BNL-71595-2003-CP

Prepared for the 42nd
IUPAC General Assembly
in Ottawa, Canada
August 8th - 17th, 2003

Half-lives of Long-lived α-decay, β-decay, electron capture decay, ββ-decay, proton decay and Spontaneous Fission decay Nuclides*

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1. Introduction

In his review of radionuclides for dating purposes, Roth noted that there were a large number of nuclides, normally considered "stable" but which are radioactive with a very long half-life. Roth suggested[1] that I review the data on the half-life values of these long-lived nuclides for the 2001 Atomic Weights Commission meeting in Brisbane. I provided a report, BNL-NCS-68377, to fulfill Roth's request. Peiser has now made a similar suggestion that I review these data for our next Commission meeting in Ottawa for their possible inclusion in our Tables. These half-life values for long-lived nuclides include those due to various decay modes, α-decay, β-decay, electron capture decay, ββ-decay, proton decay and spontaneous fission decay. This data review (post Brisbane) provides an update to the recommendation of the 2001 review.

2. Discussion

There is some vagueness in the definition of what constitutes a long-lived nuclide. A definition used for this report will be a nuclide with a half-life that exceeds the age of the universe, which is greater than approximately 12.5 billion years or $1.25 \pm 0.30 \times (10)^{10}$ years (a recent measurement of stellar age[2]). There are a number of nuclides which are normally considered stable but which can decay via normal modes such as electron capture, negative and positive beta emission, alpha emission and exotic decay modes of double beta decay, proton decay or spontaneous fission.

In the following Tables, long-lived nuclides will be given with their isotopic abundance value, their decay mode and their half-life value. In a number of cases, the decay was followed but no emission was determined. As a result, the half-life will be indicated by a lower limit on the value, which would be the symbol " > " or a greater than sign. In general, all of the data listed in the table are the result of experimental measurements. In the literature, there are also many reported

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*This work was performed under auspices of the US Department of Energy (Contract DE-AC02-98CH10886).

calculations of half-lives for the above modes of decay from various theoretical models. These theoretical results are not indicated in these Tables, which are resticted to measurement only.

3. Alpha (α) Decay

Rutherford showed that the alpha particle (α) was the doubly charged nucleus of helium and contained two protons and two neutrons. Alpha decay is relatively rare because it requires a lot of energy to take two neutrons and two protons out of a nucleus. It is only possible in some cases because a lot of energy is gained by forming the two neutrons and two protons into an alpha particle. This gain in energy is called the binding energy of the nucleons (neutrons and protons). It is because of the mass (or energy) difference that alpha particle emission from a particular nuclide can be energetically possible, while either proton emission or deuteron emission would not be energetically possible. Generally, alpha particle emission occurs in the region of bismuth and above, although there are a few scattered alpha decays beginning in the region of the rare earth elements.

Alpha particle emission is a common mode of decay for the heavier elements. The nuclides in the following Tables with half-lives longer than the age of the universe that decay by alpha emission begin in the rare earth region of the periodic table. Some of these half-life values given in the Table, have been documented in detail previously[3,4,5].

4. Beta (β) Decay

Beta particles are singly negatively charged electrons (negatrons) or singly positively charged electrons (positrons). Nuclides that have an excess of neutrons, decay by emitting negatrons. Nuclides with a deficiency of neutrons can decay by emitting positrons. Beta decay is a common mode of decay throughout the periodic table. The half-life involves is usually relatively short compared to the other types of decay modes. The only nuclides which decay by beta particle emission with half-life values longer than the age of the universe involve a relatively low energy difference between that nuclide (mother nuclide) and the ground state of the nuclide (daughter nuclide) to which it would decay and there is often a large change in angular momentum between the mother and daughter nuclides. Some half-life values have been documented previously[3,4,5].

5. Electron Capture (EC) Decay

Electron capture decay involves the absorption into the nucleus of one of the orbiting negatively charged electrons of the atom of the nuclide involved. The effect of absorbing the negatively charged electron has the same result as the emission of a positron as far as the element is concerned. Many nuclei will have both positron decay and electron capture decay as similar modes of their decay to the same final state of the daughter nucleus. Some of these half-life values have been documented previously[3,4,5].

