Chinese Physics C Vol. 38, No. 5 (2014) 054001

Calculation of prompt fission neutron spectrum for ^{233}U(n, f) reaction by the semi-empirical method *

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Abstract: The prompt fission neutron spectra for the neutron-induced fission of ^{233}U for low energy neutrons (below 6 MeV) are calculated using nuclear evaporation theory with a semi-empirical method, in which the partition of the total excitation energy between the fission fragments for the $n_{th}+^{233}$U fission reactions is determined by the available experimental and evaluation data. The calculated prompt fission neutron spectra agree well with the experimental data. The proportions of high-energy neutrons of prompt fission neutron spectrum versus incident neutron energies are investigated with the theoretical spectra, and the results are consistent with the systematics. The semi-empirical method could be a useful tool for the prompt evaluation of fission neutron spectra.

Key words: ^{233}U(n, f), fission fragment, excitation energy partition, prompt fission neutron spectrum

PACS: 25.85.Ec, 24.10.-i, 24.75.+i **DOI:** 10.1088/1674-1137/38/5/054001

1 Introduction

The prompt fission neutron spectra and the 'saw-tooth' data $\nu(A)$ of actinides are critically important nuclear data for nuclear engineering and technologies, in both energy and non-energy applications. This is especially true for the ^{233}U(n, f) reaction because as a new generation nuclear fuel [1] it is attracting growing attention. The properties of prompt neutrons are significant for the design of fusion-fission hybrid reactors, thus a new calculation of these quantities with higher accuracy is required. In addition, from a more fundamental point of view, studying the prompt fission neutron spectrum in detail can provide valuable information on the understanding of the neutron induced fission process.

The early representations of the prompt fission neutron spectrum for actinides, in which many physical effects were covered up, include the Maxwell and Watt spectrum representations, with one or two parameters that are adjusted to reproduce the experimental spectrum. The Los Alamos (LA) model [2] has been one of the most successful models for predicting the prompt fission neutron spectrum. The LA model assumes the same triangular-shaped initial nuclear temperature distribution for both light and heavy fragments and was originally developed for ^{235}U and ^{239}Pu. Based on the LA model, the multi-modal random neck-rupture model [3, 4] has been applied to some calculations of prompt neutron spectrum of several actinide nuclei isotopes by Ohsawa [5, 6], Hambach [7–9], Vladuca [10], and Zheng [11] et al. While most of these calculations are for ^{235,238}U(n, f) and ^{239}Pu(n, f) reactions, only the calculation of Ref. [11] is for the ^{233}U(n, f) reaction, the nuclear temperature is still assumed to have a simple triangular shape.

In this article we report the calculated results of the prompt fission neutron spectrum for a neutron induced ^{233}U fission reaction with a semi-empirical method that is very different from the LA model, including: the total excitation energy (E_{TXE}) partition between the two complementary fragments, the nuclear temperature of each fragment, and the weight of the prompt fission neutron spectra for the light and heavy fragments.

In this paper the information about the E_{TXE} partition between the two complementary fragments of $n_{th}+^{233}$U fission reaction is extracted from the available experimental and evaluation data, which is very important for the calculation of prompt fission neutron spectrum with the semi-empirical method. The nuclear temperature of each fragment can be calculated with the Fermi-Gas model for nuclear energy level density and the initial excitation energy of every fission fragment, in which the constant temperature model is taken into account. The spectrum in Center-of-Mass for each frag-

Received 17 June 2013
∗ Supported by National Natural Science Foundation of China (11205246, 91126010, 91226102)
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ment is calculated by the semi-empirical method, and is then transformed to the laboratory system. The calculated total spectra are synthesized by the chain yield and the prompt neutron number, they are then compared with the experimental data.

2 Methodology

2.1 $E_{\rm TXE}$ partition method

We have used the semi-empirical method to describe the prompt fission neutron spectrum and some other physical quantities of n+^{235}U fission reaction [12]. In this paper, this method has been applied to calculate both the prompt fission neutron spectrum and the prompt fission neutron number for n+^{233}U fission reaction.

