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MENDF—A Code for Calculating Nuclear Data of Fission Nuclei below 200 MeV*

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Abstract：Based on the spherical optical model, pre-equilibrium and Hauser-Feshbach statistical theory, the code MENDF (Medium Energy Nuclear Data for Fission) is written to calculate a complete set of nuclear data for fission nuclei in the medium-low energy region (⩽200 MeV). For neutron and proton induced reactions below 200 MeV, the total cross sections, reaction cross sections, elastic scattering differential cross sections, fission cross section, energy spectra of fission neutron and five kinds of emitting particles, etc. are calculated by MENDF. The calculated data generally agree with their corresponding experimental data. MENDF is widely used for nuclear data calculation and to establish ENDF-6 formatted files for the medium-low energy region in China.

Key words：MENDF program; fission; nuclear reaction; nuclear data

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1 Introduction

MENDF (Medium Energy Nuclear Data for Fission) is a special edition of the program MEND[1−2] which is used for calculating medium-heavy nuclei. MENDF is a program for calculating a complete set of nuclear data for fission nuclei ($Z \geqslant 89$) in the energy region up to 200 MeV. The incident and emission particles can be the following five kinds of light particles: n, p, α, d and t (the emission cross section of ^{3}He is much smaller than those of above 5 kinds of particles for fission nuclei, so ^{3}He emission is not considered in MENDF.). There are eighteen emission processes included in MENDF. It can calculate the total cross section, elastic scattering cross section and angular distribution, reaction cross section, inclusive cross sections and their energy spectra, fission cross section, the ν values and energy spectra of fission neutron, the charge, mass and energy distributions of fission fragments, etc..

Up to now, the program MENDF has been used to calculate a complete set of nuclear data below 200 MeV for many actinides with neutron and proton as projectile. Good results and ENDF-6 formatted libraries are obtained to be used for the ADS (Accelerator Driven sub-critical System) project.

This paper is arranged as follows. In Sec. 2, we introduce the functions and structure of MENDF briefly; the theoretical framework of MENDF are listed in Sec. 3; in Sec. 4, the calculation of fission quantities are given; Sec. 5 contains the input and output files, and Sec. 6 contains some calculation results.

2 Functions and Structure

In MENDF, the first to 18th emission processes are considered. The emitted particles can be n,

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p, α, d, t in the first to fourth emission process; only n and p are considered for the fifth to 18th emission processes. Moreover, there are some restrictions for charge particles emission in the second to 18th emission process. For the second emission process, the emission particles can be above 5 kinds of particles if the outgoing particle is n in the first emission; 4 kinds of particles (n, p, d, t,) if the outgoing particle is p, d or t in the first emission; only n if the outgoing particle is α in the first emission. For the third emission process, the emission particles can be above 5 kinds of particles if both outgoing particles are n in the first and second emissions; 4 kinds of particles (n, p, d, t) if one of the outgoing particles is n, another is p, d or t in the first and second emissions; only n if both outgoing particles are charge particles in the first and second emissions. For the fourth emission process, the emission particles can be above 5 kinds of particles if all the outgoing particles are n in the first, second and third emissions; 4 kinds of particles (n, p, d and t) if two of the outgoing particles are n, another is p, d or t in the first, second and third emissions; only n for other cases in the first, second and third emissions. For the fifth to 18th emission processes, the restrictions are those reactions emitting two p one after the other are not considered. There are also some restrictions for fission reactions in the 3～18th emission processes: after emitting charge particles, the fission reactions won't be considered, only those fission reactions after emitting n are permitted.

The reasons we give the above restrictions are that for fission nuclides, the cross section of an emitted α is much smaller than that of p, d and t; p cross section is usually larger than that of d and t; n cross section is much larger than that of p.

The calculation and output quantities in MENDF are as follows: total cross section (only for n as projectile), elastic scattering cross section and angular distribution, total reaction (or nonelastic) cross section, capture cross section, every kind of reaction cross sections (including partial fission cross section) in the first and second emission processes, the inclusive cross sections and their energy spectra and fraction of pre-equilibrium (PE) emission for five emitting particles, the production cross sections and energy spectra of γ photons produced in all kinds of reactions (but not including fission), the production cross sections and energy spectra of all kinds of recoil nuclei. Besides, the total fission cross section, the ν values and the energy spectra of the prompt fission neutrons, the mass, charge and energy distributions of all fission fragments are also calculated and given in output files. At present, MENDF can not calculate the yields and energy spectra of fission γ photons, the user has to obtain them from other approach.

