Calculations of All Kinds of Reactions for n + ^{241}Pu in E_n=0.01~20 MeV

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^{241}Pu are an important fissile nucleus for fast neutron reactor in ^{239}Pu–^{238}U recurrence, good evaluation values of its neutron reaction data are necessary. There are sufficient experimental data for σ_f, some experimental data below 0.03 MeV for $\sigma_{n,\gamma}$. There are no experimental data for other reaction cross sections, secondary neutron spectra and elastic scattering angular distributions. All experimental data are taken from EXFOR. Therefore, we have to do systematical theoretical calculations to get a complete neutron data set of ^{241}Pu.

Firstly, the code CAPFO[1] is used to automatically get the optimal parameters of spherical optical potential. There are no experimental data for total and nonelastic cross sections as well as elastic scattering angular distributions of ^{241}Pu. From the consideration of systematics, σ_{tot} of ^{241}Pu and ^{239}Pu should be almost the same. And the evaluation values of σ_f for ^{241}Pu in ENDF/B6 library are in very good agreement with the newest experimental data. So the σ_{tot} of ^{239}Pu and σ_{non} of ^{241}Pu in ENDF/B-6 library are used in automatically searching for the optimal set of spherical optical potential parameters. In this way, the final optimum set of spherical optical potential parameters for neutron channel is obtained:

V_0=46.408570, V_1=−0.471376, V_2=0.063832,
W_0=10.620060, W_1=0.178786,
U_0=0.016819, U_1=0.328978, U_2=−0.029545,
a_r=0.450434, a_s=0.620025, a_v=0.551695,
r_r=1.325580, r_s=1.137591, r_v=1.211296.

Secondarily, the coupled channel optical model code ECIS[2] is used to calculate the cross sections and angular distributions of 4 lower levels in direct inelastic scattering. The ground state and these 4 excited states in the rotational band are with excited energies 0.0, 0.0420, 0.0957, 0.1611 and 0.2350 MeV, spins 2.5, 3.5, 4.5, 5.5 and 6.5, parity +1. The coupled channel optical potential parameters[3] used in this work are: Real part potential: $51.32134-0.57E+0.02E^2-24(N-Z)/A$; Surface absorption imaginary part potential: $5.04567+0.4E+0.001E^2$; Volume absorption imaginary part potential: 0.0; Spin-orbital coupling potential: 6.0; Radial parameters are 1.256, 1.260 and 1.120 for real, imaginary and spin-orbital coupling, respectively; Diffusion parameters are 0.62, 0.58 and 0.50 for real, imaginary and spin-orbital coupling, respectively. The deformed parameters are β_2=0.22, β_4=0.07.

These direct inelastic scattering data obtained with the code ECIS and the optimum set of spherical optical potential parameters obtained with the code CAPFO are the input of the kernel calculation program FUNF[4]. Besides these two kinds of input data, for correct calculations of the complete neutron data set with FUNF, it is also necessary to find out the optimum fission parameters. With the code ADFP[5], which can automatically search for an optimum set of fission parameters for first, second and third plateau, respectively, we can obtain the optimum set of adjustable fission parameters to make σ_f and $\sigma_{n,\gamma}$ in optimum accordance with experimental data. The meaning of these fission parameters can be found in Reference [6].

The optimal fission parameters we got are: CK=6000.0, C_{E1}=1.9716, C_{in}=0.2255, C_{2n}=0.3450, DGMA=0.6; $a_{n,\gamma}$=26.4005, $\Delta_{n,\gamma}$=1.6462, $a_{n,n'}$=27.4575, $\Delta_{n,n'}$=0.1584, $\Delta_{n,f}$=0.1837, $V_f(1)$=6.1324, $\hbar\omega(1)$=0.9870, $ck_f(1)$=5.7988 for $\sigma_{n,f}$ in the first plateau; $a_{n,2n}$=26.2308, $\Delta_{n,2n}$=0.7471, $\Delta_{n,n'f}$=0.0654, V_f (2)=5.8944, $\hbar\omega(2)$=1.1348, ck_f (2)=4.4019 for $\sigma_{n,nf}$ in the second plateau; $a_{n,3n}$=26.9673, $\Delta_{n,2n}$=−0.7801, $\Delta_{n,2nf}$=0.0331, V_f (3)=5.5369, $\hbar\omega(3)$=0.7920, ck_f (3)=3.0882 for $\sigma_{n,2nf}$ in the third plateau.

The calculated σ_{tot}, σ_{el} and those from ENDF/B-6 library for ^{241}Pu as well as experimental σ_{tot} of ^{239}Pu are given in Fig. 1, respectively, from which we can see that both the calculated σ_{tot} and those in ENDF/B-6 are in good accordance with the experimental σ_{tot} of ^{239}Pu, as they should be.

