

Atomic Weights of the Elements 1995^{a)}

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The biennial review of atomic weight, $A_r(E)$, determinations and other cognate data has resulted in changes for the standard atomic weight of 21 elements. The five most significant changes are: boron from 10.811 ± 0.005 to 10.811 ± 0.007 ; carbon from 12.011 ± 0.001 to 12.0107 ± 0.0008 ; arsenic from 74.92159 ± 0.00002 to 74.92160 ± 0.00002 ; cerium from 140.115 ± 0.004 to 140.116 ± 0.001 ; and platinum 195.08 ± 0.03 to 195.078 ± 0.002 . An annotation for potassium has been changed in the Table of Standard Atomic Weights. To eliminate possible confusion in the reporting of relative lithium isotope-ratio data, the Commission recommends that such data be expressed using $^7\text{Li}/^6\text{Li}$ ratios and that reporting using $^6\text{Li}/^7\text{Li}$ ratios be discontinued. Because relative isotope-ratio data for sulfur are commonly being expressed on noncorresponding scales, the Commission recommends that such isotopic data be expressed relative to VCDT (Vienna Cañon Diablo Troilite) on a scale such that $^{34}\text{S}/^{32}\text{S}$ of IAEA-S-1 silver sulfide is 0.9997 times that of VCDT. Many elements have a different isotopic composition in some nonterrestrial materials. Some recent data on oxygen are included in this article for the information of the interested scientific community. © 1997 American Institute of Physics and American Chemical Society. [S0047-2689(97)00305-X]

Key words: atomic weight; critical evaluation; elements; isotopic composition.

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1. Introduction

The Commission on Atomic Weights and Isotopic Abundances met under the chairmanship of Professor K. G. Heumann from 4th–6th August 1995, during the 38th IUPAC General Assembly in Guildford, United Kingdom. The Commission decided to publish the report "Atomic Weights of the Elements 1995" as presented here and the report "Isotopic Compositions of the Elements 1995."¹

The Commission has reviewed the literature over the previous two years since the last report on atomic weights² 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. The last compilations of the isotopic abundances and atomic masses with all relevant data were published in 1991³ and 1993,⁴ respectively. 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.⁵

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 in this and recent reports also includes a list of past recommended values over a period in excess of the last 100 years. It should be understood that before 1961 the values quoted were intended to be consistent with $A_r(O)=16$, whereas since that time the values are consistent with $A_r(O)=15.9994$. An attempt is not generally made to follow the data to a time before 1882. Between 1882 and 1903 G. P. Baxter's data are quoted usually from his report to the *International Critical Tables* (ICT). Between 1903 and 1923, Baxter's ICT values show a few small differences from those recommended by the International Committee on Atomic Weights. It is the latter values that are here quoted. Uncertainties were given systematically only from 1969, from which time they should be considered to be expanded

uncertainties, but the factor determining the excess over single standard uncertainties has deliberately not been stated.

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

Element	From	To
boron	10.811±0.005	10.811±0.007
carbon	12.011±0.001	12.0107±0.0008
fluorine	18.9984032±0.0000009	18.9984032±0.0000005
sodium	22.989768±0.0000006	22.989770±0.000002
aluminium	26.981539±0.000005	26.981538±0.000002
phosphorus	30.973762±0.000004	30.973761±0.000002
scandium	44.955910±0.000009	44.955910±0.000008
manganese	54.93805±0.00001	54.938049±0.000009
cobalt	58.93320±0.00001	58.933200±0.000009
arsenic	74.92159±0.00002	74.92160±0.00002
rhodium	102.90550±0.00003	102.90550±0.00002
caesium	132.90543±0.00005	132.90545±0.00002
cerium	140.115±0.004	140.116±0.001
praseodymium	140.90765±0.00003	140.90765±0.00002
europium	151.965±0.009	151.964±0.001
terbium	158.92534±0.00003	158.92534±0.00002
holmium	164.93032±0.00003	164.93032±0.00002
thulium	168.93421±0.00003	168.93421±0.00002
platinum	195.08±0.03	195.078±0.002
gold	196.96654±0.00003	196.96655±0.00002
bismuth	208.98037±0.00003	208.98038±0.00002

The membership of the Commission for the period 1994–1995 was as follows: K. G. Heumann (FRG, *Chairman*); T. B. Coplen (USA, *Secretary*); J. K. Böhlke (USA, *Associate*); H. J. Dietze (FRG, *Associate*); M. Ebihara (Japan, *Associate*); J. W. Gramlich (USA, *Titular*); H. R. Krouse (Canada, *Titular*); R. D. Loss (Australia, *Associate*); G. I. Ramendik (Russia, *Titular*); D. E. Richardson (USA, *Associate*); K. J. R. Rosman (Australia, *Titular*); L. Schultz (FRG, *Titular*); P. D. P. Taylor (Belgium, *Associate*); L. Turpin (France, *Associate*); R. D. Vocke, Jr. (USA, *Associate*); P. De Bièvre (Belgium, *National Representative*); Y. Xiao (China, *National Representative*); M. Shima (Japan, *National Representative*); A. Pires de Matos (Portugal, *National Representative*); N. N. Greenwood (UK, *National Representative*).

2. Comments on Some Atomic Weights and Annotations

2.1. Boron

The Commission has changed the recommended value for the standard atomic weight of boron to $A_r(B)=10.811(7)$ based on an evaluation of the variation in isotopic abundance of naturally occurring boron-bearing substances. The Commission decided that the uncertainty of $A_r(B)$ should be increased to include boron in sea water.⁶ However, footnote "g" remains in Tables 1 and 2 to warn users that highly

TABLE 1. Standard atomic weights 1995. Alphabetical order in English. [Scaled to $A_r(^{12}\text{C}) = 12$, 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 $A_r(\text{E})$ 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 which may occur for individual elements and which may be larger than the listed uncertainties of values of $A_r(\text{E})$. Names of elements with atomic numbers 104–111 are temporary