For the calculation of the capture cross section and its γ spectra, besides the usual evaporation mechanism, the direct and PE emission γ photons are also considered in MENDF. The theoretical approach and calculation formulae are from Akkermans and Gruppelaar[3]. We get the direct γ cross section by letting $n=1$ in their Eq. (8) of that paper.

MENDF contains four source files: mendf. for, peg. for, hf. for and common. for. The user should put them in a same subdirectory to compile them. The user can put peg. for and hf. for together with mendf. for to form a much larger file (at the same time, two statements: include "peg. for" and include "hf. for" at the end of mendf. for should be deleted), but the user cannot put common. for together with other files because the statement "include common. for" appears in many subroutines. There are a main program, a block data, 71 subroutines and 55 functions in MENDF, and there are about 33200 lines in MENDF totally.

3 Theoretical Framework

The theoretical framework of MENDF consists of the spherical optical model, intranuclear cascade nucleon emissions based on empirical formulae, PE statistical theory based on exciton model, evaporation model and Hauser-Feshbach (HF) theory with width fluctuation correction.

Four kinds of spherical optical potentials can be employed to calculate the total cross section, shape elastic scattering cross section and angular distribution, absorption cross section, as well as transmission coefficients used in HF theory and "inverse cross sections" used in PE theory. Usually, the phenomenological optical potential of Becchetti and Greenlees or that of Koning and Delaroche[4] are used. MENDF can also do microscopic optical potential calculations based on Skyrme force[5] and the phenomenological optical potential calculation with CH89 parameters[6] for the n and p channel. The microscopic potential and the global phenomenological potential are very useful for those nuclide without experimental data for adjusting optical potential parameters.

The cascade emissions of one to four nucleons with certain fractions before PE and evaporation are considered in MENDF. The cascade yields of nucleons and the energy spectra of cascade nucleons are calculated with empirical formulae[7].

The PE emission mechanism is included exactly in the first to fifth emission processes for nucleons, exactly in the first to third and approximately in the fourth and fifth processes for composite particles. Combining the cascade emissions of nucleons and the PE mechanism, there are some fractions for both PE emission and evaporation in the first to sixth emission process, and there is only evaporation (without PE emission) in the 17th to 18th emission process. For emission of composite particles in PE theory, the improved Iwamoto pick-up reaction mechanism[8] is adopted. In the calculation of state densities for the exciton model, the Pauli principle is accommodated. The angular momentum and parity conservation are not considered in cascade nucleon emissions, PE theory and evaporation model.

The HF theory with width fluctuation correction is used only for the first emission process, in which the angular momentum and parity conservation are considered and the cross section and angular distribution of discrete levels can be treated. When the incoming energy is less than about 2.5 to 4 MeV, the second particle emission and (x, nf) reaction are not open, and we use HF theory to do all calculations; for higher incoming energy, we only use HF theory to calculate the cross section and angular distribution of discrete levels in the first emission process, use PE theory to calculate the cross section and angular distribution of continuous levels in the first emission process and all physical quantities in the second to 18th emission process.

MENDF do not calculate the direct reaction contributions, which are calculated with other codes (such as DWUCK4 and ECIS94) and treated as input in MENDF.

4 Calculation of Fission Reaction in the Program MENDF

The calculation methods in MENDF are the same as in MEND, and the user can find them in Sec. 4 in Ref. [1].

Most calculation formulae can be found in the MEND description[1]. In this section, we only give the formulae about fission calculations.

