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2007 Nuclear Data Review

N. E. Holden[1]

[1] *Guest Physicist, National Nuclear Data Center, Brookhaven National Laboratory, Upton, NY, USA 11973-5000*

National Nuclear Data Center
Energy Sciences & Technology Department
Brookhaven National Laboratory
P.O. Box 5000
Upton, NY 11973-5000
www.bnl.gov

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N. E. Holden[1]

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ABSTRACT: The results of a review and evaluation of neutron and non-neutron nuclear data published in the scientific literature are presented. The status of new chemical elements is examined. Data on revised values for the isotopic composition of the elements are reviewed and recommended values are presented. Half-lives of very long-lived nuclides are presented, including double beta decay, double electron capture, long-lived alpha decay and long-lived beta decay. Data from new measurements on the very heavy elements (trans-meitnerium elements) are discussed and tabulated. The first observation of the radioactive decay mode of the free neutron is discussed. New measurements that have expanded the neutron drip line for magnesium and aluminum are discussed. Data on recent neutron cross-section and resonance integral measurements are also discussed.

Introduction

The published scientific literature is scanned and periodically reviewed for both neutron and non-neutron nuclear data. The data collected from this literature search are evaluated and the resulting recommendations are published in the Handbook of Chemistry and Physics [1, 2]. In this paper, the results of the most recent review of the nuclear data that had been published in the scientific literature during the period from about 2002 (for neutron data) and from 2005 (for non-neutron data) through the end of 2007 are presented. The nuclear data on the one hundred seventeen chemical elements with almost thirty-one hundred nuclides (3091) and the hundreds of meta-stable states (660) with half-lives that are greater than one micro-second have been reviewed. Significant data in a number of topic areas are discussed and presented.

Periodic Table of the Chemical Elements

There have been recent measurements reported in the literature on the data for the very heaviest elements (see Table 11 for the latest summary of heavy element data).

The history of the process of discovery and the naming of chemical elements has been discussed previously [3]. The joint committee formed by IUPAC (the International Union of Pure and Applied Chemistry) and IUPAP (the International Union of Pure and Applied Physics) has the responsibility to review the claims of discovery of a new element and to investigate whether or not there has been a verification of each discovery. The element with proton number Z = 110, Darmstadtium, has been added to the Periodic Table [4]. The element with Z = 111, Roentgenium, has also been approved [5]. Data on elements Z = 112, 113, 114, 115, 116 and 118 are presently undergoing review. A decision on element Z = 112 should be made sometime later this year and a new name and chemical symbol will probably be available sometime in 2009.

Isotopic Composition of the Elements

Changes in the isotopic composition of the elements could impact the evaluation of the response from neutron activation detectors used in reactor dosimetry. An irradiated detector usually has a normal composition of naturally occurring stable isotopes of an element. The measured reaction rate will depend on the natural abundance of the stable isotope undergoing the reaction in the foil.

There have been many new measurements of isotopic ratios performed on a series of elements in the past half dozen years. For a number of these elements, the new measurements have resulted in improved values of the isotopic abundances. These new values of the isotopic abundance are now recommended for use both in determining the atomic weight values of the elements from their isotopic masses and for use in fitting measured values of the neutron cross-sections of the isotopes of an element with the measured value

[1] *Guest Physicist, National Nuclear Data Center, Brookhaven National Laboratory, Upton, NY, USA 11973-5000*

of the cross-section for the natural element. There have been eleven new values of the elemental atomic weights or their uncertainties or both during this period, as reported by the Sub-committee on Isotopic Abundance Measurements (SIAM) to the Commission on Isotopic Abundance and Atomic Weights (CIAAW) [6, 7]. The issue of the neutron cross-section values will be discussed later in this paper.

The elements, which have measured isotopic compositions that are recommended for revision, are the following: argon, zinc, molybdenum, lanthanum, neodymium, samarium, ytterbium, lutetium, tantalum and platinum. In addition, nickel has a revised recommended uncertainty. The effect of the new isotopic composition on the atomic weight values, which resulted in either revised atomic weight values or their uncertainties or both are shown in Table 1.

