https://doi.org/10.61092/iaea.y3a1-394h

IAEA
International Atomic Energy Agency

INDC(NDS)-0784
Distr. AD,AL,BN,J,SD

INDC International Nuclear Data Committee

New Aggregate Data in the IAEA Reference Database for Beta-delayed Neutron Emission

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May 2019

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Printed by the IAEA in Austria

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Contents

1. Numerical data on the time dependence of delayed neutron activity and its 6- and 8-group representation for the thermal and fast fission of ^{235}U, ^{238}U and ^{239}Pu

The importance of primary experimental information cannot be emphasized enough when considering the evaluation of nuclear data. Raw experimental data allow us to make more reliable estimation of the uncertainties and generate correlation and covariance data. In the case of delayed-neutron data, having such information available has additional advantages. It allows us to compare the mathematical methods used for estimating delayed-neutron temporal parameters and their uncertainties. Such information is usually lost and not available in the available literature.

This paper presents primary numerical information on the decay curves of the delayed-neutron activity measured in separate experimental runs for thermal and fast neutron-induced fission of ^{235}U, ^{238}U and ^{239}Pu (Ref. [1]). It should be noted that the 6-group data in most of the original works were obtained on the basis of data measured in the restricted range of 0.5-300 s after the end of irradiation (Ref [2]). This leads to additional uncertainties when evaluating the short-lived groups of delayed neutrons, as well as the most long-lived first group. The data presented here were obtained in experiments performed with irradiation times of 180 and 300 s. Unlike the overwhelming majority of previously performed experiments for the nuclides under consideration, in the present experiments the time range for the DN counting has been significantly extended. The DN activity measurements were carried out in the intervals of 0.1-524.5 (short irradiation, ^{238}U) and 0.1-724.5 s (^{238}U, ^{235}U, ^{239}Pu, long irradiation) which can significantly increase the reliability of the estimation of the DN group half-lives and the relative abundances for both the short-lived DN groups and the longest-lived DN groups.

We also present the results for the delayed-neutron temporal parameters in the 6- and 8-group representation, obtained for each of the presented decay curves with the improved version of the computer code ANALYSES (Ref [3]). In this procedure, the delayed-neutron temporal parameters in the 8-group representation were obtained directly from the primary experimental data, bypassing the evaluation of 6-group data. It should be noted that in the recommended data of Ref. [4], the relative abundances of delayed neutrons in the 8-group model were obtained by expanding 6-group data, since numerical information on the DN decay curves was absent in the original works. Furthermore, the data presented herein are for individual measurement runs, while the DN relative abundances and periods which were included in the CRP data sets recommended by the IPPE group, were averaged for a given nuclide over all measurement runs according to a procedure which takes into account the correlations between the group parameters of delayed neutrons (Ref [3]).

In Table 1 three decay curves for ^{235}U (two decay curves for the fast neutron induced fission and one decay curve for the thermal neutron induced fission), two decay curves for ^{238}U for fast neutron induced fission and three decay curves for ^{239}Pu (two decay curves for the thermal neutron induced fission and one decay curve for the fast neutron induced fission) are shown. These data are also provided in a separate EXEL file.

TABLE 1 The time dependence of delayed neutron activity from fission of ^{235}U, ^{238}U and ^{239}Pu by thermal and fast neutrons.

Activity of delayed neutrons									
Target nuclide		^{238}U	^{238}U	^{235}U	^{235}U	^{235}U	^{239}Pu	^{239}Pu	^{239}Pu
Neutron energy		3.75 MeV	3,75 MeV	0,8 MeV	0,8 MeV	thermal	0,8 MeV	thermal	thermal
Run number		42	10	10-2	15	95	11	96	1
Number of cycles		40	41	28	26	12	31	20	20
Irradiation time, s		180	300	300	300	180	300	180	300
t_l, s	t_u, s	N(t_k)							
0,09	0,1	613	766	680	659	638	620	538	573
0,1	0,11	601	749	701	646	625	607	526	561
0,11	0,12	624	735	690	635	614	597	517	551
……………………………………… data for interval 0.11-674,5 s are omitted intentionally ……………………………									
674,5	684,5	Up to 524 s	47	10	11	7	3512	2440	2310
684,5	694,5		37	17	7	7	3568	2345	2248
694,5	704,5		36	3	10	7	3590	2420	2205
704,5	714,5		49	8	10	9	3536	2277	2371
714,5	724,5		39	13	11	4	3634	2376	2289
Statistics		508869	615164	951761	867980	841535	1210390	1006331	1061716

