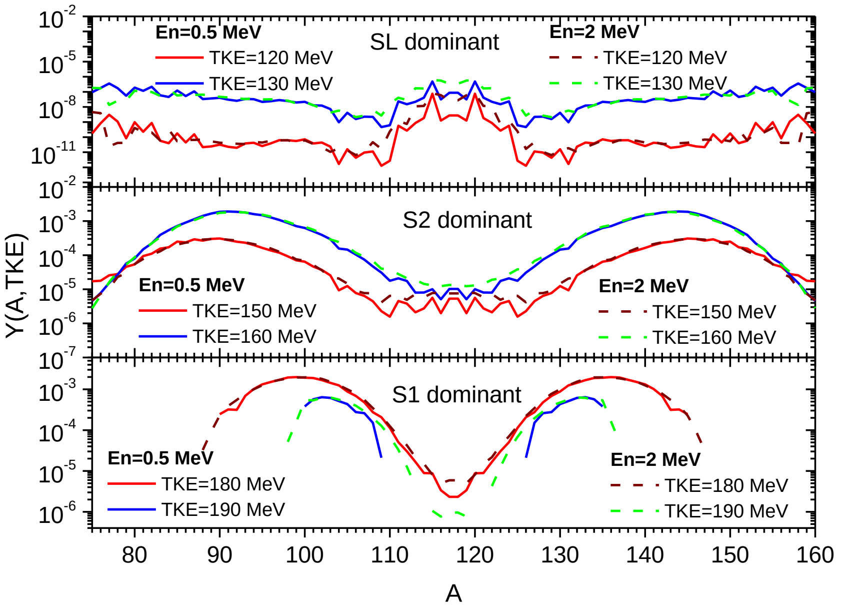

Fig. 6 – *Y(A,TKE)* as a function of *A* for two low *TKE* values (upper part), two medium *TKE* values (middle part) and two high *TKE* values (lower part) exemplified for at *En* = 0.5 MeV and 2 MeV.

4. CONCLUSIONS

The analysis of even-odd effects in the prompt emission of ^{234}U(n,f) at incident neutron energies ranging from 0.2 MeV to 5 MeV using *Y(A,Z,TKE)* distributions based on experimental *Y(A,TKE)* data and having different *Z* even-odd effects (driven by the isobaric charge distribution with different Zp model prescriptions based on available systematics) revealed the following aspects:

1) The insignificant differences between the even-odd effects in different prompt emission quantities obtained by using fragment distributions with different even-odd effects in *Y(Z)* prove the major role played by the intrinsic even-odd effect of the prompt emission. This effect is due to the even-odd character of fragments reflected in their nuclear properties. The important role of the intrinsic even-odd effect of the prompt emission is also demonstrated by the very slow decrease of even-odd effects in different prompt emission quantities with increasing *En* (while the even-odd effect in fragment distributions exhibits a pronounced decrease with increasing *En*).

2) The oscillations of *TXE(A)* and *ν(A)* of even-*Z* and odd-*Z* fragmentations with a periodicity of about 5 mass units do not depend on the even-odd effects in fragment distributions. They are a consequence of the oscillations in the *Q*-values of even-*Z* and odd-*Z* fragmentations due to the nuclear properties (*i.e.* mass excesses) in which the even-odd character of fragments is reflected.

3) As in the case of even-even fissioning nuclei previously studied, *ν(Z)* of ^{234}U(n,f) have sawtooth shapes with visible staggering for asymmetric fragmentations. The multiplicity increase with *En* mainly for heavy fragments, observed experimentally and confirmed by PbP model calculations in the case of *ν(A)*, is visible in the case of *ν(Z)* results, too.

4) The average prompt neutron multiplicity as a function of *TKE* shows an increase of the *Z* even-odd effect with increasing *TKE*. The very low effect at low *TKE* values can be explained by the behaviour of *Y(A,TKE)* as a function of *A*. At low *TKE* values this yield is dominant near symmetric fragmentations where the even-odd effect is almost inexistent.

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