In the semi-empirical method, the nuclear temperature of a fission fragment is calculated by the initial excitation energy of the fission fragment. But, how to get the initial excitation energy of each fission fragment from the available total excitation energy is one of the long-standing problems of the nuclear fission process. Consequently, it is important to know the partitioning of the total excitation energy ($E_{\rm TXE}$) between the two complementary fission fragments. In the present work, we extract the $E_{\rm TXE}$ partition information from the accumulated experimental and evaluated data for this reaction.

In the case of binary fission the initial excitation energy of each fragment is taken away by the prompt neutrons and the prompt γ rays, and can be obtained by relevant experimental data. For a pair of complementary fragments, if the initial excitation energy of each fragment is obtained, then the energy partition between the two complementary fragments can be deduced. For a fission fragment $A_{\rm L}$ or $A_{\rm H}$, its initial excitation energy can be expressed as:

$$E^*(A_{\rm L,H})=\bar{\nu}_{\rm exp}(A_{\rm L,H})\langle\eta\rangle(A_{\rm L,H})+\bar{E}_{{\rm exp},\gamma}(A_{\rm L,H}). \quad (1)$$

Where $\langle\eta\rangle$ is the average energy removed by an emitted neutron from fragment $A_{\rm L}$ or $A_{\rm H}$, which is composed of the average neutron kinetic energy $\varepsilon_{\rm exp}(i)$ and the neutron separation energy $S_{\rm n}(i)$ (i stands for $A_{\rm L}$ or $A_{\rm H}$). The sum of $E^*(A_{\rm L})$ and $E^*(A_{\rm H})$ is the total excitation energy $E_{\rm TXE}$. Using Eq. (1), the ratio $R(A_{\rm L,H})$ of $E^*(A_{\rm L,H})$ with respect to $E_{\rm TXE}$, which shows the $E_{\rm TXE}$ partition between the two fragments, can be expressed with the experimental data, as follows:

$$R(A_{\rm L,H}) = \frac{E^*(A_{\rm L,H})}{E_{\rm TXE}} = \frac{\bar{\nu}_{\rm exp}(A_{\rm L,H})\langle\eta\rangle(A_{\rm L,H})+\bar{E}_{{\rm exp},\gamma}(A_{\rm L,H})}{\sum\limits_{i=A_{\rm L},A_{\rm H}}[\bar{\nu}_{\rm exp}(i)\langle\eta\rangle(i)+\bar{E}_{{\rm exp},\gamma}(i)]}. \quad (2)$$

For the thermal neutron-induced fission reaction of ^{233}U, the relevant experimental data are taken from Ref. [13]. In this work, all of the quantities entering the calculation are replaced by the evaluated data $\bar{\nu}_{\rm eval}(A)$, $\varepsilon_{\rm eval}(A)$ and $\bar{E}_{{\rm eval},\gamma}(A)$, respectively. These values are obtained by fitting the experimental data, or by interpolation and extrapolation when no experimental data are available.

Based on the evaluated data, the energy partition between two complementary fragments of n$_{\rm th}$+^{233}U fission reaction is calculated according to Eq. (2). The results are shown in Fig. 1 by the short dotted line, the solid line is the smoothed results. This result is very similar to the case of an n+^{235}U fission reaction, and a deep valley appears around $A\sim130$. The minimum close to $A\sim130$ is due to the shell closures $N=82$, $Z=50$ that lead to spherical fission fragments.

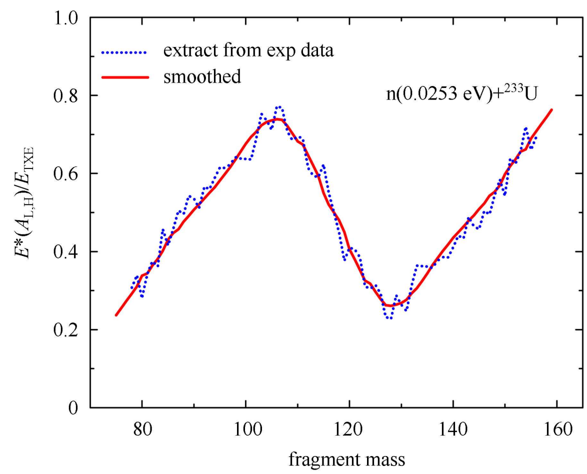

Fig. 1. (color online)The energy partition between two fragments in the thermal neutron induced ^{233}U fission reaction.