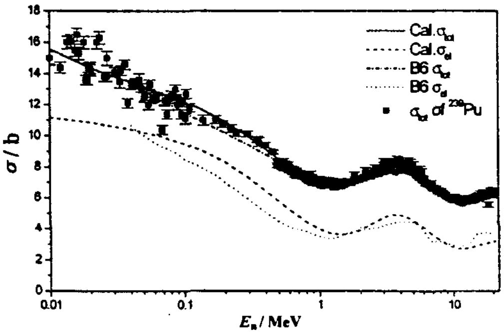

Fig. 1 Total and elastic cross sections of ^{241}Pu

For the calculated values, ENDF/B-6 and experimental data of σ_f are given in Fig. 2(a) and Fig. 2(b). Our calculated σ_f are in good agreement with the experimental data except a little worse in 0.24~0.4 MeV and 1.6~5.0 MeV energy region. The calculated and experimental $\sigma_{n,\gamma}$ are given in Fig. 3, from which we can think both our calculated values and those of ENDF/B-6 are in good agreement with the experimental data, and in higher energy region our calculated $\sigma_{n,\gamma}$ are more reasonable than those of ENDF/B-6 both in shape and in value. The total (MT=4) and the continuous (MT=91) inelastic cross sections are given in Fig. 4 (a) and Fig. 4(b), respectively, from which we can see that our calculated values are more reasonable than those of ENDF/B-6 in shape. Two calculated discrete level inelastic cross sections (MT=51,52) included direct action component are given in Fig. 5, from which we can see that the MT=51,52 cross sections of ENDF/B-6 does not include direct action component, and we can not understand why those of MT=51,52 suddenly drop to zero at 3 MeV. $\sigma_{n,2n}$ and $\sigma_{n,3n}$ are given in Fig. 6(a) and Fig. 6(b), respectively, from which we can see that our calculated $\sigma_{n,2n}$ are better than those of ENDF/B-6 in shape, and for $\sigma_{n,3n}$, ENDF/B-6 are not reasonable in shape, our calculated values are also a little better than JENDL-3 in shape. All kinds of calculated cross sections of ^{241}Pu are given in Fig. 7, in which those with charged outgoing particles, are directly calculated with the universal parameters. The calculated secondary neutron spectra of continuous inelastic (MT=91), (n,2n) reaction (MT=16) and fission (MT=18) at E_n=8 and 14 MeV are given in Fig. 8(a), Fig. 8(b) and Fig. 8(c), respectively, from which we can see that our calculated values are physically reasonable.

