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

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Abstract. The investigation of the proton even-odd effects in prompt emission in fission for even-Z actinides revealed basic features of the global even-odd effect in prompt emission similar with those in fission fragment yields and some particular aspects, such as: (1) 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 a weak even-odd effect caused by the fragment distributions (over which the multi-parametric matrices are averaged); (2) oscillations with a periodicity of about 5 mass units 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 the charge yield Y(Z). These oscillations are due to the periodicity of nuclear properties of fragments; (3) a local even-odd effect in prompt emission quantities has been recently investigated. Similarities between prompt emission quantities and fragment yields were found in the case of the local even-odd effect, too. The local even-odd effect in both fragment charge yields and prompt emission quantities exhibit a 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.

1. Introduction

Lately [1–5] our attention was turned to a subject, not yet investigated, namely proton (Z) and neutron (N) even-odd effects in prompt emission in fission. We have studied even-Z nuclei fissioning spontaneously or induced by thermal neutrons, like ^{233,235}U(n,f), ^{234}U(n,f), ^{239}Pu(n$_{\mathrm{th}}$,f), ^{236,238,240,242,244}Pu(SF), ^{252}Cf(SF), because the extensive studies (e.g., [6–9]) regarding the Z even-odd effect in fragment distributions showed that the effect is most pronounced for this type of nuclei.

This topic is of major importance for a more profound understanding of the nuclear fission process, for the determination of the fragment distributions (which depends on knowing with high accuracy the prompt emission data, including even-odd effects).

The prompt emission calculations were done in the frame of the Point-by-Point (PbP) model (described in [10] and references therein). The primary results of the PbP model 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., prompt neutron multiplicity ν(A,Z,TKE), prompt γ-ray energy Eγ(A,Z,TKE)). Average quantities as a function of Z (q(Z)), of A (q(A)), of TKE (q(TKE)) and total average <q> are obtained by averaging the PbP matrices over the fragment distributions Y(A,Z,TKE) in different ways (details are given in Refs. [1,2,10] and references therein). These distributions are constructed as Y(A,Z,TKE) = Y(A,TKE) p(Z,A) in which Y(A,TKE) are experimental distributions (usually reconstructed from the single ones Y(A), TKE(A) and σ_{TKE}(A)) and the isobaric charge distributions p(Z,A) are provided by the Zp model of Wahl [11–13].

We started to study the basic features of the even-odd effect in prompt emission quantities, e.g., the behaviour of different average quantities like q(Z), q(A) of even-*Z* and odd-*Z* fragmentations, the behaviour of the global Z even-odd effect in different total average quantities, defined as [1,2]:

$$\delta_{<q>} = \frac{<q>_{\mathrm{even}-Z} - <q>_{\mathrm{odd}-Z}}{<q>} \tag{1}$$

where <q> even-Z, <q> odd-Z and <q> are any quantities corresponding to even-*Z*, to odd-*Z* and to all-Z fragmentations, respectively.

Recently, we have investigated some particular aspects related to the even-odd effects in prompt emission [5], like: the periodicity of five mass units in average quantities as a function of fragment mass, the intrinsic even-odd effect of prompt emission, the local Z even-odd effect in prompt neutron multiplicity and TXE.

2. 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) [6–9]:

(1) the global Z even-odd effect in prompt emission decreases with increasing mass of the fissioning nucleus, e.g., from 9% (^{233,235}U(n$_{\mathrm{th}}$,f)) to about 6% (^{252}Cf(SF)). The global *Z* even-odd effect in Y(Z) decreases from about 21% (^{236}U) to 4% (^{252}Cf(SF)).

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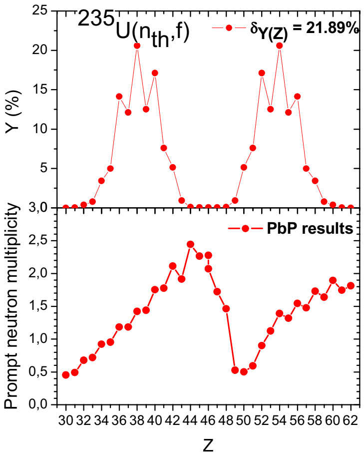

Figure 1. ^{235}U(n$_{\mathrm{th}}$,f): Y(Z) projection (upper part) and prompt neutron multiplicity as a function of Z (lower part).

