Evaluation of Neutron Cross Sections for Sm-150 and Sm-151

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ABSTRACT

The neutron induced nuclear data for Sm-150 and Sm-151 was calculated and evaluated from unresolved region to 20 MeV. The process of evaluation for deformed nuclei was setup in Ecis-Empire combination. The energy dependent optical model potential based on the recent experimental data was applied up to 20 MeV. Optical model, full featured Hauser-Feshbach model, multistep direct and multistep compound model were used in the calculation. The direct-semidirect capture model and the direct coupled-channels contribution to discrete levels were introduced to improve capture and inelastic scattering cross sections. The theoretically calculated cross sections were compared with the experimental data and the evaluated files. The model calculated total and capture cross sections were in good agreement with the reference experimental data. The evaluated cross section results were compiled to ENDF-6 format and will improve the ENDF/B-VI.

1. INTRODUCTION

Neutron induced nuclear reaction data for fission products are important for predicting burnup performance in a fission reactor, criticality for spent fuel storage design, advanced fuel performance and radiation damage estimation of structural material. The absorbed neutrons by fission products are large portion of total loss of neutrons in a reactor.

The priori fission products[1] were selected in the current evaluation, which mainly influence on reactivity in a fission reactor. The evaluation for the selected fission products has been jointly performed with National Nuclear Data Center (NNDC) of Brookhaven National Laboratory (BNL). The joint work is divided into two regions: resonance region including thermal region and upper resonance region up to 20 MeV. For resonance energy region, the evaluation[1] was done for all the selected fission products and the results were adopted in the release 8 of ENDF/B-VI last year up to unresolved energy region. Unresolved resonance region is extended up to several keV or hundreds of keV for the fission products. The current evaluation results will complement the evaluation of the resonance region from the 1st excited energy level, which corresponds to 334 keV and 5 keV for Sm-150 and Sm-151.

Neutron capture cross sections of samarium isotopes in several keV region are important because these isotopes are significant fission products in a fission reactor concerning neutron absorption loss. The selected samarium has a high yield, long lifetime and high capture rate in a reactor. In ENDF/B-VI, Sm-150 and Sm-151 were evaluated in 1992 and 1991. Therefore, a new evaluation with better theory is necessary for better application.

Ecis-Empire code combination was decided in cross section calculation of deformed nuclei for total, elastic scattering and reaction cross sections. The optical model potential depending on the incident neutron energy was decided. Ecis is well known and highly respected code based on generalized optical model and coupled-channels model (CCM) by J. Raynal[2] (CEA Saclay, France). Ecis is also important for description of strong population of collective discrete levels in the (n, n') channel. Therefore, symmetric rotational, vibrational-rotational and harmonic vibrational CCM modes are now available in model calculation.

Nuclear reaction cross sections were calculated by the recently released Empire-II code[3] using the Hauser-Feshbach model for equilibrium energy region and the quantumn mechanical approach in pre-equilibrium energy region. The width fluctuation correction was considered in Hauser-Feshbach particle decay. The direct and semi-direct capture model was introduced to increase the accuracy of the pre-equilibrium capture cross section. The Empire offers several built-in libraries including the ENSDF nuclear level, deformation parameters and decay information. The cross sections are evaluated on (n, tot), (n, n), (n, n'), (n, 2n), (n, 3n), (n, na), (n, np), (n, g), (n, p) and (n, a). The calculated cross sections are graphically compared with the experimental data and the evaluated files (ENDF/B-VI, JENDL-3.2, JEF-2.2, BROND-2 and CENDL-2).

