Present Status of JENDL High-Energy File

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The high energy nuclear data evaluation working group in the Japanese Nuclear Data Committee has a mission to evaluate neutron and proton nuclear data for energies ranging from 20 MeV to 3 GeV, and to compile the evaluated data as JENDL high-energy file. The present status of this activity is reported.

1. Introduction

In recent years, high-energy nuclear data are required for various applications of accelerators, such as accelerator-driven transmutation system and advanced cancer therapy with particle beams, and space development [1]. Proton data as well as neutron data are necessary in these high-energy applications. It should be noted that "high-energy" stands for incident nucleon energies above 20 MeV that corresponds to the upper limit of existing data files for fission and fusion reactors. Major nuclear data required in high-energy files are as follows: cross sections relevant to particle transport calculations, such as total cross sections, elastic scattering cross sections, and double-differential particle production cross sections, isotope production cross sections for dosimetry and activation, and gas production cross sections for material damage evaluation. Nuclear data evaluation is generally carried out on the basis of experimental data and theoretical model calculations. However, the experimental data are sparse for neutron-induced reactions in the high-energy region and systematic measurements are not necessarily enough for proton data. Therefore, theoretical model calculations play a major role in the high-energy nuclear data evaluation.

Under these circumstances, the Japanese Nuclear Data Committee (JNDC) continues some activities concerning neutron and proton nuclear data evaluation for energies ranging from 20 MeV to 3 GeV towards completion of JENDL high-energy file [2]. The present status is reported below.

2. High-energy nuclear reactions

Some features of high-energy nuclear reactions are summarized in Fig. 1. First, dynamical processes, such as preequilibrium process and multi-fragmentation process, become dominant. Particle emission via such processes shows forward-peaked angular distribution in the center of mass system. Second, reaction products over a wide range of mass and atomic numbers are generated via high-energy nuclear reactions with high multiplicity of light charged particles and neutrons as shown in the right panel of Fig.1. Third, the degree of freedom of pions and excited nucleons, such as Δ and N^*, becomes important as the incident energy increases. Therefore, it is also necessary to take into account such hadrons by regarding a nucleus as hadron many-body system beyond a picture of nucleon many-body.

High-energy nuclear data evaluation needs reliable theoretical models that can account for these features well over the wide incident energy range: statistical multistep models for preequilibrium process, simulation methods using molecular dynamics for hadronic reactions followed by multi-fragmentation, and so on.

3. JENDL High-Energy File

3.1 Outline

Nuclides to be evaluated are summarized in Table 1. They are categorized into three parts in accordance with users' priority. The upper limit of incident energy is 3 GeV. The following cross sections are evaluated on the basis of experimental data and theoretical model calculations: total cross sections, elastic scattering cross sections and their angular distributions, particle production cross sections and double-differential cross sections, and isotope production cross sections. These cross section data are stored in the JENDL high-energy file in the ENDF-6 format.

3.2 Evaluation method

A theoretical model calculation system for JENDL high-energy evaluation is illustrated in Fig.2. Different theoretical models are used in accordance with incident energies: (I) intermediate energies ranging from 20 MeV to 250 MeV and (II) high energies above 150 MeV. A major code used in (I) is the GNASH code [3] based on statistical Hauser-Feshbach plus preequilibrium models. The other code, such as EXIFON [4], is partially used for evaluation of light nuclei, such as N and O. The ECIS code [5] or the OPTMAN code[6] is used for optical model calculations. It should be noted that the ECIS plus GNASH code system is basically same as that used in LA150 evaluation [7]. In (II), the code JQMD[8] based on Quantum Molecular Dynamics (QMD) plus statistical decay model is employed. Also, the code TOTELA [9] based on systematics is employed as a tool for evaluation of total, elastic, and proton reaction cross-sections in (II). Both calculation results for (I) and (II) are combined in the overlapping energy region between 150 and 250 MeV. Isotope production cross sections are evaluated using the GMA code[10] based on the generalized least-squares method or empirical fits in cases where there are a lot of available experimental data.

3.3 Results

Some results of evaluations of ^{12}C and ^{63,65}Cu are shown below in comparisons with experimental data and the other evaluated high-energy file. Other results for several nuclides have also been reported elsewhere, *e.g.*, ^{27}Al [11], ^{28}Si [12], W-isotopes[13], and ^{56}Fe [14].

