GAMMA-1 Emission of Prompt Gamma-Rays in Fission and Related Topics

Prompt gamma-ray energy in the frame of prompt neutron emission models

A. Tudora a, C. Morariu a, F.-J. Hambsch b, S. Oberstedt b, C. Manailescu a

a University of Bucharest, Faculty of Physics, Atomistilor 405, Bucharest-Magurele, Jud. Ilfov, RO-077125, Romania
b European Commission, DG Joint Research Centre (IRMM), B-2440-Geel, Belgium

Abstract

As output of the Point by Point model (taking into account the entire fission fragment range) and of the most probable fragmentation approach (working with one fragmentation and average values of model parameters) not only prompt neutron quantities are provided but also the prompt γ-ray energy as a function of fragment Eγ(A) and the total average prompt γ-ray energy <Eγ>.

The almost linear behaviour of the total average <Eγ> with the prompt neutron multiplicity was observed experimentally in the incident neutron energy range where only the first fission chance is involved. This was parameterised as a function of Z and A of the fissioning nucleus. This parameterisation was validated by <Eγ> calculations in the frame of the most probable fragmentation approach. The results describe well the experimental data measured by J. Fréhaut from thermal up to about 15 MeV incident energy for three fissioning systems 235U(n,f), 237Np(n,f) and 232Th(n,f).

The Point by Point model provides average prompt γ-ray energy as a function of the fragment pair in very good agreement with the existing experimental data of 252Cf(SF) and 233U(nth,f).

The unique experimental data of prompt γ-ray energy as a function of fragment measured for 235U(nth,f) is very well described by the Point by Point model results obtained by using two methods of total excitation energy partition between complementary fission fragments.

© 2012 Published by Elsevier B.V. Selection and/or peer-review under responsibility of Institute for Reference Materials and Measurements. Open access under CC BY-NC-ND license.

Keywords: prompt gamma-ray emission; prompt fission neutron emission; prompt fission neutron multiplicity; prompt fission neutron spectrum; prompt fission modeling

* Anabella Tudora. Tel.: +40-21-4574666; fax: +40-21-4574521
E-mail address: anabellatudora@hotmail.com, anabella.tudora@brhaps.fizica.unibuc.ro
1. Total average prompt gamma-ray energy as a function of the incident neutron energy

In the frame of the prompt neutron emission models Point by Point (PbP) and “most probable fragmentation”, the energy of prompt $\gamma$-rays is also obtained concomitantly with prompt neutron quantities.

In the case of the most probable fragmentation approach, the input model parameters are taken as average values. They are obtained by averaging the parameters corresponding to each pair of fission fragments (FF) over the fragment mass and charge distributions in the frame of the so-called PbP treatment. This treatment played a very important role in the development of systematics of average input model parameters: energy release $<Er>$, total kinetic energy of FF $<TKE>$, average neutron separation energy from FF $<Sn>$ and total average level density parameter $<a>$ (usually given as $<C>=A_{CN}/<a>$, with $A_{CN}$ the mass number of the fissioning nucleus), see details in Ref. [1].

But the first systematic behaviour was mentioned 10 years ago in the case of the total average prompt gamma-ray energy $<E_\gamma>$. This was based on the experimental observation of J.Fréhaut [2] consisting in an almost linear behaviour of $<E_\gamma>$ with the total average prompt neutron multiplicity $<\nu_p>$ in the incident neutron energy ($E_n$) range where only the first fission chance is involved: $<E_\gamma> = p <\nu_p> + q$. The slope and intercept of this dependence were parameterised as a function of the charge and mass numbers of the fissioning nucleus:

$$
p = 6.710 - 0.156 \frac{Z_{CN}^2}{A_{CN}}, \quad q = 0.750 + 0.088 \frac{Z_{CN}^2}{A_{CN}}
$$

(1)

Details are given in Refs. [1, 3-6].

