Subcommittee on Natural Assessment of Fundamental Understanding of Isotopes of IUPAC

Summary Minutes of Meeting December 5 – 6, 2016, U.S. Geological Survey, Reston, Virginia, USA

IUPAC Project 2015-030-2-200
Assessment of fundamental understanding of isotopic abundances and atomic weights of the chemical elements (2016—2017)

1. Opening and Welcome

Dr. Holden welcomed the members of the Subcommittee on Natural Assessment of Fundamental Understanding of Isotopes (SNAFUI) to Reston, Virginia. The following members were in attendance:

Dr. N. E. Holden (Chair), Brookhaven National Laboratory, Upton, New York, USA
Dr. T. B. Coplen (Secretary), U.S. Geological Survey, Reston, Virginia, USA
Dr. J.K. Böhlke, U.S. Geological Survey, Reston, Virginia, USA
Prof. M. E. Wieser, University of Calgary, Calgary, Alberta, Canada

Sadly, Dr. Paul De Bièvre was not in attendance, having passed away in April 2016 at age 82. The Subcommittee greatly missed this dear colleague.

2. Agenda

The principal objectives of SNAFUI (Subcommittee hereafter) are to (1) review fundamental issues and concerns that have been raised by members of the Commission on Isotopic Abundances and Atomic Weights (Commission) and IUPAC members, (2) discuss these issues at length for time periods not available during Commission meetings, and (3) present recommendations to the Commission on solutions to problems that will help to provide future direction for their work on atomic weights and isotopic abundances of the chemical elements. The following issues were discussed during this meeting.

- An Interdivisional Committee on Terminology, Nomenclature, and Symbols (ICTNS) review of the Commission's recent publications indicated that the term "normal material" needs an updated definition. This term is fundamental to both the Table of Standard Atomic Weights (TSAW) and the Table of Isotopic Compositions (TICE).
- Several terms for subcategories or types of atomic weights with unclear or possibly evolving meanings have appeared in Commission literature and Commission discussion, and they would benefit from definitions. Such terms include "practical", "conventional", "reference", "representative", and "standard."

- According to guidelines on expression of uncertainty defined by the Joint Committee for Guides in Metrology (JCGM), the expression of standard atomic weight in a format such as “78.971(8)” suggests to users that 0.008 is the standard uncertainty of the value 78.971 [1]. This requires discussion by the Subcommittee because the value 0.008 in this example was never intended to be understood by users of TSAW and TICE as the standard uncertainty.
- The feasibility of a consolidation of TSAW and TICE should be considered because such a consolidation might improve the understanding of the basic connection between the isotopic abundances and atomic weights of the elements.
- The Subcommittee needs to consider a table of atomic weights for general science and for educational communities that may have fewer digits with uncertainties than the full table. This table for general science and educational communities should change less frequently than the full unabridged table of standard atomic weights.

3. Normal Material

From its inception in 1919, the International Union of Pure and Applied Chemistry (IUPAC) took over the careful evaluation and dissemination of atomic weights from critically assessed, published information through its Commission on Isotopic Abundances and Atomic Weights. Each standard atomic weight value reflects the best knowledge of evaluated, published data [2, 3] of normal materials. The implied range of each standard atomic weight is intended to apply to all sources of normal materials of that element. In the Commission’s 1969 report [4], a “normal” material was defined as:

> “. . . one that contains as a major constituent a specified element with an atomic weight value that does not display a significant difference from the accepted value of that atomic weight because of:
> (a) its radiogenic source;
> (b) its extraterrestrial origin;
> (c) artificial alteration;
> (d) mutation; or
> (e) a rare geological occurrence in small quantity.”

This definition for normal material in the 1969 Commission report [4] resulted in several decrees:

- “In assessing variations in isotopic composition, the Commission will continue to disregard other than ‘normal’ materials.”
- “To arrive at the recommended value for an atomic weight the Commission will use weighting procedures so that the value will be optimized for materials in world science, chemical technology and trade, rather than represent an estimated geochemical average [of the Earth].”
- “The Commission must attempt to state the atomic weight values so that they are as precise as possible. At the same time, they must be sufficiently imprecise so that all normal specimens fall within the implied tolerance range. In other words, large quantities of available materials should not lie outside the tolerance range. The difficult judgment

has to be made when only a small fraction of normal material falls outside the tolerance range. The Commission has decided in such cases not to discard useful accuracy applicable to the great majority of practical condition, but to exclude from the definition of 'normal', geological oddities."

