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Review of Non-neutron and Neutron Nuclear Data, 2004

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Abstract. Review articles are in preparation for the 2004 edition of the CRC Handbook of Chemistry and Physics dealing with the evaluation of both non-neutron and neutron nuclear data. Data on the discovery of element 110, Darmstadtium, and element 111 have been officially accepted, while data on element 118 have been withdrawn. Data to be presented include revised values for very short-lived nuclides, long-lived nuclides and beta-beta decay measurements. There has been a reassessment of the spontaneous fission (sf) half-lives, which distinguishes between sf decay half-lives and cluster decay half-lives and with cluster-fission decay. New measurements of isotopic abundance values for many elements will be discussed with an emphasis on the minor isotopes of interest for use in neutron activation analysis measurements. Neutron resonance integrals will be discussed emphasizing the differences between the calculated values obtained from the analytical integration over neutron resonances and the measured values in a neutron reactor-spectrum, which does not quite conform to the assumed 1/E neutron energy spectrum. The method used to determine the neutron resonance integral from measurement, using neutron activation analysis, will be discussed.

INTRODUCTION

The published scientific literature is scanned and periodically evaluated for any new or revised nuclear data measurements. Pertinent information on isotopic masses, isotopic composition, radioactive half-lives, atomic weights, alpha particle, beta, proton, positron, isomeric transition energy and branching ratios, γ-ray energies and intensities. Nuclear spin, parity, magnetic dipole and electric quadrupole moments and other nuclear information are reviewed and "best values" are recommended and published [1]. For neutron data, cross sections for thermal energy (room temperature) reactions, resonance integrals, scattering lengths and Maxwellian averaged cross sections at a neutron energy value of 30 keV for astrophysical applications are reviewed and "best values" are recommended and published [2].

ELEMENTS AND NUCLIDES

Data reported for new elements to be placed on the Periodic Table of Chemical Elements are reviewed. It is determined which set of data is the first to have found that new element and whether or not there has been verification of that claim. One group is allowed to claim discovery and have the privilege of supplying the name of this new element. New claims of discovery for elements with Z=113 and Z=115 has appeared in the literature [3]. Data supporting a discovery of element Z=118 was withdrawn, when the data could not be confirmed. Another claim of discovery of element Z=118 has been made [4].

Two claims of discovery have been acknowledged, which resulted in officially naming element Z=110 Darmstadtium and its addition to the Periodic Table [5]. A second element Z=111, Roentgenium, is in the process of being officially approved later this year.

There have been a number of new short-lived nuclides discovered, which are located far from the line of beta stability. In the past eight years, there has been a 20% increase in the number of nuclides discovered. There have been 504 new nuclides added to bring the total number of nuclides to 3060, which does not include electromagnetic isomers. The newly discovered nuclides have been found with 40% on the neutron deficient side of stability (lighter masses of an element) and 60% on the neutron excess side (heavier masses of that element). This ratio has not been systematic throughout the periodic table. For the light and medium weight elements up to Z=75, 2 out of 3 new nuclides have been discovered on the neutron excess side of stability, while for heavier elements, Z=76 to Z=100, 3 out of 4 new nuclides have been found on the neutron deficient side of stability. For many of these nuclides, some radiation

has been followed to allow an estimate of the radioactive half-life. In other cases, only the existence of the nuclide from its mass and charge can be inferred.

ISOTOPIC COMPOSITION

The isotopic composition of an element is determined by measuring the ratio of the individual stable nuclides of the element. The abundance values of the stable nuclides are normalized to unity. The number of significant digits in the major isotope(s) may require truncation in the number of significant digits (lost information) in the minor isotope. This minor isotope is often the one isotope of interest for neutron activation analysis purposes in determining the cross section or the resonance integral. If one uses the original isotope ratio measurements with the isotopic composition, one can usually obtain an extra significant digit for the minor isotope. In Table 1, the first value listed is the isotopic composition followed by the calculated value from isotope ratios. This latter abundance value has not been normalized to unity.