2. MODEL THEORY

2.1 EMPIRE

The code accounts for the major nuclear reaction mechanisms, such as optical model, Multistep Direct (MSD), Multistep Compound (MSC) and the full featured Hauser-Feshbach model. The Multistep direct model takes care of the inelastic scattering to vibrational collective levels and decay information. The modeling of Multistep Compound processes follows the approach of Nishioka et at. (NVWY)[3]. Like most of the pre-compound models, the NVWY theory describes the equilibration of the composite nucleus as a series of transitions along the chain of classes of closed channels of increasing complexity. The direct-semidirect (DSD) capture model was recently provided in Empire to improve (n, g) reactions for fast neutrons.
In the statistical model of nuclear reactions, the Compound Nucleus (CN) state a with spin J, parity $\prod$ and excitation energy E to a channel b is given by the ratio of the channel width Γ_b to the total width $\Gamma_{tot} = \sum_c \Gamma_c$ multiplied by the population of this state $\sigma_a(E,J,\Pi)$. This also holds for secondary Compound Nuclei which are formed due to subsequent emissions of particles. Each such state contributes to the cross section.

$$\sigma_b(E,J,\Pi) = \sigma_a(E,J,\Pi)\frac{\Gamma_b(E,J,\Pi)}{\sum_c \Gamma_c(E,J,\Pi)} \tag{1}$$

These have to be summed over spin J and parity $\prod$ and integrated over excitation energy E (in case of daughter CN) to obtain observable cross sections.
The shape of each nucleus affects parameters of the Giant Dipole Resonance and level density parameter a. The deformation in Empire enters level densities formulae through moments of inertia and through the level density parameter a that increases with the increasing nucleus surface. The Gilbert-Cameron level density formula[4] was used for the current evaluation.

2.2 ECIS

Ecis is important for modelling of reactions on deformed nuclei. Spherical and deformed nucleus is now possible by the option in the code. Majority of deformed nuclei is covered, rotational and vibrational, even-even and even-A with integer spins, as well as odd-A with half-integer spins. Vibrational even-even nuclei are also covered.

Discrete level schemes and deformation parameters are automatically prepared from the built-in library. Ecis can be invoked by Empire call.

3. CALCULATIONS

The theoretically calculated cross sections were compared with the experimental data and the evaluated files on (n, tot), (n, n), (n, n'), (n, g), (n, p), (n, a), (n, 2n), (n, 3n), (n, np), (n, na) reactions. However, in this paper, (n, tot), (n, g) and (n, p) cross sections are introduced. The present work will be merged with the resonance evaluation to make nuclear data full set. The energy boundary for the merge in the unresolved region was at the energy where the inelastic scattering reaction channel opens.
Table I shows the summary of collective levels, spin, parity and deformation parameters for coupled channel calculation. Table II shows the used energy dependent optical model potential parameters. The potential depth and radius for real and imaginary part were expanded as a function of incident neutron energy, E_n.

$$V = V_o + V_1 x E_n,\ r = r_o + r_1 x E_n \qquad (2a)$$

$$W = W_o + W_1 x E_n,\ r_w = r_{wo} + r_{w1} x E_n \qquad (2b)$$

Table shows the much different real potential depth in the nuclei. However, the potential calculated the agreed total cross section to the experimental data.
Fig. 1 shows the calculated total cross section with the reference experimental data[5]. The calculated total cross section follows the experimental data[5,6] well. Above 300 keV, the calculation has the different shape from the ENDF/B-VI. However, the calculation is rather continuous than ENDF/B-VI at 345 keV. Fig. 2 shows the calculated capture cross section with the experimental data and ENDF/B-VI. The calculated capture cross section is in good agreement with the reference experimental data[5]. Also, around 14 MeV, the calculation shows the improved capture shape following the giant dipole resonance. In the measured energy region[5,7], the calculation and the ENDF/B-VI are in good agreement. Fig. 3 is the (n, p) cross section. Unfortunately, there is no (n, p) cross section in ENDF/B-VI. The calculation is in good agreement with the measured data[8,9,10,11] at 14.7 MeV.
There is no experimental data for the total cross section of Sm-151. The experimental data[12,13,14] of the natural samarium was used instead. Fig. 4 is the calculated total cross section with the experimental data and ENDF/B-VI. The calculated and ENDF/B-VI cross sections are in good agreement with the natural experimental data in the higher

