2.9 Nuclear Data Project in Korea and Resonance Parameter Evaluation of Fission Products

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Nuclear data activities in the fields of evaluation, processing, measurement, and service in Korea are presented in this paper. As one of the current activities, the neutron resonance parameters for stable or long-lived nineteen fission products have been evaluated and the results are presented here.

1. Introduction

Until mid-nineties, nuclear data relevant activity in Korea Atomic Energy Research Institute (KAERI) had been limited to the generation of the multi-group constant libraries for reactor physics codes to support the design of a research reactor and the localization of nuclear fuel and of power plant design technology. In 1997, the Nuclear Data Evaluation Laboratory (NDEL) was established in KAERI. Korea Ministry of Science and Technology has included the nuclear data project in the long-term nuclear research and development program. The nuclear data services, evaluations, and measurements have been included as a part of the work scopes of nuclear data project. KAERI/NDEL is now leading the nuclear data project in Korea with 12 staffs including 4 temporal staffs. The Pohang Accelerator Laboratory, Seoul National University, Korea Institute of Geology, Mining and Materials, and others are participating in the project.

Current activities are briefly introduced in the next section. As one of the activities, we have evaluated resonance parameters in both resolved and unresolved resonance energy regions for selected 19 stable or long-lived fission products. The next release of ENDF/B-VI will include this new evaluation. The results are presented in Section 3.

2. Nuclear Data Activities in Korea

The KAERI/NDEL has generated and benchmarked the multi-group libraries for lattice physics codes such as WIMS/D, CASMO-3, and HELIOS based on up-to-date evaluated libraries such as JENDL-3 and ENDF/B-VI. Those libraries are used for the design of the research reactor HANARO, advanced fuels for an advanced PWR, and the fast reactor KALIMER. In addition, the libraries for the neutron transport codes such as DANTSYS, DOORS, and MCNP have been generated and benchmarked for the reactor shielding and PWR pressure vessel surveillance.

The evaluation activity has rather short history. The current issue is the burnup credit problem of the spent fuel storage. Among many of related directions, KAERI/NDEL is collaborating on the neutron data of the long-lived fission product nuclides. This work is undergoing together with the Brookhaven National Laboratory as one of the international collaborations. We have completed the evaluation of individual resonance parameters. This work will be presented in the next section. For the higher energy applications such as the transmutation of radwaste, KAERI/NDEL is working on the model calculation for the neutron and proton reaction data at the intermediate energy region. This work is underway as the collaboration with JAERI/NDC. In addition, the photo-nuclear data evaluation up to 140 MeV is under progress as an IAEA CRP to provide data for the electron linac-based isotope production. The evaluation for more than 130 nuclides has been completed. The charged particle nuclear data up to 60 MeV is also under progress. These data are useful for the medical isotope production for PET and SPECT using a cyclotron and also useful for the thin layer activation analysis of metallic materials.

Current objective of the nuclear data experiments is to develop capability and manpower for nuclear data measurements in Korea. The Pohang Accelerator Laboratory is leading the activities. One of them is to construct a pulsed neutron source using a 100 MeV electron linac. The other activity is to obtain and develop measurement skills by participating in the experiments at foreign facilities such as KURRI's. Domestic efforts are the proton scattering experiment using a cyclotron at KAERI hospital by the physics department of Seoul National University and the fast neutron generation using a Van de Graaff at the Korea Institute of Geology, Mining and Materials.

The nuclear data service is provided through internet for domestic and foreign users. The target of the internet web service is to provide data to novice users in the area of nuclear data. The web service consists of a table of nuclide, a cross section plotter, decay schemes, and a capture cross section plotter. Based on the IP address, the number of users who have retrieved the data at least once is 25,817 in the year 1998. Among them, about 1,000 are the frequent users; they have retrieved 7.6 times on the average.

