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ScienceDirect
Nuclear Data Sheets 118 (2014) 132–135
Nuclear Data Sheets
www.elsevier.com/locate/nds

Theoretical Calculation of Actinide Nuclear Reaction Data

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All cross sections, angular distributions, energy spectra of neutron, proton, deuteron, triton, helium and alpha-particle emission, as well as the prompt fission neutron spectra for n+^{232}Th, ^{233,234,236,238}U, ^{237}Np, ^{239,240,241,242}Pu and ^{241,242,243}Am reactions are consistently calculated and analyzed at incident neutron energies from 0.01 to 200 MeV. Calculated results are compared with recent experimental data and other evaluated data from ENDF/B-VII and JENDL-3.

I. INTRODUCTION

Neutron-induced reactions on actinide nuclei in the energy range below 200 MeV are important in the field of nuclear energy and nuclear transmutation. For example, these interactions are relevant in neutron generation and neutron transport in systems such as the proposed accelerator driven system [1]. Knowledge of accurate neutron-induced fission cross sections is crucially important for the design of various reactor systems. New precision data will allow accurate prediction of transmutation rates and reduce calculation uncertainties of reactor design and safety parameters. On the other hand, since neutron, proton, deuteron, triton, helium and alpha-particle emission double differential cross sections and spectra provide a complementary information on prompt fission neutrons and nuclear reaction mechanisms, theoretical models can obtain more information about nucleus structure and nuclear reactions.

In the present work, all reaction cross sections, average number of neutron per fission, the prompt fission neutron spectra, the angle-integrated spectra and the double differential cross sections of neutron, proton, deuteron, triton, helium and alpha-particle emission for n+^{232}Th, ^{233,234,236,238}U, ^{237}Np, ^{239,240,241,242}Pu and ^{241,242,243}Am reactions are calculated using the optical model, the intra-nuclear cascade model, the unified Hauser-Feshbach theory and the exciton model which includes the improved Iwamoto-Harada model, the fission model, the linear angular momentum dependent exciton density model and the distorted wave Born approximation theory, and compared to recent experimental data for the incident neutron energy region $E_n \leq 200$ MeV.

Section II provides a description of the theoretical models. Section III gives analysis and comparisons of calculated results with experimental data. Section IV gives simple conclusions.

II. THEORETICAL MODEL AND PARAMETERS

The optical model is used to describe measured neutron-induced total, nonelastic, elastic cross section and elastic scattering angular distributions and to calculate the transmission coefficient of the compound nucleus and the pre-equilibrium emission process. The optical model potentials considered here are of Woods-Saxon [2] type for the real part, Woods-Saxon and derivative Woods-Saxon for the imaginary parts corresponding to the volume and surface absorptions respectively, and the Thomas type for the spin-orbit part.

The unified Hauser-Feshbach and exciton model [3] are used to describe the equilibrium and pre-equilibrium decay processes. The Hauser-Feshbach model with width fluctuation corrections describes the emissions from compound nucleus to the discrete levels and continuum states of the residual nuclei in equilibrium processes, while the pre-equilibrium process is described by the angular momentum and parity dependent exciton model. The pre-equilibrium statistical theory based on exciton model, evaporation models and Hauser-Feshbach theory with width fluctuation correction, and intranuclear cascade model are used to describe the nuclear reaction pre-equilibrium and equilibrium decay processes for incident neutron energies above 20 MeV. The improved Iwamoto-Harada model [4, 5] is used to describe the composite particle emission in compound nucleus, and is included in the exciton model for the light composite particle emissions.

Fission is included as a decay channel, that is, a fis-

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http://dx.doi.org/10.1016/j.nds.2014.04.018
0090-3752/2014 Published by Elsevier B.V.

sion competitive width can be estimated at every step of the cascades. Fifteen uncoupled fission barriers are used to represent the fission system and describe (n,f), (n,nf), (n,2nf), and up to (n,15nf) channels, respectively. The Bohr-Wheeler theory [6, 7] is used to calculate the fission rate. The fission spectrum is calculated by the Madland-Nix formula [8], and the parameters are taken from ENDF/B-VII.0 [9]. The average number of neutron per fission are calculated with the systematic formula.

The double differential cross section are calculated by generalized master equation to get the angular momentum dependent lifetime with the Legendre expansion form below incident neutron energy 20 MeV. In order to simplify the calculations, the angular dependent formula form of Kalbach phenomenological approach [10] is used in present calculation of the double differential cross sections for emission neutrons, protons, deuterons, tritons, helium and alpha-particles above incident neutron energy 20 MeV.

