Status of the JENDL project

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Abstract. Status of the JENDL project after releasing the latest general purpose file JENDL-4.0 is described. By correcting errors and adding covariance data of JENDL-4.0, 38 files have been released as JENDL-4.0u. Development of next general purpose file JENDL-5 is also in progress. New evaluations have been performed for light nuclei, structural materials and fission products. Two special purpose files, JENDL-4.0/HE and JENDL/DDF-2015 were released in 2015. The former includes neutron induced reaction data for 130 nuclides in the energy region up to 200 MeV as well as proton induced reaction data for 133 nuclides. The latter is the decay data file of 3,237 nuclides from Z = 1 to 104 and neutron. Other two special purpose files of activation cross section and photonuclear data are under preparation and will be released soon.

1. Introduction

The latest version of the general purpose file JENDL-4.0 [1] was released in 2010 with improving fission-product and minor-actinide data as well as covariance data to meet needs of innovative reactors. To address problems found in JENDL-4.0 without delay, their updated files have been released as JENDL-4.0u . They fixed not only serious errors but also minor bugs. Due to increased demands of uncertainties of nuclear data, it also includes newly evaluated covariance data of JENDL-4.0.

After the release of JENDL-4.0, efforts to extend energy range up to 200 MeV have been made in order to meet needs from various accelerator applications such as the accelerator driven system (ADS). They were compiled with proton induced reaction data into JENDL-4.0/HE and released in 2015. The JENDL Decay Data File 2015 was released in 2015. It would be used in estimation of radio-isotope production by radioactive decay in materials for the decommissioning of nuclear reactors.

Two special purpose files are under development. One is a neutron activation cross section file for decommission of light water reactors. It will contain data for approximately 300 nuclides. The other is a photonuclear data file which updates the previous version JENDL/PD-2004.

Evaluation of nuclear data for the next version of the general purpose file JENDL-5 is also in progress. It is planned to be released by 2022. Several new evaluations mainly for fission products were already done. Data for light nuclei and structural materials are intensively evaluated. Minor actinides data will be improved becaue of their importance for development of transmutation systems of nuclear waste.

Section 2 describes the status of general purpose file including JENDL-4.0u and JENDL-5. Section 3 provides information on the special purpose files. Conclusions are given in Sect. 4.

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2. General purpose file

2.1. JENDL-4.0u

JENDL-4.0 Update Files (JENDL-4.0u) are intended to provide corrected data as well as newly evaluated covariances for JENDL-4.0. Until August in 2016, 38 updated files have been released for nuclei of ^{2}H, ^{10}B, ^{48}Ti, ^{52}Cr, ^{53}Cr, ^{59}Ni, ^{109}Ag, ^{127m}Te, ^{129m}Te, ^{233}U, ^{234}U, ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu, ^{242m}Am, ^{243}Am, ^{129m}Te, ^{156}Eu, ^{39}K, ^{48}Ti, ^{196}Hg, ^{202}Hg, ^{204}Hg, ^{224}Ra, ^{225}Ra, ^{234}U, ^{237}Np, ^{238}Pu, ^{242}Pu, ^{241}Am, ^{197}Au, ^{88}Sr, ^{204}Pb, ^{206}Pb, ^{207}Pb, ^{208}Pb and ^{105}Rh in released order. Note that some of them were updated twice where the first release is labeled as JENDL-4.0u1 and second one as JENDL-4.0u2.

Serious compilation errors were corrected after the release of JENDL-4.0. For example, the elastic scattering cross sections of ^{10}B exhibit strange fluctuations in the energy region from 1 eV to 10 keV. This is due to the fact that the elastic scattering cross section was obtained by subtracting the non-elastic cross section from the total cross section. In the case of ^{10}B, the total cross section is comparable to the non-elastic cross section in the low energy region, since the (n, α) cross section is dominant. Therefore, subtraction of a large number from a comparable large number led to computation errors. The updated cross section is illustrated in Fig. 1.