Name	Symbol	Atomic Number	Atomic weight	Footnotes ^c	Name	Symbol	Atomic Number	Atomic weight	Footnotes ^c
Actinium ^a	Ac	89			Neptunium ^a	Np	93		
Aluminium (Aluminum)	Al	13	26.981538(2)		Nickel	Ni	28	58.6934(2)	
Americium ^a	Am	95			Niobium	Nb	41	92.90638(2)	
Antimony (Stibium)	Sb	51	121.760(1)	g	Nitrogen	N	7	14.00674(7)	g r
Argon	Ar	18	39.948(1)	g r	Nobelium ^a	No	102		
Arsenic	As	33	74.92160(2)		Osmium	Os	76	190.23(3)	g
Astatine ^a	At	85			Oxygen	O	8	15.9994(3)	g r
Barium	Ba	56	137.327(7)		Palladium	Pd	46	106.42(1)	g
Berkelium ^a	Bk	97			Phosphorus	P	15	30.973762(4)	
Beryllium	Be	4	9.012182(3)		Platinum	Pt	78	195.078(2)	
Bismuth	Bi	83	208.98038(2)		Plutonium ^a	Pu	94		
Boron	B	5	10.811(7)	g m r	Polonium ^a	Po	84		
Bromine	Br	35	79.904(1)		Potassium (Kalium)	K	19	39.0983(1)	
Cadmium	Cd	48	112.411(8)	g	Praseodymium	Pr	59	140.90765(2)	
Caesium (Cesium)	Cs	55	132.90545(2)		Promethium ^a	Pm	61		
Calcium	Ca	20	40.078(4)	g	Protactinium ^a	Pa	91	231.03588(2)	
Californium ^a	Cf	98			Radium ^a	Ra	88		
Carbon	C	6	12.0107(8)	g r	Radon ^a	Rn	86		
Cerium	Ce	58	140.116(1)	g	Rhenium	Re	75	186.207(1)	
Chlorine	Cl	17	35.4527(9)	m	Rhodium	Rh	45	102.90550(2)	
Chromium	Cr	24	51.9961(6)		Rubidium	Rb	37	85.4678(3)	g
Cobalt	Co	27	58.933200(9)		Ruthenium	Ru	44	101.07(2)	g
Copper	Cu	29	63.546(3)	r	Samarium	Sm	62	150.36(3)	g
Curium ^a	Cm	96			Scandium	Sc	21	44.955910(8)	
Dysprosium	Dy	66	162.50(3)	g	Selenium	Se	34	78.96(3)	
Einsteinium ^a	Es	99			Silicon	Si	14	28.0855(3)	r
Erbium	Er	68	167.26(3)	g	Silver	Ag	47	107.8682(2)	g
Europium	Eu	63	151.964(1)	g	Sodium (Natrium)	Na	11	22.989770(2)	
Fermium ^a	Fm	100			Strontium	Sr	38	87.62(1)	g r
Fluorine	F	9	18.9984032(5)		Sulfur	S	16	32.066(6)	g r
Francium ^a	Fr	87			Tantalum	Ta	73	180.9479(1)	
Gadolinium	Gd	64	157.25(3)	g	Technetium ^a	Tc	43		
Gallium	Ga	31	69.723(1)		Tellurium	Te	52	127.60(3)	g
Germanium	Ge	32	72.61(2)		Terbium	Tb	65	158.92534(2)	
Gold	Au	79	196.96655(2)		Thallium	Tl	81	204.3833(2)	
Hafnium	Hf	72	178.49(2)		Thorium ^a	Th	90	232.0381(1)	g
Helium	He	2	4.002602(2)	g r	Thulium	Tm	69	168.93421(2)	
Holmium	Ho	67	164.93032(2)		Tin	Sn	50	118.710(7)	g
Hydrogen	H	1	1.00794(7)	g m r	Titanium	Ti	22	47.867(1)	
Indium	In	49	114.818(3)		Tungsten (Wolfram)	W	74	183.84(1)	
Iodine	I	53	126.90447(3)		Unnilennium ^a	Une	109		
Iridium	Ir	77	192.217(3)		Unnilhexium ^a	Unh	106		
Iron	Fe	26	55.845(2)		Unniloctium ^a	Uno	108		
Krypton	Kr	36	83.80(1)	g m	Unnilpentium ^a	Unp	105		
Lanthanum	La	57	138.9055(2)	g	Unnilquadium ^a	Unq	104		
Lawrencium ^a	Lr	103			Unnilseptium ^a	Uns	107		
Lead	Pb	82	207.2(1)	g r	Ununnilium ^a	Uun	110		
Lithium	Li	3	[6.941(2)] ^b	g m r	Ununonium ^a	Uuu	111		
Lutetium	Lu	71	174.967(1)	g	Uranium ^a	U	92	238.0289(1)	g m
Magnesium	Mg	12	24.3050(6)		Vanadium	V	23	50.9415(1)	
Manganese	Mn	25	54.938049(9)		Xenon	Xe	54	131.29(2)	g m
Mendelevium ^a	Md	101			Ytterbium	Yb	70	173.04(3)	g
Mercury	Hg	80	200.59(2)		Yttrium	Y	39	88.90585(2)	
Molybdenum	Mo	42	95.94(1)	g	Zinc	Zn	30	65.39(2)	
Neodymium	Nd	60	144.24(3)	g	Zirconium	Zr	40	91.224(2)	g
Neon	Ne	10	20.1797(6)	g m					

^aElement 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.

^bCommercially available Li materials have atomic weights that range between 6.94 and 6.99; if a more accurate value is required, it must be determined for the specific material.

^c(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 $A_r(\text{E})$ being given; the tabulated $A_r(\text{E})$ value should be applicable to any normal material.

TABLE 2. Standard atomic weights 1995. Order of atomic number. [Scaled to $A_r(^{12}\text{C}) = 12$, 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 $A_r(\text{E})$ 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 which may occur for individual elements and which may be larger than the listed uncertainties of values of $A_r(\text{E})$. Names of elements with atomic numbers 104 to 111 are temporary

Atomic Number	Name	Symbol	Atomic weight	Footnotes ^c	Atomic Number	Name	Symbol	Atomic weight	Footnotes ^c
1	Hydrogen	H	1.00794(7)	g m r	57	Lanthanum	La	138.9055(2)	g
2	Helium	He	4.002602(2)	g r	58	Cerium	Ce	140.116(1)	g
3	Lithium	Li	[6.941(2)] ^b	g m r	59	Praseodymium	Pr	140.90765(2)	
4	Beryllium	Be	9.012182(3)		60	Neodymium	Nd	144.24(3)	g
5	Boron	B	10.811(7)	g m r	61	Promethium ^a	Pm		
6	Carbon	C	12.0107(8)	g r	62	Samarium	Sm	150.36(3)	g
7	Nitrogen	N	14.00674(7)	g r	63	Europium	Eu	151.964(1)	g
8	Oxygen	O	15.9994(3)	g r	64	Gadolinium	Gd	157.25(3)	g
9	Fluorine	F	18.9984032(5)		65	Terbium	Tb	158.92534(2)	
10	Neon	Ne	20.1797(6)	g m	66	Dysprosium	Dy	162.50(3)	g
11	Sodium (Natrium)	Na	22.989770(2)		67	Holmium	Ho	164.93032(2)	
12	Magnesium	Mg	24.3050(6)		68	Erbium	Er	167.26(3)	g
13	Aluminium (Aluminum)	Al	26.981538(2)		69	Thulium	Tm	168.93421(2)	
14	Silicon	Si	28.0855(3)	r	70	Ytterbium	Yb	173.04(3)	g
15	Phosphorus	P	30.973761(2)		71	Lutetium	Lu	174.967(1)	g
16	Sulfur	S	32.066(6)	g r	72	Hafnium	Hf	178.49(2)	
17	Chlorine	Cl	35.4527(9)	m	73	Tantalum	Ta	180.9479(1)	
18	Argon	Ar	39.948(1)	g r	74	Tungsten (Wolfram)	W	183.84(1)	
19	Potassium (Kalium)	K	39.0983(1)		75	Rhenium	Re	186.207(1)	
20	Calcium	Ca	40.078(4)	g	76	Osmium	Os	190.23(3)	g
21	Scandium	Sc	44.955910(8)		77	Iridium	Ir	192.217(3)	
22	Titanium	Ti	47.867(1)		78	Platinum	Pt	195.078(2)	
23	Vanadium	V	50.9415(1)		79	Gold	Au	196.96655(2)	
24	Chromium	Cr	51.9961(6)		80	Mercury	Hg	200.59(2)	
25	Manganese	Mn	54.938049(9)		81	Thallium	Tl	204.3833(2)	
26	Iron	Fe	55.845(2)		82	Lead	Pb	207.2(1)	g r
27	Cobalt	Co	58.933200(9)		83	Bismuth	Bi	208.98038(2)	
28	Nickel	Ni	58.6934(2)		84	Polonium ^a	Po		
29	Copper	Cu	63.546(3)	r	85	Astatine ^a	At		
30	Zinc	Zn	65.39(2)		86	Radon ^a	Rn		
31	Gallium	Ga	69.723(1)		87	Francium ^a	Fr		
32	Germanium	Ge	72.61(2)		88	Radium ^a	Ra		
33	Arsenic	As	74.92160(2)		89	Actinium ^a	Ac		
34	Selenium	Se	78.96(3)		90	Thorium ^a	Th	232.0381(1)	g
35	Bromine	Br	79.904(1)		91	Protactinium ^a	Pa	231.03588(2)	
36	Krypton	Kr	83.80(1)	g m	92	Uranium ^a	U	238.0289(1)	g m
37	Rubidium	Rb	85.4678(3)	g	93	Neptunium ^a	Np		
38	Strontium	Sr	87.62(1)	g r	94	Plutonium ^a	Pu		
39	Yttrium	Y	88.90585(2)		95	Americium ^a	Am		
40	Zirconium	Zr	91.224(2)	g	96	Curium ^a	Cm		
41	Niobium	Nb	92.90638(2)		97	Berkelium ^a	Bk		
42	Molybdenum	Mo	95.94(1)	g	98	Californium ^a	Cf		
43	Technetium ^a	Tc			99	Einsteinium ^a	Es		
44	Ruthenium	Ru	101.07(2)	g	100	Fermium ^a	Fm		
45	Rhodium	Rh	102.90550(2)		101	Mendelevium ^a	Md		
46	Palladium	Pd	106.42(1)	g	102	Nobelium ^a	No		
47	Silver	Ag	107.8682(2)	g	103	Lawrencium ^a	Lr		
48	Cadmium	Cd	112.411(8)	g	104	Unnilquadium ^a	Unq		
49	Indium	In	114.818(3)		105	Unnilpentium ^a	Unp		
50	Tin	Sn	118.710(7)	g	106	Unnilhexium ^a	Unh		
51	Antimony (Stibium)	Sb	121.760(1)	g	107	Unnilseptium ^a	Uns		
52	Tellurium	Te	127.60(3)	g	108	Unniloctium ^a	Uno		
53	Iodine	I	126.90447(3)		109	Unnilennium ^a	Une		
54	Xenon	Xe	131.29(2)	g m	110	Ununnilium ^a	Uun		
55	Caesium (Cesium)	Cs	132.90545(2)		111	Ununonium ^a	Uuu		
56	Barium	Ba	137.327(7)						

^aElement 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.