4.1 Calculation of cross section

The traditional Bohr-Wheeler formula is used in fission calculation.

$$T_f=\left[\sqrt{\frac{a_f}{U_x}}-\frac{1.5}{U_x}\right]^{-1}, \tag{1}$$

$$\rho_f(Z, A, U)=K_1\exp\left(2\sqrt{a_fU_x}+\frac{U-U_x-\Delta_f}{T_f}\right), \quad \text{if } U\leqslant U_x+\Delta_f$$

$$\rho_f(Z, A, U)=\frac{K_1\exp[2a_fU_e]}{12\sqrt{2\times 0.0888}A^{1/3}U_e\sqrt{a_fU_e}}, \quad \text{if } U>U_x+\Delta_f \tag{2}$$

where

$$U_x = U_c + \frac{U_a}{A}, \qquad U_e = U - \Delta_f. \qquad (3)$$

This means that similar formulae are taken to calculate the level densities for both the fission saddle state and the final state of a compound or residual nucleus. However， $a_f \neq a$， $\Delta_f \neq \Delta$， usually a and Δ are calculated with Gilbert-Cameron-Cook-Ignatyk （GCCI） formula and parameters. In MENDF， the effective single-peak fission potential barrier is used to substitute the double-peak fission potential barrier. The fission width in the evaporation model is

$$\Gamma_f(Z, A, U) = \frac{1}{2}\int_0^{U-V_f+1.6\hbar\omega} \frac{\rho_f(Z, A, x)}{1+\exp\left[\frac{2\pi}{\hbar\omega}(x+V_f-U)\right]}\mathrm{d}x \ . \qquad (4)$$

The penetration factor of the fission potential barrier in HF theory is

$$T_f^{J\Pi}(Z, A, U) = \int_0^{U-V_f+1.6\hbar\omega} \frac{J+1/2}{2\sigma^2(Z, A, x)} \times \exp\left[-\frac{(J+1/2)^2}{2\sigma^2(Z, A, x)}\right] \times \frac{\rho_f(Z, A, x)}{1+\exp\left[\frac{2\pi}{\hbar\omega}(x+V_f-U)\right]}\mathrm{d}x \ , \qquad (5)$$

where[9]

$$V_f = V_{f_0}, \qquad \text{for fission nuclei}$$

$$V_f = V_{f_0} + 319.0 - \frac{16.7Z^2}{A} + 0.218\left(\frac{Z^2}{A}\right)^2, \quad \text{for sub-fission nuclei.} \qquad (6)$$

Here， the V_{f_0} for sub-fission and fission nucleus have about the same values （4.5～7.5 MeV）.

For the first emission process， HF and PE theory are used in lower and higher energy region （the transitional energy region is about 2.5～4 MeV）， respectively. We do not demand all parameters with same values in HF and PE theory. There are 7 adjustable parameters in PE theory： a， Δ， a_f， Δ_f， V_{f_0}， $\hbar\omega$， K_1. There are 5 adjustable parameters in HF theory： a_f， Δ_f， V_{f_0}， $\hbar\omega$， K_1； a and Δ are taken as the same as in PE theory.

For the second to 18th emission process， there are also 7 adjustable parameters a， Δ， a_f， Δ_f， V_{f_0}， $\hbar\omega$， K_1 in PE theory. All these parameters are arranged as adjustable in order to make the larger fractional cross section σ_f， σ_{in}， σ_{2n}， σ_{3n}， …， σ_{18n} in accordance with experimental data.

To make the calculating cross section of charged particle emission in accordance with experimental data， we need also adjust a and Δ values in the corresponding channel by hand. In MENDF， we consider the height of fission potential barrier in Eqs. （4） and （5） is a function of nuclear temperature T （i.e. the excited energy E^*）[10]

$$V_f(T) = V_f(1 - 0.009T^2) \ , \qquad (7)$$

$$T = \frac{2}{\pi}\sqrt{\frac{\varepsilon_f E^*}{A}} \ , \qquad (8)$$

where A is the number of nucleons of the pre-fission nucleus， $\varepsilon_f \approx 31$ MeV is the Fermi energy. In Eqs. （4） and （5）， we should use U to substitute E^* for calculation of $V_f(T)$ in the integral upper limit， and use x to substitute E^* for calculation of $V_f(T)$ in the integrand.

4.2 Mass and charge distribution of fission fragments

4.2.1 Mass distribution[9]

The mass distribution of fission fragments depends on whether the fission is symmetric or asymmetric. For a pre-fission nucleus with $Z^2/A \leqslant 35$， only symmetric fission is allowed； for a pre-fission nucleus with $Z^2/A > 35$， both symmetric and asymmetric fissions are allowed， depending on the excitation energy of the pre-fission nucleus. For a nucleus with $Z^2/A > 35$， the asymmetric fission probability P_{asy} is

$$P_{asy} = \frac{4870.0\exp(-0.36U)}{1 + 4870.0\exp(-0.36U)} \ , \qquad (9)$$

and the symmetric fission probability is $P_{sy} = 1 - P_{asy}$.