At the moment, except for thermal neutrons, there are not enough experimental data available for other neutron energy induced ^{233}U fissions. Consequently, how to get the $E_{\rm TXE}$ partition for other incident neutron energy ($R_{E_{\rm n}}(A)$) is a critical problem. We have discussed this problem for an n+^{235}U fission reaction with a semi-empirical method, and some technical details concerning this method are given in Ref. [14]. In this paper, we adopt a similar method to get the $E_{\rm TXE}$ partition dependence of the incident neutron energies (below 6 MeV) for an n+^{233}U fission reaction. The systematic parameters of the fission fragment mass distribution of the n+^{233}U fission system are taken from Refs. [15, 16].

For a binary fission reaction, the total excitation energy $E_{\rm TXE}$ of a fission fragment pair is given as follows:

$$E_{\rm TXE}=E_{\rm r}^*(A_{\rm L}+A_{\rm H})+B_{\rm n}(A_{\rm c})+E_{\rm n}-E_{\rm TKE}(A_{\rm L}+A_{\rm H}), \quad (3)$$

where $E_{\rm r}^*(A_{\rm L}+A_{\rm H})$ is the energy released in the fission process, which is given by the difference between the compound nucleus and the FF masses; $B_{\rm n}(A_{\rm c})$ is the neutron binding energy of the fission compound nucleus;

$E_{\rm n}$ is the kinetic energy of the neutron inducing fission; and, $E_{\rm TKE}(A_{\rm L}+A_{\rm H})$ is the total kinetic energy of both light and heavy fragments. For the n+^{233}U fission reaction, the initial excitation energy of each fragment, $E^*(A)$, can be obtained by means of the energy partition $R_{E_{\rm n}}(A)$ and the total excitation energy $E_{\rm TXE}$:

$$E^*(A)=R_{E_{\rm n}}(A)\times E_{\rm TXE}. \quad (4)$$

2.2 Neutron evaporation

At higher nuclear excitation energies, within the Fermi gas model for nuclear energy level density, the initial fission fragment energy $E^*(A)$ is simply related to the nuclear temperature T, as follows:

$$T=\sqrt{\frac{E^*(A)-S_{\rm n}(A)}{a_{\rm A-1}}}, \quad (5)$$

where a_{A-1} and $S_{\rm n}$ are the level density parameter and the neutron separation energy, respectively. At lower excitation energies, we assumed a constant temperature regime for neutron evaporation. The probability for the fission fragment to emit a neutron at a given kinetic energy is obtained by the Weisskopf spectrum at this particular temperature [17]. Assuming a constant value of the cross section of inverse process of compound nucleus formation, the normalized prompt fission neutron spectrum $\phi(\varepsilon)$ in the center of mass system is

$$\phi(A,T,\varepsilon)=\frac{\varepsilon}{T^2}\exp(-\varepsilon/T)], \quad (6)$$

where ε is the center-of-mass neutron energy.

For a fragment with excitation energy $E^*(A)$, this could de-excite through emitting neutrons and γ rays. The excitation energy of a fragment will decrease after a neutron is emitted from the fragment, this will also decrease the nuclear temperature T. The prompt fission neutron spectra at different temperatures T_i were calculated by using Eq. (5) for each fragment. The total prompt fission neutron spectrum in the Center-of-Mass of every fragment is written as $\phi(A,\varepsilon)$ and can be obtained by summing all of them up with the corresponding weight $P_N''(i)$:

$$\phi(A,\varepsilon)=\sum_i\frac{\varepsilon}{T_i^2}\exp(-\varepsilon/T_i)\times P_N''(i). \quad (7)$$

$P_N''(i)$ is the number of the i-th neutron emitted from the fragment. For a given fragment A, the sum of $P_N''(i)(i=1,N)$ is equal to $\bar{\nu}(A)$. A detailed discussion of $P_N''(i)$ can be found in Ref. [12].

Given the center-of-mass neutron energy spectra of every fragment, the neutron energy spectra $\Phi(A,E)$ in the laboratory system can be obtained by assuming that neutrons are emitted isotropically in the center of mass frame of a fission fragment. The total prompt fission neutron spectra of all fragments can be expressed as:

$$N(E)=\sum_j Y(A_j)\bar{\nu}(A_j)\Phi(A_j,E), \quad (8)$$

where j stands for all of the fission fragments. $Y(A)$ is the chain yield, and $\bar{\nu}(A)$ is the average prompt fission neutron number as a function of the fission fragment mass number, which has also been calculated in this work.