This definition was updated in the 1971 Table of Standard Atomic Weights (TSAW) [5], where "artificial alteration" was updated to "artificial isotopic fractionation" and "mutation" was updated to "artificial nuclear reaction." In 1984, the Commission revised the definition of a normal material to a material from a terrestrial source that satisfies the following criteria [2]:

> "The material is a reasonably possible source for this element or its compounds in commerce, for industry or science; the material is not itself studied for some extraordinary anomaly and its isotopic composition has not been modified significantly in a geologically brief period."

Consideration of the this definition of normal materials by the Commission has resulted in several changes in standard atomic weights in the last three decades, for example:

1. The uncertainty value of the standard atomic weight of boron was expanded in 1995 (from 10.811(5) to 10.811(7)) to include boron in sea water because it was decided that boron in sea water was a normal material [6].
2. In 1995, the Commission decided it could reduce the uncertainty value of the standard atomic-weight of carbon from 12.011(1) to 12.0107(8), noting that specimens outside these limits could be covered by footnote "g" for rare geological occurrences in small quantities [6].
3. In 1999, the Commission recognized that the standard atomic weight of nitrogen did not include a substantial fraction of naturally occurring materials in the terrestrial environment, and the Commission changed the standard atomic weight from 14.006 74(7) to 14.0067(2) [7].

Although this definition of normal material has served the Commission for the last three decades [8], a revised definition is needed, in part, because the clause "its isotopic composition has not been modified significantly in a geologically brief period" is not clear to many readers. Considering the intended meaning of normal materials since the 1960s, the Subcommittee suggests that confusion in its definition could be reduced by revising this definition to the following:

> "**Normal materials** include all substances, except (1) those subjected to substantial deliberate, undisclosed, or inadvertent artificial isotopic modification, (2) extraterrestrial materials, and (3) isotopically anomalous specimens, such as ~~Oklo~~ natural nuclear reactor products from Oklo (Gabon) or other rare terrestrial occurrences."

This revised definition of normal material no longer includes the exclusion that "its isotopic composition has not been modified significantly in a geologically brief period." This modification recognizes the fact that much of the atomic-weight variation of some elements is caused by isotopic fractionation processes that operate on many different time scales.

The revised definition also anticipates that materials with radiogenic or nucleogenic isotopic variability may no longer be excluded in the definition of a normal material, except in very exceptional situations, such as the occurrence of ^{87}Sr in a pure rubidium sample. For example, with this revised definition of normal materials, based on the recent evaluation of argon (Fig. 1) by Böhlke [9], the standard atomic weight of argon might be changed from the current value of 39.948 ± 0.001 [10] to [39.7931, 39.9624], when expressed as an interval, to include naturally occurring sources having nucleogenic and radiogenic isotopic variation. Similar evaluations of other such elements (e.g., strontium) are underway by the IUPAC project titled "Evaluation of Radiogenic Abundance Variations in Selected Elements (#2009-023-1-200)." The chair of this project is M. E. Wieser. The Commission may want to reassess whether materials with radiogenic or nucleogenic isotopic variability should or should not be excluded in the revised definition.

It is the mission of the Commission at its biennial meetings to evaluate peer-reviewed literature and determine new atomic-weight values. In addition, it is the task of the Commission to determine what categorizes a substantial isotopic modification and an isotopically anomalous specimen when evaluating published scientific data. In the revised definition of normal material, exceptions (1) and (3) would be assigned footnotes "m" and "g," respectively, in the Table of Standard Atomic Weights and the Table of Isotopic Compositions of the Elements. We note that footnotes "g" and (or) "m" may be needed for some of the 12 elements having intervals for their standard atomic weights (hydrogen, lithium, boron, carbon, nitrogen, oxygen, magnesium, silicon, sulfur, chlorine, bromine, and thallium).

