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INTERNATIONAL UNION OF PURE AND APPLIED CHEMISTRY

INORGANIC CHEMISTRY DIVISION
COMMISSION ON ATOMIC WEIGHTS AND ISOTOPIC ABUNDANCES*

ATOMIC WEIGHTS OF THE ELEMENTS 1991

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Atomic weights of the elements 1991

Abstract — The biennial review of atomic weight, A_r(E), determinations and other cognate data has resulted in changes for the standard atomic weight of indium from 114.82±0.01 to 114.818±0.003, for tungsten from 183.85±0.03 to 183.84±0.01 and for osmium from 190.2±0.1 to 190.23±0.03 due to new high precision measurements. Recent investigations on silicon and antimony confirmed the presently accepted A_r values. The footnote "g" was added for carbon and potassium because it has come to the notice of the Commission that isotope abundance variations have been found in geological specimens in which these elements have an isotopic composition outside the limits for normal material. The value of 272 is recommended for the $^{14}N/^{15}N$ ratio of N_2 in air for the calculation of atom percent ^{15}N from measured $\delta^{15}N$ values. Because many elements have a different isotopic composition in non-terrestrial materials, recent data on non-terrestrial material are included in this report for the information of the interested scientific community.

INTRODUCTION

The Commission on Atomic Weights and Isotopic Abundances met under the chairmanship of Professor J. R. De Laeter from 8th–10th August, 1991, during the 36th IUPAC General Assembly in Hamburg, Federal Republic of Germany. The Commission decided to publish the report "Atomic Weights of the Elements 1991" as presented here.

The Commission has reviewed 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).

COMMENTS ON SOME ATOMIC WEIGHTS AND ANNOTATIONS

Indium

The Commission has changed the recommended value for the atomic weight of indium to A_r(In) = 114.818(3) based on recent high precision measurements of the metal and its compounds by Chang and Xiao (ref. 3). The previous value, A_r(In) = 114.82(1), was based on measurements by White *et al.* (ref. 4). The new measurement represents a significant improvement in the precision of the atomic weight and is in agreement with the previous value. The new value also agrees with the value reported by Saito *et al.* in 1987 (ref. 5).

Tungsten (Wolfram)

The Commission has changed the recommended value for the atomic weight of tungsten to A_r(W) = 183.84(1) based on high precision measurements with negative thermal ionization mass spectrometry by Völkening *et al.* (ref. 6). The previous value of A_r(W) = 183.85(3) was assigned in 1969 (ref. 7), based on the average of the available mass spectrometric measurements. At this time there was some concern that earlier chemical determinations gave a significantly higher value, *e.g.*, A_r(W) = 183.90 (ref. 8). However, the present value confirms the mass spectrometric measurements.

Osmium

The atomic weight of osmium, $A_r(Os)$ = 190.2(1), was one of the most poorly known. This value was based on a measurement made by Nier (ref. 9) in 1937. Recent measurements by Völkening *et al.* (ref. 10) using negative thermal ionization mass spectrometry have yielded an atomic weight having a significantly improved precision, $A_r(Os)$ = 190.23(3), which is in agreement with the value of Nier.

It should be noted that ^{187}Os is the product of the radioactive decay of ^{187}Re; therefore, the abundance of ^{187}Os will vary in nature, leading to corresponding changes in the atomic weight.

Silicon

Recent work has produced new calibrated atomic weights for silicon reference materials through the measurement of absolute isotopic compositions for these materials (ref. 11). CBNM-IRM 017, silicon, was found to be $A_r(Si)$ = 28.08540(19) and CBNM-IRM 018, silicon dioxide, was found to be $A_r(Si)$ = 28.08565(19). This work confirms the presently accepted value, $A_r(Si)$ = 28.0855(3), but the range in isotopic compositions of normal terrestrial materials prevents a more precise standard $A_r(Si)$ being given.

Antimony

In 1989 the Commission changed the atomic weight of antimony to $A_r(Sb)$ = 121.757(3) based on a measurement by De Laeter and Hosie (ref. 12). Other high quality measurements by Chang *et al.* (ref. 13) and by Wachsmann and Heumann (ref. 14) have since become available which support the present value.

Carbon (footnote "g")

In their calibrated measurement of the atomic weight of carbon, Chang and Li (ref. 15) have, for the first time, determined the isotopic abundance of NBS-19 (TS limestone), upon which the stable isotope ratio scale is based. They found NBS-19 to contain 1.1078(28) atom percent ^{13}C. Their $^{13}C/^{12}C$ values of NBS-18 (carbonatite) and NBS-20 (Solenhofen limestone) are in good agreement with relative isotope ratio measurements.