3 Results and discussions

The experimental data of prompt fission neutron spectrum for n+^{233}U fission reaction are scarce, only thermal and 0.55 MeV neutron induced data are available. Fig. 2 shows the calculated prompt fission neutron spectra for two energies and compares them with the experimental data, as well as with the Maxwell spectra. Here, the mean laboratory neutron energy of the Maxwell spectrum is equal to that given by the calculated theoretical spectrum. In Fig. 2, the solid curves indicate the calculated results, the dashed lines show the Maxwell spectra, and the other symbols are the experimental data taken from the International Experimental Neutron Data Library EXFOR [18]. It is clear from Fig. 2 that the calculated spectra are in much better agreement with the experimental data than the Maxwell spectra. For the thermal case, the calculated spectra are in good agreement with the most experimental data over different energy ranges, except for the experimental data of B. I. Starostov (1985) above 5 MeV, but in fact their two sets of data are discrepant with each other. For the 0.55 MeV case, we note that the agreement between the present calculation and the experimental data is good, but the calculated spectrum appears to be somewhat harder from 6.0 MeV to 9.0 MeV. Moreover, we have calculated the data for the entire energy range (0–20 MeV) required in evaluations. Unfortunately, there are no experimental data above 12 MeV for these fission spectra, so it is not possible to determine whether or not the agreement is good at the tail region of the spectrum.

The good agreement between experiment and calculation in Fig. 2 shows that the method used in this work for ^{233}U(n, f) reaction is valid. Although for other energies below 6 MeV, no experimental data are available, the calculated prompt fission neutron spectra are also presented in Fig. 3. It is clear from this figure that with increasing incident neutron energy the spectra become generally harder in the tail region and softer in the low-energy region. The proportions of high-energy tail above 7 MeV as a function of incident neutron energies are shown in Fig. 4. The proportions of high-energy neutrons varies from 1.9% to 2.7%, with incident neutron energies from 0.0253 eV to 6 MeV. This tendency is reasonable because increasing the incident neutron energies increases the total excitation energy (E_{TXE}). It should be noted that the high-energy outgoing neutrons of prompt fission neutron spectrum attract more attention from various nuclear energy applications.

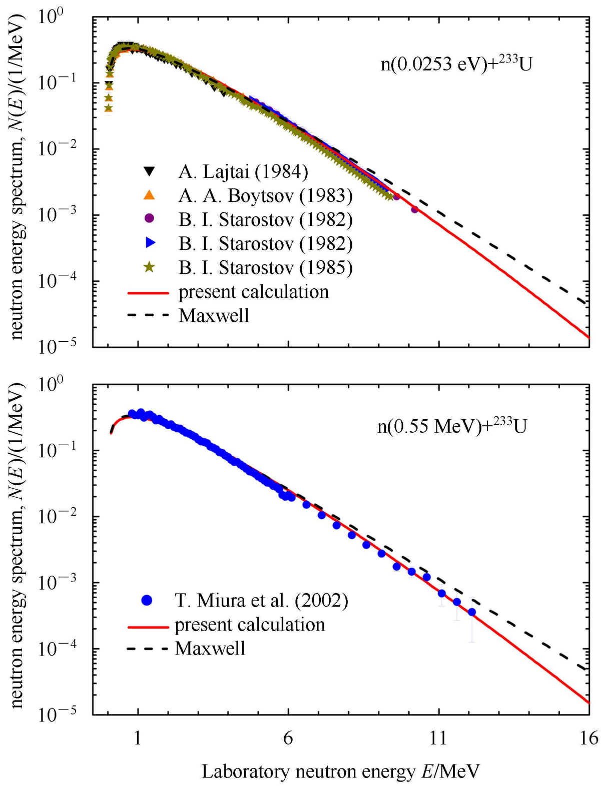

Fig. 2. (color online)The total prompt fission neutron spectra for thermal neutron and 0.55 MeV compared with the experimental data [18] and the Maxwell spectra for n+^{233}U fission reaction.