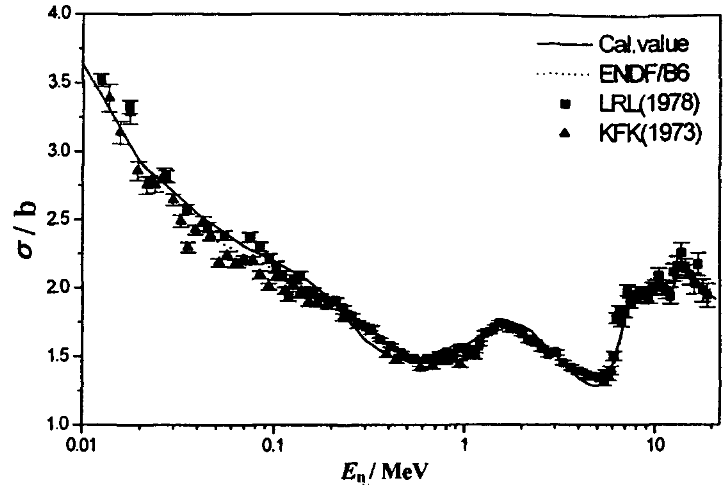

Fig. 2(a) Fisson cross sections of ^{241}Pu

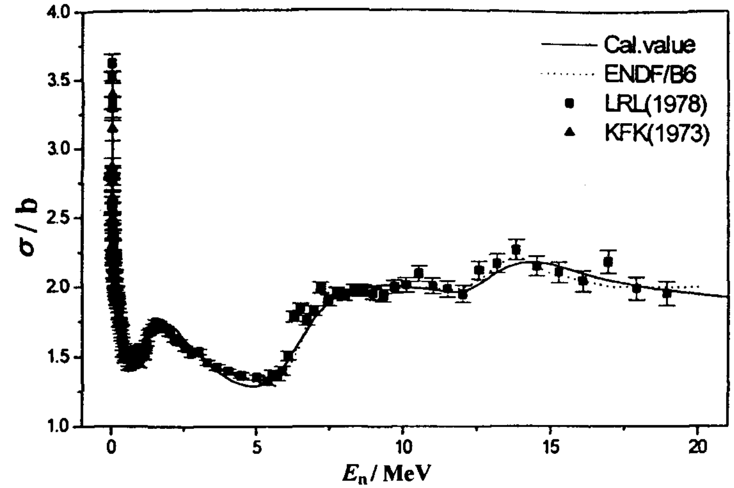

Fig. 2(b) Fisson cross sections of ^{241}Pu

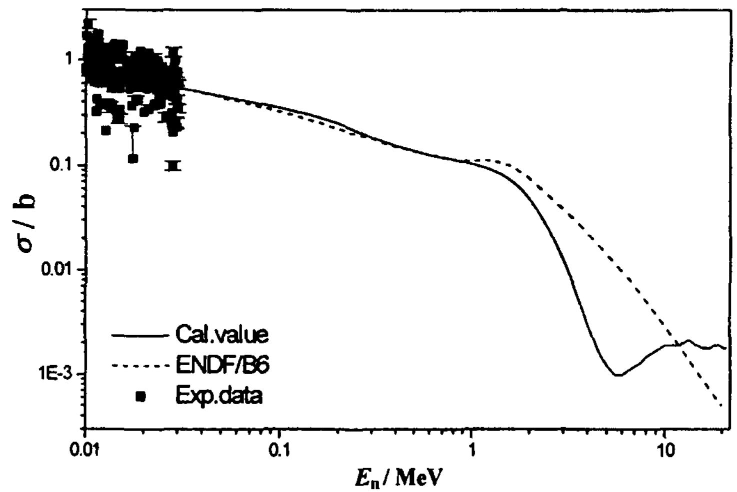

Fig. 3 Radiative capture cross sections of ^{241}Pu

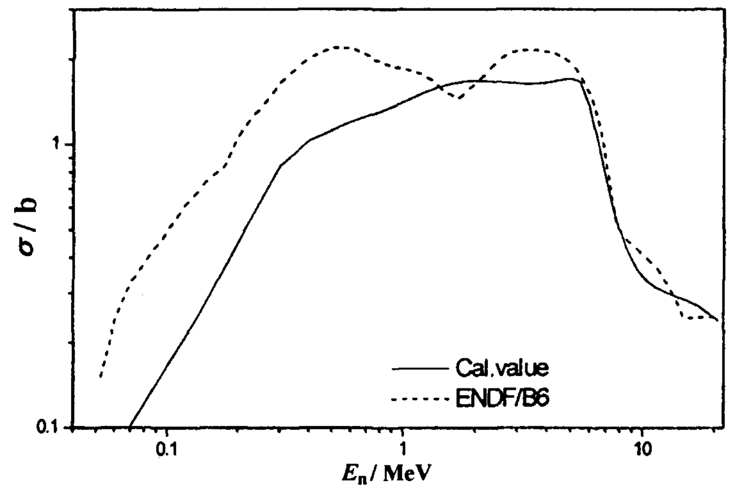

Fig. 4(a) Total inelastic(MT=4) cross sections of ^{241}Pu

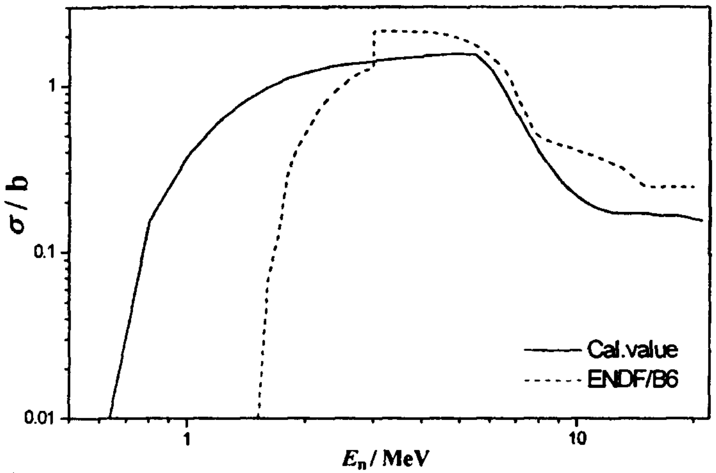

Fig. 4(b) Continuous inelastic(MT=91) cross sections of ^{241}Pu

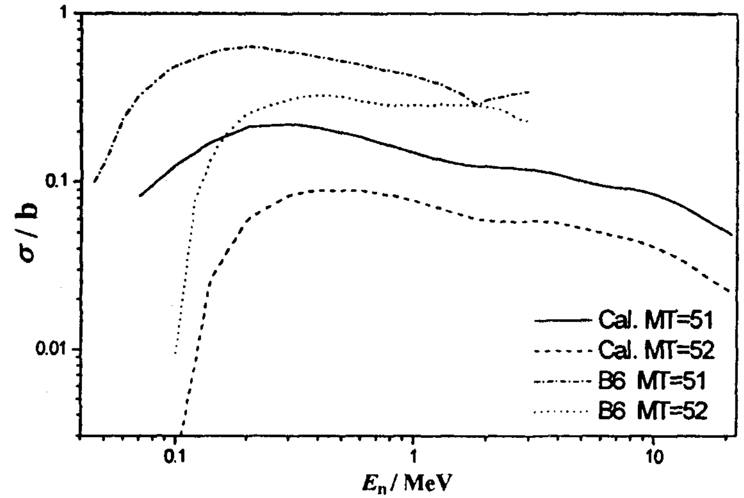