The general equation for estimating the total delayed neutron yields and temporary delayed neutron characteristics (a_i, λ_i) on the basis of measured values is the following (cyclic irradiation)

$$N(t_k) = A \cdot \sum_{i=1}^{m} T_i \cdot \frac{a_i}{\lambda_i} \cdot (1 - e^{-\lambda_i \cdot \Delta t_k}) \cdot e^{-\lambda_i \cdot t_k} + B \cdot \Delta t_k ,$$

$$T_i = (1 - e^{-\lambda_i \cdot t_{irr}}) \cdot \left(\frac{n}{1 - e^{-\lambda_i \cdot T}} - e^{-\lambda_i \cdot T} \cdot \left(\frac{1 - e^{-n \cdot \lambda_i \cdot T}}{((1 - e^{-\lambda_i \cdot T})^2} \right) \right) ,$$

$$A = \varepsilon_n \, \sigma_f \, \varphi \, N_f \, \nu_d ,$$

where $N(t_k)$ - the number of counts registered by the neutron detector in the time-channel t_k with time-channel width Δt_k, ν_d - the total delayed neutron yield per one fission, B - the intensity of neutron background, λ_i и a_i - the decay constant and relative abundance of i -the group of DN, n - the number of cycles, m - the number of delayed neutron groups, T - the duration of one cycle of measurements, which includes the irradiation and the delayed neutron counting time, t_{ir} - irradiation time, ε_n - efficiency of neutron detector, φ - the neutron flux, σ_f - fission cross section, N_f - the number of atoms in fissionable nuclide under investigation.

All information needed for processing each of the DN decay curves is shown in Table 1: irradiation time, number of irradiation-counting cycles and time scale. The data are presented in a histogram form with specified time bins that allows one to convert them in any suitable format. As an example, these data were processed with the purpose of estimating the relative abundances and periods of delayed neutrons in a 6- and 8-group model with the computer code ANALYSES (Ref [3]). **The obtained results including delayed neutron parameters, their uncertainties and corresponding correlation matrixes are provided in suitable tables in EXEL format and are also shown in Tables 2-17 below.**

The present numerical data will help us to:

1) validate the computer codes used for the estimation of delayed neutron parameters and corresponding correlation and covariance data;
2) explore the efficiency of the computer codes in calculating the 8-group data on the basis of primary experimental data;
3) compare such 8-group data with the corresponding data obtained on the basis of the 6-group data sets.

2. Results of estimation of 6- and 8-group DN temporal parameters for the measured delayed neutron decay curves

TABLE 2 DN group parameters in a 6-group model for fission of ^{235}U by thermal neutrons (run# 95, thermal neutrons, sample irradiation time - 180 s, 12 cycles of irradiation).

Group number, i	Half-life, T_i, s	Uncertainty, dT_i	Relative abundance, a_i	Uncertainty, da_i
1	55.26086	0.29626	0.03495	6.4E-4
2	22.21357	0.14675	0.22147	0.00405
3	6.19525	0.08848	0.19429	0.0046
4	2.28264	0.02548	0.38629	0.00413
5	0.60483	0.01778	0.11879	0.00342
6	0.22883	0.00685	0.04421	0.00132

Saturation activity: 5557.28775+/- 24.14116 counts/s, background: 0.01715+/- 0 .00165 counts/s, average half-life: 9.018397+/- 0.237874 s.

TABLE 3 DN group parameters in a 8-group model for fission of ^{235}U by thermal neutrons (run# 95, thermal neutrons, sample irradiation time - 180 s, 12 cycles of irradiation).

Group number, i	Half-life, T_i, s	Uncertainty, dT_i	Relative abundance, a_i	Uncertainty, da_i
1	55.6	0	0.03294	5.1E-4
2	24.5	0	0.15017	0.00233
3	16.3	0	0.09431	0.00163
4	5.21	0	0.20487	0.00315
5	2.37	0	0.30471	0.00354
6	1.04	0	0.10407	0.00262
7	0.424	0	0.07112	0.00208
8	0.195	0	0.0378	0.00113

Saturation activity: 5577.96690±18.06369 counts/s. background: 0.01934±0.00184 counts/s. average half-life: 8.983418±0.140565 s.

TABLE 4 DN group parameters in a 6-group model for fission of ^{235}U by fast neutrons (run# 10-2. neutron energy - 0.8 MeV, sample irradiation time - 300 s. 28 cycles of irradiation).