Potassium (footnote "g")

During the last two years it has come to the notice of the Commission that isotope abundance variations have been found in terrestrial minerals (ref. 16). The present value for the atomic weight of potassium is based on a fully calibrated isotope abundance measurement made by Garner *et al.* (ref. 17). A "g" has been added to this element since the atomic weight of some minerals lies outside of the range indicated by the uncertainty on the accepted atomic weight.

Nitrogen ($^{15}N/^{14}N$ ratio of N_2 in air)

In 1958 Junk and Svec (ref. 18) determined $^{14}N/^{15}N = 272.0 \pm 0.3$ in atmospheric nitrogen. The Commission's 1989 Report entitled "Isotopic Compositions of the Elements 1989" (ref. 19) rounds these data and reports 99.634 ± 0.009 and 0.366 ± 0.009 atom percent for ^{14}N and ^{15}N, respectively. On this basis some workers have used $^{14}N/^{15}N = 272.22$ despite the fact that five significant figures are not justified. The Commission, therefore, recommends that the value of 272 be employed for the $^{14}N/^{15}N$ ratio of nitrogen in air for the calculation of atom percent ^{15}N from measured $\delta^{15}N$ values. A separate publication was prepared on this topic which will be published in *Pure and Applied Chemistry* (ref. 20).

THE TABLE OF STANDARD ATOMIC WEIGHTS 1991

Following past practice the Table of Standard Atomic Weights 1991 is presented both in alphabetical order by names in English of the elements (Table 1) and in the order of atomic number (Table 2).

TABLE 1. Standard atomic weights 1991

[In alphabetical order; 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 (in parentheses, following the last significant figure to which they are attributed) apply to elements as they are known to exist on earth.

Alphabetical order in English

Name	Symbol	Atomic Number	Atomic Weight	Footnotes
Actinium*	Ac	89		
Aluminium	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)	g 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	114.818(3)	
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
Neptunium*	Np	93		
Nickel	Ni	28	58.6934(2)	
Niobium	Nb	41	92.90638(2)	

TABLE 1. Standard atomic weights 1991 (contd)

Name	Symbol	Atomic Number	Atomic Weight	Footnotes
Nitrogen	N	7	14.00674(7)	g r
Nobelium*	No	102		
Osmium	Os	76	190.23(3)	g
Oxygen	O	8	15.9994(3)	g r
Palladium	Pd	46	106.42(1)	g
Phosphorus	P	15	30.973762(4)	
Platinum	Pt	78	195.08(3)	
Plutonium*	Pu	94		
Polonium*	Po	84		
Potassium (Kalium)	K	19	39.0983(1)	g
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	183.84(1)	
Unnilennium*	Une	109		
Unnilhexium*	Unh	106		
Unniloctium*	Uno	108		
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 stated uncertainty.

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

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

TABLE 2. Standard atomic weights 1991

[In order of atomic number; 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 (in parentheses, following the last significant figure to which they are attributed) apply to elements as they are known to exist on earth.

Order of atomic number

Atomic Number	Name	Symbol	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)	g 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	Aluminium	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)	g
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	114.818(3)	
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)	

TABLE 2. Standard atomic weights 1991 (contd)

Atomic Number	Name	Symbol	Atomic Weight	Footnotes
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
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	183.84(1)	
75	Rhenium	Re	186.207(1)	
76	Osmium	Os	190.23(3)	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		
108	Unniloctium*	Uno		
109	Unnilennium*	Une		

*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 stated uncertainty.

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

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

The names and symbols for those elements with atomic numbers 104 to 109 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. 21). 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.

Figure 1 shows the changes in the relative uncertainties, $U_r(E)$, of the recommended standard atomic weights of the elements from 1969 to 1991. The length of each arrow equals the $U_r(E)$ improvement factor (deterioration only for Xe). Although 66 elements were given more precise standard atomic weights since 1969, the uncertainties of 24 elements remain in excess of 0.01%. However, some of these uncertainties are due to problems in the mass spectrometric techniques for precise isotope abundance measurements, *e.g.*, Ti and Se; some others are due to natural isotope variations, *e.g.*, Li and B.

