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Standard atomic weights of the elements 2021 (IUPAC Technical Report)

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Abstract: Following the reviews of atomic-weight determinations and other cognate data in 2015, 2017, 2019 and 2021, the IUPAC (International Union of Pure and Applied Chemistry) Commission on Isotopic Abundances and Atomic Weights (CIAAW) reports changes of standard atomic weights. The symbol $A_r°(E)$ was selected for standard atomic weight of an element to distinguish it from the atomic weight of an element E in a specific substance P, designated $A_r(E, P)$. The CIAAW has changed the values of the standard atomic weights of five elements based on recent determinations of terrestrial isotopic abundances:

Ar (argon):	from 39.948 ± 0.001	to	[39.792, 39.963]
Hf (hafnium):	from 178.49 ± 0.02	to	178.486 ± 0.006
Ir (iridium):	from 192.217 ± 0.003	to	192.217 ± 0.002
Pb (lead):	from 207.2 ± 0.1	to	[206.14, 207.94]
Yb (ytterbium):	from 173.054 ± 0.005	to	173.045 ± 0.010

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The standard atomic weight of argon and lead have changed to an interval to reflect that the natural variation in isotopic composition exceeds the measurement uncertainty of A_r(Ar) and A_r(Pb) in a specific substance. The standard atomic weights and/or the uncertainties of fourteen elements have been changed based on the Atomic Mass Evaluations 2016 and 2020 accomplished under the auspices of the International Union of Pure and Applied Physics (IUPAP). $A_r°$ of Ho, Tb, Tm and Y were changed in 2017 and again updated in 2021:

Al (aluminium), 2017:	from 26.981 5385 ± 0.000 0007	to	26.981 5384 ± 0.000 0003
Au (gold), 2017:	from 196.966 569 ± 0.000 005	to	196.966 570 ± 0.000 004
Co (cobalt), 2017:	from 58.933 194 ± 0.000 004	to	58.933 194 ± 0.000 003
F (fluorine), 2021:	from 18.998 403 163 ± 0.000 000 006	to	18.998 403 162 ± 0.000 000 005
(Ho (holmium), 2017:	from 164.930 33 ± 0.000 02	to	164.930 328 ± 0.000 007)
Ho (holmium), 2021:	from 164.930 328 ± 0.000 007	to	164.930 329 ± 0.000 005
Mn (manganese), 2017:	from 54.938 044 ± 0.000 003	to	54.938 043 ± 0.000 002
Nb (niobium), 2017:	from 92.906 37 ± 0.000 02	to	92.906 37 ± 0.000 01
Pa (protactinium), 2017:	from 231.035 88 ± 0.000 02	to	231.035 88 ± 0.000 01
Pr (praseodymium), 2017:	from 140.907 66 ± 0.000 02	to	140.907 66 ± 0.000 01
Rh (rhodium), 2017:	from 102.905 50 ± 0.000 02	to	102.905 49 ± 0.000 02
Sc (scandium), 2021:	from 44.955 908 ± 0.000 005	to	44.955 907 ± 0.000 004
(Tb (terbium), 2017:	from 158.925 35 ± 0.000 02	to	158.925 354 ± 0.000 008)
Tb (terbium), 2021:	from 158.925 354 ± 0.000 008	to	158.925 354 ± 0.000 007
(Tm (thulium), 2017:	from 168.934 22 ± 0.000 02	to	168.934 218 ± 0.000 006)
Tm (thulium), 2021:	from 168.934 218 ± 0.000 006	to	168.934 219 ± 0.000 005
(Y (yttrium), 2017:	from 88.905 84 ± 0.000 02	to	88.905 84 ± 0.000 01)
Y (yttrium), 2021:	from 88.905 84 ± 0.000 01	to	88.905 838 ± 0.000 002

Keywords: Argon; ciaaw.org; hafnium; iridium; lead; LSVEC; ytterbium.

Dedicated to Paul de Bièvre (1933–2016), a long-serving member of the CIAAW and the inaugural Chairman of its Subcommittee on Isotopic Abundance Measurements.

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1 Introduction

The Commission on Isotopic Abundances and Atomic Weights (CIAAW, hereafter called the Commission) convenes biennially to evaluate recent developments in isotope measurement science and deliberate on related matters. The Commission met in Tulln (Austria) from 3 to 4 August 2015, Groningen (The Netherlands) from 16 to 18 September 2017, in Berlin (Germany) from 3 to 4 July 2019 and in a virtual meeting 27 to 28 July 2021 under the chairmanship of Juris Meija. At these meetings, the Commission reviewed recommendations of its Subcommittees (Subcommittee on Natural Assessment of Fundamental Understanding of Isotopes, Subcommittee on Isotopic Abundance Measurements, and Subcommittee on Stable Isotope Reference Material Assessment). The recommendations included modifying the definition of normal materials and changing the expression of uncertainty of standard atomic weights and isotopic composition values. Additionally, the Commission reviewed the recommendations to change the standard atomic weights of Yb (2015), Ar (2017), Ir (2017), Hf (2019), and Pb (2021) based on the review of published data on the isotopic composition of these elements, as well as the standard atomic weights of 14 other elements (2017, 2021) based on the Atomic Mass Evaluation 2016 and 2020 under the auspices of the International Union of Pure and Applied Physics (Al, Au, Co, F, Ho, Mn, Nb, Pa, Pr, Rh, Sc, Tb, Tm, Y).

The creation of an international commission assigned with the evaluation of the atomic weights dates back to 1897, when soon-to-be Nobel laureate Hermann Emil Fischer proposed the creation of a working committee to report on atomic weights. The working committee consisted of Wilhelm Ostwald (University of Leipzig), Karl Seubert (University of Hanover), and Hans H. Landolt (Berlin University), serving as chair. This committee published its first report in 1898, wherein it suggested the desirability of an International Committee on Atomic Weights. To this end, on 30 March 1899 the invitation was sent to national scientific organizations worldwide to appoint delegates to the International Committee on Atomic Weights, which was formed in 1899, and consisted of 56 delegates from 11 countries. Dated Tables of Atomic Weights published by the Commission refer to our best knowledge of the elements in natural terrestrial sources and have been published since 1902 [1]. The previous Commission report was published following its 2013 meeting [2] and the current report is a result of the deliberations during the 2015, 2017, 2019 and 2021 meetings of the Commission. Data are also provided in IUPAC news releases [3–5] and the IUPAC Periodic Table of the Elements and Isotopes (IPTEI) for the Education Community [6]. Additionally, data are reported on the CIAAW website (ciaaw.org), and the online periodic table of the elements and isotopes is provided by the IUPAC [7, 8].

Because standard atomic weights of elements in normal terrestrial materials and chemicals are widely used in science and the uncertainties associated with these values are not well understood, a technical report provides guidelines for the use of standard atomic weights [9].

2 General terms

The **atomic mass**, $\boldsymbol{m_a(^iE)}$, of an unbound neutral atom of a nuclide ^iE of an element E with the mass number i is defined as "rest mass of an atom in its ground state" [10]. The commonly used unit is the unified atomic mass unit or dalton [10]. The 2020 Atomic Mass Evaluation report (AME2020) is a recent authoritative document containing the nuclide masses and their uncertainties using least-squares adjustments of all evaluated and accepted experimental data [11]. These masses are used for calculating the atomic weights and standard atomic weights of the elements.

The **atomic weight** (this term is further used in the manuscript) or **relative atomic mass**, $A_r(^iE)$, **of an atom** (the unbound neutral nuclide) ^iE of element E is defined as the "ratio of the mass of the atom to the unified atomic mass unit" [10]. The atomic mass constant m_u is equal to the dalton, Da, or the unified atomic mass unit, u, and is defined in terms of the mass of the carbon-12 atom: $m_u = 1\ u = 1\ Da = m_a(^{12}C)/12$ [12]. Thus, the atomic weight is a quantity of dimension 1 (dimensionless quantity):

$$A_r(^iE) = m_a(^iE)/[m_a(^{12}C)/12] \quad (1)$$

The **atomic weight of an element** E, in a substance P, $A_r(E, P)$, is the weighted average of the atomic weights $A_r(^iE)$ of the isotopes (nuclides) ^iE of this element in substance P:

$$A_r(E, P) = \sum x(^iE, P)A_r(^iE) \quad (2)$$

Here, $x(^iE, P)$ is the amount fraction of isotope ^iE in substance P (also called the isotopic abundance) and the summation is over all stable isotopes and radioactive isotopes having characteristic terrestrial isotopic signatures [6], and they are listed in the Commissions Table of Isotopic Compositions of the Elements. The atomic weight of an element in a given substance can be determined from the knowledge of the atomic masses of the isotopes and the corresponding amount fractions of the isotopes of that element in this specific substance.

The **standard atomic weight of an element**, $A_r°(E)$, is the "recommended value of atomic weight (relative atomic mass) of an element revised biennially by the CIAAW and applicable to elements in any normal material with a high level of confidence" [10]. It is comprised of either an interval (currently used for 14 elements) or a value and an uncertainty (a standard atomic-weight uncertainty), which are currently used for 71 elements (see also Sections 4 and 6). A standard atomic weight is determined from an evaluation of peer-reviewed scientific publications. The standard atomic weights are consistent with the atomic weight values calculated from the isotopic abundances listed in Column 9 of the Table of Isotopic Composition of the Elements [13].

Based on the report of the Subcommittee on Natural Assessment of Fundamental Understanding of Isotopes of the Commission, a **normal material** is a material which originates from a terrestrial source that satisfies the following definition [14]:

> 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 natural nuclear reactor products from Oklo (Gabon) or other unique occurrences.

In contrast to the previous definition (see [14]), this revised definition recognizes the fact that the variation of the atomic weight of some elements is caused by isotopic fractionation processes that operate on many different time scales. It also reintroduces the exclusion of extraterrestrial materials from the determination of standard atomic weights. The new definition is more inclusive than some earlier versions with respect to naturally occurring materials having nucleogenic and radiogenic isotopic variation, as exemplified by argon [15] and lead [16].

3 Categorization of elements by their atomic weight and isotopic composition variations

Because variation in isotopic composition of an element impacts its atomic weight, the Commission has undertaken a periodic assessment of variations of isotopic compositions in the published literature, both through its Subcommittees and through IUPAC projects [17]. All known elements can be categorized according to the following constraints on their standard atomic weights:

(1) Elements with no stable isotope and with no characteristic terrestrial isotopic composition in normal materials (*e.g.* radon). No standard atomic weight can be determined and no value is provided in the Table of Standard Atomic Weights for these elements. These elements have a white background of the entries in the IUPAC Periodic Table of the Elements and Isotopes [6].