Group number. i	Half-life. T_i. s	Uncertainty. dT_i	Relative abundance. a_i	Uncertainty. da_i
1	55.75492	0.28555	0.03464	6.20E-04
2	22.0625	0.14063	0.22644	0.00405
3	5.85699	0.08439	0.19015	0.00464
4	2.2447	0.02374	0.40176	0.00404
5	0.52942	0.01558	0.12261	0.00352
6	0.18055	0.00541	0.0244	7.30E-04

Saturation activity: 2643.46894±11.28849 counts/s. background: 0.01422±0.00127 counts/s. average half-life: 9.012122±0.231408 s.

Table 5 DN group parameters in a 8-group model for fission of ^{235}U by fast neutrons (run# 10-2. neutron energy- 0.8 MeV, sample irradiation time - 300 s, 28 cycles of irradiation).

Group number. i	Half-life. T_i. s	Uncertainty. dT_i	Relative abundance. a_i	Uncertainty. da_i
1	55.6	0	0.03331	5.2E-4
2	24.5	0	0.14417	0.00224
3	16.3	0	0.10225	0.00156
4	5.21	0	0.17302	0.00301
5	2.37	0	0.35239	0.00333
6	1.04	0	0.0731	0.00198
7	0.424	0	0.09462	0.00269
8	0.195	0	0.02715	8.1E-4

Saturation activity: 2673.72319±8.53843 counts/s. background: 0.01746±0.00149 counts/s. average half-life: 8.908658±0.136059 s.

TABLE 6 DN group parameters in a 6-group model for fission of ^{235}U by fast neutrons (run# 15, neutron energy -0.8 MeV, sample irradiation time - 300 s, 26 cycles of irradiation).

Group number. i	Half-life. T_i. s	Uncertainty. dT_i	Relative abundance. a_i	Uncertainty. da_i
1	54.44377	0.28288	0.03719	6.8E-4
2	21.54162	0.14428	0.22693	0.00413
3	5.78872	0.08617	0.18518	0.00455
4	2.23088	0.02494	0.39182	0.00414
5	0.4897	0.01439	0.13229	0.00378
6	0.18013	0.0054	0.02659	8E-4

Saturation activity: 2619.41150±11.83897 counts/s. background: 0.02123±0.00175 counts/s. average half-life: 8.928804±0.234371 s.

TABLE 7 DN group parameters in a 8-group model for fission of ^{235}U by thermal neutrons (run# 15, thermal neutrons, sample irradiation time - 300 s, 26 cycles of irradiation).

Group number. i	Half-life. T_i. s	Uncertainty. dT_i	Relative abundance. a_i	Uncertainty. da_i
1	55.6	0	0.03337	5.4E-4
2	24.5	0	0.14315	0.00231
3	16.3	0	0.10638	0.00164
4	5.21	0	0.17323	0.00308
5	2.37	0	0.34572	0.00344
6	1.04	0	0.07406	0.00202
7	0.424	0	0.09675	0.00276
8	0.195	0	0.02734	8.2E-4

Saturation activity: 2615.60491±8.55153 counts/s. background: 0.0198±0.0016 counts/s. average half-life: 8.941981±0.140846 s.

TABLE 8 DN group parameters in a 6-group model for fission of ^{239}Pu by thermal neutrons (run# 01, thermal neutrons, sample irradiation time - 300 s, 20 cycles of irradiation).

Group number. i	Half-life. T_i. s	Uncertainty. dT_i	Relative abundance. a_i	Uncertainty. da_i
1	53.29216	0.48274	0.03496	7.6E-4
2	22.68841	0.12548	0.29934	0.00649
3	5.63535	0.08759	0.20601	0.00476
4	2.15589	0.03038	0.33366	0.00412
5	0.61902	0.01838	0.08248	0.00243
6	0.25536	0.00765	0.04354	0.0013

Saturation activity: 2950.69946±12.58476 counts/s. background: 11.54403±0.03374 counts/s. average half-life: 10.596941±0.309751 s.

TABLE 9 DN group parameters in a 6-group model for fission of ^{239}Pu by thermal neutrons (run# 01. thermal neutrons, sample irradiation time - 300 s, 20 cycles of irradiation).

Group number. i	Half-life. T_i. s	Uncertainty. dT_i	Relative abundance. a_i	Uncertainty. da_i
1	55.6	0	0.02917	5.6E-4
2	24.5	0	0.23757	0.00454
3	16.3	0	0.08403	0.00189
4	5.21	0	0.18629	0.00331
5	2.37	0	0.29234	0.00372
6	1.04	0	0.08847	0.00236
7	0.424	0	0.059	0.00174
8	0.195	0	0.02313	6.9E-4

Saturation activity: 2951.49522±8.54818 counts/s. background: 11.53597±0.03357 counts/s. average half-life: 10.596912±0.202445 s.