In this manner $<\nu_p>$ of each compound nucleus (CN) undergoing fission (obtained from energy conservation) can be expressed as a function of average model parameters $<Er>$, $<TKE>$, $<Sn>$ and of the slope $p$ and intercept $q$ given by the systematic behaviour mentioned above.

The total average $<E_\gamma>$ in the $E_n$ range where multiple fission chances participate is given by:

$$
<E_\gamma> = \sum_{i=1}^{n} RF_i <E_\gamma>_i
$$

(2)

where the fission probability of each CN is given by the fission cross section ratios $RF_i = \sigma_{f_i}/\sigma_{f_{tot}}$. These expressions become more complicated if the secondary nucleus chains and paths formed by charged particle emission at high $E_n$ (above 20 MeV) are taken into account, for details see Ref. [7].

$<E_\gamma>$ as a function of $E_n$, obtained for $^{235}$U(n,f) and $^{237}$Np(n,f) in the frame of the most probable fragmentation approach describe well the unique experimental data measured by Fréhaut [2] as it can be seen in Fig. 1. In this figure the old $<E_\gamma>(E_n)$ results, reported in Refs. [3, 4] are plotted with dash-dotted lines and more recent results (partially reported in Refs. [8, 9]) with solid lines. These results are obtained by using average model parameters resulted from the PbP treatment (in the case of the main fissioning nuclei $^{235}$U and $^{237}$Np) and provided by the systematic of Ref. [1] (in the case of secondary fission chances), as well as fission cross-section ratios from recent evaluations. The PbP model calculations of $<E_\gamma>(E_n)$ (given with full red circles in Fig.1) describe well the experimental data, too. As observation, in Refs. [8, 9] as well as in other papers regarding the PbP model we focused on prompt neutron emission quantities. $<E_\gamma>$ obtained concomitantly from PbP calculations (compared with experimental data of
Fréhaut) being used only as an additional validation of the model and parameters used. For this reason the PbP results of \(<E_\gamma>\) were not entirely reported.

![Figure 1: \(<E_\gamma>\) results in comparison with experimental data (open squares) for \(^{235}\text{U}(n,f)\) in the upper part and \(^{237}\text{Np}(n,f)\) in the lower part. Most probable fragmentation calculation with dash dotted line (old results) and solid line (recent results). PbP calculation with full circles.](image)

2. \(^{232}\text{Th}(n,f)\) PbP model and most probable fragmentation approach calculations

For the first time prompt neutron emission quantities and prompt \(\gamma\)-ray energies of \(^{232}\text{Th}(n,f)\) are calculated in the frame of the PbP model (in the En range from thermal up to about 6 MeV) and the most probable fragmentation approach (up to 20 MeV incident energy).

As usually in the PbP treatment the FF range was chosen as following: the entire range of fragment masses covered by the experimental Y(A,TKE) distributions taken from EXFOR [10] with a step of one mass unit. For each mass number two fragments are taken with the charge numbers Z chosen as the nearest integer values above and below the most probable charge Zp (determined from the unchanged charge distribution \(Z_{\text{UCD}}\) corrected with a possible charge polarization \(\Delta Z\)). Details about the PbP model can be found in [8, 9, 11-13] and references therein. Here we mention only that a triangular form of the fragment residual temperature distribution is used. For all fragments taken in the PbP calculation, the CN cross-sections of the inverse process of neutron evaporation from fragments were obtained from optical model calculations (provided by the SCAT2 computer code with the optical potential parameterisation of Becchetti-Greenless). The level density parameters of the fully accelerated FF are provided by the generalized super-fluid model (with shell corrections taken from the recommended data bases of RIPL3), the calculations being done at the fragment excitation energy values obtained from the total excitation energy (TXE) partition method of [12].

The total average prompt neutron emission quantities are obtained in very good agreement with existing experimental data. In the following we give only two examples.
The first example is referring to the PbP model calculation of the prompt neutron spectrum describing well the experimental data at $E_n = 2$ MeV and $E_n = 2.9$ MeV (taken from EXFOR [14]) as it can be seen in Fig. 2.

