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

Georgiana Giubega1,2, Anabela Tudora1, and Franz-Josef Hambsch3

1 University of Bucharest, Faculty of Physics, Bucharest Magurele POB MG-11, 077125, Romania
2 National Institute for Laser, Plasma and Radiation Physics, Bucharest Magurele POB MG-36, 077125, Romania
3 EC-JRC Directorate G – Nuclear Safety and Security, Retieseweg 111, 2440, Geel, Belgium

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 235,238U(n,f), 233U(n,f), 238Pu(238Pu, f), 236,238,240,242,244Pu(SF), 252Cf(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 σTKE(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]:

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

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% (233,235U(nθ,f)) to about 6% (232Cf(SF)). The global Z even-odd effect in Y(Z) decreases from about 21% (236U) to 4% (232Cf(SF)).
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 $\Delta Z(A)$ 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 $\Delta Z(A)$ and rms(A) with a period $\Delta A \approx 5$ and the presence of even-odd effects in charge yield $Y(Z)$ [6].

In the case of $\Delta Z(A)$, 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 fissioning nuclei (the extreme fissioning systems in terms of the size of the even-odd effect in $Y(Z)$: $^{235}\text{U}(n_{th},f)$ (upper part) and $^{252}\text{Cf}(SF)$ (lower part). It can be observed that $Y(A)$ of even-Z and odd-Z fragmentations oscillate in anti-phase with a period $\Delta A \approx 5$. It can be also seen that in the case of $^{235}\text{U}(n_{th},f)$ (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 $^{252}\text{Cf}(SF)$ (with a lower $\Delta \approx 5$) the amplitudes are almost equal. Thus, higher amplitudes of $Y(A)$ of even-Z fragmentations compared to those of odd-Z fragmentations mean 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 $\Delta Z(A)$ 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 $\Delta Z(A)$ 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 $\Delta A \approx 5$ 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

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

Figure 2. Z even-odd effect in $<\nu>$(TKE) for: $^{235,233}\text{U}(n_{th},f)$, $^{239,237}\text{Pu}(n_{th},f)$, $^{252}\text{Cf}(SF)$ (upper part) [1] and $^{236,238,240,242,244}\text{Pu}(SF)$, $^{242}\text{Pu}(SF)$ and $^{244}\text{Pu}(SF)$ (lower part) [2].

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 $^{235}\text{U}(n_{th},f)$ (upper part) and $^{252}\text{Cf}(SF)$ (lower part).
(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 distributions: one with even-odd effects (constructed by considering for all fragments (TXE), were averaged over two types of Y(A,Z,TKE) distributions. As it can be seen, the even-odd effect in Y(Z) disappears when constant ∆Z 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 (235U(nth,f)) and 6 252Cf(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) distributions. As it can be seen, the even-odd effect in Y(Z) disappears when constant ∆Z 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 (235U(nth,f)) and 6 252Cf(SF)), respectively.

The dominance of the intrinsic even-odd effect was also demonstrated by the even-odd nucleus 234U(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]:

\[ \delta_p q = \frac{1}{2} \frac{<q>_{even-Z} - <q>_{odd-Z}}{<q>_{even-Z} + <q>_{odd-Z}} \] (2)

where \(<q>_{even-Z}\) and \(<q>_{odd-Z}\) are normalized quantities corresponding to even-Z and to odd-Z fragmentations.
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 $a_y = (Z_H - Z_L)/Z_0$, for $^{235}$U(n,t0,f). The pronounced increase of 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.

5. Conclusions

The basic features of the even-odd effect in prompt emission are similar with those in fragment yields. The periodicity $\Delta A \approx 5$ of the oscillations in the charge polarization $\Delta Z(A)$, 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.

References

[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, I. Visan, Phys. Proc. 64, 62–72 (2015)
[4] A. Tudora, F.-J. Hambsch, G. Giubega, I. Visan, Rom. Rep. Phys. 68(2), 571–581 (2016)
[5] A. Tudora, F.-J. Hambsch, G. Giubega, Eur. Phys. J. A 52, 182–193 (2016)
[6] C. Wagemans The Nuclear Fission Process (CRC Press, BocaRaton, chapter 8, 1991)
[7] F. Gönnekein, Physics Procedia 47, 107–114 (2013)
[8] B.L. Tracy, J. Chaumont, R. Klapisch, J.M. Nitschke, A.M. Paskanzer, E. Raeckl, C. Thibault, Phys. Rev. C 5(1), 222–234 (1972)
[9] M. Caamaño, F. Rejmund, K.H. Schmidt, J. Phys. G. Nucl. Part. Phys. 38, 035101 (2011)
[10] R. Capote, Chen Y.J., F.-J. Hambsch, N. Kornilov, J.P. Lestone, O. Litaize, B. Morillon, D. Neudecker, S. Oberstedt, N. Otuka, V.G. Pronyaev, A. Saxena, O. Serot, O.A. Scherbakov, Shu N.C., D.L. Smith, P. Talou, A. Trkov, A.C. Tudora, R. Vogt and A.S. Vorobyev, Nucl. Data Sheets 131, 1 (2016)
[11] A.C. Wahl, Atomic Data and Nuclear Data Tables 39, 1–156 (1988)
[12] A.C. Wahl, Compilation and evaluation of fission yield nuclear data (Final report of CRP 1991–1996)
[13] A.C. Wahl, Fission Product Yield Data for the Transmutation of Minor Actinide Nuclear Waste (IAEA STI/PUB/1286, 2008)