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INORGANIC CHEMISTRY DIVISION
COMMISSION ON ATOMIC WEIGHTS AND ISOTOPIC ABUNDANCES*

ATOMIC WEIGHTS OF THE ELEMENTS 2001

(IUPAC Technical Report)

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Atomic weights of the elements 2001

(IUPAC Technical Report)

Abstract: The biennial review of atomic-weight, A_r(E), determinations and other cognate data have resulted in changes for the standard atomic weights of the following elements:

	From	To
Zinc	65.39 ± 0.02	65.409 ± 0.004
Krypton	83.80 ± 0.01	83.798 ± 0.002
Molybdenum	95.94 ± 0.01	95.94 ± 0.02
Dysprosium	162.50 ± 0.03	162.500 ± 0.001

Presented are updated tables of the standard atomic weights and their uncertainties estimated by combining experimental uncertainties and terrestrial variabilities. In addition, this report again contains an updated table of relative atomic-mass values and half-lives of selected radioisotopes. Changes in the evaluated isotope abundance values from those published in 1997 are relatively minor and will be published in a major review of each element in 2003.

Many elements have a different isotopic composition in some nonterrestrial materials. Some recent data on parent nuclides that might affect isotope abundances or atomic-weight values are included in this report for the information of the interested scientific community.

INTRODUCTION

The Commission on Atomic Weights and Isotopic Abundances met under the chairmanship of Prof. L. Schultz from 30 June–2 July 2001 during the 41st IUPAC General Assembly in Brisbane, Australia. The Commission decided to publish the report "Atomic Weights of the Elements 2001" as presented here. The resulting current Table of Standard Atomic Weights is given in alphabetical order of the principal English names in Table 1 and in order of atomic number in Table 2. The atomic weights reported in Tables 1 and 2 are for atoms in their electronic and nuclear ground states.

The Commission reviewed the literature over the previous two years since the last report on atomic weights [1] and evaluated the published data on atomic weights and isotopic compositions on an element-by-element basis. The atomic weight, A_r(E), of element E can be determined from a knowledge of the isotopic abundances and corresponding atomic masses of the nuclides of that element. Compilations of the abundances of the isotopes were published in 1998 [2] and the atomic-mass evaluations of 1993 [3] have been used by the Commission. The Commission periodically reviews the history of the atomic weight of each element, emphasizing the relevant published scientific evidence on which decisions have been made [4,35].

The Commission wishes to emphasize the need for new precise calibrated isotope composition measurements in order to improve the atomic weights of a number of elements, which are still not known to a satisfactory level of accuracy. However, for many elements the limited accuracy of measurements is overshadowed by terrestrial variability, which is included in the tabulated uncertainty of the atomic weights.

For all elements for which a change in the A_r(E) value or its uncertainty, $U[A_r(E)]$ (in parentheses, following the last significant figure to which it is attributed), is recommended, the Commission by custom makes a statement on the reason for the change and includes a list of past recommended values

over a period in excess of the last 100 years, which are taken from Coplen and Peiser, 1998 [5]. Values before the formation of the International Committee on Atomic Weights in 1900 come from F. W. Clarke [6].

The names and symbols for those elements with atomic numbers 110 to 116 referred to in the following tables are systematic and based on the atomic numbers of the elements recommended for provisional use by the IUPAC Commission on the Nomenclature of Inorganic Chemistry [7]. These systematic names and symbols will be replaced by a permanent name approved by IUPAC, once the priority of discovery is established and the name suggested by the discoverers is examined and reviewed. The name is derived directly from the atomic number of the element using the following numerical roots:

1 un	2 bi	3 tri	4 quad	5 pent
6 hex	7 sept	8 oct	9 enn	0 nil

The roots are put together in the order of the digits that make up the atomic number and terminated by "ium" to spell out the name. The final "n" of "enn" is deleted when it occurs before "nil", and the final "i" of "bi" and of "tri" is deleted when it occurs before "ium".

Table 1 Standard atomic weights 2001.
[Scaled to $A_r(^{12}C) = 12$, where ^{12}C is a neutral atom in its nuclear and electronic ground state.]

The atomic weights of many elements are not invariant, but depend on the origin and treatment of the material. The standard values of A_r(E) and the uncertainties (in parentheses, following the last significant figure to which they are attributed) apply to elements of natural terrestrial origin. The footnotes to this table elaborate the types of variation that may occur for individual elements and that may be larger than the listed uncertainties of values of A_r(E). Names of elements with atomic numbers 110 to 116 are provisional.

