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Annals of Nuclear Energy 32 (2005) 1032–1046
annals of NUCLEAR ENERGY
www.elsevier.com/locate/anucene

Prompt fission neutron spectrum evaluation for ^{252}Cf(SF) in the frame of the multi-modal fission model

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Received 7 January 2005; accepted 15 February 2005
Available online 7 April 2005

Abstract

In the present work, an attempt to improve the evaluation of the prompt fission neutron spectrum of ^{252}Cf(SF) is made. The multi-modal fission concept is included into the Los Alamos model. A more generalized form of the fission fragment residual nuclear temperature distribution and a possible anisotropy effect of the prompt neutron emission in the center-of-mass system are taken into account, too. The multi-modal fission parameters entering the prompt fission neutron spectrum model are determined on the basis of the experimental data concerning the fission fragment total kinetic energy TKE(A) and mass distribution $Y(A)$ measured at IRMM. The calculated prompt neutron spectrum is obtained in better agreement with the standard point-wise evaluation of Mannhart and compared to other evaluations made with different models.

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0306-4549/$ - see front matter
doi:10.1016/j.anucene.2005.02.006

1. Introduction

1.1. Status of the prompt fission neutron spectrum evaluation of $^{252}Cf(SF)$

For spontaneous fission (SF) of ^{252}Cf much more effort than for other nuclei was devoted to the measurement and interpretation of the prompt fission neutron spectrum (PFNS), because this spectrum is also used as a neutron standard for the shape of PFNS.

Since much more experimental data of the PFNS for ^{252}Cf exit than for any other nucleus the PFNS could be evaluated only on the basis of experimental data (''free of model''). This standard evaluation was made by Mannhart (1985, 1987, 1989) using the existing sets of experimental data (Poenitz and Tamura, 1983a,b; Blinov et al., 1983, 1985; Boldeman et al., 1986; Lajtay et al., 1983; Böttger et al., 1983, 1987; Märten et al., 1983a, 1984) and a ''reduction procedure'' (the prompt fission neutron energy range was divided in bins and for each bin an equivalent experimental point was determined). The evaluation resulted in a χ^2 per degree of freedom of nearly unity and indicated no real inconsistencies between the various experiments (Mannhart, 1985, 1987, 1989). Based on this evaluation, the PFNS of ^{252}Cf was established as an internationally accepted reference standard for metrological applications. Mannhart's ''point-wise'' evaluation (Mannhart, 1985, 1987, 1989) (full circles) and another older version, also made by Mannhart with the same procedure but using less experimental data sets (open squares) are shown in Fig. 1. Also in this figure the new experimental data measured by Märten et al. (at fission neutron energies above 5 MeV) and taken from the EXFOR library (EXFOR, 2004) are given (up-down open triangles and open and full gray diamonds). These experimental data were obtained after the Mannhart evaluation and, consequently, they were not taken into account in the frame of the ''point-wise'' evaluation work (Mannhart, 1985, 1987, 1989).

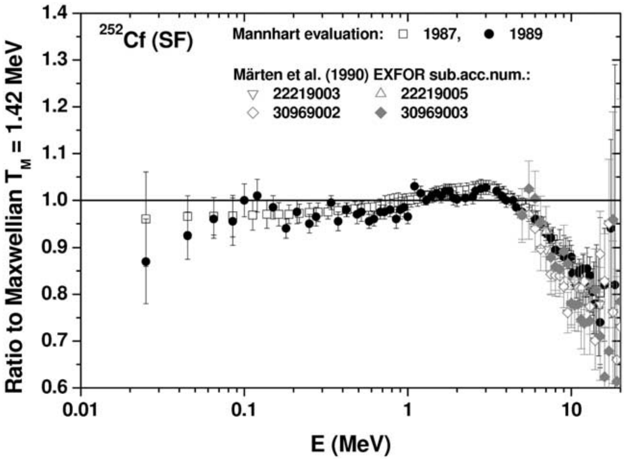

Fig. 1. The PFNS standard evaluation of Mannhart and the experimental data of Märten et al. (EXFOR, 2004) represented as a ratio to the Maxwellian spectrum with $T_M = 1.42$ MeV.

All data of Fig. 1 are given as ratios to the well-known Maxwellian spectrum of ^{252}Cf with a temperature $T_M = 1.42$ MeV (this Maxwellian spectrum was the first model evaluation applied to ^{252}Cf(SF)).

In the last 20 years, several attempts (Madland and Nix, 1982; Märten et al., 1983b, 1989a,b; Madland et al., 1989) have been made to give a theoretical description of the PFNS of ^{252}Cf(SF). These models were based on the assumption that the mechanism of neutron emission is evaporation by fully accelerated fission fragments (FF).

The Los Alamos (LA) model in its basic form (Madland and Nix, 1982) was used as first for the spontaneous fission of ^{252}Cf. The authors have used the "*7 point approximation*" for the determination of the input model parameters and only *the most probable fragmentation* {Mo-108, Ba-144} was taken into account ("single-mode" calculation). The model parameters used by Madland and Nix in the frame of their model were (Madland and Nix, 1982): the average energy released $\langle E_r \rangle = 219.408$ MeV, the average total kinetic energy of the FF $\langle \mathrm{TKE} \rangle = 185.9$ MeV, the average level density parameter $a = A/C$ (where A is the mass number of fissioning nucleus and usually $C = 11$ MeV), the average neutron separation energy from the FF: $\langle S_n \rangle = 5.473$ MeV and the average prompt γ-ray energy $\langle E_{\gamma\mathrm{tot}} \rangle = 6.95$ MeV.