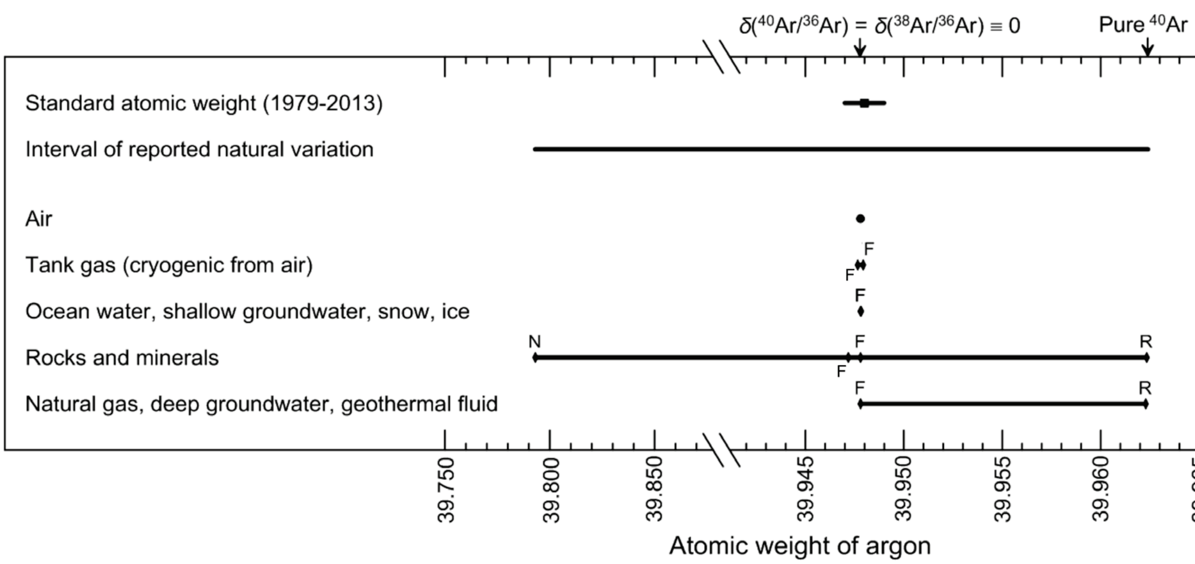

Fig.1: Argon atomic weights in normal terrestrial materials compared with the current standard atomic weight [10] (modified from [9]). "F" indicates variation primarily related to isotopic fractionation. "N" indicates variation primarily related to nucleogenic ^{38}Ar and (or) ^{36}Ar production. "R" indicates variation primarily related to radiogenic ^{40}Ar production.

4. Terms needing clarification

Several terms have been used or discussed for various categories or types of atomic-weight values including “representative”, “reference”, “practical”, “standard”, and “conventional”. Below are comments and (or) potential definitions for these and other selected terms. Current Commission practice is to define some of these terms as indicated, but future work could consider whether all of these terms are necessary. For example, the Subcommittee agreed that the definitions of “standard”, “reference”, and “representative” atomic-weight values describe distinct and valuable concepts, whereas one member (JKB) suggested that the meaning and value of the terms “conventional” and “practical” atomic weights could be confusing.

standard atomic weight

According to rule 5 of the Commission’s Technical Booklet (5th edition):

> “A_r(E) ± $U[A_r$(E)] defines the upper and lower bounds of the range of normal occurrences according to guidelines of the Commission.”

This statement is in agreement with the Element-By-Element review [2], and it applies to elements having two or more stable isotopes with a measured range in isotopic composition and atomic-weight values. The Commission may want to revisit this rule because it applies to elements that display variations in isotopic composition or atomic weight, but it does not apply to (1) elements having a single stable isotope or (2) elements having two or more stable isotopes, but there is no measureable variation in isotopic composition or atomic weight.

Note that $U[A_r$(E)] is an alternative way the Commission has used to print U_r(E). For the 12 elements having interval atomic-weight values, the atomic-weight interval encompasses atomic-weight values of all normal materials (rule 3 in ref. [11]). Rule 4 in ref. [12] indicates that “The atomic-weight interval is the standard atomic weight and is the best knowledge of atomic weights of natural terrestrial sources.” This rule is applicable to all 84 elements having standard atomic-weight values.