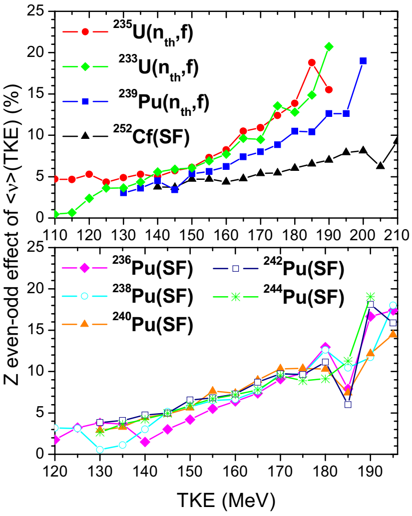

Figure 2. Z even-odd effect in $<\nu>$(TKE) for: ^{235,233}U(n$_{\mathrm{th}}$,f), ^{239}Pu(n$_{\mathrm{th}}$,f), ^{252}Cf(SF) (uppert part) [1] and ^{236}Pu(SF), ^{238}Pu(SF), ^{240}Pu(SF), ^{242}Pu(SF) and ^{244}Pu(SF) (lower part) [2].

(2) prompt neutron multiplicity as a function of Z, ν(Z), exhibit a visible staggering in the asymmetric fission region as Y(Z) does. This fact can be seen in the examples given in Fig. 1.

(3) the Z even-odd effect increases with increasing kinetic energy of the fission fragments. In the case of prompt emission, this fact is emphasized by the following function: $\delta_{<q>}(TKE) = (<\text{q}>_e(TKE)$-$<\text{q}>_o(TKE))/<\text{q}>(TKE)$ introduced in Ref. [1]. An example of this function is given in Fig. 2 for $<\nu>$(TKE) of ^{233,235}U(n$_{\mathrm{th}}$,f), ^{239}Pu(n$_{\mathrm{th}}$,f) and ^{252}Cf(SF) (upper part) and ^{236,238,240,242,244}Pu(SF) (lower part).

3. Particular aspects related to even-odd effects in prompt emission

We have seen in our studies that average quantities as a function of A corresponding to even-Z and to odd-Z fragmentations exhibit oscillations with a periodicity of about 5 mass units [1–5].

The same periodicity was seen in experimental data of charge polarization ΔZ(A) and the root-mean-square rms(A) of the isobaric charge distribution p(Z,A), well described by the Zp model of Wahl [11–13], in the asymmetric fission region [6]. Gönnenwein has made a connection between the oscillations of ΔZ(A) and rms(A) with a period ΔA ≈ 5 and the presence of even-odd effects in charge yield Y(Z) [6].

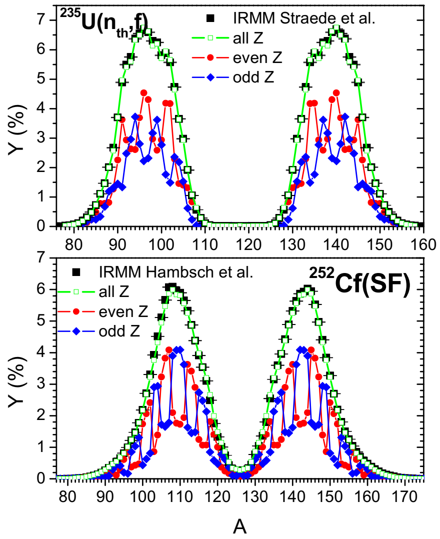

Figure 3. Y(A) of even-Z fragmentations (red circles) and odd-Z fragmentations (blue diamonds), Y(A) of all fragmentations (open green squares) and experimental Y(A) data (full black squares) for the fissioning systems ^{235}U(n$_{\mathrm{th}}$,f) (upper part) and ^{252}Cf(SF) (lower part).

In the case of ΔZ(A), rms(A) and Y(A) of even-Z and odd-Z fragments, only the magnitude of the oscillations amplitudes is related to the size of the even-odd effect in Y(Z). This fact can be seen in the example given in Fig. 3 where Y(A) is plotted separately for even-Z (red circles), odd-Z (blue diamonds) and all-Z fragmentations (black squares) for two fisioning nuclei (the extreme fissioning systems in terms of the size of the even-odd effect in Y(Z)): ^{235}U(n$_{\mathrm{th}}$,f) (upper part) and ^{252}Cf(SF) (lower part). It can be observed that Y(A) of even-Z and odd-Z fragmentations oscillate in anti-phase with a period ΔA ≈ 5. It can be also seen that in the case of ^{235}U(n$_{\mathrm{th}}$,f) (for which the global even-odd effect in Y(Z) is high, of about 22%) the amplitudes of the oscillations are visibly higher for even-Z fragmentations than for odd-Z ones while for ^{252}Cf(SF) (with a lower $\delta_{Y(Z)}$, of about 4%) the amplitudes of the oscillations are almost equal. Thus, higher amplitudes of Y(A) of even-Z fragmentations compared to those of odd-Z fragmentations means the presence of the even-odd effect in Y(Z). At limit, equal amplitudes in anti-phase cancel the even-odd effect in Y(Z).