^bCommercially available Li materials have atomic weights that range between 6.94 and 6.99; if a more accurate value is required, it must be determined for the specific material.

^c(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 $A_r(\text{E})$ being given; the tabulated $A_r(\text{E})$ value should be applicable to any normal material.

unusual naturally occurring boron-bearing substances can be found with an atomic weight that falls outside the implied range. The previous value, $A_r(\text{B})=10.811(5)$, was adopted by the Commission in 1983⁷ and was based on calibrated mass spectrometric measurements by Finley *et al.*,⁸ De Bièvre and DeBus,⁹ and Catanzaro *et al.*,¹⁰ and on a mineral survey by Agyei *et al.*¹¹ Historical values of $A_r(\text{B})$ include: 1882, 10.97; 1894, 11; 1896, 10.95; 1900, 11.0; 1919, 10.9; 1925, 10.82; 1961, 10.811(3); 1969, 10.81(1); and 1983, 10.811(5).

2.2. Carbon

The Commission has changed the recommended value for the standard atomic weight of carbon to $A_r(\text{C})=12.0107(8)$ based on an evaluation of the variation in isotopic abundance of naturally occurring carbon-bearing substances. The Commission decided that it could reduce the uncertainty in $A_r(\text{C})$ and changed the value of $A_r(\text{C})$ from 12.011(1) to 12.0107(8). The footnote "g" remains to warn users of the existence of highly unusual naturally occurring carbon-bearing substances with an atomic weight that falls outside the implied range. The previous value, $A_r(\text{C})=12.011(1)$, was adopted by the Commission in 1969¹² with the intent that this value covered all known terrestrial sources of carbon. The Commission recognized the calibrated mass spectrometric measurement by Chang *et al.*¹³ Historical values of $A_r(\text{C})$ include: 1885, 12.00; 1894, 12; 1896, 12.01; 1898, 12.00; 1916, 12.005; 1925, 12.000; 1938, 12.010; 1953, 12.011; 1961, 12.01115(5); and 1969, 12.011(1).

2.3. Fluorine

The Commission has changed the recommended value for the standard atomic weight of fluorine to $A_r(\text{F})=18.9984032(5)$, based on new atomic mass data.⁴ The previous value, $A_r(\text{F})=18.9984032(9)$, was based on the atomic mass determination of Wapstra and Audi.¹⁴ Historical values of $A_r(\text{F})$ include: 1882, 19.03; 1894, 19; 1896, 19.03; 1897, 19.06; 1900, 19.05; 1903, 19.0; 1925, 19.00; 1961, 18.9984; 1969, 18.9984(1); 1971, 18.99840(1); 1975, 18.998403(1); and 1985, 18.9984032(9).

2.4. Sodium

The Commission has changed the recommended value for the standard atomic weight of sodium to $A_r(\text{Na})=22.989770(2)$, based on new atomic mass data.⁴ The previous value, $A_r(\text{Na})=22.989768(6)$, was based on the atomic mass determination of Wapstra and Audi.¹⁴ Historical values of $A_r(\text{Na})$ include: 1882, 23.05; 1909, 23.00; 1925, 22.997; 1953, 22.991; 1961, 22.9898; 1969, 22.9898(1); 1971, 22.98977(1); and 1985, 22.989768(6).

2.5. Aluminium

The Commission has changed the recommended value for the standard atomic weight of aluminium to $A_r(\text{Al})=26.981538(2)$, based on new atomic mass data.⁴ The previous value, $A_r(\text{Al})=26.981539(5)$, was based on the atomic mass determination of Wapstra and Audi.¹⁴ Historical values of $A_r(\text{Al})$ include: 1888, 27.08; 1894, 27; 1896, 27.11; 1900, 27.1; 1922, 27.0; 1925, 26.97; 1951, 26.98; 1961, 26.9815; 1969, 26.9815(1); 1971, 26.98154(1); and 1985, 26.981539(5).

2.6. Phosphorus

The Commission has changed the recommended value for the standard atomic weight of phosphorus to $A_r(\text{P})=30.973761(2)$, based on new atomic mass data.⁴ The previous value, $A_r(\text{P})=30.973762(4)$, was based on the atomic mass determination of Wapstra and Audi.¹⁴ Historical values of $A_r(\text{P})$ include: 1882, 31.03; 1894, 31; 1896, 31.02; 1900, 31.0; 1911, 31.04; 1925, 31.027; 1947, 30.98; 1951, 30.975; 1961, 30.9738; 1969, 30.9738(1); 1971, 30.97376(1); and 1985, 30.973762(4).

2.7. Scandium

The Commission has changed the recommended value for the standard atomic weight of scandium to $A_r(\text{Sc})=44.955910(8)$, based on new atomic mass data.⁴ The previous value, $A_r(\text{Sc})=44.955910(9)$, was based on the atomic mass determination of Wapstra and Audi.¹⁴ Historical values of $A_r(\text{Sc})$ include: 1882, 44.08; 1894, 44.0; 1897, 44.12; 1900, 44.1; 1921, 45.10; 1951, 44.96; 1961, 44.956; 1969, 44.9559(1); 1983, 44.95591(1); and 1985, 44.955910(9).

2.8. Manganese

The Commission has changed the recommended value for the standard atomic weight of manganese to $A_r(\text{Mn})=54.938049(9)$, based on new atomic mass data.⁴ The previous value, $A_r(\text{Mn})=54.93805(1)$, was based on the atomic mass determination of Wapstra and Audi.¹⁴ Historical values of $A_r(\text{Mn})$ include: 1882, 54.03; 1894, 55; 1896, 54.99; 1900, 55.0; 1909, 54.93; 1953, 54.94; 1961, 54.9380; 1969, 54.9380(1); and 1985, 54.93805(1).

2.9. Cobalt

The Commission has changed the recommended value for the standard atomic weight of cobalt to $A_r(\text{Co})=58.933200(9)$, based on new atomic mass data.⁴ The previous value, $A_r(\text{Co})=58.93320(1)$, was based on the atomic mass determination of Wapstra and Audi.¹⁴ Historical values of $A_r(\text{Co})$ include: 1882, 59.02; 1894, 59; 1895, 59.5; 1896, 58.95; 1897, 58.93; 1898, 58.99; 1900, 59.0; 1909, 58.97; 1925, 58.94; 1961, 58.9332; 1969, 58.9332(1); and 58.93320(1).

2.10. Arsenic

The Commission has changed the recommended value for the standard atomic weight of arsenic to $A_r(\text{As}) = 74.92160(2)$, based on new atomic mass data.⁴ The previous value, $A_r(\text{As}) = 74.92159(2)$, was based on the atomic mass determination of Wapstra and Audi.¹⁴ Historical values of $A_r(\text{As})$ include: 1882, 75.09; 1894, 75.0; 1896, 75.09; 1897, 75.01; 1900, 75.0; 1910, 74.96; 1934, 74.91; 1961, 74.9216; 1969, 74.9216(1); and 1985, 74.92159(2).

2.11. Rhodium

The Commission has changed the recommended value for the standard atomic weight of rhodium to $A_r(\text{Rh}) = 102.90550(2)$, based on new atomic mass data.⁴ The previous value, $A_r(\text{Rh}) = 102.90550(3)$, was based on the atomic mass determination of Wapstra and Audi.¹⁴ Historical values of $A_r(\text{Rh})$ include: 1882, 104.29; 1894, 103; 1896, 103.01; 1900, 103.0; 1909, 102.9; 1925, 102.91; 1961, 102.905; 1969, 102.9055(1); and 1985, 102.90550(3).