(2) Elements whose standard atomic weights are determined by only one isotope (*e.g.* sodium). The standard atomic weight is derived from the atomic weight of its stable or long-lived isotope (*e.g.* bismuth or protactinium). These elements have a blue background of the entries in the IUPAC Periodic Table of the Elements and Isotopes [6].
(3) Elements whose standard atomic weights are determined by more than one isotope are shown on the IUPAC Periodic Table of the Elements and Isotopes with a yellow background of the entries [6]. They are subdivided into three subcategories:
    a. Elements that have no documented evidence of variation in the atomic weight for normal materials, or elements that have not been evaluated for variation in isotopic composition by an IUPAC project (*e.g.* indium). Elements in this subcategory may enter category 3b as more accurate isotopic abundance measurements are published.
    b. Elements that have known variations in the atomic weight in normal materials, but these variations do not exceed the evaluated measurement uncertainty of the atomic weight derived from the "best measurement" of the isotopic abundances of an element (*e.g.* molybdenum). Elements in this subcategory can advance to category 3c or 4 as measurement results improve.
    c. Elements that have known variations in the atomic weight in normal materials that exceed the uncertainty of the atomic weight derived from a "best measurement" of isotopic abundances, but are not yet assigned a standard atomic weight interval by the Commission (*e.g.* copper). Elements in this subcategory can advance to category 4 as the Commission completes evaluations and assigns standard atomic weight intervals. The Commission uses the footnote "r" to identify elements in this subcategory for which the standard atomic weight uncertainty has been expanded to account for known atomic weight variability.
(4) Elements with two or more isotopes having known variations in the atomic weight in normal materials that exceed the uncertainty of the atomic weight derived from a "best measurement" of isotopic abundances and having upper and lower atomic weight bounds determined by the Commission from evaluated, peer reviewed, published data (*e.g.* hydrogen). These elements have a pink background for each element cell on the IUPAC Periodic Table of the Elements and Isotopes [6].

The Commission uses the footnote "g" to identify chemical elements for which the reported standard atomic weight and its associated uncertainty do not include all known variations (see definition of the term "normal" material above). For example, some elements are anomalously enriched in fissionogenic or nucleogenic isotopes at the Oklo natural nuclear reactor site in Gabon, Africa, and the atomic weights in those materials are not included in the determination of the standard atomic weight (exception (3) in the definition of the term "normal" material). For elements in categories 3 and 4, the Commission uses the footnote "m" to identify those elements for which the standard atomic weight and its associated uncertainty in commercially available material do not include variations due to undisclosed or inadvertent isotopic fractionation (exception (1) in the definition of the term "normal" material). Minor periodic changes to the standard atomic weight values and uncertainties result from improved measurements of the atomic masses, and these changes primarily affect category-2 elements.

4 Standard atomic weight intervals

Many elements can be found on Earth in a variety of substances with substantially different genesis. As a consequence, the atomic weights of some elements vary significantly depending on the origin and age of these substances. In 2009 the Commission introduced the interval notation for those elements whose atomic weights vary significantly in nature, exceeding the measurement uncertainty of A_r for an element in a specific substance, and where such variations have been well documented. "Well-documented" is to be understood as reported in a peer-reviewed publication on the matter of natural variations of an element. The interval notation does not alter the meaning of the standard atomic weight, nor does it constitute "a new definition" of standard

atomic weights. Rather, it is an alternative means for expressing the uncertainty of this quantity. Writing the standard atomic weight of carbon as $A_r°(C) = [12.0096, 12.0116]$ indicates that at the current status of knowledge its atomic weight in any normal material will be greater than or equal to 12.0096 and will be less than or equal to 12.0116 [18]. Thus, the standard atomic weight is represented by an interval, which encompasses atomic weights of normal materials. It is important to note that no particular value in the interval should be regarded as more representative than any other and that the natural variability of the isotopic composition is the dominant source of the uncertainty expressed by the interval. To date, the Commission provides the standard atomic weight as an interval for 14 elements: argon, boron, bromine, carbon, chlorine, hydrogen, lead, lithium, magnesium, nitrogen, oxygen, silicon, sulfur, and thallium [4, 18, 19].

For some elements, atomic weights calculated from published variations in isotopic compositions of different substances can span intervals which are large compared to measurement uncertainties of atomic weights, which are determined in a specific substance P, $A_r(E, P)$. For example, the atomic weight of carbon in normal materials spans the interval from 12.0096 to 12.0116 and leads to a standard atomic weight of $A_r°(C) = [12.0096, 12.0116]$. In contrast, the uncertainty of the atomic weight calculated from the isotopic abundance of carbon in a specific material (NBS 19 calcium carbonate) is approximately 50 times smaller [18]: $A_r(C, \text{NBS 19}) = 12.011\,12 \pm 0.000\,02$ ($k = 2$). The atomic weight of boron in normal materials spans an interval from 10.806 to 10.821 (standard atomic weight $A_r°(B) = [10.806, 10.821]$). In contrast, the atomic weight of boron in a specific substance can be measured down to the fourth decimal place. For example, the atomic weight of boron in the NIST reference material of boric acid SRM 951a [20] is $A_r(B, \text{SRM 951a}) = 10.8118 \pm 0.0001$ ($k = 2$).

This span of atomic weight values in normal materials is termed "interval". The interval $[a, b]$ is the set of values x for which $a \le x \le b$, where $a < b$ and where a and b are the lower and upper bounds of the interval [21]. Lower bounds are rounded downward and upper bounds are rounded upward. Each bound is a considered decision by the Commission determined from the lowest and highest atomic weight based on professional evaluation and judgment of published, peer reviewed data with consideration of measurement uncertainties.

The range of an interval $[a, b]$ is the difference between its upper and lower bounds, that is $b - a$ [21]. Thus, the range of the standard atomic weight interval of carbon is calculated as $12.0116 - 12.0096 = 0.0020$. The interval does not imply any statistical distribution of atomic weight values between the lower and upper bound (*e.g.* the arithmetic mean of a and b is not necessarily the most likely value). Similarly, the interval does not convey a simple statistical representation of uncertainty. The probability density function may differ case by case, due to varying sources and their proportions may need to be considered. If no additional information is available or utilized, the probability density function associated with the standard atomic weights can be considered as uniform (rectangular). Information on the range of standard atomic weights expressed in interval notation is available for argon in Figs. 3–5, for lead in Figs. 6–9 and for the other 12 such elements in the papers of Meija et al. [2] and Coplen and Shrestha [22–24]. These ranges have to be interpreted as uniform probability density functions because there is no information available on the relative probability of encountering any specific value in the ranges displayed.

5 Isotope delta measurements

Commonly, isotope delta measurements are the basis for the determination of the atomic weight [25–27]. The isotope delta is obtained from the isotope number ratio $R(^{i/j}E)$ in a substance P:

$$R\left(^{i/j}E, P\right) = N\left(^{i}E, P\right) / N\left(^{j}E, P\right) \tag{3}$$

where $N(^{i}E, P)$ and $N(^{j}E, P)$ are the numbers of atoms of each isotope, and ^{i}E denotes in general the higher (superscript i) and ^{j}E the lower (superscript j) atomic mass numbers of the isotopes of the chemical element E in substance P. ^{j}E represents the reference isotope which is not necessarily the isotope with the lowest atomic mass number. The isotope delta value (symbol δ), also called the relative isotope ratio difference, is a

differential measurement obtained from isotope number ratios of substance P and a scale represented by a reference material [28].

$$\delta_{\mathrm{Ref}}\left({}^{i/j}\mathrm{E},\ \mathrm{P}\right) = R\left({}^{i/j}\mathrm{E},\ \mathrm{P}\right)/R\left({}^{i/j}\mathrm{E},\ \mathrm{Ref}\right) - 1 \tag{4}$$

Isotope delta values are small numbers and therefore frequently presented in multiples of 10^{-3} or per mil (symbol ‰). To match an isotope delta scale of an element to an isotope amount scale, a substance is needed whose isotopic abundances and whose isotope delta value is also well known relative to the isotope delta scale. Commonly this substance is an isotopic reference material [28] that has served as the "best measurement" material for the determination of isotopic abundances [13]. For carbon, as an example, the $x({}^{13}\mathrm{C})$ abundance scale is matched to the $\delta_{\mathrm{VPDB}}({}^{13/12}\mathrm{C})$ scale through the measurement of the isotopic reference material NBS 19 (calcium carbonate), which has been assigned the consensus $\delta_{\mathrm{VPDB}}({}^{13/12}\mathrm{C},\ \mathrm{NBS\ 19})$ value of +1.95 ‰. The carbon isotope number ratio of NBS 19 was measured by Zhang and Li [29] and is $R({}^{13/12}\mathrm{C},\ \mathrm{NBS\ 19}) = 0.011\,202 \pm 0.000\,028$. This measurement serves as the "best measurement" of a single terrestrial source [13]. Vienna Peedee belemnite (VPDB) is the zero point on the carbon isotope-delta scale and therefore $\delta_{\mathrm{VPDB}}({}^{13/12}\mathrm{C},\ \mathrm{VPDB}) = 0$. Since 1 ‰ = 0.001, it follows:

$$R\left({}^{13/12}\mathrm{C},\ \mathrm{VPDB}\right) = 0.011\,202/\left(1 + 1.95 \times 0.001\right) = 0.011\,180 \tag{5}$$

Therefore, ignoring the uncertainty, the relation between carbon isotope delta values (δ) and $^{13}\mathrm{C}$ amount fractions (x) of a material P is:

$$x\left({}^{13}\mathrm{C},\ \mathrm{P}\right) = 1/\left[1 + 1/\left\{R\left({}^{13/12}\mathrm{C},\ \mathrm{VPDB}\right) \times \left[1 + \delta_{\mathrm{VPDB}}\left({}^{13}\mathrm{C},\ \mathrm{P}\right)\right]\right\}\right] \tag{6}$$

For example, consider the material with the lowest measured isotopic abundance of carbon-13, crocetane (2,6,11,15-tetramethylhexadecane), produced at cold seeps of the eastern Aleutian subduction zone. The material has a published $\delta_{\mathrm{VPDB}}({}^{13}\mathrm{C})$ value of (-130.3 ± 0.3) ‰ ($k = 1$) [30]. The isotopic abundance of carbon-13 of this specimen is determined using eq. (5) and is $x({}^{13}\mathrm{C}) = 0.009\,630 \pm 0.000\,003$. Likewise, the isotopic abundance of carbon-12 is $x({}^{12}\mathrm{C}) = 1 - x({}^{13}\mathrm{C})$. The atomic weight of carbon in this specimen is determined using the carbon isotope number ratio of VPDB as calculated in eq. (2), the isotopic abundances of carbon-12 and carbon-13, and the atomic weight values of carbon-12 and carbon-13 isotopes ($A_{\mathrm{r}}({}^{12}\mathrm{C}) = 12$ and $A_{\mathrm{r}}({}^{13}\mathrm{C}) = 13.003\,354\,835 \pm 0.000\,000\,002$). For this material, $A_{\mathrm{r}}(\mathrm{C}) = 12.009\,662 \pm 0.000\,003$ ($k = 1$).

If material P is the normal material having the lowest atomic weight of element E, then the lower bound is $A_{\mathrm{r}}(\mathrm{E},\ \mathrm{P}) - U[A_{\mathrm{r}}(\mathrm{E},\ \mathrm{P})]$ where $U[A_{\mathrm{r}}(\mathrm{E},\ \mathrm{P})]$ is the expanded uncertainty that incorporates the uncertainty in the measurement of the delta value of material P and the uncertainty in relating the delta-value scale to the isotope amount fraction and atomic weight scales. The latter is the uncertainty in relating an isotope delta scale to an atomic weight scale.

The expanded uncertainty U is obtained by multiplying the combined standard uncertainty of a quantity y, $u_{\mathrm{c}}(y)$, by a coverage factor k, $U = k \times u_{\mathrm{c}}(y)$. The value of k varies between elements and is at least 2.

6 Uncertainty of standard atomic weights

Uncertainties of standard atomic weights are estimated by the Commission through evaluation of the relevant published literature. The atomic weight of any element is expected to be within the interval indicated by the uncertainty of the standard atomic weight (or within the explicit standard atomic weight interval for 14 elements) at great certitude for normal materials which have been investigated at the time of the compilation of the data. The values are the result of a decision reached after consideration of the relevant data [31, 32], which includes the quality of the measurements [2, 33]. The intervals, in which the atomic weight values of elements in normal materials are expected, are either given by the reported $A_{\mathrm{r}}°(\mathrm{E})$ values and their uncertainties $U[A_{\mathrm{r}}°(\mathrm{E})]$ (Table 1, columns 4 and 5) or as explicit intervals (for 14 elements, see Table 1, column 4).