TABLE 1. Isotopic Abundances of Minor Isotopes

Isot.	Comp.	New	Isot.	Comp.	New
^{36}S	.01(1)	.0146(1)	^{40}K	.0117(1)	.01167(2)
^{46}Ca	.004(3)	.0035(10)	^{78}Kr	.355(3)	.3552(3)
^{84}Sr	.56(1)	.557(2)	^{152}Gd	.20(1)	.203(1)
^{156}Dy	.056(3)	.0549(1)	^{158}Dy	.095(3)	.0951(2)
^{174}Hf	.16(1)	.162(4)	^{190}Pt	.014(1)	.0136(1)
^{196}Hg	.15(1)	.153(1)			

In recent years, many isotopic compositions of chemical elements have been revised to better fit the average properties of the elements. The philosophy is to examine the total range in nature of the abundance of each isotope and to position the recommended value as the midpoint of this total range, independent of the value for the most common source of the element. One result is the much larger uncertainty assigned to the mean value compared to previous values. Variations of isotopic abundances for selected elements have been reviewed recently [6]. Fortunately, most natural variations occur in light isotopes, where the neutron cross sections are usually relatively small.

RADIOACTIVE HALF-LIVES

In electrodynamics, symmetry principles guarantee the absence of a mass for the photon and the absolute conservation of the electric charge. In theories of particle physics, neutrinos and electrons (leptons) and protons and neutrons (baryons) have lepton numbers and baryon numbers of +1, while their anti-particles have lepton numbers and baryon numbers of –1. The "Standard Model" (SM) of particle physics explains the stability of the proton by the law of baryon number conservation. In modern theories, this law is not considered to be absolute because of the lack of an underlying symmetry principle. Extensions of the SM theory incorporate interactions that would violate baryon number conservation by assuming the symmetry associated with baryon number conservation is broken at a certain energy scale. Such interactions could lead to processes such as the decay of the proton, where the baryon number would change from +1 to 0. Proton stability has been searched for in various experiments. It has not yet been found and the upper limit [7] for the half-life of the proton can be seen in Table 2.

One of the upper limits in Table 2 is due to the search for charge non-conservation (CNC) reactions, a violation of charge conservation in ^{71}Ga decay. The normal β decay process in ^{71}Ga is energetically forbidden. In the case of CNC, no electron would be emitted and its rest mass energy of 511 keV would be available as extra decay energy. The CNC decay energy is positive by +275 keV (or energetically possible), while for charge conserving decay, the decay energy is negative, -236 keV, (or energetically forbidden). If this decay process can be detected, it would mean that the electric charge is not conserved in this reaction. This would correspond to a violation of a basic law in physics that has long been assumed to be true. The ^{71}Ga solar neutrino experiments placed an upper limit of 3.5×10^{26} years on this decay [8], so CNC has not yet been observed.

Double beta decay ($\beta\beta$) is a rare transition between two nuclei with the same mass number that changes the nuclear charge number by two units. It is of interest as a tool for the study of lepton conservation and neutrino properties. Two electrons (and possibly two anti-neutrinos) must be emitted to conserve electric charge. Only $2\nu\beta\beta$ decays are listed in Table 2. No $0\nu\beta\beta$ decays are listed. Note also that ^{209}Bi, which was thought to be a stable nuclide, actually decays by α particle emission [9].