The covariances of the resolved resonance parameters (MF32) for ^{233,235,238}U and ^{239}Pu were converted to the cross section covariances (MF33), since some drawbacks were found especially for the uranium isotopes. The original covariances were taken from those obtained by the ORNL group, but they were truncated to smaller incident energies due to too large size. This matrix truncation obviously neglected a long-range correlation between the thermal region and the distant resonances, leading to a large uncertainty (∼ 5%) for ^{235}U(n, f) at thermal energy. As seen in Fig. 2, the relative uncertainty of the updated data becomes much smaller than that of the original ones.

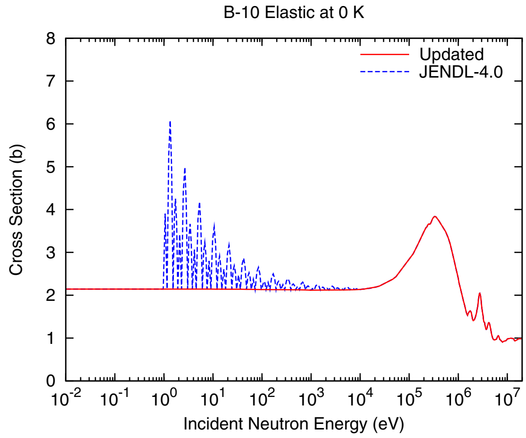

Figure 1. Neutron elastic scattering cross section of ^{10}B.

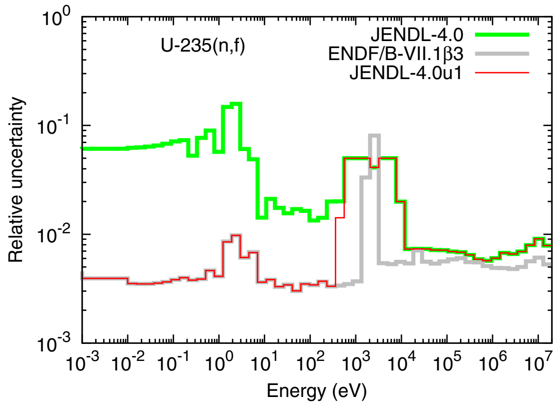

Figure 2. Relative uncertainty of ^{235}U(n, f).

Moreover, from the view points of applications, the fast-energy covariances for ^{52,53}Cr and the full covariances for ^{204,206,207,208}Pb were newly evaluated. In addition, the neutron-induced fission yields of ^{241}Pu were corrected for the mass numbers larger than 160.

Detailed information and evaluated files of JENDL-4.0u are available from our web site [2].

2.2. Next version of general purpose file

Aiming at improving completeness and reliability of nuclear data required in various application fields, evaluation of nuclear data for the next version of the general purpose file JENDL-5 is in progress. It is intended to cover all of stable isotopes and to include plenty of covariance data. Isomer productions cross sections which are evaluated consistently with other cross sections will be also stored.

New evaluations for several tens of fission products not revised at the release of JENDL-4.0 were already done. Data for light nuclei and structural materials will be updated including new resonance analyses. Minor actinides data are one of main targets of JENDL-5 which are important to develop transmutation system of nuclear waste.

JENDL-5 is planned to be released by 2022.

2.2.1. Light nuclei

The cross sections on the light mass nuclei are important not only for the nuclear engineering but also for the astrophysics and the medical applications. Looking at JENDL, however, a number of evaluations had not been updated over the past few decades for the light nuclei.

We plan to newly evaluate cross sections on the light mass nuclei as much as possible, starting from the resonance energy region. AMUR, which is now under development by one of the authors, is a multi-channel R-matrix code to interpolate/extrapolate experimental data by imposing physical constraint from the quantum mechanics. The theory we adopted is the standard one proposed by Wigner and Eisenbud [3], except for the γ-ray channels which are treated by the Reich-Moore approximation [4]. The code also estimates the data covariance with the method equivalent to the KALMAN code [5]. Preliminary evaluations have been already made for the ^{16}O and ^{19}F [6].