![Figure 2: PbP results of the prompt fission neutron spectrum of $^{232}$Th(n,f) in comparison with experimental data from EXFOR [14] at $E_n = 2$ MeV (upper part) and $E_n = 2.9$ MeV (lower part) given as ratios to the equivalent Maxwellian spectrum.](image)

The second example is referring to the PbP model result of total average $<\nu_p>$. Again excellent agreement is obtained with experimental data from EXFOR [14] as it can be seen in Fig. 3 (where the PbP multiplicity is plotted with full red circles and the experimental data with different full grey and open symbols).

The PbP result of the total average $<E_\nu>$ (plotted with open red circles) succeeds to give an overall good description of the experimental data of Fréhaut [2] (full black squares) as it can be seen in Fig. 4. The thin line connecting the full red points is only to guide the eye.

The calculation up to 20 MeV incident energy in the frame of the most probable fragmentation approach is made by using average model parameter values. They are obtained from the PbP treatment in the case of the main fissioning nucleus $^{233}$Th and average parameters provided by the systematic of Ref. [1] in the case of secondary compound nuclei undergoing fission $^{232-230}$Th. The fission cross-section ratios are taken from recent evaluations (JEFF3.1.1 and JENDL4).

As it can be seen in Fig. 3, the total average $<\nu_p>$ obtained by using RF from JEFF3.1 (plotted with red solid line) describes very well the experimental data over the entire incident energy range up to 20 MeV. In the case of RF from JENDL4 the $<\nu_p>$ result (plotted with magenta dashed line) agrees very well with the experimental data up to 17 MeV. Above this energy it slightly underestimates the experimental data (but remaining in the error bar limits). In the same figure, for comparison, the $<\nu_p>$ evaluations of ENDF/B-VII, JEFF3.1 and JENDL4 (plotted with different dash dotted lines) are given, too.

The total average $<E_\nu>$ obtained in the frame of the most probable fragmentation approach, (obviously concomitantly with the total average multiplicity and spectra) is in good agreement with the experimental data, as it can be seen in Fig. 4 (the solid line).
Figure 3: $^{232}$Th(n,f) total average prompt neutron multiplicity calculations in comparison with experimental data from EXFOR (plotted with full grey squares and different open symbols): PbP model result with full red circles, most probable fragmentation results with red solid line (using RF from JEFF3.1) and magenta dashed line (using RF from JENDL4). $\langle \gamma \rangle$ evaluations of ENDF/B-VII, JEFF3.1 and JENDL4 are plotted with different dash dotted lines.

Figure 4: $^{232}$Th(n,f) Total average prompt $\gamma$-ray energy calculations in comparison with experimental data of Fréhaut (full squares). PbP model result with full red circles, most probable fragmentation result with blue line.
3. Prompt gamma-ray energy as a function of fragment

The PbP model provides all prompt neutron quantities and gamma-ray energies as a function of fragment. The model gives the so-called multi-parametric matrix \( v(Z,A,TKE) \) that allows to obtain prompt neutron emission quantities as a function of fragment as well as total average quantities (by averaging over the fragment distributions \( Y(A,TKE) \)). All these quantities can be compared with existing experimental data, for instance \( v(A), \varepsilon(A), \langle \epsilon \rangle(TKE), P(v) \) and obviously the total average prompt neutron multiplicity and spectra. This kind of PbP results was already reported in Refs. [11-13, 15-17] for many neutron induced and spontaneously fissioning nuclei such as \( ^{233,235}\text{U}(n_{th,f}), ^{237}\text{Np}(n,f) \) at \( E_n = 0.8 \) MeV and 5.5 MeV, \( ^{239}\text{Pu}(n_{th,f}), ^{240,242}\text{Pu}(SF), ^{244,248}\text{Cm}(SF), ^{252}\text{Cf}(SF) \).

