Status of JENDL High Energy File

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The present status of the JENDL high-energy file is reported. The recent version (referred to as JENDL/HE-2007) contains neutron and proton cross section data for energies up to 3 GeV for 107 nuclides over the wide mass range from H to Am. The newly evaluated data for 41 nuclides have been added to the first version (JENDL/HE-2004) along with some revisions. The JENDL/HE-2007 includes neutron total cross sections, nucleon elastic scattering cross sections and angular distributions, nonelastic cross sections, production cross sections and double-differential cross sections of secondary light particles (n, p, d, t, ^{3}He, α, and π) and gamma-rays, isotope production cross sections, and fission cross sections in the ENDF-6 format. The evaluations were performed on the basis of experimental data, nuclear model calculations, and systematics based on measurements. The evaluated cross sections are compared with available experimental data and the other evaluations. Some results of benchmark tests with MCNPX codes are shown.

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I. INTRODUCTION

Recently, there have been increasing needs of intermediate and high energy nuclear data in various applications, such as accelerator-driven transmutation systems, particle radiation therapy, radioisotope production, space development, and so on. These applications require not only neutron data but also charged-particle data, particularly proton data, in particle transport and activation calculations. To meet the requirements, the activities on high-energy nuclear data evaluation have so far been undertaken all over the world, and have produced some avaliable nuclear data libraries, such as general purpose libraries like ENDF/B-VII.0 [1], JEFF-3.1.1 [2], and TENDL-2009 [3] for energies up to 150 or 200 MeV, and activation libraries like EAF-2007 [4] for energies up to 60 MeV.

In Japan, the Japanese Nuclear Data Committee (JNDC) had initiated the JENDL high-energy file project [5,6] to create high-energy neutron and proton libraries for energies up to 3 GeV on all the 132 nuclides listed in Table 1. One of the features is the extension of the maximum energy to 3 GeV from the 150 – 250 MeV range of the above-mentioned libraries. The first version was released as the JENDL/HE-2004 [6] for 66 nuclides. Then, evaluations for additional 40 nuclides were performed and the extended version called JENDL/HE-2007 was released in December 2007, which includes some minor revisions of the JENDL/HE-2004. Recently, a new evaluation of deuterium has been completed and the result has been supplemented in the JENDL/HE-2007.

Many benchmark tests have been performed to validate the JENDL/HE-2007 since its release, such as deep-penetration of high-energy neutrons in shielding materials, thick target neutron yields (TTNY) from high-energy proton bombardments, spallation experiments with high-energy protons, light-ion production from targets bombarded by high-energy neutrons, and so on. Some of them have been published in Refs. 7 - 11. In addition, PHITS and MCNPX simulations with the JENDL/HE library have been applied successfully in the topics relevant to high-energy cosmic-ray neutrons [12, 13] as examples of the practical use.

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Table 1. List of nuclides in JENDL high-energy file.

Newly-Added in JENDL/HE-2007 (41 nuclides)	^{2}H, ^{19}F, ^{23}Na, ^{35,37}Cl, ^{36,38,40}Ar, ^{69,71}Ga, ^{70,72,73,74,76}Ge, ^{75}As, ^{92,94,95,96,97,98,100}Mo, ^{181}Ta, ^{197}Au, ^{204,206,207,208}Pb, ^{209}Bi, ^{235,238}U, ^{237}Np, ^{238,239,240,241,242}Pu, ^{241,242,242m}Am
JENDL/HE-2004 (66 nuclides)	^{1}H, ^{12,13}C, ^{14}N, ^{16}O, ^{24,25,26}Mg, ^{27}Al, ^{28,29,30}Si, ^{39,41}K, ^{40,42,43,44,46,48}Ca, ^{46,47,48,49,50}Ti, ^{51}V, ^{50,52,53,54}Cr, ^{55}Mn, ^{54,56,57,58}Fe, ^{59}Co, ^{58,60,61,62,64}Ni, ^{63,65}Cu, ^{64,66,67,68,70}Zn, ^{90,91,92,94,96}Zr, ^{93}Nb, ^{180,182,183,184,186}W, ^{196,198,199,200,201,202,204}Hg
In preparation (25 nuclides)	^{6,7}Li, ^{9}Be, ^{10,11}B, ^{15}N, ^{18}O, ^{74,76,77,78,80,82}Se, ^{89}Y, ^{113,115}In, ^{232}Th, ^{233,234,236}U, ^{243}Am, ^{243,244,245,246}Cm

In this paper, the status of the JENDL/HE library is outlined. The evaluation methodology is briefly summarized in Sec. II. The evaluated cross sections are compared with available experimental data and other evaluations in Sec. III. Results of the benchmark test of TTNY experiments are shown in Sec. IV. Finally, a summary and future work are mentioned in Sec. V.