6. Double Beta (ββ) Decay

The ββ decay mode is a process whereby the charge of the decaying nucleus increases by two units as a result of the simultaneous transformation of two neutrons into two protons, that is accompanied by the emission of two electrons and two electron anti-neutrinos (2β-2ν decay). Since the anti-neutrino is identical to the neutrino, ββ decay can also occur without neutrino emission (2β-0ν decay). This decay mode may appear in a number of combinations. There can be $\beta^- \beta^-$ decay, $\beta^+ \beta^+$ decay, electron capture - electron capture (EC-EC) decay, or a combination of electron capture - β^- or electron capture - β^+ decay modes.

In this neutrino-less mode, ββ decay can be visualized as a two step process; first the neutron that has decayed in a nucleus emits a neutrino, which is absorbed by the second neutron and transforming it into a proton. The neutrino appears as a virtual particle, only two electrons are produced in the final state. Since there are only two electrons produced rather than two electrons and two neutrinos, neutrino-less double beta would have a higher probability of occurrence than the 2β-2ν mode. As a result, neutrino-less decay would result in a larger half-life value. As such, if there is a lower limit established for neutrino-less decay, the 2ν mode would actually be lower than this lower limit. In the following table, I have not included the 0ν mode lower limit values, since there could be an even lower limit value for the 2β-2ν mode of decay. In some cases, e.g., ^{46}Ca, ^{54}Fe, ^{70}Zn, ^{84}Sr, ^{98}Mo, ^{112}Sn, ^{122}Sn, ^{120}Te, ^{180}W, ^{184}Os, ^{192}Os, ^{190}Pt and ^{198}Pt, the only lower limits measured are for the 2β-0ν mode of decay. As a result, these nuclides are not listed in the following tables.

One of the requirements for neutrino-less double beta decay to occur can be fulfilled if the neutrino has a non-zero rest mass. As a result, there is extensive interest in searching for the 0ν decay mode to try to determine the rest mass of the neutrino. The most recent results reported[6] from the Sudbury Neutrino Observatory in Sudbury, Ontario provided the first direct evidence for the changing of solar neutrinos from electron type to another type. According to the equations of particle physics, for this transformation to occur, at least one of the neutrino types must possess a small amount of mass. An estimate for the upper limit for the mass of the neutrino is 1/60,000th of the mass of the electron. However, no experimental evidence for the neutrino-less mode of ββ decay has as yet been found. A recent measurement[7] claims to have observed a 0ν ββ decay in ^{76}Ge with a half-life of 1.5×10^{25} years, which implies lepton non-conservation and a mass for the neutrino of 0.39 eV. Other researchers disagree and suggest this claim is based upon a flawed analysis of data.

This double beta decay that is characterized by the simultaneous emission of two electrons is a very rare mode of decay. The corresponding half-life values are some of the longest observed in nature. Since an isobar corresponds to two nuclides which have the same mass number but different chemical properties because they have different atomic numbers, there are “stable” isobar pairs where the energy differences are on the order of several MeV or less. Some of these half-life values have been documented previously[4,5].

7. Proton Decay

The proton decay mode is a process whereby the proton undergoes decay in any of a variety of possible modes (some 75 known modes[8] and possibly some unknown modes) involving both strongly and electromagnetically interacting particles (such as mesons, leptons and photons) and weakly interacting particles (neutrinos). No evidence for nucleon decay has been found up to now. Lifetime limits for the strongly interacting modes are 10^{30} to 10^{33} years, while for the weakly interacting modes the lifetime limits are up to ten orders of magnitude lower. Although the standard model (SM) of particle physics explains proton stability using the law of baryon conservation, there is no underlying symmetry principle involved to support that law. In the Grand Unified Theory of fundamental interactions (GUT), protons are predicted to decay at a small but quite possibly measurable rate. Since it is not known what mode of proton decay is possible, limits are set for proton stability using methods that are decay mode independent.

8. Spontaneous Fission (SF) Decay

Spontaneous fission (SF) decay is a phenomenon that is exhibited by heavy nuclei in which that nucleus spontaneously fragments into two approximately equal parts. It can be a major mode of decay of nuclei heavier than thorium and can be a determining factor in their stability and will ultimately limit the number of new chemical elements that can exist. Generally, SF half-lives decrease with increasing atomic number. Some of these half-life values have been documented previously[5,9].

There is also a decay mode called heavy fragment emission[10]. In this decay mode, various fragments of nuclei heavier than an alpha particle are emitted but not as large as those from spontaneous fission. Normally, nuclei that undergo heavy fragment emission also have other decay modes, which have a much shorter half-life. As a result, the total half-life for the nuclide would be determined primarily by the other modes of decay and not by heavy fragment emission.