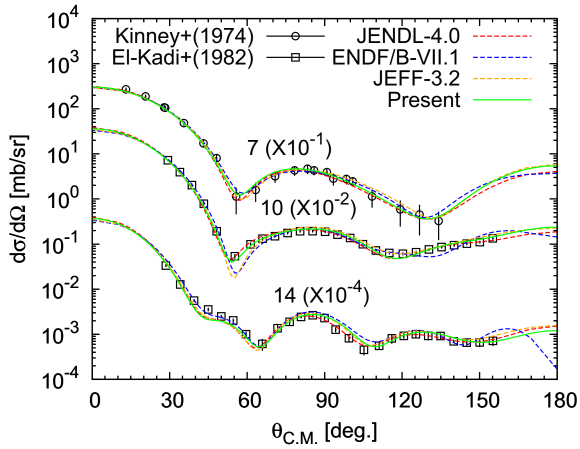

Figure 3. Differential cross sections of neutron elastic scattering from ^{63}Cu. The number at the top of each plot denotes incident energy in MeV.

2.2.2. Structural materials

Structural materials are important in all nuclear facilities but old evaluated data still remained and covariance data are not enough in the library. New evaluations are in progress to improve this situation. Isomer production data will be also added to the library. As examples, recent activities for copper and niobium isotopes are briefly mentioned below.

Copper is one of important elements in structural materials. In the evaluation on copper isotopes of JENDL-4.0 [1], the neutron total cross sections on ^{63,65}Cu were obtained from least-square fit to experimental data. In addition, the cross sections for several reactions were calculated by the different computational codes, respectively. Therefore, we calculated all cross sections for the neutron induced reactions on ^{63,65}Cu using only the CCONE code [7,8]. In the new calculation [9], the dispersive optical model potential (OMP) by Soukhovitskii et al. [10] with a couple-channel method was adopted. Consequently, the consistently calculated results reproduced the available measured cross sections and angular distributions as well as the other existing evaluated data [9] as shown in Fig. 3. Covariance will be deduced based on these calculations.

^{93}Nb, whose natural isotopic abundance is 100%, is being employed as an element of fuel cladding materials. Cross sections of ^{93m}Nb and ^{92m}Nb production by neutrons

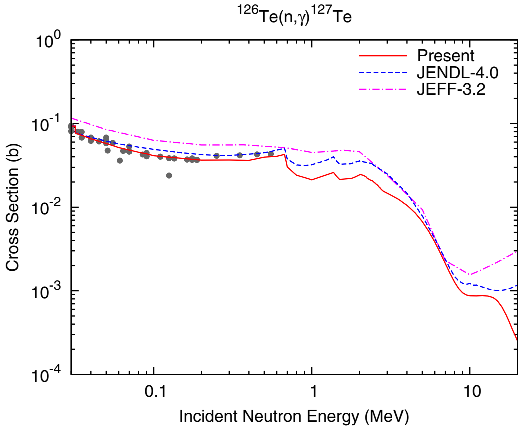

Figure 4. Neutron capture cross section of ^{126}Te. Evaluated and experimental data are shown by lines and points, respectively.

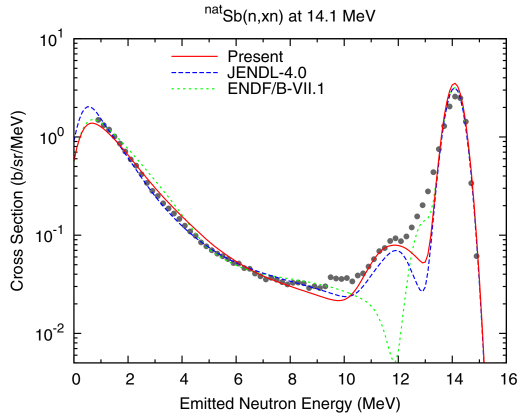

Figure 5. Neutron emission spectra for elemental Sb at 14.1 MeV. Evaluated and experimental data are shown by lines and points, respectively.

are important as a long-term activation monitor in the reactor dosimetry and a standard for the 14 MeV neutron flux determination, respectively. The ^{93}Nb cross sections were evaluated by the CCONE code. Agreement with the experimental data has been improved compared with the JENDL/A-96 evaluation [11].