Table I. Levels for coupled-channel calculation

	Level (MeV)	Spin	Parity	Deformation Parameter
Sm-150	0.0 0.334 0.773 1.279	0 2 4 6	1 1 1 1	0.206
Sm-151	0.0 0.066 0.175 0.261	2.5 3.5 4.5 5.5	-1 -1 -1 -1	0.215

Table II. Potential parameters as a function of incident neutron energy

Parameter (unit)	Sm-150	Sm-151
V_o(MeV)	54.5000	46.9678
V_1(MeV)	-0.3250	-0.0172
r_o(fm)	1.280	1.248
a_v(fm)	0.630	0.655
W_o(MeV)	9.000	8.455
r_{wo}(fm)	1.2800	1.3723
a_w(fm)	0.500	0.448
V_{so}(MeV)	6.000	7.000
r_{so}(fm)	1.280	1.279
a_{so}(fm)	0.630	0.600
W_1(MeV)	0.010	0.000
r_{w1}(fm)	0.000	0.000
r_1(fm)	0.000	0.000

energy region. However, in the low energy, the calculation shows lower value than ENDF/B-VI. The ENDF/B-VI has discontinuity around 10 and 70 keV. Fig. 5 and 6 are capture and (n, p) cross sections. There is no experimental data for those reactions. For the capture, above 600 keV, the calculation has the different cross section from the ENDF/B-VI. The other threshold reaction cross sections are not shown here, but compiled in ENDF-6 format.

CONCLUSIONS

The evaluation process for deformed nuclei was successfully setup and the most proper model theory was applied into the Sm-150 and Sm-151 evaluation. Further, fast neutron capture by direct and semi-direct capture model was substantially improved. Empire package becomes a highly competitive tool for evaluation of nuclear reaction data for a broad class of nuclei. The selected energy dependent optical model potential was proper to calculate the total and reaction cross sections in Ecis-Empire package. The evaluated cross sections are in good agreement with the experimental data. They represented improvement over current ENDF/B-VI.

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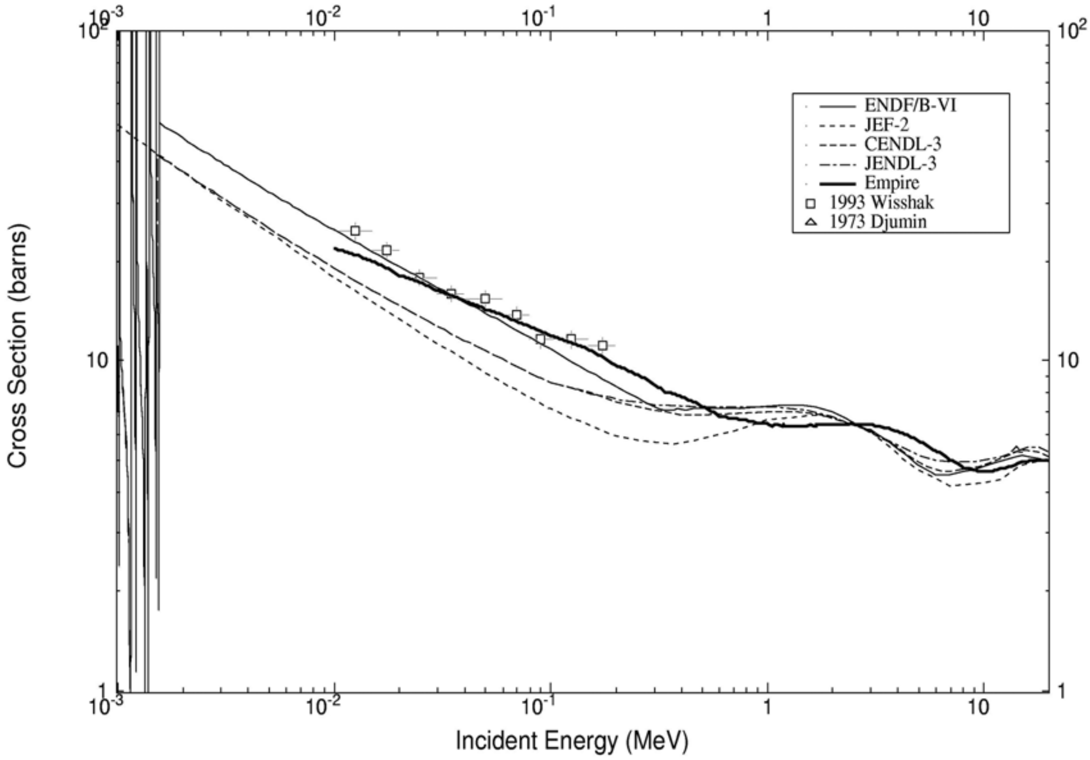