TABLE 10 DN group parameters in a 6-group model for fission of ^{239}Pu by thermal neutrons (run# 96, thermal neutrons, sample irradiation time - 180 s, 20 cycles of irradiation).

Group number. i	Half-life. T_i. s	Uncertainty. dT_i	Relative abundance. a_i	Uncertainty. da_i
1	53.65433	0.55198	0.0341	7.4E-4
2	22.58273	0.12038	0.30753	0.00666
3	5.5494	0.08907	0.20334	0.00478
4	2.18518	0.03136	0.33341	0.00417
5	0.63574	0.01889	0.0798	0.00235
6	0.2569	0.00769	0.04182	0.00125

Saturation activity: 2773.90498±11.91972 counts/s. background11.81226±0.03386 counts/s. average half-life: 10.693086±0.313702 s.

TABLE 11 DN group parameters in a 6-group model for fission of ^{239}Pu by thermal neutrons (run# 96, thermal neutrons, sample irradiation time - 180 s, 20 cycles of irradiation).

Group number, i	Half-life, T_i, s	Uncertainty, dT_i	Relative abundance, a_i	Uncertainty, da_i
1	55.6	0	0.0284	5.8E-4
2	24.5	0	0.24088	0.00492
3	16.3	0	0.08563	0.00196
4	5.21	0	0.18605	0.00336
5	2.37	0	0.29425	0.00382
6	1.04	0	0.08561	0.00231
7	0.424	0	0.05678	0.00168
8	0.195	0	0.02239	6.7E-4

Saturation activity: 2781.55950±7.95205 counts/s, background: 11.82179±0.03369 counts/s, average half-life: 10.660479±0.214624 s.

TABLE 12 DN group parameters in a 6-group model for fission of ^{239}Pu by fast neutrons (run# 11, neutron energy –0.8 MeV, sample irradiation time - 300 s, 31 cycles of irradiation).

Group number. i	Half-life. T_i. s	Uncertainty. dT_i	Relative abundance. a_i	Uncertainty. da_i
1	53.27903	0.48379	0.03685	8E-4
2	22.40498	0.1296	0.29015	0.00626
3	5.35271	0.08007	0.21641	0.00493
4	2.10233	0.02963	0.32524	0.00408
5	0.56908	0.01683	0.09785	0.00285
6	0.21588	0.00647	0.0335	1E-3

Saturation activity: 2069.98324±8.80779 counts/s, background: 11.53709±0.02668 counts/s, average half-life: 10.369396±0.303685 s.

TABLE 13 DN group parameters in a 8-group model for fission of ^{239}Pu by fast neutrons (run# 11, neutron energy –0.8 MeV, sample irradiation time - 300 s, 31 cycles of irradiation).

Group number. i	Half-life. T_i. s	Uncertainty. dT_i	Relative abundance. a_i	Uncertainty. da_i
1	55.6	0	0.03077	6.1E-4
2	24.5	0	0.22065	0.00436
3	16.3	0	0.09072	0.00193
4	5.21	0	0.17728	0.00323
5	2.37	0	0.30435	0.00362
6	1.04	0	0.08352	0.00224
7	0.424	0	0.07167	0.00209
8	0.195	0	0.02103	6.3E-4

Saturation activity: 2072.23900±6.14253 counts/s, background: 11.528±0.026 counts/s, average half-life: 10.361919±0.200733 s.

TABLE 14 DN group parameters in a 6-group model for fission of ^{238}U by fast neutrons (run# 10, neutron energy 3.75MeV, sample irradiation time - 300 s, 41 cycles of irradiation).

Group number. i	Half-life. T_i. s	Uncertainty. dT_i	Relative abundance. a_i	Uncertainty. da_i
1	53.05585	0.38892	0.01281	2.7E-4
2	21.71571	0.13452	0.13027	0.00279
3	5.15921	0.07268	0.1612	0.004
4	1.94992	0.02097	0.38209	0.00497
5	0.4965	0.01375	0.23903	0.00614
6	0.17373	0.00519	0.0746	0.00222

Saturation activity: 2010.19203±11.53869 counts/s, background: 0.09744±0.00277 counts/s, average half-life: 5.217066±0.154755 s.

TABLE 15 DN group parameters in a 8-group model for fission of ^{238}U by fast neutrons (run# 10, neutron energy 3.75MeV, sample irradiation time - 300 s, 41 cycles of irradiation).