2.12. Caesium

The Commission has changed the recommended value for the standard atomic weight of caesium to $A_r(\text{Cs}) = 132.90545(2)$, based on new atomic mass data.⁴ The previous value, $A_r(\text{Cs}) = 132.90543(5)$, was based on the atomic mass determination of Wapstra and Audi.¹⁴ Historical values of $A_r(\text{Cs})$ include: 1882, 132.92; 1894, 132.9; 1896, 132.89; 1900, 132.9; 1903, 133.0; 1904, 132.9; 1909, 132.81; 1934, 132.91; 1961, 132.905; 1969, 132.9055(1); 1971, 132.9054(1); and 1985, 132.90543(5).

2.13. Cerium

The Commission has changed the recommended value for the standard atomic weight of cerium to $A_r(\text{Ce}) = 140.116(1)$ based on the calibrated thermal ionization mass-spectrometric determination by Chang *et al.*¹⁵ The previous value of $A_r(\text{Ce}) = 140.115(4)$ was adopted in 1985 following the application of a new set of guidelines for assessing data.¹⁶ The new measurement was also accompanied by a limited mineral survey which showed no measurable variation in the isotopic composition of terrestrial materials. Other high precision measurements of isotopic abundances have been made on cerium since 1985 (e.g., Refs. 17 and 18), but these were not calibrated measurements. Historical values of $A_r(\text{Ce})$ include: 1882, 140.75; 1894, 140.25; 1898, 139.35; 1900, 139; 1903, 140; 1904, 140.25; 1929, 140.13; 1961, 140.12; 1969, 140.12(1); and 1985, 140.115(4).

2.14. Praseodymium

The Commission has changed the recommended value for the standard atomic weight of praseodymium to $A_r(\text{Pr}) = 140.90765(2)$, based on new atomic mass data.⁴ The previous value, $A_r(\text{Pr}) = 140.90765(3)$, was based on the atomic mass determination of Wapstra and Audi.¹⁴ Historical values

of $A_r(\text{Pr})$ include: 1894, 143.5; 1897, 143.60; 1900, 140.5; 1909, 140.6; 1916, 140.9; 1925, 140.92; 1961, 140.907; 1969, 140.9077(1); and 1985, 140.90765(3).

2.15. Europium

The Commission has changed the recommended value for the standard atomic weight of europium to $A_r(\text{Eu}) = 151.964(1)$, based on the calibrated thermal ionization mass-spectrometric determination by Chang *et al.*¹⁹ The previous value of $A_r(\text{Eu}) = 151.965(9)$ was adopted in 1985 following the application of a new set of guidelines for assessing data.¹⁶ The new measurement was also accompanied by a survey of 12 minerals and chemicals, but no variations in isotopic abundance were detected. This new value of $A_r(\text{Eu})$ has a significantly improved uncertainty. Historical values of $A_r(\text{Eu})$ include: 1901, discovered; 1907, 152.0; 1961, 151.96; 1969, 151.96(1); and 1985, 151.965(9).

2.16. Terbium

The Commission has changed the recommended value for the standard atomic weight of terbium to $A_r(\text{Tb}) = 158.92534(2)$, based on new atomic mass data.⁴ The previous value, $A_r(\text{Tb}) = 158.92534(3)$, was based on the atomic mass determination of Wapstra and Audi.¹⁴ Historical values of $A_r(\text{Tb})$ include: 1894, 160; 1907, 159.2; 1953, 158.93; 1961, 158.924; 1969, 158.9254(1); and 1985, 158.92534(3).

2.17. Holmium

The Commission has changed the recommended value for the standard atomic weight of holmium to $A_r(\text{Ho}) = 164.93032(2)$, based on new atomic mass data.⁴ The previous value, $A_r(\text{Ho}) = 164.93032(3)$, was based on the atomic mass determination of Wapstra and Audi.¹⁴ Historical values of $A_r(\text{Ho})$ include: 1913, 163.5; 1925, 163.4; 1941, 164.94; 1961, 164.930; 1969, 164.9303(1); 1971, 164.9304(1); and 1985, 164.93032(3).

2.18. Thulium

The Commission has changed the recommended value for the standard atomic weight of thulium to $A_r(\text{Tm}) = 168.93421(2)$, based on new atomic mass data.⁴ The previous value, $A_r(\text{Tm}) = 168.93421(3)$, was based on the atomic mass determination of Wapstra and Audi.¹⁴ Historical values of $A_r(\text{Tm})$ include: 1894, 170.7; 1903, 171; 1909, 168.5; 1922, 169.9; 1925, 169.4; 1953, 168.94; 1961, 168.934; 1969, 168.9342(1); and 1985, 168.93421(3).

2.19. Platinum

The Commission has changed the recommended value for the standard atomic weight of platinum to $A_r(\text{Pt}) = 195.078(2)$, based on electron impact ionization of gaseous $\text{Pt}(\text{PF}_3)_4$ and measurement of Pt^+ ions in a mass spec-

trometer by Taylor *et al.*²⁰ The previous value of $A_r(\text{Pt}) = 195.08(3)$, adopted in 1979, was based on a thermal ionization mass-spectrometric determination by White *et al.*²¹ in 1955. The uncertainty on the new atomic weight is calculated using new guidelines approved by the Commission at its meeting in 1993. This new measurement of $A_r(\text{Pt})$, although it is not a calibrated measurement, has led to a substantial improvement in the uncertainty of $A_r(\text{Pt})$. Historical values of $A_r(\text{Pt})$ include: 1882, 194.87; 1894, 195; 1896, 194.89; 1900, 194.9; 1903, 194.8; 1909, 195.0; 1911, 195.2; 1925, 195.23; 1955, 195.09; 1969, 195.09(3); and 1979, 195.08(3).

2.20. Gold

The Commission has changed the recommended value for the standard atomic weight of gold to $A_r(\text{Au}) = 196.96655(2)$, based on new atomic mass data.⁴ The previous value, $A_r(\text{Au}) = 196.96654(3)$, was based on the atomic mass determination of Wapstra and Audi.¹⁴ Historical values of $A_r(\text{Au})$ include: 1882, 196.61; 1894, 197.3; 1896, 197.24; 1897, 197.23; 1900, 197.2; 1953, 197.0; 1961, 196.967; 1969, 196.9665(1); and 1985, 196.96654(3).

2.21. Bismuth

The Commission has changed the recommended value for the standard atomic weight of bismuth to $A_r(\text{Bi}) = 208.98038(2)$, based on new atomic mass data.⁴ The previous value, $A_r(\text{Bi}) = 208.98037(3)$, was based on the atomic mass determination of Wapstra and Audi.¹⁴ Historical values of $A_r(\text{Bi})$ include: 1882, 208.00; 1894, 208.9; 1895, 208; 1896, 208.11; 1900, 208.1; 1903, 208.5; 1907, 208.0; 1922, 209.0; 1925, 209.00; 1961, 208.980; 1969, 208.9806(1); 1971, 208.9804(1); and 1985, 208.98037(3).

2.22. Potassium (footnote "g")

The Commission has removed the footnote "g" from potassium. In 1991 the Commission added the footnote "g" to potassium in Tables 1 and 2 because Hinton *et al.*²² reported isotopic abundances in naturally occurring materials outside $A_r(\text{K})$. The work of Humayun and Clayton²³ does not support the results of Hinton *et al.*, but instead indicates that isotopic fractionation in terrestrial potassium-bearing materials must be less than 0.5%.

3. Table of Standard Atomic Weights 1995

Following past practice, the Table of Standard Atomic Weights 1995 is presented both in alphabetical order by names in English of the elements (Table 1) and in the order of atomic numbers (Table 2).

The atomic weights reported in Tables 1 and 2 are for atoms in their electronic and nuclear ground states. The unified atomic mass unit (u) is equal to $1/12$ of the rest mass of the neutral atom of ^{12}C in its nuclear and electronic ground state.

The Commission wishes to emphasize the need for new precise calibrated 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.

The names and symbols for those elements with atomic numbers 104–111 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.²⁴ 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,	0 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.

For atomic-weight values the uncertainties are routinely called "expanded uncertainties" with the symbol U in italic font. The symbol $U[A_r(\text{E})]$ is an acceptable alternative to U . In past reports the Commission has referred to relative uncertainty, which is the magnitude of the uncertainty divided by $A_r(\text{E})$. Therefore, relative expanded uncertainty is indicated alternatively as $U/A_r(\text{E})$ or $U[A_r(\text{E})]/A_r(\text{E})$.