Figure 3 presents comparisons of experimental and calculated angular distributions for elastically scattered nucleons from ^{12}C. The calculation was carried out using the OPTMAN code based on the coupled-channels method with the nuclear Hamiltonian parameters determined by the soft-rotator model [15]. Both experimental data for neutron and proton are reproduced well by the CC calculation. Thus, these calculated results were adopted as evaluated values of total cross sections, elastic and inelastic scattering cross sections, and total reaction cross sections up to 150 MeV. Transmission coefficients obtained by the CC calculation were used in GNASH calculations of particle and gamma-ray emission cross sections and isotope production cross sections up to 150 MeV. Two examples of evaluated production cross sections are shown with experimental data and LA150 evaluation[7] in Fig. 4. For energies above 150 MeV, the QMD+SDM calculation was used. Double-differential cross sections calculated with the Kalbach systematics[16] are compared with measured ones for the ^{12}C (p,xp) reaction at 90 MeV, showing overall good agreement with measured data.

For ^{63,65}Cu, the ECIS code was employed for analyses of total cross sections and elastic scattering cross sections, and spherical optical potential parameters were adjusted for neutron and proton up to 250 MeV. Calculated angular distributions of nucleon elastic scattering from ^{63}Cu are compared with experimental ones in Fig. 5. Evaluated total cross sections are plotted together with experimental data and JENDL-3.3 evaluation less than 20 MeV in Fig.7. Niita's systematics [17] was used for energies above 250 MeV. The evaluated cross section shows excellent agreement with the experimental data in the energy range between 20 MeV and 3 GeV. Isotope production cross sections were evaluated with the GMA code[10] based on experimental data of each isotope and natural Cu. In the case of sparse measurement, theoretical calculations with GNASH and QMD were mainly adopted. Those results are shown in Figs. 8 to 10.

4. Summary and future plan

The present status of JENDL high-energy file was reported. The evaluations of cross sections for nuclides with the 1st priority have almost been completed and the compilation work is now in progress. For nuclides with the 2nd and 3rd priorities, evaluations and their compilation are intensively in progress. Review and benchmark test should be performed for the data file of the nuclides that have already been evaluated. Results of the related benchmark test for iron are reported elsewhere [14]. Finally, it is planned to release the 1st version of JENDL high-energy file in March 2001.

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Table 1. Nuclides to be stored in JENDL high-energy file

1st priority	^{1}H, ^{12}C, ^{14}N, ^{16}O, ^{23}Na, ^{27}Al, ^{50,52,53,54}Cr, ^{54,56,57,58}Fe, ^{58,60,61,62,64}Ni, ^{63,65}Cu, ^{181}Ta, ^{180,182,183,184,186}W, ^{197}Au, ^{196,198,199,200,201,202,204}Hg, ^{204,206,207,208}Pb, ^{209}Bi, ^{235,238}U
2nd priority	^{9}Be, ^{24,25,26}Mg, ^{28,29,30}Si, ^{39,41}K, ^{40,42,43,44,46,48}Ca, ^{46,47,48,49,50}Ti, ^{51}V, ^{55}Mn, ^{59}Co, ^{90,91,92,94,96}Zr, ^{93}Nb, ^{92,94,95,96,97,98,100}Mo, ^{238,239,240,241,242}Pu
3rd priority	^{2}H, ^{6,7}Li, ^{10,11}B, ^{13}C, ^{19}F, ^{35,37}Cl, ^{35,38,40}Ar, ^{50}V, ^{64,66,67,68,70}Zn, ^{69,71}Ga, ^{70,72,73,74,76}Ge, ^{75}As, ^{89}Y, ^{232}Th, ^{233,234,236}U, ^{237}Np, ^{241,242,242m,243}Am, ^{243,244,245,246}Cm