For asymmetric fission, the mass distribution of one post-fission fragment A_1 is a Gaussian distribution with mean value $A_f = 140$ and width $\sigma_M = 6.5$, another post-fission fragment $A_2 = A - A_1$.

For symmetric fission, the mass distribution of one post-fission fragment A_1 is a Gaussian distribution with mean value $A_1 = A/2$ and width σ_M as follows:

$$\sigma_M = C_3\left(\frac{Z^2}{A}\right)^2 + C_4\left(\frac{Z^2}{A}\right) + C_5(U - V_f) + C_6\,, \tag{10}$$

with $C_3 = 0.122$, $C_4 = -7.77$, $C_5 = 0.0332$ and $C_6 = 134.0$, the fission barrier V_f is given by Myers and Swiatecki[11].

4.2.2 Charge distribution[9]

The charge distribution of a fission fragment is assumed to be a Gaussian distribution with mean Z_f and width σ_Z as follows:

$$Z_f = \frac{Z + Z_1' - Z_2'}{2.0}\,, \tag{11}$$

where

$$Z_k' = \frac{65.5A_k}{131.0 + A_k^{2/3}}\,, \qquad k = 1 \text{ or } 2\,, \tag{12}$$

and $\sigma_Z = 0.75$.

4.3 Kinetic energy distribution of fission fragments

The kinetic energy of the post-fission fragment is determined[9] by a Gaussian distribution with mean ε_f and width σ_{ε_f}

$$\begin{aligned} \varepsilon_f &= \frac{0.131Z^2}{A^{1/3}}, \qquad \text{if } \frac{Z^2}{A^{1/3}} \leqslant 900\,, \\ \varepsilon_f &= \frac{0.104Z^2}{A^{1/3}} + 24.3, \qquad \text{if } 900 < \frac{Z^2}{A^{1/3}} \leqslant 1800\,; \end{aligned} \tag{13}$$

$$\begin{aligned} \sigma_{\varepsilon_f} &= C_2\,, \text{ if } \frac{Z^2}{A^{1/3}} \leqslant 1000, \\ \sigma_{\varepsilon_f} &= C_1\left(\frac{Z^2}{A^{1/3}} - 1000.0\right) + C_2\,, \text{ if } \frac{Z^2}{A^{1/3}} > 1000\,, \end{aligned} \tag{14}$$

where $C_1 = 5.70 \times 10^{-4}$, $C_2 = 86.5$. The kinetic energy is the relative motion energy of one fragment moving against another, and A, Z are the mass and charge number of the pre-fission nucleus, respectively.

For those pre-fission nuclides with good evaluation and/or experimental fission ν values, we shall calculate the ε_f with another approach instead of using Eq. (13), see next section.

4.4 Energy spectra and ν values of fission neutrons

The calculation formulae are taken from Madland and Nix[12] with constant compound nucleus cross section.

4.4.1 Center-of-mass-system energy spectra of fission neutrons

$$\Phi(\varepsilon) = \frac{2\varepsilon}{T_m^2}\int_0^{T_m} \frac{\exp(-\varepsilon/T)}{T}\mathrm{d}T = \frac{2\varepsilon}{T_m^2}E_1\left(\frac{\varepsilon}{T_m}\right)\,, \tag{15}$$

where

$$E_1(x) = \int_0^{\infty} \frac{\mathrm{e}^{-u}}{u}\mathrm{d}u = \int_0^{1/x} \frac{\exp(-1/v)}{v}\mathrm{d}v\,. \tag{16}$$

From Eqs. (15) and (16) we can calculate

$$\langle \varepsilon^n \rangle = \int_0^{\infty} \varepsilon^n \Phi(\varepsilon)\mathrm{d}\varepsilon = \frac{2(n+1)!}{n+2}T_m^n\,, \tag{17}$$

especially, let $n=1$ and $n=2$ in Eq. (17), we obtain

$$\langle \varepsilon \rangle = \frac{4T_m}{3}\,, \tag{18}$$

$$\langle \varepsilon^2 \rangle = 3T_m^2\,, \tag{19}$$

where

$$T_m = \sqrt{\frac{E^*}{a}}\,, \qquad a = \frac{A}{adeno}\ (\text{MeV})\,. \tag{20}$$