The UNF code [3] is used at incident neutron energies below 20 MeV. The MEND [11] code is used in the energy range up to 200 MeV. The angular momentum and parity dependent exciton model is used in UNF code, other models are the same as MEND code. The level density and pair correction parameters of the Gilbert-Cameron level density [12] for low energy are used. The Ignatyuk model [13] for level density properties of excited nuclei is particularly appropriate for the relatively high energies, and is used. The parameters of the fission, level densities and pair correction are taken from RIPL [14], and adjusted by fitting the experimental data. The neutron and proton optical model potential parameters [15] are obtained from experimental data of total, nonelastic cross sections and elastic scattering angular distributions. The optical model potential parameters for deuteron are taken from Han's results [16]. The ^{3}He global optical model potential [17] with energies below 250 MeV is used, and are used as triton and alpha optical model potential parameters. The code DWUCK4 [18] of the distorted wave Born approximation theory is used to pre-calculate the direct inelastic scattering cross sections and angular distributions of discrete levels.

III. THEORETICAL RESULTS AND ANALYSIS

All reaction cross sections, the energy spectra of neutron, proton, deuteron, triton, helium and alpha emission for n+^{232}Th, ^{233,234,236,238}U, ^{237}Np, ^{239,240,241,242}Pu and ^{241,242,243}Am reactions are calculated. The calculated results of total, nonelastic and elastic scattering cross sections, elastic scattering angular distributions and inelastic scattering angular distributions are in agreement with the experimental data as shown in Ref. [15].

The calculated results of (n,γ) reaction cross sections were compared with the experimental data and the calculated results are consistent with the experimental data in the entire energy region. As an example, the comparison of calculated results of ^{232}Th(n,γ) reaction cross sections with new experimental data are given in Fig. 1. The cross sections of (n,p), (n,d), (n,t), (n,^{3}He) and (n,α) reactions are less than 15 mb, and there are no experimental data.

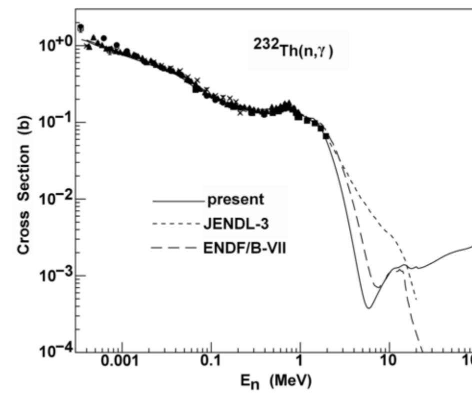

FIG. 1. Calculated ^{232}Th(n,γ) reaction cross sections compared with the experimental data.

There are significant differences in the experimental data for (n,2n) and (n,3n) reaction cross sections measured in different laboratories. For example, the calculated results for ^{241}Am(n, 2n) reaction are shown in Fig. 2.

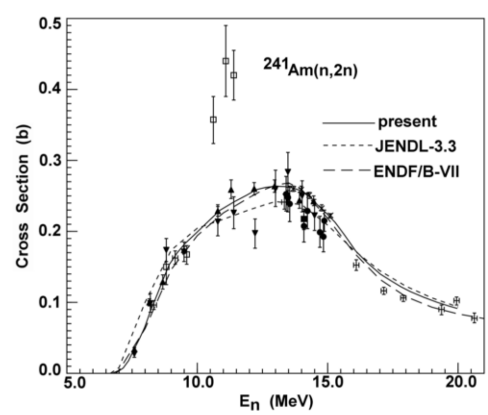

FIG. 2. Calculated ^{241}Am(n,2n) reaction cross sections compared with the experimental data.

The fission cross section obtained from theoretical calculations are in good agreement with some experimental data in the entire energy region. For instance, the calculated results of ^{239}Pu, ^{243}Am(n,f) cross sections are given in Fig. 3 and Fig. 4. The experimental data (n,γ), (n,2n) and (n,f) reaction cross sections are taken from EXFOR Library.

The present calculated results of double differential cross sections and energy spectra for neutron emission are compared with the experimental data for n+^{232}Th, ^{238}U, ^{237}Np reactions below incident neutron energy 20.0 MeV. The calculated results are in good agreement with the experimental data for the position and height of the