II. EVALUATION METHODOLOGY

The JENDL/HE-2007 has been evaluated in accordance with a schematic flow diagram illustrated in Fig. 1. A hybrid calculation code system combining some available nuclear model codes and systematics-based codes [5] was employed as in the JENDL/HE-2004 evaluation [6]. The GNASH code [14] based on statistical Hauser-Feshbach plus preequilibrium exciton models was used as the major code for the intermediate energy range below the matching energy E_c, which was set to be between 150 and 250 MeV, depending on target nuclei. A microscopic simulation code (either JAM [15] or JQMD [16]) was applied for energies above E_c, which is based on either the intra-nuclear cascade model or the quantum molecular dynamics for dynamical processes and the generalized evaporation model (GEM) [17] for the subsequent statistical decay processes. It should be noted that the JQMD calculations were adopted to only three elements, C, Mg, and Si. For neutrons, the evaluated cross section data were merged with the data below 20 MeV taken from the JENDL-3.3 [18].

In the following, newly-adopted evaluations in the JENDL/HE-2007 are described briefly: nucleon optical potentials, improvement of the preequilibrium exciton model, and cross section evaluation for deuterium.

Total, reaction, and elastic scattering cross sections above 20 MeV were evaluated based on optical model calculations with ECIS96 [19] or OPTMAN [20]. The code OPTMAN is based on the coupled-channels method with the nuclear Hamiltonian parameters determined by the soft-rotator model [21]. For Zr-isotopes,

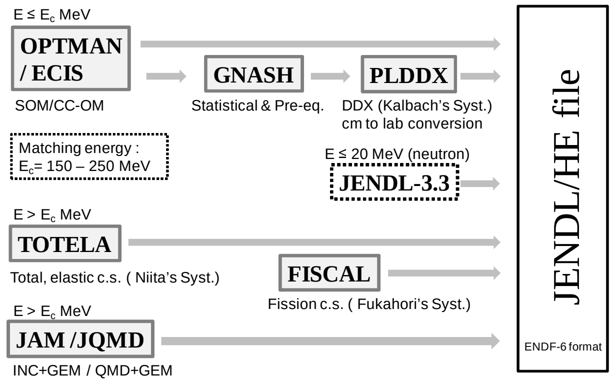

Fig. 1. Schematic evaluation flow diagram for JENDL high-energy file.

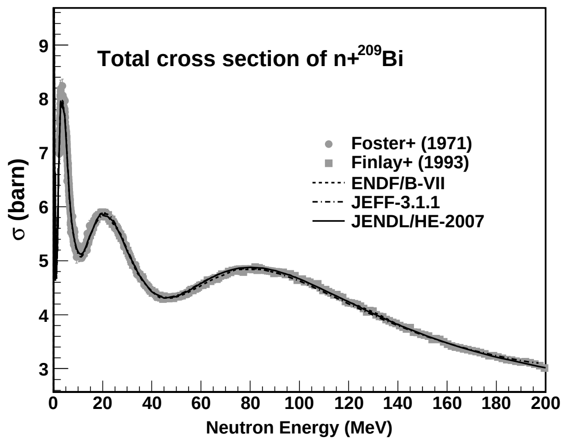

Fig. 2. Neutron total cross section of ^{209}Bi.

^{93}Nb, W-isotopes, Pb-isotopes, and ^{209}Bi, OPTMAN calculations were performed with nucleon optical potential parameters for energies below 200 MeV determined from recent systematic analyses by Kunieda *et al.* [22,23].