In MENDF, $adeno = 11.0$ is an important adjustable parameter in one of the input file "fiparm.dat" for fission neutron spectra, and the user can change it a little to make fission neutron spectra in better accordance with experimental data. In Eq. (20),

$$E^* = E_c^* + \langle E_r \rangle - \langle E_f^{\text{tot}} \rangle\,, \tag{21}$$

where E^* is the total excited energy of two fragments after fission of a nucleus, E_c^* is the excited energy of A nucleus, $\langle E_r \rangle$ is the average energy release in fission of a nucleus (which are calculated from mass and charge distributions of fission fragments and mass table; therefore, it would be changed if the mass and charge distributions of fission fragments are changed, and then the fission neutron spectra are also changed), $\langle E_{\mathrm{f}}^{\mathrm{tot}} \rangle$ is just the average kinetic energies ε_{f} of fission fragments calculated from Eq. (13) in Sec. 4.3.

4.4.2 Laboratory-system energy spectra of fission neutrons

Here we use

$$N(E) = \frac{1}{2}\left[N(E, E_{\mathrm{f}}^{\mathrm{L}}) + N(E, E_{\mathrm{f}}^{\mathrm{H}})\right] \quad , (22)$$

where

$$E_{\mathrm{f}}^{\mathrm{L}} = \frac{A_{\mathrm{H}}}{A_{\mathrm{L}}}\frac{\langle E_{\mathrm{f}}^{\mathrm{tot}} \rangle}{A}, \quad E_{\mathrm{f}}^{\mathrm{H}} = \frac{A_{\mathrm{L}}}{A_{\mathrm{H}}}\frac{\langle E_{\mathrm{f}}^{\mathrm{tot}} \rangle}{A} \qquad (23)$$

is the average kinetic energy per nucleon of the light and heavy fragments, respectively; A_{L} and A_{H} are the average mass numbers of the light and heavy fragments, respectively.

$$\begin{aligned} N(E, E_{\mathrm{f}}) &= \frac{1}{4\sqrt{E_{\mathrm{f}}}}\int_{(\sqrt{E}-\sqrt{E_{\mathrm{f}}})^2}^{(\sqrt{E}+\sqrt{E_{\mathrm{f}}})^2} \frac{\Phi(\varepsilon)}{\sqrt{\varepsilon}} \mathrm{d}\varepsilon \\ &= \frac{1}{3\sqrt{E_{\mathrm{f}} T_{\mathrm{m}}}}\Big[u_2^{3/2} E_1(u_2) - u_1^{3/2} E_1(u_1) + \\ &\quad \gamma\left(\frac{3}{2}, u_2\right) - \gamma\left(\frac{3}{2}, u_1\right)\Big] , \end{aligned} \qquad (24)$$

where

$$u_1 = \frac{(\sqrt{E} - \sqrt{E_{\mathrm{f}}})^2}{T_{\mathrm{m}}}, \quad u_2 = \frac{(\sqrt{E} + \sqrt{E_{\mathrm{f}}})^2}{T_{\mathrm{m}}} , \qquad (25)$$

$$\gamma(a, x) = \int_0^x u^{a-1} \mathrm{e}^{-u} \mathrm{d}u \qquad (26)$$

is the incomplete γ function. And the average energy of fission neutron is

$$\langle E \rangle = \frac{1}{2}(E_{\mathrm{L}} + E_{\mathrm{H}}) + \frac{4}{3} T_{\mathrm{m}}. \qquad (27)$$

