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COMMISSION ON ATOMIC WEIGHTS AND
ISOTOPIC ABUNDANCES

ELEMENT BY ELEMENT REVIEW OF THEIR ATOMIC WEIGHTS

Prepared by Subcommittee on Assessment of Isotopic Composition of the Elements whose Membership during its preparation (1981–83) was as given below

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ELEMENT BY ELEMENT REVIEW OF THEIR ATOMIC WEIGHTS

Endorsed by the Commission on Atomic Weights and Isotopic Abundance (CAWIA),
of the International Union of Pure and Applied Chemistry (IUPAC)

Abstract - The IUPAC "standard" atomic weights of the terrestrially occurring chemical elements are individually reviewed tracing changes during the past 25 years. Emphasized is the relevant published scientific evidence which in each case constitutes the basis for the expert judgment by the responsible IUPAC Commission. It biennially reports on, recommends, and tabulates the best values of these atomic weights with an implied judgment of their individual reliability.

In the introductory part of this Review the history of atomic-weight determinations is sketched. The IUPAC leadership in this data-evaluation project is described as it benefits science, technology, and trade. The remaining experimental uncertainties and natural variabilities are discussed. The treatment of abnormal materials is explained. The principal techniques for determining atomic weights are outlined. The effects of naturally occurring radioactive nuclides are characterized in their essentials.

ACKNOWLEDGMENTS

The International Union of Pure and Applied Chemistry has since its founding encouraged and supported the assessment and dissemination of atomic-weight data. This function is assigned to its Commission for Atomic Weights and Isotopic Abundances (CAWIA) which in 1981 decided that the time had come to prepare an Element-by-Element Review of their Atomic Weights. That Commission accordingly entrusted to the Subcommittee for the Assessment of the Isotopic Composition of the Elements (SAIC), the preparation of this Review.

This task could not have been undertaken without continuing interest and backing from the employing organizations of all SAIC members, who are the authors of this Review. Very special acknowledgments should be expressed to those organizations which also hosted recent meetings of SAIC. These host organizations are:

the Central Bureau for Nuclear Measurements of the Commission of European Communities,
the Brookhaven National Laboratory, and
the National Bureau of Standards.

They made important meeting facilities available to the authors including computer services which enabled the SAIC members to compute atomic weights and associated uncertainties on the spot as the joint assessment of published information proceeded during these meetings. The encouragement of the Western Australian Institute of Technology, the Centre d'Etudes Nucléaires de Saclay (of France), the National Science Museum (of Japan), and McMaster University (of Canada) is also sincerely appreciated.

Unforgettable to the authors is the late Dr. Angus E. Cameron, formerly of the Oak Ridge National Laboratory. He was not only one of two authors of the previous element-by-element review but also — except for his sudden and unexpected death — would have been a co-author of this Review. During the intervening period, he was constantly active in the field, his views have been an inspiration to all the authors, and he took part in the initial planning for this Review. The authors owe Gus Cameron, their former colleague and friend, lasting gratitude and profound respect.

Acknowledgment is also due to Professor A. H. Wapstra, Dr. K. Bos, and their publishers, the Academic Press, for permission to quote extensively from The 1977 Atomic Mass Evaluation Tables. The authors express thanks to D. Garvin and N. N. Greenwood for helpful comments on portions of the manuscript. Tables 3 and 4 were typed at Brookhaven National Laboratory. Much appreciation is expressed to Gelene Hensley, Anne Lawrence, and Joy Shoemaker at the National Bureau of Standards who typed the text and skillfully applied word-processing technology to prepare a concise document.

PART I. INTRODUCTION

1. Preamble

Although theories postulating the existence of atoms, indivisible smallest particles of materials, are deeply rooted in Greek metaphysics of ancient times, the wide acceptance of the atomic theory lies surprisingly late in the last century. John Dalton early in that century had published the first atomic-weight tables, but their values are today hard to recognize. Since then the determination of these numbers has attracted the efforts and skills of many famous chemists. Atomic weights are needed in science, technology, trade and commerce. In particular, no use can be made of the results of analytical chemistry without atomic weights which relate mass to molar quantities.

The American Chemistry Society in 1894 published F. W. Clarke's remarkably accurate standard table of atomic weights, followed a few years later by a similar German table published by the Deutsche Chemische Gesellschaft. Together with D. I. Medeleev's periodic table of the elements, the foundations were thus laid for the development of modern chemistry.

The importance of a consistent scale and internationally recognized values for the atomic weights now led to the formation of the first international committee which for practical reasons in communication elected an action committee of three: F. W. Clarke (U.S.A.), T. E. Thorpe (England), and K. Seubert (Germany). They published annual revisions of the atomic weights from 1903 until the first World War disrupted their efforts. In the meantime H. Moissan had joined the small Committee as representative of France to be replaced after his death by G. Urbain. Seubert resigned in 1906 and was replaced by W. Ostwald, with whom communication was not resumed after 1916. In 1913 this Committee affiliated itself to the International Association of Chemical Societies and in 1919 subordinated itself to the International Union of Pure and Applied Chemistry, which had just been constituted. In 1921 the Committee was enlarged and renamed "Committee of the Chemical Elements" with enhanced terms of reference, but redivided in 1930 with the formation of the "Atomic Weights Committee" plus two other committees. This "Atomic Weights Committee" went through further minor reorganizations and changes in name until in 1979 it became the present Commission on Atomic Weights and Isotopic Abundances (CAWIA). Since 1930 CAWIA and its predecessor committees have been chaired successively by G. Baxter (U.S.A.), E. Wichers (U.S.A.), N. N. Greenwood (U.K.), E. Roth (France), N. E. Holden (U.S.A.), and R. L. Martin (Australia).

IUPAC from its inception has expended, and as the Commission's parent organization continues to undertake, much effort for the careful evaluation and dissemination of atomic weights and their uncertainties derived from critically assessed published information. The current values, now called 'standard atomic weights', are virtually unchallenged throughout the world. Contrary to wide-spread misconceptions, the available accuracy of all atomic weights does not surpass scientific and technological concerns. In fact, the estimated uncertainties of some of these numbers can be shown to be limiting in chemical determinations or commercial transactions at the level of precision of other related measurements, such as weighings in a chemical laboratory or cost by invoice. Under these circumstances confusion and discord could be aggravated if more than one 'best set' of atomic weights were extant at any one time. IUPAC thus renders the world's science and industries an invaluable service by publishing standard atomic weights.

CAWIA in 1979 adopted the following definition of atomic weight (mean relative atomic mass) of an element from a specific source: "the ratio of the average mass per atom of the element to 1/12 of the mass of an atom of ^{12}C". The novelty of this definition was emphasized by the following clarifying remarks:

"(1) atomic weights can be defined for any sample;
"(2) atomic weights are evaluated for atoms in their electronic and nuclear ground states;
"(3) the 'average mass per atom' in a specified source is the total mass of the element divided by the total number of atoms of that element; and
"(4) dated tables of Standard Atomic Weights published by the Commission refer to our best knowledge of the elements in natural terrestrial sources."

Atomic weights, therefore, are dimensionless numbers numerically equal to the molar masses of the elements when expressed in grams per mole.

2. The Previous Element-by-Element Review

The predecessor of CAWIA in 1959, at that time called the IUPAC "International Commission on Atomic Weights" (ICAW), assigned to Cameron and Wichers the preparation of an element-by-element review of the atomic weights. The time for a complete re-assessment was appropriate in anticipation of the adoption of the universally acceptable atomic-weight scale proposed by Mattauch and Wichers. It was based on $A_r({}^{12}_{6}C) = 12$ exactly, instead of $A_r(O) = 16$. The latter had been used by chemists since it was introduced by Stas in 1860. By the turn of the century the alternative scale of $A_r(H) = 1$, introduced by Dalton in 1803, had lost favor with most chemists. (Throughout this review A_r(E) is used for the atomic weight of element "E" as a dimensionless number. $A_r(^{12}\mathrm{C})$ can be read as the atomic weight of a sample of carbon containing only the isotope of mass number 12.)

After the discovery of the minor isotopes $^{17}_{8}\mathrm{O}$ and $^{18}\mathrm{O}$ isotopes in 1929, physicists abandoned the "chemical scale" of $A_r(\mathrm{O}) = 16$ and instead used the atomic mass of the $^{16}\mathrm{O}$ isotope equal to exactly 16 amu (atomic-mass units) as the basis of a "physical scale". Although the slight variability of the $^{17}\mathrm{O}/^{16}\mathrm{O}$ and $^{18}\mathrm{O}/^{16}\mathrm{O}$ ratios caused additional complications, the conversion factor for atomic weights from the chemical to the physical scale was used to the sixth decimal figure at 1.000 275 (0.1a)*. This variability introduces an uncertainty in the fifth decimal of the conversion factor as is readily calculated from the range of sample atomic weights for oxygen (see Section on oxygen).

The uniform adoption of the $A_r(^{12}\mathrm{C}) = 12$ scale by both chemists and physicists was finally approved in 1960 by the International Union of Pure and Applied Physics (IUPAP). It required recalculation of both the nuclidic-mass tables (0.2a) and atomic-weight tables for which an acceptably small but not negligible factor was needed. The atomic weights would decrease by a factor of 4.29×10^{-5}, derived from the previously quoted factor for conversion of chemical to physical-scale atomic weights and the factor 0.999 682 184(17)* found for the conversion from the scale based on $A_r(^{16}\mathrm{O}) = 16$ amu to $A_r(^{12}\mathrm{C}) = 12$ u (unified atomic-mass units).

Cameron and Wichers (0.1a) found that they could not execute their task adequately simply by applying the conversion factor. Reference to the original literature proved essential, and from it a complete recalculation was needed, especially for A_r(Ag), A_r(Cl), and A_r(Br), on which three values so many other atomic weights depended. Whereas up to that time most atomic weights were based on chemical determinations, Cameron and Wichers gave increased recognition to physical data. In particular, the nuclidic masses of the mononuclidic elements (see Section 7 below) were so accurately known that they could displace from consideration all chemical determinations of atomic weights. For an increasing number of the other elements, mass-spectrometric-abundance data coupled with the relevant nuclidic masses were judged superior to — or comparable with — the previously considered atomic-weight determinations based on chemical work. At the same time the confidence in the atomic-weight values was enhanced, as it was found that in most instances there was, within estimated uncertainties, good agreement between chemical and mass-spectrometric data. Some of the few exceptional discrepancies have since been resolved. However, titanium, zinc, germanium, and selenium continue to show less than satisfactory agreement, as discussed in the relevant sections of the elements in Part II of this Review.

3. The IUPAC Tables

Cameron and Wichers in 1961 submitted their Atomic Weights Table based on $A_r(^{12}_{6}\mathrm{C}) = 12$ to the International Commission on Atomic Weights for a detailed appraisal. It was accepted with some modifications and recommended with appropriate concurrences to the IUPAC Council with the title of "Table of Relative Atomic Masses". However, that Council, on advice from the Commission on Nomenclature of IUPAC, changed the name of the table to "Table of Relative Atomic Weights". It was so published with the full element-by-element review as the 1961 Report of ICAW (0.1a). In 1967 the Commission** again dropped the term "Relative" in the Table headings and, in 1969, explained the reasons for doing so, which included the view that it was redundant because "relative" was implicit in the chemists' understanding of "atomic weight".

As mentioned in the preamble (Section 1), the Commission, in 1979, agreed that an atomic weight could be defined for any specified sample and decreed that the dated Tables, referring to the best IUPAC knowledge of the elements in "normal" (defined more carefully in the following section natural, terrestrial sources, would in the future be called "Tables of Standard Atomic Weights". The Commission plans to continue its policy of reviewing the literature on a biennial cycle, to report to IUPAC at every General Assembly, and there to amend the Table of Standard Atomic Weights only on the basis of cogent new evidence. On such evidence the Commission tabulates atomic weights as precisely as reasonably possible. It never eliminates conservatively assessed published information despite the fact that a chemist is almost never interested in more than the fifth significant figure in atomic weights. The Commission emphasizes that the Tables have full validity for a two-year period only. Chemists should refer to the Tables only with their appropriate years. In the 1981 Commission Report (0.1i) an atomic-weight table abbreviated to five significant figures was

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[*] In this Review figures in parentheses without decimal point are uncertainties of the last digit outside the brackets, figures with decimal points are references to the literature. All references in Part I start with a zero, subsequent section references start with the atomic number of the element to which the reference applies.

[**] Here and below the "Commission" refers to ICAW or, later, CAWIA.

included for users who do not wish to be distracted by the details in the full Table of Standard Atomic Weights. Another anticipated advantage of the abbreviated table is that, if periodic revisions are recommended by the Commission, they will show fewer changes than does the full table.

Since 1975 the Commission in its biennial reports also publishes data on mass-spectrometrically determined isotopic compositions of the elements (0.1f to 0.1j), (0.3). For elements with three or more stable isotopes this information is more detailed than the atomic-weight value. Atomic weights calculated from the tabulated isotopic abundances are generally consistent with $\underline{A}_{\underline{r}}$(E) values in the Table of (Standard) Atomic Weights. Small differences arise because the standard atomic weights take into consideration significant chemical determinations (see Section 8).

4. Reasons for a New Element-by-Element Review

Meeting at Leuven, Belgium, in 1981, CAWIA confirmed an earlier decision that the time had come to prepare a new element-by-element review. The task was given to the Subcommittee for the Assessment of the Isotopic Composition of the Elements (SAIC) which is directly subordinated to CAWIA by provision of the Inorganic Chemistry Division of IUPAC.

A good reason for the new review is that more than twenty years have passed since the previous review by Cameron and Wichers (0.1a). The intervening biennial Commission reports (0.1b) to (0.1i) contain many new evaluations and assessments of newly published work predominantly in mass spectrometry. New nuclidic-mass data have also been published (0.2d) and (0.2e). The need for accurate isotopic-abundance data has greatly increased for instance in neutron-activation analysis (see Section 10). In recent years the Commission has given more attention to abnormal geological occurrences with anomalous atomic weights, and it has been addressing problems of inadvertent or undisclosed modifications of isotopic composition. Most importantly, with the 1969 Report (0.1c), and subsequently, the Commission has systematically assigned uncertainties to all atomic-weight, $\underline{A}_{\underline{r}}$(E), values on the same ^{12}C-scale. These uncertainties are reflected in the precision of the tabulated atomic weights (see Section 5). They are intended to apply only to "normal" materials. By "normal" the Commission refers to terrestrial occurrences that satisfy the following criterion:

> 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.

The Commission now aims to disseminate standard atomic weights applicable to all normal materials with the greatest possible precision consistent with an uncertainty of between ±1 and ±9 in the last tabulated figure. However, in previous years (1969-1981) uncertainties were restricted to two alternative values, either ±1 or ±3. (One exception was made for hydrogen in the 1981 Report (0.1j) (see Part II)). This policy has had a number of undesirable consequences. For instance, any change in $\underline{A}_{\underline{r}}$(E) value of elements with uncertainty ±1 had to equal the full magnitude of that uncertainty unless the change was accompanied by a better than three-fold reduction of estimated uncertainties. Although the Commission now permits any uncertainty between ±1 and ±9, changes in assigned uncertainties are made only when there is convincing evidence that an increase or decrease in that uncertainty corresponds to an increased level of confidence in the implied precision of the tabulated standard atomic weight or permits the Commission to disseminate an atomic-weight value with an additional digit. It is therefore important in this Element-by-Element Review to describe the estimation of uncertainties, and to discuss the extent to which abnormal materials may be encountered with anomalous atomic-weight values (see Sections 5 and 6).

5. The Assignment of Uncertainties and their Indication by the Tabulated Standard Atomic Weight

Prior to 1983, the Commission had not published a detailed discussion of the meaning of the indicated range in its tabulated standard atomic weights. The authors of this Review have recommended, and the Commission in 1983 accepted, that an attempt be now made, consistent with previous practice, to specify and sharpen the interpretation of these implied uncertainties of the standard $\underline{A}_{\underline{r}}$(E) values. Since 1969 these uncertainties have been given for each $\underline{A}_{\underline{r}}$(E) value in the IUPAC Table of (Standard) Atomic Weights. Use of the symbol $\underline{U}_{\underline{r}}$(E) is proposed for this indicated uncertainty in the tabulated standard atomic weight, $\underline{A}_{\underline{r}}$(E). It combines the experimental uncertainties (including random and reasonably conceivable systematic errors for the one or several published $\underline{A}_{\underline{r}}$(E) determinations that are judged significant) with the range of variability of "normal" sources of the element E plus the estimated uncertainties in the upper and lower bounds of that range.

The Commission aims at disseminating value pairs [$\underline{A}_{\underline{r}}$(E), $\underline{U}_{\underline{r}}$(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 $\underline{A}_{\underline{r}}$(E) by more than $\underline{U}_{\underline{r}}$(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.

These are demands on the trustworthiness of the atomic-weights data that could readily be met by a restriction of the precision of the tabulated data, that is by severely limiting the number of significant figures or unduly increasing the $U_r(E)$ values. However, the Commission has another equally important aim, namely to disseminate the most precise but reliable data. The balance between the highest precision in the Tables (largest number of significant figures and smallest $U_r(E)$ values) and near-perfect reliability is the challenge faced by the Commission. Its never-ending task is to weigh the published experimental evidence element by element and, often, source by source.

Practical considerations that concern the users of the Tables are also important and may lead the Commission to compromise slightly in the precision of the tabulated data, but not with their perceived reliability. From time to time, therefore, the Commission sets itself "policies" such that the users find the Tables conveniently simple and that few changes are needed in any one of the biennial revisions. See, for example, the definition of "normal" in Section 4, the policy of equal single-digit $U_r(E)$ values for positive and negative deviations from $A_r(E)$ values later in this Section, the use of the footnotes in Section 6, the required cogency for any recommended change in Section 3, and the $A_r(E)$ values of mononuclidic elements in Section 7.

Whereas the atomic-weight data critically depend on nuclidic-mass values, neither the Commission nor its Subcommittee, SAIC, evaluates nuclidic-mass data. Instead, they rely on the data published with encouragement of the Commission on Atomic Masses and Fundamental Constants of IUPAP (0.2a - 0.2e). The latest available published tables are those by Wapstra and Bos (0.2e). The accuracies of nuclidic masses relative to the mass of $^{12}_{6}C$ exceed the precision of most mass-spectrometric determinations of the abundances of polynuclidic elements (Section 9). For these elements the uncertainties in the nuclidic masses do not significantly influence the $U_r(E)$ values. The same does not apply to mononuclidic elements and some elements (as for instance silver) for which the abundance has been measured with a very high precision. Consideration of elements for which the $U_r(E)$ depends partly on the uncertainties in the nuclidic masses is given in Section 7 below.

To achieve the above balanced objectives, the Commission searches the literature for significant atomic-weight determinations. As many independent experimental $A_r(E)$ values, V_i from as many diverse normal sources of that element as possible are considered in detail (refer to Fig. 1). Each V_i has an estimated standard deviation, ε_i, derived from some combination of random and systematic errors. Since many publications are not clear even on the random errors, that could be investigated by statistical measurement of reproducibilities, the Commission members may question an author to assist them in the ultimate judgment of the reliability of V_i values. In the end the Commission must take responsibility for the acceptance of a V_i to which they may assign their own ε_i value. When several significant V_i values are based on closely similar techniques, it may be possible to systematize the assessment of the ε_i values. This has been practiced by the Commission for mass-spectrometric determinations (see Report on the Isotopic Composition of the Elements, 1981) (0.1i).

It should be noted that for a particular sample there is a true value for the atomic weight, and therefore, one can speak of an accuracy or an inaccuracy that is readily defined. The same holds true for a geologically defined ore body or a large amount of a substance at a plant, provided only that sampling procedures are introduced and relevant added uncertainties are taken into account.

The variability of some atomic weights in normal materials prevents the attainment of a simple but precise definition for the atomic weight of an element. One reason is the difficulty in deciding what materials can be considered as being available. Do we include the earth's core — conceptually at least? If so, how do we know the element's isotopic composition in the core? Consequently, the aim is by mineral surveys to obtain V_i values as close as possible to $L_r(E)$ and $H_r(E)$, defined as lower and higher bounds of the true range of sample atomic weights from normal available material sources (see Fig. 1). $H_r(E) - L_r(E)$, the range, is generally measurable but small, often negligible by comparison with the precision of the tabulated standard atomic weights. Selenium is an example (see Part II). The probability of encountering any one sample atomic weight in a range is often known to be far from statistically "normal". A skew distribution in a range has so far never led the Commission to recommend the adoption of a standard atomic weight different from the simple arithmetic mean of the extremes of the tabulated range, that is by recommending $U_r(E)$ values differing for positive and negative values. Up to this time there has never been a cogent reason for adopting that refinement, although there are some other situations in which a difference of sign for $U_r(E)$ could with a marginal advantage be linked with a change in magnitude of $U_r(E)$. Examples might be cases in which the "best" value for an $A_r(E)$ would

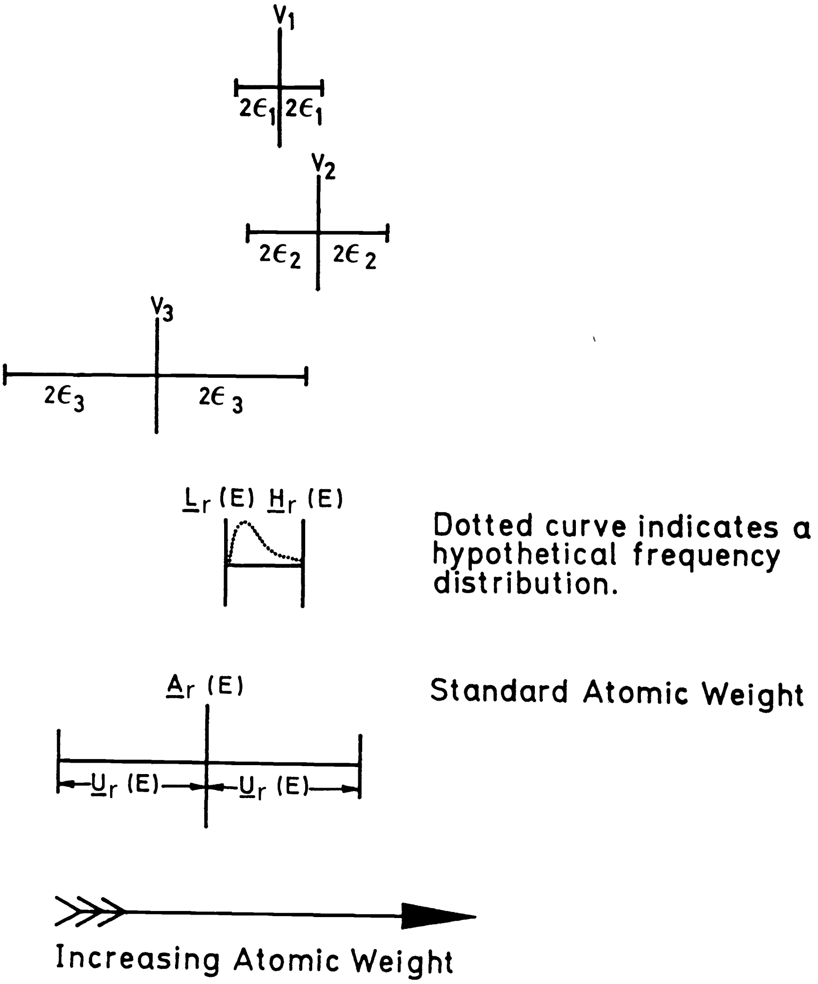

Figure 1.

have a digit beyond the last tabulated figure equal to or near five. Equality of positive and negative $U_r(E)$ values would then result in an unsymmetric range around the rounded tabulated "best" value of $A_r(E)$. For $U_r(E) = 1$, the implied range could be up to three times larger on one side of the tabulated rounded value than on the other.