Figure 1 shows the changes in the relative uncertainties, $U[A_r(\text{E})]/A_r(\text{E})$, of the recommended standard atomic weights of the elements from 1969 to 1995. Arrowheads mark the 1995 relative uncertainties. The base of each arrow marks the position of the relative uncertainty estimate in 1969. The change factor is represented by the length of an arrow and equals the ratio of the relative uncertainty at the base to that at the tip of the arrow. The symbol \circ indicates no change since 1969, corresponding to an "improvement factor" of 1—this applies to fourteen elements. Only one element (Xe) has an "improvement factor" less than 1, indicating a loss in the estimate of relative uncertainty.

4. Reporting Relative Abundance Data for Lithium Isotopes

Relative lithium isotope-ratio data in geochemical and environmental studies are commonly reported as $\delta^7\text{Li}$ values in terms of $^7\text{Li}/^6\text{Li}$ abundance ratios. It was brought to the attention of the Commission that some laboratories are reporting $\delta^6\text{Li}$ values by using $^6\text{Li}/^7\text{Li}$ abundance ratios. This is confusing because: (i) $\delta^7\text{Li}$ values are opposite in sign to $\delta^6\text{Li}$ values; (ii) the absolute values of $\delta^7\text{Li}$ and $\delta^6\text{Li}$ are not equal; and (iii) samples with more positive δ values are commonly thought of as being more dense or "heavier," but samples with more positive $\delta^6\text{Li}$ values are less dense. Therefore, to eliminate possible confusion in the reporting of lithium isotope-ratio data, the Commission recommended that relative lithium isotopic measurements of all substances be expressed as $\delta^7\text{Li}$ values in terms of $^7\text{Li}/^6\text{Li}$ abundance

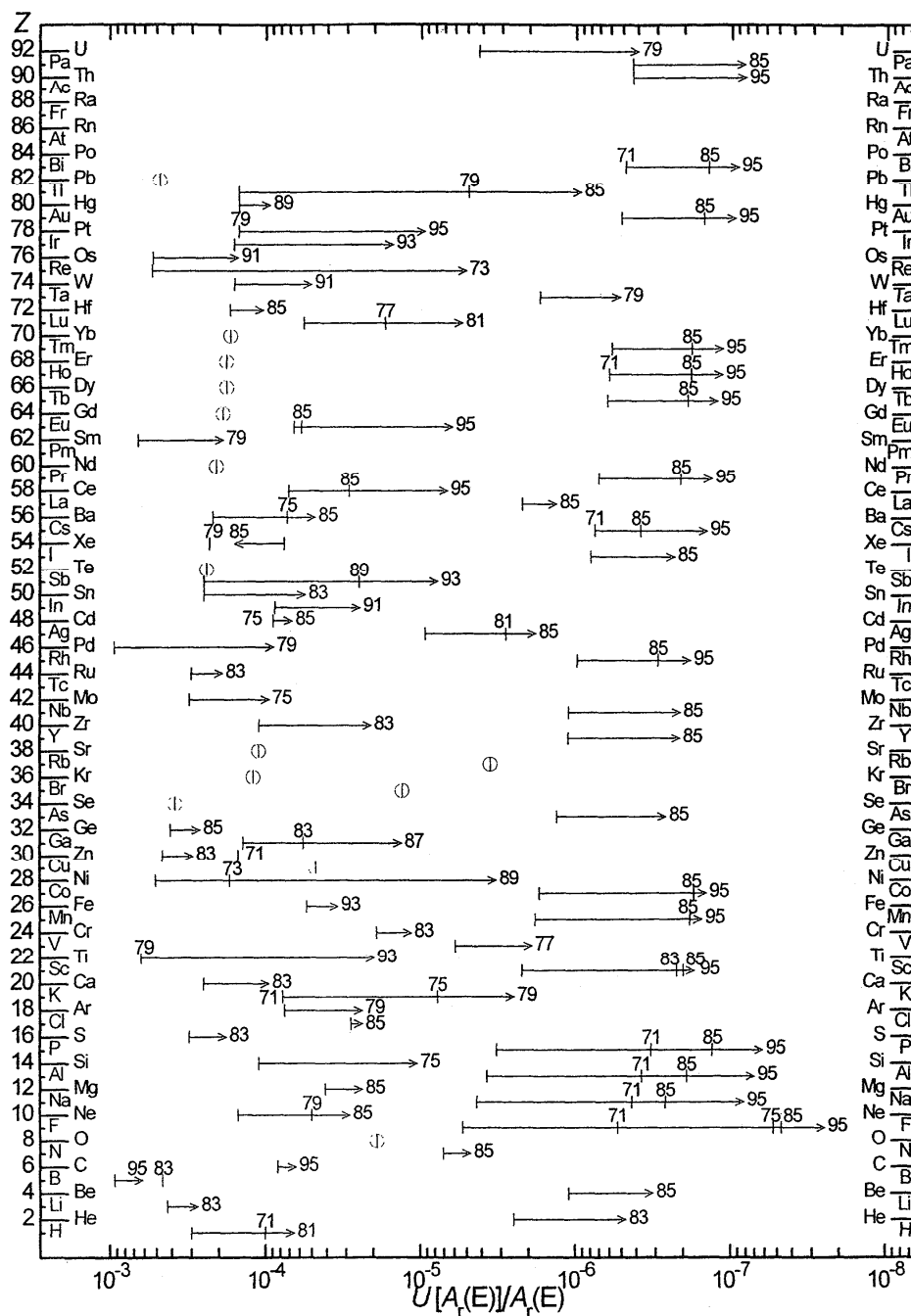


FIG. 1. Changes in relative uncertainty, $U[A_r(E)]/A_r(E)$, of the IUPAC-recommended atomic weights of the elements between 1969 and 1995 (Ref. 25). The symbol \circ indicates no change. Number where given is last two digits of the year of the last change. Intermediate changes are indicated by the symbol $|$ and the year of the change.

ratios relative to the internationally distributed lithium carbonate isotopic reference material L-SVEC. Reporting of $\delta^6\text{Li}$ values, expressed in terms of $^6\text{Li}/^7\text{Li}$ ratios, should be discontinued. A separate publication was prepared on this topic for publication in *Pure and Applied Chemistry*.²⁶

5. Reporting Relative Abundance Data for Sulfur Isotopes

Relative sulfur isotope-ratio data in geochemical and environmental studies are traditionally reported as $\delta^{34}\text{S}$ values

in parts per thousand (‰ or per mill) difference from a standard. The standard may be real or hypothetical. In the latter case, it is defined in terms of an existing internationally distributed reference material. For several decades troilite (FeS) from the Cañon Diablo meteorite, CDT, has been employed as the standard because it was thought to be isotopically homogeneous.²⁷

At the "Consultants' Meeting on Stable Isotope Standards and Intercomparison Materials" sponsored by the International Atomic Energy Agency and held in Vienna in December 1993, it was noted that $\delta^{34}\text{S}$ values reported for SF_6 prepared from the reference material IAEA-S-1 silver sulfide (previously called IAEA-NZ1) ranged from about -0.35‰ to -0.26‰ . Recently, high precision sulfur isotope-ratio analyses using SF_6 , have established a range of $\delta^{34}\text{S}$ values for CDT of 0.4‰ with an analytical uncertainty of 0.05‰ .²⁸ This group recommended²⁹ that a VCDT scale be established and defined by assigning a $\delta^{34}\text{S}$ value of -0.3‰ exactly (relative to VCDT) to IAEA-S-1.

To eliminate possible confusion in the reporting of sulfur isotope-ratio data, the Commission on Atomic Weights and Isotopic Abundances supports the IAEA Consultants and recommends that relative $^{34}\text{S}/^{32}\text{S}$ ratios of all sulfur-bearing substances be expressed on the VCDT scale, defined by assigning a $\delta^{34}\text{S}$ value of -0.3‰ exactly (relative to VCDT) to the silver sulfide reference material IAEA-S-1. Reporting of sulfur isotope-ratio analyses relative to CDT should be discontinued. A separate publication was prepared on this topic for publication in *Pure and Applied Chemistry*.³⁰

6. Reporting Relative Abundance Data for Stable Hydrogen, Carbon, and Oxygen Isotopes

The Commission made recommendations on the reporting of stable hydrogen, carbon, and oxygen isotope-ratio data at the last General Assembly.^{2,31} In past guidelines the Commission has recommended that hydrogen and oxygen isotopic data be expressed on scales normalized using the water reference materials VSMOW and SLAP. It has come to the attention of the Commission that $\delta^{18}\text{O}$ values of some oxygen-bearing materials, such as oxides, silicates, organic material, and gaseous oxygen, cannot easily be expressed on a scale normalized using water reference materials in some laboratories because the capability to analyze water samples does not exist in these laboratories. In such cases the Commission recommends that the author's measured $\delta^{18}\text{O}$ of NBS 28 quartz, NBS 30 biotite, NBS 127 barium sulfate, or other internationally distributed reference material should be reported, as appropriate to the analytical method.