Table 1. Recent Revised Values of Atomic Weights of the Elements

Chemical Element	Revised Value of Atomic Weight	Revised Uncertainty	Previous Atomic Weight	Previous Uncertainty
Nickel	58.6934	0.0004	58.6934	0.0002
Zinc	69.38	0.02	65.409	0.004
Molybdenum	95.96	0.02	95.94	0.02
Lanthanum	138.90547	0.00007	138.9055	0.0002
Neodymium	144.242	0.003	144.24	0.03
Samarium	150.36	0.02	150.36	0.03
Ytterbium	173.054	0.005	173.04	0.03
Lutetium	174.9668	0.0001	174.967	0.001
Tantalum	180.94788	0.00002	180.9497	0.0001
Platinum	195.084	0.009	195.078	0.002

The recent changes, in these recommended isotopic composition values for various polynuclidic chemical elements with multiple stable isotopes, are presented in Tables 2 through 9, where the new recommended values and uncertainties for the latest measurements are listed first in the Tables, followed by the previously recommended values and uncertainties. It should be noted that for the new measurement on argon recommended in Table 2, the $^{40}Ar/^{36}Ar$ isotope ratio was determined to be 298.56 ± 0.31, which is 0.85% larger than the previously accepted 1950 measurement by Nier and this change should have an impact on the argon-potassium dating method for geological materials.

Table 2. Changes in the Isotopic Composition of Argon

Isotope Number	Revised Abundance	Revised Uncertainty	Previous Abundance	Previous Uncertainty
36	0.3336	0.0021	0.3365	0.0030
38	0.06289	0.00072	0.0632	0.0005
40	99.6035	0.0025	99.6003	0.0030

To meet the requirement that all isotopic abundance values sum to one exactly, the ^{38}Ar value would have to be rounded from 0.06289 (72) % in the table above to 0.0629 (7) %, where the uncertainty is listed in parentheses following the value.

Table 3. Changes in the Isotopic Composition of Nickel

Isotope Number	Revised Abundance	Revised Uncertainty	Previous Abundance	Previous Uncertainty
58	68.077	0.016	68.0769	0.0089
60	26.223	0.013	26.2231	0.0077
61	1.1399	0.0012	1.1399	0.0006
62	3.6345	0.0035	3.6345	0.0017
64	0.9256	0.0017	0.9256	0.0009

Table 4. Changes in the Isotopic Composition of Zinc

Isotope Number	Revised Abundance	Revised Uncertainty	Previous Abundance	Previous Uncertainty
64	49.17	0.75	48.268	0.321
66	27.73	0.98	27.975	0.077
67	4.04	0.16	4.102	0.021
68	18.45	0.63	19.024	0.123
70	0.61	0.10	0.631	0.009

Table 5. Changes in the Isotopic Composition of Molybdenum

Isotope Number	Revised Abundance	Revised Uncertainty	Previous Abundance	Previous Uncertainty
92	14.53	0.31	14.77	0.31
94	9.15	0.09	9.23	0.10
95	15.84	0.11	15.90	0.09
96	16.67	0.15	16.68	0.01
97	9.60	0.14	9.56	0.05
98	24.39	0.37	24.19	0.26
100	9.82	0.31	9.67	0.20

Table 6. Changes in the Isotopic Composition of Neodymium

Isotope Number	Revised Abundance	Revised Uncertainty	Previous Abundance	Previous Uncertainty
142	27.153	0.040	27.2	0.5
143	12.173	0.026	12.2	0.2
144	23.798	0.019	23.8	0.3
145	8.293	0.012	8.3	0.1
146	17.189	0.032	17.2	0.3
148	5.756	0.021	5.7	0.1
150	5.638	0.028	5.6	0.2

Table 7. Changes in the Isotopic Composition of Samarium

Isotope Number	Revised Abundance	Revised Uncertainty	Previous Abundance	Previous Uncertainty
144	3.083	0.020	3.07	0.07
147	15.017	0.075	14.99	0.18
148	11.254	0.051	11.24	0.10
149	13.830	0.056	13.82	0.07
150	7.351	0.036	7.38	0.01
152	26.735	0.048	26.75	0.16
154	22.730	0.078	22.75	0.29

Table 8. Changes in the Isotopic Composition of Ytterbium

Isotope Number	Revised Abundance	Revised Uncertainty	Previous Abundance	Previous Uncertainty
168	0.1233	0.0029	0.13	0.01
170	2.982	0.038	3.04	0.15
171	14.09	0.13	14.28	0.57
172	21.68	0.13	21.83	0.67
173	16.103	0.062	16.13	0.27
174	32.026	0.078	31.83	0.92
176	12.996	0.081	12.76	0.41

Table 9. Changes in the Isotopic Composition of Platinum

Isotope Number	Revised Abundance	Revised Uncertainty	Previous Abundance	Previous Uncertainty
190	0.0117	0.0017	0.014	0.001
192	0.782	0.024	0.782	0.007
194	32.86	0.40	32.967	0.099
195	33.78	0.24	33.832	0.010
196	25.21	0.34	25.242	0.041
198	7.356	0.130	7.163	0.055

To meet the aforementioned requirement that all abundance values sum to one exactly, the ^{168}Yb value in Table 8 would have to be rounded from 0.1233 (29) % to 0.123 (3) % and the ^{190}Pt value in Table 9 would have to be rounded from 0.0117 (17) % to 0.012 (2) %.