The Iwamoto-Harada coalescence model [24, 25] for preequilibrium complex particle emission was incorporated into the framework of the Kalbach exciton model in the GNASH code, and was applied to evaluations for ^{56}Fe, Zr-isotopes, ^{93}Nb, W-isotopes, Pb-isotopes, and ^{209}Bi. The work associated with the adopted Iwamoto-Harada model calculation has been presented in Ref. 26.

In the evaluation of deuterium up to 250 MeV, three-body Faddeev calculations [27,28] with realistic NN interactions were used along with experimental data, *e.g.*, elastic nucleon scattering, D$(n, 2n)$ and D$(p, n)2p$ reactions. Neutron total cross sections were evaluated using the least-square code GMA [29].

The cross section evaluations were performed for neutron and proton-induced reactions on the nuclides listed in Table 1, mainly using the above-mentioned model calculation codes. The parameters containing in the calculations were adjusted by using existing experimental data. The evaluated cross sections are as follows: neu-

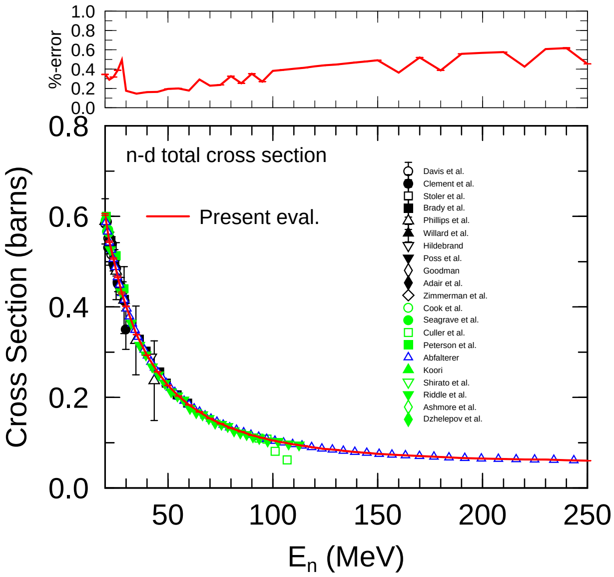

Fig. 3. (Color online) $n + d$ total cross section.

tron total cross sections, nucleon elastic scattering cross sections and angular distributions, nonelastic cross sections, production cross sections and double-differential cross sections of secondary light particles (n, p, d, t, ^{3}He, α, and π) and gamma-rays, isotope production cross sections, and fission cross sections. Neutron total cross sections and isotope production cross sections were evaluated using a fitting procedure of experimental data in the case where systematic measurements are available over the broad range of incident energy. Finally, the evaluated cross section data were tabulated in the ENDF-6 format.

III. COMPARISONS WITH MEASUREMENTS AND OTHER EVALUATIONS

Some results of the evaluated cross sections are shown below with experimental data [30] and the other evaluations (ENDF/B-VII.0 [1], JEFF-3.1 [2], and TENDL-2009 [3]).

Neutron total cross sections of ^{209}Bi is shown in the energy range up to 200 MeV in Fig. 2. Three evaluations almost coincide and are in excellent agreement with experimental data [31,32]. In Fig. 3, the JENDL/HE-2007 evaluation for neutron total cross sections of deuterium is compared with experimental data in the energy range between 20 and 250 MeV. The present evaluation reproduces the experimental data fairly well as can be seen from the GMA fitting errors in the upper figure.

In Fig. 4, the JENDL/HE-2007 evaluation for differential cross sections of neutron elastic scattering from Pb are compared with measurements [30] and the other evaluations (ENDF/B-VII.0 and JEFF-3.1.1). Each evaluations provides fairly good agreement with the experimental data at small angles. Some differences appear at

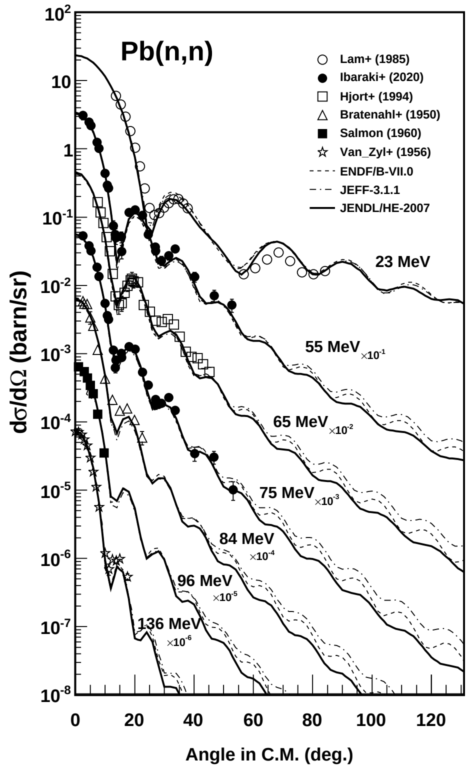

Fig. 4. Angular distributions of neutron elastic scattering from Pb.