In 1989, Madland et al. (1989) provided an improved calculation of the standard PFNS of ^{252}Cf(SF) also in the frame of the LA model (Madland and Nix, 1982) but using the "*point by point approximation*" (Madland et al., 1989). The use of input parameters based upon average values of the FF mass, charge and kinetic energy distributions was replaced by the use, on a point-by-point basis, of the distributions themselves. The first calculation using the refined model was again made for ^{252}Cf(SF). The FF mass and charge distributions were represented by 28 fragments: 14 approximately equispaced fragment masses in the range $88 \leqslant A \leqslant 164$ with a spacing of about 6 a.m.u. and two isobars per FF mass with values of Z that are the nearest integer values above and below the most probable charge (Madland et al., 1989).

1.2. Present evaluation

In the present work, an attempt to improve the ^{252}Cf(SF) PFNS evaluation is made.

The multi-modal fission concept included into the LA model, already used for the PFNS and multiplicity calculation for the neutron induced reactions on ^{237}Np, ^{238}U (Hambsch et al., 2002) and ^{235}U (Hambsch et al., 2003), is applied also in the case of ^{252}Cf(SF). The multi-modal parameters entering the PFNS model are determined on the basis of experimental data concerning the FF total kinetic energy TKE(A) and the FF mass distribution $Y(A)$ measured at IRMM. In contrast to the earlier calculations for ^{238}U, ^{237}Np (Hambsch et al., 2002) and ^{235}U (Hambsch et al., 2003), where it was sufficient to assume three different fission modes to get an excellent description of the experimental fission fragment yield and total kinetic energy (TKE) distribution, for ^{252}Cf(SF) this is not possible. Here, five fission modes are necessary to reproduce the mass yield and TKE distributions: four asymmetric modes named Standard I (S1), Standard II (S2), Standard III (S3) and Standard X (SX) and one symmetric mode named Super-long (SL). The existence of a weak contribution of the S3 mode had already been verified in case of neutron induced fission of ^{237}Np ($Z = 93$) (Siegler et al., 1995) and ^{239}Pu ($Z = 94$) (Schillebeeckx et al., 1992). If it is a question of nuclear charge whether new modes arise or not, in ^{252}Cf, with $Z = 98$, the contribution of S3 should be much higher. Hence, the need of five modes in case of ^{252}Cf(SF) might be justified, following the trend of increasingly broader mass distribution with increasing Z, although no physical proof has been found so far. A more elaborated paper on the ^{252}Cf experiment and its interpretation in terms of fission modes will be published elsewhere (Hambsch et al., 2005). Also from the theoretical calculations of the potential energy surface within the multi-modal random neck-rupture model, even more modes have been predicted (Oberstedt et al., 1998).

A more generalized form of the FF residual nuclear temperature distribution and a possible anisotropy effect of the prompt neutron emission in the center-of-mass system (CMS) are taken into account, too.

In this way the total ^{252}Cf(SF) PFNS, calculated as a superposition of the modal contributions, was obtained in better agreement with the evaluated points of Mannhart (1985, 1987, 1989) and the experimental data from EXFOR (2004) than other evaluations made with different models, as it will be discussed below.

2. New features of the Los Alamos model

2.1. Fission fragment residual nuclear temperature distribution

Starting with an initial distribution of the FF excitation energy obtained from the experimental FF kinetic energy distribution and the neutron number, Terrell (1959) summed the residual distributions following the emission of successive neutrons to obtain the distribution of the excitation energy that governs neutron emission. This distribution was then transformed into the FF residual nuclear temperature distribution $P(T)$ by using a Fermi gas model, where the excitation energy E^* is related to the nuclear temperature T and the level density parameter a by $E^* = aT^2$. The resulting temperature distribution is approximately triangular in shape with a moderately broad high-temperature cutoff (Terrell, 1959). The original LA model (Madland and Nix, 1982) used Terrell's observation in a way that this diffuse cutoff is replaced by a sharp cutoff, so that $P(T)$ is approximated by the following triangular distribution (Madland et al., 1989) (see the solid line in Fig. 2(b)):

$$P(T) = \begin{cases} \frac{2}{T_{\mathrm{m}}^2} T, & T \leqslant T_{\mathrm{m}}, \\ 0, & T > T_{\mathrm{m}}, \end{cases} \tag{1}$$

where the maximum temperature T_{m} is related to the initial total average FF excitation energy approximated by $T_{\mathrm{m}} = (\langle E^* \rangle / a)^{1/2}$.