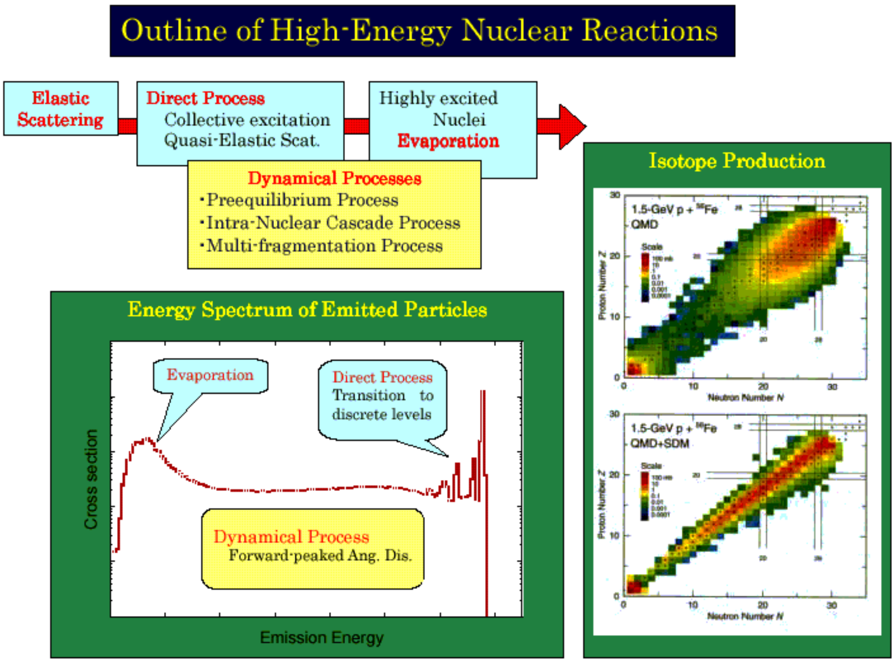

Fig.1 High-energy nuclear reactions

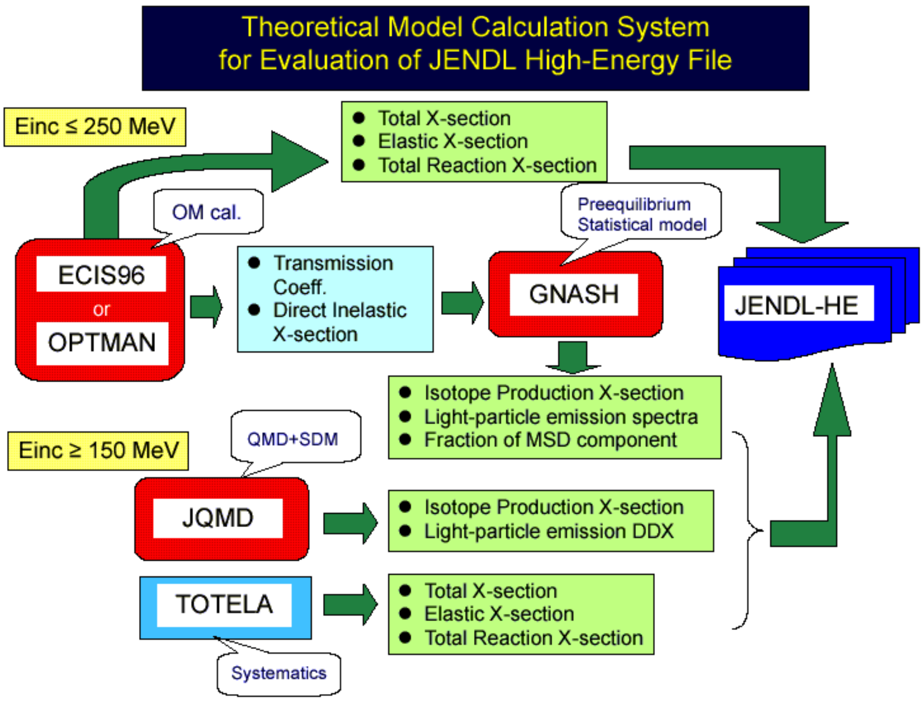

Fig.2 Model calculation code system for JENDL high-energy nuclear data evaluation.