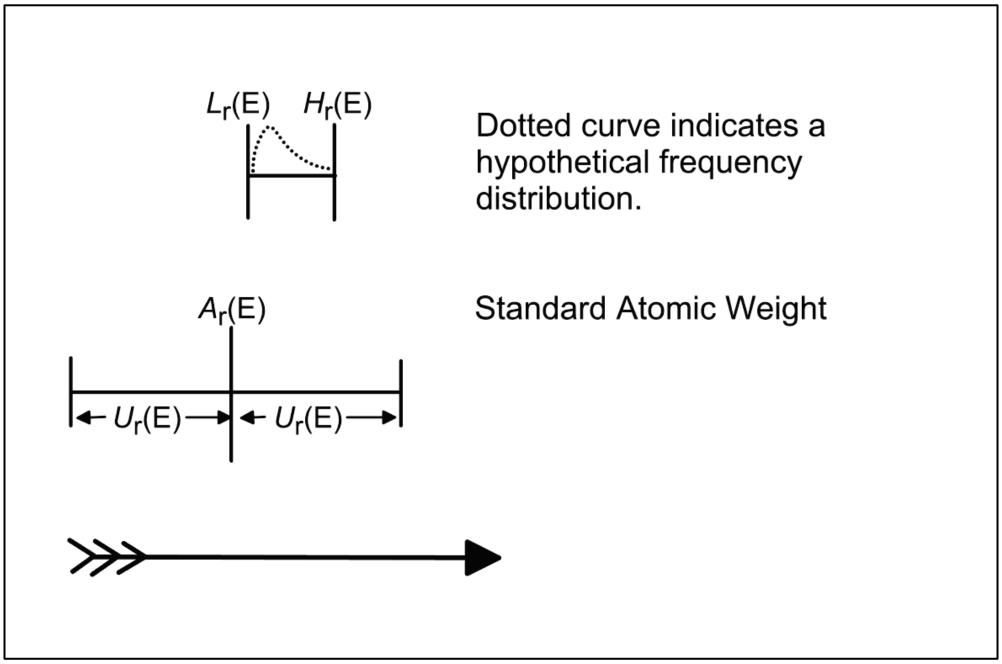

Fig. 2: Relation between (1) the standard atomic weight, A_r(E) of element E, (2) the uncertainty in the standard atomic weight, U_r(E), (3) the lower bound of the standard atomic weight, $A_r(E) – U_r(E) = L_r(E)$, and (4) the upper bound of the standard atomic weight, $A_r(E) – U_r(E) = H_r(E)$. This figure is modified from the Element-By-Element report [2].

<u>conventional atomic-weight value</u>

A "conventional value," also called a "conventional quantity value" in metrology, is a quantity value attributed by agreement to a quantity for a given purpose according to section 2.12 of the vocabulary of metrology [1]. Following reference [1], the Commission in its 2009, 2011, and 2013 reports [10, 11, 12] defined conventional atomic-weight values for each of the 12 elements having interval atomic weights. This was done for users seeking an atomic-weight value that is not an interval, such as for trade, commerce, and educational purposes. The value selected is not the mean of the lower and upper bounds of atomic weight, but is a decisional value determined from a figure of distribution of atomic-weight variation of reagents and materials of the element in normal materials. The name "conventional" atomic-weight value was first suggested to the Commission by IUPAC's ICTNS (Interdivisional Committee on Terminology, Nomenclature and Symbols).

<u>practical atomic weight</u>

The Subcommittee prepared a Table of Practical Atomic Weights for the Commission in July 2015 that showed five-digit atomic weights. Their values and associated uncertainties were selected so that most atomic-weight variations in normal materials were covered. For example, practical atomic weights of hydrogen, beryllium, and nitrogen, respectively, were 1.0079(2), 9.0122, and 14.007. The Subcommittee proposes that this term be dropped because to date, the Commission has not used, accepted, nor published any documents utilizing the term "practical atomic weight." Practical has no metrological definition.

reference atomic weight

The Subcommittee concluded that the term "reference" is best used exclusively for reference materials, best measurement materials, and zero-isotope-delta materials. It is envisioned that there would be only one material used to define the zero point for each isotope-delta scale. For these materials the Commission would derive isotopic abundances and atomic weights from evaluated isotope ratio values and (or) isotope-delta measurements. For a specified reference material, one might provide a reference atomic-weight value. We note that the metrological definition of reference is "A reference can be a measurement unit, a measurement procedure, a reference material, or a combination of such" according to section 1.1 of reference [1].

representative atomic weight

It is proposed that "representative" atomic weight values should refer to other selected materials, such as air or seawater or various general categories of substances, such as those summarized in Subcommittee for Natural Isotopic Fractionation (SNIF)-type products [13]. It is envisioned that representative data could be used to reduce the uncertainty of atomic weights used for some specific applications, such as calculating molecular weights of compounds from specified sources. The Subcommittee notes that the term "representative" has been used previously in TICE in the column 9 heading: "Representative isotopic composition." The term, representative isotopic composition, has not been well defined by the Commission and there have been regular discussions about the meaning of the column 9 heading over the years. We note that "representative" has no metrological definition.

atomic-weight interval

In metrology [1], the term "interval" is used together with the symbol $[a, b]$ to denote the set of real numbers x for which $a \leq x \leq b$, where a and b are real numbers, and where $b > a$. The symbols a and b denote the 'end-points' of the interval $[a, b]$. For 12 elements, the standard atomic weight is given as $[a, b]$, where a is the lower bound and b is the upper bound of the atomic weight.