Alphabetical order in English				
Name	Symbol	Number	Atomic weight	Footnotes
Actinium*	Ac	89		
Aluminium (Aluminum)	Al	13	26.981 538(2)	
Americium*	Am	95		
Antimony (Stibium)	Sb	51	121.760(1)	g
Argon	Ar	18	39.948(1)	g r
Arsenic	As	33	74.921 60(2)	
Astatine*	At	85		
Barium	Ba	56	137.327(7)	
Berkelium*	Bk	97		
Beryllium	Be	4	9.012 182(3)	
Bismuth	Bi	83	208.980 38(2)	
Bohrium*	Bh	107		
Boron	B	5	10.811(7)	g m r
Bromine	Br	35	79.904(1)	
Cadmium	Cd	48	112.411(8)	g
Caesium (Cesium)	Cs	55	132.905 45(2)	
Calcium	Ca	20	40.078(4)	g
Californium*	Cf	98		
Carbon	C	6	12.0107(8)	g r

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Table 1 (*Continued*).

Alphabetical order in English				
Name	Symbol	Number	Atomic weight	Footnotes
Cerium	Ce	58	140.116(1)	g
Chlorine	Cl	17	35.453(2)	g m r
Chromium	Cr	24	51.9961(6)	
Cobalt	Co	27	58.933 200(9)	
Copper (Cuprum)	Cu	29	63.546(3)	r
Curium*	Cm	96		
Dubnium*	Db	105		
Dysprosium	Dy	66	162.500(1)	g
Einsteinium*	Es	99		
Erbium	Er	68	167.259(3)	g
Europium	Eu	63	151.964(1)	g
Fermium*	Fm	100		
Fluorine	F	9	18.998 4032(5)	
Francium*	Fr	87		
Gadolinium	Gd	64	157.25(3)	g
Gallium	Ga	31	69.723(1)	
Germanium	Ge	32	72.64(1)	
Gold (Aurum)	Au	79	196.966 55(2)	
Hafnium	Hf	72	178.49(2)	
Hassium*	Hs	108		
Helium	He	2	4.002 602(2)	g r
Holmium	Ho	67	164.930 32(2)	
Hydrogen	H	1	1.007 94(7)	g m r
Indium	In	49	114.818(3)	
Iodine	I	53	126.904 47(3)	
Iridium	Ir	77	192.217(3)	
Iron (Ferrum)	Fe	26	55.845(2)	
Krypton	Kr	36	83.798(2)	g m
Lanthanum	La	57	138.9055(2)	g
Lawrencium*	Lr	103		
Lead (Plumbum)	Pb	82	207.2(1)	g r
Lithium	Li	3	[6.941(2)]†	g m r
Lutetium	Lu	71	174.967(1)	g
Magnesium	Mg	12	24.3050(6)	
Manganese	Mn	25	54.938 049(9)	
Meitnerium*	Mt	109		
Mendelevium*	Md	101		
Mercury (Hydrargyrum)	Hg	80	200.59(2)	
Molybdenum	Mo	42	95.94(2)	g
Neodymium	Nd	60	144.24(3)	g
Neon	Ne	10	20.1797(6)	g m
Neptunium*	Np	93		
Nickel	Ni	28	58.6934(2)	
Niobium	Nb	41	92.906 38(2)	
Nitrogen	N	7	14.0067(2)	g r
Nobelium*	No	102		

(*continues on next page*)

Table 1 (*Continued*).

Alphabetical order in English					
Name	Symbol	Number	Atomic weight	Footnotes	
Osmium	Os	76	190.23(3)	g	
Oxygen	O	8	15.9994(3)	g	r
Palladium	Pd	46	106.42(1)	g	
Phosphorus	P	15	30.973 761(2)		
Platinum	Pt	78	195.078(2)		
Plutonium*	Pu	94			
Polonium*	Po	84			
Potassium (Kalium)	K	19	39.0983(1)		
Praseodymium	Pr	59	140.907 65(2)		
Promethium*	Pm	61			
Protactinium*	Pa	91	231.035 88(2)		
Radium*	Ra	88			
Radon*	Rn	86			
Rhenium	Re	75	186.207(1)		
Rhodium	Rh	45	102.905 50(2)		
Rubidium	Rb	37	85.4678(3)	g	
Ruthenium	Ru	44	101.07(2)	g	
Rutherfordium*	Rf	104			
Samarium	Sm	62	150.36(3)	g	
Scandium	Sc	21	44.955 910(8)		
Seaborgium*	Sg	106			
Selenium	Se	34	78.96(3)		r
Silicon	Si	14	28.0855(3)		r
Silver (Argentum)	Ag	47	107.8682(2)	g	
Sodium (Natrium)	Na	11	22.989 770(2)		
Strontium	Sr	38	87.62(1)	g	r
Sulfur	S	16	32.065(5)	g	r
Tantalum	Ta	73	180.9479(1)		
Technetium*	Tc	43			
Tellurium	Te	52	127.60(3)	g	
Terbium	Tb	65	158.925 34(2)		
Thallium	Tl	81	204.3833(2)		
Thorium*	Th	90	232.0381(1)	g	
Thulium	Tm	69	168.934 21(2)		
Tin (Stannum)	Sn	50	118.710(7)	g	
Titanium	Ti	22	47.867(1)		
Tungsten (Wolfram)	W	74	183.84(1)		
Ununbium*	Uub	112			
Ununhexium*	Uuh	116			
Ununnilium*	Uun	110			
Ununquadium*	Uuq	114			
Unununium*	Uuu	111			
Uranium*	U	92	238.028 91(3)	g	m
Vanadium	V	23	50.9415(1)		
Xenon	Xe	54	131.293(6)	g	m
Ytterbium	Yb	70	173.04(3)	g	

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Table 1 (*Continued*).