large angles where there are no available experimental data.

Differential cross sections of $p + d$ elastic scattering are shown in Fig. 5. The JENDL/HE-2007 evaluation based on the Faddeev calculation including a Δ-excitation in the intermediate state reproduces the experimental data well over the wide incident energy range, although systematic underestimation is seen at angles larger than 120° as the incident energy becomes large over 100 MeV. However, the discrepancy is considered to be still an open problem, because the present Faddeev calculation provides better agreement with the recent data measured at CNS-RIKEN [33] as shown in Fig. 5.

Double-differential neutron production cross sections are presented for proton-induced reaction on ^{208}Pb at 120 MeV in Fig. 6. Three evaluations give close agreement with each other and the experimental data [34] in the continuum region between 30 to 90 MeV. The ENDF/B-VII.0 evaluation overestimates the experimental data around the high energy end at forward angles. Meanwhile, the JENDL/HE-2007 and JEFF-3.1.1 show rather good agreement with them to a similar extent, except a giant resonance like peak structure around 100 MeV seen at 0°.

Figure 7 shows a comparison between experimental data [35,36] and the evaluations for α-production cross sections for neutron-induced reaction on Fe. The ENDF/B-VII.0 evaluation is in excellent agreement with the experimental data because it adopts the data of

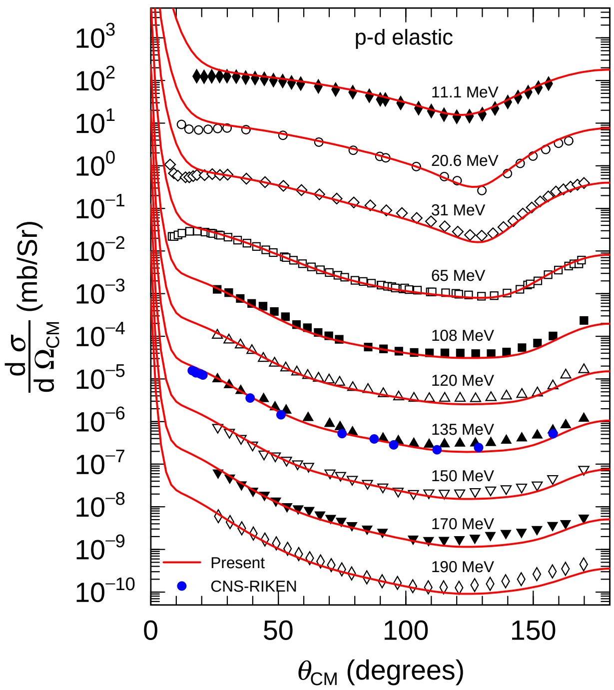

Fig. 5. (Color online) $p + d$ elastic scattering.

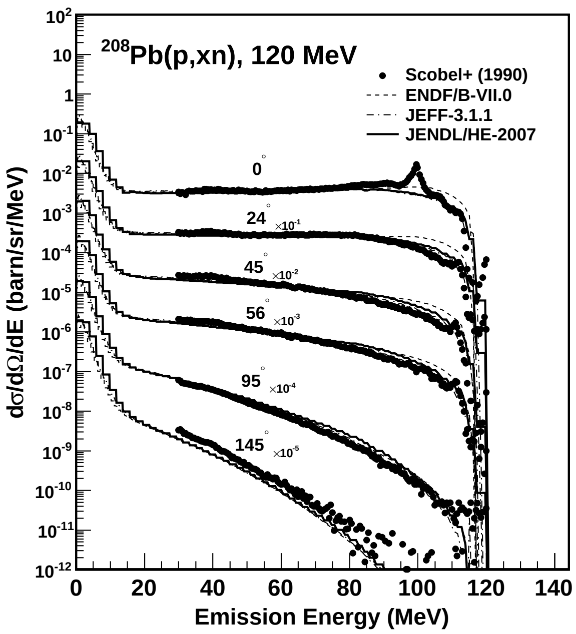

Fig. 6. Double-differential neutron production cross sections for the Pb(p, xn) reaction at 120 MeV, compared with the experimental data [34].