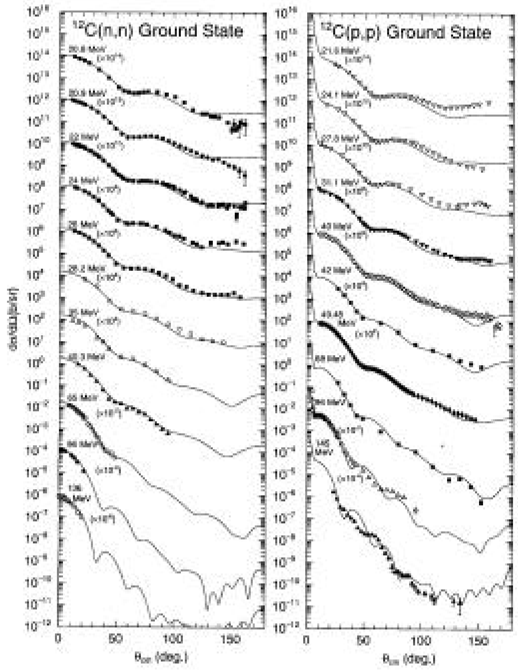

Fig.3 Comparison of measured (symbols) and calculated (solid lines) angular distributions for elastically scattered nucleons from ^{12}C. This figure is taken from Ref.[15].

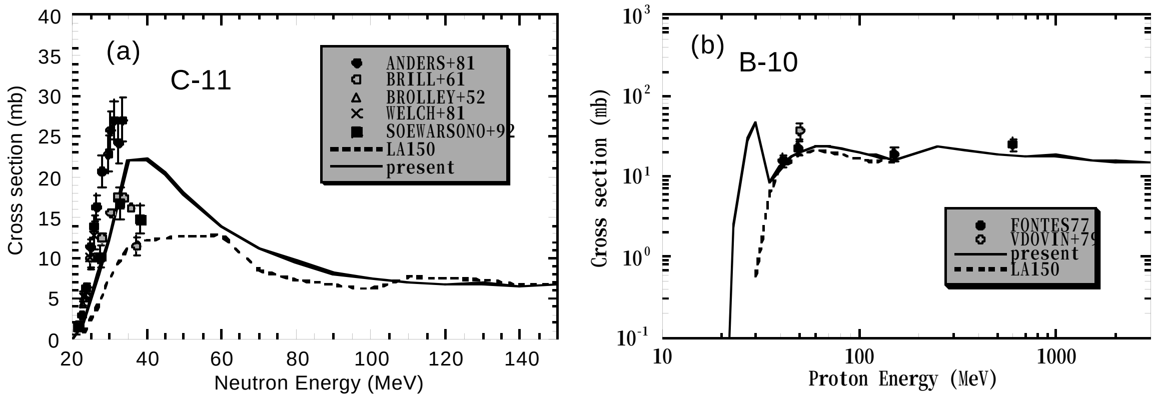

Fig.4 Isotope production cross sections: (a) $^{12}C(n,2n)^{11}C$ and (b) $^{12}C(p,x)^{10}B$.

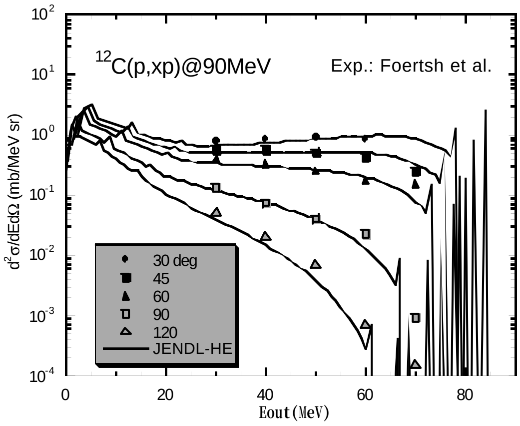

Fig.5 Double-differential cross sections of the (p,xp) reaction on ^{12}C at 90 MeV.