Fig. 1. Total cross section for Sm-150.

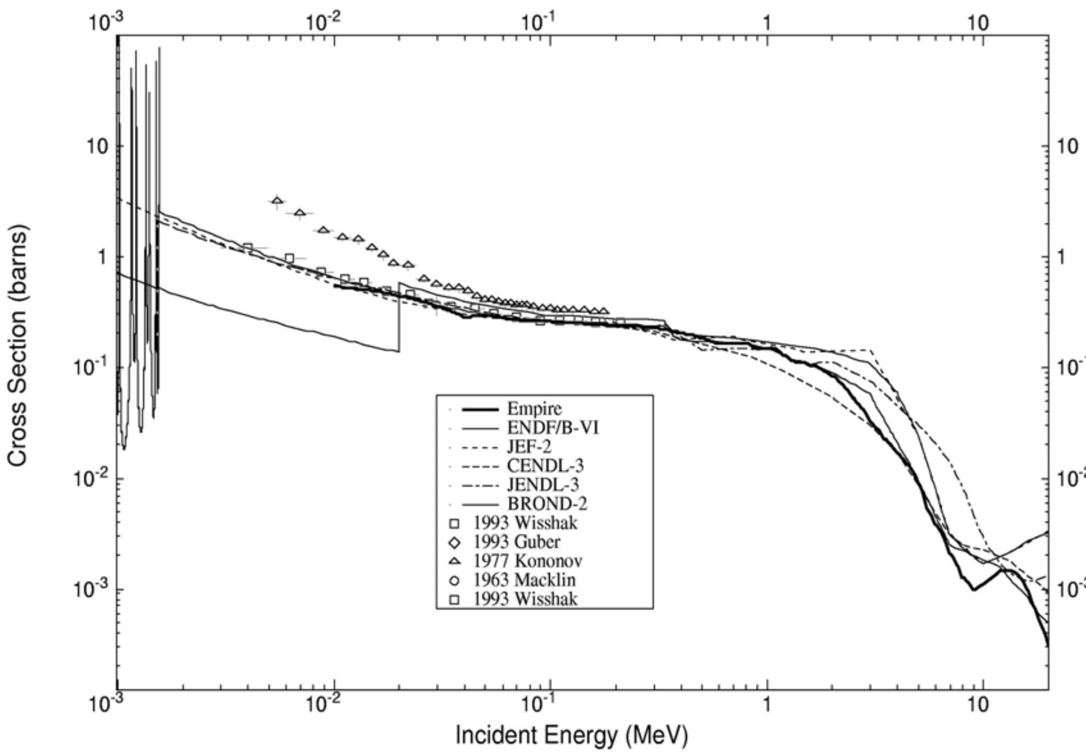

Fig. 2. Capture cross section for Sm-150.