Isotopic δ values are determined from isotope-ratio measurements of a sample and a standard. The standard may be real or hypothetical. In the former case it is a well characterized, homogeneous, internationally distributed reference material. In the latter case it is defined in terms of (algebraically related to) a well characterized, homogeneous, internationally distributed reference material. For hydrogen and oxygen,

VSMOW reference water fulfills these requirements. Standard Mean Ocean Water (SMOW) does not.³¹ SMOW is neither distributed internationally nor algebraically related to a well characterized reference material. Thus, the Commission, following the lead of the International Atomic Energy Agency several years earlier,³² recommended that $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values of all substances should be expressed relative to VSMOW.

The aim of the Commission is to provide a mechanism whereby isotopic analysis of the same homogeneous sample reported from different credible laboratories should show the same δ value within the uncertainty of the measurements. This mechanism consists of a set of guidelines that is Appendix A, titled "Manuscript guidelines for the reporting of stable hydrogen, carbon, and oxygen isotope-ratio data."

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

The Commission on Atomic Weights and Isotopic Abundances as in previous years publishes a table of relative atomic masses and half-lives of selected radionuclides for elements without a stable nuclide (see Table 3). 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 to 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." Various criteria such as "longest half-life," "production in quantity," "used commercially," etc., have been applied in the Commission's choice. The relative atomic masses are derived from the atomic masses (in u) recommended by Audi and Wapstra.⁴ The half-lives listed are those provided by Holden.³³⁻³⁶

8. Nonterrestrial Data

8.1. Introduction

The exploration of our solar system by analyses of meteorites and interplanetary dust particles as well as the use of space vehicles has enabled a large number of isotopic abundance measurements of the elements in extraterrestrial materials and sources to be performed. Furthermore, isotopic abundance data are obtained from stellar objects using ground-based astronomical observations. Many elements present in these extraterrestrial materials have different isotopic compositions than those of terrestrial matter, and their magnitudes often exceed by far the effects observed by natural isotopic fractionation on earth. These observations are explained by a number of different processes, such as nuclear reactions or radioactive decay of now extinct nuclides, or as products of individual stages of nuclear synthesis. A summary of these processes and sources of materials with different isotopic compositions of elements was given in an earlier report.²

TABLE 3. Relative atomic masses and half-lives of selected radionuclides

Atomic Number	Name	Symbol	Mass Number	Relative Atomic Mass	Half-Life and Uncertainty	Unit ^a
43	Technetium	Tc	97	96.9064	$2.6 \pm 0.4 \times 10^6$	a
			98	97.9072	$4.2 \pm 0.3 \times 10^6$	a
			99	98.9063	$2.1 \pm 0.3 \times 10^5$	a
61	Promethium	Pm	145	144.9127	17.7 ± 0.4	a
			147	146.9151	2.623 ± 0.003	a
84	Polonium	Po	209	208.9824	102 ± 5	a
			210	209.9828	138.4 ± 0.1	d
85	Astatine	At	210	209.9871	8.1 ± 0.4	h
			211	210.9875	7.21 ± 0.01	h
86	Radon	Rn	211	210.9906	14.6 ± 0.2	h
			220	220.0114	55.6 ± 0.1	s
			222	222.0176	3.823 ± 0.004	d
87	Francium	Fr	223	223.0197	22.0 ± 0.1	min
88	Radium	Ra	223	223.0185	11.43 ± 0.01	d
			224	224.0202	3.66 ± 0.02	d
			226	226.0254	1599 ± 4	a
			228	228.0311	5.75 ± 0.03	a
89	Actinium	Ac	227	227.0277	21.77 ± 0.02	a
90	Thorium	Th	230	230.0331	$7.54 \pm 0.03 \times 10^4$	a
			232	232.0380	$1.40 \pm 0.01 \times 10^{10}$	a
91	Protactinium	Pa	231	231.0359	$3.25 \pm 0.01 \times 10^4$	a
92	Uranium	U	233	233.0396	$1.592 \pm 0.002 \times 10^5$	a
			234	234.0409	$2.455 \pm 0.006 \times 10^5$	a
			235	235.0439	$7.04 \pm 0.01 \times 10^8$	a
			236	236.0456	$2.342 \pm 0.004 \times 10^7$	a
			238	238.0508	$4.47 \pm 0.02 \times 10^9$	a
93	Neptunium	Np	237	237.0482	$2.14 \pm 0.01 \times 10^6$	a
			239	239.0529	2.355 ± 0.006	d
94	Plutonium	Pu	238	238.0496	87.7 ± 0.01	a
			239	239.0522	$2.41 \pm 0.003 \times 10^4$	a
			240	240.0538	$6.56 \pm 0.003 \times 10^3$	a
			241	241.0568	14.4 ± 0.1	a
			242	242.0587	$3.75 \pm 0.02 \times 10^5$	a
95	Americium	Am	244	244.0642	$8.00 \pm 0.09 \times 10^7$	a
			241	241.0568	432.7 ± 0.6	a
			243	243.0614	$7.37 \pm 0.2 \times 10^3$	a
96	Curium	Cm	243	243.0614	29.1 ± 0.1	a
			244	244.0627	18.1 ± 0.1	a
			245	245.0655	$8.48 \pm 0.06 \times 10^3$	a
			246	246.0672	$4.76 \pm 0.04 \times 10^3$	a
			247	247.0703	$1.56 \pm 0.05 \times 10^7$	a
			248	248.0723	$3.48 \pm 0.06 \times 10^5$	a
97	Berkelium	Bk	247	247.0703	$1.4 \pm 0.3 \times 10^3$	a
			249	249.0750	$3.20 \pm 0.06 \times 10^2$	d
			249	249.0748	351 ± 2	a
98	Californium	Cf	250	250.0764	13.1 ± 0.1	a
			251	251.0796	$9.0 \pm 0.5 \times 10^2$	a
			252	252.0816	2.64 ± 0.01	a
			252	252.0830	472 ± 2	d
100	Einsteinium	Es	252	252.0830	472 ± 2	d
100	Fermium	Fm	257	257.0951	100.5 ± 0.2	d
101	Mendelevium	Md	256	256.0941	78 ± 2	min
			258	258.0984	51.5 ± 0.3	d
102	Nobelium	No	259	259.1011	58 ± 5	min
103	Lawrencium	Lr	262	262.110	3.6 ± 0.3	h
104	Unnilquadium	Unq	261	261.1089	1.1 ± 0.2	min
105	Unnilpentium	Unp	262	262.1144	34 ± 5	s
106	Unnilhexium	Unh	263	263.1186	0.8 ± 0.2	s
107	Unnilseptium	Uns	264	264.12	0.44^b	s
108	Unniloctium	Uno	265	265.1306	$0.002^{b,c}$	s
109	Unnilennium	Une	268		$0.07^{b,c}$	s
110	Ununnilium	Uun	269		$0.17^{b,c}$	ms
111	Ununium	Uuu	272		$1.5^{b,c}$	ms

^aa=year; d=day; h=hour; min=minute; s=second; ms=millisecond. Names of elements with atomic number 104–111 are temporary.

^bThe uncertainties of these elements are unsymmetric.

^cThe value given is determined from only a few decays.