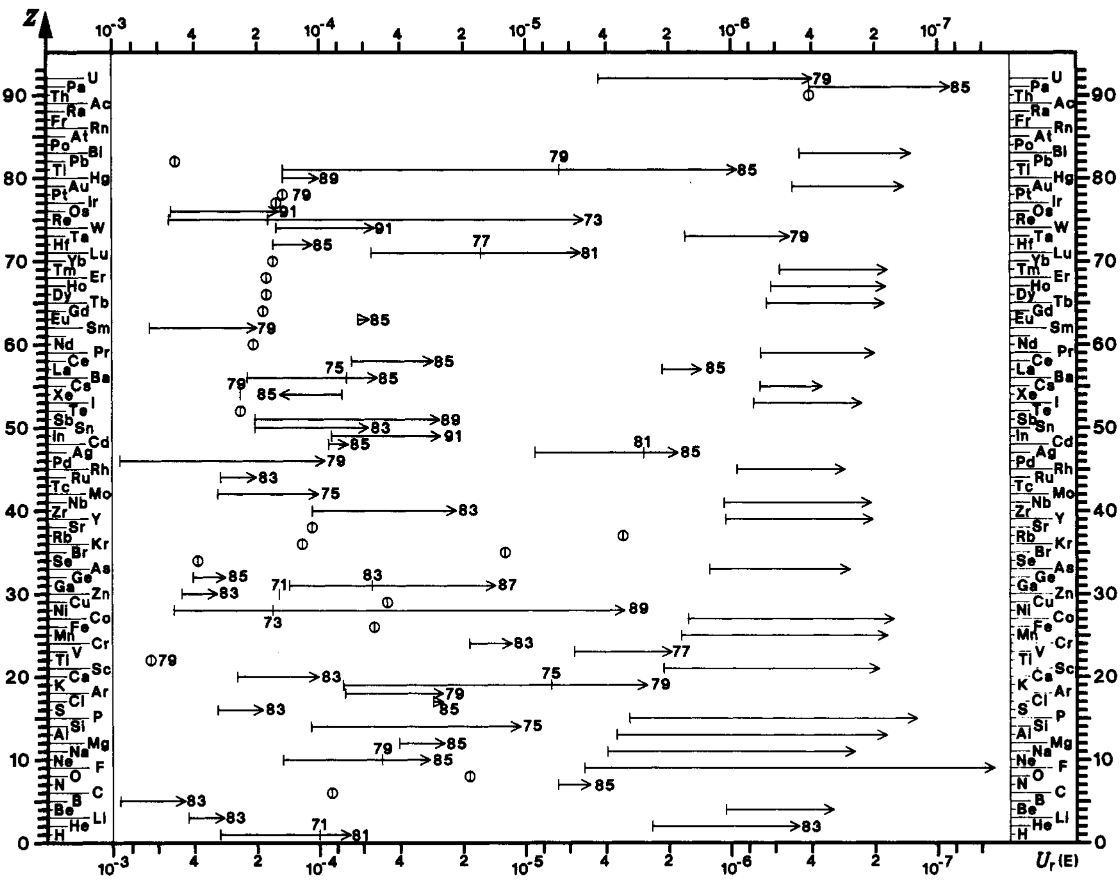

Fig. 1. Changes in $U_r(E)$ from 1969 to 1991 (ref. 22). The symbol ⌽ indicates no change. Number where given is last two digits of the year of the last change. Number (year) is not listed for monoisotopic elements. Intermediate changes for all but the monoisotopic elements are indicated by short vertical lines together with the year of the change.

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 (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 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. 23, 24 & 25).

NON-TERRESTRIAL DATA

The isotopic abundance of elements from non-terrestrial sources form a rapidly expanding body of knowledge. Information about non-terrestrial isotopic abundances can be obtained from mass spectrometric studies of meteoritic, lunar or interplanetary dust materials, from space probes using mass and far-infrared to ultraviolet spectra, and from ground-based astronomical photoelectric and radio observations.

It has been established that many elements have a different isotopic composition in non-terrestrial materials when compared to normal terrestrial matter. These effects have been substantiated by recent precise mass spectrometric measurements of meteorites, lunar materials and interplanetary dust. Figure 2 shows—as an example—the wide range of isotopic composition of neon from different extraterrestrial sources, as well as from the terrestrial atmosphere.