Consequently, the prompt neutron spectrum in CMS for a FF (indexed f) is given by

$$\phi(\varepsilon, \sigma_{\mathrm{cf}}) = \sigma_{\mathrm{cf}}(\varepsilon) \int_0^{T_{\mathrm{m}}} k_{\mathrm{f}}(T) P(T) \exp(-\varepsilon / T) \, \mathrm{d}T \tag{2}$$

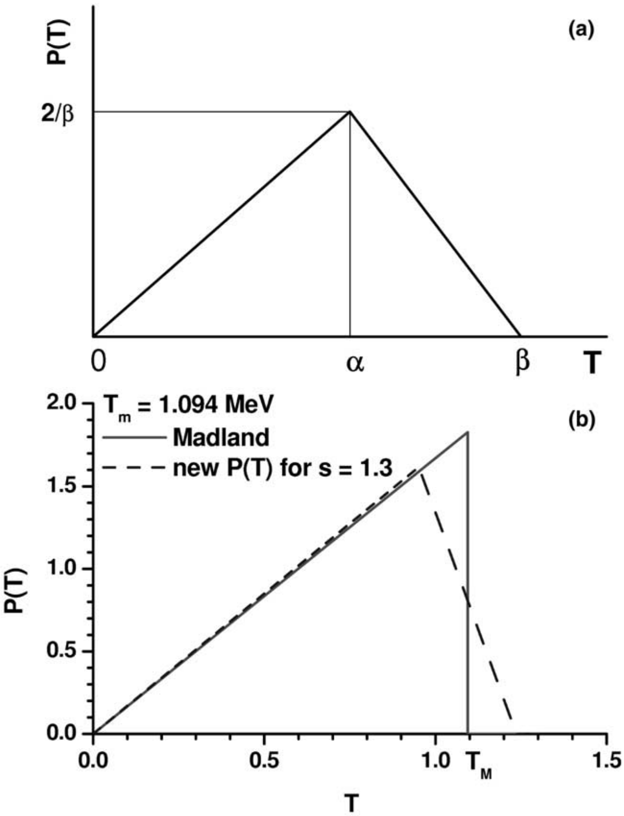

Fig. 2. (a) Example for the new FF residual nuclear temperature distribution $P(T)$, (b) the FF residual nuclear temperature distribution for $T_m = 1.094$ MeV: the solid line indicates the "classical" $P(T)$ expression (Madland and Nix, 1982) and the dashed line represents the new expression of $P(T)$ with $s = 1.3$.

with

$$k_{\mathrm{f}}(T) = \left[\int_0^\infty \sigma_{\mathrm{cf}}(\varepsilon)\varepsilon \exp(-\varepsilon/T)\,\mathrm{d}\varepsilon\right]^{-1}.$$

In these relations, the CMS neutron energy is ε and $\sigma_{\mathrm{cf}}(\varepsilon)$ is the compound nucleus (CN) formation cross section in the inverse process.

Some discrepancies could arise, because the triangular temperature distribution given in Eq. (1) eliminates the high-energy contributions to the spectrum that would otherwise be present from temperatures larger than T_{m} (Kapoor et al., 1963).

In the present work, we propose therefore another shape for the FF residual temperature distribution (see Fig. 2(a)), starting also from Terrell's results (Terrell, 1959) but trying to take into account a diffuse high-temperature cutoff

$$P(T) = \begin{cases} \frac{2}{\alpha\beta}T, & 0 \leqslant T \leqslant \alpha \\ \frac{2}{\beta-\alpha}\left(-\frac{T}{\beta}+1\right), & \alpha \leqslant T \leqslant \beta \end{cases} \quad \text{with } \alpha+\beta = 2T_{\mathrm{m}}. \tag{3}$$

The above $P(T)$ distribution takes into account the following conditions: continuity at the point $T = \alpha$, $P(T = \beta) = 0$, normalization to unity and the mean value $\langle T \rangle = \frac{2}{3}T_{\mathrm{m}}$

Using the parameterization

$$\beta = s\alpha \text{ with } s \geqslant 1, \tag{4}$$

the new expression proposed for the FF residual nuclear temperature distribution is the following:

$$P(T) = \begin{cases} \frac{2}{T_{\mathrm{m}}^2}\frac{(s+1)^2}{4s}T, & 0 \leqslant T \leqslant \frac{2T_{\mathrm{m}}}{s+1}, \\ \frac{2}{T_{\mathrm{m}}^2}\frac{s+1}{2(s-1)}\left(-\frac{s+1}{2s}T+T_{\mathrm{m}}\right), & \frac{2T_{\mathrm{m}}}{s+1} \leqslant T \leqslant \frac{2sT_{\mathrm{m}}}{s+1}, \end{cases} \tag{5}$$

and it is obvious that for $s = 1$ the $P(T)$ expression of the classical LA model (Eq. (1)) is re-obtained.

An example of such a residual temperature distribution is illustrated in Fig. 2(b) by the dashed line (for $T_{\mathrm{m}} = 1.094$ MeV and the parameter $s = 1.3$) together with the $P(T)$ distribution used in the classical LA model (Eq. (1)) represented by the solid line.

2.2. Anisotropy effect

As it was written in Hambsch et al. (2003), the most important emission of prompt neutrons is from fully accelerated FF but neutron evaporation during fragment acceleration can be also possible (Kornilov et al., 1999) and these neutrons can lead to a non-isotropic neutron spectrum in CMS. Another source of non-isotropic neutrons can be neutron emission at the moment of scission, so-called scission neutrons. Presently, the search for scission neutrons is being performed, but with no success so far. Our calculations can not distinguish between an anisotropy introduced by neutrons emitted during acceleration or due to scission neutrons. Nevertheless, as one will see later, the assumption of anisotropic neutron emission will improve the agreement between calculated PFNS and experimental values.