Alphabetical order in English				
Name	Symbol	Number	Atomic weight	Footnotes
Yttrium	Y	39	88.905 85(2)	
Zinc	Zn	30	65.409(4)	
Zirconium	Zr	40	91.224(2)	g

*Element has no stable nuclides. One or more well-known isotopes are given in Table 3 with the appropriate relative atomic mass and half-life. However, three such elements (Th, Pa, and U) do have a characteristic terrestrial isotopic composition, and for these an atomic weight is tabulated.

†Commercially available Li materials have atomic weights that range between 6.939 and 6.996; if a more accurate value is required, it must be determined for the specific material.

g Geological specimens are known in which the element has an isotopic composition outside the limits for normal material. The difference between the atomic weight of the element in such specimens and that given in the table may exceed the stated uncertainty.

m Modified isotopic compositions may be found in commercially available material because it has been subjected to an undisclosed or inadvertent isotopic fractionation. Substantial deviations in atomic weight of the element from that given in the table can occur.

r Range in isotopic composition of normal terrestrial material prevents a more precise A_r(E) being given; the tabulated A_r(E) value should be applicable to any normal material.

Table 2 Standard atomic weights 2001.
[Scaled to $A_r(^{12}C) = 12$, where ^{12}C is a neutral atom in its nuclear and electronic ground state.]

The atomic weights of many elements are not invariant, but depend on the origin and treatment of the material. The standard values of A_r(E) and the uncertainties (in parentheses, following the last significant figure to which they are attributed) apply to elements of natural terrestrial origin. The footnotes to this table elaborate the types of variation that may occur for individual elements and that may be larger than the listed uncertainties of values of A_r(E). Names of elements with atomic number 110 to 116 are provisional.

Order of atomic number				
Number	Name	Symbol	Atomic weight	Footnotes
1	Hydrogen	H	1.007 94(7)	g m r
2	Helium	He	4.002 602(2)	g r
3	Lithium	Li	[6.941(2)]†	g m r
4	Beryllium	Be	9.012 182(3)	
5	Boron	B	10.811(7)	g m r
6	Carbon	C	12.0107(8)	g r
7	Nitrogen	N	14.0067(2)	g r
8	Oxygen	O	15.9994(3)	g r
9	Fluorine	F	18.998 4032(5)	
10	Neon	Ne	20.1797(6)	g m
11	Sodium (Natrium)	Na	22.989 770(2)	
12	Magnesium	Mg	24.3050(6)	
13	Aluminium (Aluminum)	Al	26.981 538(2)	
14	Silicon	Si	28.0855(3)	r
15	Phosphorus	P	30.973 761(2)	
16	Sulfur	S	32.065(5)	g r

(*continues on next page*)

Table 2 (*Continued*).

Order of atomic number				
Number	Name	Symbol	Atomic weight	Footnotes
17	Chlorine	Cl	35.453(2)	g m r
18	Argon	Ar	39.948(1)	g r
19	Potassium (Kalium)	K	39.0983(1)	
20	Calcium	Ca	40.078(4)	g
21	Scandium	Sc	44.955 910(8)	
22	Titanium	Ti	47.867(1)	
23	Vanadium	V	50.9415(1)	
24	Chromium	Cr	51.9961(6)	
25	Manganese	Mn	54.938 049(9)	
26	Iron (Ferrum)	Fe	55.845(2)	
27	Cobalt	Co	58.933 200(9)	
28	Nickel	Ni	58.6934(2)	
29	Copper (Cuprum)	Cu	63.546(3)	r
30	Zinc	Zn	65.409(4)	
31	Gallium	Ga	69.723(1)	
32	Germanium	Ge	72.64(1)	
33	Arsenic	As	74.921 60(2)	
34	Selenium	Se	78.96(3)	r
35	Bromine	Br	79.904(1)	
36	Krypton	Kr	83.798(2)	g m
37	Rubidium	Rb	85.4678(3)	g
38	Strontium	Sr	87.62(1)	g r
39	Yttrium	Y	88.905 85(2)	
40	Zirconium	Zr	91.224(2)	g
41	Niobium	Nb	92.906 38(2)	
42	Molybdenum	Mo	95.94(2)	g
43	Technetium*	Tc		
44	Ruthenium	Ru	101.07(2)	g
45	Rhodium	Rh	102.905 50(2)	
46	Palladium	Pd	106.42(1)	g
47	Silver (Argentum)	Ag	107.8682(2)	g
48	Cadmium	Cd	112.411(8)	g
49	Indium	In	114.818(3)	
50	Tin (Stannum)	Sn	118.710(7)	g
51	Antimony (Stibium)	Sb	121.760(1)	g
52	Tellurium	Te	127.60(3)	g
53	Iodine	I	126.904 47(3)	
54	Xenon	Xe	131.293(6)	g m
55	Caesium (Cesium)	Cs	132.905 45(2)	
56	Barium	Ba	137.327(7)	
57	Lanthanum	La	138.9055(2)	g
58	Cerium	Ce	140.116(1)	g
59	Praseodymium	Pr	140.907 65(2)	
60	Neodymium	Nd	144.24(3)	g
61	Promethium*	Pm		
62	Samarium	Sm	150.36(3)	g
63	Europium	Eu	151.964(1)	g
64	Gadolinium	Gd	157.25(3)	g