At its biennial reviews, the Commission chooses a pair: $[A_r(E), U_r(E)]$ for each element such that both $L_r(E)$ and $H_r(E)$ are reliably included in the implied range: $A_r(E) - U_r(E)$ to $A_r(E) + U_r(E)$ even after full allowance for estimated errors in experimental determinations and inadequacies of mineral surveys of "normal" occurrences. The pair $[A_r(E), U_r(E)]$ is here defined as inaccurate if even one normal source material has a true $A_r(E)$ that, without rounding off, falls outside the implied range. At its periodic reviews the Commission almost invariably — and the authors of this Review recommend a policy that would be invariable — corrects any substantively suspected inaccuracies in the Table of Standard Atomic Weights. The only case in the 1983 Table for which this rule has not been strictly applied is that of palladium as described in Part II.

The Commission's overall purpose then is to disseminate at the highest possible precision, highly reliable, easily understood, rarely amended, almost universally applicable atomic-weight values with their ranges. It should be recognized that future atomic-weight and mineral-survey studies will lead to some changes of these values at virtually every biennial review by the Commission. The great majority of these changes will be within the previously implied ranges; they will mean more accurate atomic weights for those elements that have no significant variability in normal samples. Variable elements may be given smaller implied ranges due to better determinations or more reliable mineral surveys. Inevitably, a small number of corrections of the ranges in the Tables must be expected. A new "best" $A_r(E)$ value outside the previously implied range, however, should be a very rare event. Two such cases occurred in the past 25 years (potassium and bismuth as described with specific details in Part II). Both these instances were caused by the 1969 review (0.1c) the first time the Commission assigned $U_r(E)$ values to all $A_r(E)$'s. Without trying to hide the concern of the Commission for any correction of a prior tabulated value outside its uncertainty, it should be emphasized that, if no such event ever occurred, it would force the conclusion that the Commission had been too conservative.

The evaluation of the Commission's performance under its own guidelines is difficult, but has been and must continue to be attempted. An independent assessment of the literature even for one element is not likely to be attempted but would clearly be of interest. Discoveries of significant determinations that have been published but overlooked by the Commission have occurred in a few instances, but these have not led to major revisions of the Tables (see, for instance, nickel in Part II). More significant has been the influence of some reevaluations of previously considered data that have led to changes in weighting different determinations and resulting in different $A_r(E)$ values. Such a situation led to the recent change in $A_r(Zn)$ (see Part II), but even that — as is typical for similar cases — did not take the new value of $A_r(E)$ outside the previous uncertainty range; nor did the old and new ranges fail to overlap over large portions of these ranges. During the past 25 years new experimental data, that were judged to be superior to older determinations, have overwhelmingly confirmed previous values. New ranges tended to lie entirely within older uncertainties as has been analyzed in the Commission Report of 1981 (0.1i). In addition to the above-mentioned case of potassium, for which $U_r(K)$ has decreased by a factor of 30, there have been a few exceptions. They include some mononuclidic elements with very small $U_r(E)$ values discussed in detail in Section 7, and xenon and zinc (see Part II) for which the uncertainties were increased.

It appears generally, therefore, that the Commission has neither grossly underestimated nor unduly overestimated the uncertainties. The number and magnitude of revisions at the biennial reviews would have given clear evidence if such unbalance had occurred between the Commission's two major aims of highest precision and great reliability. Because in any one biennial period there are unfortunately very few truly independent significant new determinations, and because the Commission has not departed very widely from a good balance between its aims, a simple relationship between the number of revisions at the periodic reviews and the achievement of that balance cannot be expected.

6. "Abnormal" Materials

At the time of the previous element-by-element review (0.1a), long after the discovery of isotopes, chemists still tended to regard atomic weights as fundamental constants of nature. Even now for most practical purposes a standard value can be tabulated with adequate precision to serve for most elements in most normal applications. Moreover, there is overwhelming evidence that the atomic weights of most elements in abnormal occurrences, such as for instance in trace constituents, also fall within normal ranges. The exceptions, however, have become numerous at the precision of some current interest. Physical and chemical properties of elements are often significantly affected by isotopic mass. Isotopic effects will continue to be discovered at an accelerating pace due to:

i) progress and practice in nuclear science and technology;
ii) considerable advances in analytical chemistry;
iii) increased understanding of geological, geophysical, biological, atmospheric, and astrophysical phenomena;
iv) introduction of methods in materials processing which lead to isotope fractionations; and
v) increase in precision of mass-spectrometric measurements leading to the detection of more instances of variability in isotopic composition.

At the beginning of this century before the discovery of isotopes, T. W. Richards (0.4a) came to the inescapable conclusion from chemical measurements that the atomic weight of lead was variable. In the 1961 Report, Cameron and Wichers (0.1a) warned of that variability due to the admixture of "radiogenic" with "common" lead. They warned that the atomic weight of some samples of lead and uranium must be calculated from their isotopic composition.

The proliferation and awareness of "abnormal" materials since then has required increasing attention from the Commission, which therefore has emphasized the following:

a.) The Tables of (Standard) Atomic Weights should not be used for data on separated isotopes or materials whose isotopic composition has been deliberately modified.

b.) The Commission, while disseminating some information on the atomic weights of materials of extra-terrestrial origin, does not have or seek a mandate for compiling systematic or exhaustive data on current knowledge of such materials. Many elements in diverse occurrences on the moon, and in meteors, stars, and space exhibit different or more variable isotopic compositions than are observed in terrestrial sources.

c.) Some elements have no stable nuclide and no normal terrestrial composition but they all have several radionuclides. For completeness such radioactive elements are included in the

IUPAC Tables of Atomic Weights, although for them the concept of a standard atomic weight has no meaning. Until 1971 the column for atomic weights was left blank for these elements. Since 1973 (0.1e) the Tables list parenthetically the mass number of the radionuclide of such an element with the longest half-life. The Commission was never well satisfied with that solution, because in several instances the radionuclide with the longest half-life is not the best known or the most commonly available. In the atomic-weights table abbreviated to five significant figures (0.1i) these elements are represented by one or more selected nuclides whose mass numbers are indicated by the conventional superscript prefixes and whose nuclidic masses are entered in the atomic-weights column. This method of representation of radioactive elements will also be used in future Tables of Standard Atomic Weights.

d.) Unusual, but still "normal", geological occurrences displaying atomic weights varying from their more usual values force the Commission to decrease the precision of the standard atomic weights, in order to encompass these unusual sources in the implied range. This procedure is substituted by that in the following paragraph when the occurrence or source is no longer "normal" and the departure from usual atomic-weight values considerable.

e.) For quite extraordinary occurrences and other abnormal sources with abnormal atomic weights outside an otherwise acceptable range, the Commission uses annotations given in footnotes that are an integral part of the Tables of Standard Atomic Weights. Describing such abnormalities merely in the text of biennial reports would surely cause the warnings to be overlooked by more of the affected users. The detailed wording, not so much their intended meaning, has been modified from time to time. The 1981 (0.1i) version, for instance, of the footnotes is here reproduced:

"g geologically exceptional specimens are known in which the element has an isotopic composition outside the limits for normal material. The difference between the atomic weight of the element in such specimens and that given in the Table may exceed considerably the implied uncertainty."

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

Two other currently used footnotes are in part explanatory, but they also warn the user that it may be necessary to ascertain the isotopic composition of the material, if a more precise atomic weight is required than that entered in the Table of Standard Atomic Weights. These footnotes indicate the following:

"r range in isotopic composition of normal terrestrial material prevents a more precise atomic weight being given; the tabulated $A_r(E)$ value should be applicable to any normal material". With the use of more variable $U_r(E)$ values "more precise" now means one additional significant figure.

"L Longest half-life isotope mass is chosen for the tabulated $A_r(E)$ value".

In some earlier Commission Reports additional explanatory footnotes were also used, but they were later discarded since they had no consequential effect for the user other than was inherent in the tabulated $A_r(E)$ and $U_r(E)$ values. These footnotes were: a.) mononuclidic element; b.) element with a predominant isotope; and c.) element with isotopic abundance determined by an absolute (calibrated) mass-spectrometric measurement.

The Commission has used the footnote "g" for products of a natural chain reaction (fission). This event in geologically remote time is here described in a little detail, in order to avoid repetition in the element-by-element description of the many elements affected.

In 1972 the scientific community was made aware of large natural isotopic anomalies in many elements present in samples from a location called Oklo in Gabon, West Africa. Fission reactions had spontaneously occurred there some two billion years ago in high-grade uranium ore which at that time had a ${}^{235}_{92}U$ abundance greater than three percent. As a result of this phenomenon all stable end products of the fission chains are found there in nature and must therefore be considered "natural" though highly anomalous. The elements concerned include primarily the uranium fission products with mass numbers between 80 and 160 and daughter elements from isotopes with an appreciable neutron-capture cross section. The extent of the anomalies can be appreciated from the fact that about five metric tonnes of fission products have been generated in localized zones of some tens of cubic meters (0.5a and b). For many elements present in such samples only the direct measurement of the actual isotopic composition can provide a representative value of the atomic weight. For example, the atomic weight of europium in one Oklo sample is 152.66 (${}^{151}_{63}Eu$ at 12.8 atom percent) instead of $A_r(Eu) = 151.96$ (${}^{151}Eu$ at 47.77 atom percent), the standard value.

Even if no other natural nuclear reactor is ever found to be locally preserved in a similar manner, it is not unlikely that such a phenomenon occurred in other places on earth. The action of geological events during the eons (1 to 2.5 billion years) may have led to a dispersion of the reactor products. Consequently appreciable isotopic anomalies could still be detected in the future for elements that are abundantly formed following uranium fission but are rare in the earth's crust as a whole.

With respect to footnote "r", there exist relevant publications which document measurements showing wider variability than, in the opinion of the Commission, are trustworthy. Other than for Cu, Sr, Pd, Pb, Th, U, and several of the elements of atomic number up to 18, the terrestrial variabilities are still significantly less than other uncertainties in atomic weights. As previously mentioned, variability can be positively detected — for instance in neodymium — even when it is smaller than the experimental uncertainty in the atomic weight. As stated at the beginning of this Section, at the indicated precision and for normal samples, the concept of an atomic-weight constant is still operationally valid for the majority of elements.

7. The Mononuclidic Elements

The definition of a mononuclidic element in this Review is one that has one and only one nuclide which is either stable or quasi-stable, that is with a half-life greater than 4 x 10^8a (for a list of relevant half-lives see Ref. 0.6). Almost precisely the same elements would be designated as mononuclidic, had the definition been based on the standard atomic weight at the current precision of its tabulated value being based on only one nuclide's mass value. The near identity of classifications by these two definitions arises because no unstable nuclei (with half-lives shorter than the chosen limit of 4 x 10^8a) affect the standard atomic weights at current precisions, whereas the other radionuclides all do. The only case until now for which the two definitions classify an element differently is the following: prior to 1983, ${}^{3}_{2}$He, a stable isotope, did not influence A_r(He). With the introduction of one additional significant figure for A_r(He) in 1983 (0.1j) that value is no longer identical with the nuclidic mass of ${}^{4}_{2}$He. By both definitions now helium is not mononuclidic.

Many unstable nuclides occur in normal materials, but do not affect the standard atomic weights (see Section 11). On either of the above definitions niobium (see Part II) would continue to be regarded as mononuclidic even if ${}^{92}_{41}$Nb were confirmed as a constituent of terrestrial niobium in a concentration far below that needed to affect its very precise standard atomic weight. Similarly aluminium remains mononuclidic although ${}^{26}_{13}$Al is a widely dispersed, detectable cosmic-ray product (Section 11). Several elements were once but are no longer considered mononuclidic, such as tantalum for which a terrestrially occurring quasi-stable nuclide (see Part II) has been discovered in an abundance that does affect the standard atomic weight. Similar discoveries of quasi-stable isomers of radionuclides can hardly be expected (see below).

The least-squares adjustments of experimental nuclear-reaction energies and mass-spectrometrically measured mass differences (0.2a) to (0.2e) establish the nuclidic masses of all common nuclides very precisely, that is better than to about 1 part in 10^7. Chemical determinations of the atomic weights of the truly mononuclidic elements can no longer contribute to their assessed best values. Comparison with chemical determinations now serves merely to demonstrate the excellence of the best earlier chemical work (see Section 8).

The latest IUPAP-encouraged Tables published by Wapstra and Bos (0.2e) are the basis for the Standard Atomic Weights 1983 of the mononuclidic elements. The Commission only had to make judgments on the following two questions: how should the uncertainties in the IUPAP-associated Tables of nuclidic masses compare with those for Standard Atomic Weights disseminated by IUPAC? What are the estimated probabilities that one or more of the mononuclidic elements have, in reality, naturally occurring, but as yet undiscovered stable or quasi-stable isotopes such that the standard atomic weights at the indicated precision would be affected? Such a discovery would result in a change in that element's classification as mononuclidic. Anticipating such an event, should the Commission make an allowance by increasing the values for U_r(E) of some or all mononuclidic elements?

For dealing with the first question, an examination of the listed nuclidic masses of the mononuclidic elements as published from time to time (0.2a) to (0.2e) reveals changes that are large compared with the stated standard deviations. For example the mass differences between the 1971 and 1977 Tables (0.2d) and (0.2e) show that 12 out of 20 mononuclidic and stable nuclides changed by more than one standard deviation, and 5 out of 20 changed by more than twice the standard deviation anticipated in 1971. One can therefore conclude that the standard deviations may well reflect an internal consistency of the least-squares adjustment, but fail to account fully for systematic errors that may appear as trends over different portions of the mass scale. This interpretation is borne out by a recent discovery of a probable systematic error in the published masses of all mercury isotopes (see article on gold in Part II).

As discussed in Section 5 this Commission, in assessing the uncertainty of the standard atomic weights, is obliged to allow for both random and systematic errors, and wants to avoid unnecessarily frequent changes in the $A_r(E)$ values especially for the mononuclidic elements. For these reasons the Commission from 1961 to 1969 abbreviated their mass values to five or six significant figures and equated them numerically to atomic weights with the justification that chemists were uninterested in additional significant figures. That argument was rejected by the Commission in 1969 when it decided to disseminate the most precise $A_r(E)$ values consistent with all reasonably reliable (see Section 3) published information. From then onwards, with advice from IUPAP Commission members, CAWIA arbitrarily multiplied the standard deviation in the Atomic Mass Table by a factor of six and rounded off the last decimal of $A_r(E)$ if it was uncertain by more than ±1. That means that, for all mononuclidic elements, the only significant figure permitted for $U_r(E)$ is one. This restriction was again debated by the Commission in 1983 but not yet relaxed so as to permit any single digit uncertainty as for other $A_r(E)$ values. This change in policy would lead to an increase in the precision of the tabulated standard atomic weights of all 20 mononuclidic elements, but it was at least postponed to coincide with the completion of the next updating of the IUPAP-encouraged Table of Atomic Masses expected in 1984.

Since 1969 the Commission has partly justified the procedure of reducing the precision of the nuclidic masses when translating these values into atomic weights of mononuclidic elements, by the above-mentioned remote possibility of the existence of a significant undetected isotope or isomer with very long half-life. In future the Commission is likely to discount these possibilities more and more, for good reasons:

a) Many a search for specific isotopes by mass spectrometry has been unsuccessful (see sections in Part II on the mononuclidics). Admittedly, in most cases the lower detection limits were estimated to be insufficient for proof positive of the absence of a significant amount of a hypothetical isotope.

b) Since the discovery of $^{180}_{73}Ta$ (see Part II) almost thirty years ago, no new naturally occurring isotope has been found in significant abundance, despite searches with more sensitive techniques.

c) The possible identification of $^{92}_{41}Nb$ (see Part II) as a naturally occurring nuclide by a highly sensitive technique is relevant, although the authors expressed some fear that the sample might have been contaminated by nuclear technology. The ratio of $^{92}Nb/^{93}Nb$ was estimated to have been about 10^{-12}, much below a significant level for the precision of $A_r(Nb)$, with $U_r(Nb) = \pm 0.0001$. It is reasonable to expect this discovery to be typical of any future identifications of new isotopes in normal samples in exceedingly small concentrations.

d) With the exception of $^{9}_{4}Be$, all mononuclidic elements have an odd number of protons and an even number of neutrons. The mass formula in nuclear physics has a pairing term such that nuclei with even numbers of protons or neutrons are more stable than nuclides with single unpaired particles. As a result, one would expect to see the great majority of mononuclidics among elements with an odd atomic number, and for those to have also an odd mass number, as is the case. Because the island of beta stability is so narrow, one would also expect to find any naturally occurring odd atomic-number nuclides to lie near the stability line, i.e., within one or two mass units of the stable nuclide for that element. For these reasons the search for possible isotopes of the mononuclidics can be limited to a very narrow range.

e) From the discussion on the radioactive nuclides (see Section 11) it can be seen that the unstable nuclides of longest half-life for these mononuclidic elements have short half-lives compared with the age of the earth and not even 1 atom per primordial mole would still be present. For the few cases in which other nuclides of mononuclidic elements have been detected, the level has been at 10^{-10} atom percent or smaller, which would have negligible effects on the atomic weights.

f) Most naturally occurring radionuclides of the mononuclidic elements (other than $^{232}_{90}Th$) have been generated by cosmic-ray reactions. They will not necessarily be associated with the stable nuclide of the element, so that their discovery in such an occurrence would be highly anomalous. The atomic weight could deviate widely from the standard value, but the appropriate indication in the IUPAC Table would be — if anything at all — a "g" footnote (see Section 6).

g) In the case of $^{180}_{73}Ta$ it has recently been determined (see Part II) that the naturally occurring state is actually an excited state with a long half-life rather than the ground state. It confirms the possibility of undiscovered isomers having sufficiently long half-lives to be naturally occurring. The fact that they have never been found would imply that they must be very rare or very difficult to produce. At the present level of detectability they would almost certainly be below the level at which they would affect the standard atomic-weight values.

8. Chemical Determinations of Atomic Weights

Almost all of the modern measurements of atomic-weight values are based on physical methods even though they needed to be associated with preliminary chemical manipulations. In addition, there are still eleven elements whose atomic weights are based wholly or partly on purely chemical methods (Ca, Ti, Ni, Zn, Ge, Se, Mo, Sb, Te, Sm, and Hg). The most common chemical method used in these measurements is precise gravimetric determination using chemical stoichiometry. During the 19th century and until the early 1940's, these methods provided the basis for most atomic-weight values. Illustrious chemists devoted their entire careers to this work.

Most of the best chemical atomic weights were those carried out by the so-called Harvard method. T. W. Richards (1860 — 1928) of Harvard University pioneered the method in which atomic weights were determined by the preparation of high-purity chlorides or bromides of the element followed by the measurement of the mass ratio to silver or to the corresponding silver halide. Solutions containing nearly equivalent amounts of reactants were mixed and the point of exact equivalence was determined. This was often followed by the quantitative collection and weighing of the precipitated silver halide. These measurements were often of extremely high precision attaining a few parts in 100 000 for some elements.

Richards' work on atomic weights received world-wide recognition, and for it he was awarded the Nobel Prize for Chemistry in 1914. G. P. Baxter (1876 - 1953) was Richards' principal associate and succeeded him as head of the atomic-weights laboratory at Harvard. He not only applied the Harvard method to more elements but also made highly precise determinations of the atomic weights of gaseous elements by gas-density measurements. O. Hönigschmid (1878 - 1945) came to Harvard to work with Richards and then returned to the University of Munich where he devoted the remainder of his career to atomic-weight determinations.

Richards, Baxter, Hönigschmid, and their associates compiled a remarkable record in atomic-weights research. Of the 194 independent determinations of atomic weights reported in the literature from 1893 to 1947 using the Harvard method, these three scientists and their associates accounted for 142 of them (0.7a). The atomic weights of 65 elements were determined by this method and some eleven elements are still based wholly or partly on these measurements.

Even though these determinations were usually of high precision, it was virtually impossible to evaluate the accuracy of the method until accurate nuclidic-mass data became available for the mononuclidic elements. Cameron and Wichers (0.1a) compared the values obtained by chemical and physical techniques for the mononuclidic elements. The chemical values in Table 1 have been recalculated based on current atomic weights (0.1j) for silver, chlorine, and bromine. With the exception of scandium which has a 0.3% error, probably due to inadequate purity of the scandium bromide (0.7b), no error is larger than 4 parts in 10 000 and for most elements the error is less than 1 part in 10 000. When disregarding scandium the average error per element is 0.014 percent.