Table 2. Radioactive Half-lives, Long-lived Nuclei

Isot.	Decay	Years	Isot.	Decay	Years
^{1}H	proton	$> 35\cdot10^{27}$	^{40}Ca	ec-ec	$> 59\cdot10^{20}$
^{48}Ca	$\beta^-\beta^-$	$43\cdot10^{18}$	^{50}Cr	β^+-ec	$> 13\cdot10^{17}$
^{58}Ni	β^+-ec	$> 4\cdot10^{19}$	^{64}Zn	ec-ec	$> 23\cdot10^{17}$
^{71}Ga	β^-	$> 35\cdot10^{25}$	^{76}Ge	$\beta^-\beta^-$	$18\cdot10^{20}$
^{82}Se	$\beta^-\beta^-$	$12\cdot10^{19}$	^{78}Kr	$\beta^+\beta^+$	$20\cdot10^{20}$
^{94}Zr	$\beta^-\beta^-$	$> 1\cdot10^{17}$	^{96}Zr	$\beta^-\beta^-$	$21\cdot10^{18}$
^{92}Mo	β^+-ec	$> 19\cdot10^{18}$	^{100}Mo	$\beta^-\beta^-$	$80\cdot10^{17}$
^{96}Ru	$\beta^+\beta^+$	$> 31\cdot10^{15}$	^{106}Cd	$\beta^+\beta^+$	$> 24\cdot10^{19}$
^{108}Cd	ec-ec	$> 41\cdot10^{16}$	^{114}Cd	$\beta^-\beta^-$	$> 6\cdot10^{17}$
^{116}Cd	$\beta^-\beta^-$	$38\cdot10^{18}$	^{124}Sn	$\beta^-\beta^-$	$> 22\cdot10^{17}$
^{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	$22\cdot10^{20}$
^{132}Ba	ec-ec	$13\cdot10^{20}$	^{136}Ce	$\beta^+\beta^+$	$> 18\cdot10^{15}$
^{138}Ce	ec-ec	$> 9\cdot10^{13}$	^{150}Nd	$\beta^-\beta^-$	$7\cdot10^{18}$
^{160}Gd	$\beta^-\beta^-$	$>19\cdot10^{18}$	^{176}Yb	$\beta^-\beta^-$	$> 16\cdot10^{16}$
^{180}W	ec-ec	$7\cdot10^{16}$	^{186}W	$\beta^-\beta^-$	$37\cdot10^{17}$
^{209}Bi	α	$19\cdot10^{18}$	^{238}U	$\beta^-\beta^-$	$20\cdot10^{20}$

Other Nuclear Information

For heavy elements, decay modes include spontaneous fission (sf) decay [10] and cluster decay [11]. In sf decay, the nucleus breaks up into two approximately equal reaction products, both of which have very large masses (15 to 40 times an α particle). In cluster decay, the emitted particle has a smaller mass (about 3 to 8 times an α particle). Using the sf and total half-life values, the sf branching ratio (percentage of the time that a nucleus decays by sf mode) has been determined [12] for heavy nuclides. These sf branching ratios are listed in Table 3.

For heavy chemical elements, a path to the super heavy elements is being explored. Among new elements being discovered, element 113 and 115 were mentioned earlier.

Table 3. Spontaneous Fission Branching Ratios

Isot.	Percent	Isot.	Percent	Isot.	Percent
^{232}Th	$12\cdot10^{-10}$	^{234}U	$16\cdot10^{-10}$	^{235}U	$70\cdot10^{-10}$
^{236}U	$94\cdot10^{-6}$	^{238}U	$54\cdot10^{-6}$	^{236}Pu	$19\cdot10^{-8}$
^{238}Pu	$18\cdot10^{-8}$	^{239}Pu	$3\cdot10^{-12}$	^{240}Pu	$57\cdot10^{-7}$
^{241}Pu	$24\cdot10^{-15}$	^{242}Pu	$56\cdot10^{-5}$	^{244}Pu	0.12
^{241}Am	$36\cdot10^{-11}$	^{243}Am	$37\cdot10^{-10}$	^{240}Cm	$39\cdot10^{-7}$
^{242}Cm	$64\cdot10^{-7}$	^{243}Cm	$52\cdot10^{-10}$	^{244}Cm	$14\cdot10^{-5}$
^{245}Cm	$61\cdot10^{-8}$	^{246}Cm	0.026	^{248}Cm	0.082
^{250}Cm	86.	^{249}Bk	$49\cdot10^{-9}$	^{237}Cf	10.
^{238}Cf	100.	^{240}Cf	~2	^{246}Cf	0.00023
^{248}Cf	0.0029	^{249}Cf	$44\cdot10^{-8}$	^{250}Cf	0.077
^{252}Cf	3.08	^{254}Cf	99.3	^{256}Cf	100.
^{253}Es	$89\cdot10^{-7}$	^{255}Es	0.0042	^{244}Fm	100.
^{246}Fm	8.	^{248}Fm	0.10	^{250}Fm	0.007
^{252}Fm	0.0023	^{254}Fm	0.059	^{255}Fm	$24\cdot10^{-6}$
^{256}Fm	91.9	^{257}Fm	0.21	^{258}Fm	100.
^{259}Fm	100.	^{260}Fm	100.	^{245}Md	100.
^{247}Md	100.	^{259}Md	~100.	^{250}No	~100
^{252}No	32.	^{254}No	0.17	^{256}No	0.53
^{258}No	100.	^{260}No	100.	^{262}No	100.
^{253}Lr	1.3	^{259}Lr	20.	^{261}Lr	100.
^{153}Rf	~100.	^{255}Rf	52.	^{256}Rf	99.7
^{258}Rf	87.	^{259}Rf	8.	^{260}Rf	100.
^{255}Db	~20.	^{260}Db	9.6	^{263}Db	55.
^{258}Sg	100.	^{260}Sg	50.	^{264}Hs	50.

