

Study of the $(n,\gamma f)$ process on ^{239}Pu

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Abstract. In the neutron resonance range, fission cross section of ^{239}Pu can be seen as a sum of the immediate (n,f) and the two-step $(n,\gamma f)$ fission reactions. In that case, five channel widths should be considered for a proper evaluation, those are: two opened fission channels for $J^\pi = 0^+$, one opened fission channel for $J^\pi = 1^+$ and two J-dependent for the $(n,\gamma f)$ reaction. The sizeable contribution of the $(n,\gamma f)$ process should have an impact on the determination of the capture and fission widths involved in the Reich-Moore approximation of the R-matrix theory. The present work aims to investigate this impact by using the CONRAD code and the $\Gamma_{\gamma f}$ available from literature. Prompt neutron multiplicity (ν_p) has been also reproduced including the contributions of the $(n,\gamma f)$ process.

1 Introduction

When a low-energy neutron collides with a target nucleus there is a high probability to form a compound nucleus in a given excited state. This compound nucleus may decay in different manner as by neutron or γ -ray emission, or by fission. The probability of each of these reactions to occur is weighted through partial reaction cross sections: scattering, capture or fission in each case. In fission reactions, neutrons may be emitted in different time windows, depending on which they are called *prompt* and *delayed* neutrons. It may happen that one γ -ray is emitted before fission occurs, through a two-step fission reaction, contributing to the total fission cross section. In this case, the available excitation energy to the fission fragment is lower and less prompt neutrons are emitted, leading to an anticorrelation between prompt-neutron emission and γ -ray emitted before fission multiplicities.

The fission process can be described using a potential barrier expressed as a function of the compound nucleus deformation. When this potential barrier has a double-humped shape, it presents two wells populated by energy states through which fission may happen. Two-step fission reactions are related to dipole electric (E1) and magnetic (M1) transitions between states, occurring in the first well of the fission barrier [1].

Following the studies initiated by E. Fort [2], this work aims to provide a description of the prompt-neutron multiplicity for neutron-induced fission reactions on ^{239}Pu by analyzing together a set of experimental data, including in the calculations the partial cross sections of the different channels, and taking into account the immediate and the two-step fission reactions for the total fission cross section.

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2 Neutron-induced fission on ^{239}Pu

2.1 $^{239}\text{Pu}(n,f)$ cross section

The $^{239}\text{Pu}(n,f)$ cross section can be described by:

$$\sigma_f(E_n) = \sigma(E_n)_{(n,f)} + \sigma(E_n)_{(n,\gamma f)} \quad (1)$$

where the two-step fission cross section may be expressed as:

$$\sigma(E_n)_{(n,\gamma f)} = \sigma_\gamma(E_n) \cdot \frac{\Gamma_{\gamma f}}{\Gamma_\gamma} \quad (2)$$

The partial fission widths are required to perform the calculations in R-Matrix Theory. Three immediate fission channels have been considered in this work, two for $J^\pi = 0^+$ with partial fission widths $\Gamma_{1f}(0^+)$ and $\Gamma_{2f}(0^+)$ and one for $J^\pi = 1^+$, with partial fission width $\Gamma_f(1^+)$ [3]. Because of its fluctuating feature, only two γ -fission channels have been considered in the two-step fission process, with partial fission widths $\Gamma_{\gamma f}(0^+)$ and $\Gamma_{\gamma f}(1^+)$, and the second partial width for $J^\pi = 0^+$ has been considered negligible. Resonances 0^+ dominate for immediate fission, while resonances 1^+ dominate for two-step fission reactions.

2.2 Prompt neutron multiplicity (ν_p) experimental data

The experimental prompt neutron multiplicity datasets available in EXFOR, measured by Gwin [4, 5] and Fréhaut [6] (Figure 1), have been analyzed.

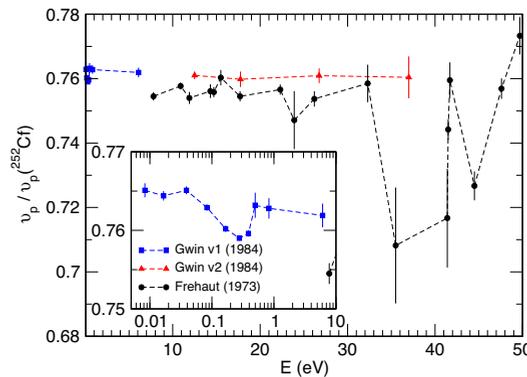


Figure 1. Prompt neutron multiplicity experimental data from Fréhaut [6] and Gwin [4, 5] up to 50 eV normalized to the ν_p of ^{252}Cf .