TABLE 1. Comparison of Atomic Weights of Mononuclidic Elements as Determined by Physical and Chemical Techniques

Element	Physical Value	Chemical Value*	Error in Percent
Be	9.012 18	9.0144	+0.025
Na	22.989 77	22.9944	+0.020
Al	26.981 54	26.972	-0.035
P	30.973 76	30.976	+0.007
Sc	44.955 91	45.096	+0.31
Mn	54.9380	54.928	-0.018
Co	58.9332	58.936	+0.005
As	74.9216	74.905	-0.022
Y	88.9059	88.916	+0.011
Nb	92.9064	92.902	-0.005
I	126.9045	126.902	-0.002
Cs	132.9054	132.897	-0.006
Pr	140.9077	140.917	+0.007
Ho	164.9304	164.925	-0.003
Bi	208.9804	208.972	-0.004
Th	232.0381	232.134	+0.041
Average value of error per element omitting Sc:			0.014

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*Recalculated using current atomic weights (0.1j).

There is yet another means of judging the accuracy of the Harvard method. Over the last 20 years, the atomic weights of a number of polynuclidic elements have been determined using absolute or calibrated mass spectrometry which must be acknowledged as a superior method. A comparison of these absolute physical values with recalculated chemical values is shown in Table 2. For only one element, silicon, the error exceeds 4 parts in 10 000. For most elements it is less than 1 part in 10 000. The average error per element is almost the same as for the mononuclidics, 0.019 percent. The results of these comparisons reinforce the opinion of Wichers (0.7b) that, while the Harvard method was relatively free from inaccuracies, "the results obtained with it could not be regarded as having an assured accuracy better than 1 or 2 parts in 10 000" (0.01 to 0.02 percent). For those elements still based on chemical determinations, more accurate atomic weights will have to await measurements by "absolute" or calibrated mass spectrometry or other new methods discussed in Section 10.

TABLE 2. Comparison of Atomic Weights of Polynuclidic Elements as Determined by Absolute Physical and Chemical Techniques

Element	Physical Value	Chemical Value*	Error in Percent
Li	6.941	6.939	-0.029
Mg	24.305	24.314	+0.037
Si	28.0855	28.103	+0.062
K	39.0983	39.093	-0.014
Cl	45.453	45.453	0.000
Cr	51.9961	52.001	+0.010
Cu	63.546	63.536	-0.016
Br	79.907	79.904	-0.004
Rb	85.4678	85.471	+0.004
Ag	107.8682	107.870	+0.002
Re	186.207	186.282	+0.040
Tl	204.383	204.371	-0.006
		Average value of error per element	0.019

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*Recalculated using current atomic weights (0.1j).

9. Mass Spectrometric Techniques for the Determination of Atomic Weights

The atomic weight of an element may be determined from knowledge of the atom fraction and the nuclidic mass of each of its isotopes by the formula:

$$\underline{A}_r(E) = \Sigma f_i M_i$$

where f_i is the fraction of the number of atoms of isotope i in a normal source of element E and M_i is the corresponding nuclidic mass.

Nuclidic masses, M_i, are nowadays known as a consistent set to a precision better than one part in 10^7. They are derived by least-squares adjustments from mass-spectrometric doublet measurements and nuclear-reaction energies (0.2e). Except for mononuclidic elements (for which $f \equiv 1$) the uncertainty in $\underline{A}_r(E)$ is determined virtually exclusively by the f_i's. These are determined in isotope-ratio mass spectrometers in which the element or one of its simple compounds is ionized and the different isotope ions are magnetically separated according to their ion mass. The ratios of the intensities of the separated ion beams are determined and appropriate corrections discussed below to give the set of f_i's.

An optimal atomic-weight determination involves:

a) a measurement of the complete set of isotopic abundance ratios to the best achievable precision;

b) calibration of these ratio measurements by means of synthetic mixtures of chemically pure, highly enriched isotopes to give gravimetrically defined ratios. These are used to make the ratio measurement "absolute" by allowing a correction for effects including isotope fractionation in the mass spectrometer; and

c) a survey of the normal natural sources of the element to discover variations in the isotopic composition, which, if existent, are incorporated in the uncertainty of the tabulated standard atomic weight.

Though there are exceptions, the larger the number of isotopes, the larger tends to be the uncertainty of the mass spectrometrically determined atomic weight. The smaller the abundance of an isotope and the smaller its mass difference from the mean, the smaller its contribution to the overall uncertainty. Atomic weights of nearly mononuclidic elements, those with an isotope having an abundance of 98 atom percent or more, approach in uncertainties those of the mononuclidic elements, that are those of the nuclidic masses.

The science (and the art!) of measuring isotope ratios has progressed impressively in the last few decades. Accuracies of a few parts in 10^4 are common, and a few parts in 10^5 have been achieved, thus leading to much better atomic-weight values. Further improvement will make the uncertainty contributions from isotope-ratio measurements approach those from the nuclidic-mass determinations, making the uncertainties of the latter significant in their contribution. This situation has already been achieved for silver (see Part II).

The uncertainties in the ratio measurements that have not been made absolute by the method described above can be reduced by "internal normalization" with one of the following techniques:

d) Incorporation of a known ratio in the measurement using two isotopes not normally present in the natural sources (e.g., $^{233}_{92}U/^{236}U$ in a sample of natural uranium consisting of ^{234}U, ^{235}U, and ^{238}U only). A virtually exact correction, at least for isotopic fractionation, is thereby introduced. This correction makes use of the observation that all fractionation effects for a given element appear to be a linear function of mass.

e) A less satisfactory, but still useful version of the above is the addition of a "spike" made of two separated or highly enriched isotopes that are present in the normal sample. A measurement of the ratios of both the altered and unaltered samples gives information on a suitable correction for fractionation, but, usually, with a greater uncertainty than is achieved by the method described in b) above.

For uncalibrated measurements isotope fractionation remains as the biggest contribution to the uncertainty. Chemical contamination can cause problems, but the mass spectrometer by its basic principle discriminates greatly against most impurities. Chemical mixing of solutions or the introduction of aliquots can introduce errors and the minimization of errors from these sources is the challenge of a good experimental plan.

Traditional chemical measurements of atomic weights (Section 8) suffer many more hazards due to unwanted chemical effects. It is therefore not surprising that present-day standard atomic weights are mostly based on mass spectrometry. Indeed, during the period covered by this Review significant progress in atomic-weight determinations has been derived overwhelmingly from mass-spectrometric measurements.

10. Possible Future Techniques of Atomic-Weight Determinations

Two types of experimental techniques for determining atomic weights are readily distinguished:

Type 1: Measurements based on elemental attributes which are related to the overall isotopic composition; and

Type 2: Measurements for derivation of isotopic abundances based on distinct attributes of individual isotopes or on their separation. By combination with nuclidic masses the abundances yield the atomic weight (see Section 11).

The "chemical" methods (Section 8) fall under type 1, the "physical" mass-spectrometric techniques (Section 9) under type 2. Some interdependence exists between physical and chemical methods. As the physical methods become more accurate they place more exacting demands on chemical manipulations, while more rigorously controlled chemical procedures will show more isotope fractionation. Crystallization and diffusion, for instance, as involved in most purifications, can no longer be assumed to be invariant for isotopes when working at highest attainable levels of precision. Some chemical reactions, laser-induced reactions for example, are markedly isotope dependent. Many biological processes which are effective in concentrating specific ions or molecules also show significant isotope enrichment (see for example boron in Part II).

Type 1: These measurements comprise principally the chemical and density methods in gases and solids. Well tried chemical methods have been discussed in Section 8. Future conceivable variants might arise from:

i) wider use of coulometry;
ii) radically improved techniques for achieving stoichiometry;
iii) radically improved methods for achieving element-specific transport in vapors, solutions, or through membranes.

The density methods are not new. Until 1967, for example, the atomic weight of neon (see Part II) was based on a density determination. The method depends on the ideal-gas laws from which the density ratio of two gases is the ratio of their molecular weights summed over the atoms in the molecules. The behavior of gases above their triple-point temperatures tend to that ideal as the pressure tends to zero. It is not surprising, therefore, that this method of atomic-weight determination entails a difficult challenge to the experimenter's skill in the design, construction, and use of appropriate equipment. At this time not a single tabulated atomic-weight value is based on this technique. However, improvements in gas-density determinations are being made and further advances can be confidently expected. The use, for example, of a precise electronic balance with an object of known mass and volume entirely immersed in the gas holds promise. The weighings would be repeated at decreasing pressures down to a vacuum.

A different but excellent new opportunity for atomic-weight determinations of monoatomic gases arises from the demonstration by Moldover et al. (0.8a) that spherical acoustic cavities can be built with characteristic, sharply defined, radially-symmetric resonance frequencies that are accurately related to the speed of sound in the gas within the cavity. The square of that speed equals $\gamma p/\rho$, where ρ is the density, p the pressure and γ the ratio of the specific heats at constant pressure and volume, respectively. It is exactly 5/3 for monoatomic gases. It can be shown that most residual uncertainties are eliminated by comparing two such gases, one with known atomic weight, and extrapolating the measurements to zero pressure and frequency. This is experimentally possible because such cavities have numerous resonances.

Measurements on gases at reasonable temperatures are necessarily limited in their applications to the Table of Standard Atomic Weights. However, the density of highly perfect crystals provides a strong possibility, waiting for the effort to be expended by careful experimenters. The technique has been well proved for silicon (see Part II) and used for an as yet unconvincing challenge of the atomic weight of germanium (see Part II). The method depends on equating the macroscopic crystal density with the atomic-scale unit-cell density of the crystal (0.8b). Unfortunately there still exists a surprising lack of macroscopic-density measurements to better than 1 part in 10^4, whereas the state of the art is one or two orders of magnitude better. This greater accuracy is needed for significant atomic-weight determinations. By contrast, the volumes of many crystal cells of interest are known to adequate accuracies. The conversion factor from atomic-scale masses to the kilogram is also known to about 1 part in 10^6. However, the method still has substantial pitfalls arising from requirements for chemical purity, stoichiometry, and homogeneity, as well as for limitations of vacancies and other point defects, dislocations, and mosaic structure. Corrections for incipient isotopic fractionations may also be involved. Nevertheless, there can be little doubt that by this crystallographic technique many of the most uncertain values in the Table of Standard Atomic Weights could be improved.

Type 2: During the past twenty years virtually all significant atomic-weight determinations have come from mass-spectrometric measurements described in Section 9. Ongoing improvements in instrument design and experimental procedures give promise of a continuing flow of new improved determinations. However, the supply of highly purified isotopes has been interrupted from some traditional sources (e.g., from "calutrons" at Oak Ridge, Tennessee, U.S.A.). New laser techniques for achieving separations may not become commercially available for some years. In addition the developments for improved mass-spectrometric instrument design are concentrated on different objectives. Greater precision of determining relative differences of selected pairs of isotopes are needed more widely in other fields of science than absolute abundance values of all isotopes of an element, as are needed for atomic-weight determinations. Thus it would not be wise to rely solely for improved atomic-weight values on mass spectrometry, especially for elements having a large number of stable isotopes.

Among alternative methods of type 2, are optical techniques depending on the isotope shifts of atomic or molecular spectral lines under conditions that avoid overlapping from Doppler broadening. With the incentive of the Os/Re method of dating, a CO_2-laser saturation-absorption technique has been used for one of the isotope-abundance ratios in osmium (see Part II). However, with seven naturally occurring osmium isotopes, an atomic-weight determination would require a great deal of additional work. Nevertheless, the feasibility has been demonstrated that one is not restricted to measurements of mass-spectrometrically separated beams.

One could use a wide variety of physical characteristics of isotopes for abundance measurements. It is possible to exploit optical, magnetic, and Mössbauer effects in numerous cases, and to apply calibration procedures for neutron-absorption measurements as has been done for $^{58}_{26}Fe$ (see Part II). Whereas neutron-activation analysis generally depends on isotope-abundance data (0.8c), it can conversely be applied to abundance measurements by use of pure isotopes on synthetic mixtures. Even one ratio determined with superior accuracy could be used as a constraint on the interpretation of mass-spectrometric data and improve the confidence in an atomic weight. Future Commission meetings are likely to make statements encouraging the exploitation of many diverse kinds of measurements.

11. Radionuclides in Normal and "Abnormal" Materials

Richards (0.4b) in his Nobel Prize Lecture in Chemistry in 1919, stated:

> "If our inconceivably ancient Universe even had any beginning, the conditions determining that beginning must even now be engraved in the atomic weights. They are the hieroglyphics which tell in a language of their own the story of the birth or evolution of all matter..."

At the birth of the solar system, the isotopic compositions of many elements were in a state of flux as short-lived radioactive isotopes decayed to stable daughter products. During all evolutionary processes, elements associate and segregate by their physical and, especially, their chemical properties. When the solar system had evolved to the point where the meteorites had become closed isotopic systems some 4.6 x 10^{9}a ago, some radioactive nuclides, now extinct in the solar system, were still present. For example, ${}^{129}_{53}\text{I}$ (half-life $T_{\frac{1}{2}}$ = 1.6(1) x 10^{7}a), ${}^{107}_{46}\text{Pd}$ ($T_{\frac{1}{2}}$ = 6.4(3) x 10^{6}a), and ${}^{26}_{13}\text{Al}$ ($T_{\frac{1}{2}}$ = 7.14(31) x 10^{5}a) (0.6) are known to have existed in meteorites at this time since their daughter products have been identified in meteoritic material in anomalous amounts compared to the other isotopes of the daughter elements. In fact these three decay schemes have been used to estimate the time interval between the end of nucleosynthesis and the formation of the solar system. These and other primordial isotopes of similar half-life, notably ${}^{92}_{41}\text{Nb}$ ($T_{\frac{1}{2}}$ = 3.7(5) x 10^{7}a), ${}^{146}_{62}\text{Sm}$ ($T_{\frac{1}{2}}$ = 1.03(5) x 10^{8}a), ${}^{154}_{66}\text{Dy}$ ($T_{\frac{1}{2}}$ = 3(1.5) x 10^{6}a), ${}^{205}_{82}\text{Pb}$ ($T_{\frac{1}{2}}$ = 1.9(3) x 10^{7}a), ${}^{236}_{92}\text{U}$ ($T_{\frac{1}{2}}$ = 2.342(3) x 10^{7}a), ${}^{244}_{94}\text{Pu}$ ($T_{\frac{1}{2}}$ = 8.15(20) x 10^{7}a), and ${}^{247}_{96}\text{Cm}$ ($T_{\frac{1}{2}}$ = 1.58(5) x 10^{7}a) (0.6), which were produced by nucleosynthesis no longer exist in the solar system; their unstable daughter products, too, have decayed, and therefore have no influence on the atomic weights of present-day material.

Elements which possess radioactive isotopes whose half-lives are of comparable magnitude to the age of the solar system will produce daughter products which may have measurable effects on the atomic weights of the daughter elements. For example ${}^{87}_{37}\text{Rb}$ ($T_{\frac{1}{2}}$ = 4.88(5) x 10^{10}a) (0.6) decays to the stable daughter isotope ${}^{87}_{38}\text{Sr}$. The isotopic composition and hence the atomic weight of strontium varies considerably, depending on the age and Rb/Sr ratio of the source of the strontium-bearing sample. Old, biotite-rich rocks will be enriched in radiogenic ${}^{87}\text{Sr}$ and will therefore contain strontium with a lower atomic weight than that in ultra-basic (low Rb/Sr) rocks. In geochronological studies (0.9) the isotopic composition of strontium has to be measured in each sample, together with the Rb/Sr ratio, to enable the age of a suite of cogenetic samples to be determined. Of course the isotopic composition and hence the atomic weight of the parent element will also vary over the age of the solar system, but for all practical considerations the isotopic composition of modern-day parent-element material is constant.

Similar situations occur for ${}_{18}\text{Ar}$ and ${}_{20}\text{Ca}$ from the decay of ${}^{40}_{19}\text{K}$ ($T_{\frac{1}{2}}$ = 1.25(2) x 10^{9}a), for ${}_{58}\text{Ce}$ from ${}^{138}_{57}\text{La}$ ($T_{\frac{1}{2}}$ = 1.06(4) x 10^{11}a), for ${}_{60}\text{Nd}$ from ${}^{147}_{62}\text{Sm}$ ($T_{\frac{1}{2}}$ = 1.06(1) x 10^{11}a), for ${}_{72}\text{Hf}$ from ${}^{176}_{71}\text{Lu}$ ($T_{\frac{1}{2}}$ = 3.74(7) x 10^{10}a), and for ${}_{76}\text{Os}$ from ${}^{187}_{75}\text{Re}$ and ${}^{190}_{78}\text{Pt}$ ($T_{\frac{1}{2}}$ = 4.3(5) x 10^{10}a and 6.9(6) x 10^{11}a respectively) (0.6). The magnitude of the variation in atomic weight in the daughter element would depend on the half-life of the parent radionuclide, the age of the material concerned, the abundance of the daughter isotope in relation to the other stable isotopes comprising the element, and the geological association of the parent and daughter elements (0.9).

Of particular interest is the uranium/thorium-lead system. Lead has four stable isotopes, three of which are the daughter products of radioactive-decay series. ${}^{206}_{82}\text{Pb}$ from ${}^{238}_{92}\text{U}$ ($T_{\frac{1}{2}}$ = 4.468(5) x 10^{9}a), ${}^{207}\text{Pb}$ from ${}^{235}\text{U}$ ($T_{\frac{1}{2}}$ = 7.037(11) x 10^{8}a), and ${}^{208}\text{Pb}$ from ${}^{232}_{90}\text{Th}$ ($T_{\frac{1}{2}}$ = 1.40(1) x 10^{10}a) (0.6). Thus the isotopic composition and hence the atomic weight of modern-day lead varies considerably, depending on whether the lead has been derived from material which has contained uranium or thorium. The isotopic composition of uranium varies considerably with time because of the different half-lives of the three isotopes of uranium. In the past history of the solar system the ${}^{235}\text{U}/{}^{238}\text{U}$ ratio was larger than the present-day ratio, whilst the proportion of the third isotope, ${}^{234}\text{U}$, depends on the decay of ${}^{238}\text{U}$ and is controlled by its own half-life ($T_{\frac{1}{2}}$ = 2.454(6) x 10^{5}a) (0.6) which is relatively short compared with that of ${}^{238}\text{U}$. A number of radionuclides of extremely long half-lives such as ${}^{82}_{34}\text{Se}$, ${}^{113}_{48}\text{Cd}$, ${}^{115}_{49}\text{In}$, ${}^{123}_{52}\text{Te}$, ${}^{128}_{52}\text{Te}$, ${}^{130}_{52}\text{Te}$, ${}^{144}_{60}\text{Nd}$, ${}^{145}_{60}\text{Nd}$, ${}^{148}_{62}\text{Sm}$, ${}^{152}_{64}\text{Gd}$, ${}^{174}_{72}\text{Hf}$, ${}^{180}_{73}\text{Ta}$, and ${}^{186}_{76}\text{Os}$ also exist in nature. However they do not cause any significant variations in the atomic weights of normal terrestrial materials. In special locations minor sources may show anomalies in atomic weights as indicated by annotation "g" in the Table of Standard Atomic Weights and in this Review with explanations, as for instance for xenon (see Part II).

In addition to the radionuclides which were formed in nucleosynthesis and were part of the initial composition of the primordial solar system, others have been added to the terrestrial mix over the past 4.6 x 10^9 years. These have been produced not only by the decay of the the radioactive heavy elements but also by the following mechanisms:

a) Cosmic-ray interactions in the upper atmosphere produce spallation products such as ${}^{3}_{1}\mathrm{H}$, ${}^{10}_{4}\mathrm{Be}$, ${}^{14}_{6}\mathrm{C}$, ${}^{26}_{13}\mathrm{Al}$, ${}^{32}_{14}\mathrm{Si}$, ${}^{36}_{17}\mathrm{Cl}$, and ${}^{39}_{18}\mathrm{Ar}$.

b) Cosmic-ray interactions with the earth's surface produce ${}^{26}_{13}\mathrm{Al}$ which decays to ${}^{26}_{12}\mathrm{Mg}$ with a half-life of 7.14(31) x 10^5a (0.6).

c) Meteoritic and cosmic dust have been estimated to be falling to the earth at the rate of some thousands of tons per year. Radioactive isotopes introduced in this way include ${}^{3}_{1}\mathrm{H}$, ${}^{10}_{4}\mathrm{Be}$, ${}^{14}_{6}\mathrm{C}$, ${}^{26}_{13}\mathrm{Al}$, ${}^{32}_{14}\mathrm{Si}$, ${}^{36}_{17}\mathrm{Cl}$, ${}^{39}_{18}\mathrm{Ar}$, ${}^{41}_{20}\mathrm{Ca}$, ${}^{44}_{22}\mathrm{Ti}$, ${}^{53}_{25}\mathrm{Mn}$, and ${}^{59}_{28}\mathrm{Ni}$.

d) Alpha particles and neutrons from radioactive elements and naturally-induced fussion reactions interact with other nuclides to form a variety of radionuclides. The content of ${}^{4}_{2}\mathrm{He}$ in terrestrial rocks is enhanced by alpha decay of some of these radioactive elements.

e) Nuclear reactors and particle accelerators also produce radionuclides which may be used for medical or industrial purposes. These radionuclides are contained and labeled, but many find their way into commonly used materials. Radioactive waste also contains material of abnormal isotopic composition, but strict safety controls should preclude the inadvertent distribution of such materials.

It should be noted that in a) to c) above, only radionuclides of relatively long half-life have been mentioned. No attempt has been made to list all the short-lived radionuclides produced by these mechanisms. In fact none of these processes affects the isotopic composition of the elements in normal materials as here reviewed, to any significant extent.

12. Aims and Format of the Sections in Part II on Each of the Elements

The aim of the Element-by-Element Review is to provide interested specialists and scholars with a condensed account of the assessment of individual atomic weights and their uncertainties, with emphasis on the developments during the past twenty-five years, as they have arisen almost exclusively from mass spectrometry. The literature that is most significant from the viewpoint of the assessments is directly quoted within the section for each element. A comprehensive list of all relevant mass-spectrometric papers is being published elsewhere (0.3). The Review here presented does not describe or analyze details of the experimental techniques, and does not discuss issues of nomenclature.

A section for an element is included if it occurs naturally on earth with a characteristic isotopic composition and if it has at least one stable or quasi-stable (see Section 7) isotope. The entries are in order of atomic number. Each section begins with a heading comprising the chemical symbol,with its preceding subscript atomic number, and the chemical name or names in English. This is followed by the atomic-weight value $A_r(E)$, and its uncertainty, which is the quantity $U_r(E)$. This uncertainty is numerically the same in the positive and negative directions and is expressed only by a single digit in parentheses applicable to the last figure of decimal in $A_r(E)$. Thus, for example, $A_r(\mathrm{Zn})$ = 65.39(2) means that the Commission expresses confidence that the true atomic weight of every normal sample of zinc falls between 65.37 and 65.41. The Commission expresses overwhelming confidence approaching certainty that the atomic weight of any one randomly chosen normal sample of zinc falls within the above range.