2.2.3. *Fission products*

In JENDL-4.0, the FP data on about 50 nuclides were not fully reviewed due to the deadline of the release. Hence, these data may need improvements for JENDL-5. As a matter of fact, the following FP data have been evaluated since JENDL-4.0 was released: ^{69,71}Ga, ^{93}Nb, ^{99}Tc, $^{96,98,99-106}$Ru, $^{121,123-126}$Sb, $^{120,121m,122-126,127m,128,129m,130,131m,132}$Te, $^{127-131,135}$I, and $^{162,164,166-168}$Er. Evaluations of these nuclides were performed by using the CCONE or POD [12] code in the fast-neutron energy region. We usually employed the coupled-channel neutron optical model parameters obtained by Kunieda et al. [13] because total cross section is often in better agreement with measurements than that using the spherical optical model potentials. The systematics of Mengoni and Nakajima [14] was used for the level-density parameterization, and the densities were smoothly connected with the discrete levels that were taken from the RIPL database [15]. It is normal to adjust the γ-ray strength functions so as to reproduce measured capture cross sections in the energy region of 10–100 keV. Figure 4 shows the capture cross section of ^{126}Te thus obtained [16]. In this case, the present and JENDL-4.0 evaluations are consistent with measurements, while the JEFF-3.2 evaluation is slightly larger than them. Neutron emission spectra are useful for demonstrating the validity of the nuclear models used for an evaluation. Figure 5 shows the angle-integrated neutron emission spectra for elemental Sb [17] at 14.1 MeV. In this case, we assumed a pseudo-resonance at an excitation energy of 2.3 MeV for ^{121,123}Sb, which can substitute for the missing collective enhancement phenomenologicaly.

2.2.4. *Actinides*

Nuclear data of minor actinide (MA) have large uncertainties compared with ones required on design of transmutation system of radioactive nuclear wastes.

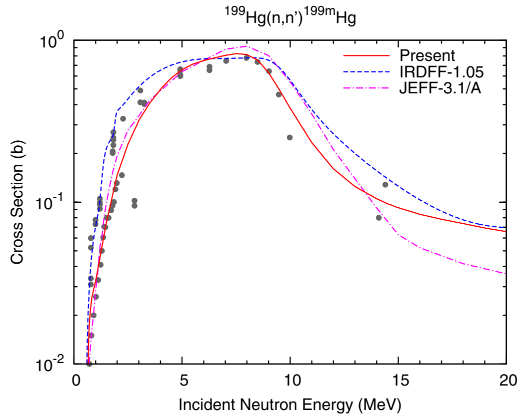

Figure 6. ^{199}Hg$(n,n')^{199m}$Hg reaction cross section. Evaluated and experimental data are shown by lines and circles, respectively.

Activity to improve MA nuclear data titled the AIMAC project [18] is in progress. New experimental data of TOF and activation cross section measurements for Np and Am isotopes will be available. Nuclear data of MA will be evaluated using those new data as well as the other available data.

For major actinides, significant progresses have been found in the CIELO project [19] that intends a world collaboration on nuclear data evaluations. JENDL-5 will be improved taking accounts of their achievements.

2.2.5. *Other nuclei*

As for medium-heavy nuclei, we have evaluated the data on ^{179,180m,181,182}Ta, $^{189-198}$Pt, $^{195-203}$Hg, and $^{203-205}$Tl. The evaluation methods and procedures are almost the same as those for fission products. Figure 6 shows the $^{199}Hg(n,n')^{199m}$Hg cross section [20] which is important as one of the dosimetry cross sections. The IRDFF-1.05 data [21] are based on a least-squares fit to the renormalized experimental data below 10 MeV, although the theoretical calculations were taken into consideration above 10 MeV. The present evaluation yields the dosimetry cross sections by placing much emphasis on the theoretical understanding of the reaction.