According to Terrell's (1959) work and also to Hambsch et al. (2003), Kornilov et al. (1999), Gerasimenko and Rubchenya (1989), Budtz-Jørgensen and Knitter (1989), Batenkov et al. (1989), Ericson and Strutinski (1958) and Terrell (1962), it was assumed that the anisotropy of neutron emission, if present, is symmetrical about 90° and the FF prompt neutron spectrum in the CMS could be described by the following equation:

$$\Phi(\varepsilon, \theta_{\mathrm{cm}}) = \Phi(\varepsilon)\frac{1 + b\cos^2\theta_{\mathrm{cm}}}{1 + b/3}, \tag{6}$$

where $\Phi(\varepsilon)$ is the center-of-mass fission neutron spectrum from Madland and Nix (1982) and Vladuca and Tudora (2000) and b is the anisotropy parameter.

Taking into account the generalized form of the FF residual nuclear temperature distribution $P(T)$ from Eq. (5) and the possible anisotropy effect (Eq. (6)), the relation giving the PFNS in the laboratory system (LS) for an individual FF (indexed f) becomes the following:

$$N(E, E_{\mathrm{f}}, \sigma_{\mathrm{cf}}) = \frac{1}{2T_{\mathrm{m}}^2\sqrt{E_{\mathrm{f}}}} \int_{(\sqrt{E}-\sqrt{E_{\mathrm{f}}})^2}^{(\sqrt{E}+\sqrt{E_{\mathrm{f}}})^2} \sigma_{\mathrm{cf}}(\varepsilon)\sqrt{\varepsilon}\left(\frac{1}{1+b/3} + \frac{b(E-\varepsilon-E_{\mathrm{f}})^2}{4\varepsilon E_{\mathrm{f}}(1+b/3)}\right) I(\varepsilon)\,\mathrm{d}\varepsilon$$

with

$$I(\varepsilon) = \begin{cases} \frac{1}{4s}\int_0^a k_{\mathrm{f}}(T)(s+1)^2 T\exp(-\varepsilon/T)\,\mathrm{d}T, \\ \frac{s+1}{2(s-1)}\int_a^{sa} k_{\mathrm{f}}(T)\left(-\frac{s+1}{2s}T + T_{\mathrm{m}}\right)\exp(-\varepsilon/T)\,\mathrm{d}T, \end{cases} \quad a = \frac{2T_{\mathrm{m}}}{s+1}, \tag{7}$$

and

$$k_{\mathrm{f}}(T) = \left[\int_0^\infty \sigma_{\mathrm{cf}}(\varepsilon)\varepsilon\exp(-\varepsilon/T)\,\mathrm{d}\varepsilon\right]^{-1},$$

where E is the prompt fission neutron energy in the LS and the quantity E_{f} is the average FF kinetic energy per nucleon. Obviously, if in Eq. (7) the anisotropy parameter b is taken zero and the parameter $s = 1$ the individual FF PFNS formula as given in Madland and Nix (1982) and Vladuca and Tudora (2000) is re-obtained.

The features and the relations describing the total PFNS calculation in the frame of the multi-modal approach, as a superposition of spectra associated with each fission mode, are the same as already given in Hambsch et al. (2002, 2003).

3. Multi-modal parameters entering the PFNS model

The data needed for the determination of the multi-modal parameters entering the PFNS model are the following:

(i) The experimental data concerning the FF mass distribution $Y(A)$ and the total FF kinetic energy versus the FF mass, TKE(A), both measured at IRMM (Hambsch et al., 1997).

(ii) The multi-modal data (Brosa et al., 1990; Hambsch et al., 2005) calculated at IRMM for the five fission modes involved in the spontaneous fission of ^{252}Cf, the four asymmetric modes S1, S2, SX and S3 and the SL symmetric mode, concerning the following quantities (the fission mode being indexed "m"):

- the average FF mass of each mode $\langle A\rangle_m$,
- the standard deviation of the FF mass distribution of each mode σ_{Am},
- the average total kinetic energies, $\langle \mathrm{TKE}\rangle_m$
- the multi-modal branching ratios w_m.

These multi-modal parameters were obtained by fitting the two-dimensional experimental distribution, $Y(A, \mathrm{TKE}) = \sum_m w_m Y_m(A, \mathrm{TKE})$, and are given in Table 1.

Table 1
The set of multi-modal data used for the calculation of the parameters entering the PFNS model

Modes	$\langle A_{H}\rangle$	σ_{AH}	$\langle$TKE$\rangle$ (MeV)	W (%)
S1	135.557	3.184	194.544	12.6676
S2	143.031	4.445	186.747	46.9569
SX	146.887	7.206	176.951	36.2905
S3	157.494	5.346	157.914	0.9284
SL	126	14	184.802	3.1566

As an example Fig. 3 shows the quality of the superposition of the modes compared to the experimental data (Hambsch et al., 1997) for the total FF mass yield $Y(A)$ (upper part) and the total FF kinetic energy TKE(A) (lower