This heavy fragment decay mode is usually important for making corrections to spontaneous fission decay rates. As a result, the heavy fragment decay mode does not appear in any of the following Tables.

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10. Acknowledgement

This work was aided by the use of facilities at the National Nuclear Data Center (NNDC) of the Brookhaven National Laboratory and are hereby acknowledged.

Table I - Half-lives of Long-lived Nuclides, Hydrogen to Cadmium

NUCLIDE	MOLE FRACTION	DECAY MODE	HALF-LIFE (YEARS)	REFERENCE(S)
^{1}H	0.999885	p	$> 3.5 \times (10)^{28}$	11, 12, 13
^{40}Ca	0.96941	EC EC	$> 5.9 \times (10)^{21}$	14
^{48}Ca	0.00187	$\beta^- \beta^-$	$4.3 \times (10)^{19}$	15, 16
		β^-	$> 1.4 \times (10)^{20}$	17, 18
^{50}V	0.00250	EC / β^-	$1.5 \times (10)^{17}$	19, 20
^{50}Cr	0.04345	β^+ EC	$> 1.3 \times (10)^{18}$	21
^{58}Ni	0.680769	EC EC	$> 4. \times (10)^{19}$	22
^{64}Zn	0.4827	EC EC	$> 2.3 \times (10)^{18}$	23, 24
^{71}Ga	0.39892	β^-	$> 3.5 \times (10)^{26}$	25
^{73}Ge	0.07759	β^-	$> 2.6 \times (10)^{23}$	26
^{76}Ge	0.07835	$\beta^- \beta^-$	$1.77 \times (10)^{21}$	27, 28
^{82}Se	0.0873	$\beta^- \beta^-$	$1.2 \times (10)^{20}$	29, 30
^{78}Kr	0.00355	EC EC	$> 2.3 \times (10)^{20}$	31
^{87}Rb	0.2783	β^-	$4.88 \times (10)^{10}$	3
^{94}Zr	0.1738	$\beta^- \beta^-$	$> 1.1 \times (10)^{17}$	32
^{96}Zr	0.0280	β^-	$> 1.7 \times (10)^{18}$	33
		$\beta^- \beta^-$	$> 2.3 \times (10)^{19}$	32, 34, 35
^{92}Mo	0.1477	β^+ EC	$> 1.9 \times (10)^{19}$	36
^{100}Mo	0.0967	$\beta^- \beta^-$	$7.9 \times (10)^{18}$	37, 38, 39, 40, 41
^{96}Ru	0.0554	$\beta^+ \beta^+$	$> 3.1 \times (10)^{16}$	23
^{110}Pd	0.1172	$\beta^- \beta^-$	$> 6. \times (10)^{17}$	42
^{106}Cd	0.0125	$\beta^+ \beta^+$	$> 2.4 \times (10)^{20}$	43
^{108}Cd	0.0089	EC EC	$> 4.1 \times (10)^{17}$	44

Table II. Half-lives of Long-lived Nuclides, Cadmium to Samarium

NUCLIDE	MOLE FRACTION	DECAY MODE	HALF-LIFE (YEARS)	REFERENCES
^{113}Cd	0.1222	β^-	$7.9 \times (10)^{15}$	45, 46, 47
^{114}Cd	2873	$\beta^- \beta^-$	$> 9.2 \times (10)^{16}$	44
^{116}Cd	0.0749	$\beta^- \beta^-$	$3.8 \times (10)^{19}$	48
^{115}In	0.9571	β^-	$4.4 \times (10)^{14}$	4
^{124}Sn	0.0579	$\beta^- \beta^-$	$> 2.2 \times (10)^{18}$	49
^{123}Te	0.0089	EC	$> 9.2 \times (10)^{16}$	50, 51
^{128}Te	0.3174	$\beta^- \beta^-$	$2. \times (10)^{24}$	52, 53
^{130}Te	0.3408	$\beta^- \beta^-$	$8. \times (10)^{20}$	29, 53
^{124}Xe	0.000953	EC EC	$> 1.1 \times (10)^{17}$	54
^{134}Xe	0.10436	$\beta^- \beta^-$	$> 1.1 \times (10)^{16}$	55
^{136}Xe	0.08858	$\beta^- \beta^-$	$> 0.8 \times (10)^{21}$	56
^{130}Ba	0.00106	EC EC	$2.2 \times (10)^{21}$	57
^{132}Ba	0.00101	EC EC	$1.3 \times (10)^{21}$	57
^{138}La	0.00090	EC / β^-	$1.1 \times (10)^{11}$	58, 59, 60, 61
^{136}Ce	0.00185	$\beta^+ \beta^+$	$> 1.8 \times (10)^{16}$	62
^{138}Ce	0.00251	EC EC	$> 9.0 \times (10)^{13}$	62
^{142}Ce	0.11114	α $\beta^- \beta^-$	$> 5. \times (10)^{16}$ $> 1.6 \times (10)^{17}$	63 62
^{144}Nd	0.238	α	$2.1 \times (10)^{15}$	4
^{145}Nd	0.083	α	$> 1. \times (10)^{17}$	4, 64
^{148}Nd	0.057	$\beta^- \beta$	$> 3. \times (10)^{18}$	65