A small tabulation next lists all the stable and quasistable (see Section 7) nuclides of that element in columns by chemical symbol with preceding mass number in superscript. The following column lists the nuclidic masses with their uncertainties from Wapstra and Bos (0.2e). The last column records the abundances of these isotopes in atomic percent for a representative normal occurrence. Figures in parentheses are the estimated uncertainties of the measurement. They are not restricted to one digit. The representative compositions are identical to those quoted in the 1983 Commission Report (0.1j) and are recommended for evaluating average properties of materials of unspecified terrestrial origin. However, an exact sample of that composition may not always be available. The given uncertainties in isotopic composition are based on experimental evaluation and, in general, do not correspond to the full range of $A_r(E)$ values implied in their given uncertainties. Conversely, and unfortunately perhaps, in some elements the uncertainty range in composition is partly outside the corresponding uncertainty limits in the $A_r(E)$ values. It must be remembered, however, that the $A_r(E)$ range is based on additional evidence, such as chemical determinations, and should not be lightly disregarded in such situations.

The final symbols, if any, in the heading call attention to abnormalities known to exist for that element by annotation codes from the Table of Standard Atomic Weights in accordance with the sumbols described in Section 6.

The text for each element begins with a summary of the information and its literature sources as given in the former element-by-element review (0.1a). Developments are then followed through the more than twenty years of Commission analysis of significant literature publications. Relevant concepts and discussions in the Commission's biennial reports are described. The sections emphasize the present status and mention any additional pertinent comparisons. The text for some elements ends with notes on radioactive properties of some nuclides and their possible effect on the atomic weights. Half-lives are from a recent compilation by Holden (0.6).

13. Changes in Atomic Weights and Their Uncertainties

All recommended values for the atomic weights since 1961 and their uncertainties since 1969, are summarized and changes are analyzed in Tables 3 and 4 in order to provide a general overview. Each row applies to one element. In the columns the following information is listed:

Table 3

Column 1: Atomic number, Z.

Column 2: Corresponding element name(s) in English as recommended by IUPAC.

Column 3: The atomic weight, $A_r(E)$, from the 1961 Commission Report and the uncertainty $U_r(E)$ (see Section 5), where given in 1961 (0.1a).

Column 4: $A_r(E)$ and $U_r(E)$ from the 1969 Commission Report (0.1c). It was the first year in which $U_r(E)$ was systematically given for every element. In this and subsequent columns a horizontal arrow points back to the value in a previous year when no change in $A_r(E)$ or $U_r(E)$ was made in that year for that element.

Columns 5-11: The value of $A_r(E)$ with $U_r(E)$ from the Commission Reports 1971, 1973, 1975, 1979, 1981, and 1983 respectively (0.1d to 0.1j). The uncertainties now range from 10^{-1} (Os, Pb) to 10^{-6} (F).

Table 4

Columns 1-2: As for Table 3.

Column 3: Relative uncertainty $U_r(E)/A_r(E)$ multiplied for convenience by 10^6 as applicable to the 1983 value. Fluorine which is mononuclidic, has the most precisely tabulated atomic weight. Titanium remains the element with the least precisely tabulated atomic weight.

Column 4: Overall change in atomic weight, $\Delta A_r(E)$ from 1969 to 1983, multiplied for convenience by 10^3. Samarium in 1979 was given the largest change although it amounted to only 0.4 times the previously estimated uncertainty.

Column 5: $\Delta A_r(E)/U_r(E)$ for the uncertainty estimated in 1969. It is a test of the Commission's judgment in 1969. A value greater than one implies that an underestimate of $U_r(E)$ may have been made. This conclusion becomes inescapable when $\Delta A_r(E)$ is equal or greater than the sum of the $U_r(E)$ values in 1969 and 1983. This situation has arisen for bismuth, a mononuclidic element, for which the total change amounted only to 1 part per million of the atomic weight, and for potassium for which the 1983 uncertainty is only a thirtieth of that applicable in 1969.

Column 6: The relative change $\Delta A_r(E)/A_r(E)$, multiplied for convenience by 10^6. These values range from 0.2 (F, Sc) to 400 (Ti), in parts per million, and are here given without sign, rounded to one significant figure.

Table 3

ATOMIC NUMBER	ELEMENT NAME IN ENGLISH	$A_r^{1961}(E)$	$A_r^{1969}(E)$	$A_r^{1971}(E)$	$A_r^{1973}(E)$	$A_r^{1975}(E)$	$A_r^{1977}(E)$	$A_r^{1979}(E)$	$A_r^{1981}(E)$	$A_r^{1983}(E)$
1	HYDROGEN	1.00797(1)	1.0080(3)	1.0079(1)	←	←	←	←	1.00794(7)	←
2	HELIUM	4.0026	4.00260(1)	←	←	←	←	←	←	4.002602(2)
3	LITHIUM	6.939	6.941(3)	←	←	←	←	←	←	6.941(2)
4	BERYLLIUM	9.0122	9.01218(1)	←	←	←	←	←	←	←
5	BORON	10.811(3)	10.81(1)	←	←	←	←	←	←	10.811(5)
6	CARBON	12.01115(5)	12.011(1)	←	←	←	←	←	←	←
7	NITROGEN	14.0067	14.0067(1)	←	←	←	←	←	←	←
8	OXYGEN	15.9994(1)	15.9994(3)	←	←	←	←	←	←	←
9	FLUORINE	18.9984	18.9984(1)	18.99840(1)	←	18.998403(1)	←	←	←	←
10	NEON	20.183	20.179(3)	←	←	←	←	20.179(1)	←	←
11	SODIUM (NATRIUM)	22.9898	22.9898(1)	22.98977(1)	←	←	←	←	←	←
12	MAGNESIUM	24.312	24.305(1)	←	←	←	←	←	←	←
13	ALUMINIUM	26.9815	26.9815(1)	26.98154(1)	←	←	←	←	←	←
14	SILICON	28.086(1)	28.086(3)	←	←	28.0855(3)	←	←	←	←
15	PHOSPHORUS	30.9738	30.9738(1)	30.97376(1)	←	←	←	←	←	←
16	SULFUR	32.064(3)	32.06(1)	←	←	←	←	←	←	32.066(6)
17	CHLORINE	35.453(1)	←	←	←	←	←	←	←	←
18	ARGON	39.948	39.948(3)	←	←	←	←	39.948(1)	←	←
19	POTASSIUM (KALIUM)	39.102	39.102(3)	39.098(3)	←	39.0983(3)	←	39.0983(1)	←	←
20	CALCIUM	40.08	40.08(1)	←	←	←	←	←	←	40.078(4)
21	SCANDIUM	44.956	44.9559(1)	←	←	←	←	←	←	44.95591(1)
22	TITANIUM	47.90	47.90(3)	←	←	←	←	47.88(3)	←	←
23	VANADIUM	50.942	50.9414(3)	←	←	←	50.9415(1)	←	←	←
24	CHROMIUM	51.996(1)	←	←	←	←	←	←	←	51.9961(6)
25	MANGANESE	54.9380	54.9380(1)	←	←	←	←	←	←	←
26	IRON	55.847(3)	←	←	←	←	←	←	←	←
27	COBALT	58.9332	58.9332(1)	←	←	←	←	←	←	←
28	NICKEL	58.71	58.71(3)	←	58.70(1)	←	←	58.69(1)	←	←
29	COPPER	63.54	63.546(3)	←	←	←	←	←	←	←
30	ZINC	65.37	65.37(3)	65.38(1)	←	←	←	←	←	65.39(2)
31	GALLIUM	69.72	69.72(1)	←	←	←	←	←	←	69.723(4)
32	GERMANIUM	72.59	72.59(3)	←	←	←	←	←	←	←
33	ARSENIC	74.9216	74.9216(1)	←	←	←	←	←	←	←
34	SELENIUM	78.96	78.96(3)	←	←	←	←	←	←	←
35	BROMINE	79.909(2)	79.904(1)	←	←	←	←	←	←	←
36	KRYPTON	83.80	83.80(1)	←	←	←	←	←	←	←
37	RUBIDIUM	85.47	85.4678(3)	←	←	←	←	←	←	←
38	STRONTIUM	87.62	87.62(1)	←	←	←	←	←	←	←
39	YTTRIUM	88.905	88.9059(1)	←	←	←	←	←	←	←
40	ZIRCONIUM	91.22	91.22(1)	←	←	←	←	←	←	91.224(2)
41	NIOBIUM	92.906	92.9064(1)	←	←	←	←	←	←	←
42	MOLYBDENUM	95.94	95.94(3)	←	←	95.94(1)	←	←	←	←
44	RUTHENIUM	101.07	101.07(3)	←	←	←	←	←	←	101.07(2)
45	RHODIUM	102.905	102.9055(1)	←	←	←	←	←	←	←
46	PALLADIUM	106.4	106.4(1)	←	←	←	←	106.42(1)	←	←
47	SILVER	107.870(3)	107.868(1)	←	←	←	←	←	107.8682(3)	←
48	CADMIUM	112.40	112.40(1)	←	←	112.41(1)	←	←	←	←
49	INDIUM	114.82	114.82(1)	←	←	←	←	←	←	←
50	TIN	118.69	118.69(3)	←	←	←	←	←	←	118.710(7)
51	ANTIMONY	121.75	121.75(3)	←	←	←	←	←	←	←
52	TELLURIUM	127.60	127.60(3)	←	←	←	←	←	←	←
53	IODINE	126.9044	126.9045(1)	←	←	←	←	←	←	←
54	XENON	131.30	131.30(1)	←	←	←	←	131.29(3)	←	←
55	CAESIUM	132.905	132.9055(1)	132.9054(1)	←	←	←	←	←	←
56	BARIUM	137.34	137.34(3)	←	←	137.33(1)	←	←	←	←
57	LANTHANUM	138.91	138.9055(3)	←	←	←	←	←	←	←
58	CERIUM	140.12	140.12(1)	←	←	←	←	←	←	←
59	PRASEODYMIUM	140.907	140.9077(1)	←	←	←	←	←	←	←
60	NEODYMIUM	144.24	144.24(3)	←	←	←	←	←	←	←
62	SAMARIUM	150.35	150.4(1)	←	←	←	←	150.36(3)	←	←
63	EUROPIUM	151.96	151.96(1)	←	←	←	←	←	←	←
64	GADOLINIUM	157.25	157.25(3)	←	←	←	←	←	←	←
65	TERBIUM	158.924	158.9254(1)	←	←	←	←	←	←	←
66	DYSPROSIUM	162.50	162.50(3)	←	←	←	←	←	←	←
67	HOLMIUM	164.930	164.9303(1)	164.9304(1)	←	←	←	←	←	←
68	ERBIUM	167.26	167.26(3)	←	←	←	←	←	←	←
69	THULIUM	168.934	168.9342(1)	←	←	←	←	←	←	←
70	YTTERBIUM	173.04	173.04(3)	←	←	←	←	←	←	←
71	LUTETIUM	174.97	174.97(1)	←	←	←	174.967(3)	←	174.967(1)	←
72	HAFNIUM	178.49	178.49(3)	←	←	←	←	←	←	←
73	TANTALUM	180.948	180.9479(3)	←	←	←	←	180.9479(1)	←	←
74	TUNGSTEN	183.85	183.85(3)	←	←	←	←	←	←	←
75	RHENIUM	186.2	186.2(1)	←	186.207(1)	←	←	←	←	←
76	OSMIUM	190.2	190.2(1)	←	←	←	←	←	←	←
77	IRIDIUM	192.2	192.22(3)	←	←	←	←	←	←	←
78	PLATINUM	195.09	195.09(3)	←	←	←	←	195.08(3)	←	←
79	GOLD	196.967	196.9665(1)	←	←	←	←	←	←	←
80	MERCURY	200.59	200.59(3)	←	←	←	←	←	←	←
81	THALLIUM	204.37	204.37(3)	←	←	←	←	204.383(1)	←	←
82	LEAD	207.19	207.2(1)	←	←	←	←	←	←	←
83	BISMUTH	208.980	208.9806(1)	208.9804(1)	←	←	←	←	←	←
90	THORIUM	232.038	232.0381(1)	←	←	←	←	←	←	←
92	URANIUM	238.03	238.029(1)	←	←	←	←	238.0289(1)	←	←

Table 4

ATOMIC NUMBER	ELEMENT NAME IN ENGLISH	$\frac{U_r^{1983}(E)}{A_r^{1983}(E)} \times 10^6$	$\Delta A_r^{1983-69}(E) \times 10^3$	$\frac{\Delta A_r^{1983-69}(E)}{U_r^{1969}(E)}$	$\frac{\lvert\Delta A_r^{1983-69}(E)\rvert}{A_r(E)} \times 10^6$
1	HYDROGEN	69	− 0.06	−0.2	60
2	HELIUM	0.50	+ 0.002	+0.2	0.5
3	LITHIUM	290	—	—	—
4	BERYLLIUM	1.1	—	—	—
5	BORON	460	+ 1	+0.1	90
6	CARBON	83	—	—	—
7	NITROGEN	7.1	—	—	—
8	OXYGEN	19	—	—	—
9	FLUORINE	0.053	+ 0.003	+0.03	0.1
10	NEON	50	—	—	—
11	SODIUM (NATRIUM)	0.43	− 0.03	−0.3	1
12	MAGNESIUM	41	—	—	—
13	ALUMINIUM	0.37	+ 0.04	+0.4	1
14	SILICON	11	− 0.5	−0.17	18
15	PHOSPHORUS	0.32	− 0.04	−0.4	1
16	SULFUR	190	+ 6	+0.6	200
17	CHLORINE	28	—	—	—
18	ARGON	25	—	—	—
19	POTASSIUM (KALIUM)	2.6	− 3.7	−1.2	90
20	CALCIUM	100	− 2	−0.2	50
21	SCANDIUM	0.22	+ 0.01	+0.1	0.2
22	TITANIUM	630	−20	−0.67	400
23	VANADIUM	2.0	+ 0.1	+0.33	2
24	CHROMIUM	12	+ 0.1	+0.10	2
25	MANGANESE	1.8	—	—	—
26	IRON	54	—	—	—
27	COBALT	1.7	—	—	—
28	NICKEL	170	−20	−0.67	300
29	COPPER	47	—	—	—
30	ZINC	310	+20	+0.67	300
31	GALLIUM	57	+ 3	+0.30	40
32	GERMANIUM	410	—	—	—
33	ARSENIC	1.3	—	—	—
34	SELENIUM	380	—	—	—
35	BROMINE	13	—	—	—
36	KRYPTON	120	—	—	—
37	RUBIDIUM	3.5	—	—	—
38	STRONTIUM	114	—	—	—
39	YTTRIUM	1.1	—	—	—
40	ZIRCONIUM	22	+ 4	+0.4	40
41	NIOBIUM	1.1	—	—	—
42	MOLYBDENUM	104	—	—	—
44	RUTHENIUM	200	—	—	—
45	RHODIUM	0.97	—	—	—
46	PALLADIUM	94	+20	+0.2	200
47	SILVER	2.8	+ 0.2	+0.2	2
48	CADMIUM	89	+10	+1.0	90
49	INDIUM	87	—	—	—
50	TIN	59	+20	+0.67	200
51	ANTIMONY	250	—	—	—
52	TELLURIUM	240	—	—	—
53	IODINE	0.79	—	—	—
54	XENON	230	−10	−1.0	80
55	CAESIUM	0.75	− 0.1	−1.0	0.8
56	BARIUM	73	−10	−0.33	70
57	LANTHANUM	2.2	—	—	—
58	CERIUM	71	—	—	—
59	PRASEODYMIUM	0.71	—	—	—
60	NEODYMIUM	210	—	—	—
62	SAMARIUM	200	−40	−0.40	300
63	EUROPIUM	66	—	—	—
64	GADOLINIUM	190	—	—	—
65	TERBIUM	0.63	—	—	—
66	DYSPROSIUM	180	—	—	—
67	HOLMIUM	0.61	+ 0.1	+1.0	0.6
68	ERBIUM	180	—	—	—
69	THULIUM	0.59	—	—	—
70	YTTERBIUM	170	—	—	—
71	LUTETIUM	5.7	− 3	−0.3	20
72	HAFNIUM	170	—	—	—
73	TANTALUM	0.55	—	—	—
74	TUNGSTEN	160	—	—	—
75	RHENIUM	5.4	+ 7	+0.07	40
76	OSMIUM	530	—	—	—
77	IRIDIUM	160	—	—	—
78	PLATINUM	150	−10	−0.33	50
79	GOLD	0.51	—	—	—
80	MERCURY	150	—	—	—
81	THALLIUM	4.9	+13	+0.43	60
82	LEAD	480	—	—	—
83	BISMUTH	0.48	− 0.2	−2.0	1
90	THORIUM	0.43	—	—	—
92	URANIUM	0.42	− 0.1	−0.1	0.4

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PART II THE ELEMENTS (in ascending order of atomic number)

$_1$H HYDROGEN

$A_r(\mathrm{H}) = 1.007\ 94(7)$

Nuclide	Nuclidic Mass	Atom Percent in Element
^{1}H	1.007 825 037(10) u	99.985(1)
^{2}H	2.014 101 787(21) u	0.015(1)

Annotation Codes: g, m, and r

The atomic-weight, A_r(H), value has been based on mass-spectrometric measurements since 1938. The relative ease of preparing enriched isotopes of hydrogen has made calibrated measurements readily available and the mass-spectrometric measurements are far more accurate than corresponds to the variability of natural terrestrial sources. The extent of the variability must be assessed for disseminating a standard A_r(H) value (see Part I).

In its Report for 1961 (0.1a) the Commission recommended A_r(H) = 1.007 97(1) based on an average for only water sources (fresh and salt) of hydrogen. The uncertainty there refers to the uncertainty on the average. The acknowledged values for waters in the quoted literature show a range wider than ±1 in the fifth decimal. When in 1969 the Commission (0.1c) decided to indicate uncertainties in the Atomic-Weights Tables which would include variations in all normal terrestrial sources, a change for hydrogen was needed to include not only waters but also non-aqueous sources. At that time the Commission limited the statements on uncertainties to either ±1 or ±3 in the last decimal (see Part I, Section 4). By these policies A_r(H) = 1.0080(3) had to be adopted. The indicated range at the low end was now larger than could possibly be needed as this value included values lower than A_r(^{1}H). It would have been misleading to increase the tabulated value by 0.0001, to include more strongly deuterated sources of hydrogen, because the recommended value already exceeded the true A_r(H) for the majority of hydrogen sources.

For water sources the range of published deuterium contents extends from 0.0082 atom percent (1.1) up to 0.0173 atom percent (1.2) corresponding to A_r(H) = 1.007 907 5 and 1.007 999 1, respectively, when calculating with the most recently published nuclidic-mass data by Wapstra and Bos (0.2e). This range excludes exceptionally high and isolated values of 0.023 atom percent (1.2) and 0.0214 atom percent (1.3), that is up to A_r(H) = 1.008 056 5. From non-water sources, atmospheric hydrogen gas (1.4) has been measured to have a deuterium content as high as 0.0184 atom percent; automobile hydrogen gas (1.4) and electrolytic hydrogen gas (1.5) have measured deuterium contents as low as 0.0048 atom percent and 0.0044 atom percent respectively, corresponding to an overall range for these hydrogen gases of A_r(H) = 1.007 869 to 1.008 01. While electrolytic hydrogen cannot be regarded as a normal terrestrial material, the Commission drew it into consideration because it is such a common laboratory and industrial source of hydrogen.

The best "absolute" measurement of the deuterium content from a single natural source, in the opinion of the Commission, was performed on Vienna SMOW (the IAEA's "standard mean ocean water") and found to equal 0.015 574(5) atom percent (1.6) corresponding to $A_r(\mathrm{H}_{\mathrm{SMOW}})$ = 1.007 981 75(5).

For the representative isotopic composition the Commission has chosen one based on an average deuterium content of fresh water (1.1) (1.7) and ocean water (1.6) in temperate climates with the corresponding A_r(H) = 1.007 976(10) very close to the tabulated 1961 value.

The Commission in 1981 (0.1i) decided to disseminate in the Table of Standard Atomic Weights an A_r(H) value that included in its implied range not only water, but also the hydrogen gas values discussed above. However, the Commission abandoned strict adherence to the arbitrary rule that all tabulated values must have assigned uncertainties of either ±1 or ±3 in the last quoted decimal. Thus the Commission recommended A_r(H) = 1.007 94(7). Only very exceptional natural samples may perhaps be found with values outside this implied range.

The minor isotope, ^{2}H, is known by a distinct name, deuterium, with symbol D. The two stable isotopes of hydrogen differ from one another more in their properties and are separated with less difficulty than the isotopes of other elements. The low concentration of ^{2}H in normal sources of hydrogen no doubt is responsible for the delay in its discovery until 1931, when isotope fractionation was demonstrated by distillation, electrolysis, evaporation, at geological sites and in high branches of trees.

A special name, tritium, symbol t or T, is occasionally also given to ^{3}H which is radioactive with a half-life of 12.3(1)a (0.6). It is continuously formed in the atmosphere by cosmic-ray reactions such as $^{14}_{7}N$ (n,T) $^{12}_{6}C$ and by nuclear reactors. Although it reacts to form HTO and other compounds, and although its concentrations vary widely, it never is found in normal sources of hydrogen in concentrations that affect the $\underline{A}_r$(H) value at the indicated precision of standard atomic weights.

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$_2$He HELIUM

$\underline{A}_r$(He) = 4.002 602(2)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{3}He	3.016 029 297(33) u	0.000 138(3)
^{4}He	4.002 603 25(5) u	99.999 862(3)

Annotation Codes: g and r

In its 1961 Report (0.1a) the Commission recommended for the atomic weight of helium $\underline{A}_r$(He) = 4.0026 based on the nuclidic mass of ^{4}He to four decimal places from Everling et al. (0.2a). The ^{3}He content in air of 0.000 137 atom percent determined by Nier (2.1) had a negligible effect on this atomic weight. This isotope is present in natural sources of helium with a smaller abundance than that of any other stable, or quasi-stable (see Part I, Section 7), isotope relative to its elemental composition.

