Atomic Weights of the Elements 1989

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Atomic Weights of the Elements 1989[a)]

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The biennial review of atomic weight, A_r(E), determinations, and other cognate data has resulted in changes for nickel from 58.69 ± 0.01 to 58.6934 ± 0.0002 and for antimony from 121.75 ± 0.03 to 121.757 ± 0.003 due to new calibrated measurements. Because the measurement of the isotopic composition of mercury has also been improved during the last two years, the Commission was able to reduce the uncertainty of the atomic weight of this element from 200.59 ± 0.03 to 200.59 ± 0.02. Due to the nearly constant isotopic composition of protactinium in nature, where ^{231}Pa is the predominant isotope, the atomic weight of this element was fixed to 231.03588 ± 0.000 02. The Table of Isotopic Compositions of the Elements 1989 will be published as a companion paper to that on Atomic Weights of the Elements 1989. The Table of Standard Atomic Weights Abridged to Five Significant Figures and current data on isotopic compositions of nonterrestrial material are included to benefit users who are more concerned with the length of time during which a given table has full validity to the precision limit of their interest. The Table of Atomic Weights to Four Significant Figures was prepared and has been published separately.

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1. Introduction

The Commission on Atomic Weights and Isotopic Abundances met under the chairmanship of Professor J. R. De Laeter from 10–12 August 1989, during the 35th IUPAC General Assembly in Lund, Sweden. It was decided to publish the Table of Isotopic Compositions of the Elements 1989 as determined by mass spectrometry as a companion paper to the Report on the Atomic Weights of the Elements 1989 presented here.

The Commission has monitored the literature over the previous two years since the last report (Ref. 1) and evaluated the published data on atomic weights and isotopic compositions on an element-by-element basis. The atomic weight of an element can be determined from a knowledge of the isotopic abundances and corresponding atomic masses of the nuclides of that element. The latest compilation of the atomic masses with all relevant data was published in 1985 (Ref. 2) which resulted in a number of small changes in the atomic weights that were reported in the 1985 table (Ref. 3). Although a table with some new data was published in 1988 (Ref. 4) the Commission decided not to take them into account at the present because the description of these data was incomplete.

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Membership of the Commission for the period 1987–1989 was as follows:

J. R. De Laeter (Australia, *Chairman*); K. G. Heumann (FRG, *Secretary*); R. C. Barber (Canada, Associate); I. L. Barnes (USA, Associate); J. Césario (France, Titular); T. L. Chang (China, Titular); T. B. Coplen (USA, Titular); J. W. Gramlich (USA, Associate); H. R. Krouse (Canada, Associate); I. A. Lebedev (USSR, Associate); T. J. Murphy (USA, Associate); K. J. R. Rosman (Australia, Titular); M. P. Seyfried (FRG, Associate); M. Shima (Japan, Titular); K. Wade (UK, Associate); P. De Bièvre (Belgium, National Representative); N. N. Greenwood (UK, National Representative); R. L. Martin (Australia, National Representative); H. S. Peiser (USA, National Representative).

The commision dedicates this report to Dr. I. Lynus Barnes who died in January, 1990. Dr. Barnes was an associate and titular member of the Commission for 14 years, Secretary of the Subcommittee on the Assessment of the Isotopic Composition of the Elements (SAIC) from 1975 to 1983 and Chairman of the Commission's Subcommittee for Isotopic Abundance Measurements (SIAM) from 1983 to 1989.

2. Comments on Some Atomic Weights

Nickel: At this meeting, the Commission has changed its recommended value for the atomic weight of nickel to $A_r(\mathrm{Ni}) = 58.6934(2)$ based on the calibrated mass spectrometric determination by Gramlich *et al.* (Ref. 5). The previous value of $A_r(\mathrm{Ni}) = 58.69(1)$, which was adopted by the Commission in 1979, was weighted toward the chemical determinations of Baxter and associates (Refs. 6–8), which gave an average value of $A_r(\mathrm{Ni}) = 58.694$. The uncertainty of the 1979 value included the published mass spectrometric values (Ref. 9–11). The excellent agreement between the average of the chemical values and this new determination illustrates the remarkable accuracy of the determinations of Baxter and associates.

Gramlich *et al.*, in a second paper (Ref. 12), have compared the isotopic composition of nickel in 29 minerals, salts, and metals and found no statistically significant variations. Therefore, no additional allowance to the overall uncertainty was necessary since the isotopic composition of terrestrial nickel is apparently invariant within the measurement uncertainty.

It should be noted that with this change the atomic weight of nickel is now one of the most accurately known for a polynuclidic element, with a relative uncertainty of $U_r(\mathrm{Ni}) = 3\times10^{-6}$, whereas the 1979 value had a relative uncertainty of 0.02%. This represents an improvement in accuracy of almost two orders of magnitude.

Antimony (stibium): The Commission has changed the recommended value for the atomic weight of antimony to $A_r(\mathrm{Sb}) = 121.757(3)$ from 121.75(3) based on new mass spectrometric meausrements by De Laeter and Hosie (Ref. 13) on the isotopic composition of antimony. The Commission also added footnote "g" to the atomic weight of antimony because of abnormal isotopic composition found at the natural fission reactor site at Oklo, Gabon, West Africa (Ref. 14).