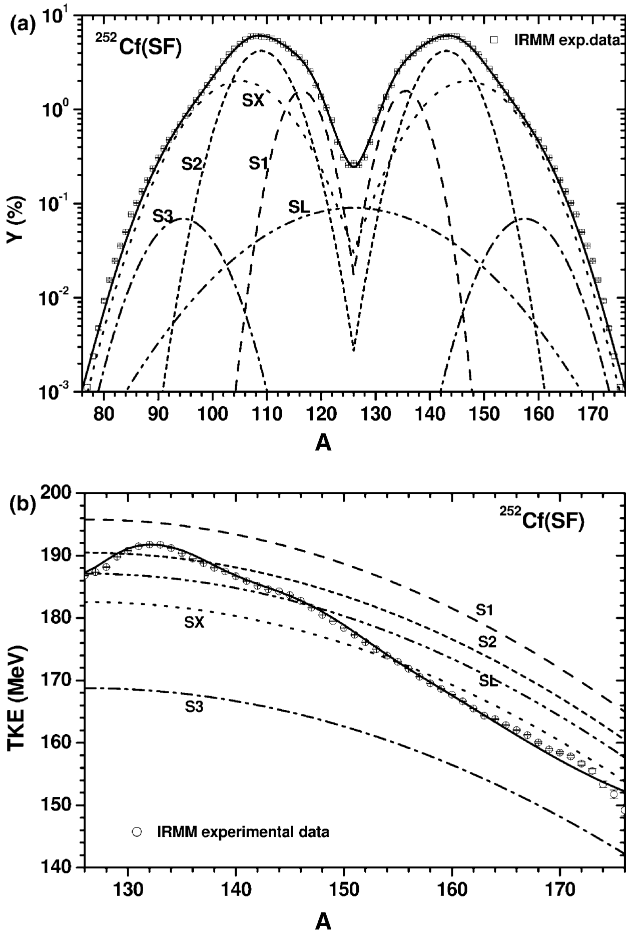

Fig. 3. The comparison with the IRMM experimental data (a) of the total FF mass distribution (obtained as a superposition of fission mode mass yields) and (b) of the TKE versus FF mass. In both cases the fission mode contributions are given with broken lines.

Table 2
Multi-modal input parameters for the PFNS model

Modes	$\langle E_r \rangle$ (MeV)	$\langle C \rangle$ (MeV)	Fragmentation
S1	228.242	10.661	Rh-116, I-136
S2	218.358	8.602	Mo-109, Ba-143
SX	214.187	8.407	Nb-105, La-147
S3	203.784	8.464	Rb-95, Pm-157
SL	225.438	10.149	In-126, In-126

part) both calculated using the modal data of Table 1 and the following relations:

$$Y(A) = \sum_m Y_m(A), \quad Y_m(A) = \frac{w_m}{\sigma_{\mathrm{Am}}\sqrt{2\pi}} \exp\left(-\frac{(A - \langle A \rangle_m)^2}{2\sigma_{Am}^2}\right), \tag{8}$$

$$\begin{aligned} \mathrm{TKE}(A) &= \frac{1}{Y(A)} \sum_m Y_m(A)\mathrm{TKE}_m(A), \\ \mathrm{TKE}_m(A) &= \frac{A(A_0 - A)}{\langle A \rangle_m (A_0 - \langle A \rangle_m) - \sigma_{\mathrm{Am}}^2} \langle \mathrm{TKE} \rangle_m. \end{aligned} \tag{9}$$

The contribution of each fission mode is given by the thin solid and different broken lines.

The multi-modal parameters entering the PFNS model are determined using "the entire FF range procedure" [already described in detail in Hambsch et al. (2002, 2003)]. In the case of ^{252}Cf(SF) the entire experimental FF mass range (A_H from 126 up to 176 and A_L from 76 to 126) is taken into account, in total 51 mass pairs. For each FF mass pair two isobars per FF mass are considered with the values of the nuclear charge Z as the nearest integer values above and below the most probable charge, here Z_{UCD} (unchanged charge distribution) (Wagemans, 1991). Consequently, in the present calculations 102 FF pairs are used.

The obtained multi-modal parameters entering the PFNS model together with the most probable fragmentation of each fission mode are given in Table 2.

4. Results and discussions

The same computer codes (SCAT2 and MODPAR) as in Hambsch et al. (2002, 2003) were used to perform the calculation of the CN cross sections of the inverse process and, respectively, the multi-modal input model parameters.

The computer code SPECMOD was modified to allow the use of the generalized FF residual temperature distribution and to take into account the anisotropy effect (according to Eq. (7)). The corresponding input parameters are s (with the condition $s \geqslant 1$) and the anisotropy parameter b. Several physical scenarios have been considered:

(a) No anisotropy effect and using the "classical" expression of the FF residual nuclear temperature $P(T)$ from Madland and Nix (1982) ($b = 0$ and $s = 1$).
(b) Taking into account the anisotropy effect and the classical $P(T)$ ($b \neq 0$ and $s = 1$).
(c) Taking into account the anisotropy effect and the new expression of the FF residual temperature $P(T)$ ($b \neq 0$ and $s > 1$).
(d) No anisotropy and taking into account the new expression of $P(T)$ ($b = 0$ and $s > 1$).

Using the multi-modal input data from Tables 1 and 2, the PFNS of ^{252}Cf(SF) was calculated at first without anisotropy effect and using the classical expression of the FF residual temperature distribution from Madland and Nix (1982) (dashed line in Fig. 4). The overall agreement with Mannhart's evaluation and the experimental data from EXFOR (2004) is good and also the PFNS is rather close to the results of Madland and Nix (1982) and Madland et al. (1989). But the PFNS calculation underestimates Mannhart's evaluation in the low-energy part ($E \leqslant 0.3$ MeV), as can be seen in Fig. 4 where the PFNS is given as a ratio to the Maxwellian spectrum with $T_M = 1.42$ MeV.

As a conclusion one can state that the PFNS evaluations performed by models based on neutron evaporation from fully accelerated FF not taking into account anisotropy underestimate the "experimental" evaluation of Mannhart in the lower energy part (soft part) of the spectrum.