3. Resonance Parameter Evaluation of Fission Products

In many engineering fields dealing with spent nuclear fuels such as storage of spent fuels and transmutation of long-lived isotopes as well as in basic research fields such as astrophysics, the neutron data for fission products are very important especially in the viewpoint of neutron absorption. However, even in the latest release of ENDF/B-VI, most of resonance data for major fission products are those based on old measurements, about 20 years old or more. Although rather recent libraries such as JENDL-3.2 and JEF-2.2 had adopted some recent measurements, still the source for many isotopes was the Mughabghab's BNL compilations published in 1981 and 1984[1,2] as those were. Therefore a need for new evaluations incorporating new measurements has arisen. For selected 19 fission products that largely contribute to the total neutron absorption in a system, we have evaluated resonance parameters in both resolved and unresolved resonance energy regions. In the evaluation, we reviewed all available measured data not only new but also old.

In the resolved resonance region, we adopted the multi-level Breit-Wigner formula. The resonance energy, orbital angular momentum of incident neutron (l), resonance spin (J), neutron scattering width, and radiative width are the parameters to be provided for each resonance. The BNL compilations[1,2] were adopted as the primary sources of resolved resonance parameters and thermal cross sections at 0.0253 eV. Then values recommended in the compilations were revised and/or supplemented by taking into account recent measurements. The old measurements were also revisited: the old ones were corrected, re-normalized, or revived according to relevant new measurements or evaluator's decision, if necessary. In the next step, the bound level resonances were invoked, if necessary, to reproduce reference thermal cross sections and scattering lengths. For a resonance with unknown l value, the Bayesian approach[1] was applied to the calculation of probability that the resonance is due to p-wave neutron. Then l was assigned as either 0 or 1 from the probability. Resonance spins were randomly assigned to resonances for which the spins were unknown. After the assignment of l values for all resonances of an isotope, the distribution of reduced neutron widths was analyzed in terms of the Porter-Thomas distribution. The fit of distribution of measured widths to the theoretical distribution results in the average level spacing and neutron strength function, especially, of s-wave resonances.

The unresolved resonance region was set to cover an energy range up to the first excited level for inelastic scattering, 50~200 keV for most fission products under consideration. The present evaluation provides average resonance parameters for s-, p- and d-wave resonances. In principle, we adopted the average parameters that had been obtained from the analyses of resolved resonances. The level spacing varies with neutron energy according to the Bethe's level density formula,

$$1/D(U,\mathrm{J}) \propto \frac{(2\mathrm{J}+1)}{U^{5/4}} e^{2\sqrt{aU}} \, e^{-(\mathrm{J}+1/2)^2/2\sigma^2} ,$$

where U is the effective excitation energy that depends on the incident neutron energy, a the level density parameter, and σ the spin cutoff factor. Values of a and parameters for calculating U were adopted from Refs. 3 and 4. The proportional constant was determined from the s-wave level spacing D_0, which had been obtained from the analysis of resolved resonances. Concerning the d-wave strength functions, as well as p-wave functions for some isotopes, we adopted values from mass-dependent systematics[1,2] for lack of measurements of resolved high *l*-value resonances. The average gamma widths for p- and d-wave resonances were assumed to be equal to the width for s-wave that had been obtained by averaging known widths of resolved resonances. In some cases, however, the average width for p-wave was adopted from systematics[2] or directly from the measurement (^{95}Mo case). Finally, the average parameters for high *l*-value resonances, if necessary, were adjusted to reproduce measured capture cross sections in the unresolved energy region.

Table 1 summarizes the sources of evaluation. The old sources before the BNL compilations are not listed except ones that are used for the revision of data in the BNL compilations. In the unresolved region, the capture cross section reproduced using present average parameters show good agreement with the measurements listed in the table. Tables 2 and 3 show the 2200 m/s capture cross sections and capture resonance integrals, respectively. There are significant differences between present evaluation and ENDF/B-VI in capture cross sections of ^{145}Nd and ^{147}Sm as well as in resonance integrals of ^{99}Tc, ^{131}Xe, ^{133}Cs, ^{149}Sm, and ^{153}Eu. However, present resonance integrals of above nuclides are rather close to those from the JENDL-3.2. The other quantities such as the s-wave strength functions and level spacing, the average capture cross sections weighted with Maxwellian spectrum at 30 keV, and so on will be found in a more detailed report. Improvements in Maxwellian-average as well as energy-dependent capture cross sections in the unresolved region are observed in most cases.

