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# Even–odd effects in prompt emission of spontaneously fissioning even–even Pu isotopes

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## Abstract

The available experimental $Y(A, \text{TKE})$ data for $^{236,238,240,242,244}$Pu(SF) together with the *Zp* model prescription with appropriate parameters allows the investigation of even–odd effects in fragment distributions. The size of the global even–odd effect in $Y(Z)$ is decreasing from $^{244}$Pu(SF) to $^{236}$Pu(SF) confirming the general observation of a decrease of the even–odd effect with the fissility parameter.

Charge polarizations ($\Delta Z$) and root-mean squares (rms) as a function of $A$ of $^{236–244}$Pu(SF) were obtained for the first time. In the asymmetric fission region both $\Delta Z(A)$ and rms($A$) exhibit oscillations with a periodicity of about 5 mass units due to the even–odd effects. The total average charge deviations $\langle \Delta Z \rangle$ (obtained by averaging $\Delta Z(A)$ over the experimental $Y(A)$ distribution) are of about $|0.5|$ for all studied Pu(SF) systems. The comparison of the calculated $\Delta Z(A)$ and rms($A$) of $^{240}$Pu(SF) with those of $^{239}$Pu($n_{\text{th}}$, $f$) reported by Wahl shows an in-phase oscillation with a higher amplitude in the case of $^{240}$Pu(SF), confirming the higher even–odd effect in the case of SF.

As in the previously studied cases ($^{233,235}$U($n_{\text{th}}$, $f$), $^{239}$Pu($n_{\text{th}}$, $f$), $^{252}$Cf(SF)) the even–odd effects in the prompt emission of $^{236–244}$Pu(SF) are mainly due to the $Z$ even–odd effects in fragment distributions and charge polarizations and the $N$ even–odd effects in the average neutron separation energies from fragments $\langle Sn \rangle$. The size of the global $N$ even–odd effect in $\langle Sn \rangle$ is decreasing with the fissility parameter, being higher for the Pu(SF) systems compared to the previously studied systems. The prompt neutron multiplicities as a function of $Z$, $\nu(Z)$, exhibit sawtooth shapes with a visible staggering for asymmetric fragmentations. The size of the global $Z$ even–odd effect in $\nu(Z)$ exhibits a decreasing trend with increasing fissility. The average prompt neutron multiplicities as a function of TKE show an increase of the even–odd effect with increasing TKE, with global effect sizes close to each other (a decrease of the effect for heavier fissioning nuclei is not observed here). The amounts of the global even–odd effect in $Y(Z)$ and of the $N$

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even–odd effect in $\langle Sn \rangle$ of $^{240}$Pu(SF) are larger compared to $^{239}$Pu($n_{\text{th}}, f$). This fact affects the prompt emission leading to a lower $Z$ even–odd effect in the prompt neutron multiplicity of $^{240}$Pu(SF) compared to $^{239}$Pu($n_{\text{th}}, f$).


*Keywords:* Prompt emission in fission; Prompt fission neutron multiplicity; Even–odd effects in prompt emission

## 1. Introduction

The present paper, devoted to even–odd effects in spontaneously fissioning even–even Pu isotopes, is a continuation of the previous study of even–odd effects in the prompt emission of $^{233,235}$U($n_{\text{th}}, f$), $^{239}$Pu($n_{\text{th}}, f$) and $^{252}$Cf(SF) reported in Ref. [1].

The availability of experimental $Y(A, \text{TKE})$ data for $^{236,238,240,242,244}$Pu(SF) (Refs. [2–4] and references therein) and the "*Zp* model" prescription for charge distributions at each $A$ give the possibility to obtain multi-dimensional fragment distributions $Y(A, Z, \text{TKE})$ and to investigate the even–odd effects in the $Y(Z)$ projections.

From the fit of the charge distributions at each $A$ with Gaussian functions, the charge polarizations (deviations) $\Delta Z(A)$ and the root-mean squares rms($A$) were obtained for the first time for $^{236,238,240,242,244}$Pu(SF).

These charge polarizations are used in the construction of the fragmentation range of the Point-by-Point (PbP) model of prompt emission. The primary results of the model are the so-called multi-parametric matrices of different quantities characterizing both the fragments and the prompt emission, generically labeled $q(A, Z, \text{TKE})$. They are then averaged over the $Y(A, Z, \text{TKE})$ distributions giving average quantities as a function of $A$, of $Z$, of $N$, of TKE and total average ones. The very good agreement of the PbP model results with the existing experimental data of $^{236–244}$Pu(SF) (i.e. total average prompt neutron multiplicities, prompt neutron multiplicity distributions P($\nu$) and prompt fission neutron spectra) assures the validation of the present prompt emission calculations.

Even–odd fluctuations due to both proton and neutron numbers are present in different average quantities, e.g. in the average prompt neutron multiplicity as a function of $Z$, $\bar{\nu}(Z)$, as a function of A, $\bar{\nu}(A)$, ones as a function of TKE, $\langle \nu \rangle(\text{TKE})$. They are also visible in the average neutron separation energy resulting from the sequential emission ($\langle Sn \rangle(N)$ and $\langle Sn \rangle(A)$), in the total excitation energy at full acceleration $\langle \text{TXE} \rangle(A)$ and others. Global sizes of even–odd effects in different fragment and prompt emission quantities are calculated, too.

As in the previous paper [1] cold fission fragmentations are not taken into account because the present work is referring to prompt neutron emission. To avoid any limiting situation, in the present prompt emission calculations the fragmentations with TXE values less than 9 MeV were excluded.

## 2. Proton even–odd effects in the fragment distributions of $^{236–244}$Pu(SF)

Experimental fragment mass and total kinetic energy distributions of $^{236,238,240,242,244}$Pu(SF) were measured in the 1990ties (e.g. Refs. [2–4] and references therein). Experimental single distributions $Y(A)$, $Y(\text{TKE})$, TKE($A$) and $\sigma_{\text{TKE}}(A)$ referring to $^{236–244}$Pu(SF) are available in Ref. [2] and for $^{238,240,242}$Pu(SF) in the EXFOR library [5].