(*continues on next page*)

Table 2 (*Continued*).

Order of atomic number				
Number	Name	Symbol	Atomic weight	Footnotes
65	Terbium	Tb	158.925 34(2)	
66	Dysprosium	Dy	162.500(1)	g
67	Holmium	Ho	164.930 32(2)	
68	Erbium	Er	167.259(3)	g
69	Thulium	Tm	168.934 21(2)	
70	Ytterbium	Yb	173.04(3)	g
71	Lutetium	Lu	174.967(1)	g
72	Hafnium	Hf	178.49(2)	
73	Tantalum	Ta	180.9479(1)	
74	Tungsten (Wolfram)	W	183.84(1)	
75	Rhenium	Re	186.207(1)	
76	Osmium	Os	190.23(3)	g
77	Iridium	Ir	192.217(3)	
78	Platinum	Pt	195.078(2)	
79	Gold (Aurum)	Au	196.966 55(2)	
80	Mercury (Hydrargyrum)	Hg	200.59(2)	
81	Thallium	Tl	204.3833(2)	
82	Lead (Plumbum)	Pb	207.2(1)	g r
83	Bismuth	Bi	208.980 38(2)	
84	Polonium*	Po		
85	Astatine*	At		
86	Radon*	Rn		
87	Francium*	Fr		
88	Radium*	Ra		
89	Actinium*	Ac		
90	Thorium*	Th	232.0381(1)	g
91	Protactinium*	Pa	231.035 88(2)	
92	Uranium*	U	238.028 91(3)	g m
93	Neptunium*	Np		
94	Plutonium*	Pu		
95	Americium*	Am		
96	Curium*	Cm		
97	Berkelium*	Bk		
98	Californium*	Cf		
99	Einsteinium*	Es		
100	Fermium*	Fm		
101	Mendelevium*	Md		
102	Nobelium*	No		
103	Lawrencium*	Lr		
104	Rutherfordium*	Rf		
105	Dubnium*	Db		
106	Seaborgium*	Sg		
107	Bohrium*	Bh		
108	Hassium*	Hs		
109	Meitnerium*	Mt		
110	Ununnilium*	Uun		
111	Unununium*	Uuu		
112	Ununbium*	Uub		

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Table 2 (*Continued*).

Order of atomic number				
Number	Name	Symbol	Atomic weight	Footnotes
114	Ununquadium*	Uuq		
116	Ununhexium*	Uuh		

*Element has no stable nuclides. One or more well-known isotopes are given in Table 3 with the appropriate relative atomic mass and half-life. However, three such elements (Th, Pa, and U) do have a characteristic terrestrial isotopic composition, and for these an atomic weight is tabulated.

†Commercially available Li materials have atomic weights that range between 6.939 and 6.996; if a more accurate value is required, it must be determined for the specific material.

g Geological specimens are known in which the element has an isotopic composition outside the limits for normal material. The difference between the atomic weight of the element in such specimens and that given in the Table may exceed the stated uncertainty.

m Modified isotopic compositions may be found in commercially available material because it has been subjected to an undisclosed or inadvertent isotopic fractionation. Substantial deviations in atomic weight of the element from that given in the table can occur.

r Range in isotopic composition of normal terrestrial material prevents a more precise A_r(E) being given; the tabulated A_r(E) value should be applicable to any normal material.

COMMENTS ON SOME ATOMIC WEIGHTS AND ANNOTATIONS

Zinc

The Commission has changed the recommended value for the standard atomic weight of zinc to A_r(Zn) = 65.409(4) based on a new calibrated measurement by Chang et al. [8] that yielded 65.409(4). This represents an increase in the atomic weight by 0.019 with a significantly improved uncertainty derived using the Commission's technical guidelines. The range of reported natural variations in the $^{66}Zn/^{64}Zn$ ratio is 0.1 % [9] corresponding to a shift of 0.001 in A_r(Zn), which is small compared to the quoted uncertainty. The previous value, A_r(Zn) = 65.39(2), was adopted by the Commission in 1983 when it was increased from 65.38(1) to 65.39(2) following the reassessment of a calibrated measurement by Rosman [10] that yielded 65.396(5). Historical values of A_r(Zn) include [5]: 1882, 65.05; 1894, 65.3; 1896, 65.41; 1900, 65.4; 1909, 65.7; 1910, 65.37; 1925, 65.38; 1961, 65.37(3); 1969, 65.37(3); 1971, 65.38(1); 1983, 65.39(2).