We took all available measured data into account for the new evaluation of resonance parameters of major fission products. Therefore, generally speaking, present resonance parameters are more reliable than those in existing libraries are. In addition, the evaluation methods and physics models developed or adopted during this work may be used as standard ones for future evaluations. We have proposed to the Cross Section Evaluation Working Group to substitute newly evaluated resonance parameters for those in current release of the ENDF/B-VI.

4. Concluding Remarks

KAERI/NDEL is working on the evaluation and the processing of the nuclear data and supporting the activities to buildup the capability for the nuclear data measurements in Korea. KAERI/NDEL is also providing an internet service for novice users.

We will continue the nuclear data activity to support the research and development of nuclear energy and radiation applications. In addition to the effort for concentrating domestic capabilities, it is necessary to extend and strengthen the international collaborations, especially with Japan, to meet the needs effectively from various R&D fields.

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Table 1. Sources of Evaluation [a]

Isotope	Thermal Characteristics [b]	Resolved Resonance Parameters	Capture Cross Section in Unresolved Resonance Region [c]
42-Mo-95	87 Koester	68 Wynchank, 76 Musgrove	76 Musgrove, 64 Kapchigashev
43-Tc-99	-	97 Gunsing, 97 Raepsaet	82 Macklin
44-Ru-101	-	85 Anufriev	80 Macklin
45-Rh-103	91 Koester, 70 Ribon	80 Macklin	90 Wisshak, 85 Bokhovko
46-Pd-105	87 Glaettli, 82 Buyl, 80 Antonov	-	82 Cornelis, 79 Macklin
47-Ag-109	-	97 Corvi, 97 Lowie, 83 Mizumoto, 82 Macklin	87 Bokhovko, 83 Mizumoto, 82 Macklin
54-Xe-131	-	96 Skoy, 69 Ribon	-
55-Cs-133	91 Koester, 79 Glaettli	90 Nakajima, 82 Macklin, 81 Popov	91 Bokhovko, 83 Yamamuro, 82 Macklin
59-Pr-141	91 Knopf, 76 Akopian	82 Alfimenkov, 79 Taylor, 69 Morgenstern	79 Taylor, 71 Zaikin, 64 Konks
60-Nd-143	-	77 Musgrove	98 Wisshak
60-Nd-145	-	77 Musgrove, 71 Rohr	98 Wisshak, 85 Bokhovko
62-Sm-147	67 Fenner	93 Georgiev	93 Wisshak, 86 Macklin, 85 Bokhovko
62-Sm-149	82 Word	92 Georgiev	93 Wisshak, 86 Macklin
62-Sm-150	74 Eiland, 62 Halperin, 61 Aitken	-	93 Wisshak, 86 Winters, 63 Macklin
62-Sm-151	-	-	-
62-Sm-152	-	-	94 Luo, 93 Wisshak, 85 Bokhovko
63-Eu-153	-	-	94 Xia, 93 Yu, 87 Macklin, 85 Bokhovko
64-Gd-155	-	90 Belyaev	95 Wisshak, 89 Nakajima, 88 Beer
64-Gd-157	-	90 Belyaev	95 Wisshak, 89 Nakajima, 88 Beer

a: BNL compilations are included in all cases.
b: Capture and elastic scattering cross sections, scattering lengths.
c: ORNL data were corrected according to Refs. 5 and 6.

Table 2. Capture Cross Sections at 0.0253 eV (barn)