When in 1969 the Commission (0.1c) was able to evaluate the natural variations in isotopic abundance for helium, based chiefly on the paper by Mamyrin et al. (2.2), it was possible to recommend $\underline{A}_r$(He) = 4.002 60(1) which still equaled the nuclidic mass of ^{4}He, but to five decimals.

A later absolute determination of the isotopic composition of atmospheric helium by Clarke et al. (2.3) confirmed the Commission's earlier value yielding $\underline{A}_r$(He) = 4.002 601 9. So precise a value can not be used for the standard atomic-weight value of helium. Although atmospheric helium does not vary appreciably at different locations, helium from gas and inclusions in rocks does vary. The evaluated published range of these variations, however, does permit the Commission now (0.1j) to include the sixth decimal in the recommended value for the standard atomic weight of helium, which from 1983 becomes $\underline{A}_r$(He) = 4.002 602(2). For the first time the recommended value for $\underline{A}_r$(He) differs from the nuclidic mass of ^{4}He which to the sixth decimal equals 4.002 603. This is still in the range of the indicated atomic-weight variation, as it should be because almost pure ^{4}He can be found in the ores of the naturally occurring radioactive elements, from which only that isotope emanates.

The indicated range for the standard atomic weight of helium has a lower limit of 4.002 600, corresponding to a ^{3}He abundance of 3.3 x 10^{-4} atom percent. Included in that range are ^{3}He-depleted sources from well gas and ^{3}He-enriched sources from deep wells (2.2) to (2.7). It does not include some recently discovered (2.8) and (2.9) helium from gases evolved from the mid-Pacific Ocean rise. This helium has a most exceptional abundance of up to 4 x 10^{-3} atom percent, corresponding to a ^{3}He content even higher than previous estimates of mantle helium. The footnote "g" is therefore now applied to helium. In addition the annotation "r" has been added in the 1983 Table of Standards Atomic Weights to indicate that known natural variations of helium prevent the Commission from recommending an atomic weight with an additional decimal.

Helium, a "noble" gas, is chemically the most unreactive element with the lowest boiling point (4.2 K). Apart from presence in occlusions, interstitial positions in crystals and voids in clathrate compounds, it occurs naturally only as monatomic gas, too light to be held in the atmosphere by the earth's gravitation over periods comparable with the age of the earth. Thus, virtually all ^{4}He in the atmosphere has emanated from the heavy radioactive elements as α particles, whereas ^{3}He the minor isotope derives mostly from β-decay of ^{3}H, tritium, from ^{6}Li(n,α)T and cosmic-ray reactions. Helium thus is the only element which in its normal terrestrial sources is almost exclusively radiogenic.

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$_3$Li LITHIUM

A_r(Li) = 6.941(2)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{6}Li	6.015 123 2(8) u	7.5(2)
^{7}Li	7.016 004 5(9) u	92.5(2)

Annotation Codes: g, m, and r.

In its 1961 Report (0.1a) the Commission altered A_r(Li) from 6.940 to 6.939 based on the recalculation to the ^{12}C = 12 scale of the chemical determinations by Richards and Willard (3.1). The Commission gave credence to evidence of natural variability of the isotopic composition of lithium from mass spectrometry by Cameron (3.2). In 1969 the Commission (0.1c) evidently changed the basis to absolute mass-spectrometric measurements by Svec and Anderson (3.3) and other mass-spectrometric data. Thus A_r(Li) = 6.941(3) became the new recommended atomic weight. That value has remained unchanged but is now based on other calibrated mass-spectrometric measurements of superior accuracy by Flesch et al. (3.4), Callis et al. (3.5) and Michiels and De Bièvre (3.6), yielding with current nuclidic masses, (0.2e) A_r(Li) = 6.939 1(2), 6.940 15(30) and 6.940 69(24), respectively. Although lithium occurs in diverse geological associations and although the relative mass difference of the isotopes is large, the variability in terrestrial sources appears to be smaller than the implied range ± 0.003 in the A_r(Li) value. The Commission in 1983 felt justified in lowering U_r(Li) to ±0.002, but the annotations "g" and "r" could not be deleted.

The minor isotope ^{6}Li is a potentially valuable nuclear source material for tritium production and a neutron absorber for the nuclear-fusion reaction. Lithium depleted of that isotope may be distributed in commerce with anomalous atomic weight near 7.0. This is the justification for the "m" annotation. Lithium standard reference materials are available for comparison with unknown lithium samples. Such a comparison of the isotopic composition of lithium can be accomplished by a measurement of the difference in density of lithium fluoride (3.7).

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$_4$Be BERYLLIUM

$A_r(\mathrm{Be}) = 9.012\ 18(1)$

Nuclide	Nuclidic Mass	Atom Percent in Element
^{9}Be	9.012 182 5(4) u	100.000

The Commission Report in 1961 (0.1a) proposed A_r(Be) = 9.0122 based on nuclidic mass data by Everling et al. (0.2a). In 1969, the Commission (0.1c), reassessing the data quoted in reference (0.1a) with the then new policy of passing on confidently known accuracies and expressing remaining uncertainties by the precision limits of A_r(E) values, found it safe to give one more significant figure as follows: A_r(Be) = 9.012 18(1), which has remained unchanged since. This value is consistent with the most recently published compilation of nuclidic masses by Wapstra and Bos (0.2e) as quoted above.

A search by mass spectrometry for other stable isotopes of beryllium had failed to detect any (4.1), but the estimated limit of detection for ^{6}Be was as high as 0.001 atom percent which if present would lower the sixth significant figure in A_r(Be) by 3. However, the hypothesis of a long-lived isomer of ^{6}Be seems grotesque.

^{10}Be is a cosmic-ray spallation product from N, O, Ne and Ar. With a half-life of 1.6(2) x 10^6a (0.6) it is pervasive on the earth's surface in equilibrium concentrations of less than 10^{-9} atom percent, decaying into $^{10}_{5}$B. These distributed Be concentrations are two orders of magnitude below the parts per billion level, the lowest generally detectable level by refined chemical methods. An annotation of "g" has therefore not been given to beryllium in the Table of Standard Atomic Weights.

Beryllium is the only mononuclidic element with an even atomic number, but it has an odd mass number like all other mononuclidic elements.

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$_5$B BORON

$A_r(\mathrm{B}) = 10.811(5)$

Nuclide	Nuclidic Mass	Atom Percent in Element
^{10}B	10.012 938 0(5) u	19.9(2)
^{11}B	11.009 305 3(5) u	80.1(2)

Annotation Codes: m and r

In its 1961 Report (0.1a) the Commission recommended A_r(B) = 10.811(3) based on calibrated mass-spectrometric measurements on brines and minerals from Searles Lake by McMullen et al. (5.1) and on nuclidic masses by Everling et al. (0.2a). The uncertainty was for variations in natural abundances reported by McMullen et al. (5.1) and Thode et al. (5.2).

In 1969 the Commission (0.1c) decided to reduce the number of significant figures based on new calibrated data showing wider variability of natural abundances of boron isotopes by Finley et al. (5.3) and Schwarcz et al. (5.4). New isotopic-abundance data of high precision further confirmed earlier results (5.5) and (5.6).

In 1981 the Commission (0.1i) concluded that the range of isotope abundance variations typical of the most common sources is covered by A_r(B) = 10.811(2). This value would include the California and Turkish occurrences(5.7). However, the existence of normal terrestrial occurrences with sample atomic weights outside these implied limits could not be denied. Only under the new 1983 policy of a more liberal use of any single-digit uncertainty (see Part I, Section 4) was the Commission able to change the recommended standard atomic weight to A_r(B) = 10.811(5) to which the annotation "r" clearly applies.

Compared with most other standard atomic weights, the tabulated value for boron is still imprecise with U_r(B)/A_r(B) = 460 parts per million (see Part I, Table 4). In 1981 -

before the above change - boron had the least precise standard atomic weight with an uncertainty of 925 parts per million which exceeds that of good analytical measurements.

Separated and enriched isotopes of boron are commercially available; the atomic weights of such samples can differ from one another by up to almost 10 percent. Although the Commission is unaware of undisclosed commercial sales of such material, an "m" annotation warns users of the possibility of its inadvertant dissemination. Boron standard reference materials are available for comparison with unknown boron samples.

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$_6$C CARBON

$\underline{A}_r(C) = 12.011(1)$

Nuclide	Nuclidic Mass	Atom Percent in Element
^{12}C	12 u (exact)	98.90(3)
^{13}C	13.003 354 839(17) u	1.10(3)

Annotation Code: r

In its 1961 Report (0.1a) the Commission recommended $\underline{A}_r$(C) = 12.011 15(5) based on an average of the values corresponding to the extremes of the natural variations reported by Craig (6.1), and the nuclidic masses by Everling et al. (0.2a). However, in its 1969 Report (0.1c) the Commission recommended $\underline{A}_r$(C) = 12.011(1). The quoted uncertainty now covered all terrestrial sources of carbon. The Commission added the needed annotation which currently is indicated by an "r", and which indicates that natural variability prevents the Commission from recommending an additional decimal being given in the tabulated standard atomic-weight value.

Variations in the ^{13}C content of terrestrial sources of carbon have been measured as high as 1.14 atom percent for carbonate from Pennsylvania by Deines (6.2) and as low as 1.01 atom percent for biogenic methanes by Schoell (6.3) as well as for carbon in sulfur deposits by Kaplan and Nissenbaum (6.4). The corresponding $\underline{A}_r$(C) range is from 12.011 44 to 12.010 13 using current nuclidic masses (0.2e).

About 73 percent of the total carbon in the crust of the earth is contained in sedimentary carbonate rocks with a ^{13}C content close to 1.11 atom percent. The remaining 27 percent is in the form of fossil fuel and disseminated amorphous carbon of sedimentary rocks with a ^{13}C content close to 1.08 atom percent. The atmosphere, hydrosphere and biosphere contain less than 0.2 percent of the total amount of carbon in the crust. Using these figures Fuex and Baker (6.5) estimated that the average ^{13}C content of carbon in the crust of the earth is 1.104 atom percent.

The best measurement from a single natural source was derived by Craig (6.6) from a measurement by Nier (6.7) on carbon dioxide from a Solenhofen limestone sample. Craig adopted for the ratio ^{13}C/^{12}C in the PDB standard (Belemnitella Americana, Peedee Formation, Cretaceous, South Carolina) the absolute value 0.011 237 2(300), corresponding to a ^{13}C abundance of 1.111(3) atom percent and an $\underline{A}_r$(C) value = 12.011 15(3).

Isotope effects in a magnetic field and due to hyperfine coupling affecting chemical reactions (triplet-sensitized photolysis) have been noted but so far without observably influencing the standard atomic weight of carbon at its precision (6.8). Differences in isotopic depletion of ^{13}C during photosynthesis differentiate clearly groups of plants and can identify some features of human diet in archeological research (6.9). Marine planktons and leaves from Bavarian forests have $\underline{A}_r(C)$ values close to the lower implied limit in the standard atomic weight.

The radioactive ^{14}C isotope has a half-life of 5.717(40) x 10^3a (0.6). It is continuously introduced by cosmic ray reactions, from cosmic dust, and by modern nuclear technology. It is of great interest for prehistoric dating as well as archeological, anthropological, palaeotemperature and zoological studies. Yet this isotope never occurs in normal carbon sources in concentrations affecting significantly the $\underline{A}_r(C)$ value. Before nuclear weapons tests, the abundance of ^{14}C in the atmosphere averaged only about 10^{-14} atom percent.

The ^{12}C isotope serves as the scale-determining reference for all atomic weights and also for the definition of the unified atomic mass unit (see Part I, Sections 1 and 2).

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$_7$N NITROGEN

$\underline{A}_r(N)$ = 14.0067(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{14}N	14.003 074 008(23) u	99.634(9)
^{15}N	15.000 108 978(38) u	0.366(9)

Annotation Code: g

In its 1961 Report (0.1a) the Commission recommended $\underline{A}_r(N)$ = 14.0067 based on the calibrated measurement by Junk and Svec (7.1) and on nuclidic masses by Everling et al. (0.2a). In 1969 the Commission (0.1c) assigned $\underline{U}_r(N)$ = 0.0001 in recognition of the effect of the predominance of one isotope, ^{14}N.

These values have remained unchanged since. One recorded extreme in the variations in the isotopic composition has been published by Hoering (7.2) who measured an ^{15}N abundance as low as 0.362 in nitrogen from exceptional oil and gas wells. The corresponding atomic weight $\underline{A}_r(N)$ = 14.006 68 is well within the implied range of the standard atomic weight. The other extreme has been published by Cheng et al. (7.3) who measured an unusual ^{15}N abundance as high as 0.375 in nitrogen from a deep-lying clay sample. The corresponding atomic weight $\underline{A}_r(N)$ = 14.006 81 unrounded is just outside the implied range of the standard atomic weight. The Commission, therefore, in 1983 (0.1j) added the annotation "g".

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$_8$O OXYGEN

$\underline{A}_r(\mathrm{O}) = 15.9994(3)$

Nuclide	Nuclidic Mass	Atom Percent in Element
^{16}O	15.994 914 64(5) u	99.762(15)
^{17}O	16.999 130 6(8) u	0.038(3)
^{18}O	17.999 159 39(32) u	0.200(12)

Annotation Codes: g and r

In its 1961 Report (0.1a) the Commission adopted $\underline{A}_r(\mathrm{O}) = 15.9994(1)$ although the uncertainty did not cover the possible natural variations. In its 1969 Report (0.1c) the Commission increased $\underline{U}_r(\mathrm{O})$ to 0.0003 to cover the range of all normal terrestrial sources of oxygen. This value has remained unchanged.

The two major sources of oxygen are air and water. The best measurement for the complete isotopic composition of oxygen from air remains the work of Nier (8.1) with atomic percentages of ^{16}O, ^{17}O and ^{18}O respectively 99.7587, 0.0374 and 0.2039, corresponding to $\underline{A}_r(\mathrm{O})$ = 15.999 376 when calculated with current nuclidic masses (0.2e). Dole (8.2), and Kroopnick and Craig (8.3) detected no variation in isotopic composition of atmospheric oxygen, but after low-temperature fractional distillation for separation from nitrogen, ^{18}O is measurably enriched.

For water the best measurement of the isotopic composition of oxygen is that of Baertschi (8.4) who used Vienna SMOW (Standard Mean Ocean Water distributed by IAEA). The absolute amount of ^{18}O was found to be 0.200 045(40) atom percent. One could adopt for ^{17}O the value mentioned by Craig (8.5) which was 0.0372(4) atom percent. That uncertainty has not been well established, but would lead to $\underline{A}_r(\mathrm{O})$ = 15.999 304.

The range of published isotopic compositions, including data by Lorius and Merlivat (8.6) who measured ^{18}O/^{16}O ratios in antarctic ice, is very wide:

^{16}O	99.7771	to	99.7539	atom percent
^{17}O	0.0407	to	0.035	atom percent
^{18}O	0.2084	to	0.1879	atom percent

This range illustrates the considerable terrestrial variations in isotopic composition that may be found in unusual water and mineral samples. It corresponds to $\underline{A}_r(\mathrm{O})$ from 15.9990 to 16.0000. These facts fully justify the annotations "g" and "r".

Variations in isotopic composition of oxygen in rocks are smaller than those indicated above. The trend is for ^{18}O to be more highly enriched in sedimentary minerals formed at low temperature than in magmatic minerals. The change in ^{18}O/^{16} ratio with respect to Vienna SMOW (see above) ranges from about +0.5 percent in ultrabasic rocks and basalts to +3.5 percent for carbonates (8.7). A typical reference sample (reference material 19 of the National Bureau of Standards) is a marble with a ratio change versus VSMOW of 2.865 percent corresponding to $\underline{A}_r(\mathrm{O})$ = 15.9994 in agreement with the recommended standard atomic weight of oxygen.

The ^{16}O nuclide is by far the most abundant in the earth's crustal rocks accounting for about 48 percent by weight.

References

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(8.5) Craig, H., Geochim. Cosmochim. Acta, 12, 133 (1957).

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$_9$F FLUORINE

A_r(F) = 18.998 403(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{19}F	18.998 403 25(14) u	100.0000

The Commission Report in 1961 (0.1a) proposed A_r(F) = 18.9984 based on nuclidic-mass data by Everling et al. (0.2a). The revision of these data by Wapstra and Gove (0.2d) led to a refinement of A_r(F) to 18.998 40 in the Commission Report of 1971 (0.1d) and to 18.998 403 in 1975 (0.1f). This value is consistent with the most recently published compilation by Wapstra and Bos (0.2e) as quoted above.

With an uncertainty of U_r(F) = 0.000 001 which relative to A_r(F) is only 5 parts 10^8, the standard atomic weight of fluorine is the most precisely given atomic weight in the IUPAC Table, (compare Part I, Tables 3 and 4), corresponding to the more rapid average rise of nuclide energy with change of number of neutrons as compared with that for other mononuclidic elements.

$_{10}$Ne NEON

A_r(Ne) = 20.179(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{20}Ne	19.992 439 1(5) u	90.51(9)
^{21}Ne	20.993 845 3(12) u	0.27(2)
^{22}Ne	21.991 383 7(6) u	9.22(9)

Annotation Codes: g and m

In its 1961 Report (0.1a) the Commission recommended A_r(Ne) = 20.183 based on gas-density measurements by Baxter and Starkweather (10.1) and Baxter (10.2) recalculated to the ^{12}C = 12 scale. At that time only uncalibrated measurements by mass spectrometry were available. They were not in good agreement and were mistrusted.

However, in 1967 (0.1b) the Commission evaluated the results of two calibrated measurements which appeared almost simultaneously. These measurements by Eberhardt, et al. (10.3) and by Walton and Cameron (10.4) were in excellent agreement and the Commission recommended A_r(Ne) = 20.179(3). Both groups compared their calibrated samples with various commercial sources of neon and reported that no differences were found. The assignment of U_r(Ne) = 0.003 was due to a concern by the Commission that, since almost all neon was liquified for purification, all laboratory samples might be enriched in the heavy isotope relative to natural atmospheric neon. On a thorough review of the published data in 1979 the Commission (0.1h) found such an appreciable isotopic fractionation effect to be incompatible with the available data and therefore reduced U_r(Ne) to 0.001.

This conclusion was unexpected to those who remembered the history. Late in the 1920's isotopes were still believed to be inseparable. Only Keesom et al. (10.5) had presented credible evidence of some separation of neon isotopes by fractional distillation before the discovery and partial separation of deuterium.

Neon with diverse and very anomalous isotopic compositions, most probably in part from the mantle and in part as the result of various nuclear reactions, such as $^{18}_{8}$O(α,n)^{21}Ne and $^{25}_{12}$Mg(n,α)^{22}Ne has been found in natural gases and in some minerals (10.5) (10.7) so that the atomic weight given carries an appropriate annotation of "g". The isotopic composition of neon in the atmosphere differs markedly from samples of extra-terrestrial neon.

References

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(10.7) Emerson, D. E., Stroud, L. and Meyer, T. O., Geochim. Cosmochim. Acta, 30, 847 (1966).

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$_{11}$Na SODIUM (NATRIUM)

$\underline{A}_r$(Na) = 22.989 77(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{23}Na	22.989 769 7(9) u	100.000

The Commission Report in 1961 (0.1a) proposed the atomic weight for sodium $\underline{A}_r$(Na) = 22.9898 based on nuclidic-mass data by Everling et al. (0.2a), and also quoted experimental evidence from the literature concerning upper limits for the hypothetical presence of ^{21}Na and ^{22}Na which were determined as 10^{-6} and 3 x 10^{-6} atom percent respectively. These stable isotopes -- if they exist at all -- can therefore no more than cause a change in the eighth significant figure in $\underline{A}_r$(Na). However, the upper limits of detection for hypothetical heavier isotopes would be higher because of inevitable sample contamination with traces of magnesium.

The revision of the nuclidic-mass data by Wapstra and Gove (0.2c) led to a refinement of $\underline{A}_r$(Na) to 22.989 77(1) in the 1971 Commission Report (0.1d). That value has remained unchanged since then. It is consistent with Wapstra and Bos' (0.2e) most recently published compilation of nuclidic masses quoted above.

$_{12}$Mg MAGNESIUM

$\underline{A}_r$(Mg) = 24.305(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{24}Mg	23.985 045 0(8) u	78.99(3)
^{25}Mg	24.985 839 2(12) u	10.00(1)
^{26}Mg	25.982 595 4(10) u	11.01(2)

In the 1961 Report (0.1a), the atomic weight of magnesium was based on the isotopic composition reported by White and Cameron (12.1) and the atomic masses from the 1960 compilation of Everling et al. (0.2a). In its 1967 Report (0.1b), the Commission adopted $\underline{A}_r$(Mg) = 24.305 based on the absolute isotopic measurements of Catanzaro et al. (12.2) and the mineral survey of Catanzaro and Murphy (12.3) who reported no detectable variations in 60 samples of natural magnesium from various geological sources. In 1969, the Commission assigned the uncertainty $\underline{U}_r$(Mg) = 0.001 to this value (0.1c).

The annotation "g" was added to magnesium by the Commission in its 1971 Report (0.1d) based on a published abstract report of a partial mineral survey by Lepin et al. (12.4) who documented considerable natural variability in sources from the U.S.S.R. Since there were no comparable findings in other publications on magnesium such as that by Catanzaro and Murphy (12.3), the Commission concluded that the specimens studies by Lepin et al. must have been very exceptional, thereby justifying the annotation "g" in preference to reducing the precision of the tabulated value. A later credible study by Shramm et al. (12.5) found no anomalies in atomic-weight values greater than experimental error. The Commission, therefore, decided to make a study of the actual data obtained by Lepin et al. As a result, the Commission concluded that experimental uncertainties not atomic-weight variability have probably caused a considerable range of values to be reported. The annotation "g" was, therefore, now removed from magnesium for lack of good evidence for its retention.

References

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$_{13}$Al ALUMINIUM

A_r(Al) = 26.981 54(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{27}Al	26.981 541 3(7) u	100.000

The Commission Report in 1961 (0.1a) proposed for the atomic-weight of aluminium A_r(Al) = 26 9815, based on nuclidic-mass data by Everling et al. (0.2a), and also quoted experimental evidence from the literature concerning upper limits for the hypothetical presence of ^{25}Al, ^{26}Al, ^{28}Al, ^{29}Al, and ^{30}Al. This evidence shows that these isotopes could at most affect A_r(Al) in the seventh significant figure.