atomic-weight range

The range of an interval is the difference between the upper and lower bounds [1]. For the 72 elements whose lower and upper bounds are defined by $A_r(\mathrm{E}) \pm U_r(\mathrm{E})$, the range or span is $2 \times U_r(\mathrm{E})$. Therefore, $U_r(\mathrm{E})$ is the atomic-weight half-range, although the Commission has never used the term half-range in its publications. For these elements, $U_r(\mathrm{E})$ values represent conservative estimates of the combined effects of measurement uncertainties (e.g., elements having one stable isotope and some elements having two or more stable isotopes) and (or) known atomic-weight variability in normal materials (some elements with two or more stable isotopes, designated by footnote "r"). The 12 elements whose upper and lower atomic-weight bounds are expressed as the symbol $[a, b]$ and the atomic-weight range of these elements is $b - a$. These elements do not have a half-range.

The Commission should consider whether some of these terms should be eliminated because they are redundant or distinctions are too subtle. The Commission may want to create a Commission glossary that includes some of these terms.

5. How Certain are the Values of the Standard Atomic Weights?

The 1984 Element by Element Review [2] states:

> "The Commission aims at disseminating value pairs [A_r(E), U_r(E)] such that it can claim at a high level of confidence that any element in question in all known normal sources will have an atomic weight that will not differ from the relevant A_r(E) by more than U_r(E). At an even much higher level of confidence, bordering on complete certainty, any chemist sampling any given "normal" (see Section 4) material, be it any ore in trade, or any product at a chemical plant, or any substance at any chemical laboratory, shall be justified in expecting all elements in that material to possess atomic weights within the implied tabulated ranges of the standard atomic-weight values."

The quantity A_r(E) – U[A_r(E)] denotes the lower bound of standard atomic weight, and the quantity A_r(E) + U[A_r(E)] denotes the upper bound of standard atomic weight (Fig. 2). The difference between the upper and lower bounds is the range and is 2 × U[A_r(E)] (Fig. 2). The distribution of atomic-weight values may not be Gaussian as shown in Fig. 2.

At the 1983 Commission meeting in Lyngby, Denmark [14], a Working Party was formed to examine the procedures that had been used to assign uncertainties to atomic weights and to report to the Commission at the next meeting on those and other procedures, which might be used in the future. The Working Party provided recommendations at the 1985 Commission meeting in Lyon, France [15]. One of the recommendations of the Working Party was that uncertainties be quoted (or implied) by single digit values (1–9) applicable with both signs to the last decimal of each tabulated standard atomic weight. For example, the standard atomic weight of selenium, which is 78.971 having a decisional uncertainty of ± 0.008, would be tabulated as 78.971(8). This single digit provides the Commission's decisional uncertainty of standard atomic-weight values, and the selenium standard atomic-weight value of 78.971(8) is intended to be applicable to the vast majority of normal materials containing selenium.

The decisional uncertainty (e.g. ±0.008 for selenium) is an expanded uncertainty and is the product of a combined standard measurement uncertainty and a factor larger than the number one. This factor is referred to as the coverage factor, and a coverage factor is usually symbolized by k [1, 16]. Although the Commission declines to specify the coverage factor [2], the lower and upper bounds are assigned so that standard atomic weights are highly reliable and have great certitude [2]. For example, the coverage factor for the approximately 20 elements having one stable isotope is six (k = 6) [4]. Additionally, the expansion of the uncertainties of atomic masses by six by the Commission resulted in only one stable isotope out of 294 stable isotopes being inconsistent between the 2003 and 2012 Atomic Mass Evaluations [17, 18], namely lithium-7 [10]. For elements having two or more stable isotopes (or radioactive isotopes that contribute to the standard atomic weight), the Commission intentionally has declined to specify the coverage factor [2], but De Bièvre et al. [19] state, "The aim of IUPAC has been fulfilled by which any chemist – taking any natural sample from research, industry, or commerce can confidently expect his or her true sample atomic weight to lie within the tabulated range with a probability far in excess of 95 %." If needed for their own statistical purposes, it will be up to users of the table to select an appropriate coverage factor, k, based on these principles.

The expression of a standard atomic weight as 78.971(8) is confusing because the Commission never intended that the value in parentheses be a standard uncertainty. The

Subcommittee evaluated reducing this confusion by presenting decisional uncertainty values in another format. Three formats considered at the meeting, or in subsequent emails, included:

1. Expressing the decisional uncertainties of A_r(E) values as half-ranges in a separate column. For example, "78.971(8)" would be divided into two columns named "value" and "half-range" with entries of "78.971" and "0.008," respectively.
2. Expressing A_r(E) values and their decisional uncertainties in curly brackets, following the last significant digit to which they are attributed. For example, "78.971(8)" would be printed as "78.971{8}."
3. Expressing A_r(E) values and their decisional uncertainties in square brackets, following the last significant digit to which they are attributed. For example, "78.971(8)" would be printed as "78.971[8]."