The previous value, $A_r(\mathrm{Sb}) = 121.75$, was adopted in 1962 (Ref. 15) and the uncertainty, $U_r(\mathrm{Sb}) = 0.03$, was assigned in 1969 (Ref. 16). The value was based both on chemical measurements by Willard and McAlpine (Ref. 17), Hönigschmid *et al.* (Ref. 18), Weatherill (Ref. 19), and Krishnaswami (Ref. 20) which gave an average chemical value of $A_r(\mathrm{Sb}) = 121.751$, and on the mass spectrometric measurements of White and Cameron (Ref. 9) which gave a calculated value of $A_r(\mathrm{Sb}) = 121.759$ using current atomic mass data (Ref. 2). The assigned uncertainty included all of the chemical and mass spectrometric data.

The new measurement of $A_r(\mathrm{Sb})$ by De Laeter and Hosie (Ref. 13) contains an allowance for known sources of possible systematic errors and is in excellent agreement with the earlier measurement of White and Cameron (Ref. 9). The Commission, therefore, decided to exclude the chemical values from consideration and to base the atomic weight of antimony on this new measurement by mass spectrometry. There are no known variations of the isotopic composition of antimony except in samples from the Oklo Natural Reactor, but no systematic study of possible variations in other terretrial samples has been published.

Mercury: The Commission Report of 1961 proposed an $A_r(\mathrm{Hg}) = 200.59$ based on chemical determinations (Ref. 21). Mass spectrometric measurements of the isotopic composition of mercury agreed with the chemical measurements, thus in 1969 the Commission assigned an uncertainty of $U_r(\mathrm{Hg}) = 0.03$ (Ref. 16). Resulting $A_r(\mathrm{Hg})$ values range only from 200.58 to 200.60. In 1989, the Commission considered and accepted the recent gas mass spectrometric measurements by Zadnik, Specht, and Begemann (Ref. 22).

The Commission saw no compelling evidence to change the proposed value for the atomic weight of mercury, $A_r(\mathrm{Hg}) = 200.59$, but proposed a decrease in the uncertainty to $U_r = 0.02$. The values reported for the isotopic composition of mercury in Ref. 22 were also proposed by the Commission as the best measurements from a single natural source.

3. The Table of Standard Atomic Weights 1989

Following past practice the Table of Standard Atomic Weights 1989 is presented both in alphabetical order by names in English of the elements (Table 1) and in the order of atomic number (Table 2).

The names and symbols for those elements with atomic numbers 104–107 referred to in the following tables are systematic and based on the atomic numbers of the elements recommended for temporary use by the IUPAC Commission of the Nomenclature of Inorganic Chemistry (Ref. 23). The names are composed of the following roots representing digits of the atomic number:

1 un,	2 bi,	3 tri,	4 quad,	5 pent,
6 hex,	7 sept,	8 oct,	9 enn,	10 nil.

The ending "ium" is then added to these three roots. The three-letter symbols are derived from the first letter of the corresponding roots.

The Commission again wishes to emphasize the need for new precise isotopic composition measurements in order to improve the accuracy of the atomic weights of a number of elements which are still not known to a satisfactory level of accuracy.

TABLE 1. Standard atomic weights 1989. [Scaled to $A_r(^{12}C) = 12$.] The atomic weights of many elements are not invariant but depend on the origin and treatment of the material. The footnotes to this table elaborate the types of variation to be expected for individual elements. The values of $A_r(E)$ and uncertainties, $U_r(E)$, in parentheses follow the last significant figure to which they are attributed, apply to elements as they exist on Earth.

Alphabetical Order in English						
Name	Symbol	Atomic number	Atomic weight	Footnotes		
Actinium*	Ac	89				
Aluminum	Al	13	26.981539(5)			
Americium*	Am	95				
Antimony (Stibium)	Sb	51	121.757(3)	g		
Argon	Ar	18	39.948(1)	g		r
Arsenic	As	33	74.92159(2)			
Astatine*	At	85				
Barium	Ba	56	137.327(7)			
Berkelium*	Bk	97				
Beryllium	Be	4	9.012182(3)			
Bismuth	Bi	83	208.98037(3)			
Boron	B	5	10.811(5)	g	m	r
Bromine	Br	35	79.904(1)			
Cadmium	Cd	48	112.411(8)	g		
Caesium	Cs	55	132.90543(5)			
Calcium	Ca	20	40.078(4)	g		
Californium*	Cf	98				
Carbon	C	6	12.011(1)			r
Cerium	Ce	58	140.115(4)	g		
Chlorine	Cl	17	35.4527(9)		m	
Chromium	Cr	24	51.9961(6)			
Cobalt	Co	27	58.93320(1)			
Copper	Cu	29	63.546(3)			r
Curium*	Cm	96				
Dysprosium	Dy	66	162.50(3)	g		
Einsteinium*	Es	99				
Erbium	Er	68	167.26(3)	g		
Europium	Eu	63	151.965(9)	g		
Fermium*	Fm	100				
Fluorine	F	9	18.9984032(9)			
Francium*	Fr	87				
Gadolinium	Gd	64	157.25(3)	g		
Gallium	Ga	31	69.723(1)			
Germanium	Ge	32	72.61(2)			
Gold	Au	79	196.96654(3)			
Hafnium	Hf	72	178.49(2)			
Helium	He	2	4.002602(2)	g		r
Holmium	Ho	67	164.93032(3)			
Hydrogen	H	1	1.00794(7)	g	m	r
Indium	In	49	114.82(1)			
Iodine	I	53	126.90447(3)			
Iridium	Ir	77	192.22(3)			
Iron	Fe	26	55.847(3)			
Krypton	Kr	36	83.80(1)	g	m	
Lanthanum	La	57	138.9055(2)	g		
Lawrencium*	Lr	103				
Lead	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	54.93805(1)			
Mendelevium*	Md	101				
Mercury	Hg	80	200.59(2)			
Molybdenum	Mo	42	95.94(1)	g		
Neodymium	Nd	60	144.24(3)	g		
Neon	Ne	10	20.1797(6)	g	m	