The revision of the nuclidic-mass data by Wapstra and Gove (0.2c) led to a refinement of A_r(Al) to 26.981 54(1) in the 1971 Commission Report (0.1d). That value has remained unchanged since then. It is consistent with the most recently published compilation of nuclidic masses by Wapstra and Bos (0.2e) as quoted above.

^{26}Al is radioactive with a half life of 7.14(31) x 10^5a (0.6), too short for survival of a detectable amount of primordial nuclide. However, ^{26}Al is recognized as a spallation product of argon from cosmic-ray attack. In addition, secondary cosmic rays including muons interact with silicon-bearing rocks to produce ^{26}Al in measurable amounts but far below significant levels that would affect atomic-weight values (13.1).

^{27}Al is the most abundant nuclide in the earth's crustal rocks with an uneven atomic number (8.5 percent by weight).

Reference

(13.1) Hampel, W. Takagi, J., Sakamoto, K., and Tanaka, S. J. Geophys. Res., 80, 3757 (1975).

$_{14}$Si SILICON

A_r(Si) = 28.0855(3)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{28}Si	27.976 928 4(7) u	92.23(1)
^{29}Si	28.976 496 4(9) u	4.67(1)
^{30}Si	29.973 771 7(10) u	3.10(1)

Annotation Code: r

In its 1961 Report (0.1a) the Commission recommended A_r(Si) = 28.086(1) based on the average value of seven reported mass-spectrometric determinations and nuclidic masses by Everling et al. (0.2a). In 1969 the Commission (0.1c), noting that the range of these seven values was greater than ± 0.001, recommended A_r(Si) = 28.086(3).

In 1975, the Commission (0.1f) recommended the current value A_r(Si) = 28.0855(3) based on superior absolute mass-spectrometric measurements by Barnes et al. (14.1) and nuclidic masses by Wapstra and Gove (0.2d). The Commission at that time already had judged some of the reported variability of the isotopic composition of silicon to be excessive. This is borne out by an investigation by Douthitt (14.2) who studied silicon in 132 terrestrial materials and comprehensively reviewed the literature. He found that the variability in igneous rocks is much smaller than the above indicated range, but it is real and correlated with oxygen isotope fractionation. The silicon fractionation in some clays, marine sediments and opals is larger, but still within the range implied by the U_r(Si) value of 0.0003. However, in 1983 (0.1j) the Commission added the annotation "r" because a more precisely stated standard atomic weight with a single-digit uncertainty would conflict with the actual sample atomic weights of possible sources of silicon.

In recent history A_r(Si) determinations have been directly related to attempts to quantify as accurately as possible the relationship between atomic-scale and macroscopic physical quantities as represented by determinations of Avogadro's constant (14.3) and (14.4). In the course of this work it was also clearly demonstrated that careful crystallization of silicon is accompanied by isotopic fractionation. The general effect has long been predicted but rarely demonstrated. Detailed atomic-scale theories of the growing crystal-liquid interface are being developed such as are needed to predict the isotopic composition changes as a function of the parameters controlling crystallization.

References

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(14.4) Deslattes, R. D., Proc. Int. Sch. Phys. Enrico Fermi, 68, 38 (1980).

$_{15}$P PHOSPHORUS

$A_r(P) = 30.973\ 76(1)$

Nuclide	Nuclidic Mass	Atom Percent in Element
^{31}P	30.973 763 4(7) u	100.000

The Commission Report in 1961 (0.1a) proposed the atomic weight for phosphorus $A_r(P) = 30.9738$, based on nuclidic-mass data by Everling et al. (0.2a), and quoted experimental evidence from the literature concerning upper limits for the hypothetical presence of ^{28}P, ^{29}P, ^{30}P, ^{32}P, ^{33}P, and ^{34}P. This evidence, however, does not rule out an effect on $A_r(P)$ in the sixth significant figure.

The revision of the nuclidic-mass data by Wapstra and Gove (0.2c) led to a refinement of $A_r(P)$ to 30.973 76(1) in the 1971 Commission Report (0.1d). That value has remained unchanged since then. It is consistent with the most recently published compilation of nuclidic masses by Wapstra and Bos (0.2e) as quoted above.

$_{16}$S SULFUR

$A_r(S) = 32.066(6)$

Nuclide	Nuclidic Mass	Atom Percent in Element
^{32}S	31.972 071 8(6) u	95.02(9)
^{33}S	32.971 459 1(8) u	0.75(1)
^{34}S	33.967 867 74(29) u	4.21(8)
^{36}S	35.967 079 0(16) u	0.02(1)

Annotation Codes: g and r

In its 1961 Report (0.1a) the Commission recommended $A_r(S) = 32.064(3)$ based on the abundances of sulfur isotopes in virgin Texas sulfur by Bradt et al. (16.1), and nuclidic masses by Everling et al. (0.2a). In that Report the Commission mentioned that this value agrees excellently with chemical determinations and with a mass-spectrometric determination of meteoritic sulfur, but that the uncertainty is almost exclusively a variability in nature investigated by Rankama (16.2) and Duckworth (16.3) corresponding to the current annotation "r".

In 1969 the Commission (0.1c) recommended a change in the value of A_r from 32.064(3) to 32.06(1). This reduction in the number of significant figures took into account variations in the isotopic abundance of sulfur in natural samples reported in the literature (16.4) and (16.5). It was forced by the policy of restricting the uncertainties to either 1 or 3 in the last digit of the atomic-weight value (see Part I, Section 4).

Since then further publications (16.6) to (16.8) have established a range of $A_r(S)$ values from 32.060 to 32.072. Thus in 1983 the Commission (0.1j) decided to adopt the standard atomic weight for sulfur 32.066(6) to cover all normal sources, but to add the annotation "g" thereby acknowledging the existence of some minor sources of sulfur outside the implied range, and the absence of calibrated mass-spectrometric measurements.

The case of sulfur well illustrates the Commission's difficulties in disseminating the most precise atomic-weight values applicable to the element as met in laboratories or in technology, when the element displays terrestrial variability. It becomes necessary then to judge what constitutes an abnormal source, that can be covered by the "g" annotation rather than by unduly degrading the precision of the standard atomic weight (see Part I, Section 5).

It is noteworthy also that the single most probable $\underline{A}_r$(S) value is believed to be 32.064 which differs from the mean between the lowest and highest values for normal sources. The standard values is chosen to minimize the range under a policy of equal positive and negative $\underline{U}_r$(E) values (compare Part I, Section 5).

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$_{17}$Cl CHLORINE

$\underline{A}_r$(Cl) = 35.453(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{35}Cl	34.968 852 729(68) u	75.77(5)
^{37}Cl	36.965 902 624(105) u	24.23(5)

In its 1961 Report (0.1a) the Commission recommended $\underline{A}_r$(Cl) = 35.453(1) based directly on the atomic weight of silver by silver-silver chloride ratios determined chemically by many well-known authorities. The Commission noted that this value was in excellent agreement with the absolute mass-spectrometric value of 35.4527(7) reported by Shields et al. (17.1) who also provided evidence of absence of natural variability.

In an extensive discussion of the atomic weights of silver (which see), bromine (which see) and chlorine in the 1967 Report (0.1b) the Commission retained the 1961 value but stated that it was based on the physical measurement by Shields et al. with the nuclidic-mass data by Mattauch et al. (0.2c). This change also removed a basic difficulty some readers had expressed with the discussion in the 1961 Report of the Commission (0.1a). Whereas the purely chemical determinations of $\underline{A}_r$(Cl), $\underline{A}_r$(Br) and $\underline{A}_r$(Ag) were well linked to each other and to a majority of other elements, the chemical relationship of definition to $\underline{A}_r$(^{12}C), or even to $\underline{A}_r$(O) was not analysed in detail. No one suspected serious discrepancies because there existed numerous chemical measurements, such as especially the $AgNO_3$/Ag and $AgNO_3$/AgCl ratios, which pointed to a good set of self-consistent chemical data. However, from 1967 onwards, it was no longer useful to attempt to define even a single atomic weight based on purely chemical measurements.

Reference

(17.1) Shields, W. R., Murphy, T. J., Garner, E. L., and Dibeler, V. H., J. Am. Chem. Soc., 84, 1519 (1961).

$_{18}$Ar ARGON

$\underline{A}_r$(Ar) = 39.948(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{36}Ar	35.967 545 605(291) u	0.337(3)
^{38}Ar	37.962 732 2(8) u	0.063(1)
^{40}Ar	39.962 383 1(7) u	99.600(3)

Annotation Codes: g and r

The Commission in 1961 (0.1a) recommended the value of $\underline{A}_r$(Ar) = 39.948 (previously 39.944 from gas density) based on the calibrated measurements by Nier (18.1). In 1969, the Commission (0.1c) recommended $\underline{A}_r$(Ar) = 39.948(3) after a general reevaluation of uncertainties.

However, at its meeting in 1979 (0.1h), the Commission examined all the available literature and felt justified in lowering the uncertainty so that A_r(Ar) = 39.948(1) was accepted for the Table of Standard Atomic Weights.

Radioactive decay of the minor isotope of potassium, ${}^{40}_{19}$K (half-life of 1.25(2) x 10^9a) (0.6) to ^{40}Ar (and also ${}^{40}_{20}$Ca) gives rise to many samples of argon in small quantity with anomalous isotopic composition and their exploitation in geochronology (0.9). The annotation of "g" is therefore needed. In addition, owing to the wide distribution of potassium, even major sources of argon are slightly variable. Therefore, a more precise atomic weight cannot be given. For that reason, the annotation "r" has also been applied.

^{39}Ar is continuously formed in the upper atmosphere as a product of cosmic-ray reactions. It is also a component of cosmic dust entering the earth's atmosphere. At this time most of the ^{39}Ar introduced into the atmosphere has escaped from nuclear reactors. ^{39}Ar is radioactive decaying with a half-life of 268(8)a(0.6) to ^{39}K. The amount of ^{39}Ar in normal samples is variable but always several orders of magnitude too small to affect the standard atomic weight of argon at its current precision.

Reference

(18.1) Nier, A. O. C., Phys. Rev., 77, 789 (1950).

$_{19}$K POTASSIUM (KALIUM)

A_r(K) = 39.0983(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{39}K	38.963 707 9(8) u	93.2581(30)
^{40}K	39.963 998 8(8) u	0.0117(1)
^{41}K	40.961 825 4(9) u	6.7302(30)

The value of A_r(K) = 39.102 for the atomic weight of potassium was adopted by the Commission in its 1961 Report (0.1a) based on the mass-spectrometric measurements of Nier (19.1) and nuclidic masses by Everling et al. (0.2a). This value was near the upper range of the best chemical determinations.

In the 1969 Report (0.1c) the Commission assigned an uncertainty U_r(K) = 0.003 to this value.

A new analysis by Marinenko (19.2) of older chemical data by Bates and Wichers (19.3) led the Commission in 1971 (0.1d) to assign more credence to the chemical evidence for a lower value, and A_r(K) = 39.098(3) was recommended based on the mean value of chemical and mass-spectrometric determinations.

In the 1975 Report (0.1f) the Commission recommended A_r(K) = 39.0983(3) based on the absolute mass-spectrometric measurements of Garner et al. (19.4) who also reported on the results of a mineralogical study of possible isotopic variations. The uncertainty was reduced to U_r(K) = 0.0001 in the 1979 Report (0.1h) based on completion by the Commission of an evaluation of possible variations of the isotopic abundances and the effects of small errors in the abundance measurements.

The minor isotope, ^{40}K, is radioactive with a half-life of 1.25(2) x 10^9a (0.6). Daughter elements are ${}^{40}_{18}$Ar and ${}^{40}_{20}$Ca. Whereas A_r(K) as a result will only decrease by 1.5 x 10^{-4} atom percent in one half-life, small samples of anomalous argon are found.

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$_{20}$Ca CALCIUM

$\underline{A}_r(\text{Ca}) = 40.078(4)$

Nuclide	Nuclidic Mass	Atom Percent in Element
^{40}Ca	39.962 590 7(9) u	96.941(13)
^{42}Ca	41.958 621 8(15) u	0.647(3)
^{43}Ca	42.958 770 4(15) u	0.135(3)
^{44}Ca	43.955 484 8(15) u	2.086(5)
^{46}Ca	45.953 689(4) u	0.004(3)
^{48}Ca	47.952 532(4) u	0.187(3)

Annotation Code: g

The recommended atomic weight of calcium, $\underline{A}_r(\text{Ca}) = 40.08$, in the 1961 Report of the Commission (0.1a) was given the uncertainty $\underline{U}_r(\text{Ca}) = 0.01$ in 1969 (0.1c). This value was based on the chemical measurements of Hönigschmid and Kempter (20.1) and isotope abundance measurements by Nier (20.2). A recalculation of the chemical ratios using current values of the atomic weights of the other elements involved (0.1j) gives the following results from the listed comparisons:

$\text{CaCl}_2/2\text{Ag} = 0.514\ 451$	$\underline{A}_r(\text{Ca}) = 40.080$	(20.1)
$\text{CaCl}_2/\text{AgCl} = 0.387\ 200$	$\underline{A}_r(\text{Ca}) = 40.082$	(20.1)

More recent, and in the Commission's view the best, mass-spectrometric measurements are those by Moore and Machlan (20.3), yielding $\underline{A}_r(\text{Ca}) = 40.078$. Since these measurements were not calibrated for bias, some weight is still given to the chemical determinations. Further evidence is provided by the X-ray density method (0.8b) which on recalculation with the current atomic weights of the other elements involved yields $\underline{A}_r(\text{Ca}) = 40.079(2)$.

In 1983 the Commission with its liberalized policy on uncertainties (see Part I, Section 4) was able to recommend as standard atomic weight $\underline{A}_r(\text{Ca}) = 40.078(4)$ weighted towards the mass-spectrometric measurement (20.3). It would take a large error even to come close to the limit of the indicated uncertainty, since calcium has a predominant isotope. Moreover, the stated uncertainty includes all chemical, X-ray and mass-spectrometric measurements believed to be significant by the Commission and enumerated in the Commission's 1983 Report (0.1j).

There are many reports of anomalous isotopic composition of some minor samples of calcium; some of these may have arisen from the decay of $^{40}_{19}$K. The annotation of "g" is therefore maintained for this element. There is some evidence for small but distinct fractionation in nature (20.4) causing variability in normal sources within ±0.001 in $\underline{A}_r(\text{Ca})$. The annotation "r" can therefore not be applied at this time.

The percentage of ^{46}Ca in normal calcium is smaller than that of any other known stable isotope, other than ^{3}He.

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$_{21}$Sc SCANDIUM

$\underline{A}_r(\text{Sc}) = 44.955\ 91(1)$

Nuclide	Nuclidic Mass	Atom Percent in Element
^{45}Sc	44.955 913 6(15) u	100.000

Scandium is a mononuclidic element, for which the Commission in 1961 (0.1a) recommended the atomic weight, $\underline{A}_r(\text{Sc}) = 44.956$, although the mass of its nuclide was known with far superior accuracy. At that time the Commission had in mind the possibility of the discovery of stable isomers of neighboring scandium radionuclides. In the above reference the Commission refers to a paper placing an experimental limit of 10^{-2} atom percent on the hypothetical presence of ^{46}Sc. On that evidence, an effect on the fifth significant figure in the atomic weight of scandium cannot be ruled out. In 1969, however, the Commission (0.1c) considered that viewpoint unduly conservative and recommended $\underline{A}_r$(Sc) = 44.9559(1), because on the basis of theory and experience the likelihood of the existence of such a long-lived isotope of scandium must be considered as exceedingly remote.

In the nuclidic-mass tables published with encouragement by the International Union of Pure and Applied Physics by Wapstra and Gove in 1973 (0.2d) the mass of ^{45}Sc is given as 44.955 917 4(22) u. This uncertainty was calculated from the least-squares adjustment and is largely a measure of the consistency of mass values for nuclides with similar mass and atomic numbers. For conversion of nuclidic masses to atomic weights of mononuclidic elements the Commission, somewhat arbitrarily, rounds the values to fewer digits, so that the uncertainty in the nuclidic-mass table multiplied by six is equal or less than one in the last decimal for the atomic-weight value (See Part I, Section 7). By this rule no change in the atomic-weight value was needed.

When, however, in 1977 the nuclidic mass table was revised by Wapstra and Bos (0.2e) ^{45}Sc was given a mass of 44.955 913 6(15) u which by the above rule should lead to $\underline{A}_r$(Sc) = 44.955 91(1) with an additional decimal. The Commission, however, at that time did not act. It hesitates to recommend a rounding-off change in the atomic weight of one of the mononuclidic elements which are tabulated to higher precision than is required for the great majority of applications. Such a change is especially undesirable when in future it might have to be reversed due to a very small change in the best value within the estimated uncertainty range.

In a review of that decision in 1983, it was pointed out that in the case of scandium the additional digit represented reliable accuracy. The mass of ^{45}Sc was closely tied to that of titanium (21.1) which itself is closely tied to $^{12}_{6}$C, the isotope that defines the atomic-weight scale. The Commission, under these circumstances felt justified in refining the standard atomic weight of scandium to $\underline{A}_r$(Sc) = 44.955 91.

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$_{22}$Ti TITANIUM

$\underline{A}_r$(Ti) = 47.88(3)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{46}Ti	45.952 632 7(15) u	8.0(1)
^{47}Ti	46.951 764 9(16) u	7.3(1)
^{48}Ti	47.947 946 7(15) u	73.8(1)
^{49}Ti	48.947 870 5(15) u	5.5(1)
^{50}Ti	49.944 785 8(28) u	5.4(1)

In its 1961 Report (0.1a), the Commission recalculated the chemical ratios of Baxter and Butler (22.1) upon which $\underline{A}_r$(Ti) had been based since 1927. It recommended $\underline{A}_r$(Ti) = 47.90 be retained. In 1969 the Commission (0.1c) gave the same value with an uncertainty of 0.03 based on the chemical work (22.1) coupled with consideration of the isotopic abundance measurements by Nier (22.2), Hibbs (22.3), Mattraw and Pachucki (22.4), Hogg (22.5), Darwin (22.6), and Belsheim (22.7) which yielded values of $\underline{A}_r$(Ti) ranging from 47.87 to 47.89. Hogg (22.5) and Belsheim (22.7) searched for but discovered no terrestrial variability in $\underline{A}_r$(Ti).

Recalculation of the chemical ratios (22.1) based on current values of the other atomic weights involved (0.1j) yields the following results for the listed comparisons:

$TiCl_4/4Ag$ = 0.439 680	$\underline{A}_r$(Ti) = 47.878	(22.1)(1926)
$TiBr_4/4Ag$ = 0.851 788	$\underline{A}_r$(Ti) = 47.907	(22.1)(1928)

In 1979 (0.1g) the Commission reexamined the chemical and mass-spectrometric determinations and recommended A_r(Ti) = 47.88(3), which includes consideration of all the above values but is weighted towards the calibrated mass-spectrometric measurements of Belsheim (22.7). Recalculated with the more recent nuclidic masses by Wapstra and Bos (0.2e), they yield A_r(Ti) = 47.87(1). Since then two papers have been published by Heydegger et al., (22.8) and Niederer et al., (22.9), reporting isotopic abundance measurements for titanium. Although neither is a calibrated measurement, they are both of high precision. When these are normalized to the ^{46}Ti/^{48}Ti ratio of Belsheim (22.7), the new values confirm the work of Belsheim. However, if Belsheim's ratios are in error, it would be carried as a systematic error to the more recent work. For that reason, the Commission has retained the high uncertainty of U_r(Ti) = 0.03, and continues to be especially concerned in its search for new evidence that might lead to an improvement of A_r(Ti) or U_r(Ti). Titanium is an abundant, widely distributed element, yet it is the element that has the most uncertain atomic weight with U_r(Ti)/A_r(Ti) = 630 parts per million (see Part I, Table 4). This is so for reasons of experimental uncertainty not because of terrestrial variability. Titanium has undergone in 1979 the largest relative change in standard atomic-weight value recommended by the Commission during the past 25 years (see Part I, Table 4).

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$_{23}$V VANADIUM

A_r(V) = 50.9415(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{50}V	49.947 161 3(17) u	0.250(2)
^{51}V	50.943 962 5(15) u	99.750(2)

In its 1961 Report (0.1a) the Commission accepted A_r(V) = 50.942 based on mass-spectrometric data by Hess and Inghram (23.1), Leland (23.2), and White et al. (23.3). The Commission in 1969 (0.1c) recommended a more precise A_r(V) = 50.9414(3) because it is an element with a predominant isotope. A number of determinations of the isotopic composition of vanadium, for instance (23.4) and (23.5), have since been considered. As a result the Commission in the 1977 Report (0.1g) refined A_r(V) to 50.9415(1).

Balsiger et al. (23.4) have also shown that the isotopic composition of five chondritic meteorites were identical within experimental error to the terrestrial diabase W-1 and a laboratory standard.

Two stable isobars, $^{50}_{22}$Ti and $^{50}_{24}$Cr, are the immediate neighbors in the chart of nuclides, to ^{50}V, whose β+ and β- decay modes are therefore predictable. The nuclear angular momentum of ^{50}V, however, is high consistent with long half-lives, evidently too long to be readily observed. The isobars render the mass-spectrometric determination of the abundance of the isotope ^{50}V subject to careful chemical determination of the trace presence of titanium and chromium.

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$_{24}$Cr CHROMIUM

$A_r(\text{Cr}) = 51.9961(6)$

Nuclide	Nuclidic Mass	Atom Percent in Element
^{50}Cr	49.946 046 3(15) u	4.345(9)
^{52}Cr	51.940 509 7(16) u	83.789(12)
^{53}Cr	52.940 651 0(17) u	9.501(11)
^{54}Cr	53.938 882 2(17) u	2.365(5)

In its 1961 Report (0.1a) the Commission recommended $A_r(\text{Cr}) = 51.996(1)$ calculated from the isotopic composition reported by Flesch et al. (24.1) with nuclidic masses from Everling et al. (0.2a). The mass-spectrometric measurements were corrected for mass bias by calibration with known mixtures of separated nitrogen isotopes.