A number of papers in the last 15 years, Gerasimenko and Rubchenya (1987, 1989), Budtz-Jørgensen and Knitter (1989), Batenkov et al. (1989) and Kornilov et al. (2001a,b) have treated the inclusion of the anisotropy into the models build

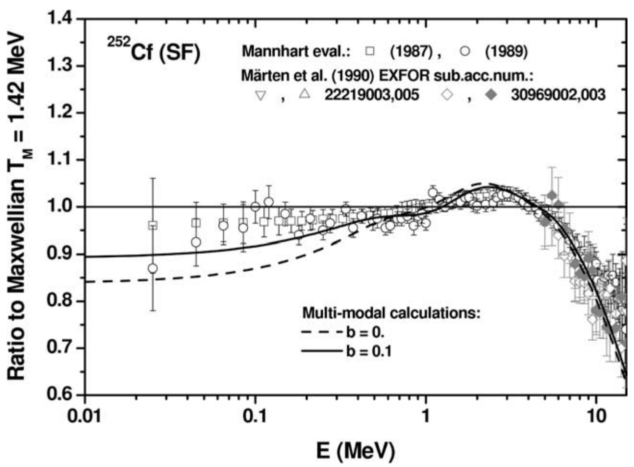

Fig. 4. PFNS calculation in the frame of the multi-modal fission model in comparison with the evaluation of Mannhart and the experimental data of Märten et al. (EXFOR, 2004) represented as a ratio to a Maxwellian spectrum with $T_M = 1.42$ MeV. The dashed lines represent the calculation without anisotropy and the solid line the calculation made with an anisotropy effect taken into account.

on the assumption that all prompt neutrons are emitted from the fully accelerated FF. For instance, statistical calculations done only for the few most important FF appearing in the spontaneous fission of ^{252}Cf (Gerasimenko and Rubchenya, 1989), using both the current phenomenological approximation of the anisotropy parameter $b = 0.1$ and b depending on the neutron energy in the CMS, show mainly an increase of the neutron yield in the region of low ($E \leqslant 0.5$ MeV) and high fission neutron energies in the LS. The same behavior of the LS spectrum, when the anisotropy is taken into account, is pointed out in Budtz-Jørgensen and Knitter (1989) and Batenkov et al. (1989) from where also possible values for the anisotropy parameter can be extracted, for instance $b = 0.05$ (Budtz-Jørgensen and Knitter, 1989), $b = 0.06$ (Batenkov et al., 1989). Consequently, the PFNS of ^{252}Cf was calculated using the following values of the anisotropy parameter: $b = 0.05$, $b = 0.06$ and the recommended phenomenological value from Gerasimenko and Rubchenya (1989), $b = 0.1$. The best agreement with Mannhart's data, based on χ^2 calculations, is obtained for the case $b = 0.1$.

The result is given in Fig. 4 by the solid line. It is evident from this figure that the inclusion of the anisotropy leads to an better agreement of the present calculation with Mannhart‘s evaluation especially in the soft part of the spectrum. The behavior of the present calculated spectra taking into account the anisotropy effect is the same with those said in the above references. That means an increase of the LS neutron spectrum especially in the low-energy region (soft part of the spectrum) and a moderate increase at high fission neutron energies (hard part of the spectrum).

Up to now we can conclude that the inclusion of the anisotropy effect in the LA model (with the classical $P(T)$ distribution with sharp cutoff as of Eq. (1)) used in the frame of the multi-modal fission approach leads to an improved agreement of the calculated spectra with the Mannhart standard spectrum particularly in the soft part of the spectrum.

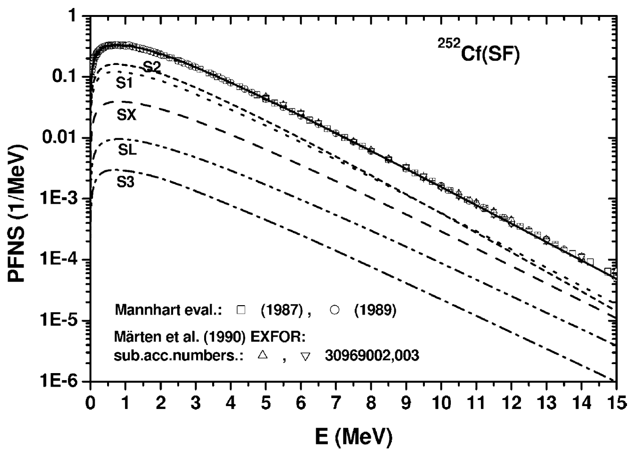

Fig. 5. The total PFNS (solid line) calculated in the frame of the multi-modal model taking into account the anisotropy effect and the new $P(T)$ expression in comparison with Mannhart's evaluation and the Märten et al. (EXFOR, 2004) data. The fission mode contributions are given with different broken lines.

When the new FF residual nuclear temperature distribution is introduced, a better agreement with Mannhart's data, in the hard part of the spectrum (high energy) is obtained. Taking as anisotropy parameter $b = 0.1$, the best result (χ^2 calculation) is obtained in case of $s = 1.3$. The corresponding multi-modal total PFNS is shown in Fig. 5 together with the contribution of each fission mode.

An even better agreement with the evaluation of Mannhart in the low-energy part of the spectrum can be obtained if the value of the anisotropy parameter is increased above the phenomenological value $b = 0.1$ (Gerasimenko and Rubchenya, 1989).