TABLE 1. Standard atomic weights 1989. [Scaled to $A_r(^{12}C) = 12$.] The atomic weights of many elements are not invariant but depend on the origin and treatment of the material. The footnotes to this table elaborate the types of variation to be expected for individual elements. The values of $A_r(E)$ and uncertainties, $U_r(E)$, in parentheses follow the last significant figure to which they are attributed, apply to elements as they exist on Earth —*Continued.*

Name	Symbol	Atomic number	Atomic weight	Footnotes	
		Alphabetical Order in English			
Neptunium*	Np	93			
Nickel	Ni	28	58.6934(2)		
Niobium	Nb	41	92.90638(2)		
Nitrogen	N	7	14.00674(7)	g	r
Nobelium*	No	102			
Osmium	Os	76	190.2(1)	g	
Oxygen	O	8	15.9994(3)	g	r
Palladium	Pd	46	106.42(1)	g	
Phosphorus	P	15	30.973762(4)		
Platinum	Pt	78	195.08(3)		
Plutonium*	Pu	94			
Polonium*	Po	84			
Potassium (Kalium)	K	19	39.0983(1)		
Praseodymium	Pr	59	140.90765(3)		
Promethium*	Pm	61			
Protactinium*	Pa	91	231.03588(2)		
Radium*	Ra	88			
Radon*	Rn	86			
Rhenium	Re	75	186.207(1)		
Rhodium	Rh	45	102.90550(3)		
Rubidium	Rb	37	85.4678(3)	g	
Ruthenium	Ru	44	101.07(2)	g	
Samarium	Sm	62	150.36(3)	g	
Scandium	Sc	21	44.955910(9)		
Selenium	Se	34	78.96(3)		
Silicon	Si	14	28.0855(3)		r
Silver	Ag	47	107.8682(2)	g	
Sodium (Natrium)	Na	11	22.989768(6)		
Strontium	Sr	38	87.62(1)	g	r
Sulfur	S	16	32.066(6)	g	r
Tantalum	Ta	73	180.9479(1)		
Technetium*	Tc	43			
Tellurium	Te	52	127.60(3)	g	
Terbium	Tb	65	158.92534(3)		
Thallium	Tl	81	204.3833(2)		
Thorium*	Th	90	232.0381(1)	g	
Thulium	Tm	69	168.93421(3)		
Tin	Sn	50	118.710(7)	g	
Titanium	Ti	22	47.88(3)		
Tungsten (Wolfram)	W	74	183.85(3)		
Unnilhexium*	Unh	106			
Unnilpentium*	Unp	105			
Unnilquadium*	Unq	104			
Unnilseptium*	Uns	107			
Uranium*	U	92	238.0289(1)	g	m
Vanadium	V	23	50.9415(1)		
Xenon	Xe	54	131.29(2)	g	m
Ytterbium	Yb	70	173.04(3)	g	
Yttrium	Y	39	88.90585(2)		
Zinc	Zn	30	65.39(2)		
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.

[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 implied uncertainty.

[m] Modified isotopic compositions may be found in commercially available material because it has been subjected to an undisclosed or inadvertent isotopic separation. 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 1989. [Scaled to $A_r(^{12}C) = 12$.] The atomic weights of many elements are not invariant but depend on the origin and treatment of the material. The footnotes to this table elaborate the types of variation to be expected for individual elements. The values of $A_r(E)$ and uncertainties, $U_r(E)$, in parentheses follow the last significant figure to which they are attributed, apply to elements as they exist on Earth.

Atomic number	Name	Symbol	Order of Atomic Number Atomic weight	Footnotes		
1	Hydrogen	H	1.00794(7)	g	m	r
2	Helium	He	4.002602(2)	g		r
3	Lithium	Li	6.941(2)	g	m	r
4	Beryllium	Be	9.012182(3)			
5	Boron	B	10.811(5)	g	m	r
6	Carbon	C	12.011(1)			r
7	Nitrogen	N	14.00674(7)	g		r
8	Oxygen	O	15.9994(3)	g		r
9	Fluorine	F	18.9984032(9)			
10	Neon	Ne	20.1797(6)	g	m	
11	Sodium (Natrium)	Na	22.989768(6)			
12	Magnesium	Mg	24.3050(6)			
13	Aluminum	Al	26.981539(5)			
14	Silicon	Si	28.0855(3)			r
15	Phosphorus	P	30.973762(4)			
16	Sulfur	S	32.066(6)	g		r
17	Chlorine	Cl	35.4527(9)		m	
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	44.955910(9)			
22	Titanium	Ti	47.88(3)			
23	Vanadium	V	50.9415(1)			
24	Chromium	Cr	51.9961(6)			
25	Manganese	Mn	54.93805(1)			
26	Iron	Fe	55.847(3)			
27	Cobalt	Co	58.93320(1)			
28	Nickel	Ni	58.6934(2)			
29	Copper	Cu	63.546(3)			r
30	Zinc	Zn	65.39(2)			
31	Gallium	Ga	69.723(1)			
32	Germanium	Ge	72.61(2)			
33	Arsenic	As	74.92159(2)			
34	Selenium	Se	78.96(3)			
35	Bromine	Br	79.904(1)			
36	Krypton	Kr	83.80(1)	g	m	
37	Rubidium	Rb	85.4678(3)	g		
38	Strontium	Sr	87.62(1)	g		r
39	Yttrium	Y	88.90585(2)			
40	Zirconium	Zr	91.224(2)	g		
41	Niobium	Nb	92.90638(2)			
42	Molybdenum	Mo	95.94(1)	g		
43	Technetium*	Tc				
44	Ruthenium	Ru	101.07(2)	g		
45	Rhodium	Rh	102.90550(3)			
46	Palladium	Pd	106.42(1)	g		
47	Silver	Ag	107.8682(2)	g		
48	Cadmium	Cd	112.411(8)	g		
49	Indium	In	114.82(1)			
50	Tin	Sn	118.710(7)	g		
51	Antimony (Stibium)	Sb	121.757(3)	g		
52	Tellurium	Te	127.60(3)	g		
53	Iodine	I	126.90447(3)			
54	Xenon	Xe	131.29(2)	g	m	
55	Caesium	Cs	132.90543(5)			
56	Barium	Ba	137.327(7)			
57	Lanthanum	La	138.9055(2)	g		
58	Cerium	Ce	140.115(4)	g		
59	Praseodymium	Pr	140.90765(3)			
60	Neodymium	Nd	144.24(3)	g		
61	Promethium*	Pm				
62	Samarium	Sm	150.36(3)	g		
63	Europium	Eu	151.965(9)	g		
64	Gadolinium	Gd	157.25(3)	g		
65	Terbium	Tb	158.92534(3)			
66	Dysprosium	Dy	162.50(3)	g		