Molybdenum

The Commission has changed the recommended value for the standard atomic weight of molybdenum to A_r(Mo) = 95.94(2) based on a new mass-spectrometric measurement by Wieser and De Laeter [11]. This change leads to an increase in the uncertainty because of the application of accepted Commission guidelines. In addition, the previous value A_r(Mo) = 95.94(1) from Moore et al. [12] was derived from isotopic abundance data that was corrected to enable comparisons to earlier results [13] that were normalized to previous uncalibrated measurements from ref. [14]. The new uncertainty was based upon the average of values measured by ref. [13]. Historical values of A_r(Mo) include [5]: 1882, 95.75; 1894, 96; 1896, 95.98; 1897, 95.99; 1900, 96; 1938, 95.95; 1961, 95.94; 1969, 95.94(3); 1975, 95.94(1).

Krypton

The Commission has changed the recommended value for the standard atomic weight of krypton A_r(Kr) to 83.798(2) because of calibrated mass-spectrometric measurements by Aregbe et al. [15] on a tank of krypton separated cryogenically from air. As no natural samples were directly measured, a conservative

uncertainty statement was made based on an estimate of a maximum of 0.001 % per amu fractionation effect due to the separation procedure from air. The footnote "g" in Tables 1 and 2 arises from naturally occurring fission products found at fossil reactors at Gabon, Africa. The previous value, A_r(Kr) = 83.80(1), was adopted by the Commission in 1969 [16] and was based on a change in the procedures for reporting uncertainties and took into account mass-spectrometric measurements of Nier [17]. Historical values of A_r(Kr) include [5]: 1902, 81.76; 1903, 81.8; 1910, 83.0; 1911, 82.92; 1925, 82.9; 1932, 83.7; 1951, 83.80; 1969, 83.80(1).

Dysprosium

The Commission has changed the recommended value for the standard atomic weight of dysprosium to A_r(Dy) = 162.500(1) based on calibrated mass-spectrometric measurements with highly enriched dysprosium isotopes using positive thermal ionization mass spectrometry and a multi-collector system by Chang et al. [19]. The footnote "g" in Tables 1 and 2 arises from the presence of naturally occurring fission products found at fossil reactors at Gabon, Africa. The previous value, A_r(Dy) = 162.50, was adopted by the Commission in 1961, based on isotopic abundance measurements of dysprosium by Inghram et al. [19] and atomic masses by Bhanot et al. [20]. In 1969, the Commission assessed U[A_r(Dy)] as 0.03. Historical values of A_r(Dy) include [5]: 1908, 162.5; 1925, 162.52; 1930, 162.46; 1955, 162.46; 1961, 162.50(3); and 1969, 162.50(3).

RELATIVE ATOMIC-MASS VALUES AND HALF-LIVES OF SELECTED RADIONUCLIDES

For elements that have no stable or long-lived nuclides, the data on radioactive half-lives and relative atomic-mass values for the nuclides of interest and importance have been evaluated, and the recommended values and uncertainties are listed in Table 3.

As has been the custom in the past, the Commission publishes a table of relative atomic-mass values and half-lives of selected radionuclides. The Commission has no prime responsibility for the dissemination of such values. There is no general agreement on which of the nuclides of the radioactive elements is, or is likely to be judged, "important". Various criteria such as "longest half-life", "production in quantity", "used commercially", have been applied in the past to the Commission's choice.

The information contained in this table will enable the user to calculate the atomic weight for radioactive materials with a variety of isotopic compositions. Atomic-mass values have been taken from the 1993 Atomic Mass Table [4]. Some of these half-lives have already been documented [21–24].

Table 3 Relative atomic masses and half-lives of selected radionuclides.
[Prepared, as in previous years, by N. E. Holden, a former Commission member; a = year; d = day; h = hour; min = minute; s = second. Names of elements with atomic number 110 to 116 are provisional.]

Atomic number	Element name	Symbol	Mass no.	Atomic mass	Half-life	Unit
43	Technetium	Tc	97	96.9064	$4.0(3) \times 10^6$	a
			98	97.9072	$6.6(10) \times 10^6$	a
			99	98.9063	$2.1(3) \times 10^5$	a
61	Promethium	Pm	145	144.9127	17.7(4)	a
			147	146.9151	2.623(3)	a
84	Polonium	Po	209	208.9824	102(5)	a
			210	209.9829	138.4(1)	d
85	Astatine	At	210	209.9871	8.1(4)	h
			211	210.9875	7.21(1)	h

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Table 3 (*Continued*).