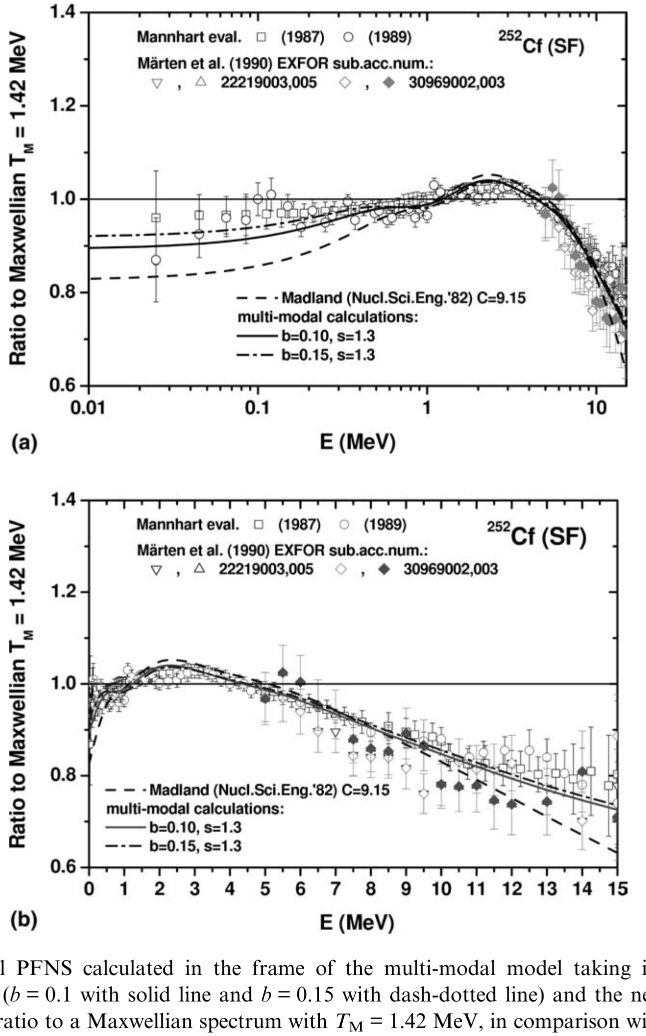

Fig. 6. The total PFNS calculated in the frame of the multi-modal model taking into account the anisotropy effect ($b = 0.1$ with solid line and $b = 0.15$ with dash-dotted line) and the new $P(T)$ ($s = 1.3$) represented as a ratio to a Maxwellian spectrum with $T_M = 1.42$ MeV, in comparison with the Mannhart point-wise evaluation, the Märten et al. (EXFOR, 2004) experimental data and Madland's single-mode calculation (Madland and Nix, 1982) (dashed line). In the upper part the low fission neutron energy region is focused, in the lower part the attention is drawn to the high-energy part of the spectrum.

In Fig. 6 the multi-modal calculation, with both the anisotropy and the new $P(T)$ distribution taken into account, is given as a ratio to a Maxwellian spectrum with $T_M = 1.42$ MeV. An increased agreement is obvious. In the upper part of Fig. 6, which focuses on the low-energy part of the spectrum, it can be seen that the best result is obtained for an anisotropy parameter $b = 0.15$ (dash-dotted line). In the bottom part of Fig. 6, where the focus is on the high-energy part of the spectrum, the contribution of the new $P(T)$ distribution ($s = 1.3$) leads again to an increased agreement with the evaluation of Mannhart (see both the solid and dash-dotted lines). As a comparison also the calculation of the spectrum ratio of Madland and Nix (1982) is given as a dashed line.

5. Conclusions

- For the first time the multi-modality of fission based on experimental input data (Hambsch et al., 1997) is applied to the PFNS evaluation of ^{252}Cf(SF). For this fissioning nucleus five fission modes are taken into account, four asymmetric modes (S1, S2, SX and S3) and one symmetric mode (SL). The parameters entering the spectrum model have been determined according to Hambsch et al. (2002, 2003).
- The LA model was extended to take into account the anisotropy effect and a new expression for the FF residual nuclear temperature distribution was proposed.
- The PFNS evaluation of ^{252}Cf(SF) is obtained in better agreement with the standard point-wise evaluation of Mannhart and new experimental data (not included in the Mannhart evaluation) than the previous evaluations based on models.
- The use of the LA model including the anisotropy effect and the new expression of the FF residual nuclear temperature distribution to calculate the prompt neutron spectra as a superposition of the fission mode contributions (based on experimental data and multi-modal parameters entering in a new procedure for the determination of the input parameters of the LA model) turns out to be a powerful tool for PFNS evaluations.

Acknowledgements

Two of us (A.T. and G.V.) thank the EC-JRC-IRMM for the hospitality during their stay and the European Commission for supporting this work with a grant.

References

Batenkov, C.I., Blinov, A.B., Blinov, M.V., Smirnov, S.N., Khlopin, V.G., 1989. Theory of prompt fission neutron emission, IAEA-INDC(NDS)-220, pp. 207–219.

Blinov, M.V., Boykov, G.S., Vitenko, V.A., 1983. In: Böckhoff, K.H. (Ed.), Nuclear Data for Science and Technology. Reidel, Dordrecht, p. 479.