TABLE 2. Standard atomic weights 1989. [Scaled to $A_r(^{12}C) = 12$.] The atomic weights of many elements are not invariant but depend on the origin and treatment of the material. The footnotes to this table elaborate the types of variation to be expected for individual elements. The values of $A_r(E)$ and uncertainties, $U_r(E)$, in parentheses follow the last significant figure to which they are attributed, apply to elements as they exist on Earth —Continued.

Order of Atomic Number				
Atomic number	Name	Symbol	Atomic weight	Footnotes
67	Holmium	Ho	164.93032(3)	
68	Erbium	Er	167.26(3)	g
69	Thulium	Tm	168.93421(3)	
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	183.85(3)	
75	Rhenium	Re	186.207(1)	
76	Osmium	Os	190.2(1)	g
77	Iridium	Ir	192.22(3)	
78	Platinum	Pt	195.08(3)	
79	Gold	Au	196.96654(3)	
80	Mercury	Hg	200.59(2)	
81	Thallium	Tl	204.3833(2)	
82	Lead	Pb	207.2(1)	g r
83	Bismuth	Bi	208.98037(3)	
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	231.03588(2)	
92	Uranium*	U	238.0289(1)	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	Unnilquadium*	Unq		
105	Unnilpentium*	Unp		
106	Unnilhexium*	Unh		
107	Unnilseptium*	Uns		

*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.

[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 implied uncertainty.

[m] Modified isotopic compositions may be found in commercially available material because it has been subjected to an undisclosed or inadvertent isotopic separation. 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 3. Relative atomic masses and half-lives of selected radionuclides.

Atomic number	Name	Symbol	Mass number	Relative atomic mass	Half-life	Unit*
43	Technetium	Tc	97	96.9064	2.6×10^{6}	a
			98	97.9072	4.2×10^{6}	a
			99	98.9063	2.1×10^{5}	a
61	Promethium	Pm	145	144.9127	18	a
			147	146.9151	2.62	a
84	Polonium	Po	209	208.9824	102	a
			210	209.9828	138	d
85	Astatine	At	210	209.9871	8	h
			211	210.9875	7.2	h
86	Radon	Rn	211	210.9906	15	h
			220	220.0114	56	s
			222	222.0176	3.82	d
87	Francium	Fr	223	223.0197	22	m
88	Radium	Ra	223	223.0185	11	d
			224	224.0202	3.7	d
			226	226.0254	1.6×10^{3}	a
			228	228.0311	5.8	a
89	Actinium	Ac	227	227.0278	21.8	a
90	Thorium	Th	230	230.0331	7.54×10^{4}	a
			232	232.0381	1.40×10^{10}	a
91	Protactinium	Pa	231	231.0359	3.25×10^{4}	a
92	Uranium	U	233	233.0396	1.59×10^{5}	a
			234	234.0409	2.46×10^{5}	a
			235	235.0439	7.04×10^{8}	a
			236	236.0456	2.34×10^{7}	a
			238	238.0508	4.47×10^{9}	a
93	Neptunium	Np	237	237.0482	2.14×10^{6}	a
			239	239.0529	2.35	d
94	Plutonium	Pu	238	238.0496	87.7	a
			239	239.0522	2.41×10^{4}	a
			240	240.0538	6.56×10^{3}	a
			241	241.0568	14.4	a
			242	242.0587	3.75×10^{5}	a
			244	244.0642	8.0×10^{7}	a
95	Americium	Am	241	241.0568	433	a
			243	243.0614	7.37×10^{3}	a
96	Curium	Cm	243	243.0614	29.1	a
			244	244.0627	18.1	a
			245	245.0655	8.5×10^{3}	a
			246	246.0672	4.8×10^{3}	a
			247	247.0703	1.6×10^{7}	a
			248	248.0723	3.5×10^{5}	a
97	Berkelium	Bk	247	247.0703	1.4×10^{3}	a
			249	249.0750	3.2×10^{2}	d
98	Californium	Cf	249	249.0748	3.5×10^{2}	a
			250	250.0764	13.1	a
			251	251.0796	9.0×10^{2}	a
			252	252.0816	2.64	a
99	Einsteinium	Es	252	252.083	1.3	a
100	Fermium	Fm	257	257.0951	101	d
101	Mendelevium	Md	256	256.094	76	m
			258	258.10	52	d
102	Nobelium	No	259	259.1009	58	m
103	Lawrencium	Lr	262	262.11	216	m
104	Unnilquadium	Unq	261	261.11	65	s
105	Unnilpentium	Unp	262	262.114	34	s
106	Unnilhexium	Unh	263	263.118	0.8	s
107	Unnilseptium	Uns	262	262.12	0.10	s

*a = years; d = days; h = hours; m = minutes; s = seconds.