Radioactive Decay Constants

The radioactive half-life of a nuclide (the reciprocal of the radioactive decay constant) is of interest to reactor dosimetry because the half-life of the product nucleus in a nuclear reaction has a direct impact on the determination of the reaction rates.

Nuclei are composed of protons and neutrons, which are bound together by the strong nuclear force. This attraction is stronger between a proton and a neutron than between two like particles. Electric repulsion between protons is counterbalanced by the attraction between extra neutrons, so most stable isotopes have more neutrons than protons. As you keep adding neutrons to a given nucleus, you eventually reach the neutron drip line, which is the limiting number of neutrons that can be added for that element. Theoreticians need to modify their model for the neutron drip line limit with the recent discovery of ^{42}Al, with 13 protons and 29 neutrons, which was not predicted by theory.

Long-lived nuclides, such as ^{87}Rb, ^{138}La, ^{147}Sm, ^{176}Lu and ^{187}Re, have half-life values that are of interest to the geological community because of their use in dating samples. There are discrepancies in the reported half-lives of these nuclides. Problems arise in connection with the estimation of the systematic component of the uncertainty in the half-life or decay constant measurement. A collaborative effort, between the IUPAC and the International Union of Geological Sciences (IUGS), is presently under way [8] to resolve the discrepancy between the physical and geological measurements. The Task Group is concentrating on the decay constant or half-life values of ^{40}K, ^{235}U and ^{238}U, which involve the majority of the dating method applications.

The theory of quantum electrodynamics predicts that beta decay of the neutron into a proton, electron and antineutrino should be accompanied by a continuous spectrum of soft photons. This bremsstrahlung has been measured in beta decay and electron capture decay but never in free neutron decay. This free neutron decay mode has recently been measured with a branching ratio of 0.31 %, which is consistent with the theoretical calculations [9].

For very long-lived nuclides, which had been considered stable isotopes there have been attempts to determine the decay rate for proton decay, long lived alpha decay, long lived beta and double beta decay. ^{151}Eu is the latest (formerly stable) nuclide whose long-lived alpha decay has recently been measured (see Table 10).

A few years ago, half-lives and decay modes of long-lived nuclides were presented [10]. A latest revision [1] of these data is presented in Table 10. Only double beta decay ($\beta\beta$) modes that involve the emission of two neutrinos are listed in the table, since ($\beta\beta$) decay modes without the emission of neutrinos (0ν) have never been detected. Their lower limits are one or more orders of magnitude larger than ($2\nu\ \beta\beta$) decay modes.

Table 10. Radioactive Half-lives and Decay Modes of Long-Lived (Quasi-Stable) Nuclides