4.4.3 Average prompt neutron multiplicity

Here we use

$$\nu = \frac{\langle E_{\mathrm{r}} \rangle + E_{\mathrm{c}}^{*} - \langle E_{\mathrm{f}}^{\mathrm{tot}} \rangle - \langle E_{\gamma}^{\mathrm{tot}} \rangle}{\langle S_{\mathrm{n}} \rangle + \langle \varepsilon \rangle} , \qquad (28)$$

where $\langle S_{\mathrm{n}} \rangle$ is the average fission-fragment neutron separation energy (taken as one-half of the average two-neutron separation energy $\langle S_{2\mathrm{n}} \rangle$ to avoid the fluctuation coming from odd-even properties), $\langle E_{\mathrm{r}} \rangle$ is mentioned in Eq. (21), both $\langle S_{2\mathrm{n}} \rangle$ and $\langle E_{\mathrm{r}} \rangle$ are calculated from the mass and charge distributions of fission fragments and the mass table. $\langle \varepsilon \rangle$ is given in Eq. (18), E_{c}^{*} is the excited energy of pre-fission nucleus A, $\langle E_{\gamma}^{\mathrm{tot}} \rangle$ is the total average prompt γ energy, which is taken as

$$\langle E_{\gamma}^{\mathrm{tot}} \rangle = C_{\mathrm{Egt0}} + C_{\mathrm{Egt1}} A + C_{\mathrm{Eges}} \sqrt{E_{\mathrm{L}}} + C_{\mathrm{Egel}} E_{\mathrm{L}} , \qquad (29)$$

where $C_{\mathrm{Egt0}} = 0.09$, $C_{\mathrm{Egt1}} = 0.028$[13], $C_{\mathrm{Eges}} = 0.0$, $C_{\mathrm{Egel}} = 0.0$ at present; these 4 parameters can be slightly changed.

Further, $\langle E_{\mathrm{f}}^{\mathrm{tot}} \rangle$ is the average total kinetic energies of fission fragments which can be calculated from Eq. (13) in Sec. 4.3. If we do so, the ν value calculated from Eq. (28) will differ a lot from the evaluation and/or experimental data. Therefore, in real calculation, if there are good evaluation and/or experimental ν values, we use 4 parameters ν_0, C_{s}, C_1 and C_2 to imitate the ν values,

$$\nu = \nu_0 + C_{\mathrm{s}} \sqrt{E_{\mathrm{c}}^{*}} + C_1 E_{\mathrm{c}}^{*} + C_2 E_{\mathrm{c}}^{*2} \qquad (30)$$

and inversely to determine $\langle E_{\mathrm{f}}^{\mathrm{tot}} \rangle$ (also as a function of E_{c}^{*}) from Eq. (28). Afterwards, we should substitute ε_{f} in Eq. (13) and $\langle E_{\mathrm{f}}^{\mathrm{tot}} \rangle$ in Eqs. (21), (23) with the value of $\langle E_{\mathrm{f}}^{\mathrm{tot}} \rangle$ determined here, recalculate E^{*} in Eq. (21) and T_{m} in Eq. (20), and then recalculate the energy spectra of fission neutron from Eqs. (15)～(19), Eq. (22) and Eqs. (24)～(27). For (x, f), (x, nf), (x, 2nf), (x, 3nf) and (x, 4nf), each has its own 4 parameters to calculate ν values. For (x, 5nf) and higher fission, their 4 parameters are taken as the same in (x, 4nf).

We must emphasize that in MENDF, the pre-fission neutrons are not contained in the energy spectra and ν values of fission neutrons, which are already included in the spectra of the emitting neutrons (like the emitting p, α, d and t; in MENDF, for all five kinds of emitting light particles, we have to give the inclusive cross sections and their energy spectra as ENDF/B6 format output). However, the experimental ν values indeed include the contributions of pre-fission neutrons; therefore, besides NUp (ν values not including pre-fission neutrons), NUpt (ν values including pre-fission neutrons) are also given in the output file "CStabl. out". The user should adjust each set of four parameters ν_0, C_s, C_1 and C_2 in (x, f), (x, nf), (x, 2nf), (x, 3nf) and (x, 4nf) reactions to make the calculated total ν values NUpt in accordance with the experimental ν values.

5 Input and Output Files

In MENDF, similar to MEND, the input files include "mendfi. dat" and "fdir. dat"; the output files include mendfo. dat (general output), CStabl. out (tables of cross sections), specp. dat (normalized energy spectra of five emission particles and total γ-ray), specr. dat (norma- lized energy spectra of all kinds of recoil nuclei), sptabl. out (tables of differential cross sections of five emission particles and total γ-ray) and B6out. dat (ENDF/B6 format output file); besides, mendv. dat ("inverse cross sections" table) is output file if $INCS=0$ and input file if $INCS>0$; aaDLTA. dat (tables of level density parameters and pair energy corrections) is output file calculated with GCCI formula and parameters if $IaDL=0$ and input file if $IaDL=1$. In this way, user can adjust some parameters in aaDLTA. dat to make corresponding fractional reaction cross sections in better accordance with experimental data.