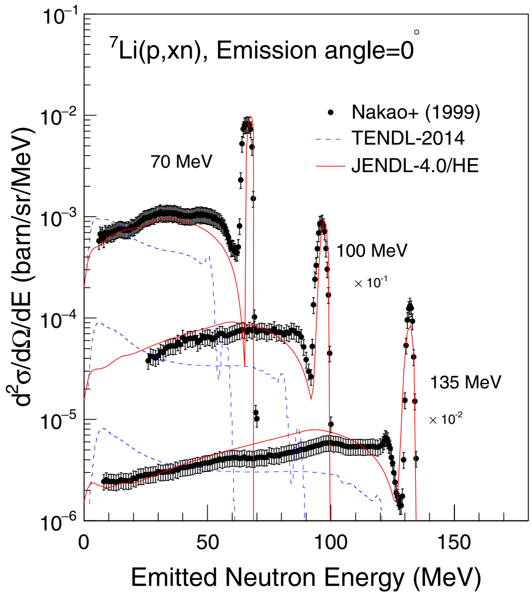

Figure 7. Neutron emission spectrum at 0 degree from proton induced reaction on ^{7}Li at incident energies of 70, 100 and 135 MeV.

3. Special purpose file

3.1. JENDL-4.0/HE

To meet needs of the design of various accelerator applications, by extending incident energy of JENDL-4.0 a new library including evaluated nuclear data for incident neutrons and protons up to 200 MeV have been released.

The neutron induced reaction data below 20 MeV were carried over from JENDL-4.0 and JENDL-4.0u. Some of the data mainly for actinides were taken from JENDL/HE-2007 [22]. Due to the limitation of available experimental data at high energy region, systematical calculations using the CCONE code with updating pre-equilibrium model [23] were performed for many nuclides for medium mass regions such as isotopes of Si, P, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Zr, Nb, Mo, In, Sn, I, Cs, Ta, W, Au, Hg, Pb and Bi using globally optical model parameterization [13]. They show reasonable agreement with available experimental data without tuning the model parameter in particular.

For the light nuclei, new evaluation was done for proton induced reactions on ^{6,7}Li and ^{9}Be. For ^{7}Li, a new R-matrix analysis including channels of proton, neutron and α resulted in reliable evaluation in resonance region. Calculated data with CCONE were applied to obtain continuum emission spectra. Neutron emission spectra are shown in Fig. 7. JENDL-4.0/HE agrees with experimental data of Nakao et al. [24] well.

3.2. JENDL/PD-2016

The previous version of photonuclear data file JENDL/PD-2004 was released [25]. It includes photon induced reaction data on 68 nuclides from ^{2}H to ^{237}Np. The energy range was set to be from particle threshold to 140 MeV, at which the pion production takes place.

Evaluation efforts to develop new file have been continued. A new photonuclear data file is now ready for release. The purpose is mainly to improve evaluations by

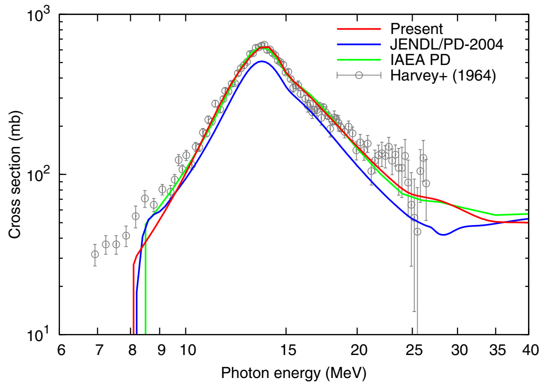

Figure 8. Comparison of the present results for ^{206}Pb(γ, xn) with experimental data. The data of evaluated libraries, JENDL/PD-2004 and IAEA photonuclear data, are shown.