Nuclide	Decay Mode	Years	Nuclide	Decay Mode	Years	Nuclide	Decay Mode	Years
^{1}H	proton	$>35\cdot10^{27}$	^{40}Ca	ec-ec	$59\cdot10^{20}$	^{48}Ca	$\beta^-\beta^-$	$43\cdot10^{18}$
^{50}V	β^-/ec	$14\cdot10^{16}$	^{50}Cr	β^+-ec	$13\cdot10^{17}$	^{54}Fe	ec-ec	$>31\cdot10^{21}$
^{58}Ni	ec-ec	$>4\cdot10^{19}$	^{64}Zn	ec-β^+	$>43\cdot10^{17}$	^{70}Zn	$\beta^-\beta^-$	$>13\cdot10^{15}$
^{71}Ga	β^-	$24\cdot10^{25}$	^{73}Ge	β^-	$>1.8\cdot10^{23}$	^{76}Ge	$\beta^-\beta^-$	$16\cdot10^{20}$
^{74}Se	ec-ec	$>55\cdot10^{17}$	^{82}Se	$\beta^-\beta^-$	$>95\cdot10^{18}$	^{78}Kr	ec-ec	$>15\cdot10^{20}$
^{94}Zr	$\beta^-\beta^-$	$>1\cdot10^{17}$	^{96}Zr	$\beta^-\beta^-$	$3\cdot10^{19}$	^{92}Mo	β^+-ec	$>19\cdot10^{18}$
^{100}Mo	$\beta^-\beta^-$	$82\cdot10^{17}$	^{96}Ru	$\beta^-\beta^-$	$>31\cdot10^{15}$	^{106}Cd	$\beta^+\beta^+$	$>24\cdot10^{19}$
^{108}Cd	$\beta^+\beta^+$	$10\cdot10^{17}$	^{113}Cd	β^-	$8.04\cdot10^{15}$	^{114}Cd	$\beta^-\beta^-$	$>6\cdot10^{17}$
^{116}Cd	$\beta^+\beta^+$	$38\cdot10^{19}$	^{115}In	β^-	$4.4\cdot10^{14}$	^{124}Sn	$\beta^-\beta^-$	$>22\cdot10^{17}$
^{120}Te	$\beta^-\beta^-$	$19\cdot10^{16}$	^{123}Te	$\beta^-\beta^-$	$>92\cdot10^{17}$	^{128}Te	$\beta^-\beta^-$	$2\cdot10^{24}$
^{130}Te	$\beta^-\beta^-$	$8\cdot10^{20}$	^{124}Xe	ec-ec	$>1\cdot10^{17}$	^{134}Xe	$\beta^-\beta^-$	$>11\cdot10^{15}$
^{136}Xe	$\beta^-\beta^-$	$>8\cdot10^{20}$	^{130}Ba	ec-ec	$2\cdot10^{20}$	^{132}Ba	ec-ec	$13\cdot10^{20}$
^{136}Ce	$\beta^-\beta^-$	$>18\cdot10^{15}$	^{138}Ce	ec-ec	$>9\cdot10^{13}$	^{142}Ce	$\beta^-\beta^-$	$>16\cdot10^{16}$
^{144}Nd	α	$2.1\cdot10^{15}$	^{150}Nd	$\beta^-\beta^-$	$1.4\cdot10^{20}$	^{147}Sm	α	$1.06\cdot10^{11}$
^{148}Sm	α	$7\cdot10^{15}$	^{149}Sm	α	10^{16}	^{151}Eu	α	$>17\cdot10^{17}$
^{160}Gd	$\beta^-\beta^-$	$>19\cdot10^{18}$	^{176}Yb	$\beta^-\beta^-$	10^{26}	^{174}Hf	α	$20\cdot10^{14}$
^{180m}Ta	$\beta^-\beta^-$	$>71\cdot10^{14}$	^{180}W	α	$18\cdot10^{17}$	^{182}W	α	$>77\cdot10^{20}$
^{183}W	α	$>41\cdot10^{20}$	^{184}W	α	$>89\cdot10^{20}$	^{186}W	α	$>82\cdot10^{20}$
^{186}Os	α	$2\cdot10^{15}$	^{190}Pt	α	$45\cdot10^{10}$	^{196}Hg	α	$>25\cdot10^{17}$
^{208}Pb	sf	$>2\cdot10^{19}$	^{209}Bi	α	$19\cdot10^{18}$			

Data on the Very Heavy Chemical Elements

For very heavy elements (trans-meitnerium elements, Z > 109), there are other modes of decay (determining factors in stability), spontaneous fission (sf) decay and cluster decay. In sf decay, the nucleus breaks up into two approximately equal reaction products, both of which have very large masses (some 15 to 40 times larger than an alpha particle). Cluster decay is radioactive decay in which the emitted particle has a much smaller mass than a fission product but it is still larger than the alpha particle (some 3 to 8 times larger). For very heavy chemical elements, a path to the super-heavy elements is being explored. In the process of this investigation, new nuclides and elements are being discovered. The present list [1] of the highest Z elements (Z > 109) and their nuclides is shown in Table 11.