4. Relative Atomic Masses and Half-Lives of Selected Radionuclides

The Commission on Atomic Weights and Isotopic Abundances has, for many years, published a Table of Relative Atomic Masses and Half-Lives of Selected Radionuclides for elements without a stable nuclide. Since the Commission has no prime responsibility for the dissemination of such values, it has not attempted either to record the best precision possible or make its tabulation comprehensive. There is no general agreement on which of the isotopes of the radioactive elements is, or is likely to be judged, "important" and various criteria such as "longest half-life," "production in quantity," "used commercially," etc., will be apposite for different situations. The relative atomic masses are derived from the atomic masses (in u) recommended by Wapstra and Audi (Ref. 2). The half-lives listed are those provided by Holden (Refs. 24–26). The data is listed in Table 3.

5. Nonterrestrial Data

A rapidly expanding body of knowledge is forming on the isotopic abundances of elements from nonterrestrial sources. Information about nonterrestrial isotopic abundances can be obtained from mass spectrometric studies of meteoritic, lunar and interplanetary dust materials, from space probes using mass and far-infrared to ultraviolet spectra, from ground-based astronomical photoelectric and radio observations, and from cosmic ray analyses.

It has been established that many elements have a different isotopic composition in nonterrestrial materials when compared with normal terrestrial materials. These effects have been demonstrated by recent precise mass spectrometric measurements of meteorite, lunar materials, and interplanetary dust. Excellent reviews describing isotopic anomalies in nonterrestrial materials are given by Anders (Ref. 27), Begemann (Ref. 28), Clayton (Ref. 29), Clayton *et al.* (Ref. 30), Esat (Ref. 31), Geiss and Bochsler (Ref. 32), Kerridge and Matthews (Ref. 33), Pillinger (Ref. 34), Reynolds (Ref. 35), Takaoka (Ref. 36), Wasserburg (Ref. 37), Wasserburg *et al.* (Ref. 38), and Wiedenbeck (Ref. 39). Fowler (Ref. 40) also touched on this problem in his Nobel lecture in Stockholm, Sweden. Those interested in a more comprehensive review should refer to Shima (Refs. 41 and 42) and Shima and Ebihara (Ref. 43).

It is important to realize that, although most of the reported isotopic anomalies are small, some variations are quite large. For this reason, scientists dealing with nonterrestrial samples should exercise caution when the isotopic composition or the atomic weight of a nonterrestrial sample is required.

The data have been classified according to the major natural alteration or production *processes*, or the *sources* of materials as described in the following outline.

Process

(A) *Mass fractionation*

Mass dependent fractionation can occur both before and after the formation of the solar system.

(A-1) Fractionation by volatilization and condensation.

(A-2) Fractionation by chemical processes: This grouping includes some special cases, such as the production of organic matter.

(B) *Nuclear reactions*

(B-1) Nucleosynthesis: The mechanism of formation of these nucleosynthetic materials is open to question. Tabulated here are samples identified by the authors as products of nucleosynthesis.

(B-2) Spallation reactions: Nuclear reactions produced by galactic and solar cosmic ray bombardment prior to the fall of the meteorite.

(B-3) Low-energy thermal neutron capture reactions: Bombardment of the lunar surface or the interior of meteorites by thermal neutrons originating from cosmic rays.

(C) *Radioactive decay products*

(C-1) Products from extinct nuclides: When the solar system had evolved to the point where the meteorites had become closed isotopic systems some 4.6×10^9 years ago, some radioactive nuclides, now extinct in the solar system, were still present. Decay products of such nuclides are responsible for the anomalous isotopic composition of certain elements.

(C-2) Enrichments in the decay products of radioactive nuclides which are commonly used for geochronology.

(C-3) Enrichments as a result of double β decay of radioactive nuclides with long half-lives.

(C-4) Enrichments as the result of the decay of fission products.

(C-5) Preferential loss of hydrogen and other light gases from the gravitational field of the object. For example, the helium and argon in the Earth's atmosphere are presently composed of very little of the original helium and argon gas but instead are composed of the outgassed helium and argon decay products from the heavy, naturally radioactive elements and from ^{40}K, respectively.

Sources

(a) *Interplanetary dust (cosmic dust)*

Isotopic ratios of H, He, C, O, Ne, Mg, and Si in so-called interplanetary dust collected in the stratosphere, near the polar region or from deep-sea sediments have been determined.

(b) *Solar particles*

(b-1) Solar wind: Lunar samples and gas rich chondrites have shown evidence of isotopic modification because of ancient and recent solar wind.

(b-2) Solar flare: During the solar event of 23 September 1978, a satellite-born "heavy isotope spectrometer telescope" (HIST) successfully measured isotopic ratios of several elements found in the energetic particle fluxes emitted by the sun.

(c) *Cosmic rays*

Data included in this category are the results of cosmic-ray measurements in the near-earth environment by balloon and satellite experiments.