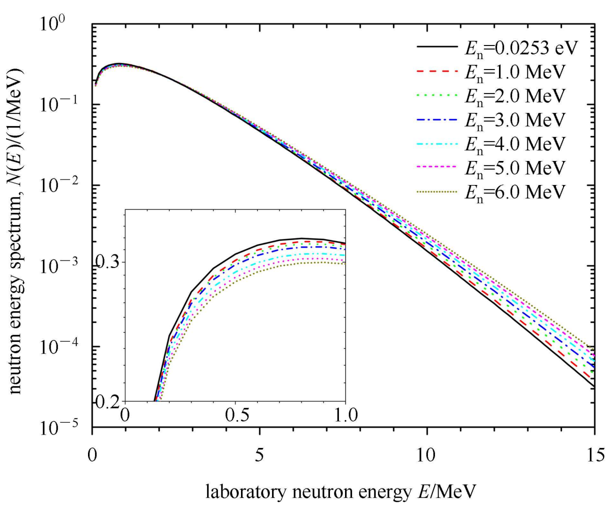

Fig. 3. (color online)The total prompt fission neutron spectra versus incident neutron energies.

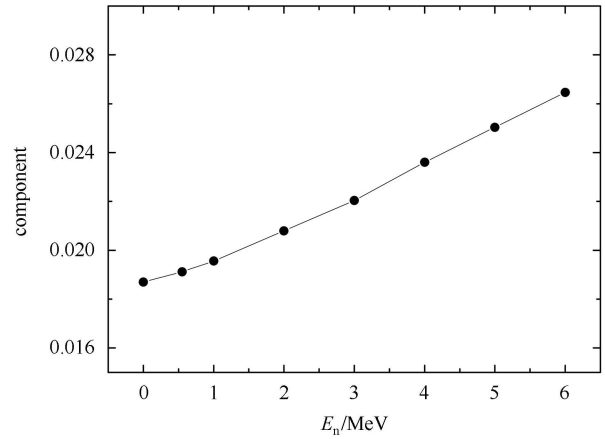

Fig. 4. The proportion of high-energy outgoing neutron as a function of incident neutron energies for ^{233}U(n,f) reaction.

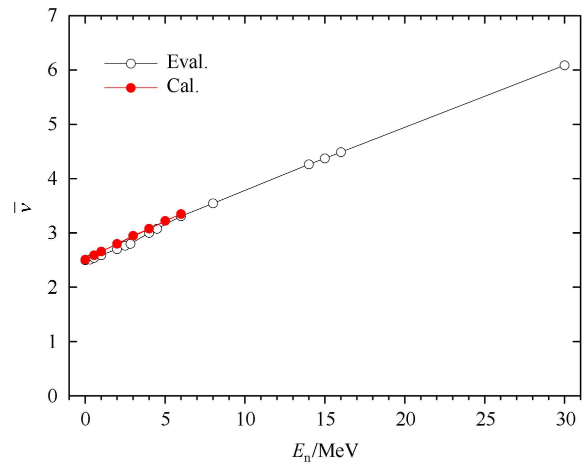

Fig. 5. (color online)The total prompt neutron number as a function of incident neutron energies.

The prompt fission neutron multiplicity for ^{233}U(n, f) reaction as a function of incident neutron energy was also calculated. Fig. 5 shows the calculated results (solid circle) and a comparison with the evaluated data (open circle) taken from the ENDF/B-Ⅶ library [19]. The calculated results agree well with the evaluated results at E_{n} below 6 MeV.

4 Summary

In this work, the information about the E_{TXE} partition of $\mathrm{n_{th}}$+^{233}U fission reaction was extracted from the available experimental and evaluation data, and a semi-empirical method was used to calculate the prompt fission neutron spectrum of neutron-induced ^{233}U fission reaction below 6 MeV. The results show that the semi-empirical method has described the prompt fission neutron spectra of neutron-induced ^{233}U and ^{235}U fission reactions very well. The good agreement between calculated and evaluated prompt fission neutron multiplicity also indicates that the semi-empirical method is reasonable and valid. This method may be a useful tool for evaluation of prompt fission neutron spectra, and can be applied on other actinide neutron induced fissions.

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