The reported uncertainties of the standard atomic weights, $U[A_r°(E)]$, are such that the atomic weight values of normal materials are expected to lie between $A_r°(E) - U[A_r°(E)]$ and $A_r°(E) + U[A_r°(E)]$ with great certitude. Hence, for example, the standard atomic weight of iridium, 192.217 ± 0.002, indicates that atomic weight values of iridium in normal materials are expected to be equal to or higher than 192.215 and equal to or lower than 192.219.

The uniform distribution on these intervals (specified either as the uncertainty $U[A_r°(E)]$ or as an explicit interval) can be used as a simple and practically useful model for a complex reality [34]. The interpretation of a standard atomic weight in terms of a uniform distribution, concentrated either on the given interval itself or on the interval determined by that uncertainty, serves to summarize the knowledge about the natural variability of atomic weight values while disregarding the anatomy of this variability among the vast collection of all normal materials [34]. Other statistical models may be more appropriate and can provide a better representation of this anatomy.

With improvements in analytical instrumentation during the last three decades, documented variations in atomic weight values of some elements in normal materials exceed the uncertainty of the atomic weight determined from a "best measurement". These elements are given footnote "r" in the IUPAC Table of Standard Atomic Weights (Table 1) to indicate that the range of the isotopic composition of normal material prevents the assignment of a lower uncertainty value for the standard atomic weight of these elements (unless they are assigned intervals for their standard atomic-weight values).

7 The Table of Standard Atomic Weights

The Table of Standard Atomic Weights is given in the order of increasing atomic number (Table 1). The Table of Standard Atomic Weights is intended to apply to all normal terrestrial materials with minor exceptions covered by footnotes. Standard atomic weights do not apply to extraterrestrial materials nor do they apply to materials with deliberately altered isotopic composition with the exception of lithium, for which artificially ^{6}Li-depleted substances have been included in the determination of its $A_r°$ value. Standard atomic weights are given as a single value with uncertainties or as an interval (Table 1, columns 4 and 5).

During the review of the last Commission report [2], it was noted that the expression of uncertainty of standard atomic weights was not in compliance with the GUM (Guide to the Expression of Uncertainty in Measurement) [35]. For example, the standard atomic weight of iridium, which is 192.217, having an uncertainty of ±0.002, would be tabulated as 192.217(2). However, this format does not comply with the expression of uncertainty in the GUM [35] as this format suggests that the stated uncertainty is a standard uncertainty. Based on the work of the Subcommittee on Natural Assessment of Fundamental Understanding of Isotopes [17], the Commission selected the format in which the uncertainty value is delineated with the symbol "±"; *e.g.*, the standard atomic weight of iridium is now expressed as 192.217 ± 0.002. In the Table of Standard Atomic Weights 2021 the uncertainty is tabulated in a new column, or in interval notation. In addition, based on a collaboration between the Subcommittee and the Commission, a new footnote with the symbol double dagger (‡) was added to the Table of Standard Atomic Weights (Table 1) to emphasize that an atomic-weight uncertainty is a consensus based on expert judgement [17, 31, 36].

The detail and number of significant digits reported in the Table of Standard Atomic Weights (Table 1) exceeds in many cases the needs of users and in some cases, a single value is needed for further calculations considering interval elements. Therefore, tables of abridged standard atomic weights have been published since 1981 with the expectation that revisions of these abridged values will be minimal if changes to the corresponding standard atomic weights should become necessary. Additionally, a table abridged to four significant digits was published along with the standard atomic weight table and a table with conventional atomic-weight values for interval elements.

In order to provide clearer recommendations to serve the needs of commerce, education, industry and research, the Commission has decided in its 2015, 2017 and 2019 meetings to provide a single table containing both standard atomic weights and abridged standard atomic weights for general use. The CIAAW

acknowledges that standard atomic weights might provide too many details. For this purpose, abridged atomic weights are quoted to five significant figures (Table 1, column 7) unless such precision cannot be attained due to the variability of isotopic composition in normal materials or due to the limitations of the measurement capability. A conservative +/– value (Table 1, column 8) is given as a simplified measure of the reliability of the abridged values.

The "conventional atomic weights" of previous reports for interval elements were included in this column in order to provide a single table for further usage. The previous "conventional atomic weights" can be extracted from this column except that for hydrogen, which was 1.008, and has been expanded to 1.0080 to provide a lower uncertainty value in column 8. The columns 7 and 8 provide a single atomic weight value (column 7) including an uncertainty (column 8) for all elements having a standard atomic weight value or standard atomic weight interval according to the following rules:

i) For elements that do not have a standard atomic weight expressed as an interval and have a standard atomic weight value expressed with five or fewer significant digits, the value in column 7 (abridged standard atomic weight) corresponds to the value in column 4. The uncertainty (column 8) corresponds to the uncertainty in column 5 (Table 1).

ii) For elements that do not have their standard atomic weight expressed as an interval and have a standard atomic weight with more than 5 significant digits, the standard atomic weight value is abridged to 5 significant digits in column 7. The conservative uncertainty value given in column 8 for these elements corresponds to the place value of the last rounded and thus least significant digit of the value in column 8 providing the reliability of the abridged values.

iii) For 14 elements (argon, boron, bromine, carbon, chlorine, hydrogen, lead, lithium, magnesium, nitrogen, oxygen, silicon, sulfur, and thallium) the standard atomic weight is given as an atomic weight interval in column 4 (Table 1). For these elements, a single value is provided in column 7, replacing the former conventional atomic weights for education, trade and commerce published in a "Table of Conventional Atomic Weights" in previous reports [2, 18, 19]. These values can be used if a single atomic-weight value is required and the significant numbers of digits are sufficient for further use. The value provided in column 7 for these elements does not correspond necessarily to the midpoints of the intervals (in case of Li, Mg, S, Ar and Pb), and many correspond to the A_r values of frequently used reference materials (*e.g.* NIST SRM 981 for Pb; argon in tropospheric air for Ar). A corresponding conservative +/– value is provided in column 8 which corresponds to the smallest symmetric number in order to cover the standard atomic weight interval. The significant numbers of digits after the decimal point of the abridged atomic weights corresponds to the significant numbers of digits after the decimal point of this value.

Table 1: Standard atomic weights of the elements (Table of Standard Atomic Weights 2021). Standard atomic weights, $A_r°(E)$, are listed in increasing atomic number (column 3) with the element name (column 1) and element symbol (column 2). Commonly used alternative spellings for aluminium and caesium are aluminum and cesium. Standard atomic weights are given as single values (column 4) with uncertainties (column 5) or as intervals (column 4). Standard atomic weights are expressed as the ratio of the average mass of the atom to the unified atomic mass unit. The stated uncertainties (column 5) are uncertainties for normal materials and include evaluations of measurement uncertainty and natural variability. The footnotes (column 6) to this table elaborate the types of variations that may occur for individual elements and that may lie outside the values listed.
Standard atomic weight intervals are given in column 4 with the symbol [a, b] to denote the set of atomic weight values in normal materials for 14 elements ($a \le A_r(E) \le b$ for element E). For these 14 elements, abridged atomic weight values including a +/– value corresponding to the smallest symmetric number in order to cover the standard atomic weight interval are given in column 7 and 8. These values replace the previously published conventional atomic weights, except that for hydrogen, which was 1.008, and has been expanded to 1.0080 to provide a lower value in column 8.

1	2	3	4	5	6	7	8
Element	**Symbol**	**Atomic number**	**Standard atomic weight**		**Foot-note**	**Abridged standard atomic weight**	
			Value	**Uncertainty‡**		**Value**	+/–
hydrogen	H	1	[1.007 84, 1.008 11]		m	1.0080	0.0002
helium	He	2	4.002 602	0.000 002	g r	4.0026	0.0001
lithium	Li	3	[6.938, 6.997]		m	6.94	0.06

Table 1: (continued)

1	2	3	4	5	6	7	8
Element	**Symbol**	**Atomic number**	**Standard atomic weight**		**Foot-note**	**Abridged standard atomic weight**	
			Value	**Uncertainty‡**		**Value**	+/−
beryllium	Be	4	9.012 1831	0.000 0005		9.0122	0.0001
boron	B	5	[10.806, 10.821]		m	10.81	0.02
carbon	C	6	[12.0096, 12.0116]			12.011	0.002
nitrogen	N	7	[14.006 43, 14.007 28]		m	14.007	0.001
oxygen	O	8	[15.999 03, 15.999 77]		m	15.999	0.001
fluorine	F	9	18.998 403 162	0.000 000 005		18.998	0.001
neon	Ne	10	20.1797	0.0006	g m	20.180	0.001
sodium	Na	11	22.989 769 28	0.000 000 02		22.990	0.001
magnesium	Mg	12	[24.304, 24.307]			24.305	0.002
aluminium	Al	13	26.981 5384	0.000 0003		26.982	0.001
silicon	Si	14	[28.084, 28.086]			28.085	0.001
phosphorus	P	15	30.973 761 998	0.000 000 005		30.974	0.001
sulfur	S	16	[32.059, 32.076]			32.06	0.02
chlorine	Cl	17	[35.446, 35.457]		m	35.45	0.01
argon	Ar	18	[39.792, 39.963]			39.95	0.16
potassium	K	19	39.0983	0.0001		39.098	0.001
calcium	Ca	20	40.078	0.004	g	40.078	0.004
scandium	Sc	21	44.955 907	0.000 004		44.956	0.001
titanium	Ti	22	47.867	0.001		47.867	0.001
vanadium	V	23	50.9415	0.0001		50.942	0.001
chromium	Cr	24	51.9961	0.0006		51.996	0.001
manganese	Mn	25	54.938 043	0.000 002		54.938	0.001
iron	Fe	26	55.845	0.002		55.845	0.002
cobalt	Co	27	58.933 194	0.000 003		58.933	0.001
nickel	Ni	28	58.6934	0.0004	r	58.693	0.001
copper	Cu	29	63.546	0.003	r	63.546	0.003
zinc	Zn	30	65.38	0.02	r	65.38	0.02
gallium	Ga	31	69.723	0.001		69.723	0.001
germanium	Ge	32	72.630	0.008		72.630	0.008
arsenic	As	33	74.921 595	0.000 006		74.922	0.001
selenium	Se	34	78.971	0.008	r	78.971	0.008
bromine	Br	35	[79.901, 79.907]			79.904	0.003
krypton	Kr	36	83.798	0.002	g m	83.798	0.002
rubidium	Rb	37	85.4678	0.0003	g	85.468	0.001
strontium	Sr	38	87.62	0.01	g r	87.62	0.01
yttrium	Y	39	88.905 838	0.000 002		88.906	0.001
zirconium	Zr	40	91.224	0.002	g	91.224	0.002
niobium	Nb	41	92.906 37	0.000 01		92.906	0.001
molybdenum	Mo	42	95.95	0.01	g	95.95	0.01
technetium*	Tc	43					
ruthenium	Ru	44	101.07	0.02	g	101.07	0.02
rhodium	Rh	45	102.905 49	0.000 02		102.91	0.01
palladium	Pd	46	106.42	0.01	g	106.42	0.01
silver	Ag	47	107.8682	0.0002	g	107.87	0.01
cadmium	Cd	48	112.414	0.004	g	112.41	0.01
indium	In	49	114.818	0.001		114.82	0.01
tin	Sn	50	118.710	0.007	g	118.71	0.01
antimony	Sb	51	121.760	0.001	g	121.76	0.01
tellurium	Te	52	127.60	0.03	g	127.60	0.03
iodine	I	53	126.904 47	0.000 03		126.90	0.01
xenon	Xe	54	131.293	0.006	g m	131.29	0.01
caesium	Cs	55	132.905 451 96	0.000 000 06		132.91	0.01
barium	Ba	56	137.327	0.007		137.33	0.01