The Subcommittee noted that expressing decisional uncertainties of A_r(E) values as half-ranges could add confusion if applied to elements with no known range of atomic-weight variation. Likewise, the format "78.971[8]" might confuse readers thinking that "[8]" represents a reference, which is the standard method to identify references in *Pure and Applied Chemistry*. The format 78.971{8}" was selected as the best of the three options to reduce confusion. The unabridged standard atomic weights are presented in Table 1, which displays decisional uncertainties for 72 elements in curly brackets, following the last significant digit to which they are attributed. This new format eliminates the format "78.971(8)." In this manner, it is clarified for users that uncertainties provided for standard atomic weights of 72 elements are decisional uncertainties and the lower and upper bounds of the atomic weights of normal materials are A_r(E) – U_r(E) and A_r(E) + U_r(E), respectively. For these 72 elements, U_r(E) values represent conservative estimates of the combined effects of measurement uncertainties (e.g., elements with one stable isotope and some elements having two or more stable isotopes) and (or) known atomic-weight variability in normal materials (some elements with two or more stable isotopes, designated by footnote "r" in Table 1).

During the meeting of the Commission on Atomic Weights and Isotopic Abundances in 1985 in Lyon, France [15], the Working Party on Natural Isotopic Fractionation (subsequently named the Subcommittee on Natural Isotopic Fractionation) was formed to investigate the effects of isotope-abundance variations of elements upon their standard atomic weights and atomic-weight uncertainties [13, 20, 21]. The Subcommittee's reports formed the basis of the Commission's decision in 2009 to express the standard atomic weight of ten elements (hydrogen, lithium, boron, carbon, nitrogen, oxygen, silicon, sulfur, chlorine, and thallium) as intervals to indicate that standard atomic weights are not always constants of nature [11, 22]. In 2011, the Commission decided to express the standard atomic weights of two more elements (magnesium and bromine) as intervals [12]. The term "interval" is used together with the symbol [a, b] to denote the set of real numbers x for which $a \le x \le b$, where a and b are real numbers and where $b > a$ [1]. The symbols a and b denote the "end-points" of the interval [a, b]. Figure 3 is an example taken from ref [1] and presents the interval [–4, 2]. The two end points, a and b, respectively, are –4 and 2, which numerically can be stated as –1 ± 3. However, as noted by ref [1], –1 ± 3 does not denote the interval [–4, 2], because intervals do not have half-ranges. Thus, the 12 elements whose standard atomic weight is expressed as an interval in Table 1 do not have half-ranges. For these 12 elements, the atomic-weight interval encompasses atomic-weight values of all normal materials (rule 3 in ref. [11]). Rule 4 in ref. [11] indicates that "The atomic-weight interval is the standard atomic weight and is the best knowledge of atomic weights of natural terrestrial sources." This rule is applicable to all 84 elements in Table 1 having standard atomic-weight values. An Excel file and pdf of Table 1 is available [23].

Table 1 includes the 2015 Commission change in the standard atomic weight of ytterbium from 173.054(5) to 173.045(10), which is 173.045 ± 0.010 [24]. We note that this new value is not in accord with the Commission recommendation adopted in 1985 [15], which stated that uncertainties must be quoted (or implied) by single digit values (1–9) applicable with both signs to the last decimal of atomic-weight values.

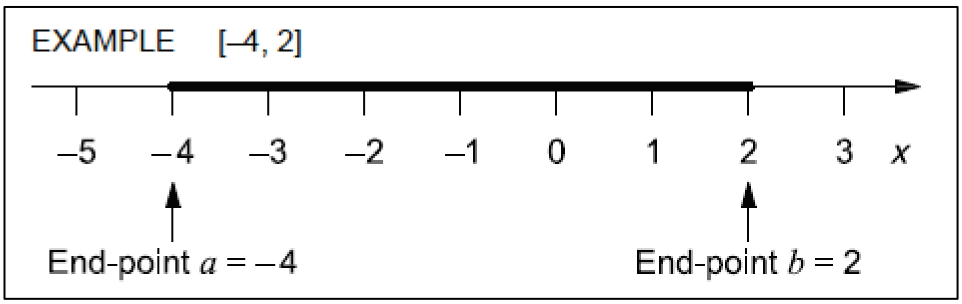

Fig. 3: The interval [–4, 2] from [1]. The two end points are –4 and 2, which numerically can be stated as –1 ± 3. However, –1 ± 3 does not denote the interval [–4, 2]; accordingly, intervals do not have half-ranges.