The data for the initial discovery of element 118 was withdrawn when no Laboratory, even the originating Lab could confirm the original data. Since then another claim has been made by another Laboratory. Table 4 lists the data on nuclides with Z>109, where superscript "g" refers to the ground state and the superscript "m" refers to an excited energy state.

Table 4. Nuclear Data on Very Heavy Elements

Nuclide	Half-life	Mode	Energy
^{267}Ds	~3 μs	α decay	11.6 Mev
^{269}Ds	0.17 ms	α decay	11.1 MeV
^{270m}Ds	~6. ms	α decay	11.0-12.2 MeV
^{270g}Ds	~ 10. μs	α decay	11.0 MeV
^{271m}Ds	~ 1.1 ms	α decay	10.7 MeV
^{271g}Ds	~ 56. ms	α decay	10.7 MeV
^{273m}Ds	0.76 ms	α decay	11.8 MeV
^{273g}Ds	118. ms	α decay	9.73 MeV
^{279}Ds	~ 0.3 s	spon. fiss.	
^{281}Ds	~ 9.6 s	spon. fiss.	
^{272}Rg	1.5 ms	α decay	11.0 MeV
^{279}Rg	~ 0.17 s	α decay	10.4 MeV
^{280}Rg	~ 3.6 s	α decay	9.8 MeV
^{277}112	0.48 ms	α decay	11.2-11.7 MeV
^{282}112	1. ms	spon. fiss.	
^{283}112	~ 6. s	α decay	9.5 MeV
^{284}112	0.1 s	spon. fiss.	
^{285}112	~34. s	α decay	9.2 MeV
^{283}113	~0.1 s	α decay	10.1 MeV
^{284}113	~0.5 s	α decay	10.0 MeV
^{286}114	0.3 s	α decay	10.0 MeV
^{287}114	~1. s	α decay	10.0 MeV
^{288}114	~0.6 s	α decay	10.0 MeV
^{289}114	~2.7 s	α decay	9.8 MeV
^{287}115	~0.03 s	α decay	10.6 MeV
^{288}115	~87. ms	α decay	10.5 MeV
^{290}116	~15. ms	α decay	10.9 MeV
^{291}116	~6. ms	α decay	10.7 MeV
^{292}116	~33. ms	α decay	10.6 MeV
^{293}116	~0.05 s	α decay	10.5 MeV
^{294}118	~1.8 ms	α decay	11.8 MeV

The neutron cross section is a measure of the probability of the interaction of a neutron with a nuclide. In thermal reactors, neutrons are produced in the fission process and are slowed down by collisions with moderator atoms. The neutron slowing down spectrum varies inversely with the energy, E. The resonance integral (RI) is the probability of neutron reactions in this region, i.e., the integral of the cross section over the epithermal flux (assumed 1/E per unit energy interval). The flux is not proportional to 1/E, but β is introduced and is reactor dependent. Flux per unit energy interval is proportional to $1/E^{1+\beta}$ [13]. RI upper limits are important in threshold reactions. Integration to 20 MeV distorts the RI [14].

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