Prompt fission neutron spectra of n+^{235}U above the (n,nf) fission threshold*

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Abstract: Calculations of prompt fission neutron spectra (PFNS) from the ^{235}U(n, f) reaction were performed with a semi-empirical method for $E_{\rm n} = 7.0$ and 14.7 MeV neutron energies. The total PFNS were obtained as a superposition of (n,xnf) pre-fission neutron spectra and post-fission spectra of neutrons which were evaporated from fission fragments, and these two kinds of spectra were taken as an expression of the evaporation spectrum. The contributions of (n,xnf) fission neutron spectra on the calculated PFNS were discussed. The results show that emission of one or two neutrons in the (n,nf) or (n,2nf) reactions influences the PFNS shape, and the neutron spectra of the (n,xnf) fission-channel are soft compared with the neutron spectra of the (n,f) fission channel. In addition, analysis of the multiple-chance fission component showed that second-chance fission dominates the PFNS with an incident neutron energy of 14.7 MeV whereas first-chance fission dominates the 7 MeV case.

Key words: ^{235}U(n, f), neutron-induced fission, prompt fission neutron spectrum

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1 Introduction

^{235}U is the most important isotope for nuclear energy production. This explains the particular interest in measurement and evaluation of ^{235}U(n,f) neutron emission data. The prompt fission neutron spectra (PFNS) from ^{235}U(n,f) have been investigated in many experiments at different incident neutron energies from the thermal to the fast region. But above the emissive fission threshold ($E_{\rm n}$ >6 MeV), there are only two measurements by Boykov et al. at $E_{\rm n}$=14.7 MeV [1], and Frehaut et al. at $E_{\rm n}$=7.0 MeV [2], for which numerical data are available.

The PFNS for the ^{235}U(n,f) reaction have been investigated by several theoretical approaches [3–7], but most of them focus on the incident-neutron energy below the (n,nf) fission threshold, namely, below 6 MeV, which can be described by a relatively simple model calculation. For the calculation above the threshold, there are only the original Los Alamos model [3] calculation and Hauser-Feshbach statistical model calculation [6] at $E_{\rm n}$=7.0 MeV and 14.7 MeV, respectively.

Usually the so-called prompt fission neutrons come from three main sources: emission from the compound nucleus, emission from the fission fragment and scission neutrons. But most of the neutrons are emitted from the fragments after their full acceleration. Information about scission neutron emission is very scarce, and the most common code, GEF [8], and some Refs. [9–12] do not give indications for neutron emission at scission either. So, in the present work, scission neutrons were not taken into account.

Therefore, only neutrons evaporated from the fragment when the incident energy is below the (n,nf) threshold contribute to the total neutron spectrum. As incident energy is raised, one or more neutrons will be evaporated from a compound nucleus, and as these neutrons emitted prior to fission are nevertheless in coincidence with the fission event from the standpoint of any physical measurement, they must be accounted for in calculating the PFNS.

At $E_{\rm n} = 14.7$ MeV, the neutron-induced fission reaction of ^{235}U is a multiple-chance fission reaction, i.e., besides ^{236}U, fission of ^{235}U and ^{234}U nuclei contribute to the PFNS via ^{235}U(n,nf) and ^{235}U(n,2nf) reactions, respectively. Emission of one or two neutrons in (n,nf) or (n,2nf) reactions strongly influences the observed shape of the PFNS.

A semi-empirical calculation of PFNS had been perf-

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ormed for the ^{235}U(n,f) reaction [13] and ^{233}U(n,f) reaction [14] below the (n,nf) fission threshold. As a continuation of previous work and validation of the semi-empirical method, we performed the model calculation of PFNS for the ^{235}U(n,f) reaction at incident neutron energies above the emissive fission threshold and up to $E_{\rm n}=14.7$ MeV. The method and the calculated results are given in Section 2 and Section 3. A summary and conclusions can be found in Section 4.

2 Method

As mentioned above, when incident neutron energy is higher than the threshold of the (n,nf) emissive fission reaction and up to 14.7 MeV, one or more neutrons will be evaporated from the compound nuclei before fission. So, the PFNS $N(E)$ (E is the energy of the emitted neutron) are calculated as a superposition of (n, xnf) pre-fission neutron spectra $\phi_i(E)$ (i stands for the i-th neutron evaporated from the compound nucleus ^{236}U) and post-fission spectra $\Phi_j(E)$ (j denotes the j-th chance fission) of neutrons, evaporated from fission fragments, weighted with the partial fission cross section,