Isotope	BNL Compilation	98CRC[7]	ENDF/B-VI [a]	JEF-2.2 [a]	JENDL-3.2 [b]	LIPAR-5[8]	Present [c]	Relative Diff. (%) [d]
42-Mo-95	14.0±0.5	13.4±0.3	14.6	14.0	14.0	–	13.6	–7.4
43-Tc-99	20±1	23±2	19.6	19.1	19.6	–	20.0	2.0
44-Ru-101	3.4±0.9	5±1	3.43	3.42	3.36	–	3.45	0.6
45-Rh-103	145±2	145	147	146	147	–	145	–1.4
46-Pd-105	20.0±3.0	22±2	20.1	21.8	20.3	–	20.9	3.8
47-Ag-109	91.0±1.0	91.2	91.0	90.8	90.5	90.7	90.8	–0.2
54-Xe-131	85±10	90±10	90.6	85.1	85.0	–	90.0	–0.7
55-Cs-133	29.0±1.5	30.4	29.7	29.1	29.0	–	29.0	–2.4
59-Pr-141	11.5±0.3	11.5	11.5	11.5	11.5	–	11.5	0.0
60-Nd-143	325±10	330±10	325	323	330	319	325	0.0
60-Nd-145	42±2	47±6	42.1	41.9	43.8	41.9	49.8	15.5
62-Sm-147	57±3	56±4	57.5	57.2	58.0	56.7	50.0	–15.0
62-Sm-149	40140±600	40100±600	39730	40480	40150	39420	40530	2.0
62-Sm-150	104±4	102±5	104	103	109	108.2	100	–3.9
62-Sm-151	15200±300	15200±300	15250	15190	15160	15160	15170	–0.5
62-Sm-152	206±6	206±15	207	206	206	202	206	–0.5
63-Eu-153	312±7	300±20	313	300	313	312	312	0.0
64-Gd-155	60900±500	61000±1000	61100	60790	60890	60710	60730	–0.6
64-Gd-157	254000±815	254000±3000	255800	253400	254100	253500	253700	–0.8

a: From JEF Report 14, OECD/NEA, Paris (1994).

b: From General Description (MF=1) of JENDL-3.2

c: Calculated using LINEAR–RECENT–SIGMA1–INTER codes

d: Relative Difference = $(1 - \sigma_\gamma^{ENDF/B\text{-}VI} / \sigma_\gamma^{Present}) \times 100$

Table 3. Capture Resonance Integrals (barn)

Isotope	BNL Compilation	98CRC	ENDF/B-VI [a]	JEF-2.2 [a]	JENDL-3.2 [b]	LIPAR-5 [c]	Present [d]	Relative Diff. (%) [e]
42-Mo-95	109±5	109±5	113	110	119	–	111	–2.2
43-Tc-99	340±20	–	350	304	312	–	312	–12.2
44-Ru-101	100±20	110±30	111	111	100	–	111	0.1
45-Rh-103	1100±50	1180	1035	1035	1040	–	1036	0.1
46-Pd-105	62.2	60±20	111	93.1	96.8	–	95.2	–16.6
47-Ag-109	1400±48	1480	1471	1473	1470	1467	1476	0.4
54-Xe-131	900±100	900±100	1016	890	900	–	882	–15.2
55-Cs-133	437±26	422	383	439	396	–	421	9.0
59-Pr-141	17.4±2.0	14±3	19.0	17.9	18.4	–	17.6	–7.7
60-Nd-143	128±30	128±30	130	130	130	127	130	0.7
60-Nd-145	240±35	260±40	231	231	204	228	245	5.7
62-Sm-147	–	710±50	789	794	781	721	777	–1.4
62-Sm-149	3390	3100±500	3258	3484	3490	3355	3482	6.4
62-Sm-150	358±50	290±30	338	339	325	334	334	–1.2
62-Sm-151	3520±160	3520±60	3449	3465	3410	3397	3430	–0.6
62-Sm-152	2970±100	3000±300	2981	2977	2770	2958	2976	–0.2
63-Eu-153	1420±100	1800±400	1499	1448	1410	1305	1408	–6.5
64-Gd-155	1447±100	1540±100	1555	1543	1540	1437	1537	–1.2
64-Gd-157	700±20	800±100	759	762	763	711	754	–0.7

a: From JEF Report 14, OECD/NEA, Paris (1994) b: From General Description (MF=1) of JENDL-3.2

c: Integrated from 0.5 eV to the upper energy of resolved resonance region

d: Integrated from 0.5 eV to 100 keV with 1/E spectrum e: Relative Difference = $(1 - I_\gamma^{ENDF/B\text{-}VI} / I_\gamma^{Present})\times100$