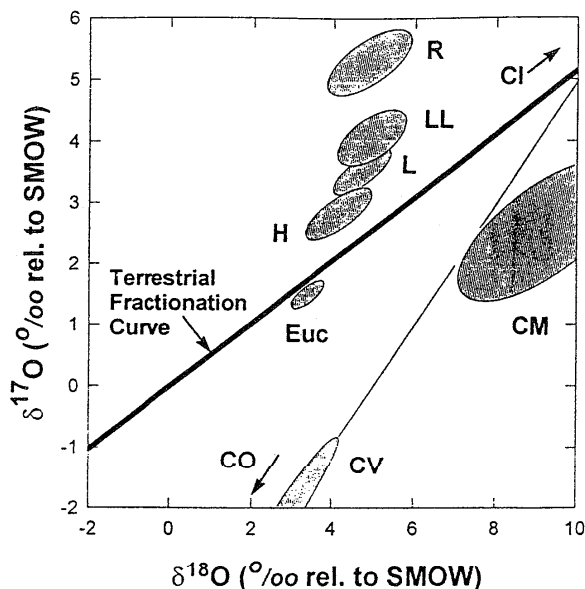


FIG. 2. The isotopic composition of oxygen in selected meteorites of different types (ordinary chondrites: H, L, LL, and R, carbonaceous chondrites: CI, CM, CO, and CV; achondrites: Euc). Shown also is the terrestrial isotopic fractionation curve (mass dependent fractionation) and a trend line observed for anhydrous minerals in carbonaceous chondrites.

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 the chemical analysis of non-terrestrial samples should exercise caution when the isotopic composition or the atomic weight of a non-terrestrial sample is required.

The Commission does not attempt to systematically review the literature on the isotopic composition of non-terrestrial materials in this article, but some examples of isotopic variations have been given in the past. Those interested in more comprehensive reviews, including specific data and additional references, should refer to Shima^{37,38} and Shima and Ebihara.³⁹ A more detailed report of published measurements during the past 10 years is in preparation.

Here we concentrate on isotopic data of oxygen because this element has properties that are significant in geochemistry and cosmochemistry: Oxygen is a major constituent of most rock-forming minerals, its three stable isotopes are formed in different nucleosynthetic processes, and it occurs in two cosmochemical reservoirs, as a gas (mostly CO and H₂O) and as a solid (oxides and silicates). The last property allows oxygen to avoid isotopic homogenization in the interstellar medium and the early solar system.

8.2. Observations

The isotopic composition of oxygen in planetary bodies of our solar system is not uniform. Figure 2 shows the result of analyses of different meteorite classes which are specimens

from individual bodies (Ref. 40 and other references therein). Shown are δ values (in ‰), where $\delta^{17}\text{O}$ and $\delta^{18}\text{O}$ are defined, respectively, by

$$\delta^{17}\text{O} = [({}^{17}\text{O}/{}^{16}\text{O})_s / ({}^{17}\text{O}/{}^{16}\text{O})_{\text{SMOW}} - 1] \cdot 1000,$$

and

$$\delta^{18}\text{O} = [({}^{18}\text{O}/{}^{16}\text{O})_s / ({}^{18}\text{O}/{}^{16}\text{O})_{\text{SMOW}} - 1] \cdot 1000,$$

where s is an extraterrestrial sample and SMOW is standard mean ocean water.⁴¹

All terrestrial samples (as well as those from the moon) plot along the terrestrial fractionation curve (TFC) in Fig. 2. The observed range of terrestrial $\delta^{18}\text{O}$ values is between -62‰ and $+73.4\text{‰}$.⁴² The TFC, approximated by the equation $\delta^{17}\text{O} = 0.52\delta^{18}\text{O}$, is the result of mass dependent fractionation. Meteorites, however, exhibit δ values divergent from this line. In addition, anhydrous minerals of primitive meteorites (carbonaceous chondrites) show a trend between $\delta^{17}\text{O}$ and $\delta^{18}\text{O}$ that deviates from the TFC; instead of a slope of ~ 0.5 , this trend line has a slope of about ~ 1 , indicating the existence of an oxygen reservoir distinct from the terrestrial oxygen reservoir.⁴³

This observation that the isotopic composition of oxygen in extraterrestrial samples does not follow the TFC implies that during formation of individual planetary bodies the material of the solar nebula was not isotopically homogeneous and thus not well mixed or uniform. Two scenarios have been proposed to explain different isotopic compositions of oxygen within the early solar system: (1) Contributions of explosive stellar nucleosynthesis—mainly ${}^{16}\text{O}$ —are added in different proportions to the material that formed planetary bodies, and (2) non-mass dependent fractionation processes based on molecular symmetry involving the formation of O₃ (Refs. 44 and 45 and references therein). Which process or processes responsible for the variation of oxygen isotopic compositions in different solar system materials remains unknown at present.

Table 4 gives examples of measurements of the isotopic composition of oxygen in selected solar system bodies as well as from astronomical objects or materials. For comparison, a mean solar value, a representative terrestrial material (VSMOW reference water) and the oxygen isotopic composition of small oxide grains (mainly Al₂O₃) separated from meteorites is shown.

Stellar oxygen shows a wide variation in isotopic composition (Fig. 3). This is due to the relative production and destruction of all oxygen isotopes in stellar environments. During main-sequence evolution of red giant stars oxygen from the interior is brought up and mixed with surface material. This shows up as highly variable oxygen isotopic ratios as measured in the outer envelopes of stars. It is interesting to note that some oxide grains separated from meteorites show similar trends, indicating the possibility that this material represents stellar ejecta that were not homogenized with the solar nebula (Refs. 46 and 47).

TABLE 4. Examples of measurements of oxygen isotopic compositions in extraterrestrial materials

Source	$^{16}\text{O}/^{17}\text{O}$	$^{16}\text{O}/^{18}\text{O}$	Method	Refs.
Venus		500(25)	Spacecraft (Pioneer V)	48
		500(80)	Ground-based Telescope	49
Mars				
Atmosphere		480(20)	Spacecraft (Viking 1)	50
Atmosphere		500(20)	Spacecraft (Viking 2)	51
Rocks (SNC Meteorites)	2673(2)	496.3(5)	Terr. Mass Spectrometer	52
Comet Halley				
H_3O^+ ions		469(40)	Spacecraft Giotto	53
H_2O		493(36)	Spacecraft Giotto	53
Interplanetary Dust Particles (IDP's)				
W7017 1A55	2514(4)	478.2(2)	Ion Probe	54
W7017 1A114a	2581(10)	496(2)	Ion Probe	54
Deep Sea Spherules	2600	487	Terr. Mass Spectrometer	55
Sun				
Photosphere	2625	489		56
Solar Energetic Particles	>417	526(390)	Spacecraft ISEE-3	57
Stars				
Red Giants				
β And	155(50)	425(150)	CO IR Spectr. ($5\mu\text{m}$)	58
α Boo	1110(400)	550(150)	CO IR Spectr. ($5\mu\text{m}$)	58
Interstellar Medium				
Galactic disk	2460(750)	675(200)	Radio Obs. of CO	59
Galactic center	890(370)	250(100)	Radio Obs. of CO	59
Galactic Cosmic Rays				
~ 0.1 to 0.3 GeV/amu	59(14)	53(6)	Spacecraft ISEE-3	60
For Comparison "Solar"	2625	500		61
VSMOW	2682(30)	498.7(2)	Terr. Mass Spectrometer	5
Selected Oxide Grains in Meteorites	385-1030	855-2330	Ion Probe	47

9. Other Projects of the Commission

The Subcommittee for Natural Isotopic Fractionation presented a report which was discussed and modified during the Subcommittee's meeting in Geel, Belgium, prior to the IUPAC General Assembly in Guildford. The Subcommittee will submit a report for *Pure & Appl. Chem.*, consisting primarily of plots (where possible) that show the variation in natural isotopic abundance, atomic weights, and standard δ values (where possible), including data for the elements H, Li, B, C, N, O, Si, S, Cl, Fe, Se, Pd, and Te. A companion report that is expected to be longer will include numerous references and will be published as a *U.S. Geological Survey Open-File Report*.

In 1989 it was recognized by the Commission that apart from those elements for which there is a "calibrated measurement" or which have an atomic number less than 19,

uncertainties calculated using the current guidelines often significantly underestimate what is considered by the Commission to be appropriate. Therefore it seemed desirable to incorporate into these guidelines some of the other factors the Commission routinely incorporated into these calculations. These guidelines, as well as recent computational procedures,⁶² will be used for the preparation of "Isotopic Compositions of the Elements 1995." J. de Laeter has incorporated these guidelines into the *Commission's Technical Handbook*, which he plans to complete following the 38th General Assembly.