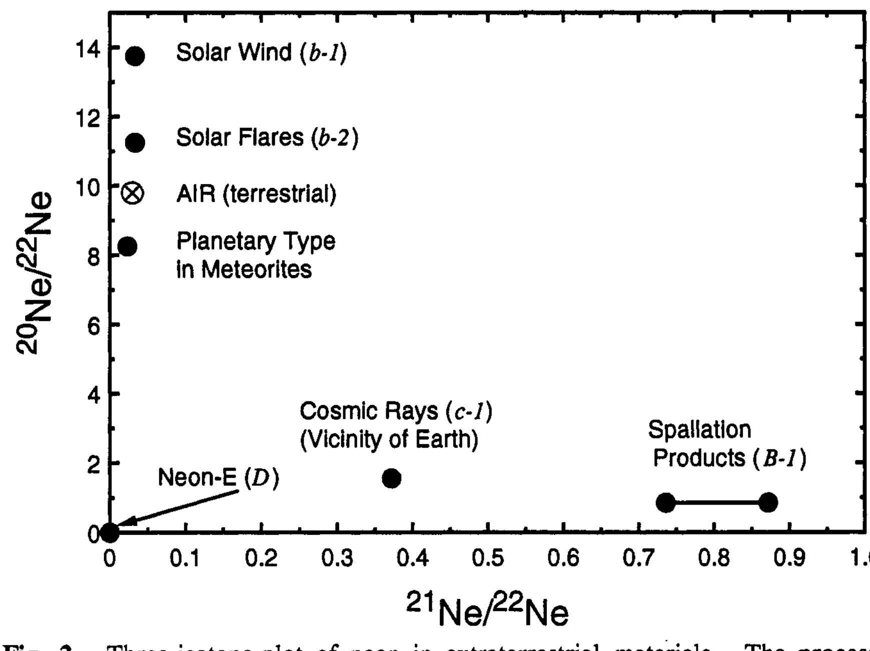

Fig. 2. Three-isotope-plot of neon in extraterrestrial materials. The processes leading to this isotopic composition, or to the sources where this isotopic composition can be found, are given in brackets.

Excellent reviews describing isotopic anomalies in non-terrestrial materials are given by Clayton *et al.* (ref. 26), Kerridge and Matthews (ref. 27), Takaoka (ref. 28), Wasserburg (ref. 29), and Wiedenbeck (ref. 30). Those interested in more comprehensive reviews should refer to Shima (refs. 31 & 32) and Shima and Ebihara (ref. 33).

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

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

Atomic Number	Name	Symbol	Mass Number	Relative Atomic Mass	Half-Life	Unit[a]
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	138.4	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	3.823	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	5.75	a
89	Actinium	Ac	227	227.0278	21.77	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	0.1	s
108	Unniloctium	Uno	265		0.002[b]	s
109	Unnilennium	Une	266		0.003[b]	s

[a]Abbrevations are: a = years; d = days; h = hours; m = minutes; s = seconds.
[b]The value given is determined from only a few decays.

The data have been classified according to (1) major alteration or production *processes* and (2) the *sources* of materials with different isotopic compositions of the element. In the following, this is described in more detail.

Processes

A. *Mass Fractionation*
Mass dependent fractionation which occurs before the formation as well as in the later stages of the history of the solar system.

A-1 Fractionation by Volatilization and Condensation.

A-2 Fractionation by Chemical Processes: This includes some specific cases, such as the production of organic compounds.

B. *Nuclear Reactions*

B-1 Spallation Reactions: Nuclear reactions of extraterrestrial matter with galactic and (or) solar cosmic energetic particles.

B-2 Low Energy Thermal Neutron Capture Reactions: Neutrons are produced in the spallation cascade and slowed down to lower energies in large meteorites or the moon.

C. *Radioactive Decay Products*

C-1 Products from Extinct Nuclides: When the solar system had evolved to the point where components of meteorites became closed isotopic systems (some 4.5 Ga ago), radioactive nuclides with suitable decay constants—now extinct in the solar system—were still present. Their decay products are responsible for anomalous isotopic compositions of certain elements.

C-2 Enrichments in decay products of radionuclides still present in the solar system. They are commonly used in geochronological and cosmochronological dating methods.

C-3 Enrichments due to double ß-decay of long-lived radioactive nuclides.

C-4 Enrichments as the result of nuclear fission.

D. *Nucleosynthesis*
The processes of the formation of these nucleosynthetic materials are still being evaluated. Tabulated here are measurements of samples which were identified by the authors as products of a specific nucleosynthetic process.

E. *Gravitational Escape*
Preferential loss of hydrogen and other volatiles from the gravitational field during the formation of planets. Radioactive decay products are also responsible for variations in isotopic compositions of some elements (like He and Ar) in planetary atmospheres.