In the case of ΔZ(A) and rms(A) the magnitude of their oscillation amplitudes is proportional with the size of the even-odd effect in Y(Z). At limit, zero amplitude, i.e., no oscillation of ΔZ(A) and rms(A), means no even-odd effect in Y(Z) (details are given in Ref. [5])

Regarding the prompt emission quantities, the oscillations with the period ΔA ≈ 5 persists even when fragment distributions without even-odd effects are used to obtain different average quantities. This fact was shown in Ref. [5], where relevant quantities for prompt emission, such as the energy release (Q-value) and the total excitation energy of fully accelerated fragments

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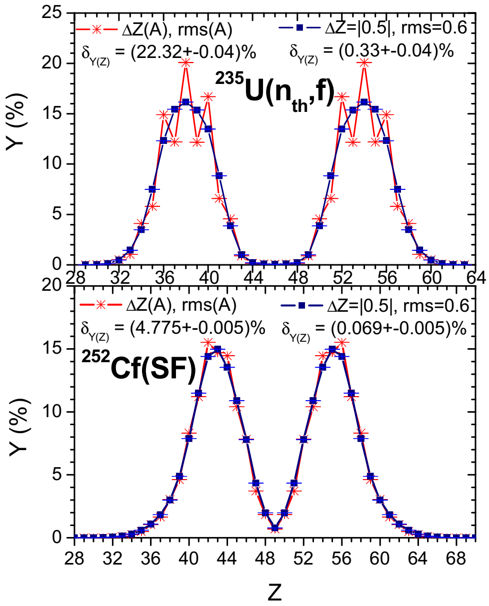

Figure 4. Y(Z) projections obtained in two cases of using ΔZ and rms: ΔZ = |0.5| and rms = 0.6 (navy squares), ΔZ(A) and rms(A) (red stars) [5].

(TXE), were averaged over two types of Y(A,Z,TKE) distributions: one with even-odd effects (constructed by taking in the Gaussian expression of p(Z,A) oscillating ΔZ(A) and rms(A)) and one without even-odd effects (constructed by considering for all fragments ΔZ = |0.5| and the same value of 0.6 for the rms of p(Z,A)).

In Fig. 4 are given examples of Y(Z) projections for ^{235}U(n$_{\rm th}$,f) (upper part) and ^{252}Cf(SF) (lower part), obtained in the two cases of Y(A,Z,TKE) distributions. As it can be seen, the even-odd effect in Y(Z) disappears when constant ΔZ and rms are used, being reflected in the lack of Y(Z) staggering and in almost equal to zero global Z even-odd effect (given in the legend) [5].

Examples of Q(A) and TXE(A), obtained by averaging over the two types of distributions, are plotted in Fig. 5 (^{235}U(n$_{\rm th}$,f)) and 6 ^{252}Cf(SF)), respectively.

For both fissioning systems Q(A) and TXE(A) of even-Z and odd-Z fragmentations exhibit oscillations with a periodicity of about 5 mass units in both cases of Y(A,Z,TKE) (with or without even-odd effect). This fact proves that the periodicity of these oscillations is independent of the existence or not of an even-odd effect in charge distributions, being a consequence of the periodicity in the nuclear properties of the fragments (e.g., mass excesses, binding energies, pairing energies).

The values of the global Z even-odd effect in <TXE>, (and <Q>), given in the legends of Figs. 5 and 6, are almost the same in both cases of fragment distributions (with and without Z even-odd effect). This fact together with the important role played by TXE in the prompt emission has demonstrated that the even-odd effects in different quantities related to the prompt emission are mainly due to the nuclear properties of fission fragments. Consequently, the even-odd effects in prompt emission are the result of two contributions [4,5]: (i) 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) and (ii) a weak even-odd effect caused by the fragment distributions.

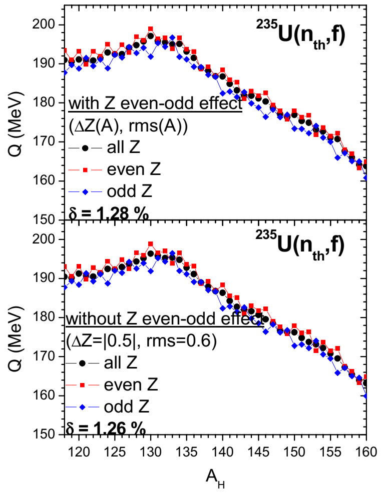

Figure 5. ^{235}U(n$_{\rm th}$,f): average Q(A) obtained by averaging Q(A,Z) over Y(A,Z,TKE) with Z even-odd effect (upper part) and another one without Z even-odd effects (lower part) [5].