Atomic number	Element name	Symbol	Mass no.	Atomic mass	Half-life	Unit
86	Radon	Rn	211	210.9906	14.6(2)	h
			220	220.0114	55.6(1)	s
			222	222.0176	3.823(4)	d
87	Francium	Fr	223	223.0197	22.0(1)	min
88	Radium	Ra	223	223.0185	11.43(1)	d
			224	224.0202	3.66(2)	d
			226	226.0254	1599(4)	a
			228	228.0311	5.75(3)	a
89	Actinium	Ac	227	227.0277	21.77(2)	a
90	Thorium	Th	230	230.0331	$7.54(3) \times 10^4$	a
			232	232.0381	$1.40(1) \times 10^{10}$	a
91	Protactinium	Pa	231	231.0359	$3.25(1) \times 10^4$	a
92	Uranium	U	233	233.0396	$1.592(2) \times 10^5$	a
			234	234.0409	$2.455(6) \times 10^5$	a
			235	235.0439	$7.04(1) \times 10^8$	a
			236	236.0456	$2.342(4) \times 10^7$	a
			238	238.0508	$4.468(3) \times 10^9$	a
93	Neptunium	Np	237	237.0482	$2.14(1) \times 10^6$	a
			239	239.0529	2.355(6)	d
94	Plutonium	Pu	238	238.0496	87.7(1)	a
			239	239.0522	$2.410(3) \times 10^4$	a
			240	240.0538	$6.56(1) \times 10^3$	a
			241	241.0568	14.4(1)	a
			242	242.0587	$3.75(2) \times 10^5$	a
			244	244.0642	$8.00(9) \times 10^7$	a
95	Americium	Am	241	241.0568	432.7(6)	a
			243	243.0614	$7.37(2) \times 10^3$	a
96	Curium	Cm	243	243.0614	29.1(1)	a
			244	244.0627	18.1(1)	a
			245	245.0655	$8.48(6) \times 10^3$	a
			246	246.0672	$4.76(4) \times 10^3$	a
			247	247.0704	$1.56(5) \times 10^7$	a
			248	248.0723	$3.48(6) \times 10^5$	a
97	Berkelium	Bk	247	247.0703	$1.4(3) \times 10^3$	a
			249	249.0750	$3.26(3) \times 10^2$	d
98	Californium	Cf	249	249.0749	351(2)	a
			250	250.0764	13.1(1)	a
			251	251.0796	$9.0(5) \times 10^2$	a
			252	252.0816	2.64(1)	a
99	Einsteinium	Es	252	252.0830	472(2)	d
100	Fermium	Fm	257	257.0951	100.5(2)	d
101	Mendelevium	Md	258	258.0984	51.5(3)	d
			260	260.1037	27.8(3)	d
102	Nobelium	No	259	259.1010	58(5)	min
103	Lawrencium	Lr	262	262.1097	3.6(3)	h
104	Rutherfordium	Rf	261	261.1088	1.3[a]	min
105	Dubnium	Db	262	262.1141	34(5)	s
106	Seaborgium	Sg	266	266.1219	~21[a]	s
107	Bohrium	Bh	264	264.12	0.44[a]	s

(*continues on next page*)

Table 3 (*Continued*).

Atomic number	Element name	Symbol	Mass no.	Atomic mass	Half-life	Unit
108	Hassium	Hs	277		16.5[a,b]	min
109	Meitnerium	Mt	268	268.1388	0.070[a,b]	s
110	Ununnilium	Uun	281		1.6[a,b]	min
111	Unununium	Uuu	272	272.1535	$1.5^{a,b} \times 10^{-3}$	s
112	Ununbium	Uub	285		15.4[a,b]	min
114	Ununquadium	Uuq	289		30.4[a,b]	s
116	Ununhexium	Uuh	289		$0.60^{a,b} \times 10^{-3}$	s

[a] The uncertainties of these elements are asymmetric.
[b] The value given is determined from only a few decays.

NONTERRESTRIAL DATA

The isotope abundance of elements in many nonterrestrial samples within the solar system can be measured directly by analysis of meteorites and other interplanetary materials. In recent years, the increasing sophistication of analytical instrumentation and techniques have enabled the isotopic composition of submicron-sized components in nonterrestrial samples to be determined. At the same time, there has also been an increase in the use of on-board spacecraft and ground-based astronomical instruments to measure isotope abundances remotely. These advances have substantially increased the number of isotopic composition data for nonterrestrial materials.

The extensive analysis of nonterrestrial materials has continued to show that many elements in nonterrestrial materials have different isotopic compositions from those in terrestrial samples. Although most of the reported differences in the isotopic compositions in nonterrestrial materials are small compared with those in normal terrestrial materials, some variations are quite large. For this reason, scientists who deal with the chemical analysis of nonterrestrial samples should exercise caution when the isotopic composition or the atomic weight of nonterrestrial samples is required.