Table 1: (continued)

1	2	3	4	5	6	7	8
Element	**Symbol**	**Atomic number**	**Standard atomic weight**		**Foot-note**	**Abridged standard atomic weight**	
			Value	**Uncertainty**[‡]		**Value**	+/−
lanthanum	La	57	138.905 47	0.000 07	g	138.91	0.01
cerium	Ce	58	140.116	0.001	g	140.12	0.01
praseodymium	Pr	59	140.907 66	0.000 01		140.91	0.01
neodymium	Nd	60	144.242	0.003	g	144.24	0.01
promethium*	Pm	61					
samarium	Sm	62	150.36	0.02	g	150.36	0.02
europium	Eu	63	151.964	0.001	g	151.96	0.01
gadolinium	Gd	64	157.25	0.03	g	157.25	0.03
terbium	Tb	65	158.925 354	0.000 007		158.93	0.01
dysprosium	Dy	66	162.500	0.001	g	162.50	0.01
holmium	Ho	67	164.930 329	0.000 005		164.93	0.01
erbium	Er	68	167.259	0.003	g	167.26	0.01
thulium	Tm	69	168.934 219	0.000 005		168.93	0.01
ytterbium	Yb	70	173.045	0.010	g	173.05	0.02
lutetium	Lu	71	174.9668	0.0001	g	174.97	0.01
hafnium	Hf	72	178.486	0.006	g	178.49	0.01
tantalum	Ta	73	180.947 88	0.000 02		180.95	0.01
tungsten	W	74	183.84	0.01		183.84	0.01
rhenium	Re	75	186.207	0.001		186.21	0.01
osmium	Os	76	190.23	0.03	g	190.23	0.03
iridium	Ir	77	192.217	0.002		192.22	0.01
platinum	Pt	78	195.084	0.009		195.08	0.02
gold	Au	79	196.966 570	0.000 004		196.97	0.01
mercury	Hg	80	200.592	0.003		200.59	0.01
thallium	Tl	81	[204.382, 204.385]			204.38	0.01
lead	Pb	82	[206.14, 207.94]			207.2	1.1
bismuth*	Bi	83	208.980 40	0.000 01		208.98	0.01
polonium*	Po	84					
astatine*	At	85					
radon*	Rn	86					
francium*	Fr	87					
radium*	Ra	88					
actinium*	Ac	89					
thorium*	Th	90	232.0377	0.0004	g	232.04	0.01
protactinium*	Pa	91	231.035 88	0.000 01		231.04	0.01
uranium*	U	92	238.028 91	0.000 03	g m	238.03	0.01
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					
nobelium*	No	102					
lawrencium*	Lr	103					
rutherfordium*	Rf	104					
dubnium*	Db	105					
seaborgium*	Sg	106					
bohrium*	Bh	107					
hassium*	Hs	108					

Table 1: (continued)

1	2	3	4	5	6	7	8
Element	**Symbol**	**Atomic number**	**Standard atomic weight**		**Foot-note**	**Abridged standard atomic weight**	
			Value	**Uncertainty**‡		**Value**	+/−
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 isotope, only radioactive isotopes. For four elements (Bi, Th, Pa, and U) a standard atomic weight is tabulated because these elements have a characteristic terrestrial isotopic composition; for the other 34 elements a standard atomic weight cannot be determined.

‡$A_r°$(E) values and their uncertainties are given for normal materials and include evaluations of measurement uncertainty as well as natural variations in atomic weight where applicable. The atomic weight of a normal material is expected to lie within the lower and upper endpoints of the standard atomic weight at the current status of knowledge. If the uncertainty in $A_r°$(E) is considered too large for a user's purpose for an element with measurable variations in atomic weight, a value of A_r(E) with a lower uncertainty might be obtained by measurement of an individual specimen.

g Geological and biological 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 uncertainty.

m Modified isotopic compositions may be found in commercially available material because the material has been subjected to some 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 being given; the tabulated value and uncertainty should be applicable to normal material.

8 Comments on standard atomic weights of selected elements

Since the inaugural International Atomic Weights report, published in 1902, the Commission has provided rationale for the changes in the reported atomic weights. This description is accompanied by the historical list of reported values. Brief descriptions of the changes to the standard atomic weights resulting from the Commission meetings in 2015, 2017, 2019, and 2021 are provided below.

8.1 Argon

The isotopic composition of argon is variable in terrestrial materials. Those variations are a source of uncertainty in the assignment of standard properties for argon, but they provide useful information in many areas of science [15]. Variations in the stable isotopic composition and atomic weight of argon are caused by several different processes, including (1) isotope production from other elements by radioactive decay (radiogenic isotopes) or other nuclear transformations (nucleogenic isotopes), and (2) isotopic fractionation by physical–chemical processes such as diffusion or phase equilibration. The latter physical–chemical processes cause correlated mass-dependent variations in the argon isotope-amount ratios $n(^{40}\mathrm{Ar})/n(^{36}\mathrm{Ar})$ and $n(^{38}\mathrm{Ar})/n(^{36}\mathrm{Ar})$, where the relative variation in the $n(^{40}\mathrm{Ar})/n(^{36}\mathrm{Ar})$ is about twice the variation in $n(^{38}\mathrm{Ar})/n(^{36}\mathrm{Ar})$ because of the factor of two difference in the isotope masses. In contrast, nuclear transformation processes cause variations

that do not follow this pattern. For example, a process producing ^{40}Ar would change the $n(^{40}\mathrm{Ar})/n(^{36}\mathrm{Ar})$ amount ratio, but not $n(^{38}\mathrm{Ar})/n(^{36}\mathrm{Ar})$; a process producing ^{36}Ar would lead to equal relative changes in both $n(^{40}\mathrm{Ar})/n(^{36}\mathrm{Ar})$ and $n(^{38}\mathrm{Ar})/n(^{36}\mathrm{Ar})$.

While atmospheric argon can serve as an abundant and homogeneous isotopic reference, deviations from the atmospheric isotopic ratios in other argon sources limit the precision with which a standard atomic weight can be given for argon. Published data indicate variation of argon atomic weights in normal terrestrial materials between 39.792 and 39.963 [15]. The upper endpoint of this interval corresponds to the atomic weight (relative atomic mass) of argon-40, as some K-rich mineral samples contain almost pure radiogenic argon-40 [15]. The atomic weight of pure argon-40, $A_r(^{40}\mathrm{Ar}) = 39.962\,383$, was rounded up to 39.963 to obtain the upper bound for the standard atomic weight of argon. The lower bound of the standard atomic weight of argon is from a sample of pitchblende (U ore from Saskatchewan, Canada) containing large amounts of nucleogenic isotopes ^{36}Ar and ^{38}Ar [37]. These measurements were calibrated against atmospheric argon. Conservatively, assuming both isotope ratios as independent and having 0.5 % expanded relative uncertainty to align with the Commission-recommended (2007) value of the isotope ratio in atmospheric argon [33, 38], we obtain isotope ratios $R(^{38}\mathrm{Ar}/^{36}\mathrm{Ar}) = 2.09 \pm 0.01$ and $R(^{40}\mathrm{Ar}/^{36}\mathrm{Ar}) = 45.2 \pm 0.22$ and the atomic weight $A_r(\mathrm{Ar}) = 39.7931 \pm 0.0009$ ($k = 2$) thus giving the lower endpoint of the standard atomic weight of argon $39.7931 - 0.0009 = 39.792$ (rounded down). Within the standard atomic weight interval of argon, measurements of different isotope ratios, $R(^{40}\mathrm{Ar}/^{36}\mathrm{Ar})$ or $R(^{38}\mathrm{Ar}/^{36}\mathrm{Ar})$ at various levels of precision are widely used for studies in geochronology, water-rock interaction, atmospheric evolution, and other fields [14]. If a single atomic-weight value is needed, the Commission recommends using 39.95 ± 0.16, which corresponds to the argon in air with an uncertainty covering normal materials. Reported historical values of the standard atomic weight of argon have been [31, 39]: 1902, 39.9; 1911, 39.88; 1920, 39.9; 1925, 39.91; 1931, 39.944; 1961, 39.948; 1969, 39.948 ± 0.003; and 1979, 39.948 ± 0.001. The proposed element cell for argon for the IUPAC Periodic Table of the Elements and Isotopes [6] is given in Fig. 1.

Fig. 1: Proposed element cell for argon for the IUPAC Periodic Table of the Elements and Isotopes [6]. The pink background designates an element for which (1) two or more isotopes are used to determine the standard atomic weight and (2) the isotopic abundances and atomic weights vary in normal materials, and these variations exceed measurement uncertainty and are well known. The standard atomic weight value, "[39.792, 39.963]", is given as a lower and upper bounds within square brackets "[ ]". The single atomic-weight value for education, commerce, and industry of 39.95, corresponding to previously published conventional atomic-weight values [2, 18, 19], is shown in white.

8.2 Ytterbium

One of the last rare earth elements to be discovered, ytterbium was first obtained in a pure state just about 50 years ago. To date, only two calibrated measurements of its isotopic composition have been made: TIMS measurements by de Laeter et al. [40] and recent work by Wang et al. [41] who reported measurements for natural ytterbium samples and the reference material GBW 04623 employing both total evaporation TIMS (thermal ionization mass spectrometry) and MC ICP-MS (multi collector inductively coupled plasma mass spectrometry). While many other measurements of ytterbium isotopic compositions are available, they do not cover all ytterbium isotopes or they rely on assumed conventional values of certain isotope ratios. These

measurements differ from one another significantly and ytterbium therefore exemplifies the situation that is also true for many other elements: well-documented isotope ratio measurements are still needed.

While both studies employed fractionated ytterbium isotopes to calibrate isotope ratios, both measurements were only partially calibrated for the instrumental isotope ratio fractionation because only two or three separated near-pure isotopes (out of seven stable isotopes) were employed for calibrating the mass spectrometers. The uncertainties of such measurement results are expanded by a factor of $k = 6$ but the Commission adopted a larger-than-usual uncertainty expansion factor ($k = 9$) to the small uncertainty estimates reported by Wang et al. [41], especially for the uncertainty contribution due to weighing of isotope mixtures. Nonetheless, the work of Wang et al. [41] is reported as the new IUPAC "best measurement" for Yb isotopic composition. Evaluated results from these studies are as follows:

de Laeter et al. (2006) [40]:	$A_r(\mathrm{Yb}) = 173.0542$ ($u = 0.0008$, $k = 1$)
Wang et al. (2015) [41]:	$A_r(\mathrm{Yb}) = 173.0417$ ($u = 0.0002$, $k = 1$)

The Commission combined these results using the multivariate random effects model as implemented in the R package CIAAWconsensus [32] for calculating the standard atomic weight. For this, a priori uncertainty expansion factor of $k = 6$ was used for isotope ratios reported by de Laeter et al. [40] and a factor of $k = 9$ for isotope ratios reported by Wang et al. [41]. This resulted in the revised standard atomic weight of ytterbium $A_r^{\circ}(\mathrm{Yb}) = 173.045 \pm 0.010$ where 0.010 is the expanded uncertainty ($k \approx 3$). Reported historical values of standard atomic weight of ytterbium have been [31, 39]: 1902, 173.0; 1909, 172.0; 1916, 173.5; 1925, 173.6; 1931, 173.5; 1934, 173.04; 1969, 173.04 ± 0.03; and 2007, 173.054 ± 0.005.