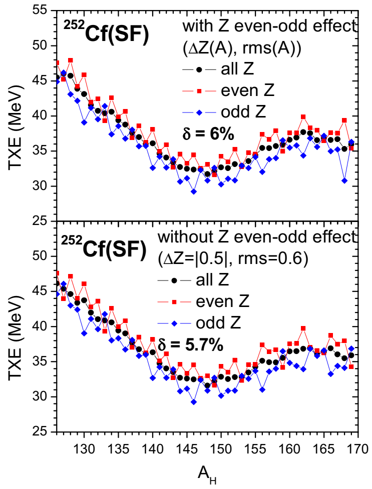

Figure 6. ^{252}Cf(SF): average TXE(A) obtained by averaging TXE(A,Z,TKE) over Y(A,Z,TKE) with Z even-odd effect (upper part) and without Z even-odd effects (lower part) [5].

The dominance of the intrinsic even-odd effect was also demonstrated by the even-odd nucleus ^{234}U(n,f) at 14 incident neutron energies ranging from 0.2 MeV to 5 MeV (see Ref. [4]).

4. Local even-odd effect in prompt emission in fission

The behavior of different quantities corresponding to the four possible types of fragmentation of a fissioning nucleus (i.e., even-even, even-odd, odd-even and odd-odd for an even-even fissioning nucleus) [1–5] suggested the possibility of defining, for the first time, a local even-odd effect in prompt emission quantities (generally labelled "q"), as [5]:

$$\delta_{p\,<q>} = \frac{1}{2}\,\frac{<q>_{\rm even-Z} - <q>_{\rm odd-Z}}{<q>_{\rm even-Z} + <q>_{\rm odd-Z}} \qquad (2)$$

where $<q>_{\text{even-Z}}$ and $<q>_{\text{odd-Z}}$ are normalized quantities corresponding to even-Z and to odd-Z fragmentations.

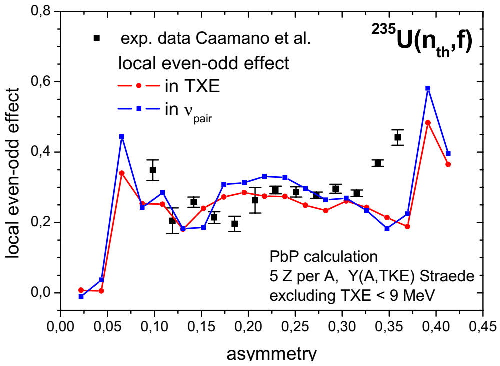

Figure 7. Local even-odd effect in TXE (red circles) and prompt neutron multiplicity of fragment pair (blue squares) for ^{235}U(n$_{\mathrm{th}}$,f) in comparison with the experimental data of the local even-odd effect in fragment distributions of Caamano et al. [9] (black squares) plotted as a function of asymmetry parameter [5].

In Fig. 7 are given examples of local even-odd effect in TXE (red circles) and prompt neutron multiplicity of fragment pair (blue squares) as a function of asymmetry parameter, defined as $a_s = (Z_H - Z_L)/Z_0$, for ^{235}U(n$_{\mathrm{th}}$,f). $\delta_{p<\nu\mathrm{pair}>}$ is a little bit higher than $\delta_{p<\mathrm{TXE}>}$ fact confirmed by the slightly higher global even-odd effect for $<\nu>$ compared to <TXE> [1]. An interesting observation is that the local even-odd effect in both TXE and ν_{pair} exhibits a similar behaviour as the experimental data of Caamaño et al. [14] (black squares) concerning the local even-odd effect in fragment distributions [5].

The pronounced increase of the local even-odd effect at asymmetry values corresponding to fragmentations in which one of the fragment is magic or double magic (seen in Fig. 7 at asymmetry values of about 0.7 corresponding to fragmentations with magic heavy fragment ($\mathrm{N_H} = 82$) and around 0.4 corresponding to very asymmetric fragmentations in which the light fragment is magic ($\mathrm{Z_L} = 28$)) is a consequence of the important role played by the fragment properties reflecting the even-odd nuclear character of fragments (i.e., the contribution of the intrinsic even-odd effect).

5. Conclusions

The basic features of the even-odd effect in prompt emission are similar with those in fragment yields.

The periodicity ΔA ≈ 5 of the oscillations in the charge polarization ΔZ(A), rms(A) of the isobaric charge distribution, as well as in the fragment mass yields 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).

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).

The local even-odd effect in TXE and prompt neutron multiplicity exhibits the same behavior as the local even-odd effect in fragment yields. The feature of the local even-odd effect, consisting in a 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, is present in both the charge yield and prompt emission quantities.

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