There are some issues concerning these data that had to be examined. There is an incongruity between the normalization of both datasets. In addition the experimental data provided in the EXFOR library by Fréhaut are given in a pointwise description. In order to treat these data using the CONRAD code, they have been averaged, specifying the edges of each energy interval, see Figure 2. Unfortunately this format is not a good description of the data, because the values given by the points are not centered in the energy interval.

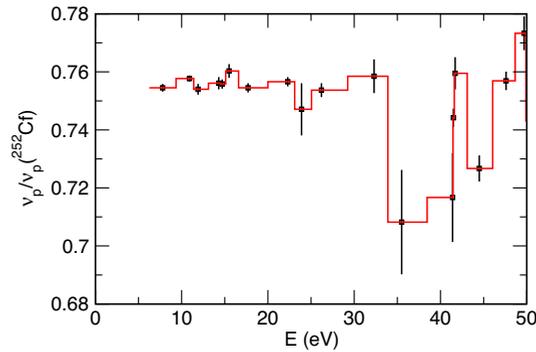


Figure 2. Comparison between the averaged and pointwise descriptions of the data from Fréhaut [6].

2.3 CONRAD resonance analysis of ^{239}Pu data

In the evaluated file of the fission cross section, the $J^\pi = 1^+$ resonances are considered as being produced only through immediate fission, however, they are also produced by two-step reactions, as previously mentioned. In order to make a more accurate evaluation including the $(n,\gamma f)$ channel for $J^\pi = 1^+$, a new resonance analysis has been done using the R-Matrix code CONRAD¹ (COde for Nuclear Reaction Analysis and Data Assimilation) [7]. Total and partial cross sections have been analyzed together with the neutron multiplicities. The values of the partial fission widths for immediate fission have been obtained from the JEFF-3.3 evaluated data library, and the partial fission widths for the two-step fission reactions have been taken from the work of Trochon et al. [8] and Lynn et al. [1], see Table 1. This parameter was calculated by Trochon et al., considering a single-humped fission barrier and taking into account only E1 transitions between states. A double-humped fission barrier was considered instead in the work from Lynn et al., taking into account a low-lying M1 resonance, known as the scissors mode, as well as E1 transitions between states. For a more detailed description of these calculations, consult the references [1, 8]. The averaged radiative width $\langle \Gamma_\gamma \rangle$ has been taken from Mughabghab [9], who gives a value of 43 ± 4 meV.

Table 1. Partial widths available in the literature for the two-step fission process.

Reference	$\Gamma_{\gamma f}(J^\pi=0^+)$ (meV)	$\Gamma_{\gamma f}(J^\pi=1^+)$ (meV)
[8]	7.3	4.2
[1]	1.5	2.29

The experimental data from Fréhaut have been introduced in the CONRAD code in both formats: the pointwise and the averaged, to fit the $\nu_{n\gamma f}$, ν_0 , ν_1 , and the normalization parameter of the experimental data from Fréhaut. Results of the fit to the prompt neutron multiplicity from Fréhaut using both $\Gamma_{\gamma f}$ parameters from [1, 8] are shown in Figure 3. In both cases the pointwise treatment of the data gives the best result. The use of $\Gamma_{\gamma f}$ from references [1, 8], does not change substantially the prompt neutron multiplicity, as this is compensated by fitting the $\langle \nu_{n\gamma f} \rangle$ parameter.

The averaged values obtained using both values of $\Gamma_{\gamma f}$ are given in Table 2, similar results are obtained for $\langle \nu_0 \rangle$, $\langle \nu_1 \rangle$ and the normalization of the data from Fréhaut, however the $\langle \nu_{n\gamma f} \rangle$ obtained in each case is slightly different.

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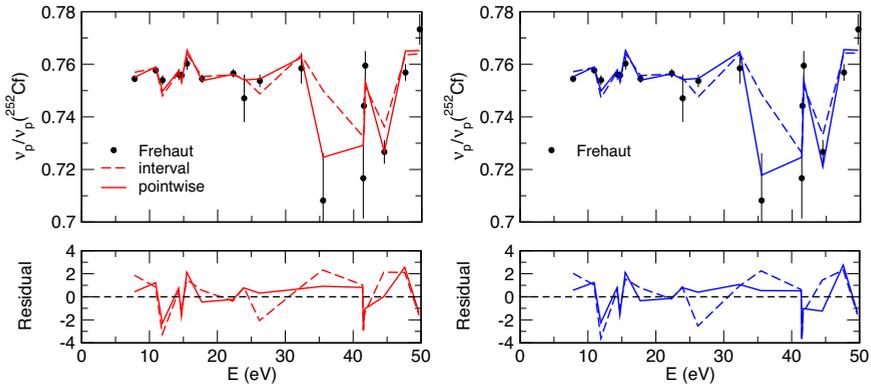


Figure 3. Comparison between the results obtained fitting the averaged and pointwise data from Fréhaut, using the $\Gamma_{\gamma f}$ from the works of Trochon et al. (left panel), and Lynn et al. (right panel).