Table 1: Standard atomic weights of the elements 2015
[Scaled to an atomic weight of 12 for carbon-12 (^{12}C), where ^{12}C is a neutral atom in its nuclear and electronic ground state, having the result that atomic-weight values are dimensionless.]

The atomic weights, A_r(E), of many elements vary because of variations in the abundances of their isotopes in normal materials. For 12 such elements, an atomic-weight interval is given with the symbol [*a*, *b*] to denote the set of atomic-weight values in normal materials; thus, $a \le A_r(E) \le b$ for element E. For 72 elements, A_r(E) values and their decisional uncertainties (in curly brackets, following the last significant digit to which they are attributed) are given for normal materials and include evaluations of measurement uncertainty and variability. The atomic weight of a normal material should lie between the lower and upper bounds of the standard atomic weight with great certitude with a probability far in excess of 95 percent. If a more accurate A_r(E) value for a specific material is required, it should be determined. The footnotes to this table elaborate the types of variation that may occur for individual elements and that may lie outside the values listed.

Element name	Symbol	Atomic number	Standard atomic weight	Footnotes
hydrogen	H	1	[1.007 84, 1.008 11]	m
helium	He	2	4.002 602{2}	g r
lithium	Li	3	[6.938, 6.997]	m
beryllium	Be	4	9.012 1831{5}	
boron	B	5	[10.806, 10.821]	m
carbon	C	6	[12.0096, 12.0116]	
nitrogen	N	7	[14.006 43, 14.007 28]	m
oxygen	O	8	[15.999 03, 15.999 77]	m
fluorine	F	9	18.998 403 163{6}	
neon	Ne	10	20.1797{6}	g m
sodium	Na	11	22.989 769 28{2}	
magnesium	Mg	12	[24.304, 24.307]	
aluminium (aluminum)	Al	13	26.981 5385{7}	
silicon	Si	14	[28.084, 28.086]	
phosphorus	P	15	30.973 761 998{5}	
sulfur	S	16	[32.059, 32.076]	
chlorine	Cl	17	[35.446, 35.457]	m
argon	Ar	18	39.948{1}	g r
potassium	K	19	39.0983{1}	
calcium	Ca	20	40.078{4}	g
scandium	Sc	21	44.955 908{5}	
titanium	Ti	22	47.867{1}	
vanadium	V	23	50.9415{1}	
chromium	Cr	24	51.9961{6}	
manganese	Mn	25	54.938 044{3}	

Element name	Symbol	Atomic number	Standard atomic weight	Footnotes
iron	Fe	26	55.845{2}	
cobalt	Co	27	58.933 194{4}	
nickel	Ni	28	58.6934{4}	r
copper	Cu	29	63.546{3}	r
zinc	Zn	30	65.38{2}	r
gallium	Ga	31	69.723{1}	
germanium	Ge	32	72.630{8}	
arsenic	As	33	74.921 595{6}	
selenium	Se	34	78.971{8}	r
bromine	Br	35	[79.901, 79.907]	
krypton	Kr	36	83.798{2}	g m
rubidium	Rb	37	85.4678{3}	g
strontium	Sr	38	87.62{1}	g r
yttrium	Y	39	88.905 84{2}	
zirconium	Zr	40	91.224{2}	g
niobium	Nb	41	92.906 37{2}	
molybdenum	Mo	42	95.95{1}	g
technetium*	Tc	43		
ruthenium	Ru	44	101.07{2}	g
rhodium	Rh	45	102.905 50{2}	
palladium	Pd	46	106.42{1}	g
silver	Ag	47	107.8682{2}	g
cadmium	Cd	48	112.414{4}	g
indium	In	49	114.818{1}	
tin	Sn	50	118.710{7}	g
antimony	Sb	51	121.760{1}	g
tellurium	Te	52	127.60{3}	g
iodine	I	53	126.904 47{3}	
xenon	Xe	54	131.293{6}	g m
caesium (cesium)	Cs	55	132.905 451 96{6}	
barium	Ba	56	137.327{7}	
lanthanum	La	57	138.905 47{7}	g
cerium	Ce	58	140.116{1}	g
praseodymium	Pr	59	140.907 66{2}	
neodymium	Nd	60	144.242{3}	g
promethium*	Pm	61		
samarium	Sm	62	150.36{2}	g
europium	Eu	63	151.964{1}	g