taking account of new experimental data especially for nuclides lighter than $Z = 20$, and to extend the number of nuclides which makes application fields wide. The cross section and angle-energy distribution for particle emissions were evaluated with the ALICE-F [26] and CCONE codes. The covered range of nuclides and the upper energy of incident photon are the same as the previous one, but the lower energy limit is 1 MeV or particle threshold energy depending on the codes used for the evaluations. For the nuclides with $Z \leq 20$ the measurement revealed that the cross sections have fine structures on resonance peaks. These features are not expressed by the simple giant resonance parameterization. Hence, the resonance analysis was performed for each cross section peak by using nuclear structure data (ENSDF [27] and RIPL-2 [28]). At the higher energy where the resonance structure was not observed, the nuclear data were calculated by the ALICE-F. For the nuclides above Ca the photonuclear data were calculated with the ALICE-F and CCONE. In this file the cross sections of residuals and emitted particles (neutron, proton, deuteron, triton, ^{3}He, α-particle and photon) and angle-energy distribution of emitted particles were included in MF6 and MT5 of the ENDF-6 format.

For the evaluation experimental data were renormalized if suggested. Figure 8 shows the comparison of the present data for ^{206}Pb(γ, xn) with the experimental data renormalized by following the suggestion of Berman [29]. The data of evaluated libraries, JENDL/PD-2004 and IAEA photonuclear data file [30] are also illustrated. The present result well reproduces the measured data. The present data is 1.22 times larger than the data of JENDL/PD-2004.

It is planned to release two types of file. The standard file consists of 181 nuclides. The data are based on the results evaluated by the ALICE-F and CCONE. Another version is an extended file which is calculation-based one, adopting ALICE-F. The number of nuclides included exceeds 2600. The extended file aims at taking care of wide application fields not only for the estimation of photon induced activation in electron linear accelerator facilities, but also for unseen subjects.

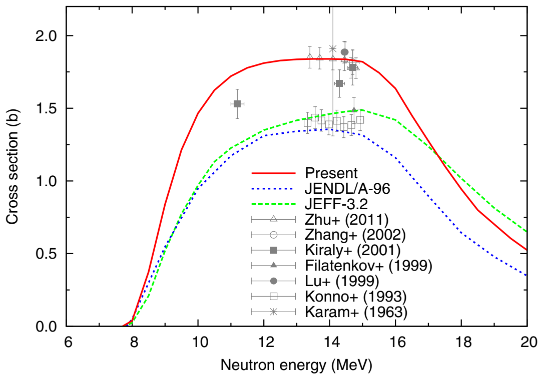

Figure 9. Comparison of the production cross section of ground state for ^{185}Re(n, $2n$) reaction with experimental data. The data of evaluated libraries, JENDL/A-96 and JEFF-3.2 are shown.

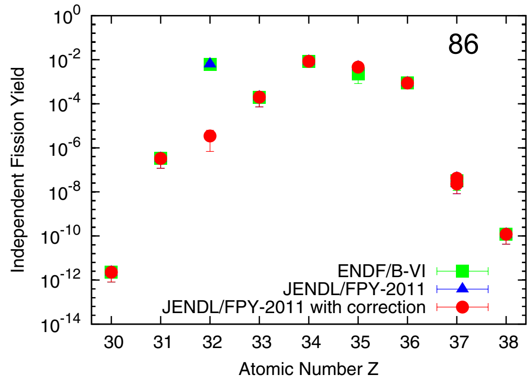

Figure 10. Independent fission yields of JENDL/FPY-2011 (triangle), JENDL/FPY-2011 with correction (circle), and ENDF/B-VI (square). One of major corrected nuclide, $^{86}_{32}$Ge, is shown.