$$N(E) = \frac{\sigma_{\rm n,f}}{\sigma_{\rm F}}\Phi_1(E)+\frac{\sigma_{\rm n,nf}}{\sigma_{\rm F}}[\phi_1(E)+\Phi_2(E)] + \frac{\sigma_{\rm n,2nf}}{\sigma_{\rm F}}[\phi_1(E)+\phi_2(E)+\Phi_3(E)], \quad (1)$$

where $\sigma_{\rm F}$ is the total fission cross-section, and $\sigma_{\rm n,f}$, $\sigma_{\rm n,nf}$, $\sigma_{\rm n,2nf}$ are the fission cross sections of (n,f), (n,nf) and (n,2nf) fission channels, respectively. In this work, we use the evaluated partial fission cross sections to estimate the multiple-chance fission contributions to the total PFNS. The evaluated data are taken from ENDF/B-Ⅶ.1 [15].

The first term of Eq. (1) is the first-chance fission component, and $\Phi_1(E)$ is the spectrum of neutrons evaporated from fission fragments of ^{236}U. The second and third terms are the second-chance fission component: $\Phi_2(E)$ is the spectrum of neutrons evaporated from fission fragments of ^{235}U, and $\phi_1(E)$ is the spectrum of the first neutron evaporated from the compound nucleus ^{236}U. The fourth, fifth, and sixth terms are the third-chance fission component of the spectrum: $\Phi_3(E)$ is the spectrum of neutrons evaporated from fission fragments of ^{234}U, and $\phi_1(E)$, $\phi_2(E)$ denote the spectrum of the first neutron and the second neutron evaporated from the compound nucleus ^{236}U.

The spectra of neutrons evaporated from all fission fragments of each fission channel, $\Phi(E)$, can be obtained by the following expression,

$$\Phi(E)=\sum_j Y(A_j)\bar{\nu}(A_j)\Phi(A_j,E), \quad (2)$$

where j stands for all fission fragments in each fission channel. $Y(A)$ is the evaluated chain yield data, and was taken from ENDF/B-Ⅶ.1. [15]. $\bar{\nu}(A)$ is the average prompt fission neutron number of the fission fragments, which was calculated in the present calculation. Similar results can be found in our previous publications [16, 17]. $\Phi(A,E)$ is the neutron energy spectra of fission fragments in the laboratory system, which is obtained by transforming the neutron energy spectrum from the center-of-mass system [3].

$\Phi_1(E)$ and $\Phi_3(E)$ from Eq. (1), in relation to the neutron-induced ^{235}U and ^{233}U fission reactions have been investigated in our previous papers [13, 14]. The detailed calculation method has been described there, and therefore is not repeated here. In this work, $\Phi_2(E)$ is obtained in a similar way for the neutron-induced ^{234}U fission reaction. For different fission channels, however, the excitation energies are different. For example, when a 9 MeV neutron induces ^{235}U fission, the (n,f) and (n,nf) channels will open. For the (n,f) reaction, the incident neutron energy is $E_{\rm n}$=9 MeV, and the compound nucleus is ^{236}U at an excitation energy of 9+6.546=15.546 MeV. For the (n,nf) channel, ^{236}U emits a neutron (with energy ε=1.056 MeV) and becomes ^{235}U with the excitation energy E^*=15.546−1.056−6.546=7.944 MeV. This can be considered as a neutron with energy $E_{\rm n}'$ inducing ^{234}U fission, and forming the compound nucleus ^{235}U with excitation energy of 7.944 MeV. Therefore, we can determine that $E_{\rm n}'$=7.944−5.297=2.647 MeV. $\Phi_2(E)$ in Eq. (1) is just calculated from neutrons with energy $E_{\rm n}'$ inducing ^{234}U fission reactions.

For $\phi_1(E)$ and $\phi_2(E)$ in Eq. (1), the spectra of the first neutron and the second neutron evaporated from the compound nucleus ^{236}U, we neglect the distinction between center-of-mass and laboratory systems for the neutrons emitted prior to fission because an actinide nucleus is kinematically a good approximation to an infinite mass nucleus for the neutron energies considered here. In this work, $\phi_1(E)$ and $\phi_2(E)$ are calculated with the evaporation spectrum expression:

$$\phi(E)=\frac{E}{T^2}\exp(-E/T), \quad (3)$$

where E is the energy of the emitted neutron, and T is the nuclear temperature.