Table 2. Output parameters obtained from the fit to the ν_p experimental data.

Parameter	Result with $\Gamma_{\gamma f}$ from [8]	Result with $\Gamma_{\gamma f}$ from [1]
$\langle v_{n\gamma f} \rangle$	2.60 ± 0.02	2.41 ± 0.03
$\langle v_0 \rangle$	2.897 ± 0.002	2.894 ± 0.002
$\langle v_1 \rangle$	2.874 ± 0.002	2.873 ± 0.002
$N_{Fréhaut}$	0.9963 ± 0.0007	0.9965 ± 0.0007

The results of the fit to the ν_p data from Gwin are shown in Figure 4. Large error bars are associated to the data in the eV energy region, detracting credibility from the data. Hence, new experimental data are required.

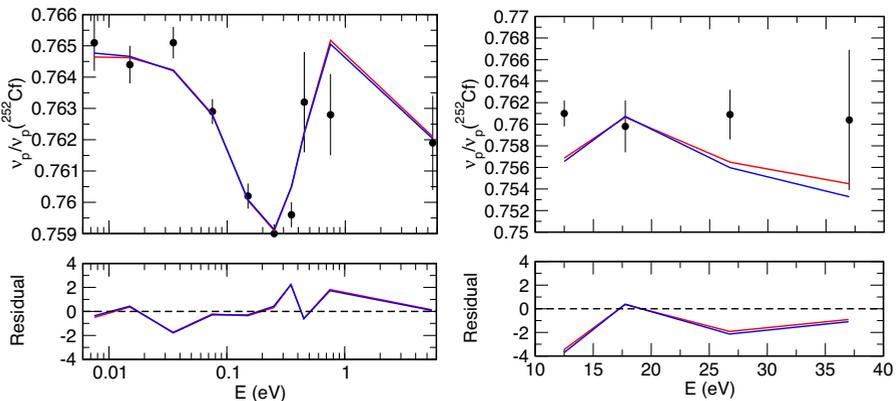


Figure 4. Comparison between the fits to the ν_p experimental data from Gwin using $\Gamma_{\gamma f}$ from Trochon et al. (red line) and Lynn et al. (blue line).

2.4 Results of ν_p up to 50 eV

The ν_p obtained in this work using both values for the $\Gamma_{\gamma f}$ parameter show that the spin contribution can reproduce the experimental data at low energies, below ~ 25 eV, above this energy and up to 50 eV, the dips of the ν_p are quite well reproduced by the $\nu_{n\gamma f}$ contribution, see Figure 5.

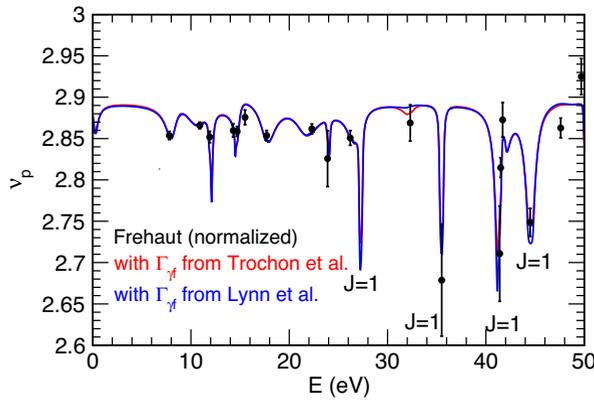


Figure 5. Comparison between the ν_p results obtained in this work and the normalized experimental data from Fréhaut up to 50 eV.

Both results are compared in Table 3 with the normalized data from Fréhaut up to 50 eV.

Table 3. Prompt neutron multiplicity obtained using both values for $\Gamma_{\gamma f}$ compared with the normalized data from Fréhaut up to 50 eV. The ratio from the experimental data to the results are given in parenthesis.