8.3 Hafnium

Prior to 2019, the standard atomic weight of hafnium was set as the average result from three uncalibrated isotope ratio measurements published in the 1940s and 50s [42–44]. The recent work of Tong et al. has provided a new measurement on the JMC-475 standard material which is used in nearly all studies concerning measurements of the isotopic composition of hafnium [45]. This work measured the isotopic composition of hafnium in the JMC-475 standard using MC ICP-MS. The isotope ratio measurements were calibrated using the regression method which has been classified by the Commission as a new IUPAC best measurement of hafnium isotopic composition (the Commission considers this a 'partially' calibrated measurement). The atomic weight of hafnium in JMC-475 is 178.4864 with standard uncertainty 0.0004. With this, it is possible now to re-evaluate its atomic weight while considering the well-documented variations of the radiogenic $^{176}\mathrm{Hf}/^{177}\mathrm{Hf}$ isotope ratio in normal materials [46].

The radioactive decay of lutetium alters the isotopic composition of hafnium by producing the light isotope of hafnium-176. The majority of geological samples have $^{176}\mathrm{Hf}/^{177}\mathrm{Hf}$ isotope ratios between 0.2797 and 0.2848 which corresponds to the isotope delta $\delta(^{176}\mathrm{Hf}/^{177}\mathrm{Hf})$ from −8 ‰ to +10 ‰ relative to JMC-475 with lutetium-free materials providing the lowest $^{176}\mathrm{Hf}/^{177}\mathrm{Hf}$ ratios [46–48]. Given that this is the first re-evaluation of the isotopic composition of hafnium since the 1950s, we conservatively adopt the interval $\delta(^{176}\mathrm{Hf}/^{177}\mathrm{Hf})$ from −20 ‰ to +20 ‰ relative to JMC-475 to cover the variations in $^{176}\mathrm{Hf}/^{177}\mathrm{Hf}$ isotope ratios in natural materials. The standard atomic weight of hafnium is centered on the best estimate corresponding to JMC-475 and the calculation of the uncertainty associated with the standard atomic weight of hafnium (and the associated isotopic composition) was obtained as follows:

(1) Measurement uncertainty associated with the isotope ratios is taken from the IUPAC Best Measurement [45] whereas uncertainty of the isotope masses is taken from the AME2016 [49], both taken with additional coverage factor $k = 6$ following the CIAAW practices.
(2) We take a conservative estimate of mass-dependent natural variations in $^{180}\mathrm{Hf}/^{177}\mathrm{Hf}$ ratio as ±1 ‰ relative to JMC-475 (corresponding two times the interval observed by Tong et al. [45] from four commercial reagents).

Changes in all other isotope ratios were modelled according to the mass-dependent behavior: $\delta(^{179}Hf/^{177}Hf) = (2/3) \times \delta(^{180}Hf/^{177}Hf)$, $\delta(^{178}Hf/^{177}Hf) = (1/3) \times \delta(^{180}Hf/^{177}Hf)$, and $\delta(^{174}Hf/^{177}Hf) = -\delta(^{180}Hf/^{177}Hf)$.

(3) Natural variations of the radiogenic $^{176}Hf/^{177}Hf$ isotope ratio of hafnium are modeled independent of all other ratios and are very conservatively modelled as ±20 ‰ relative to JMC-475 (uniform distribution).

Together, the effect of these isotope-ratio variations was evaluated using the Monte Carlo method and the resulting standard uncertainty of the atomic weight of hafnium was $u = 0.0026$. Applying a probability coverage factor of $k = 2$ for expanded uncertainty leads to the value 0.0052, which, when rounded to 0.006, effectively corresponds to coverage factor $k = 2.3$. This resulted in the revised standard atomic weight of hafnium $A_r°(Hf) = 178.486 \pm 0.006$. Reported historical values of standard atomic weight of hafnium have been [31, 39]: 1931, 178.6; 1955, 178.50; 1961, 178.49; 1969, 178.49 ± 0.03; and 1985, 178.49 ± 0.02.

We also recognize that anomalous geological samples are known to have $^{176}Hf/^{177}Hf$ values well outside the standard atomic weight which necessitates the footnote "g" in the Table of Standard Atomic Weights. One of the most radiogenic isotopic compositions of hafnium ever measured for terrestrial rocks is reported in Barberton sedimentary Chert (South Africa) with $R(^{176}Hf/^{177}Hf) = 0.3657$, $\delta(^{176}Hf/^{177}Hf) = +296$ ‰ relative to JMC 475 having $A_r(Hf) = 178.447$ [46].

8.4 Iridium

In 1993, the Commission changed the reported value for the standard atomic weight of iridium to $A_r°(Ir) = 192.217 \pm 0.003$ based on high-precision measurements using both positive and negative thermal ionization mass spectrometry (TIMS). This value was reaffirmed in 2017 with the work of Zhu et al. using MC ICP-MS [50]. Zhu et al. employed a regression-based calibration method for the isotope ratios of iridium with NIST-certified isotopic reference materials of rhenium and thallium as primary standards. This measurement was classified by the Commission as partially calibrated because the regression model is still a relatively novel technique with its full potential and limitations still to be studied. Nevertheless, the measurement of Zhu et al. represents a significant improvement in the precision of the isotopic composition and atomic weight of iridium and is reported as the new IUPAC best measurement.

The Commission considered the results of three studies for calculating the standard atomic weight of iridium:

Chang et al. (1992) [51]:	$R_{191/193} = 0.593\,99$ ($u = 0.001\,03$, $k = 1$)
Walczyk et al. (1993) [52]:	$R_{191/193} = 0.594\,18$ ($u = 0.000\,37$, $k = 1$)
Zhu et al. (2017) [50]:	$R_{191/193} = 0.592\,90$ ($u = 0.000\,21$, $k = 1$)

These three independent results were combined using the random effects statistical model and DerSimonian and Laird estimator [53]. For this, the uncertainties of the isotope ratios reported from the individual studies were a priori expanded by coverage factors $k = 6$ (Chang et al. [51]), $k = 9$ (Walczyk et al. [52]), and $k = 6$ (Zhu et al. [50]) which follows the practice of the Commission whereby uncertainties of calibrated, partially-calibrated, and non-calibrated measurement results are expanded by a factor of 3, 6, or 9, respectively [32]. This resulted in the revised standard atomic weight of iridium, $A_r°(Ir) = 192.217 \pm 0.002$ where 0.002 is the expanded uncertainty ($k = 2$). Reported historical values of standard atomic weight of iridium have been [31, 39]: 1902, 193.0; 1909, 193.1; 1953, 192.2; 1969, 192.22 ± 0.03; and 1993, 192.217 ± 0.003.

8.5 Lead

The isotopic composition and atomic weight of lead are variable in terrestrial materials because its three heaviest stable isotopes are stable end-products of the radioactive decay of uranium (^{238}U to ^{206}Pb and ^{235}U to

^{207}Pb) and thorium (^{232}Th to ^{208}Pb). These variations in isotope ratios and atomic weights provide useful information in many areas of science, including geochronology, archaeology, environmental studies, and forensic science. While elemental lead can serve as an abundant and homogeneous isotopic reference, deviations from the isotope ratios in other lead occurrences limit the accuracy with which a standard atomic weight can be given for lead.

In a comprehensive review of several hundred publications and analyses of more than 8000 samples [16], published isotope data indicate that the lowest reported lead atomic weight of a normal terrestrial material is 206.1462 ± 0.0028 (k = 2), determined for a growth of the phosphate mineral monazite from the Lewisian complex in north-western Scotland, which contains mostly ^{206}Pb and almost no ^{204}Pb [54]. The highest published lead atomic weight 207.9351 ± 0.0005 (k = 2) is for monazite from a micro-inclusion. The material is also from the Lewisian complex in north-western Scotland containing almost pure radiogenic ^{208}Pb [54]. Assigning the aforementioned lead atomic weights as the lower and upper bounds of the interval, the standard atomic weight of lead is A_r^o(Pb) = [206.14, 207.94]. If a single atomic-weight value is needed, the Commission recommends using 207.2 ± 1.1, which corresponds to the common lead with a symmetric uncertainty covering normal materials. The proposed cell for lead for the IUPAC Periodic Table of Elements and Isotopes is shown in Fig. 2 with the conventional atomic-weight value of 207.2 shown in white. Reported historical values of the standard atomic weight of lead have been [31, 39]: 1902, 206.9; 1909, 207.10; 1916, 207.20; 1937, 207.21; 1961, 207.19; and 1969, 207.2 ± 0.1.

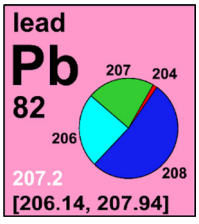

Fig. 2: Proposed element cell for lead for the IUPAC Periodic Table of the Elements and Isotopes [6]. The pink background designates an element for which (1) two or more isotopes are used to determine the standard atomic weight and (2) the isotopic abundances and atomic weights vary in normal materials, and these variations exceed measurement uncertainty and are well known. The standard atomic weight value, "[206.14, 207.94]", is given as a lower and upper bounds within square brackets [ ]. The single atomic-weight value for education, commerce, and industry of 207.2, corresponding to previously published conventional atomic-weight values [2, 18, 19], is shown in white.

9 Elements with revised atomic mass values (aluminium, cobalt, fluorine, gold, holmium, manganese, niobium, praseodymium, protactinium, rhodium, scandium, terbium, thulium, and yttrium)

In normal materials, the standard atomic weight of 19 elements is determined by only one isotope, which is stable (non-radioactive). Thus, the standard atomic weight for these elements is invariant. These elements are: Be, F, Na, Al, P, Sc, Mn, Co, As, Y, Nb, Rh, I, Cs, Pr, Tb, Ho, Tm, and Au. In addition, two elements, Bi and Pa, have only one isotope that contributes to the standard atomic weight, but that isotope is radioactive. The standard atomic weights of these 21 elements are derived directly from their atomic masses.

The two recent Atomic Mass Evaluation reports (AME2016 and AME2020) contain many advances in the measurement science of atomic masses [11, 49]. The most notable increase in the reported precision of the nuclide masses is the significant reduction in the uncertainty of the atomic masses of boron, ytterbium, strontium, and zirconium in AME2016 or hydrogen in AME2020. With respect to the consistency between the values of AME2012 and AME2016, the atomic mass of only two nuclides contributing to the standard atomic weights are inconsistent at the 3-sigma level of precision (helium-4 and palladium-102) compared to seven

nuclides between the 2003 and 2012 evaluations. Similarly, atomic mass estimates of only two nuclides (hydrogen-1 and helium-3) differ by more than 3-sigma between AME2016 and AME2020.

The coverage factor for the uncertainty of the $A_r°$ value of monoisotopic elements is $k = 6$ (for AME masses). Revised standard atomic weights are provided for 12 elements in 2017 (Al, Au, Co, Ho, Mn, Nb, Pr, Pa, Rh, Tb, Tm, and Y) and for 6 elements in 2021 (F, Ho, Sc, Tb, Tm, Y) for which improvements in the measurement precision of the atomic-mass values have been reported.