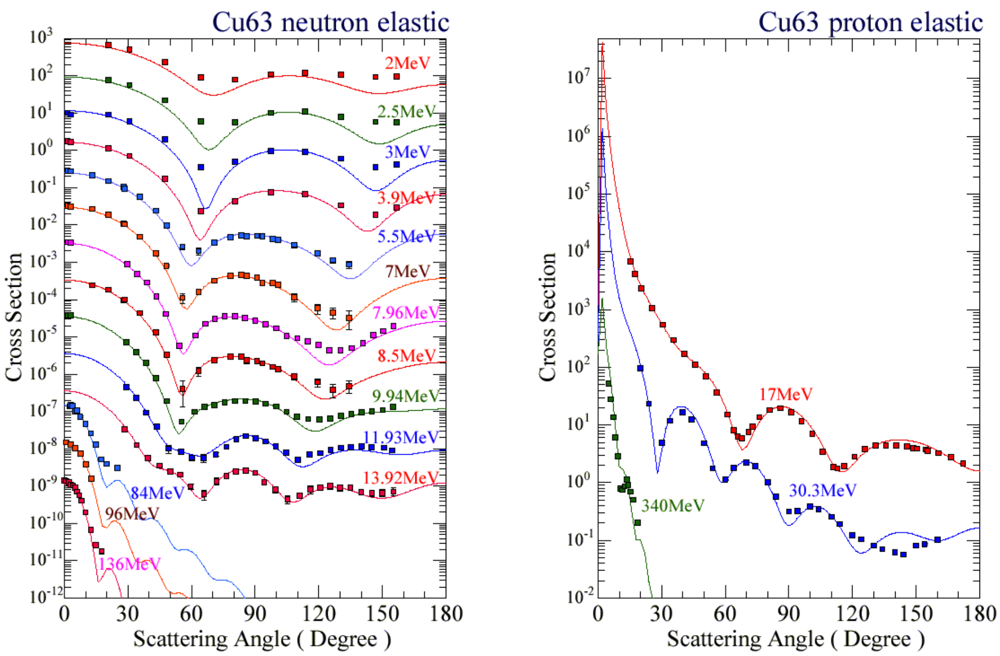

Fig.6 Comparison of calculated and measured angular distributions of nucleon elastic scattering from ^{63}Cu.

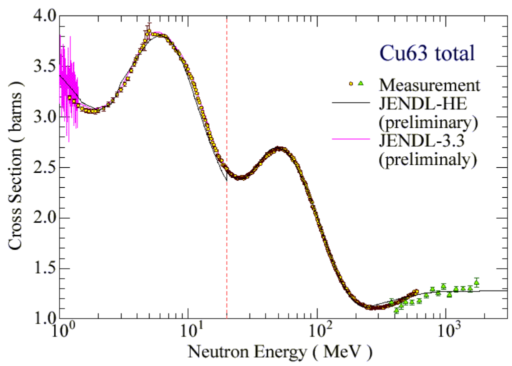

Fig.7 Total cross sections of ^{63}Cu.

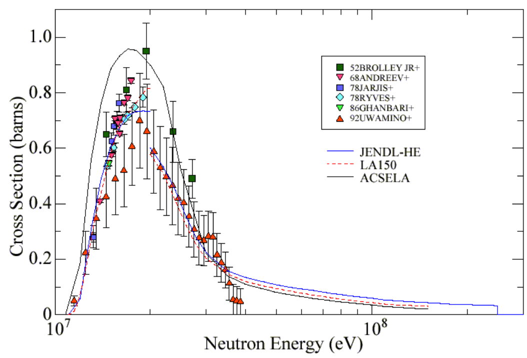

Fig.8 ^{63}Cu(n,2n)^{62}Cu production cross sections.

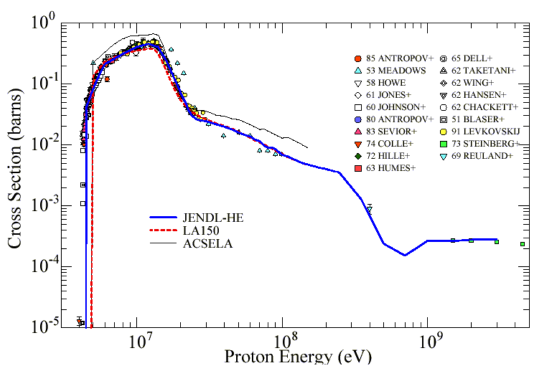

Fig.9 ^{63}Cu(p,n) ^{63}Zn production cross sections.

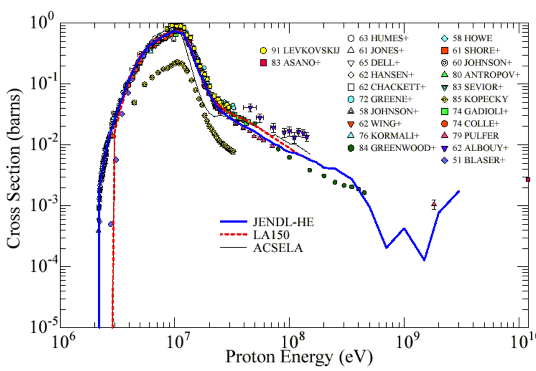

Fig.10 ^{65}Cu(p,n) ^{65}Zn production cross sections.