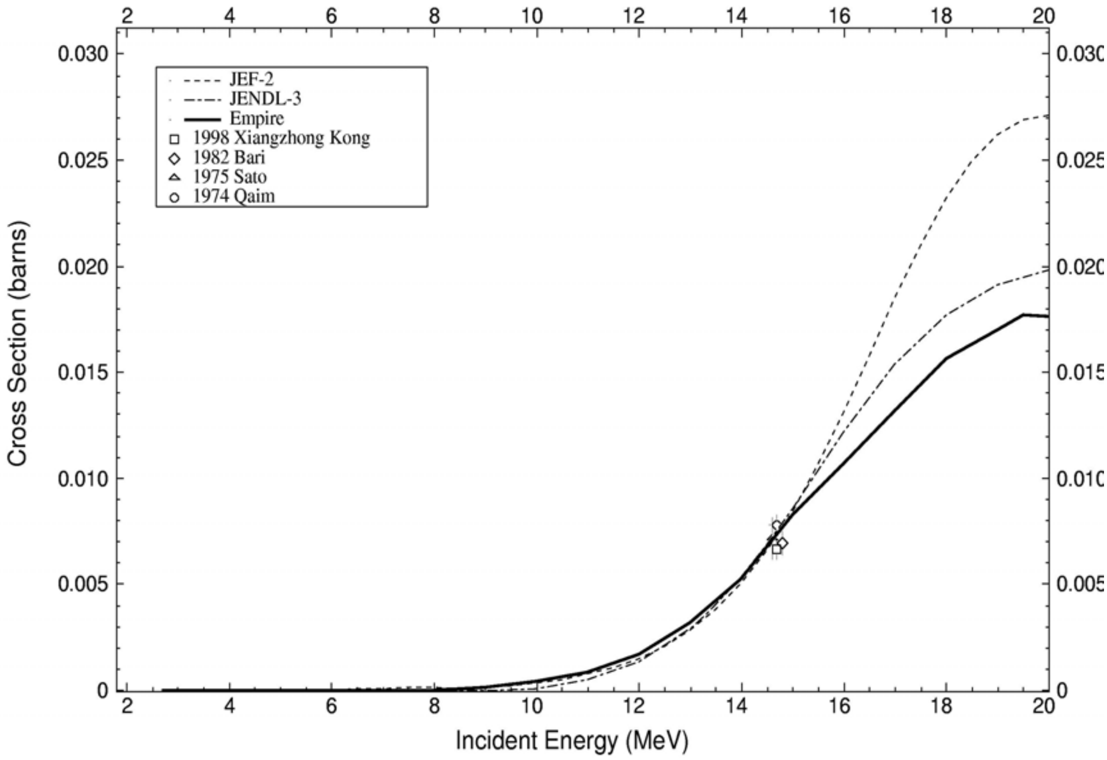

Fig. 3. (n, p) cross section for Sm-150.