Table III. Half-lives of Long-lived Nuclides, Neodymium to Rhenium

NUCLIDE	MOLE FRACTION	DECAY MODE	HALF-LIFE (YEARS)	REFERENCE
^{150}Nd	0.056	$\beta^- \beta^-$	$0.7 \times (10)^{19}$	66
^{147}Sm	0.1499	α	$1.06 \times (10)^{11}$	3
^{148}Sm	0.1124	α	$7. \times (10)^{15}$	4
^{149}Sm	0.1382	α	$1. \times (10)^{16}$	67
^{154}Sm	0.2275	$\beta^- \beta^-$	$> 2.3 \times (10)^{18}$	68
^{152}Gd	0.0020	α	$1.1 \times (10)^{14}$	63
^{160}Gd	0.2186	$\beta^- \beta^-$	$> 1.9 \times (10)^{19}$	62
^{156}Dy	0.00056	α	$> 1.0 \times (10)^{15}$	64
^{162}Er	0.00139	α	$> 1.4 \times (10)^{14}$	69
^{170}Er	0.14910	$\beta^- \beta^-$	$> 3.2 \times (10)^{17}$	67
^{168}Yb	0.0013	α	$> 1.6 \times (10)^{14}$	69
^{176}Yb	0.1276	$\beta^- \beta^-$	$> 1.6 \times (10)^{17}$	67
^{176}Lu	0.0259	β	$3.8 \times (10)^{10}$	3, 70, 71, 72, 73, 74
^{174}Hf	0.0016	α	$2.0 \times (10)^{15}$	3
^{180}Ta	0.00012	β^- / EC	$> 1.2 \times (10)^{15}$	3
^{180}W	0.0012	α	$1.1 \times (10)^{18}$	75, 76, 77
^{182}W	0.2650	α	$> 1.7 \times (10)^{20}$	76, 77
^{183}W	0.1431	α	$> 0.8 \times (10)^{20}$	76, 77
^{184}W	0.3064	α	$> 1.8 \times (10)^{20}$	76, 77
^{186}W	0.2843	α $\beta^- \beta^-$	$> 1.7 \times (10)^{20}$ $> 5.9 \times (10)^{17}$	76,77 44
^{187}Re	0.6260	β^-	$4.4 \times (10)^{10}$	3, 78, 79

Table IV. Half-lives of Long-lived Nuclides, Osmium to Uranium

NUCLIDE	MOLE FRACTION	DECAY MODE	HALF-LIFE (YEARS)	REFERENCES
^{184}Os	0.0002	α	$> 1.0 \times (10)^{17}$	69
^{186}Os	0.0159	α	$2. \times (10)^{15}$	3
^{190}Pt	0.00014	α	$4.5 \times (10)^{11}$	3, 80
^{192}Pt	0.00782	α	$> 6. \times (10)^{16}$	64
^{196}Hg	0.0015	EC EC	$> 2.5 \times (10)^{18}$	81
		α	$> 1. \times (10)^{14}$	63
^{208}Pb	0.524	Spon.Fiss.	$> 2. \times (10)^{19}$	82
^{209}Bi	1.0000	α	$1.9 \times (10)^{19}$	83
U	0.992742	$\beta^- \beta^-$	$2.0 \times (10)^{21}$	84
		α	$4.47 \times (10)^{9}$	85
		Spon.Fiss.	$8.2 \times (10)^{15}$	85