Element name	Symbol	Atomic number	Standard atomic weight	Footnotes
gadolinium	Gd	64	157.25{3}	g
terbium	Tb	65	158.925 35{2}	
dysprosium	Dy	66	162.500{1}	g
holmium	Ho	67	164.930 33{2}	
erbium	Er	68	167.259{3}	g
thulium	Tm	69	168.934 22{2}	
ytterbium	Yb	70	173.045{10}	g
lutetium	Lu	71	174.9668{1}	g
hafnium	Hf	72	178.49{2}	
tantalum	Ta	73	180.947 88{2}	
tungsten	W	74	183.84{1}	
rhenium	Re	75	186.207{1}	
osmium	Os	76	190.23{3}	g
iridium	Ir	77	192.217{3}	
platinum	Pt	78	195.084{9}	
gold	Au	79	196.966 569{5}	
mercury	Hg	80	200.592{3}	
thallium	Tl	81	[204.382, 204.385]	
lead	Pb	82	207.2{1}	g r
bismuth*	Bi	83	208.980 40{1}	
polonium*	Po	84		
astatine*	At	85		
radon*	Rn	86		
francium*	Fr	87		
radium*	Ra	88		
actinium*	Ac	89		
thorium*	Th	90	232.0377{4}	g
protactinium*	Pa	91	231.035 88{2}	
uranium*	U	92	238.028 91{3}	g m
neptunium*	Np	93		
plutonium*	Pu	94		
americium*	Am	95		
curium*	Cm	96		
berkelium*	Bk	97		
californium*	Cf	98		
einsteinium*	Es	99		
fermium*	Fm	100		
mendelevium*	Md	101		

Element name	Symbol	Atomic number	Standard atomic weight	Footnotes
nobelium*	No	102		
lawrencium*	Lr	103		
rutherfordium*	Rf	104		
dubnium*	Db	105		
seaborgium*	Sg	106		
bohrium*	Bh	107		
hassium*	Hs	108		
meitnerium*	Mt	109		
darmstadtium*	Ds	110		
roentgenium*	Rg	111		
copernicium*	Cn	112		
nihonium*	Nh	113		
flerovium*	Fl	114		
moscovium*	Mc	115		
livermorium*	Lv	116		
tennessine*	Ts	117		
oganesson*	Og	118		

* Element has no stable isotopes, only radioactive isotopes. For four elements (Bi, Th, Pa, and U) standard atomic weights are tabulated because these elements have characteristic terrestrial isotopic compositions; for the other 34 elements standard atomic weights cannot be determined.

g Geological materials 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 materials and that given in the table may exceed the stated decisional uncertainty.

m Modified isotopic compositions may be found in commercially available material because the material 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 standard atomic weight from being given; the tabulated value and decisional uncertainty should be applicable to normal material.

6. Uncertainties in the Table of Isotopic Compositions of the Elements

The best-measurement values of isotopic compositions are provided in column 6 (TICE), and the uncertainty of these isotopic compositions is conservative. Therefore, expressing an isotope-amount fraction in column 6 as “0.8018(2)” is confusing because many users will assume that 0.0002 is the standard uncertainty, according to guidelines on expression of uncertainty [16], which is not correct. To minimize confusion, it is suggested that the uncertainty value be given in curly brackets, as described above for SAW (Table 1).

In the 2013 TICE [25], column 9 values were adjusted from previous values. The 2013 values “. . . are consistent with the standard atomic weights to the stated precision, i.e. to within ±1 in the last digit quoted . . .” [25]. Because these values are consistent with standard atomic-weight values, it is suggested that this column be renamed to “SAW isotopic composition,” where SAW is standard atomic weight.

7. Consolidation of TSAW and TICE

The Subcommittee discussed the consolidation of TSAW and TICE, which was attempted by the Commission about a decade ago. Consolidation of TICE and TSAW and production of comprehensive tables might have the benefit of clarifying relations among different sources of atomic-weight uncertainty and reducing confusion about various terms for various atomic-weight values currently in use (e.g., “conventional” and “representative”) or proposed previously (e.g. “practical”), as described in Section 3. In future meetings, the Commission may want to consider a follow-up investigation using this approach.

8. Atomic Weights Table for Educational Communities

Because the Commission decided in 2015 that it would no longer publish a four-digit table of standard atomic weights and because many believe that a four-digit table is of value for the educational community, it was noted that an article titled “Clarifying Atomic Weights: A 2016 Four-Figure Table of Standard and Conventional Atomic Weights” was prepared and published in the *Journal of Chemical Education* [26]. A four-figure table in pdf format and in Microsoft Excel and Word formats is available [27].

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