Table 11. Nuclear Data of the Very Heavy Chemical Elements

Nuclide	Half-life	Mode Decay	Energy (MeV)	Nuclide	Half-life	Mode Decay	Energy (MeV)
^{267}Ds	~3 μ-sec	α	11.6	^{269}Ds	0.17 ms	α	11.11
^{270m}Ds	~6 ms	α	10.95	^{270g}Ds	0.1 ms	α	11.03
^{271m}Ds	0.07 s	α	9.9	^{271g}Ds	1.6 ms	α	10.8
^{273m}Ds	0.076 ms	α	11.8	^{273g}Ds	118 ms	α	9.73
^{279}Ds	0.20 s	sf 90% α 10%	~9.70	^{280}Ds	~7.6 s	sf	
^{281}Ds	11 s	sf		^{282}Ds	0.5 ms	sf	
^{272}Rg	~2. ms	α	10.82	^{274}Rg	~65 ms	α	11.2
^{278}Rg	~4. ms	α	10.7	^{279}Rg	~0.17 s	α	10.4
^{280}Rg	~3.6 s	α	~9.75	^{277}112	0.7 ms	α	11.5-11.7
^{282}112	0.5 ms	sf		^{283}112	~4. s	α 100% sf ≤10%	9.52
^{284}112	~ 97. ms	sf		^{285}112	~ 29 s	α	9.15
^{278}113	~ 3 ms	α	11.7	^{282}113	~0.07 s	α	10.6
^{283}113	~0.1 s	α	10.1	^{284}113	~0.48 s	α	10.0
^{286}114	0.13 s	sf 50% α 50%	10.2	^{287}114	0.5 s	α	10.02
^{288}114	0.8 s	α	9.94	^{289}114	~2.6 s	α	9.82
^{287}115	0.03 s	α	10.6	^{288}115	~0.09 s	α	10.5
^{290}116	7. ms	α	10.8	^{291}116	~18. ms	α	~10.74
^{292}116	~18 ms	α	~10.66	^{293}116	~0.06 s	α	10.5
^{294}118	~0.89 ms	α	11.7				

Note that in Tables 10 and 11, the uncertainty is 5 or less in the last digit quoted, unless the value is preceded by an approximate sign (~), in which case the uncertainty is greater than 6 and could be two digits, e.g., 34 +/- 10 would be listed as ~ 34.

Neutron Cross Sections

There have been many new neutron cross-section and resonance integral measurements in the last few years across the periodic table of elements, since a previous report [10]. Some recommended values, from a preliminary evaluation of the data, are given in the tables 12 and 13. The symbol (m + g) for the isotope ^{126}Sn in Table 13 refers to the cross section to the meta-stable state, m, and to the ground state, g. For the Table 12 isotopic abundance column, the uncertainty is given in parentheses following the value. As mentioned above, the changes in the isotopic abundance values can lead to a change in the thermal neutron cross-section and resonance integrals that are measured by activation analysis on a natural sample of an element. In the case of ^{168}Yb, the thermal neutron cross-section value becomes 2969 ± 100 barns and the resonance integral becomes 19000 ± 2000 barns. In the case of Pt, the thermal neutron cross-section becomes 157 ± 23 barns and the resonance integral becomes 69 ± 10 barns.

Table 12. Neutron Cross-Sections and Resonance Integrals of Gadolinium

Isotope	Abundance	Thermal σ	Uncertainty	Res. Int.	Uncertainty
^{152}Gd	0.20 (1)	1050. barns	150 barns	476. barns	70 barns
^{154}Gd	2.18 (3)	85.8 barns	10 barns	261. barns	60 barns
^{155}Gd	14.80 (12)	60200. barns	1000 barns	1570. barns	100 barns
^{156}Gd	20.47 (9)	1.74 barns	0.9 barns	104. barns	15 barns
^{157}Gd	15.65 (2)	226000. barns	3000 barns	789. barns	100 barns
^{158}Gd	24.84 (7)	2.19 barns	0.3 barns	71.5 barns	7 barns
^{160}Gd	21.86 (19)	0.76 barns	0.8 barns	7.7 barns	1.0 barns

Table 13. Thermal Neutron Capture and Fission Cross-Sections for Various Nuclides

Isotope	Thermal σ_γ	Uncertainty	Isotope	Thermal σ_γ	Uncertainty
^{59}Fe	6 barns	1 barn	^{57}Co	51 barns	5 barns
^{58}Ni	4.1 barns	0.1 barns	^{59}Ni	74 barns	4 barns
^{60}Ni	2.3 barns	0.1 barns	^{93}Zr	~ 0.63 barns	0.02 barns
^{102}Pd	1.8 barns	0.2 barns	^{105}Pd	19 barns	1 barn
^{107}Pd	9.2 barns	0.3 barns	^{126}Sn	0.39+0.20 barn	
^{148}Gd	9600 barns	900 barns	^{180}W	23 barns	2 barns
^{185}Re	σ_m 0.81 barns	0.08 barns	^{242m}Am	1150 barns	115 barns
^{242m}Am	σ_f 6840 barns	340 barns	^{242g}Am	σ_f 2900 barns	200 barns

Conclusions

It can be concluded from this brief survey of nuclear data in the above discussions that both neutron and non-neutron nuclear data are very robust fields. All of the above areas are included in the review of nuclear data that is performed for the annual publication of the Handbook of Chemistry and Physics. New chemical elements continue to be discovered and to be named. There are many long-lived nuclides that were considered to be stable but whose radioactive decay has now been observed. A complete evaluation of the thermal neutron cross-sections and resonance integrals should be completed by early next year.

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