10 Plots of the natural variation of atomic weights

IUPAC published plots of natural variations in isotopic abundances and atomic weights for 15 elements, 12 of which had standard atomic weights expressed as an interval [6]. These plots provide information on the likely atomic-weight values of an element in a given substance [22, 23] and are available in Excel worksheets [24]. Additionally, the Commission provides plots of natural variations in isotopic abundances and atomic weights for elements whose standard atomic weight is expressed as an interval [2, 19] which can be downloaded from the Commission's website [55] or via the online IUPAC Periodic Table of the Elements and Isotopes [8]. Argon was assigned an interval standard atomic weight at the 2017 Commission meeting based on the report by Böhlke [15] and the corresponding new graphs are displayed in Figs. 3–5. Lead was assigned an interval standard atomic weight by the Commission in 2020, via correspondence, based on the report by Zhu et al. [16] and the corresponding new graphs are displayed in Figs. 6–9.

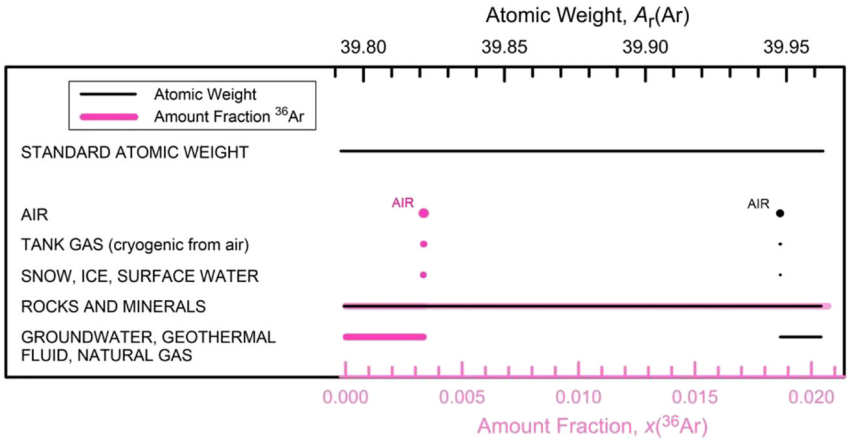

Fig. 3: Variation in atomic weight (black lines) of argon, A_r(Ar), with amount fraction (pink lines) of ^{36}Ar, $x(^{36}Ar)$, of selected argon-bearing materials. Because argon has three isotopes whose variations are not mass-dependent, the changes in the A_r(Ar) and $x(^{36}Ar)$ values are not superimposed. Each horizontal line spans the minimum and maximum values observed for the corresponding class of materials (data from [15]).

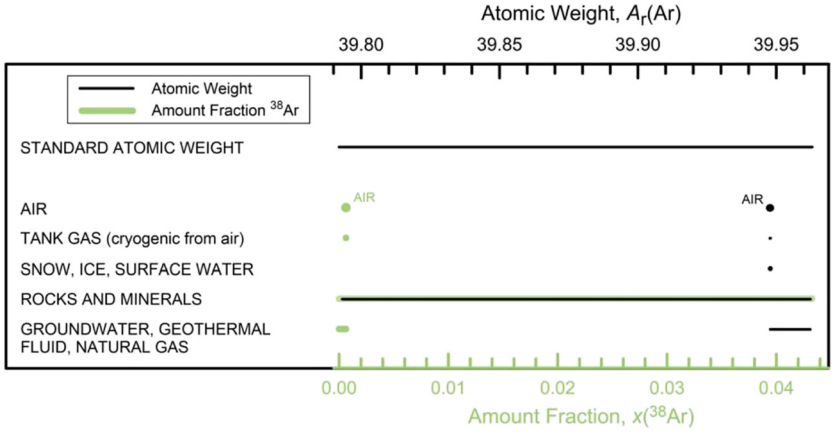

Fig. 4: Variation in atomic weight (black lines) of argon, A_r(Ar), with amount fraction (green lines) of ^{38}Ar, $x(^{38}Ar)$, of selected argon-bearing materials. Because argon has three isotopes whose variations are not mass-dependent, the changes in the A_r(Ar) and $x(^{38}Ar)$ values are not superimposed. Each horizontal line spans the minimum and maximum values observed for the corresponding class of materials (data from [15]).

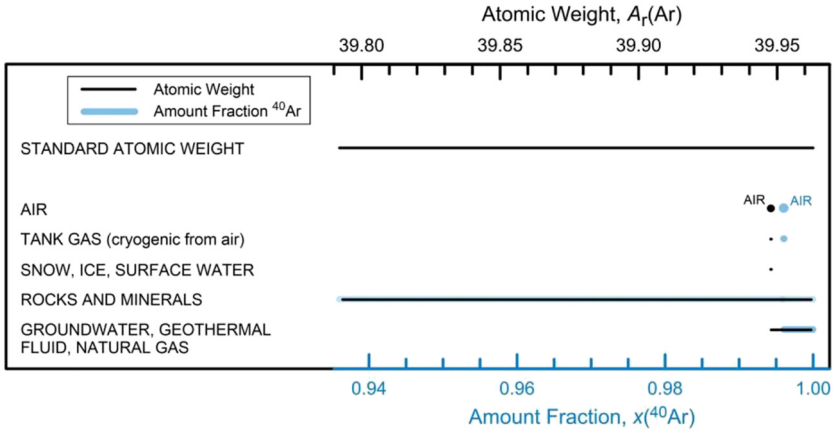

Fig. 5: Variation in atomic weight (black lines) of argon, A_r(Ar), with amount fraction (blue lines) of ^{40}Ar, $x(^{40}Ar)$, of selected argon-bearing materials. Because argon has three isotopes whose variations are not mass-dependent, the changes in the A_r(Ar) and $x(^{40}Ar)$ values are not superimposed. Each horizontal line spans the minimum and maximum values observed for the corresponding class of materials (data from [15]).

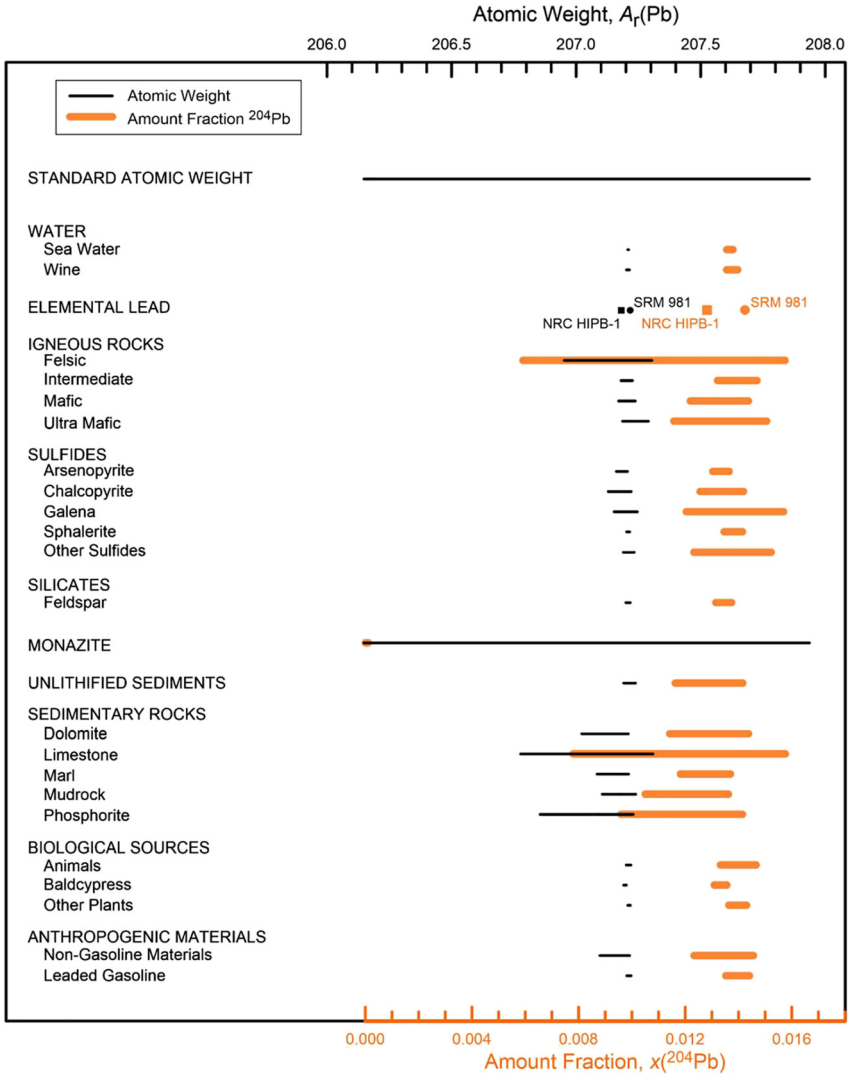

Fig. 6: Variation in atomic weight (black lines) of lead, A_r(Pb), with amount fraction (orange lines) of ^{204}Pb, $x(^{204}Pb)$, of selected lead-bearing materials. Because lead has four isotopes whose variations are not mass-dependent, the changes in the A_r(Pb) and $x(^{204}Pb)$ values are not superimposed. Each horizontal line spans the minimum and maximum values observed for the corresponding class of materials (data from [16]).

Fig. 7: Variation in atomic weight (black lines) of lead, A_r(Pb), with amount fraction (green lines) of ^{206}Pb, x(^{206}Pb), of selected lead-bearing materials. Because lead has four isotopes whose variations are not mass-dependent, the changes in the A_r(Pb) and x(^{206}Pb) values are not superimposed. Each horizontal line spans the minimum and maximum values observed for the corresponding class of materials (data from [16]).

11 Discontinuance of LSVEC as an isotopic reference material for carbon isotope delta measurements

The Commission notes that the international isotopic reference material LSVEC lithium carbonate which (together with NBS 19) has been used to define the carbon isotope-delta scale (VPDB), is able to absorb carbon dioxide from air [56]. This process changes the carbon isotopic composition of LSVEC with time. As a consequence, LSVEC is unsuitable as an isotopic reference material for carbon isotope ratio analysis. Therefore, its use as carbon isotopic reference material is no longer recommended. The carbon isotope-delta scale is defined by the virtual material Vienna Peedee belemnite (VPDB). Since 2005, the VPDB scale has been defined by assigning consensus values of –46.6 ‰ to LSVEC lithium carbonate and +1.95 ‰ to NBS 19 calcium carbonate [57, 58]. Before a proper replacement material for LSVEC is identified, the Commission gives the following recommendations:

(1) Users should refrain from using LSVEC as a carbon isotope-delta reference material.
(2) Carbon isotope-delta measurements should still be normalized to the VPDB scale using at least two suitable international reference materials selected as appropriate by the users. The applied values should be published with the measurement results. The most recent recommended values are those of Brand et al. [28].