The average prompt \( \gamma \)-ray energy as a function of fragment or fragment pair is also obtained in the same run.

Unfortunately, the experimental data regarding the prompt gamma-ray energy as a function of fragment are very scarce. In our knowledge measurements of the average prompt gamma-ray energy corresponding to the fragment pair are reported for two fissioning systems: \( ^{233,235}\text{U}(n_{th,f}) \) [18] and \( ^{252}\text{Cf}(SF) \) [19], both experimental data sets being given as a function of the light fragment mass. These experimental data are well described by the PbP results reported in [11] as it can be seen in Fig. 5. Measurements of the average prompt \( \gamma \)-ray energy as a function of fragment \( E_{\gamma}(A) \) are reported to our knowledge only for \( ^{235}\text{U}(n_{th,f}) \) [20]. These experimental \( E_{\gamma}(A) \) data exhibit the same sawtooth-like behaviour as \( \varepsilon(A) \).

The PbP results of \( E_{\gamma}(A) \), calculated with two methods of TXE partition between complementary FF give an excellent description of the experimental \( E_{\gamma}(A) \) data of \( ^{235}\text{U}(n_{th,f}) \) as it can be seen in Fig. 6. The PbP result plotted with star symbols in Fig. 6 is obtained by using the TXE partition described in Ref. [12]. This method of TXE partition can be considered as a reference method because it avoids assumptions and models at scission and it is based exclusively on the systematic behaviour of experimental \( v(A) \) data, leading to a general parameterisation of the quantity \( \frac{v_{th}v_{pas}}{v_{th}} \) as a function of the heavy fragment mass available for neutron induced fission at low and moderate energies. The PbP result plotted with full red circles in Fig. 6 is obtained by using a new TXE partition between complementary FF. This method is based on the calculation of the additional deformation energies of fragments (meaning the difference between their deformation energies at scission and full acceleration) and the partition of the total available excitation energy at scission assuming the statistical equilibrium. This new method was firstly validated by PbP calculations of prompt neutron emission quantities sensitive to the TXE partition, such as \( v(A) \) obtained in very good agreement with experimental data for many fissioning systems. The very good agreement of the calculated \( E_{\gamma}(A) \) (full red points) with experimental data [20] illustrated in Fig. 6, as well as the fact that this result is very close to \( E_{\gamma}(A) \) obtained with the reference method of TXE partition [12] (plotted with star symbols) can be considered as a second validation of the new method of TXE partition.

This method of TXE partition, based exclusively on models and straightforward assumptions, does not need any experimental data and adjustments of parameters, consequently prompt neutron emission quantities (such as \( v(A), \varepsilon(A) \)) as well as prompt gamma-ray energies \( E_{\gamma}(A) \) can be predicted by the PbP model for any fissioning system.

4. Conclusions

The prompt neutron emission models Point by Point and “most probable fragmentation” provide not only quantities related to the prompt neutron emission but also prompt gamma-ray energies as a function of fragment and total average energies.
Figure 5: $\langle E_\gamma \rangle$ of the FF pair as a function of the light fragment mass: PbP calculation for $^{235}$U(n$_{th}$,f) (upper part) and $^{252}$Cf(SF) (lower part) in comparison with experimental data [18, 19]. The experimental data are plotted with open squares and the PbP results with full red circles.