Sources

a. *Interplanetary Dust (Cosmic Dust)*
Isotopic ratios of certain elements have been measured in small particles collected in the Earth's stratosphere, found near polar regions or separated from deep-sea sediments.

b. *Solar Materials*

b-1 Solar wind: Ancient or recent solar wind particles are trapped in lunar samples or in some meteorites.

b-2 Solar flare: During the solar event of September 23, 1978, the satellite-born Heavy Isotope Spectrometer Telescope (HIST) measured isotopic ratios of several elements of energetic particles from the sun. Such particles can also be detected in meteorites.

b-3 Sun: Isotopic ratios of He and Ni were measured by ground-based infrared or near-infrared spectrometry in the solar photosphere.

c. *Cosmic Rays*
Data included in this category are the result of measurements in the near-Earth environment by balloon and satellite experiments.

c-1 Relatively Low Energy Cosmic Rays (> 20 MeV/n to 1 GeV/n; where n = nucleon): The recent developments of high resolution detectors make it possible to measure the relative isotopic abundance of several elements.

c-2 High-Energy Cosmic Rays (>6 GeV/n): Despite experimental difficulties, $^{3}He/^{4}He$ ratios have been determined.

d. *Planets and Satellites*
Isotopic ratios of some elements in planets and in Saturn's moon, Titan, were determined by spacecraft-born mass spectrometry and ground-based infrared spectrometry.

e. *Cool Stars*
The number of known isotopic ratios of H, Li, C, O and Mg in cool giant stars has recently grown remarkably. Most of them have been obtained from infrared spectra taken with ground-based telescopes.

f. *Interstellar Medium*
Isotopes of H, He, Li, C, N and O have been detected by large ground-based radiotelescopes and by satellite-born ultraviolet or far-infrared spectrometry.

g. *Comet Halley*
D/H and $^{18}O/^{16}O$ ratios in the coma of the comet Halley were measured on March 14, 1986 by the neutral gas mass spectrometer of the Giotto spacecraft. The isotopic ratios of C and N of cometary material are determined by CN rotational lines of ultraviolet spectra.

Although the Commission does not attempt to systematically review the literature on the isotopic composition of non-terrestrial materials, 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 these 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 which produces the variation in isotopic composition. Thus, for example, the table lists the largest deviation reported for Mg caused by mass fractionation (process *A-1*). Each process is listed only once. These data are measured values reported in publications and do not represent extrapolated individual compositions of specific processes.

Entries given as "δ" are in permil (parts per thousand). The "δ" values are expressed by respective mass numbers, *e.g.*, the meaning of $\delta(25,24)$ is as follows:

$$\delta(25,24) = \left[\frac{[^{25}\mathrm{Mg}/^{24}\mathrm{Mg}]_{\textit{non-terrestrial sample}}}{[^{25}\mathrm{Mg}/^{24}\mathrm{Mg}]_{\textit{terrestrial sample}}} - 1 \right] 1000$$

Where an isotopic ratio or atomic weight is given, the terrestrial value (truncated where necessary to a specific number of significant figures) is given for comparison in parentheses.

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

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

Element	Maximal Isotopic Ratios	Atomic Weight	Materials	Process	Refs
$_1H$	$\delta(2,1) = +5740$	1.0088	H_2O released from Semarkona (LL3-chondrite)	*A-2*	34
	$\delta(2,1) = -588$	1.0079	H_2 released from Abee (E4-chondrite)	*A-2*	35
		(1.0079)			
$_2He$	$^3He/^4He = 1.42\times10^{-4}$	4.00246	Planetary type He in carbonaceous chondrites	*C-5*	36
	(1.37×10^{-6})	(4.00260)			
$_6C$	$^{12}C/^{13}C = 3.0356$	12.249	SiC separated from Murchison (C2-chondrite)	*D*	37
	(89.91)	(12.010)			
$_{12}Mg$	$\delta(25,24) = +113$	24.3536	Spinel in Murchison (C2-chondrite)	*A-1*	38
	$\delta(26,24) = +231$	(24.3050)			
$_{18}Ar$	36 / 38 / 40				
	90 1.00 99500	39.959	Light inclusion of Allende (C3-chondrite)	*B-2*	39
	(5.32 1.00 1575)	(39.948)			
$_{24}Cr$	50 / 52 / 53 / 54				
	0.058 1.00 0.153 0.070	52.079	Iron meteorite Grant	*B-1*	40
	(0.052 1.00 0.113 0.028)	(51.996)			
$_{36}Kr$	$^{82}Kr/^{84}Kr = 0.355$		FeS of iron meteorite Cape York	*C-3*	41
	(0.203)				
$_{54}Xe$	$^{129}Xe/^{130}Xe = 1998$		Inclusion of Allende (C3-chondrite)	*C-1*	39
	(6.439)				
$_{54}Xe$	$^{136}Xe/^{132}Xe = 0.617$		Density separate of Allende (C3-chondrite)	*C-4*	42
	(0.331)				
$_{60}Nd$	$\delta(143,144) = +364.03$	144.18	Etched fraction of Allende (C3-chondrite)	*C-2*	43
		(144.24)			