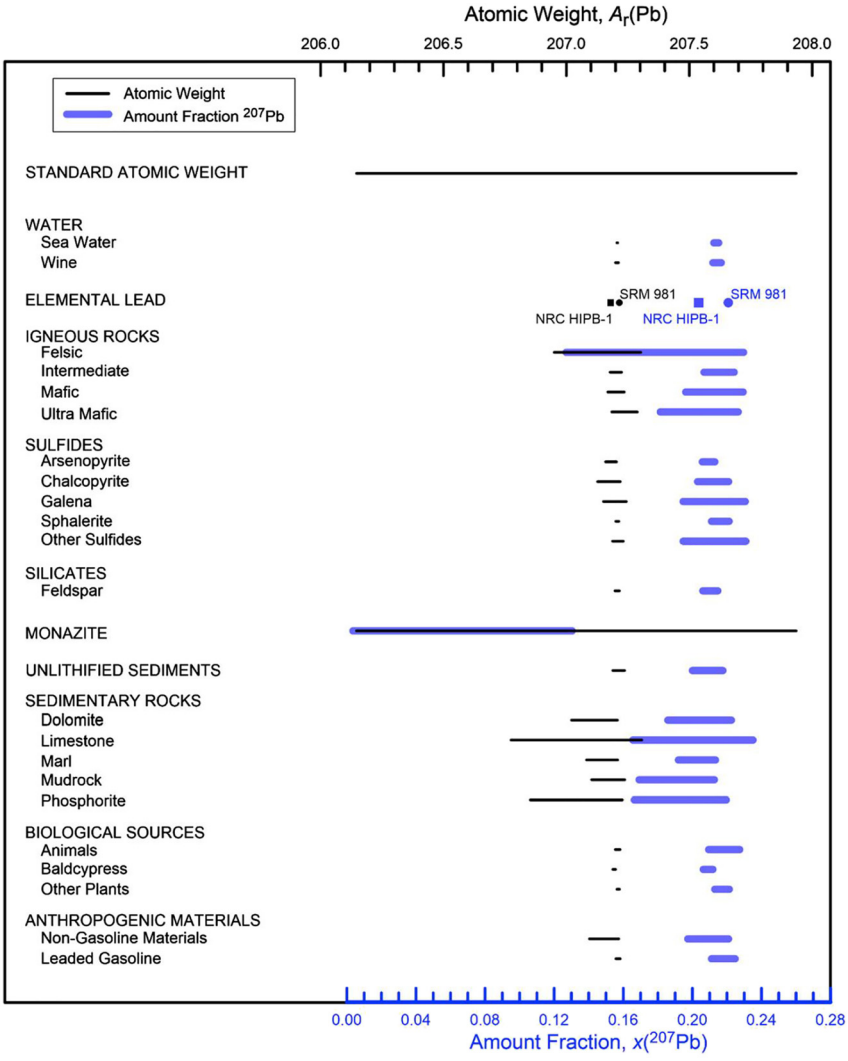

Fig. 8: Variation in atomic weight (black lines) of lead, A_r(Pb), with amount fraction (blue lines) of ^{207}Pb, x(^{207}Pb), of selected lead-bearing materials. Because lead has four isotopes whose variations are not mass-dependent, the changes in the A_r(Pb) and x(^{207}Pb) values are not superimposed. Each horizontal line spans the minimum and maximum values observed for the corresponding class of materials (data from [16]).

The Commission also notes the recommendation of the 2016 IAEA Technical Meeting on Stable Isotope Reference Materials [59], which proposed the material IAEA-603 as the future replacement of the quarantined NBS 19. The formal change of both VPDB scale-realizing materials – NBS 19 and LSVEC – will be considered by the Commission when the replacement for LSVEC is agreed upon.

12 New definition of the mole

The General Conference on Weights and Measures has adopted revised definitions of the kilogram, mole, ampere, and kelvin at its 26th meeting based on fundamental constants (Planck constant, Avogadro constant, elementary charge, and Boltzmann constant). These changes took effect on 20 May 2019. Of particular interest is the new definition of the mole in terms of the exact stipulated value for the Avogadro constant [60, 61] "One mole contains exactly $6.022\,140\,76 \times 10^{23}$ elementary entities." While this revision of the International System of Units has no practical effect on the atomic weights of the elements, calculation of molar masses to very high-precision will be affected by this change. Most notably, the molar mass of unbound carbon-12 atoms will no longer be 12 g mol^{-1} exactly. Rather, it will acquire a small uncertainty of less than one part in 10^9, which is of no consequence to chemists. This small change will arise because the 1971 definition of the mole was linked to

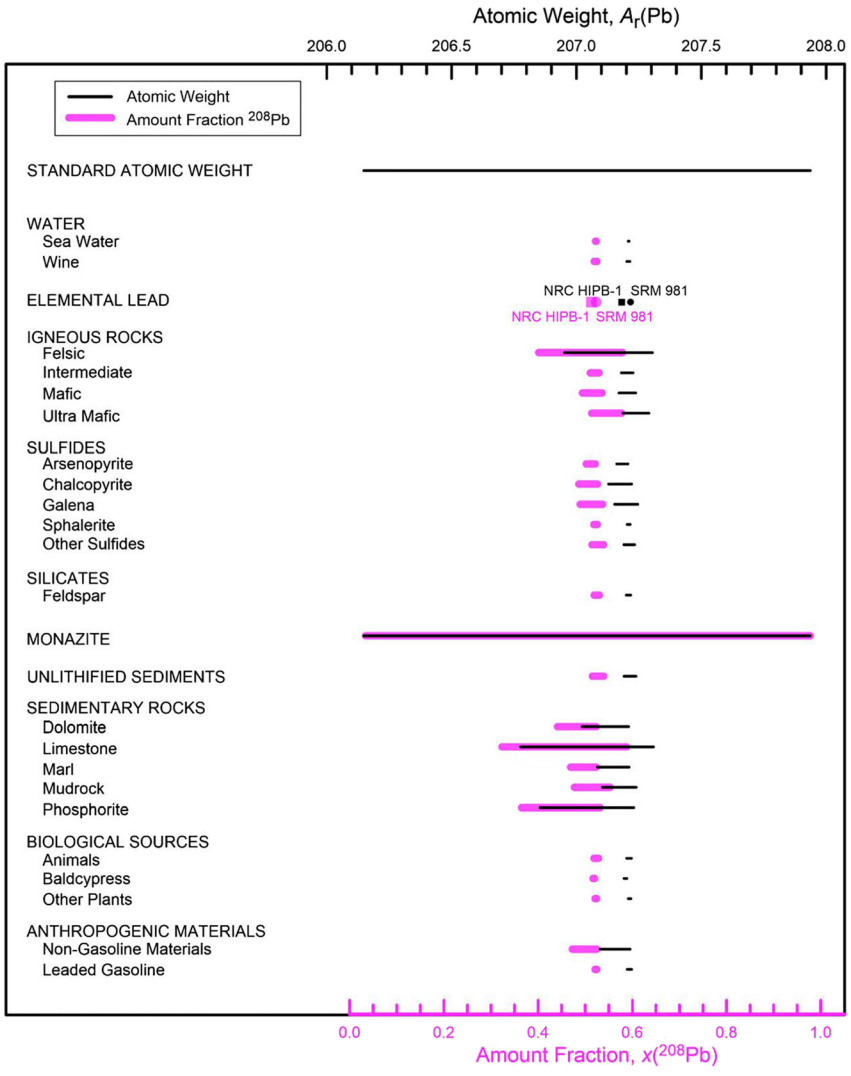

Fig. 9: Variation in atomic weight (black lines) of lead, A_r(Pb), with amount fraction (pink lines) of ^{208}Pb, x(^{208}Pb), of selected lead-bearing materials. Because lead has four isotopes whose variations are not mass-dependent, the changes in the A_r(Pb) and x(^{208}Pb) values are not superimposed. Each horizontal line spans the minimum and maximum values observed for the corresponding class of materials (data from [16]).

carbon-12 whereas this is no longer the case in the new definition of the mole (meanwhile, the atomic mass unit remains linked to carbon-12). Hence, molar masses of elementary entities (in g mol^{-1}) were numerically identical to their atomic masses (in Da). Also note that the 1971 definition of the mole, as clarified by the International Committee for Weights and Measures (CIPM) in 1980, refers to unbound carbon-12 atoms. In contrast, 12 g of pure carbon-12 bound in a substance such as diamond or graphite contains slightly more than 1 mol because an additional number of atoms is needed in order to make 12 g of substance compared to 12 g of unbound atoms as a result of mass loss ($\Delta m = \Delta E/c^2$) due to energy that is necessary to bind the atoms. The order of magnitude of this effect is one part in 10^9.

13 Atomic masses and half-lives of selected radioactive isotopes

For elements that have no stable or long-lived isotopes, data on radioactive half-lives and atomic-mass values for selected isotopes of interest are available from dedicated evaluations published in full detail elsewhere [11, 62], and a selection of the reported values is listed in Table 2. There is no general agreement on which of the various isotopes of radioactive elements are, or are likely to be judged, important. Various criteria such as longest half-life, production in quantity, and commercial relevance have been applied in the past. This

Table 2: Atomic masses and half-lives of selected radioactive nuclides. Data are transcribed from AME2020 [11] and NUBASE2020 [62] with uncertainties omitted. (Note: Element names and symbols are according to current nomenclature).

Atomic number	Element	Symbol	Mass number[a]	Atomic mass (Da)[b]	Half-life
19	potassium	K	40*	39.964 00	1.248×10^{9} a
20	calcium	Ca	48*	47.952 52	5.6×10^{19} a
23	vanadium	V	50*	49.947 16	2.7×10^{17} a
32	germanium	Ge	76*	75.921 40	1.88×10^{21} a
34	selenium	Se	82*	81.916 70	8.76×10^{19} a
37	rubidium	Rb	87*	86.909 18	4.97×10^{10} a
40	zirconium	Zr	96*	95.908 28	2.34×10^{19} a
42	molybdenum	Mo	100*	99.907 47	7.07×10^{18} a
43	technetium	Tc	97	96.906 36	4.21×10^{6} a
			98	97.907 21	4.2×10^{6} a
48	cadmium	Cd	113*	112.904 41	8.04×10^{15} a
			116*	115.904 76	2.69×10^{19} a
49	indium	In	115*	114.903 88	4.41×10^{14} a
52	tellurium	Te	128*	127.904 46	2.25×10^{24} a
			130*	129.906 22	7.91×10^{20} a
54	xenon	Xe	136*	135.907 21	2.18×10^{21} a
56	barium	Ba	130*	129.906 33	1×10^{21} a
			132*	131.905 06	$>3.00 \times 10^{20}$ a
57	lanthanum	La	138*	137.907 12	1.03×10^{11} a
60	neodymium	Nd	144*	143.910 09	2.29×10^{15} a
			150*	149.920 90	9.3×10^{18} a
61	promethium	Pm	145	144.912 76	17.7 a
62	samarium	Sm	147*	146.914 90	1.066×10^{11} a
			148*	147.914 83	6.3×10^{15} a
63	europium	Eu	151*	150.919 86	4.6×10^{18} a
71	lutetium	Lu	176*	175.942 69	3.70×10^{10} a
72	hafnium	Hf	174*	173.940 05	2.0×10^{15} a
74	tungsten	W	180*	179.946 71	1.59×10^{18} a
75	rhenium	Re	187*	186.955 75	4.16×10^{10} a
76	osmium	Os	184*	183.952 49	1.12×10^{13} a
			186*	185.953 84	2.0×10^{15} a
78	platinum	Pt	190*	189.959 95	4.83×10^{11} a
83	bismuth	Bi	209*	208.980 40	2.01×10^{19} a
84	polonium	Po	209	208.982 43	124 a
85	astatine	At	210	209.987 15	8.1 h
			211	210.987 50	7.214 h
86	radon	Rn	210	209.989 69	2.4 h
			211	210.990 60	14.6 h
			222	222.017 58	3.8215 d
87	francium	Fr	212	211.996 23	20.0 min
			222	222.017 58	14.2 min
			223	223.019 73	22.00 min
88	radium	Ra	226	226.025 41	1.600×10^{3} a
89	actinium	Ac	227	227.027 75	21.772 a
90	thorium	Th	230*	230.033 13	7.54×10^{4} a
			232*	232.038 05	1.40×10^{10} a
91	protactinium	Pa	231*	231.035 88	3.265×10^{4} a
			233	233.040 25	26.975 d
92	uranium	U	233	233.039 63	1.592×10^{5} a
			234*	234.040 95	2.455×10^{5} a
			235*	235.043 93	7.04×10^{8} a
			236	236.045 57	2.342×10^{7} a
			238*	238.050 79	4.463×10^{9} a
93	neptunium	Np	237	237.048 17	2.144×10^{6} a
94	plutonium	Pu	244	244.064 20	8.13×10^{7} a
95	americium	Am	243	243.061 38	7.350×10^{3} a