In 1966 Shields et al. (24.2) redetermined the isotopic composition of chromium calibrating the mass spectrometers with carefully prepared gravimetric standards mixed from separated isotopes of chromium of very high chemical and isotopic purity. The atomic weight calculated from this work and masses from Mattauch et al. (0.1c) was $A_r(\text{Cr}) = 51.9961(3)$. In its 1967 Report (0.1b) the Commission recommended "retaining the atomic weight of 51.996 but stating it without limit of error." However, in 1969 (0.1c) the Commission added uncertainties to all atomic weights and recommended a value of 51.996(1) for chromium.

With its liberalized policy on single-digit uncertainties (see Part I, Section 4) the Commission in 1983 (0.1j) recommended the standard atomic weight to four decimal places, $A_r(\text{Cr}) = 51.9961(6)$.

References

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$_{25}$Mn MANGANESE

$A_r(\text{Mn}) = 54.9380(1)$

Nuclide	Nuclidic Mass	Atom Percent in Element
^{55}Mn	54.938 046 3(17) u	100.00

The Commission Report in 1961 (0.1a) proposed the atomic weight of manganese $A_r(\text{Mn}) = 54.9380$ based on nuclidic-mass data by Everling et al. (0.2a). Leipziger (25.1) has confirmed experimentally that at the upper limits for the hypothetical presence of stable or quasi-stable manganese isotopes, the atomic weight of manganese would be unaffected to six significant figures.

Wapstra and Bos (0.2e) now give the nuclidic mass of ^{55}Mn as quoted above. By the Commission policy (see Part I, Sec. 7), the uncertainty is too large to permit the use of the fifth place of decimals in the Table of Standard Atomic Weights (0.1j). The quoted $A_r(\text{Mn})$ thus remains unchanged since 1961 except for the uncertainty $U_r(\text{Mn}) = 0.0001$ introduced in 1969 (0.1c).

^{53}Mn is radioactive with a half-life of $3.7(2) \times 10^6$ a (0.6), too short for survival of a detectable amount of primordialnuclide. However, ^{53}Mn has been identified on earth as a cosmic-ray product and as a constituent of cosmic dust by Imamura et al. (25.2) who measure about 1 disintegration per min. per gram of manganese in sediment cores corresponding to 3×10^{-11} atom percent much below significant concentrations to affect the standard atomic weight.

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$_{26}$Fe IRON

$\underline{A}_r$(Fe) = 55.847(3)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{54}Fe	53.939 612 1(15) u	5.8(1)
^{56}Fe	55.934 939 3(15) u	91.72(30)
^{57}Fe	56.935 395 7(15) u	2.2(1)
^{58}Fe	57.933 277 8(17) u	0.28(1)

In its 1961 Report (0.1a) the Commission recommended $\underline{A}_r$(Fe) = 55.847(3) based on the average value of two reported mass-spectrometric determinations by Valley and Anderson (26.1), and White and Cameron (26.2), and on nuclidic masses by Everling et al. (0.2a).

The SAIC ranges of variations of the isotope abundances are:

^{54}Fe	5.77 – 6.04	atom percent	^{57}Fe	2.11 – 2.25	atom percent
^{56}Fe	91.52 – 91.79	atom percent	^{58}Fe	0.28 – 0.34	atom percent

based on measurements by Valley and Anderson (26.1), White and Cameron (26.2), Nier (26.3), Hibbs (26.4), Chenouard (26.5) and Shima (26.6). Most of these ranges should be regarded as unresolved experimental discrepancies and not as natural variability.

In the absence of new calibrated mass-spectrometric measurements of the isotopic composition of iron and lacking a recent comprehensive study of possible natural variations, the Commission has not seen any evidence which would motivate a change. The abundance of ^{58}Fe, however, has been determined by James and Carni (26.7) using a calibrated neutron-activation analysis method yielding 0.280(3), probably the best value for that abundance.

References

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$_{27}$Co COBALT

$\underline{A}_r$(Co) = 58.9332(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{59}Co	58.933 197 8(16) u	100.00

The Commission Report in 1961 (0.1a) proposed for the atomic weight of cobalt $\underline{A}_r$(Co) = 58.9332 based on nuclidic-mass data by Everling et al. (0.2a). Recent significant publications are not known to the authors of this Review dealing with the search for stable isomers of radioactive cobalt nuclides.

Wapstra and Bos (0.2e) now give the nuclidic mass of ^{59}Co as quoted above. By the Commission policy (see Part I, Section 7), the standard atomic weight of $\underline{A}_r$(Co) has to remain unchanged, with $\underline{U}_r$(Co) = 0.0001.

It is of possible interest to note that in 1924, Baxter and Dorcas (27.1) published a chemical determination which with current atomic weight values for the other elements involved (0.1j) yields $\underline{A}_r$(Co) = 58.936(3). This agreement illustrates the reliability of the best early chemical determinations and tends to validate the parallel work by Baxter et al. on the atomic weight of nickel which is hardly more precisely known today than through that careful early work.

Reference

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$_{28}$Ni NICKEL

A_r(Ni) = 58.69(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{58}Ni	57.935 347 1(16) u	68.27(1)
^{60}Ni	59.930 789 0(16) u	26.10 (1)
^{61}Ni	60.931 058 6(16) u	1.13(1)
^{62}Ni	61.928 346 4(16) u	3.59(1)
^{64}Ni	63.927 968 0(17) u	0.91(1)

The 1961 Report of the Commission (0.1a) recommended A_r(Ni) = 58.71. That value was based on the isotopic-abundance measurements of White and Cameron (28.1) and the nuclidic masses determined by Collins et al., (28.2). The Commission noted in this report that all chemical determinations that had been reported and believed to be significant gave a mean value for the atomic weight of 58.69. In 1969 the Commission (0.1c) assessed the uncertainties of the above measurements and recommended a value of U_r(Ni) = 0.03, but the Commission retained A_r(Ni) = 58.71.

The Commission in 1973 (0.1e) reexamined both the chemical and mass-spectrometric measurements and so recommended a lower value of A_r(Ni) = 58.70(1). At the same time the Commission lowered the uncertainty, because Cameron now believed he could explain his higher value (28.1) through having over-estimated ^{64}Ni by failing to recognize $^{64}_{30}$Zn or $^{48}_{22}$Ti$^{16}_{8}$O traces.

The best chemical determinations appeared in a series of papers by Baxter and associates (28.3 to 28.5). Recalculation of these determinations based on the current atomic weights of the other elements involved (0.1j) yields the following results from the listed comparisons:

Ni/O (Reduction NiO) = 0.366 87	A_r(Ni) = 58.700	(28.3)
$NiCl_2$/2Ag = 0.600 729	A_r(Ni) = 58.693	(28.4)
$NiCl_2$/2AgCl = 0.452 133	A_r(Ni) = 58.694	(28.4)
$NiBr_2$/2Ag = 1.012 120	A_r(Ni) = 58.694	(28.5)
$NiBr_2$/2AgBr = 0.581 818	A_r(Ni) = 58.690	(28.5)

The Commission in 1973 (0.1e) included in their assessment two other mass-spectrometric determinations by Inghram and Hess (28.6) and Mattraw and Pachucki (28.7), which may have been overlooked in the earlier review. At any rate, both these determinations when recalculated with current nuclidic masses (0.2e) yield A_r(Ni) = 58.700. Thus, all the chemical and mass-spectrometric measurements agreed to establish a value of A_r(Ni) = 58.70(1) based on what appeared as overwhelming evidence. Nevertheless, that value is a little higher than the average (58.694) of Baxter's excellent determinations, whose credibility is increased by the proof of accuracy of the parallel work on the atomic weight of cobalt which is now known accurately as that of a mononuclidic element.

Barnes et al. (28.8) later in that same year completed a superior but not absolute mass-spectrometric measurement which gave A_r(Ni) = 58.688 now in good agreement with the chemical determinations. Following the 1977 Commission meeting, another reexamination was begun and in 1979 (0.1 h) the Commission recommended the present standard atomic-weight value of A_r(Ni) = 58.69(1). There is much evidence in the quoted and other literature that the atomic weight of nickel does not vary from one terrestrial source to another by as much as U_r(Ni), but it must be taken in conjunction with the remaining experimental uncertainty (see Part I, Section 4). Having in the last 25 years already changed the A_r(Ni) value by 2/3 of the 1969 uncertainty, and twice the present estimated uncertainty, the Commission will no doubt continue to monitor carefully any new published experimental evidence on the atomic weight of nickel.

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$_{29}$Cu COPPER

A_r(Cu) = 63.546(3)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{63}Cu	62.929 599 2(16) u	69.17(2)
^{65}Cu	64.927 792 4(21) u	30.83(2)

Annotation Code: r

In its 1961 Report, the Commission (0.1a) recommended A_r(Cu) = 63.54 based on the chemical determinations of Hönigschmid and Johannsen (29.1) and Reur and Bode (29.2).

In the 1967 Report (0.1b), the Commission recommended a value of 63.546(1) based on the absolute abundance ratio measurement by Shields et al., (29.3) who obtained A_r(Cu) = 63.5455(4). The recommended value was given an uncertainty of 0.15 percent and U_r(Cu) = 0.003 in 1969 (0.1c) to include natural variations of the abundance ratio of copper as reported by Shields et al., (29.4). The IUPAC Tables of (Standard) Atomic Weights annotate A_r(Cu) (current code "r") as being of precision limited by natural variability based on that work (29.4) which in the opinion of the Commission ranks among the very best mineral surveys in the literature.

References

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$_{30}$Zn ZINC

A_r(Zn) = 65.39(2)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{64}Zn	63.929 145 4(21) u	48.6(3)
^{66}Zn	65.926 035 2(17) u	27.9(2)
^{67}Zn	66.927 128 9(18) u	4.1(1)
^{68}Zn	67.924 845 8(18) u	18.8(4)
^{70}Zn	69.925 324 9(36) u	0.6(1)

In its 1961 Report (0.1a) the Commission recommended A_r(Zn) = 65.37 based on the earlier chemical data (recalculated on the ^{12}C scale) by Hönigschmid and v. Mack (30.1), Baxter and Grose (30.2) and Baxter and Hodges (30.3). The Commission was aware of isotopic-composition data by Hess et al. (30.4), and Leland and Nier (30.5) both of which, with nuclidic masses by Everling et al. (0.2a), yielded the higher value of $\underline{A}_r$(Zn) = 65.387. Recognizing this unresolved discrepancy the Commission in 1969 (0.1c) assessed $\underline{U}_r$(Zn) = 0.3. Marinenko and Foley (30.6) in 1971 published a coulometric determination which also yielded a higher value $\underline{A}_r$(Zn) = 65.377(3) whereupon the Commission in its 1971 Report (0.1d) changed the recommended value to $\underline{A}_r$(Zn = 65.38(1). Later still Rosman (30.7), using calibration techniques by double spiking in mass spectrometry, determined $\underline{A}_r$(Zn) = 65.396(5) opening the discrepancy once again at a higher precision between chemical and physical determinations. Unable to resolve the problem the Commission in 1983 (0.1j) increased $\underline{U}_r$(Zn) to 0.02 explaining that it was an experimental uncertainty not related to terrestrial variability which Rosman was unable to detect over a wide range of samples.

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$_{31}$Ga GALLIUM

$\underline{A}_r$(Ga) = 69.723(4)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{69}Ga	68.925 580 9(33) u	60.1(2)
^{71}Ga	70.924 700 6(28) u	39.9(2)

In its 1961 Report, the Commission (0.1a) recommended $\underline{A}_r$(Ga) = 69.72 based on the chemical ratio determinations by Richards and Craig (31.1) and Lundell and Hoffman (31.2) as well as the isotopic-abundance determinations by Inghram et al., (31.3). In 1969 the Commission assigned the uncertainty $\underline{U}_r$(Ga) = 0.01.

Recalculating the chemical ratios based on current values of the other atomic weights involved (0.1j) yields $\underline{A}_r$(Ga) = 69.735, while the mass-spectrometric value (31.3) with current nuclidic masses gives $\underline{A}_r$(Ga) = 69.72. The Commission has so far discounted Marinenko's (31.4) more recent and highly precise coulometric assay of gallium and arsenic. Based on plausible confidence in the stoichiometry of a GaAs sample, he calculated $\underline{A}_r$(Ga) = 69.737(6). In the meantime, De Laeter and Rosman (31.5) had published a calibrated mass-spectrometric measurement which was trustworthy and confirmed the earlier value yielding $\underline{A}_r$(Ga) = 69.724(2). De Laeter (31.6) found no significant differences between the isotopic composition of six iron meteorite samples, a terrestrial source and a laboratory standard.

The Commission in 1983 reviewed all the evidence for gallium and decided to recommend a standard atomic weight, based on the mass-spectrometric determination (31.5), $\underline{A}_r$(Ga) = 69.723(4) (0.1j).

Nief and Roth (31.7) observed the ^{69}Ga isotope progressively enriched towards the anode and ^{71}Ga enriched towards the cathode when an electric current is passed through a liquid gallium column just above its melting point. The triple point of gallium is very precisely known (29.773 98 °C) (31.8). Its isotopic composition may be altered by careful recrystallization or ion-exchange chromatography (31.9).

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$_{32}$Ge GERMANIUM

A_r(Ge) = 72.59(3)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{70}Ge	69.924 249 8(20) u	20.5(5)
^{72}Ge	71.922 080 0(21) u	27.4(6)
^{73}Ge	72.923 463 9(20) u	7.8(2)
^{74}Ge	73.921 178 8(20) u	36.5(7)
^{76}Ge	75.921 402 7(26) u	7.8(2)

In its 1961 Report (0.1a), the Commission recommended A_r(Ge) = 72.59 based on chemical-ratio determinations by Baxter and Cooper (32.1 and 32.2), and Hönigschmid et al. (32.3). The Commission noted that five mass-spectrometric measurements averaged to A_r(Ge) = 72.628, which conflicts with the accepted chemical values. In 1969, the Commission assigned U_r(Ge) = 0.03.

Recalculation of the chemical determinations based on current values of the other atomic weights involved (0.1j) yields the following results from the listed comparisons:

$GeCl_4/4Ag$ = 0.496 928	A_r(Ge) = 72.589	(32.1)
$GeCl_4/4AgCl$ = 0.374 010	A_r(Ge) = 72.602	(32.1)
$GeBr_4/4Ag$ = 0.909 016	A_r(Ge) = 72.600	(32.2)
$GeBr_4/4AgBr$ = 0.522 195	A_r(Ge) = 72.599	(32.2)
$GeBr_4/4Ag$ = 0.909 000	A_r(Ge) = 72.593	(32.3)
$GeBr_4/4AgBr$ = 0.522 175	A_r(Ge) = 72.584	(32.3)
$GeCl_4/4Ag$ = 0.496 893	A_r(Ge) = 72.584	(32.4)
$GeCl_4/4AgCl$ = 0.373 977	A_r(Ge) = 72.583	(32.4)

Assigning equal weight to these determinations results in a value for A_r(Ge) equaling 72.592.

Recalculation of the mass-spectrometric determinations (32.5 to 32.9) with current nuclidic-mass data (0.2e) gives A_r(Ge) values ranging from 72.602 to 72.638. Unfortunately, germanium is a difficult element to analyze by solid-source mass spectrometry. Reynolds (32.8) and Artakuni et al. (32.10) avoided the problem by the introduction of volatile GeF_4, from $BaGeF_6$, into the spectrometer, but their measurements had other difficulties.

Equating the density of the structural crystal cell of elemental germanium with the macroscopic density gives A_r(Ge) = 72.63 (32.11) in accord with the mass-spectrometric value. Graham et al. (32.5) compared six different terrestrial sources of germanium. They found only slight variation in atomic weight of one of these and showed that normal preparative procedures caused no fractionation. Shima (32.9) also showed that eight meteoritic samples had an indistinguishable isotopic composition from that of a laboratory reference standard.

The large range in the measured isotopic ratios and the absence of any calibrated or double-spike measurements still leave the Commission without a cogent reason for increasing the standard atomic-weight value of germanium. With the U_r(Ge)/A_r(Ge) about 400 parts per million (see Part I, Table 4), germanium has one of the most uncertain standard atomic weights among chemical elements that do not show appreciable natural variability. This situation is the more disturbing as the discrepancy between the chemical and physical determinations remains large and unexplained. The Commission did not wish to recommend the mean of two discordant types of measurements, but favored the chemical measurements as the more trustworthy. If in the future that judgment were to be proved in error, a change of +0.02 or even +0.03 might be necessary for the standard atomic weight of germanium.

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$_{33}$As ARSENIC

$\underline{A}_r$(As) = 74.9216(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{75}As	74.921 595 5(24) u	100.00

The Commission Report in 1961 (0.1a) proposed for the atomic weight of arsenic $\underline{A}_r$(As) = 74.9216 from nuclidic-mass data by Everling et al. (0.2a). No recent publications, of which the authors of this Review are aware, describe a search for stable isotopes of arsenic, ^{75}As.

Wapstra and Bos (0.2e) now give the nuclidic mass of ^{75}As as quoted above. By the Commission's policy (see Part I, Sec. 7), the uncertainty is too large to permit the use of the fifth place of decimals in the Table of Standard Atomic Weights (0.1j). The quoted $\underline{A}_r$(As) thus remains unchanged since 1961, with $\underline{U}_r$(As) = 0.001 since 1969 (0.1c).

$_{34}$Se SELENIUM

$\underline{A}_r$(Se) = 78.96(3)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{74}Se	73.922 477 1(28) u	0.9(1)
^{76}Se	75.919 206 6(27) u	9.0(2)
^{77}Se	76.919 907 7(27) u	7.6(2)
^{78}Se	77.917 304 0(27) u	23.6(6)
^{80}Se	79.916 520 5(38) u	49.7(7)
^{82}Se	81.916 709(11) u	9.2(5)

In its 1961 Report, the Commission (0.1a) recommended $\underline{A}_r$(Se) = 78.96 based on the chemical determinations by Hönigschmid and collaborators (34.1 and 34.2). In 1969, the Commission recommended $\underline{U}_r$(Se) = 0.03. Both values have remained unchanged since, but the underlying considerations deserve to be described here.

Hönigschmid and Kapfenberger (34.1) criticized all previous atomic-weight determinations because the methods used involved the preparation of elemental selenium and the weighing of selenium dioxide, which operations were subject to unresolved difficulties. In the Commission's view, the Hönigschmid methods were indeed superior. Recalculations of his chemical determinations using current values of the other atomic weights involved (0.1j) yields the following results from the listed comparisons:

$2Ag/Ag_2Se = 0.732\ 081$ $\underline{A}_{\underline{r}}(Se) = 78.953$ (34.1)

$SeOCl_2/2Ag = 0.768\ 794$ $\underline{A}_{\underline{r}}(Se) = 78.951$ (34.2)

$SeOCl_2/2AgCl = 0.578\ 624$ $\underline{A}_{\underline{r}}(Se) = 78.953$ (34.2)

This excellent consistency of the results from three different chemical methods, coupled with the established reliability of Hönigschmid's measurements, must be balanced against adverse factors. Inherent limitations apply to classical chemical methods such that they are uncertain by about 1 part of 10^5. Selenium chemistry also is subject to particular difficulties. Thirdly, the results all come from only one laboratory which is undesirable. The Commission had these considerations in mind, when it conceded that the above agreement could be fortuitous and chose a standard value displaced a little towards the mass-spectrometric values, which for selenium at this time are less satisfactory.

There are only two measurements of the isotopic composition reported by White and Cameron (34.3) and Hibbs (34.4). Both are dated before 1950, giving respectively $\underline{A}_{\underline{r}}(Se)$ equal to 78.99 and 78.97. They are not in good agreement with each other or with the chemical value.

Although variations in the isotope abundances of selenium in terrestrial samples have been established by Krouse and Thode (34.5) using high-precision differential methods of measurements, the range of these variations is less than the uncertainties in the absolute isotope abundances measured and reported in the literature.

^{82}Se is radioactive with the enormously long half-life of about 10^{20}a. For the purposes of this Review therefore it is a stable isotope.

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$_{35}Br$ BROMINE

$\underline{A}_{\underline{r}}(Br) = 79.904(1)$

Nuclide	Nuclidic Mass	Atom Percent in Element
^{79}Br	78.918 336 1(38) u	50.69(5)
^{81}Br	80.916 290(6) u	49.31(5)

In its 1961 Report (0.1a) the Commission recommended $\underline{A}_{\underline{r}}(Br) = 79.909(2)$ based on the chemical determination by Hönigschmid and Zintl (35.1) of the ratio AgBr/Ag = 1.740 785(6). On that declared basis the atomic weight of bromine $\underline{A}_{\underline{r}}(Br) = 79.908$ would have been a marginally better value. The importance of that atomic-weight value was well recognized in virtue of the many other elements whose atomic weights were determined by the mass ratio of their bromides to silver or silver bromide. This dependence is discussed further in the Section on silver. There, too, the Commission's 1967 re-evaluation (0.1b) is described of the key elements, Ag, Cl, and Br, as a result of the publication by Catanzaro et al. (35.2) of an absolute mass-spectrometric abundance measurement for bromine, which since has been the basis for the atomic-weight value for bromine of $\underline{A}_{\underline{r}}(Br) = 79.904(1)$. These authors, as Cameron and Lippert (35.3) had done earlier, found no significant compositional variations over many different sources of bromine. Incidentally, a better value for the AgBr/Ag ratio is now 1.740 756(4).

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$_{36}$Kr KRYPTON

$\underline{A}_r(\text{Kr}) = 83.80(1)$

Nuclide	Nuclidic Mass	Atom Percent in Element
^{78}Kr	77.920 397(9) u	0.35(2)
^{80}Kr	79.916 375(12) u	2.25(2)
^{82}Kr	81.913 483(6) u	11.6(1)
^{83}Kr	82.914 134(4) u	11.5(1)
^{84}Kr	83.911 506 4(39) u	57.0(3)
^{86}Kr	85.910 614(5) u	17.3(2)

Annotation Codes: g and m

In its 1961 Report (0.1a) the Commission recommended $\underline{A}_r$(Kr) = 83.80 based on the isotopic abundance measurements by Nier (36.1) and on the nuclidic masses by Everling et al. (0.2a). In 1969 the Commission (0.1c) assessed $\underline{U}_r$(Kr) to be 0.01. These values have remained unchanged since. Although no calibrated measurements have been reported, Walton et al. (36.2) reported measurements of the isotopic composition of a sample of krypton over a period of four years using two different mass spectrometers with results essentially identical to those of Nier. Both papers report that no variations in the isotopic composition of natural krypton were found.