3.3. JENDL/AD-2017

The previous version of JENDL activation cross section file was released in 1996 [31]. The activation cross sections are available for 233 parent nuclides from ^{1}H to ^{210}Po. The capture cross sections with the temperature of 0 K are expressed by 70 group cross sections in the resonance region. It is expected that the point-wise resonance cross sections, which are Doppler-broadened at 293.6 K, are necessary for detailed estimation of radioactivity.

The special purpose file for new activation cross section data, JENDL/AD-2017, is being developed. This file aims at specializing the estimation of activated amounts for decommissioning of a nuclear facility. The radioactive products, to which attention should be paid, are 227 nuclides with half-lives longer than 30 days and 12 nuclides with very long half-lives. The parent nuclides were selected to be included in the file by the following criterion: (i) Nuclear reactions on the nuclides produce the radioactive products and (ii) threshold energies of their reactions are smaller than 10 MeV. Hence, the total number of nuclides is planned to be 304 from ^{2}H to minor actinide of ^{254}Es. Since neutrons emerging from the reactor core are mainly responsible for the activation of materials in a nuclear facility, the file includes the neutron induced activation cross sections, whereas one proton induced data are taken into account because ^{56}Fe(p, n) reaction produces ^{56}Co which have the half-life of 77.2 d. The covered energy range is from 10^{-5} eV to 20 MeV for incident neutron data and from 1 to 20 MeV for incident proton data.

The production cross sections for ground and isomer states of radioactive nuclides are included. The resonance cross sections are represented by the point-wise form. The resonance parameters are included for self-shielding calculations. The excitation energies of ground and isomer states are only given as the information on decay data. The isomeric branching ratios are provided for the reaction with a positive Q-value (e.g., capture and (n, α) reactions). Two point-wise data are generated with temperatures of 0 and 293.6 K. The new activation cross section file for decommissioning will be released in 2017.

An example of the evaluated result is presented in Fig. 9, in which the production cross section of ground state for ^{185}Re(n, $2n$) reaction is compared with experimental data, together with that of JENDL/A-96 and JEFF-3.2. The present data are 25–35% larger than those of JENDL/A-96 and JEFF-3.2.

3.4. Correction of JENDL/FPY-2011

We released JENDL FP Fission Yields Data File 2011 (JENDL/FPY-2011) in 2011. After a while, we recognized that the summation calculation of delayed neutron yield using it showed some problems for ^{235}U. We found that fission yields of several nuclides are responsible for that problem. To remedy it, we performed corrections of fission yields of ^{86}Ge, ^{88}As, ^{100}Rb, and ^{131}Cd. The corrections are shown in Fig. 10 comparing with the previous version and ENDF/B-VI. As a result of the corrections, the summation calculation of delayed neutron yield performed with JENDL FP Decay Data File 2011 (JENDL/FPD-2011) becomes $\bar{\nu} = 0.01694$ from 0.01863 of the previous value, which is closer to experimental data ($\bar{\nu} = 0.01585 \pm 0.0005$). The corrected JENDL/FPY-2011 was released in May 2016. One should read Ref. [32] for the detail of the corrections.

3.5. JENDL/DDF-2015

JENDL Decay Data File 2015 (JENDL/DDF-2015) was released in 2015 [33], in which the decay data of nuclides ranging from the lightest elements including H-1 and n, up to Rf($Z = 104$) are included. The nuclides with unknown γ- and/or β-emission are also included in order to keep decay chains consistently. The data of 1,284 fission product nuclides with mass from 66 to 172 remain unchanged from JENDL/FPD-2011 except several corrections which had been claimed by users, and those of the newly added 1,953 nuclides are taken from ENSDF data base and transformed into the ENDF-6 format. Finally, the decay data of 3,237 nuclides including 244 stable nuclides were compiled. The main purpose of this file is to evaluate the production of radioactive isotopes (RIs) for use in decommissioning of nuclear reactors, as well as in wider applications, *e.g.* the estimation of RI production by accelerators.