Haight [36]. The JEFF-3.1.1 and TENDL-2009 evaluations fails to reproduce the experimental data above 20 MeV. On the other hand, the JENDL/HE-2007 evaluation reproduces the experimental data successfully by the GNASH calculation incorporating the Iwamoto-Harada preequilibrium coalescence model. This implies

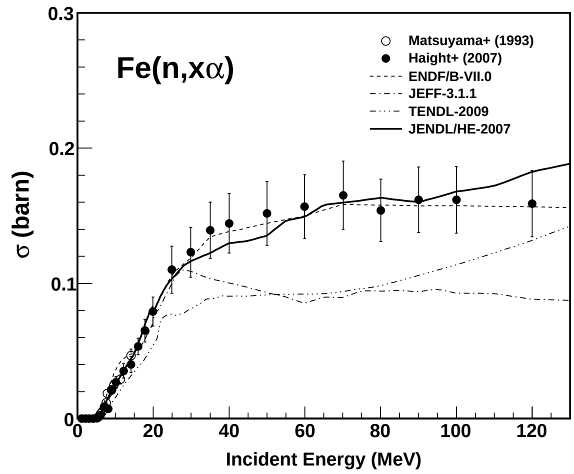

Fig. 7. Alpha particle production cross section for the neutron-induced reaction on iron.

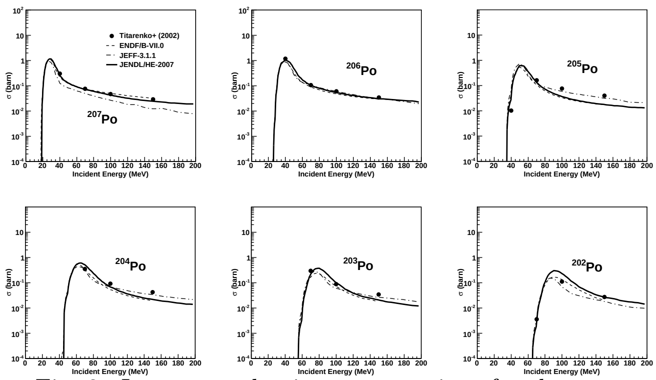

Fig. 8. Isotope production cross sections for the proton-induced reaction on ^{209}Bi.

that refinement of the preequilibrium models is essential to improve the agreement with the measurement because preequilibrium α emission is predominant at higher incident energies than 20 MeV.

In Fig. 8, isotope production cross sections for the Bi(p,x) reaction for incident energies up to 200 MeV are shown. The evaluated cross sections are compared with the experimental data [37] for production of $^{202-207}$Po. Three evaluations (JENDL/HE-2007, ENDF/B-VII.0, and JEFF-3.1) are in agreement with the experimental data to a similar extent.

Finally, pion production cross sections from proton-induced reactions on ^{12}C are shown in Fig. 9. The present evaluation based on the QMD calculation reproduces the experimental data [38] of π^+ production well.

IV. BENCHMARK TESTS

To validate the evaluated cross sections, some benchmark tests using the MCNPX transport code [39] and the PHITS code [40] were performed. Some of them have been reported in Refs. 7 - 11.

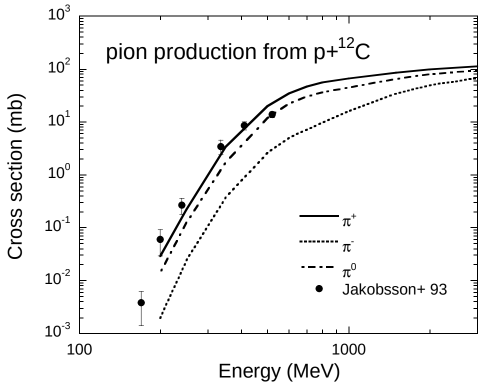

Fig. 9. Pion production cross sections for the proton-induced reaction on C.