Blinov, M.V., Boykov, G. S., Vitenko, V.A., 1985. IAEA-INDC(CCP)-238/L.
Boldeman, J.W., Clancy, B.E., Culley, D., 1986. Nucl. Sci. Eng. 93, 181.
Böttger, R., Klein, H., Chalupka, A., Strohmaiter, B., 1983. In: Böckhoff, K.H. (Ed.), Nuclear Data for Science and Technology. Reidel, Dordrecht, p. 484.
Böttger, R., Klein, H., Chalupka, A., Strohmaiter B., 1987. Properties of neutron sources, IAEA-TECDOC-410, p. 186.
Brosa, U., Grossmann, S., Müller, A., 1990. Phys. Rep. 197, 167.
Budtz-Jørgensen, C., Knitter, H.-H., 1989. Theory of prompt fission neutron emission, IAEA-INDC(NDS)-220, p. 181.
Ericson, T., Strutinski, V., 1958. Nucl. Phys. 8, 284.
EXFOR, 2004. Nuclear data library, Cf-252 nucleus, (0,f) reaction, DE quantity, (Märten, H., Richter, D., Seeliger, D., Fromm, W.D., Boettiger, R., Klein, H., J.NSE, 106, 353, 1990).
Gerasimenko, B.F., Rubchenya, V.A., 1987. In: Proceedings of the IAEA Advisory group meeting on proprieties of neutron sources, IAEA-TECDODC 410, pp. 108–112.
Gerasimenko, B.F., Rubchenya, V.A., 1989. Theory of prompt fission neutron emission, IAEA-INDC(NDS)-220, pp. 283–298.
Hambsch, F.-J., Oberstedt, S., Vladuca, G., Tudora, A., 2002. Nucl. Phys. A 709, 85.
Hambsch, F.-J., Oberstedt, S., Vladuca, G., Tudora, A., Ruskov, I., 2003. Nucl. Phys. A 726, 248.
Hambsch, F.-J., Oberstedt, S., Vivés, F., van Aarle, J., Bax, H., Barreau, G., 1997. In: Proceedings of the International Conference on Fission and Proprieties of Neutron-rich Nuclei, Sanibel Island, Florida, USA. World Scientific, Singapore, p. 86.
Hambsch, F.-J., et al., 2005, to be published.
Kapoor, S.S., Ramanna, R., Rama Rao, P.N., 1963. Phys. Rev. 131, 283.
Kornilov, N.V., Kagalenko, A.B., Hambsch, F.-J., 1999. Phys. Atom. Nucl. 62, 173.
Kornilov, N.V., Kagalenko, A.B., Poupko, S.V., Androsenko, P.A., Hambsch, F.-J., 2001a. Nucl. Phys. A 686, 187.
Kornilov, N.V., Kagalenko, A.B., Hambsch, F.-J., 2001b. Phys. Atom. Nucl. 64, 1373–1385.
Lajtay, A., Dyachenlo, P.P., Kutzaeva, S., Konov, V.N., Androsenko, P.A., Androsenko, A.A., 1983. IAEA-INDC(NDS)-146/L, p. 177.
Madland, D.G., Nix, J.R., 1982. Nucl. Sci. Eng. 81, 213–271.
Madland, D.G., LaBauve, R.J., Nix, J.R., 1989. Theory of prompt fission neutron emission, IAEA-INDC(NDS)-220, p. 259.
Mannhart, W., 1985. Nuclear standard reference data, IAEA-TECDOC-335, p. 294.
Mannhart, W., 1987. Proprieties of neutron sources, IAEA-TECDOC-410, p. 158.
Mannhart, W., 1989. Theory of prompt fission neutron emission, IAEA-INDC(NDS)-220, pp. 305–336.
Märten, H., Seeliger, D., Stobinski, B., 1983a. In: Böckhoff, K.H. (Ed.), Nuclear Data for Science and Technology. Reidel, Dordrecht, p. 488.
Märten, H., Neumann, D., Seeliger, D., 1983b. In: Proceedings of the IAEA consultants' meeting on the U-235 fast neutron fission cross sections and the Cf-252 fission neutron spectrum, IAEA-INDC(NDS)-146, p. 195.
Märten, H., Seeliger, D., Stobinski, B., 1984, IAEA-INDC(GDR)-28/L.
Märten, H., Ruben, A., Seeliger, D., 1989a. Theory of prompt fission neutron emission, IAEA-INDC(NDS)-220, pp. 245–258.
Märten, H., Ruben, A., Seeliger, D., 1989b. Theory of prompt fission neutron emission, IAEA-INDC(NDS)-220, pp. 47–57.
Oberstedt, S., Hambsch, F.-J., Vivés, F., 1998. Nucl. Phys. A 664, 289.
Poenitz, W.P., Tamura, T., 1983a. In: Böckhoff, K.H. (Ed.), Nuclear Data for Science and Technology. Reidel, Dordrecht, p. 465.
Poenitz, W.P., Tamura, T., 1983b. IAEA-INDC(NDS)-146/L, p. 175.
Schillebeeckx, P., Wagemans, C., Deruytter, A.J., Barthelemy, R., 1992. Nucl. Phys. A 545, 623.
Siegler, P., Hambsch, F.-J., Oberstedt, S., Theobald, J.P., 1995. Nucl. Phys. A 594, 45.
Terrell, J., 1959. Phys. Rev. 113, 527–541.

Terrell, J., 1962. Phys. Rev. 127, 880.
Vladuca, G., Tudora, A., 2000. Comput. Phys. Commun. 125, 221.
Wagemans, C., 1991. In: The Nuclear Fission Process. CRC Press, Boca Raton, FL (Chapter 8.III).