Besides, there are also other two files: fiparm. dat (fission parameters) and FiGama. b6 (fission γ spectra in B6 format) as input, other three files: Dmascha. dat (mass and charge distributions of fission fragments), Espeff. dat (energy distributions of fission fragments) and Specfn. dat (normalized energy spectra of fission neutrons) as output. All these files are not appeared in the code MEND.

The user can find the explanation of the meaning of all the quantities in input files from the comment lines in source files of the program MENDF. Here we do not give the example of input files, users can contact us if they need the example and the explanation.

6 Calculation Results

Using MENDF, with neutron as projectile, all kinds of cross sections, angular distributions, energy spectra and double differential cross sections of five kinds of emitting particles and the cross sections, energy spectra of every kind of recoil nuclei, as well as fission cross sections, the ν values, energy spectra of fission neutrons and the charge, mass and kinetic energy distributions of the fission fragments are consistently calculated and evaluated for ^{232}Th, ^{237}Np, $^{232\sim240}$U, $^{236\sim244,246}$Pu, ^{241,242m,242,243}Am and $^{243\sim248}$Cm as target nucleus; with proton as projectile, all the same physical quantities as for neutron are consistently calculated and evaluated for ^{232}Th, and ^{235,238}U as target nucleus at incident neutron or proton energies below 200 MeV. Generally speaking, besides the charge, mass and kinetic energy distributions of the fission fragments, as well as the yields and energy spectra of fission γ photons, good agreements are observed between the calculated results and the experimental data. Especially, if the user gives appropriate adjustable parameters, the fission cross sections calculated with MENDF are in much better accordance with experimental data than the results calculated by other codes. For n+^{237}Np as example, theoretical calculated results are compared with existing experimental data as shown in Figs. 1 to 6. At present, only one of above results calculated with MENDF has been published[14]. Others will be gradually written as research papers to be published in the future.