Most isotopic variations observed in nonterrestrial materials are currently explained by the following processes.

(i) Mass fractionation
Mass-dependent fractionation can also be observed in many terrestrial materials, but the degree of fractionation is generally smaller than that found in nonterrestrial samples. Mass fractionation observed in nonterrestrial samples is mostly due to volatilization or condensation, which most likely occurred at the early stage of the formation of the solar system. Mass fractionation may also have occurred at later stages in the evolution of the solar system by chemical processes such as the formation of organic compounds.

(ii) Nuclear reactions
Nuclear reactions triggered by cosmic rays can alter the isotopic composition of not only nonterrestrial, but also terrestrial materials. This effect in terrestrial samples is normally negligible, mainly because of effective shielding against solar cosmic rays by the Earth's magnetosphere and atmosphere. In contrast, nonterrestrial materials are often exposed to sufficient solar and galactic cosmic ray fluxes to cause significant nuclear spallation reactions, which in turn trigger secondary low-energy neutron capture reactions at specific depths from the surface or near the surface of samples.

(iii) Radioactive decay
Isotopic anomalies due to radioactive decay are not limited to nonterrestrial samples. Nevertheless, their effect can be clearly observed in nonterrestrial samples both in the degree of

the alteration of isotope abundances and in the variety of radioactive nuclides. Enrichment in decay products is the most common effect confirmed in the nonterrestrial samples. The effect is caused by long-lived nuclides (primary radioactive nuclides), whose half-lives are comparative to the age of our solar system (4.56×10^9 a). These nuclides are commonly used in geo- and cosmochronology.

The next observed effect caused by radioactive decay is due to extinct nuclides. While extinct nuclides are no longer present in the solar system, their former presence in nonterrestrial materials can be demonstrated by excesses in decay products, which together with their parent(s) have been part of a closed isotopic system. Their half-lives provide valuable information related to the time from their final nucleosynthetic contribution to the solar system, to their incorporation to solar system materials from the surrounding gas (also known as the solar system formation interval).

In addition to these two major effects, some minor effects can be observed in nonterrestrial samples, such as those caused by double β-decay of long-lived radionuclides and nuclear fission (spontaneous and neutron-induced).

(iv) Nucleosynthesis

The most significant isotopic alteration effect observed in nonterrestrial materials (mainly meteorites) is due to nucleosynthesis. Prior to the availability of secondary ion mass spectrometry (SIMS), the majority of isotopic effects due to nucleosynthesis were known to be present in only a few component samples present in a limited number of rare meteorites. The majority of these isotopic abundance variations were best ascribed to explosive nucleosynthesis effects. Some light elements, such as oxygen and noble gas elements showed ubiquitous isotopic anomalies (which were also considered to be related to nucleosynthetic effects) in virtually all kinds of meteoritic materials. The extensive application of the SIMS technique now shows that a large number of extra-solar materials appear to contain significant isotope anomalies. This indicates that many extra-solar materials appear to have survived the formation of the solar system either within meteorites or their components. Some of these components demonstrate huge isotopic variations, which are believed to be due to a wide range of nucleosynthetic effects occurring at various stages of stellar evolution. A number of examples have been listed in a previous *Pure and Applied Chemistry* [24].

The following are some examples of isotope fractionation effects caused by nuclear reactions between cosmic rays and extraterrestrial materials. Large effects of secondary neutrons due to (primary) cosmic rays on planetary surfaces have been observed. A prominent example is found in the cosmogenic xenon present in lunar rocks. While the ratio of cosmogenic $^{131}Xe/^{132}Xe$ in stony meteorites is about 4, this ratio exceeds 20 in some lunar rocks. The anomalously high yield of ^{131}Xe is mainly due to the capture of epithermal neutrons by ^{130}Ba via the reaction $^{130}Ba(n,\gamma)^{131}Ba$, and the decay of ^{131}Ba (half-life: 11.53 d) to ^{131}Cs (half-life: 9.69 d) and finally to the stable ^{131}Xe [26,27]. Figures 1a and 1b show another example of how the isotopic abundances are altered by secondary neutrons in extraterrestrial materials [28–30]. ^{149}Sm has very large capture cross-sections for thermal neutrons (4×10^6 fm^2) and epithermal neutrons (3.1×10^5 fm^2). When Sm captures secondary neutrons on or near the surface of extraterrestrial materials, the isotopic abundance of ^{149}Sm is decreased while the abundance of ^{150}Sm is proportionally increased (Fig. 1a). These isotopic effects can readily be observed in lunar rocks and meteorite samples. A similar effect is observed in Gd, where ^{157}Gd is decreased while ^{158}Gd is increased with increasing total secondary neutron flux (Fig. 1b). ^{157}Gd has similarly large neutron capture cross-sections of 2.55×10^7 fm^2 and 8×10^4 fm^2 for thermal and epithermal neutrons, respectively.