Energy (eV)	Fréhaut	Result with $\Gamma_{\gamma f}$ from [8]	Result with $\Gamma_{\gamma f}$ from [1]
7.8	2.854 ± 0.005	2.852 (1.001)	2.853 (1.000)
10.9	2.866 ± 0.004	2.867 (1.000)	2.867 (1.000)
11.9	2.852 ± 0.007	2.832 (1.007)	2.832 (1.007)
14.3	2.860 ± 0.008	2.862 (0.999)	2.862 (0.999)
14.7	2.859 ± 0.006	2.845 (1.005)	2.845 (1.005)
15.5	2.876 ± 0.009	2.892 (0.994)	2.891 (0.995)
17.7	2.854 ± 0.006	2.847 (1.002)	2.848 (1.002)
22.3	2.862 ± 0.006	2.857 (1.002)	2.857 (1.002)
23.9	2.83 ± 0.03	2.848 (0.994)	2.848 (0.994)
26.2	2.851 ± 0.009	2.850 (1.000)	2.850 (1.000)
32.3	2.87 ± 0.02	2.881 (0.996)	2.889 (0.993)
35.5	2.68 ± 0.07	2.736 (0.980)	2.711 (0.989)
41.4	2.71 ± 0.06	2.754 (0.984)	2.737 (0.990)
41.5	2.82 ± 0.01	2.777 (1.015)	2.768 (1.019)
41.7	2.88 ± 0.02	2.848 (1.011)	2.848 (1.011)
44.5	2.75 ± 0.02	2.744 (1.002)	2.723 (1.010)
47.6	2.87 ± 0.01	2.890 (0.993)	2.892 (0.992)
49.7	2.93 ± 0.02	2.891 (1.013)	2.891 (1.013)

2.5 Discussion above 50 eV

At higher energies, above 50 eV, the data from Fréhaut can not be described by the equations due to their large dispersion (1.2%), see Figure 6. New experimental data with lower statistical uncertainties are then requested in this energy region in order to correctly determine the ν_p .

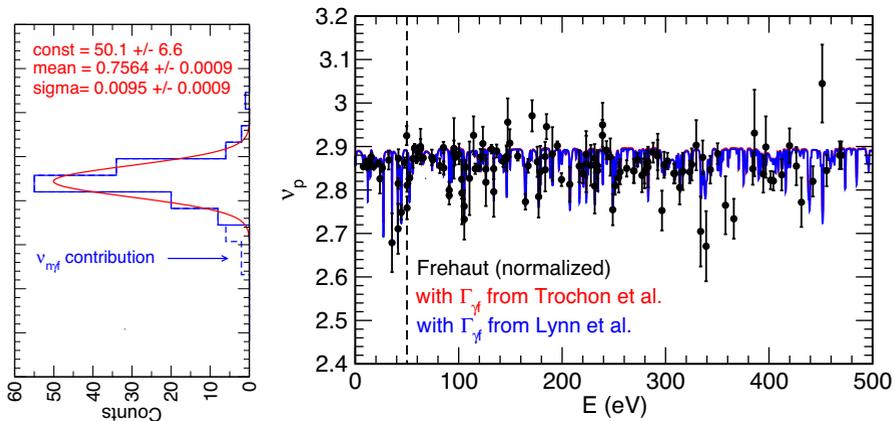


Figure 6. Comparison between the ν_p results obtained up to 500 eV using Γ_{γ_f} from Trochon et al. and Lynn et al., and the normalized data from Fréhaut (right panel). The ν_p histogram of the data from Fréhaut has been fitted to a gaussian distribution (left panel), showing a dispersion of the 1.2%.

3 Conclusions and perspectives

The prompt neutron multiplicity (ν_p) of the $^{239}\text{Pu}(n,f)$ reaction has been reevaluated taking into account both, the “immediate” and the “two-step” contributions to the total fission cross section. The multiple analysis of the total and partial cross sections, and the total and prompt neutron multiplicity has been performed using the CONRAD code developed at CEA/Cadarache. For the prompt neutron multiplicity, two sets of experimental data are provided in the EXFOR database at low energies (below 50 eV), it includes the data measured by Fréhaut and Gwin. Below 50 eV, both datasets are not normalized among themselves and, in addition large error bars are associated to the higher energy data from Gwin making them not reliable at such energies. Only the data from Fréhaut are provided above 50 eV, however the large dispersion (1.2%) does not allow to reproduce them. New experimental data need to be measured in order to perform a more accurate evaluation of the ν_p in a wide energy region.

The ν_p experimental data have been fitted in order to calculate $\nu_{n,f}$, ν_0 , ν_1 , and the normalization parameter of the measurement from Fréhaut. The values of the resonance parameters for the immediate reactions have been extracted from the JEFF-3.3 evaluation. Two values for the Γ_{γ_f} parameter have been tested, the ones from Trochon et al. and Lynn et al., both giving similar results, although a lower $\langle \nu_{n,f} \rangle$ has been obtained using the Γ_{γ_f} from [1]. The model that has been tested in this work will be officially released in CONRAD. The good results here obtained aim to apply the same model to analyze the $^{235}\text{U}(n,f)$ reaction, which will be the next step in this work line.

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