Here the results of double-differential neutron yields from stopping-length targets are presented for carbon and uranium targets bombarded by 113-MeV protons in Fig. 10. As for carbon (a), the MCNPX calculation with the JENDL/HE-2007 shows excellent agreement with the measurement [41] except underestimation seen above 30 MeV at 7.5 degrees. The calculations using the ENDF/B-VII.0 overestimate remarkably the measurement for neutrons between 3 and 20 MeV and underestimates it for neutrons above 30 MeV at 7.5 and 30 degrees. The calculation with TENDL-2009 fails to reproduce the experimental data over the whole energy range at four angles. With respect to uranium (b), the calculation with JENDL/HE-2007 is in good agreement with the measurement except at energies below 1 MeV and near the high energy end, whereas the one with the ENDF/B-VII.0 overestimates the experimental data considerably at energies above 10 MeV at forward angles.

V. SUMMARY AND FUTURE WORK

The present status of the recent version of the JENDL high-energy file, JENDL/HE-2007, was reported. The cross sections were evaluated for neutrons and protons up to 3 GeV for total 107 nuclides listed in Table 1, mainly on the basis of the nuclear model calculations and the systematics. The JENDL/HE-2007 evaluation were compared with the other evaluations and the experimental data, showing generally good agreement with them. The benchmark tests using transport codes such as MCNPX and PHITS were performed for validation of the JENDL/HE-2007 library. The superiority of the JENDL/HE-2007 was verified for some cases, such as the thick target neutron yields from proton bombardment on C and U.

Evaluations and compilations for the remaining 25 nuclides (particularly, ^{6,7}Li, ^{9}Be, ^{15}N, and ^{18}O) are underway towards completion of the JENDL high-energy file. Since the JENDL-4 general purpose file [42] has been released in 2010, the evaluated cross sections below 20 MeV in the JENDL/HE-2007 should be replaced by those in the JENDL-4 in the near future. Such revision and updating work will be continued by applying useful feedback from more benchmark tests.

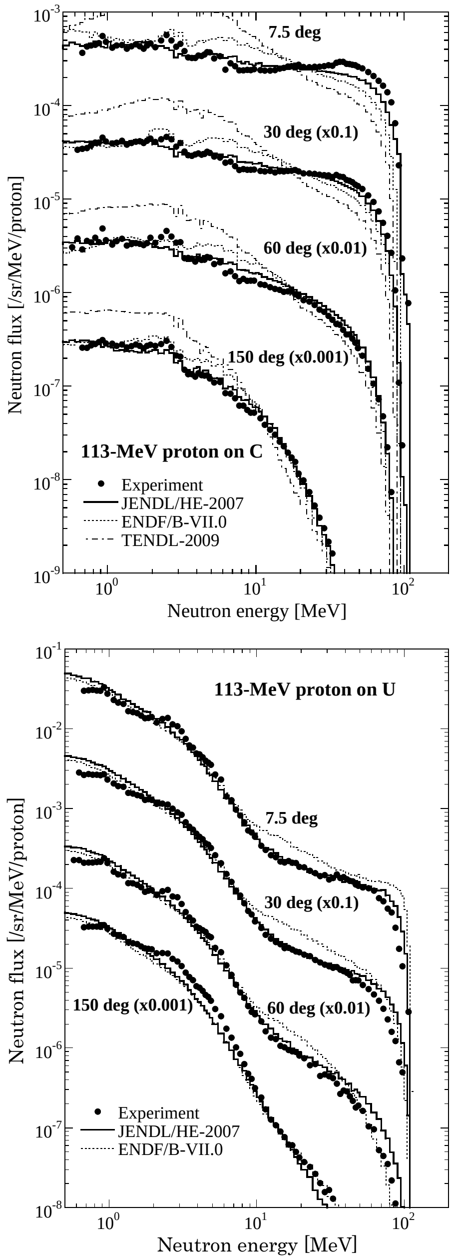

Fig. 10. Comparison of MCNPX calculations and measurements for neutron yields from stopping-length carbon target (a) and uranium target (b) for 113-MeV protons.

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