The Commission does not attempt to systematically review the literature on the isotopic compositions of nonterrestrial materials in this report. Those who are interested in more comprehensive reviews, including specific data and additional references, should refer to Shima [31] and Shima and

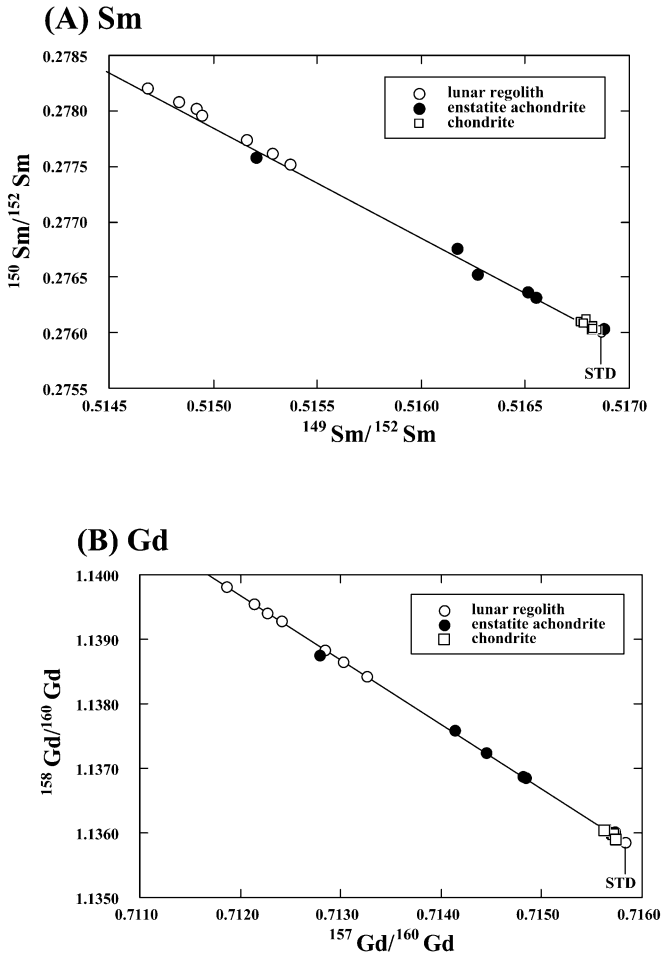

Fig. 1 Correlation diagrams of isotopic shifts for $^{149}Sm/^{152}Sm$ vs.$^{150}Sm/^{152}Sm$(a) and $^{157}Gd/^{160}Gd$ vs. $^{158}Gd/^{160}Gd$ (b) in Apollo 15 lunar regolith, enstatite achondrites (aubrites), and chondrites. Straight lines in these figures show ideal neutron capture lines.

Ebihara [32]. A more detailed report of isotopic measurements published in this field during the last decade is in preparation.

OTHER PROJECTS OF THE COMMISSION

At intervals of about six to eight years, the Division's Subcommittee for Isotopic Abundance Measurements publishes a summary of its biennial review of isotopic compositions of the elements as determined by mass spectrometry and other relevant methods. The subcommittee distributed their summary report at Berlin, titled "Isotopic compositions of the elements 1997" [2]. The very few and minor subsequent changes of the evaluated best values for some isotope abundances do not justify the publication of an updated table, which, however, is always currently maintained by and available on request from the Commission.

The rules that the Commission employs in assigning atomic-weight values are found in the Commission's *Technical Booklet*. J. de Laeter incorporated decisions made at the previous General Assembly at Geneva to produce the fifth edition of the Commission's *Technical Booklet*, which he dis-

tributed. A new addition to this booklet is a paper on the reliability of the Avogadro constant, the factor that relates measurements expressed in two SI base units (mass and amount of substance) by De Bièvre and Peiser [33].

The Subcommittee for Natural Isotopic Fractionation presented a report that was discussed and modified during the Subcommittee's meeting in Berlin, Germany, prior to the IUPAC General Assembly in Berlin. The Subcommittee has published a technical report [9] consisting primarily of plots (where possible) that show the variation in natural isotopic abundance and atomic weight for the elements H, Li, B, C, N, O, Si, S, Cl, Fe, Cu, Se, Pd, and Te. A companion report with extensive references has been published as a U.S. Geological Survey Open-File Report [34].

J. de Laeter reported on progress of the Commission-approved update to the 1984 Element-by-Element Review [4]. This important document has been published [35].

OBITUARY: DR. GREGORY RAMENDIK

On 6 July 2001, the Commission was informed of the most unexpected death of Dr. Gregory Ramendik on 4 July. Dr. Ramendik's efforts in the Commission particularly in the area of IUPAC's book on nomenclature (the Gold Book [36]) will be long remembered, and our deepest sympathy and condolences are extended to his family and colleagues.

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