The temperatures of $\phi_1(E)$ and $\phi_2(E)$ are different, because the pre-fission (n, xnf) neutron emission lowers the excitation energy of the residual nuclei. For example, a neutron with energy $E_{\rm n}$(>6 MeV) induces ^{235}U reaction and forms the compound nucleus ^{236}U at excitation energy $E_{\rm n}+B_{\rm n}^{236}$, where $B_{\rm n}^{236}$ is the neutron binding energy in ^{236}U. ^{236}U emits the first neutron with energy ε_1, forming the residual nucleus ^{235}U at excitation energy $E_{\rm n}-\varepsilon_1$, and the nuclear temperature T_1 of the residual nucleus is determined by

$$T_1=\sqrt{\frac{E_n-\varepsilon_1}{a_{235}}}, \quad (4)$$

where a_{235} is the nuclear level density parameter of ^{235}U. When ^{236}U emits the second neutron with energy ε_2, the residual nucleus ^{234}U forms with excitation energy $E_n-\varepsilon_1-B_n^{235}-\varepsilon_2$, and the nuclear temperature T_2 of the residual nucleus ^{234}U is determined by

$$T_2=\sqrt{\frac{E_n-\varepsilon_1-B_n^{235}-\varepsilon_2}{a_{234}}}. \quad (5)$$

With the above Eqs. (1)–(5), we can perform the calculation of prompt fission neutron spectra for ^{235}U(n,f) reactions above the emission fission threshold.

3 Results and discussion

Up to now, only two sets of experimental data are available for the ^{235}U(n,f) prompt fission neutron spectrum above the emission fission threshold, i.e. $E_n=7.0$ MeV [2] and 14.7 MeV [1]. As an application of the semi-empirical method for PFNS above the ^{235}U(n,nf) fission threshold, we calculated the PFNS at these two energy points and compared it with the available experimental data. At E_n=7.0 MeV, the PFNS of the first-chance fission and the second-chance fission contribute to the total PFNS. At $E_n=14.7$ MeV, all three fission channels will contribute to the total PFNS.

Figure 1 shows the measured and calculated PFNS for ^{235}U(n,f) at an incident neutron energy of 7 MeV. The experimental data are normalized to the calculated data by integrating the values in the 0.5–6.5 MeV energy range. It is clear from Fig. 1 that the agreement between the calculation and the experiment is reasonable except in the region above 6.5 MeV. Regarding this region, experimentalists comment that all experimental data above 10 MeV have less credibility than the data below 10 MeV because of the increasingly complex experimental data corrections which must be applied above 10 MeV.

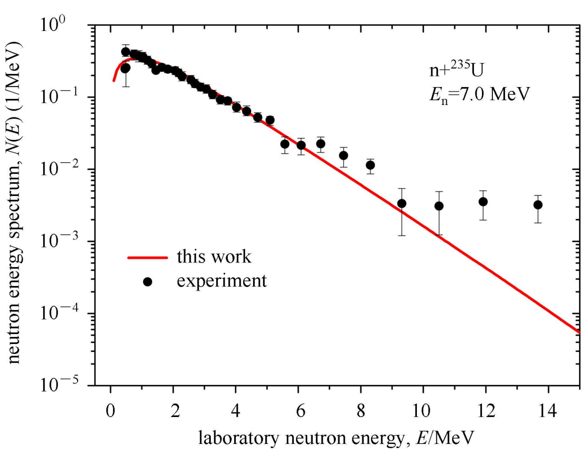

Fig. 1. Prompt fission neutron spectra in the laboratory system for the fission of ^{235}U induced by 7 MeV neutrons. The experimental data are taken from Refs. [2, 18, 19].

The contributions of different fission channels to the total spectrum are shown in Fig. 2. This figure shows that the first-chance contribution dominates the total spectrum. Only for outgoing neutron energy ⩽1.2 MeV does the second-chance fission component nearly equal that of the first-chance fission, and that is obviously due to the appreciable contribution of the pre-fission neutron. The second-chance fission component decreases more rapidly with higher energy than the first-chance fission component, and this effect is due in part to the influence of the neutron evaporation spectrum $\phi_1(E)$ on the second-chance fission component. These peculiarities, observed from the calculated PFNS, are very similar to those shown in Fig. 14 of the paper by Maslov [6].

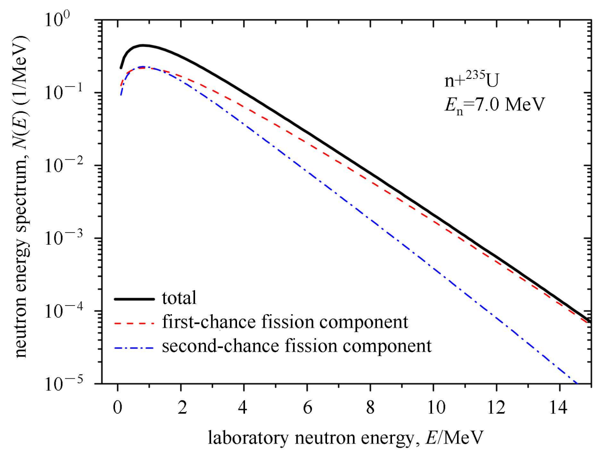

Fig. 2. Multiple-chance fission contributions to the prompt fission neutron spectrum for the fission ^{235}U induced by 7.0 MeV neutrons.