(c-1) Relatively low energy cosmic rays ($\sim$20–1000 MeV/u): The recent development of high resolution detec-

tors make it possible to measure the relative isotopic abundance of several elements.

(c-2) High-energy cosmic rays (>6 GeV/u): Despite experimental difficulties, ^{3}He/^{4}He ratios have now been determined.

(d) *Planets and satellites*

Isotopic ratios of some elements in planets and one of the satellites of Saturn (namely Titan) were determined by spacecraft-born mass and infrared spectrometers and ground-based infrared spectrometry.

(e) *Cool stars*

Isotopic ratios of C and O in cool giant and supergiant stars and Mg in metal-poor subgiant stars have been obtained from their infrared spectra taken with large ground-based telescopes.

(f) *Interstellar clouds*

Isotopes of H, He, C, N, and O have been detected by large ground-based photoelectric and radio-telescopes, and by satellite-born ultraviolet and far-infrared spectrometry.

(g) *Comet Halley*

D/H and ^{18}O/^{16}O ratios in comet Halley were measured by the Giotto spacecraft-born mass spectrometer on 14 March 1986.

Although the Commission does not attempt to review the literature on the isotopic composition of nonterrestrial materials systematically, some examples of isotopic variations have been given in past reports. In order to provide a more comprehensive view of current research on the isotopic variations found in nonterrestrial materials, we have chosen in this report to present some of these data in Tables 4 and 5.

Table 4 lists experimental results for a selection of the largest reported variations. This information has been classified in terms of the major process involved in the modification of the isotopic composition of the element concerned. Thus, for example, the table lists, as one of the items, the largest deviation of isotopic composition reported for the isotopes of silicon caused by a mass fractionation process, (A-1). Only data of enrichment or depletion of specific isotopes produced predominantly by one of the major alteration processes are listed. Data listed in Table 4 are limited to measured values reported in publications and in no instance represent interpolations or extrapolations.

Entries given as "δ" or "u" (per atomic mass unit) are all in per mil (per 1000). The "δ" values are expressed by respective mass numbers, for example, the meaning of $\delta(15,14)$ is as follows:

$$\delta(15,14) = \left(\frac{(^{15}\mathrm{N}/^{14}\mathrm{N})_n}{(^{15}\mathrm{N}/^{14}\mathrm{N})_t} - 1 \right) \times 1000$$

(n: nonterrestrial samples, t: terrestrial standard). Where an isotopic ratio or atomic weight is given, the terrestrial value

TABLE 4. Examples of observed maximum isotopic variations and corresponding atomic weights due to different processes.

Element	Isotopic ratio maximum variation	Atomic weight	Materials	Process	Reference
$_7$N	(15,14); +190	14.0074 (14.0067)	C2-chondrite Renazzo	(A-2)	44
$_{14}$Si	12.5/u		Inclusion C1S2 from C3-chondrite Allende	(A-1)	45
$_{18}$Ar	^{40}Ar/^{36}Ar = 1.2×10^{-3} (295.5)	36.29 (39.95)	1850 °C release from carbon-rich residue of ureilite Dyalpur	(C-5)	46
$_{19}$K	39 /40 /41 42.02/18.90/39.08 (93.25/0.012/6.73)	39.934 (39.098)	Iron meteorite Aroos	(B-2)	47
$_{22}$Ti	(50,48); +104.3		Hibonite, MY-H4 from C2-chondrite Murray	(B-1)	48
$_{36}$Kr	^{82}Kr/^{84}Kr − 0.355 (0.203)		1000 °C release from FeS in iron meteorite Cape York	(C-3)	49
$_{47}$Ag	^{107}Ag/^{109}Ag = 2.94 (1.08)	107.41 (107.87)	Iron meteorite Hoba #4213	(C-1)	50
$_{54}$Xe	^{136}Xe/^{132}Xe = 0.617 (0.331)		600 °C release from <2.89 g/cm^3 density fraction of C3-chrondrite Allende	(C-4)	51
$_{62}$Sm	(150,154); +7.83		Lunar rock, 10017,32	(B-3)	52
$_{82}$Pb	204 /206 /207 /208 1.00/301.2/190.8/1524 (1.00/17.2/15.8/37.4)	207.6 (207.2)	Whitlockite from augite Angra dos Reis	(C-2)	53

TABLE 5. Examples of isotopic composition and atomic weight from different sources.

Element	Source	Isotopic ratio	Atomic weight	Method	Reference
$_1$H		^{2}H/^{1}H			
	(a) Interplanetary particle	5.3×10^{-4} 0.9×10^{-4}	1.0084 1.0079	Mosquito-ϵ*, Lea-α* collected at > 18 000 m by aircraft and measured by modified SIMS	54
	(b-1) Solar wind	1.68×10^{-5}	1.0078	500–550 °C release from lunar soil 10084	55
	(d) Venus	0.022	1.029	Pioneer Venus orbiter IMS	56
	(f) Local clouds T 10 K	2.0×10^{-5}	1.0078	Ly α by Copernicus and IUE 57	
	(f) Toward HR 1099	$\geq0.09\times10^{-5}$	1.0078	Ly α by IUE	57
	(g) Comet Halley	0.6×10^{-4} $\sim4.8\times10^{-4}$	1.0079 ~1.0083	Giotto spacecraft-born MS	58
	Earth	1.50×10^{-4}	1.00794		
$_2$He		^{3}He/^{4}He			
	(b-1) Solar wind	4.8×10^{-4}	4.0021	ISEE-3-born IMS	59
	(b-2) Solar flare	0.0026	4.0000	ISEE-3-born HIST	60
	(c-1) 48–77 MeV/u	0.066	3.94	ISEE-3-born HIST	61
	(c-2) > 6 GeV/u	< 0.17	> 3.86	Balloon-born detector	62
	Earth	1.38×10^{-6}	4.00260		
$_6$C		^{12}C/^{13}C			
	(b-1) Solar wind	86.62	12.011	1200 °C release from lunar breccia 10059	63
	(b-2) Solar flare	105	12.009	ISEE-3-born HIST	60
	(c-1) 77–194 MeV/u	14.3	12.066	ISEE-3-born C.R. detector	64
	(d) Jupiter	160	12.006	Voyager IRIS	65
	(e) M giants	7–20	12.13–12.05	Infrared spectra by ground-based telescope	66
	(f) Local clouds 100–200 pc from sun	43	12.02	At 423.2 and 395.7 nm spectra by ground-based telescope	67
	Earth	89.91	12.011		