Figure 6: $^{235}$U(n$_{th}$,f) average prompt $\gamma$-ray energy as a function of the fragment mass: PbP calculations using the TXE partition method of Ref. [12] (blue stars) and a new method of TXE partition (full red circles) in comparison with experimental data of Pleasonton (open squares).
The total average $<\text{E}_{\gamma}>$ calculated in the frame of the most probable fragmentation approach at incident neutron energies from thermal up to 20 MeV or higher, describe well the unique experimental data measured by Fréhaut for $n+^{235}\text{U}$, $n+^{237}\text{Np}$ and $n+^{232}\text{Th}$. This good agreement with experimental data of total average $<\text{E}_{\gamma}>$ as a function of $E_n$ obtained concomitantly with all prompt neutron emission quantities, also describing well the experimental data, validated the general parameterisation of total average $<\text{E}_{\gamma}>$ as a linear function of total average prompt neutron multiplicity $<\nu_p>$. The total average $<\text{E}_{\gamma}>$ provided by the PbP model (by averaging $<\text{E}_{\gamma}>$ of fission fragment pairs over the mass and charge distributions) is also obtained in very good agreement with existing experimental data. $<\text{E}_{\gamma}>$ of the fission fragment pairs calculated within the PbP model describe very well the existing experimental data given as a function of the light fragment mass $A_L$ measured for $^{252}\text{Cf(SF)}$ and $^{\text{213}}\text{U(n}_{\text{th}},f)$. The unique experimental data of prompt gamma-ray energy as a function of fragment $\text{E}_{\gamma}(A)$ measured for $^{235}\text{U(n}_{\text{th}},f)$ are excellently described by our PbP model results obtained with two methods of TXE partition between complementary fission fragments. The calculated $\text{E}_{\gamma}(A)$ and $<\text{E}_{\gamma}>_{\text{pair}}(A_L)$ describing very well the existing experimental data, obtained concomitantly with prompt neutron emission quantities as a function of fragment in good agreement with experimental data prove the consistency of the Point by Point calculations and in the same time can be considered as an additional validation of the TXE partition methods used in the frame of the Point by Point model.

Acknowledgements

A part of this work (short term visit A.T.) was done in the frame of the ERINDA programme of the European Commission (agreement number 269499).

References

[1] Tudora A, Ann. Nucl. Energy 2009; 36(1): 72-84
[2] Fréhaut J, IAEA-INDC(NDS) 1989; 220: 99-111
[3] Vladuca G, Tudora A, Ann. Nucl. Energy 2000; 27(13): 1187-1197
[4] Vladuca G, Tudora A, Ann. Nucl. Energy 2001; 28(5): 419-435
[5] Vladuca G, Tudora A, Ann. Nucl. Energy 2001; 28(7): 689-700
[6] Vladuca G, Tudora A, Ann. Nucl. Energy 2001; 28(16): 1653-1665
[7] Tudora A, Vladuca G, Morillon B, Nucl. Phys. A 2004; 740: 33-58
[8] Tudora A, Morillon B, Hambsch F-J, Vladuca G, Oberstedt S, Nucl. Phys. A 2005; 756: 176-191
[9] Vladuca G, Tudora A, Morillon B, Filipescu D, Nucl. Phys. A 2006; 767: 112-137
[10] EXFOR Data Base 2011; target Th-232, reaction (n,f) quantity MASS, PRE, FY. http://www-nds.iaea.org/EXFOR
[11] Tudora A, Ann. Nucl. Energy 2008; 35(1): 1-10
[12] Manaiiescu C, Tudora A, Hambsch F-J, Morariu C, Oberstedt S, Nucl. Phys. A 2011; 867: 12-40
[13] Tudora A, Hambsch F-J, Ann. Nucl. Energy 2010; 37(6): 771-777
[14] EXFOR Data Base 2011; target Th-232, reaction (n,f) quantities DE, Prompt Nu. http://www-nds.iaea.org/EXFOR
[15] Tudora A, Ann. Nucl. Energy 2006; 33(11-12): 1030-1038
[16] Tudora A, Ann. Nucl. Energy 2010; 37(4): 492-497
[17] Tudora A, Ann. Nucl. Energy 2010; 37(1): 43-51
[18] Nifenecker H, Signarbieux C, Ribrag M, Poitou J, Matsuszek J, Nucl. Phys. A 1972; 189: 285
[19] Pleasonton F, Nucl. Phys. A 1973; 213: 413
[20] Pleasonton F, Ferguson RL, Schmitt HW, Phys. Rev. C 1972; 6: 1023