Table 2: (continued)

Atomic number	Element	Symbol	Mass number[a]	Atomic mass (Da)[b]	Half-life
96	curium	Cm	247	247.070 35	1.56×10^7 a
97	berkelium	Bk	247	247.070 31	1.38×10^3 a
98	californium	Cf	251	251.079 59	898 a
99	einsteinium	Es	252	252.082 98	471.7 d
100	fermium	Fm	257	257.095 11	100.5 d
101	mendelevium	Md	258	258.098 43	51.6 d
102	nobelium	No	259	259.101 00	58 min
103	lawrencium	Lr	262	262.109 62	4 h
104	rutherfordium	Rf	267	267.121 79	2.5 h
105	dubnium	Db	268	268.125 67	29 h
106	seaborgium	Sg	269	269.128 50	5 min
			271	271.133 78	2.2 min
107	bohrium	Bh	270	270.133 37	3.8 min
			274	274.143 60	57 s
108	hassium	Hs	269	269.133 65	15 s
			270	270.134 31	9 s
109	meitnerium	Mt	277	277.153 53	9 s
			278	278.156 49	6 s
110	darmstadtium	Ds	281	281.164 55	14 s
111	roentgenium	Rg	282	282.169 34	130 s
112	copernicium	Cn	285	285.177 23	30 s
113	nihonium	Nh	285	285.180 11	4.6 s
			286	286.182 46	12 s
114	flerovium	Fl	289	289.190 52	2.1 s
			290	290.191 88	80 s
115	moscovium	Mc	288	288.192 88	177 ms
			289	289.193 97	410 ms
			290	290.196 24	840 ms
116	livermorium	Lv	291	291.201 01	26 ms
			292	292.201 97	16 ms
			293	293.204 58	70 ms
117	tennessine	Ts	294	294.210 84	70 ms
118	oganesson	Og	294	294.213 98	0.7 ms

[a]Long-lived radioactive isotopes of elements with a characteristic terrestrial isotopic composition that contribute to the standard atomic weight determinations are marked with an asterisk (*). [b]IUPAC-recommended symbols are used for units of time: year (a), day (d), minute (min), second (s), millisecond (ms).

table contains information about selected radioactive nuclides which will enable the calculation of atomic weights of radioactive materials with a variety of isotopic compositions. Nuclide masses are taken from the AME2020 report [11] whereas the half-life values are from the NUBASE2020 report [62]. Uncertainties of these values are omitted for brevity and are available in the aforementioned reports.

14 IUPAC Periodic Table of the Elements and Isotopes

The Periodic Table of the Elements, developed independently by Mendeleev and Meyer in 1869, represents a remarkable achievement leading to improved understanding of the electronic structure of the atoms and the chemical and physical properties of the elements. In recognition of this milestone, the United Nations General Assembly proclaimed 2019 as the International Year of the Periodic Table of Chemical Elements during its 74th Plenary Meeting. Traditionally, the Periodic Table includes the standard atomic weights of the elements. With the introduction of intervals to represent the standard atomic weights for elements that have large variations in

isotopic abundance from which atomic weights are calculated, members of the Commission together with assistance from the IUPAC Committee on Chemistry Education developed a Periodic Table of the Isotopes [6, 8, 63], which has now been published as the IUPAC Periodic Table of Elements and Isotopes [6]. One goal of this IUPAC-sponsored project was to produce learner-oriented materials on an interactive periodic table to emphasize the existence of isotopes, the role of isotopic abundances in the determination of atomic weights, and applications of isotopes in science and industry.

In August 2016, IUPAC launched an interactive electronic version of the Periodic Table of the Elements and Isotopes. These new resources are created for educators and students at secondary and post-secondary levels, and they inform the public about the many uses of isotopes in our lives. They are based on educational practices that encourage engaged and active learning by students. The IUPAC Interactive Electronic Periodic Table and accompanying resources can be accessed at www.isotopesmatter.com.

15 Membership of sponsoring bodies

Membership of the Inorganic Chemistry Division Committee for the period 2020–2021 was as follows:

President: L. Öhrström (Sweden); **Vice President:** L. Armelao (Italy); **Secretary:** D. Rabinovich (USA); **Titular members:** J. Colón (Puerto Rico), M. Hasegawa (Japan), P. Knauth (France), M.H. Lim (South Korea), R. Macaluso (USA), J. Meija (Canada), X.K. Zhu (China/Beijing); **Associate members:** M. Diop (Senegal), J. Galamba Correia (Portugal), Pilar Gómez-Sal (Spain), P. Karen (Norway), A. Powell (Germany), T. Walczyk (Singapore); **National representatives:** F. Abdul Aziz (Malaysia), Y. Gorbunova (Russia), M. Gruden-Pavlovic (Serbia), P.J. Kulesza (Poland), G. J. Leigh (UK), O. Metin (Turkey), K. Sakai (Japan), V. Stilinović (Coratia), Yi-Chou Tsai (China/Taipei), and Michael Wieser (Canada).

Membership of the Inorganic Chemistry Division Committee for the period 2018–2019 was as follows:

President: L. Öhrström (Sweden); **Vice President:** J. Garcia Martinez (Spain); **Secretary:** M. Leskelä (Finland); **Titular members:** J. Reedijk (The Netherlands); X.K. Zhu (China); L. Armelao (Italy); P. Karen (Norway), R. Macaluso (USA); M. Hasegawa (Japan), M. Drabik (Slovakia); **Associate members:** A. Powell (Germany), L. Meesuk (Thailand), F. Abdul Aziz (Malaysia), J. Colón (Puerto Rico), T. Walczyk (Singapore), D. Rabinovich; **National representatives:** J. Galamba Correia (Portugal), S. Kalmykov (Russia), P. Knauth (France), K. Yoon (South Korea), M. Diop (Senegal), J. Leigh (UK), K. Sakai (Japan), N. Trendafilova (Bulgaria), V. Stilinović (Coratia), O. Metin (Turkey), M.H. Lim (South Korea), P.J. Kulesza (Poland).

Membership of the Inorganic Chemistry Division Committee for the period 2016–2017 was as follows:

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Membership of the Inorganic Chemistry Division Committee for the period 2014–2015 was as follows:

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Membership of the Commission on Isotopic Abundances and Atomic Weights for the period 2020–2021 was as follows:

Chair: J. Meija (Canada); **Secretary:** T. Prohaska (Austria); **Titular Members:** M. Gröning (Austria), J. Irrgeher (Austria), J. Vogl (Germany), H. Meijer (The Netherlands); **Associate Members:** P. Dunn (UK), H. Moossen (Germany), A. Possolo (USA), Y. Takahashi (Japan), and Jun Wang (China/Beijing).

Membership of the Commission on Isotopic Abundances and Atomic Weights for the period 2018–2019 was as follows:

Chair: J. Meija (Canada); **Secretary:** T. Prohaska (Austria); **Titular Members:** M. Gröning (Austria); J. Irrgeher (Austria); J. Vogl (Germany); H. Meijer (The Netherlands); **Associate Members:** A. Possolo (USA); J. Wang (China), P. Dunn (UK).

Membership of the Commission on Isotopic Abundances and Atomic Weights for the period 2016–2017 was as follows:

Chair: J. Meija (Canada); **Secretary:** T. Prohaska (Austria); **Titular Members:** M. Gröning (Austria); J. Irrgeher (Germany); J. Vogl (Germany); X. K. Zhu (China); **Associate Members:** L. Chesson (USA), A. Possolo (USA); H. Meijer (The Netherlands). **National Representatives:** P. De Bièvre (Belgium).

Membership of the Commission on Isotopic Abundances and Atomic Weights for the period 2014–2015 was as follows:

Chair: J. Meija (Canada); **Secretary:** T. Prohaska (Austria); **Titular Members:** W. A. Brand (Germany); M. Gröning (Austria); R. Schönberg (Germany); X. K. Zhu (China); **Associate Members:** T. Hirata (Japan); J. Vogl (Germany); J. Irrgeher (Germany); **National Representatives:** T. B. Coplen (USA); P. De Bièvre (Belgium).

16 In memoriam: Paul De Bièvre (1933–2016)

The Commission notes the death of the inaugural Chairman of the Subcommittee on Isotopic Abundance Measurements, Dr. Paul De Bièvre. Paul Jan De Bièvre (Fig. 10) was born on 7 July 1933 in Blankenberge (Belgium) and passed away on 14 April 2016 in Leuven (Belgium) at the age of 82.

He obtained his PhD from Gent University in 1959 where he continued to work as a lecturer until 1961. In 1961 he joined the Central Bureau for Nuclear Measurements of the European Commission (later renamed Institute for Reference Materials and Measurements, IRMM). Paul attended his first Commission meeting in Washington, D.C. (1971) and was elected Associate Member. He remained an active member of the Commission throughout the next five decades. At the 1973 Munich meeting, Paul (and Norman E. Holden) proposed to form a Working Party to review the data on isotopic abundance measurements and their impact on atomic weights. This started an eight-year project for IUPAC on the assessment of our knowledge of the isotopic composition of

Fig. 10: Paul De Bièvre at the 2007 Commission meeting in Pisa, Italy (Courtesy of Michael E. Wieser).

the elements and led to what is now known as the Subcommittee on Isotopic Abundance Measurements with Paul as its inaugural Chairman.

Paul's early work in the Central Bureau for Nuclear Measurements focused on the isotope dilution method and he pioneered the uncertainty analysis in this area. From the 1980s, he directed IRMM work on the improved measurements of the Avogadro constant through the single crystal route. This work, now led by the Physikalisch-Technische Bundesanstalt (PTB, Germany), formed an integral part of the new International System of Units (SI), which was changed in 2019.

Paul was very active in the international activities of chemistry and he was a charter member of many international chemistry organizations, including the Consultative Committee on the Amount of Substance (CCQM). He was co-founder (1989) and President (1993–1995) of Eurachem and co-founder (1992) of CITAC ("Co-operation on International Traceability in Analytical Chemistry"). In 1988 he was elected President of the National Committee on Chemistry of the Royal Academies of Belgium (1988–2006), he represented IUPAC to the Joint Committee for Guides in Metrology and was an active contributor to the 1998–2008 revision of the International Vocabulary of Metrology.

Paul had a penchant for philosophy of science and he believed that great measurements start with great thinking. His writings on metrology in chemistry appeared frequently in *Accreditation and Quality Assurance* (Springer) of which he was the Founding Editor-in-Chief (1995). He was a straightforward, cheerful person and his colleagues fondly remember his passion for science. Talking science for hours in the rain at a bus stop was not unusual for those who were fortunate enough to have met him. He was an inspiration to generations of analytical chemists and his passion for the highest quality measurements and accuracy in communication will be lasting memories. Paul loved a good debate and this quality placed him at the center of the decade-long discussions on the redefinition of the SI unit for the amount of substance, the mole. Fittingly, he lived only 10 km away from the city called Mol.

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