Fig. 5 Discrete level inelastic cross sections of ^{241}Pu

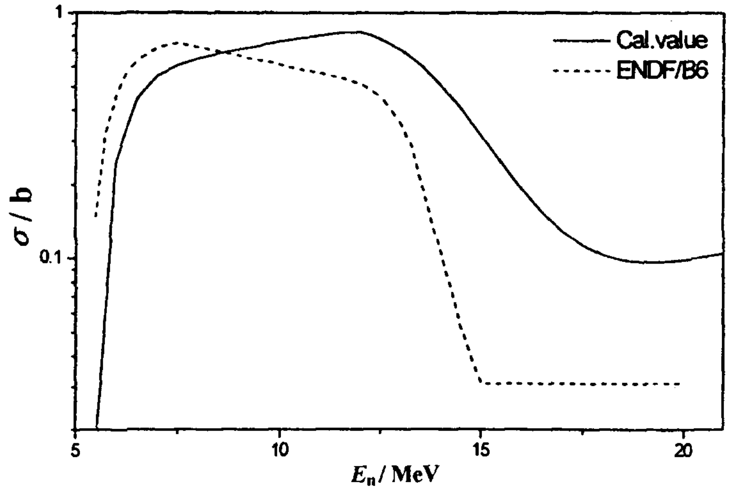

Fig. 6(a) (n,2n) reaction cross sections of ^{241}Pu

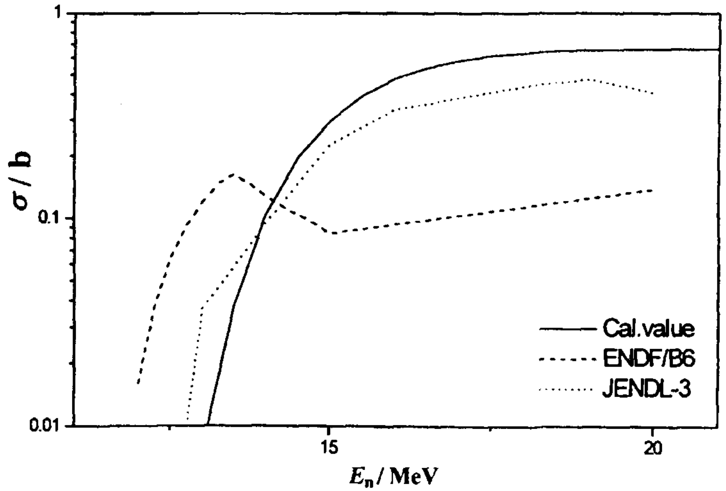

Fig. 6(b) (n,3n) reaction cross sections of ^{241}Pu

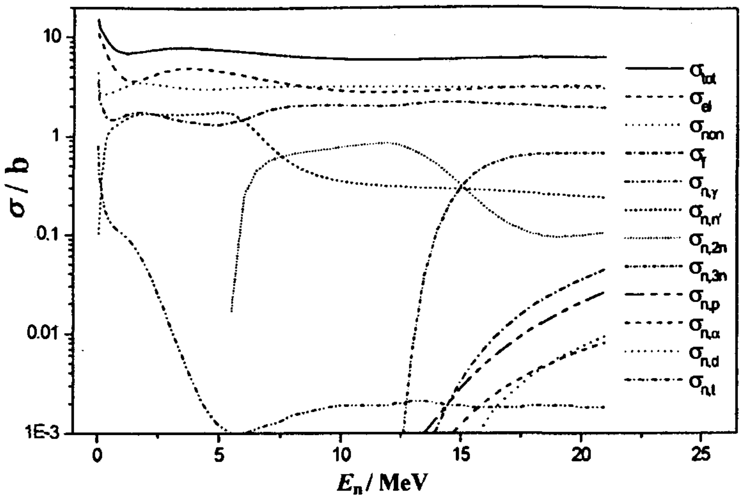

Fig. 7 All kinds of calculated cross sections of ^{241}Pu

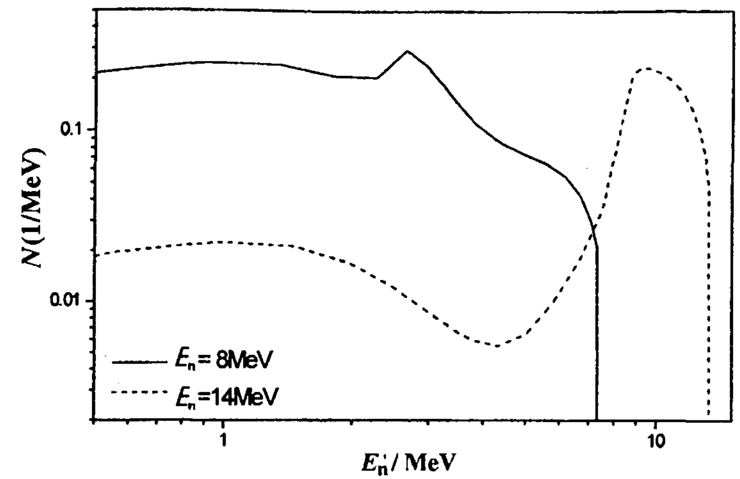

Fig. 8(a) Neutron spectra of continuous inelastic(MT=91) of ^{241}Pu

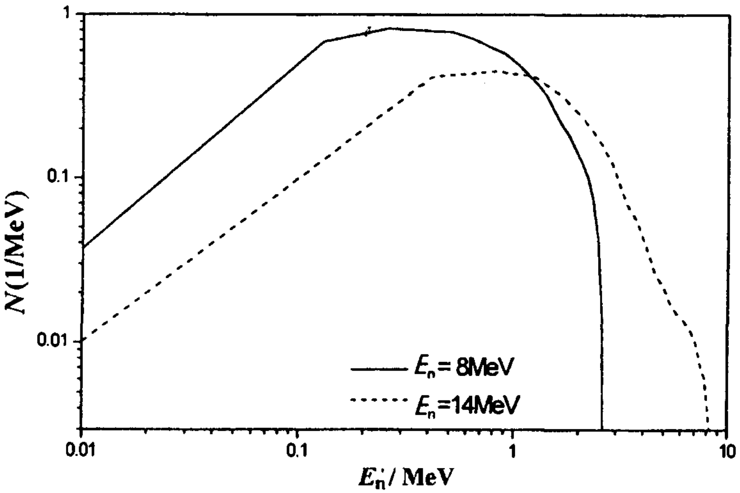