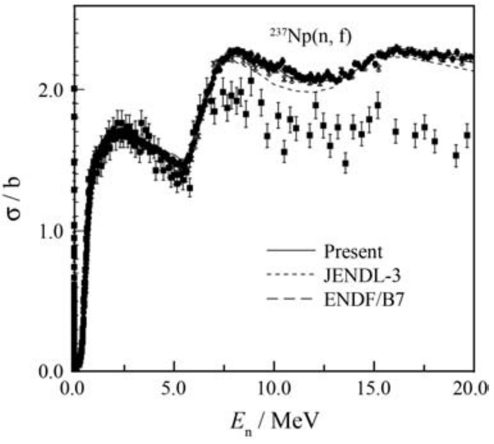

Fig. 1 Fission cross section for n＋^{237}Np（$E_{\rm n}$＝0．01～20 MeV）．

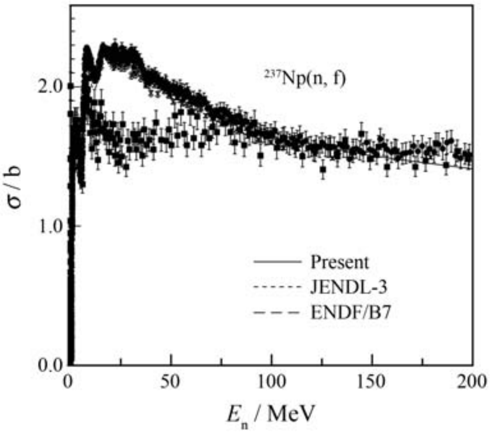

Fig. 2 Fission cross section for n＋^{237}Np（$E_{\rm n}$＝0．01～200 MeV）．

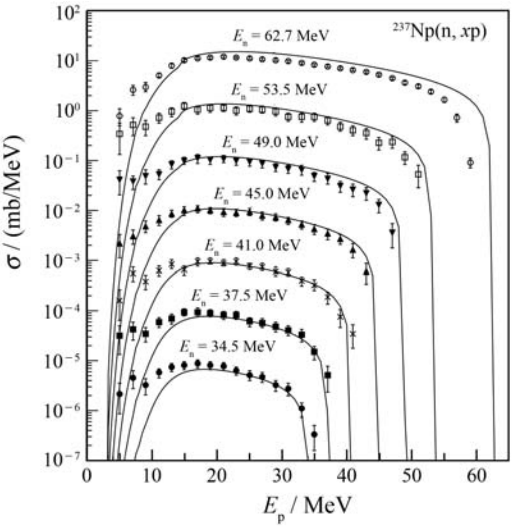

Fig. 3 The emitting proton spectra for n＋^{237}Np at different incoming neutron energies.

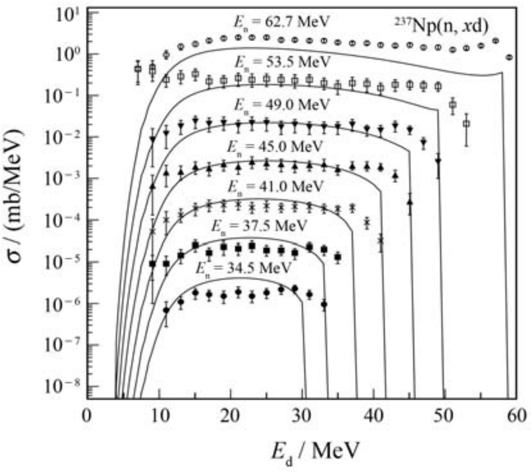

Fig. 4 The emitting deuteron spectra for n＋^{237}Np at different incoming neutron energies.

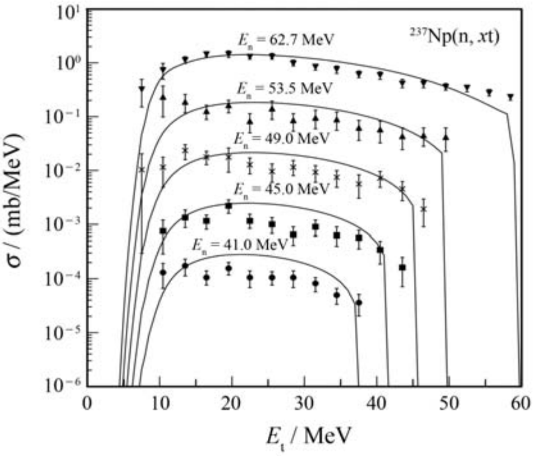

Fig. 5 The emitting triton spectra for n＋^{237}Np at different incoming neutron energies.

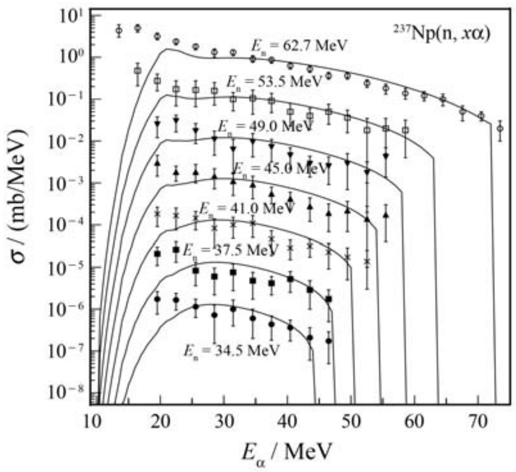

Fig. 6 The emitting α particle spectra for n＋^{237}Np at different incoming neutron energies.

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MENDF——一个计算 200 MeV 以下裂变核数据的程序*

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摘　要：基于球型光学模型、预平衡发射和 Hauser-Feshbach 统计等理论，编制了 MENDF(Medium Energy Nuclear Data for Fission)程序，该程序适用于裂变核在入射粒子能量低于 200 MeV 的中低能区的全套核数据计算。对于中子和质子在 200 MeV 以下诱发的核反应，其全截面、反应截面、弹性散射微分截面、裂变截面和裂变中子谱、5 种发射粒子的单举截面和相应的能谱等理论计算值与相应的实验值基本符合。MENDF 在我国已被广泛用于核数据计算及建立中能核数据库。

关 键 词：MENDF 程序；裂变；核反应；核数据

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