TABLE 5. Examples of isotopic compositions and corresponding atomic weights in different extraterrestrial sources

Element	Source	Isotopic Ratios or Abundances			Atomic Weight	Sample or Method	Refs
$_2$He		^{3}He/^{4}He					
	Interplanetary Dust (*a*)	0.034			3.97	Pacific deep-sea sample	44
	Solar Wind (*b-1*)	4.88×10^{-4}			4.0021	ISEE-3 borne IMS[a]	45
	Solar Flare (*b-2*)	4.1×10^{-4}			4.0022	Solar type gas-rich meteorite	46 & 47
	Sun (Photosphere) (*b-3*)	0.05			3.96	Infrared absorption lines	48
	Cosmic Rays (*c-1*) (48–77 MeV/n)[d]	0.066			3.94	ISEE-3 born HIST[b]	49
	Cosmic Rays (*c-2*) (about 6 GeV/n)[d]	0.24			3.8	Balloon borne detector	50
	Interstellar Medium (*f*)	0.4 to 7.4×10^{-4}			4.0	Ground-based radio observation	51
	Earth (air)	1.37×10^{-6}			4.0026		
$_8$O		^{16}O/^{18}O					
	Interplanetary Dust (*a*)	486.6			15.999	Pacific deep-sea sample	52
	Solar Flares (*b-2*)	670			16.0	ISEE-3 borne HIST[b]	53
	Cosmic Rays (*c-1*) (88–233 MeV/n)[d]	53			16.1	ISEE-3 borne HIST[b]	54
	Venus (atmosphere) (*d*)	500			16.0	Pioneer Venus Lander	55
	Stars (M Giants) (*e*)	425–4600			16.0	Ground-based telescopes (Infrared spectra)	56,57 & 58
	Interstellar Medium (*f*)	208–908			16.0	Ground-based radio observation	59,60 & 61
	Comet Halley (*g*)	435			16.0	Giotto spacecraft	62
	Earth (VSMOW)[c]	498.8			15.999		
$_{12}$Mg		24 /	25 /	26			
	Solar Flares (*b-2*)	0.772	0.114	0.114	24.327	ISEE-3 borne HIST[b]	53
	Cosmic Rays (*c-1*) (30–180 MeV/n)[d]	0.60	0.19	0.21	24.59	ISEE-3 borne HIST[b]	63
	Stars (*e*), (Spectr. type G, K, M)	0.79–0.88	0.10–0.03	0.11–0.03	24.3–24.0	Ground-based telescope (MgH lines)	64,65 & 66
	Earth	0.7899	0.100	0.1101	24.3050		

[a]Ion mass spectrometer
[b]California Institute of Technology Heavy Isotope Spectrometer Telescope
[c]Vienna Standard Mean Ocean Water (ref. 67)
[d]n = nucleon

OTHER PROJECTS OF THE COMMISSION

The *Working Party on Natural Isotopic Fractionation* presented a report which was produced during the Working Party's meeting in Malente, Germany, before the IUPAC General Assembly in Hamburg. The Commission authorized the Working Party to publish a final report about the variation in the isotopic composition and its effect upon the atomic weight and uncertainty in atomic weight for the elements H, Li, B, C, N, O, Ne, Mg, Si, S, Cl, K, Cu, Se, Pd, Te, and U, as soon as possible.

The *Working Party on Statistical Evaluation of Isotopic Abundances* presented a preliminary report. The Working Party needs two more years to complete its computer program and to obtain sufficient experience on its operation.

During the last two years, relevant material of the Commission was transferred to the Arnold and Mabel Beckman Center for the History of Chemistry (CHOC). Sixteen different categories of materials have been agreed on, *e.g.*, Atomic Weight Reports from 1827 to the present, minutes of meetings, isotopic abundance tables, *etc.* The Commission decided to enter into a long-term cooperative arrangement with CHOC.

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