4. Conclusions

The present status of the JENDL project was described. By correcting errors and adding covariance of JENDL-4.0, 38 updated files were released as JENDL-4.0u. Next version of general purpose file JENDL-5 is under development. The data from light to heavy nuclides will be updated and released by 2022. Two special purpose files of high energy file JENDL-4.0/HE and decay data file JENDL/DDF-2015 were released in 2015. Other new two special purpose files of photonuclear data file JENDL/PD-2016 and activation cross section file for decommissioning JENDL/AD-2017 will be also released soon.

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References

[1] K. Shibata, O. Iwamoto, T. Nakagawa et al., J. Nucl. Sci. Technol. **48**, 1 (2011)
[2] JENDL-4.0 Updated Files, Japan Atomic Energy Agency, `http://wwwndc.jaea.go.jp/jendl/j40/update/`
[3] E. P. Wigner, L. Eisenbud, Phys. Rev. **72**, 29 (1947)
[4] C. W. Reich, M. S. Moore, Phys. Rev. **111**, 929 (1958)
[5] T. Kawano, K. Shibata, JAERI-Data/Code 97-037 (1997), in Japanese
[6] S. Kunieda, to be submitted to Proceedings of ND2016
[7] O. Iwamoto, J. Nucl. Sci. Technol. **44**, 687 (2007)
[8] O. Iwamoto et al., Nucl. Data Sheets **131**, 259 (2016)
[9] S. Nakayama, JAEA-Conf. (in press)
[10] E. Sh. Soukhovitskii et al., Phys. Rev. C **72**, 024604 (2005)
[11] Y. Nakajima et al., JAERI-M 91-032, pp.43–57 (1991)
[12] A. Ichihara et al., JAEA-Data/Code 2007–012 (2007)
[13] S. Kunieda et al., J. Nucl. Sci. Technol. **44**, 838 (2007)
[14] A. Mengoni, Y. Nakajima, J. Nucl. Sci. Technol. **31**, 151 (1994)
[15] R. Capote et al., Nucl. Data Sheets **110**, 3107 (2009)
[16] K. Shibata, J. Nucl. Sci. Technol. **52**, 490 (2015)
[17] K. Shibata, J. Nucl. Sci. Technol. **51**, 425 (2014)
[18] H. Harada et al., EPJ Web of Conf. **93**, 06001 (2015)
[19] M.B. Chadwick et al., Nucl. Data Sheets **118**, 1 (2014)
[20] K. Shibata, J. Nucl. Sci. Technol. **53**, 1595 (2016)
[21] E.M. Zsolnay et al., INDC(NDS)-0616 (2012)
[22] Y. Watanabe et al., J. Kor. Phys. Soc. **59**, 1040 (2011)
[23] O. Iwamoto, J. Nucl. Sci. Technol. **50**, 409 (2013)
[24] N. Nakao et al., Nucl. Instrum. Meth. A **420**, 218 (1999)
[25] N. Kishida et al., Proc. of International Conference on Nuclear Data for Science and Technology, Santa Fe, New Mexico, USA, Sep. 26 – Oct. 1, 2004, **1**, p. 199 (2004)
[26] T. Fukahori, Proc. of the Specialists' Meeting on High Energy Nuclear Data, Tokai, Japan, 1991, JAERI-M 92-039, pp. 114–122 (1992)
[27] Evaluated Nuclear Structure Data File, NNDC, Brookhaven National Laboratory, `http://www.nndc.bnl.gov/ensdf/`
[28] T. Belgya et al., IAEA-TECDOC-1506, IAEA, Vienna (2006)
[29] B.L. Berman et al., Phys. Rev. **C36**, 1286 (1987)
[30] M.B. Chadwick et al., IAEA-TECDOC-1178, IAEA (2000)
[31] Y. Nakajima, Proc. the 1990 Symposium on Nuclear Data, JAERI-M 91–032, p.43 (1991)
[32] J. Katakura, F. Minato, and K. Ohgama, EPJ Web of Conferences **111**, 08004 (2016)
[33] J. Katakura and F. Minato, JAEA-Data/Code 2015–030 (2016)