The Commission has noted with concern (Ref. 2) the commercial dissemination of significant quantities of laboratory reagents that have been artificially depleted in ^6Li , resulting in labels on containers of reagents with incorrect atomic-weight values, which may actually range from 6.94 to 6.99. R. D. Vocke, K. J. R. Rosman, K. G. Heumann, Y. Xiao, and M. Ebihara (or M. Shima) decided to prepare a report on

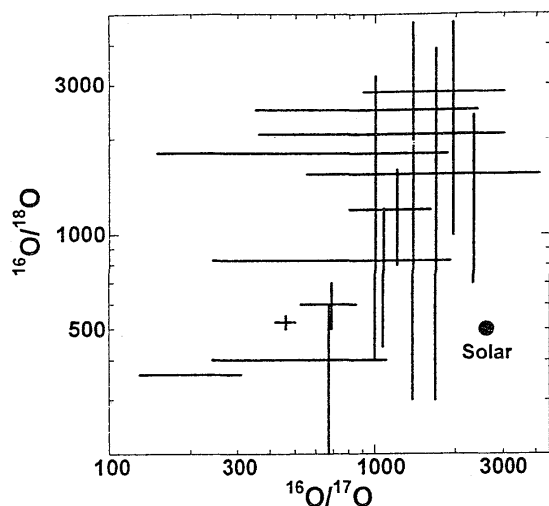


Fig. 3. Range of oxygen isotopic compositions in stars of different classes that were measured by spectroscopic methods. The wide variation within stars is caused by production and destruction of ^{17}O and ^{18}O during individual stages in their evolution that depends on their mass. Indicated also the mean value of solar system material ("solar").

variation in isotopic composition of lithium-bearing reagents and will submit it to *Pure and Applied Chemistry* during 1996.

Isotopic reference materials are becoming increasingly important in environmental, hydrological, and geochemical studies, as well as in a host of other areas. R. D. Vocke, J. K. Böhlke, and P. De Bièvre decided to prepared a condensed summary of available isotopic reference materials and submit it for publication in *Pure and Applied Chemistry* in 1996.

It was decided that an informal group consisting of R. Loss (chairman), R. D. Vocke, and P. Taylor investigate atomic-weight and isotopic-abundance data on the Internet and report to the Commission in 1996.

In a project related to Commission activities, P. Taylor advised the Commission that the update to the "Brown" Book *Isotopic Abundances and Atomic Weights of the Elements* (Ref. 63) will contain data up to August 1995 and will be submitted for publication to the *Journal of Physical and Chemical Reference Data*. It was agreed that authorship should reflect IUPAC input.

It was noted with sadness that a previous esteemed member of the Commission, Professor A. O. Nier, passed away during the past two years. Professor Nier served as a member of this Commission from 1949 to 1961 and was a major contributor in the determination of atomic weights and isotopic abundances. He was responsible for numerous developments in mass spectrometry and related instrumentation during the last half century.

During the last two years, H. S. Peiser, T. Murphy, and T. R. Coplen have provided assistance in organizing documents at the *Commission's Archive* at the Chemical Heritage Foundation (previously known as the Arnold and Mabel Beckman Center for the History of Chemistry) in Philadelphia. This

archive now contains documents (and some photographs) by Aston, Baxter, Soddy, Curie, Hahn, Richards, and others dating from about 1827.

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11. Appendix: Guidelines for the Reporting of Stable Hydrogen, Carbon, and Oxygen Isotope-Ratio Data

Following recommendations (Refs. 1 and 2) and discussions of the Commission on Atomic Weights and Isotopic Abundances of the International Union of Pure and Applied Chemistry at the 38th General Assembly in 1995 in Guildford, United Kingdom, authors are requested to report stable hydrogen, carbon, and oxygen isotopic data as follows, stating the analytical method(s) employed.

Hydrogen

Water. Relative $^2\text{H}/^1\text{H}$ values ($\delta^2\text{H}$) of water should be expressed in ‰ relative to VSMOW water (0‰) on a scale normalized such that the $\delta^2\text{H}$ of SLAP water is $-428‰$ exactly and so stated in author's report.

Other substances. Relative $^2\text{H}/^1\text{H}$ values ($\delta^2\text{H}$) of other substances should be expressed in ‰ relative to VSMOW water (0‰) on a scale normalized such that the $\delta^2\text{H}$ of SLAP water is $-428‰$ exactly and so stated in author's report. It is recommended that the author's measured $\delta^2\text{H}$ of NBS 22 oil, NBS 30 biotite, or other internationally distributed reference material be reported, as appropriate to the analytical method.

Carbon

Carbonate. Relative $^{13}\text{C}/^{12}\text{C}$ values ($\delta^{13}\text{C}$) of carbonate should be expressed in ‰ relative to VPDB by assigning a value of $+1.95‰$ exactly to NBS 19 calcite. *Other substances.* Relative $^{13}\text{C}/^{12}\text{C}$ values ($\delta^{13}\text{C}$) of other substances should be expressed in ‰ relative to VPDB by assigning a value of $+1.95‰$ exactly to NBS 19 calcite. It is recommended that the author's measured $\delta^{13}\text{C}$ of NBS 22 oil, USGS24 graphite, or other internationally distributed reference material be reported, as appropriate to the analytical method.

Oxygen

Water. Relative $^{18}\text{O}/^{16}\text{O}$ values ($\delta^{18}\text{O}$) of water should be expressed in ‰ relative to VSMOW water (0‰) on a scale normalized such that the $\delta^{18}\text{O}$ of SLAP water is $-55.5‰$ exactly and so stated in author's report.

Carbonate. Relative $^{18}\text{O}/^{16}\text{O}$ values ($\delta^{18}\text{O}$) of carbonate should be expressed in ‰ (on a scale normalized such that the $\delta^{18}\text{O}$ of SLAP water is $-55.5‰$ exactly relative to VSMOW water, and so stated in author's report) either

- (i) relative to VPDB on a scale such that the $\delta^{18}\text{O}$ of NBS 19 calcite is $-2.2‰$ exactly, stating the value of the oxygen isotopic fractionation factor used to calculate the $\delta^{18}\text{O}$ of the carbonate sample and NBS 19 if they are not identical, or
- (ii) relative to VSMOW water (0‰), stating the values of all isotopic fractionation factors upon which the $\delta^{18}\text{O}$ measurement depends.

If $\delta^{18}\text{O}$ values cannot be reported on a normalized scale (perhaps because of the inability to measure water samples), the author's measured $\delta^{18}\text{O}$ of NBS 18 carbonatite or other internationally distributed reference material should be reported, as appropriate.

Other substances (oxygen gas, sulfate, silicate, phosphate, etc.). Relative $^{18}\text{O}/^{16}\text{O}$ values ($\delta^{18}\text{O}$) of all other oxygen-bearing substances should be expressed in ‰ relative to VSMOW water (0‰) on a scale normalized such that the $\delta^{18}\text{O}$ of SLAP water is $-55.5‰$ exactly and so stated in author's report, stating either

- (i) the values of all isotopic fractionation factors upon which a $\delta^{18}\text{O}$ value depends, or
- (ii) the author's measured $\delta^{18}\text{O}$ of NBS 28 quartz,

NBS 30 biotite, NBS 127 barium sulfate, or other internationally distributed reference material.

If $\delta^{18}\text{O}$ values cannot be reported on a normalized scale (perhaps because of the inability to measure water samples), the author's measured $\delta^{18}\text{O}$ of NBS28 quartz, another internationally distributed reference material, or atmospheric oxygen should be reported, as appropriate to the analytical method.

11.1. Sources of Isotopic Reference Materials

National Institute of Standards
and Technology

Standard Reference Materials Program
Room 204, Building 202
Gaithersburg, Maryland 20899-0001
USA

Phone: 301 975 6776

Fax: 301 948 3730

e-mail: SRMINFO@enh.nist.gov

International Atomic Energy
Agency

Section of Isotope Hydrology
Wagramerstr. 5, P.O. Box 100
A-1400 Vienna
Austria

Fax: 43 1 20607

Phone: 43 1 206021735

e-mail: IAEO@iaea1.iaea.or.at

TABLE 5. Selected reference materials
(Use the name of the reference materials for IAEA orders.)

Name	Substance	NIST order number
VSMOW	water	RM 8535
SLAP	water	RM 8537
NBS 18	carbonatite	RM 8543
NBS 19	calcite	RM 8544
NBS 22	oil	RM 8539
USGS24	graphite	RM 8541
NBS 28	quartz	RM 8546
NBS 30	biotite	RM 8538
NBS 127	barium sulfate	RM 8557

11.2. References for Appendix

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