*Names of interplanetary particles. IRIS: Infrared Interferometer Spectrometer. SIMS: Secondary Ion Mass Spectrometer. IUE: International Ultraviolet Explorer satellite. IMS: Ion Mass Spectrometer. HIST: Caltech Heavy Isotope Spectrometer Telescope.

is listed in parentheses for comparison, suitably truncated where necessary to an appropriate number of significant figures.

Table 5 lists examples of the isotopic compositions and atomic weights of elements from different sources.

6. Table of Standard Atomic Weights Abridged to Five Significant Figures

The Commission on Atomic Weights and Isotopic Abundances reaffirms its basic function which is to disseminate the most accurate information on atomic weights with their associated uncertainties as they are currently published in the literature and carefully evaluated by the Commission. It does not try to judge whether the sixth, seventh or any significant figure could ever be of interest to any user of the Table of Standard Atomic Weights. If published work leads to a standard atomic weight (or its uncertainty) that is considered by the Commission to be reliable and different from the currently tabulated value, or if convincing evidence becomes available in the literature for the elimination or introduction of an annotation, a change in the full table will be recommended. The Commission will introduce every such needed change in its biennial revisions of the Standard Atomic Weights even if most common sources of the element in question are unaffected.

Thus, the details in the Table of Standard Atomic Weights in many respects exceed the needs and interests of most users who are more concerned with the length of time during which a given table has full validity to the precision limit of their interests. The Commission in 1987 therefore decided to prepare for publication a revised and updated version of the 1981 Table of Atomic Weights to Five Significant Figures (Ref. 68), or fewer where uncertainties do not warrant even five-figure accuracy (this currently applies to ten elements).

Since the publication of the earlier, first version of the abridged table, IUPAC has approved the use of the designation "standard" to its atomic weights. This adjective is now also incorporated in the title of the revised abridged table. When an atomic weight is known to more than five significant figures, it is abridged in this table to the five-figure value closest to the unabridged best value given in this report. When the sixth digit of the unabridged value is five exactly, it

TABLE 6. Standard atomic weights abridged to five significant figures. [Scaled to $A_r(^{12}C) = 12$.] Atomic weights are quoted here to five significant figures unless the dependable accuracy is more limited either by the combined uncertainties of the best published atomic-weight determinations, or by the variability of isotopic composition in normal terrestrial occurrences (the latter applies to elements annotated r). The last significant figure of each tabulated value is considered reliable to ± 1 except when a larger single-digit uncertainty is inserted in parentheses following the atomic weight. Neither the highest nor the lowest actual atomic weight of any normal sample is thought likely to differ from the tabulated value by more than the assigned uncertainty. However, the tabulated values do not apply either to samples of highly exceptional isotopic composition arising from most unusual geological occurrences (for elements annotated g) or to those whose isotopic composition has been artificially altered. Such might even be found in commerce without disclosure of that modification (for elements annotated m). Elements annotated by an asterisk (*) have no stable isotope and are generally represented in this table by just one of the element's commonly known radioisotopes, with a corresponding relative atomic mass in the atomic-weight column. However, three such elements (Th, Pa, and U) do have a characteristic terrestrial isotopic composition, and for these an atomic weight is tabulated. For more detailed information users should refer to the full IUPAC Table of Standard Atomic Weights, as is found in the biennial reports of the Commission on Atomic Weights and Isotopic Abundances. They are published in *Pure and Applied Chemistry*.