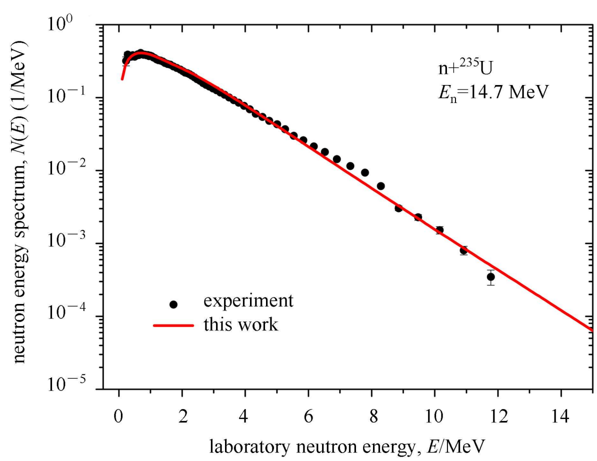

Fig. 3. Prompt fission neutron spectra in the laboratory system for the fission of ^{235}U induced by 14.7 MeV neutrons. The experimental data are taken from Ref. [1].

The calculations at $E_n = 14.7$ MeV incident neutron energy are shown in Fig. 3. In general, the calculation reproduces the PFNS experimental data very well. In the 6.5–8.0 MeV energy region, however, the calculated spectra appear to be somewhat soft.

The contribution of each fission channel to the total spectrum are shown in Fig. 4 together with their summation, the total multiple-chance fission spectrum. According to the partial and the total fission cross sections, the weights of the first-, second- and third-chances are 32%, 40% and 28%, respectively. The figure shows that the contribution from second-chance fission is higher than those from the first- and third-chance; only for outgoing energy above 9 MeV does the contribution of the first-chance fission become higher than that of the second-chance fission. This peculiarity is very similar to that shown in Fig. 40 of the paper by Madland and Nix [3] where the second-chance fission component dominates the total spectrum at $E_n = 14.0$ MeV, and is different from that shown in Fig. 12 of the paper by Maslov [6], where the first-chance fission contributes mostly to the PFNS at $E_n = 14.7$ MeV. Although the weight of the first-chance is close to that of the third-chance, the third-chance fission component is much softer than the first-chance fission component. This might be due to the presence of the two neutron evaporation spectra, $\phi_1(E)$ and $\phi_2(E)$, in the third-chance fission component. In addition, the peaks of the second- and third-chance fission components are at lower energies than the peaks of the first-fission component, which is also the hardest of the three component spectra in the tail region.

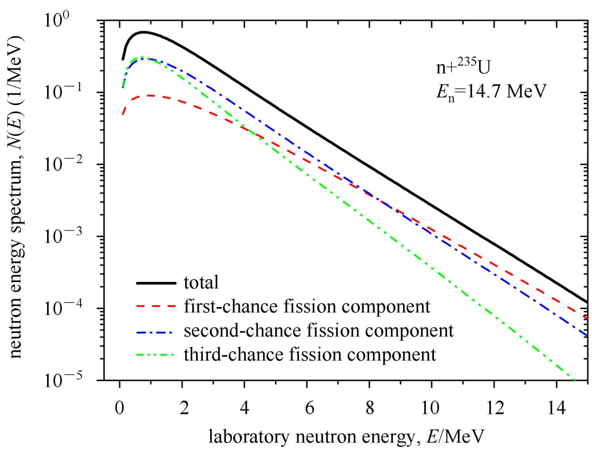

Fig. 4. Multiple-chance fission contributions to the prompt fission neutron spectrum for the fission ^{235}U induced by 14.7 MeV neutrons.

4 Summary

Multiple-chance fission calculations of the PFNS for the ^{235}U(n,F) reaction were performed. The calculated results reproduce the observed PFNS reasonably at E_n=7.0 MeV incident neutrons and very well at E_n= 14.0 MeV. Analysis of the multiple-chance fission component showed that emission of one or two neutrons in the (n,nf) or (n,2nf) reactions influences the prompt fission neutron spectra shape. Compared with the neutron spectra of the (n,f) fission channel, the neutron spectra of the (n,xnf) fission-channel are softer. Additionally, the calculated results also show that the effects of different fission channels on the total prompt fission neutron spectra are somewhat different at different incident neutron energies; for example, second-chance fission dominates the 14.7 MeV incident neutrons whereas first-chance fission dominates the 7 MeV case.

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