Fig. 8(b) (n,2n) (MT=16) outgoing neutron spectra of ^{241}Pu

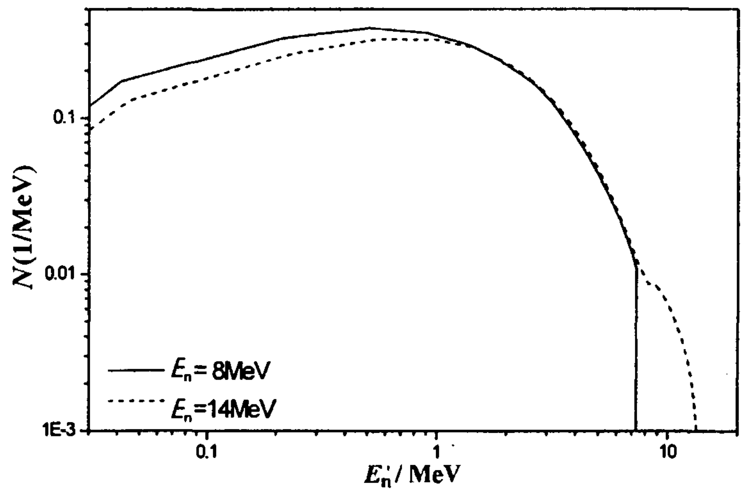

Fig. 8(c) Fisson (MT=18) neutron spectra of ^{241}Pu

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Calculations of Complete Set of Data for n+^{242}Pu Reaction up to 20 MeV

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^{242}Pu is an important fission nucleus. There are quite a lot experimental data for $\sigma_{n,F}$ and some experimental data for σ_{tot}, $\sigma_{n,}$ and elastic scattering angular