Atomic number	Name	Symbol	Atomic weight	Annotation
1	Hydrogen	H	1.0079	g m
2	Helium	He	4.0026	
3	Lithium	Li	6.941(2)	g m r
4	Beryllium	Be	9.0122	
5	Boron	B	10.811(5)	g m r
6	Carbon	C	12.011	r
7	Nitrogen	N	14.007	
8	Oxygen	O	15.999	
9	Fluorine	F	18.998	
10	Neon	Ne	20.180	m
11	Sodium (Natrium)	Na	22.990	
12	Magnesium	Mg	24.305	
13	Aluminum	Al	26.982	
14	Silicon	Si	28.086	
15	Phosphorus	P	30.974	
16	Sulfur	S	32.066(6)	g r
17	Chlorine	Cl	35.453	m
18	Argon	Ar	39.948	g r
19	Potassium (Kalium)	K	39.098	
20	Calcium	Ca	40.078(4)	g
21	Scandium	Sc	44.956	
22	Titanium	Ti	47.88(3)	
23	Vanadium	V	50.942	
24	Chromium	Cr	51.996	
25	Manganese	Mn	54.938	
26	Iron	Fe	55.847(3)	
27	Cobalt	Co	58.933	
28	Nickel	Ni	58.693	
29	Copper	Cu	63.546(3)	r
30	Zinc	Zn	65.39(2)	
31	Gallium	Ga	69.723	
32	Germanium	Ge	72.61(2)	
33	Arsenic	As	74.922	
34	Selenium	Se	78.96(3)	
35	Bromine	Br	79.904	
36	Krypton	Kr	83.80	g m
37	Rubidium	Rb	85.468	
38	Strontium	Sr	87.62	g r
39	Yttrium	Y	88.906	
40	Zirconium	Zr	91.224(2)	g
41	Niobium	Nb	92.906	
42	Molybdenum	Mo	95.94	g
43	Technetium*	^{99}Tc	98.906	
44	Ruthenium	Ru	101.07(2)	g
45	Rhodium	Rh	102.91	
46	Palladium	Pd	106.42	g
47	Silver	Ag	107.87	
48	Cadmium	Cd	112.41	
49	Indium	In	114.82	
50	Tin	Sn	118.71	
51	Antimony (Stibium)	Sb	121.76	g
52	Tellurium	Te	127.60(3)	g
53	Iodine	I	126.90	
54	Xenon	Xe	131.29(2)	g m
55	Caesium	Cs	132.91	
56	Barium	Ba	137.33	
57	Lanthanum	La	138.91	
58	Cerium	Ce	140.12	g

TABLE 6. (Continued)

Atomic number	Name	Symbol	Atomic weight	Annotation
59	Praseodymium	Pr	140.91	
60	Neodymium	Nd	144.24(3)	g
61	Promethium*	^{147}Pm	146.92	
62	Samarium	Sm	150.36(3)	g
63	Europium	Eu	151.96	g
64	Gadolinium	Gd	157.25(3)	g
65	Terbium	Tb	158.93	
66	Dysprosium	Dy	162.50(3)	g
67	Holmium	Ho	164.93	
68	Erbium	Er	167.26(3)	g
69	Thulium	Tm	168.93	
70	Ytterbium	Yb	173.04(3)	g
71	Lutetium	Lu	174.97	g
72	Hafnium	Hf	178.49(2)	
73	Tantalum	Ta	180.95	
74	Tungsten (Wolfram)	W	183.85(3)	
75	Rhenium	Re	186.21	
76	Osmium	Os	190.2	g
77	Iridium	Ir	192.22(3)	
78	Platinum	Pt	195.08(3)	
79	Gold	Au	196.97	
80	Mercury	Hg	200.59(2)	
81	Thallium	Tl	204.38	
82	Lead	Pb	207.2	g r
83	Bismuth	Bi	208.98	
84	Polonium*	^{210}Po	209.98	
85	Astatine*	^{210}At	209.99	
86	Radon*	^{222}Rn	222.02	
87	Francium*	^{223}Fr	223.02	
88	Radium*	^{226}Ra	226.03	
89	Actinium*	^{227}Ac	227.03	
90	Thorium*	Th	232.04	g
91	Protactinium*	Pa	231.04	
92	Uranium*	U	238.03	g m
93	Neptunium*	^{237}Np	237.05	
94	Plutonium*	^{239}Pu	239.05	
95	Americium*	^{241}Am	241.06	
96	Curium*	^{244}Cm	244.06	
97	Berkelium*	^{249}Bk	249.08	
98	Californium*	^{252}Cf	252.08	
99	Einsteinium*	^{252}Es	252.08	
100	Fermium*	^{257}Fm	257.10	
101	Mendelevium*	^{258}Md	258.10	
102	Nobelium*	^{259}No	259.10	
103	Lawrencium*	^{262}Lr	262.11	

is rounded up or down to make the fifth digit in this abridged table even. The single-digit uncertainty in the tabulated atomic weight is held to be symmetric, that is, it is applicable with either a positive or a negative sign.

The abridged table is given here as Table 6 with the reasonable hope that the quoted values will not need to be changed for several years at least—a desirable attribute for textbooks and numerical tables derived from atomic-weight data. However, it should be remembered that the best atomic-weight values of 30 elements are still uncertain by more than one unit in the fifth significant figure. Relevant warnings of anomalous geological occurrences, isotopically altered materials, and variability of radioactive elements are included in the abridged table. It is unlikely that it will require revision for about ten years, whereas the unabridged table is revised every two years.

This Table may be freely reprinted provided it includes the annotations and the rubric at the head of the Table, and provided the IUPAC source is acknowledged.

7. Other Projects of the Commission

The *Four Figure Table of Atomic Weights* was published in Chemistry International[69] and in International Newsletters on Chemical Education.[70]

The *Working Party on Natural Isotopic Fractionation* presented a preliminary report. It was agreed that a final report about the proposed work (for the elements H, Li, B,

C, N, O, Ne, Mg, Si, S, Cl, K, Cu, Se, Pd, Te, and U) should be presented at the next meeting of the Commission in 1991. It is intended that this information will be published.

The Commission established a new *Working Party on Statistical Evaluation of Isotopic Abundances.* The aim of this Working Party consists in presenting a classification of isotopic measurements for the next meeting of the Commission. It was agreed to revise the statistical procedures used to evaluate these data and to assign uncertainties to the final isotopic abundances.

The Commission explored the possibility of establishing an archive of historically significant events, activities, etc., at the Arnold and Mabel Beckman *Center for the History of Chemistry* (*CHOC*), Philadelphia. It was decided to enter into a long-term cooperative arrangement with CHOC from the end of 1989 onwards.

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