Group number. i	Half-life. T_i. s	Uncertainty. dT_i	Relative abundance. a_i	Uncertainty. da_i
1	55.6	0	0.01016	2E-4
2	24.5	0	0.0873	0.00172
3	16.3	0	0.05377	0.0011
4	5.21	0	0.12066	0.00229
5	2.37	0	0.31679	0.00323
6	1.04	0	0.16505	0.00342
7	0.424	0	0.16316	0.00438
8	0.195	0	0.08311	0.00247

Saturation activity: 2010.60364±9.24733 counts/s, background: 0.09663±0.00276 counts/s, average half-life: 5.216419±0.096566 s.

TABLE 16 DN group parameters in a 6-group model for fission of ^{238}U by fast neutrons (run# 42, neutron energy 3.75MeV, sample irradiation time - 180 s, 40 cycles of irradiation)

Group number. i	Half-life. T_i. s	Uncertainty. dT_i	Relative abundance. a_i	Uncertainty. da_i
1	52.65872	0.47354	0.0129	2.8E-4
2	22.1434	0.14548	0.12985	0.00286
3	5.31302	0.07726	0.16688	0.00414
4	1.97112	0.02214	0.39283	0.00515
5	0.52437	0.01474	0.22423	0.00595
6	0.1715	0.00512	0.07332	0.00219

Saturation activity: 1683.57665±9.79044 counts/s, background: 0.09647±0.00404 counts/s, average half-life: 5.345807±0.164166 s.

TABLE 17 DN group parameters in a 8-group model for fission of ^{238}U by fast neutrons (run# 42, neutron energy 3.75MeV, sample irradiation time - 180 s, 40 cycles of irradiation).

Group number. i	Half-life. T_i. s	Uncertainty. dT_i	Relative abundance. a_i	Uncertainty. da_i
1	55.6	0	0.01017	2.2E-4
2	24.5	0	0.09124	0.00193
3	16.3	0	0.05073	0.00113
4	5.21	0	0.12539	0.00248
5	2.37	0	0.32788	0.00352
6	1.04	0	0.15958	0.0035
7	0.424	0	0.15379	0.00421
8	0.195	0	0.08121	0.00241

Saturation activity: 1697.12039±8.03627 counts/s, background: 0.09339±0.00400 counts/s, average half-life: 5.305332±0.104938 s.

3. Conclusion

As a result of the work performed in the frame of a Special Service Agreement with the IAEA Nuclear Data Section on New Aggregate Data in the IAEA Reference Database for Beta-delayed Neutron Emission (Reference: TAL-NAPC20190118-001), the following new data were obtained:

Primary numerical information on the decay curves of the delayed-neutron activity measured in separate experimental runs from the fission of ^{235}U, ^{238}U and ^{239}Pu by thermal and fast neutrons have been compiled in Ref. [1]: three decay curves for ^{235}U with different irradiation time (two decay curves for the fast neutron induced fission and one decay curve for the thermal neutron induced fission), two decay curves for ^{238}U with different irradiation time for fast neutron induced fission and three decay curves for ^{239}Pu with different irradiation time (two decay curves for the thermal neutron induced fission and one decay curve for the fast neutron induced fission).

Unlike the overwhelming majority of previously performed experiments for the nuclides under consideration, in the present experiments the time range for the DN counting has been significantly extended. The DN activity measurements were carried out in the intervals of 0.1-524.5 (short irradiation, ^{238}U) and 0.1-724.5 s (^{238}U, ^{235}U, ^{239}Pu, short and long irradiation) that allow us to significantly increase the reliability of the estimated DN group half-lives and the relative abundances of both the short-lived DN groups and the longest-lived DN groups.

We also presented the results of the estimated temporal delayed-neutron parameters in the 6- and 8-group representation obtained for each of the presented decay curves with the improved version of the computer code ANALYSES [3].

The following data are available in the IAEA Reference Database for Beta-delayed Neutrons (https://www-nds.iaea.org/beta-delayed-neutron//database.html):

- DN decay curve for fission of Pu-239. xlsx
- DN decay curve for fission of U-235.xlsx
- DN decay curve for fission of U-238.xlsx

In addition to the DN decay curves, correlation matrices and DN parameters are also provided in the 6- and 8-group models. Each file comprises of 1) Preface, 2) DN decay curves, 3) DN temporal parameters estimated by the IPPE methods in both 6- and 8-group representation and corresponding correlation matrixes.

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