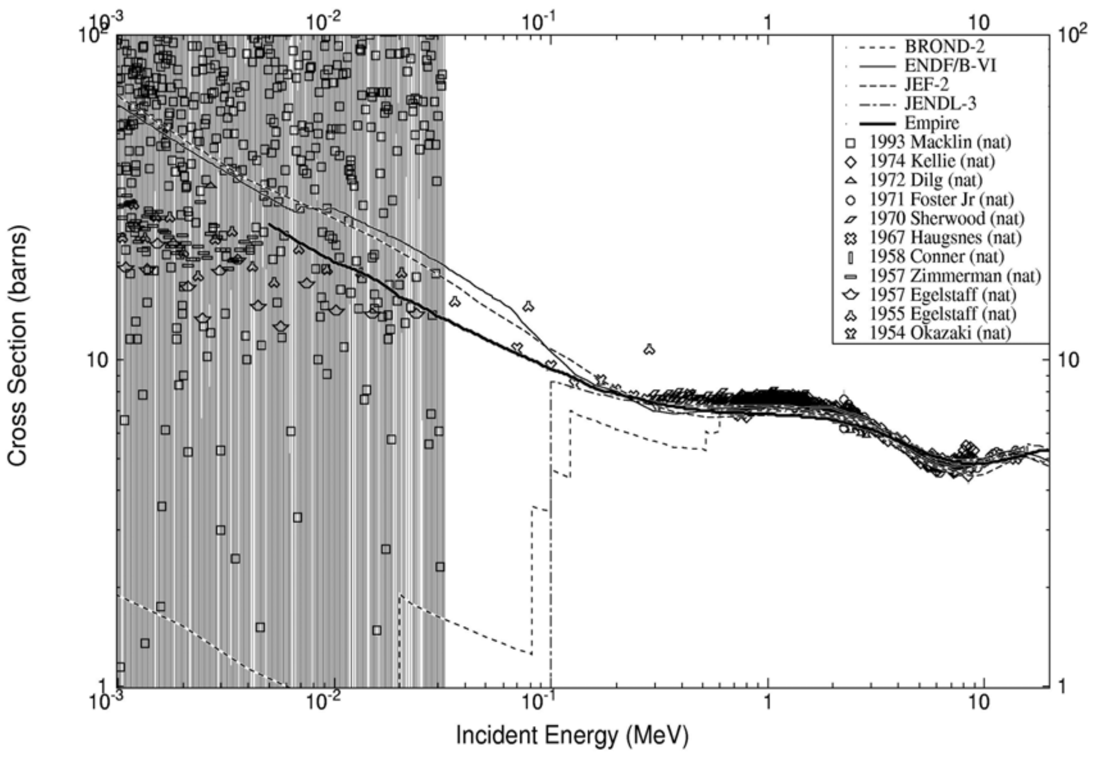

Fig. 4. Total cross section for Sm-151.

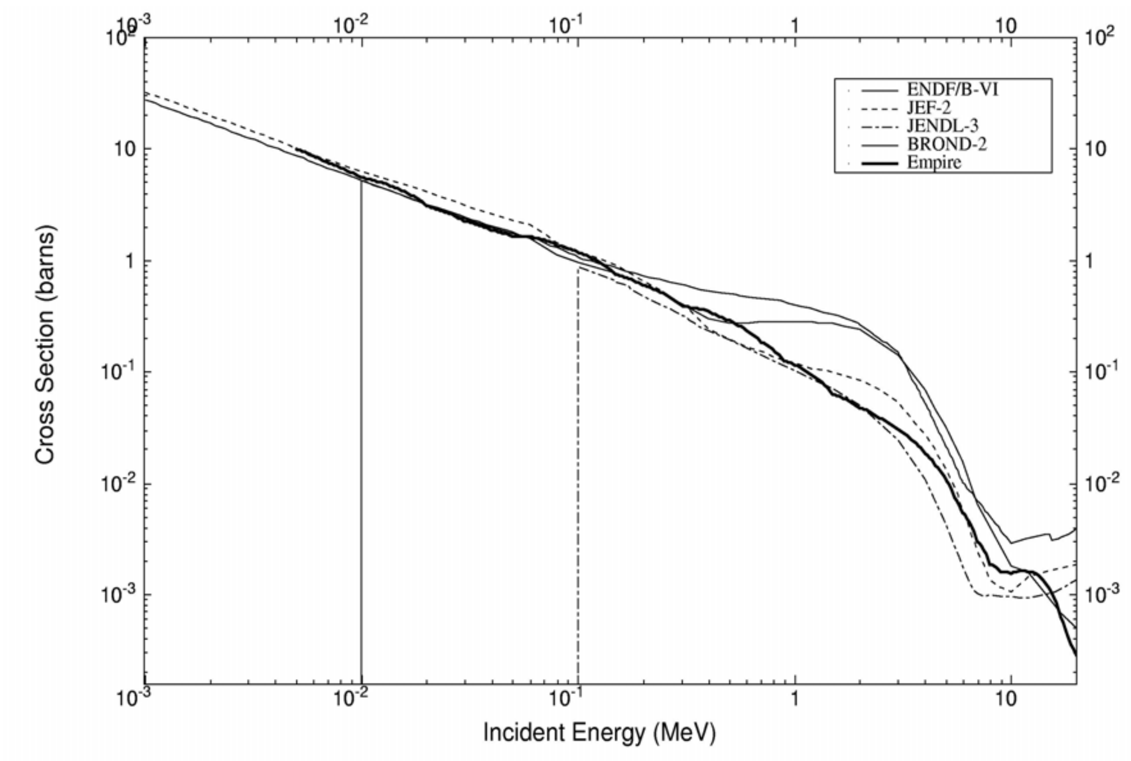

Fig. 5. Capture cross section for Sm-152.

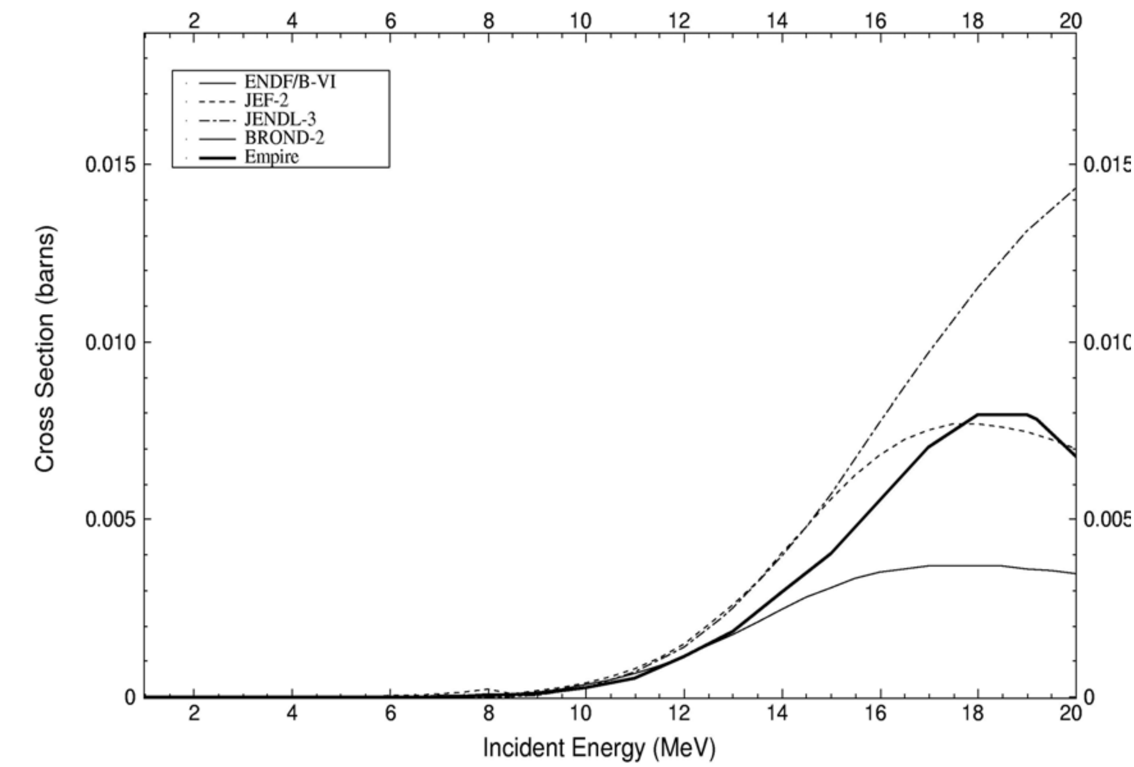

Fig. 6. (n, p) cross section for Sm-152.