Separated isotopes have been made available. Users of commercial krypton should be prepared to find isotopically depleted samples. The annotation "m" is therefore used for this element. The "g" annotation refers to fission product krypton such as is found at Oklo (see Part I, Section 6).

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$_{37}$Rb RUBIDIUM

$\underline{A}_r(\text{Rb}) = 85.4678(3)$

Nuclide	Nuclidic Mass	Atom Percent in Element
^{85}Rb	84.911 799 6(35) u	72.165(13)
^{87}Rb	86.909 183 6(32) u	27.835(13)

Annotation Code: g

In its 1961 Report the Commission (0.1a) recommended $\underline{A}_r$(Rb) = 85.47 based on the average of $\underline{A}_r$(Rb) = 85.473 for the chemical determinations by Archibald et al. (37.1) and Archibald and Hooley (37.2) and for the physical determination of Nier (37.3), who reported ^{85}Rb at 72.15 atomic percent corresponding to $\underline{A}_r$(Rb) = 85.4678(2). The Commission in 1969 (0.1c) recommended the present value of $\underline{A}_r$(Rb) = 85.4678(3) based now exclusively on the absolute measurement by Catanzaro et al. (37.4) who reported ^{85}Rb at 72.165(13) atomic percent, and on the work of Shields et al. (32.5) who found no isotopic variations in terrestrial samples, and on the nuclidic masses by Wapstra and Gove (0.2d).

^{87}Rb is β^- active with a half life of 4.88(5) x 10^{10}a (0.6) which leaves $\underline{A}_r$(Rb) unaffected at the currently given precision of about 3 in 10^6 in up to a million years. Strontium, however, the daughter element in rubidium-containing ores has anomalous atomic-weight values in some sources as noted in the following section of strontium.

References

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$_{38}$Sr STRONTIUM

A_r(Sr) = 87.62(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{84}Sr	83.913 428(4) u	0.56(1)
^{86}Sr	85.909 273 2(29) u	9.86(1)
^{87}Sr	86.908 890 2(29) u	7.00(1)
^{88}Sr	87.905 624 9(29) u	82.58(1)

Annotation Code: g

In its 1961 Report (0.1a) the Commission recommended A_r(Sr) = 87.62 based on the mass-spectrometric determination of Nier (38.1) and on the nuclidic masses by Everling et al. (0.2). In its 1969 Report (0.1c) the Commission assessed U_r(Sr) = 0.01.

An absolute abundance determination has recently been published by Moore et al. (38.2) giving a calculated A_r(Sr) = 87.616 81(12). The authors work refers to a specific sample. Known natural variations in the abundance of ^{87}Sr, the daughter nuclide from radioactive $^{87}_{37}$Rb, prevent the recommendation of a more precise standard atomic-weight value. The ^{87}Sr/^{86}Sr ratio is a convenient measure of that variability. In the above sample it was 0.7103. A value for that ratio as high as 1.200 has been reported by Compston et al. (38.3). The Commission may therefore be forced to add the annotation "r" for strontium and warns that the above representative isotopic composition cannot be applied to a few commercial samples. In any event the value of U_r(Sr) = 0.01 represents isotopic-composition variability more than experimental uncertainty. Very anomalous traces of almost pure ^{87}Sr have been reported from certain rubidium ores by Mattauch (38.4) for which the atomic weight will not even be in the tabulated standard atomic-weight range. Since 1969 the Commission (0.1c) therefore has added the appropriate annotation, now a "g", for strontium.

A low value for the ^{87}Sr/^{86}Sr ratio of 0.700 recorded by Herzog et al. (38.5) was judged also significant and abnormal, but it does not limit the precision of the standard atomic weight. The appreciable variability in the ^{87}Sr/^{86}Sr ratio introduces a powerful method for geochronology and for analysis of components in a mixture such as in ocean currents (0.9).

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$_{39}$Y YTTRIUM

A_r(Y) = 88.9059(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{89}Y	88.905 856 0(32) u	100.00

The Commission Report in 1961 (0.1a) proposed for the atomic weight of yttrium A_r(Y) = 88.905 based on nuclidic-mass data by Everling et al. (0.2a). The Commission also quoted comprehensive experimental data setting the upper limits for hypothetical other stable isotopes of yttrium with mass numbers 85 to 95 at 5 x 10^{-4} atom percent corresponding to a possible effect on A_r(Y) in the seventh significant figure.

In 1969, the Commission (0.1c) found the data quoted reliable enough to add an extra decimal in $\underline{A}_r$(Y), which thus became equal to 88.9059(1), the presently accepted value, which is consistent with Wapstra and Bos (0.2e) who in the most recent compilation give the nuclidic mass of ^{89}Y as quoted above.

$_{40}$Zr ZIRCONIUM

$\underline{A}_r$(Zr) = 91.224(2)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{90}Zr	89.904 708 0(31) u	51.45(2)
^{91}Zr	90.905 644 2(31) u	11.22(2)
^{92}Zr	91.905 039 2(30) u	17.15(1)
^{94}Zr	93.906 319 1(33) u	17.38(2)
^{96}Zr	95.908 272(4) u	2.80(1)

Annotation Code: g

The atomic weight of zirconium has been taken as $\underline{A}_r$(Zr) = 91.22 since 1927, and this value was reconfirmed by the 1961 Commission Report (0.1a) taking into consideration existing isotopic abundances by White and Cameron (40.1) and using nuclidic-mass data from Everling et al. (0.2a). The uncertainty in 1969 (0.1c) was assessed as $\underline{U}_r$(Zr) = 0.01. Since then two absolute isotopic-composition measurements have been carried out by Minster and Ricard (40.2) yielding $\underline{A}_r$(Zr) = 91.224 with an estimated uncertainty of +0.002 and -0.005, and by Nomura et al. (40.3) yielding $\underline{A}_r$(Zr) = 91.2235(5).

Shima (40.4) showed that the isotopic composition of nine meteoritic samples and two terrestrial standards were identical, within experimental error, to a laboratory standard. In a similar manner, Minster and Ricard (40.2) have shown that the isotopic composition in two meteoritic samples, one lunar sample and a terrestrial zircon are identical to a laboratory standard.

The Commission in 1983 (0.1j) on the basis of the excellent agreement between the above two absolute mass-spectrometric measurements refined the standard atomic weight to $\underline{A}_r$(Zr) = 91.224(2).

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$_{41}$Nb NIOBIUM

$\underline{A}_r$(Nb) = 92.9064(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{93}Nb	92.906 378 0(31) u	100.00

The Commission Report in 1961 (0.1a) proposed $\underline{A}_r$(Nb) = 92.906 based on nuclidic-mass data by Everling et al. (0.2a). It also quoted experimental evidence from the literature concerning upper limits for the hypothetical presence of any other stable isotopes of niobium with mass numbers between 89 to 98. Such isotopes could no more than cause a change in the seventh significant figure of $\underline{A}_r$(Nb).

On assessment of the reliability of the data, the Commission in 1969 (0.1c) decided to add one significant figure to the recommended value. $\underline{A}_r$(Nb) thus became equal to 92.9064(1) and has remained unchanged since then. This value is consistent with Wapstra and Bos (0.2e) who, in the most recently published compilation, give the nuclidic mass of ^{93}Nb as quoted above.

^{92}Nb is radioactive with a half-life of 3.7(5) x 10^7a(0.6) which is expected to be below the detection limit for primordial nuclides (see Part I, Section 11). Nevertheless, Apt et al. (41.1) using a highly specific and sensitive γ-ray coincidence-counting technique detected that nuclide at 1.2 x 10^{-10} atom percent in a 99.9 pure Nb-metal bar. Its history did not permit the exclusion of the possibility of reactor-contaminated material. Even if this observation were to be confirmed, the classification of Nb as mononuclidic should not be challenged since the concentration would be four orders below significant levels from the viewpoint of the present standard atomic weight of niobium (see discussion, Part I, Section 7).

Reference

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$_{42}$Mo MOLYBDENUM

A_r(Mo) = 95.94(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{92}Mo	91.906 809(4) u	14.84(4)
^{94}Mo	93.905 086 2(36) u	9.25(2)
^{95}Mo	94.905 837 9(26) u	15.92(4)
^{96}Mo	95.904 675 5(26) u	16.68(4)
^{97}Mo	96.906 017 9(25) u	9.55(2)
^{98}Mo	97.905 405 0(25) u	24.13(6)
^{100}Mo	99.907 473(7) u	9.63(2)

In its 1961 Report (0.1a), the Commission recommended A_r(Mo) = 95.94 based on the chemical-ratio measurements of Hönigschmid and Wittmann (42.1). Recalculation of their measurements based on current values of A_r(Ag) and A_r(Cl) (0.1j) gives the ratio $MoCl_5/5Ag$ = 0.506 552 and A_r(Mo) = 95.939. In 1969, after reevaluating the uncertainties associated with this work the Commission recommended a value of U_r(Mo) = 0.03 (0.1c).

In its 1975 Report (0.1f), the Commission evaluated five papers (42.2) to (42.6) dealing with mass-spectrometric determinations of the isotopic composition of molybdenum. Although they were judged not to be of equal reliability, their results all fall in the range of A_r(Mo) = 95.93 to 95.94 in close agreement with the chemical value. The Commission recommended retaining the value of 95.94 but with the reduced uncertainty of U_r(Mo) = 0.01.

References

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(42.5) Stevens, C. M., Int. J. Mass Spectrom. Ion Phys., 8, 251 (1972).

(42.6) Moore, L. J., Machlan, L. A., Shields, W. R. and Garner, E. L., Anal. Chem., 46, 1082 (1974).

$_{44}$Ru RUTHENIUM

$A_r(\mathrm{Ru}) = 101.07(2)$

Nuclide	Nuclidic Mass	Atom Percent in Element
^{96}Ru	95.907 596(9) u	5.52(5)
^{98}Ru	97.905 287(7) u	1.88(5)
^{99}Ru	98.905 937 1(28) u	12.7(1)
^{100}Ru	99.904 217 5(28) u	12.6(1)
^{101}Ru	100.905 580 8(31) u	17.0(1)
^{102}Ru	101.904 347 5(31) u	31.6(2)
^{104}Ru	103.905 422(6) u	18.7(2)

Annotation Code: g

In its 1961 Report (0.1a) the Commission changed the recommended atomic-weight value, $A_r(\mathrm{Ru})$, from 101.1 to 101.07. In 1969 the Commission (0.1c) assigned an uncertainty $U_r(\mathrm{Ru})$ of 0.03 to that value of $A_r(\mathrm{Ru})$ which was based on the abundance measurements by Friedman and Irsa (44.1), Baldock (44.2), and White et al. (44.3) and not on the chemical determination by Glew and Rehm (44.4) in view of the large uncertainties in the chemical determination. The best measurements of the isotopic composition on which the above representative isotopic composition is based corresponds to the more recent work by Devillers et al.(44.5) yielding $A_r(\mathrm{Ru}) = 101.068(13)$ calculated with the most recent nuclidic-mass data (0.2e). The use in 1961 of earlier nuclidic-mass data (0.2a) does not significantly affect the interpretation of the earlier $A_r(\mathrm{Ru})$ determinations. Feitknecht (44.6) found no significant differences between three meteoritic and one terrestrial sample. More recently Devillers et al. (44.5) found no significant differences between a meteoritic sample, two samples of well defined geographic origin and a commercial sample. In view of the excellent agreement between all the data, the Commission in 1983 (0.1j) recommended a reduction in $U_r(\mathrm{Ru})$ from 0.03 to 0.02.

References

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$_{45}$Rh RHODIUM

$A_r(\mathrm{Rh}) = 102.9055(1)$

Nuclide	Nuclidic Mass	Atom Percent in Element
^{103}Rh	102.905 503(5) u	100.00

The Commission in 1961 (0.1a) proposed $A_r(\mathrm{Rh}) = 102.905$ based on nuclidic-mass data by Everling et al. (0.2a). On the basis of Leipziger's search for minor stable isotopes of rhodium (45.1), it is concluded that they could at most affect the sixth decimal figure of the atomic-weight value.

On this assessment, the Commission in 1969 (0.1c) added one decimal figure and an uncertainty estimate $U_r(\mathrm{Rh}) = 0.0001$. The $A_r(\mathrm{Rh})$ value thus became 102.9055(1) and has remained the same since then. It is consistent with the latest nuclidic-mass data (0.2e).

Reference

(45.1) Leipziger, F. D., Appl. Spectros. 17, 158 (1963).

$_{46}$Pd PALLADIUM

$\underline{A}_r$(Pd) = 106.42(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{102}Pd	101.905 609(10) u	1.020(12)
^{104}Pd	103.904 026(6) u	11.14(8)
^{105}Pd	104.905 075(6) u	22.33(8)
^{106}Pd	105.903 475(6) u	27.33(5)
^{108}Pd	107.903 894(5) u	26.46(9)
^{110}Pd	109.905 169(21) u	11.72(9)

Annotation Code: g

In its 1961 Report (0.1a) the Commission recommended the atomic weight of palladium $\underline{A}_r$(Pd) = 106.4 based on the isotopic-abundance measurement by Sites et al. (46.1) using nuclidic masses by Everling et al. (0.2a). The uncertainty $\underline{U}_r$(Pd) = 0.1 was assigned by the Commission in 1969 (0.1c) which gave palladium the least precisely tabulated atomic weight at that time.

New calibrated isotope-abundance measurements of palladium were made by Shima et al. in 1978 (46.2) yielding $\underline{A}_r$(Pd) = 106.415(4). No variations outside the errors of the measurements were found among three terrestrial samples. Using these new abundance values and evidence of lack of significant natural variations, the Commission, in its 1979 Report (0.1h), recommended $\underline{A}_r$(Pd) = 106.42(1).

The reliability of the authors' work and the precision of their measurements might have led the Commission to accept an additional significant figure but caution had prevailed. That is fortunate because Mermelengas et al. (46.3) in 1981 found convincing evidence that a source from the South African Igneous Complex was enriched in the heavier isotopes to increase the sample atomic weight to 106.434. This could not be called an abnormal source, so the Commission may be forced, if the anomaly is confirmed, to increase $\underline{U}_r$(Pd) to 0.02 to span the variation in isotopic composition of palladium.

The possible recovery of significant quantities of non-radioactive ^{106}Pd from fission-product wastes has been discussed by McDuffie (46.4). This source of palladium is not likely to be available in the foreseeable future. If and when it does enter commerce further problems in the atomic weight of palladium will be introduced.

References

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(46.2) Shima, M., Rees, C. E. and Thode, H. G., Can. J. Phys., 56, 1333 (1978).

(46.3) Mermelengas, N., Rosman, K. J. R., and De Laeter, J. R., Int. J. Mass Spectrom. Ion Phys., 37, 1 (1981).

(46.4) McDuffie, H. F., Oak Ridge Natl. Lab. Rep. TM-6654 (1979).

$_{47}$Ag SILVER

$\underline{A}_r$(Ag) = 107.8682(3)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{107}Ag	106.905 095(6) u	51.839(5)
^{109}Ag	108.904 754(5) u	48.161(5)

Annotation Code: g

In its 1961 Report (0.1a) the Commission recommended $\underline{A}_r$(Ag) = 107.870(3) after carefully reviewing the reliability of this value. It was recognized to be of great importance because about 42 other elements had their atomic weights determined in terms of the equivalence of their halides to silver or silver halides. The above value for $\underline{A}_r$(Ag) was based on seven chemical (Ag/AgNO$_3$ twice; Ag/AgI; AgI/AgCl four times) and two calibrated mass-spectrometric determinations using nuclidic masses by Everling et al. (0.2a). The Commission gave equal weight to the average of these chemical determinations, A_r(Ag) = 107.8714 and two physical determinations yielding A_r(Ag) = 107.869 95. These two physical measurements differed in uncertainties by a factor of two, but yet were given equal weight.

In 1967 the Commission (0.1b) with news of an absolute isotopic-composition determination for bromine, saw that there was a self-consistent set of reliable absolute mass-spectrometric measurements for chlorine, bromine and silver. The basis for A_r(Ag) was changed to just one mass-spectrometric determination (the less uncertain one of the two used in 1961) by Shields et al. (47.1) with a value of A_r(Ag) = 107.868 and an uncertainty U_r(Ag) reduced to 0.001. The Commission pointed out that the new values gave a calculated combining ratio AgCl/Ag = 1.328 667 which is exactly the assessed best chemical ratio. Whereas this agreement amounted to about 1 part in 10^6, the ratio AgBr/Ag showed a disparity of 19 parts in 10^6 which was thought to be due to a bias in the chemical work.

In 1981 the Commission (0.1i) welcomed a superior new absolute isotopic-abundance measurement for silver by Powell et al. (47.2) yielding A_r(Ag) = 107.868 15(11). These authors found no significant difference between a number of silver metal and mineral samples with one minor exception now believed to be due to impurity. The Commission was able to recommend A_r(Ag) = 107.8682(3). In 1983 the Commission retained the "g" annotation because of the Oklo occurrence (see Part I, Section 6). That annotation had been originally assigned in response to an earlier mineral survey which was now discounted. The apparent anomaly was due to an impure sample. Through the greater use of mass-spectrometric determinations of atomic weights, silver is losing some of its key role attributable to the stability of its monovalent ion. However, the atomic weight of silver has lost none of its significance as a principal means for determining the Faraday constant. The recent atomic-weight determination (48.2) coupled with the best value of the electrochemical equivalent of silver has probably re-established the electrochemical method as the most accurate for determining the Faraday, and therefore may significantly contribute to future least-squares adjustments of the fundamental constants.

References

(47.1) Shields, W. R., Craig, D. N., and Dibeler, V. H., J. Am. Chem. Soc., 82, 5033 (1960).

(47.2) Powell, L. J., Murphy, T. J., and Gramlich, J. W., J. Res. Natl. Bur. Stand. (U.S.), 87, 9 (1982).

$_{48}$Cd CADMIUM

A_r(Cd) = 112.41(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{106}Cd	105.906 461(7) u	1.25(3)
^{108}Cd	107.904 186(7) u	0.89(1)
^{110}Cd	109.903 007(4) u	12.49(9)
^{111}Cd	110.904 182(4) u	12.80(6)
^{112}Cd	111.902 761 4(36) u	24.13(11)
^{113}Cd	112.904 401 3(37) u	12.22(6)
^{114}Cd	113.903 360 7(36) u	28.73(21)
^{116}Cd	115.904 758(4) u	7.49(9)

Annotation Code: g

In its 1961 Report (0.1a) the Commission recommended A_r(Cd) = 112.40 based on seven chemical determinations by Hönigschmid and Schlee, and Baxter in cooperation with various associates, although it was noted that several isotopic-abundance measurements yielded slightly higher values. Nevertheless, the Commission in 1969 (0.1c) assigned U_r(Cd) = 0.01.

In 1975 Rosman and De Laeter (48.1) published new isotopic abundances for eight terrestrial minerals using double spiking to correct for mass discrimination. They obtained A_r(Cd) = 112.4094(49). The Commission in 1975 (0.1f) accepted this measurement as the most reliable. It was moreover in fair agreement with earlier mass-spectrometric measurements, including those quoted in the 1961 Report as well as determinations by White and Cameron (48.2) and

Hibbs (48.3) yielding, respectively, $\underline{A}_r$(Cd) = 112.43 and 112.42. As the chemical measurements, seemingly consistent with each other, had averaged 112.400 with little spread, the Commission justified the retention of $\underline{U}_r$(Cd) = 0.01 with $\underline{A}_r$(Cd) now 112.41. Since that change was made another confirmatory measurement of abundances has been published by Rosman et al. (48.4).

It might be of some interest to note that all chemical measurements that gave an $\underline{A}_r$(Cd) value below 112.40 depended on the purity of $CdBr_2$, for which freedom from traces of chloride at the time was hard to prove. Incidentally also, it is of interest that Rosman and De Laeter (48.5) found that the majority of meteorite samples of cadmium showed no variations from the terrestrial composition. Two chondrites, however, (Browfield and Tietschitz) exhibited enhancement of the heavier isotopes.

^{113}Cd is β^-active, but its half-life is so long (9.3(19) x 10^{15}a) (0.6) that it does not affect $\underline{A}_r$(Cd) measurably even over geologic time periods. It decays into the minor isotope of indium, but abnormal occurrences of that element with anomalous $\underline{A}_r$(In) from the decay of ^{113}Cd have not been reported and cannot be expected at current precision.

References

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(48.3) Hibbs, R. F., U.S.A.E.C. Rep. AECU - 556 (1949).

(48.4) Rosman, K. J. R., Barnes, I. L., Moore, L. J., and Gramlich, J. W., Geochem. J., 14, 269 (1980).

(48.5) Rosman, K. J. R., and De Laeter, J. R., J. Geophys. Res., 83, 1279 (1978).

$_{49}$In INDIUM

$\underline{A}_r$(In) = 114.82(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{113}In	112.904 056(5) u	4.3(2)
^{115}In	114.903 875(8) u	95.7(2)

Annotation Code: g

In its 1961 Report (0.1a) the Commission recommended $\underline{A}_r$(In) = 114.82 which was the average value of two reported mass-spectrometric determinations by White and Cameron (49.1), and White et al. (49.2) calculated with nuclidic masses by Everling et al. (0.2a). The uncertainty $\underline{U}_r$(In) was assessed to be ± 0.01 in 1969 (0.1c). In the absence of new calibrated mass-spectrometric measurements and lacking a study of possible natural variations the Commission does not see compelling reasons for making a change.

It is not clear whether a third mass-spectrometric determination by Hibbs (49.3) was disregarded with cause or overlooked. However, his result $\underline{A}_r$(In) = 114.821 calculated with current nuclidic masses (0.2e), is in excellent agreement with the other determinations.

^{115}In is β^-active with a half-life so long, 4.41(25) x 10^{14}a (0.6) that it neither affects $\underline{A}_r$(In) nor has it given rise to recognized abnormal occurrences of tin.

References

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(49.3) Hibbs, R. F., U.S.A.E.C. Rep. AECU - 556 (1949).

$_{50}$Sn TIN

A_r(Sn) = 118.710(7)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{112}Sn	111.904 823(6) u	0.97(1)
^{114}Sn	113.902 781(5) u	0.65(1)
^{115}Sn	114.903 344 1(39) u	0.36(1)
^{116}Sn	115.901 743 5(38) u	14.53(11)
^{117}Sn	116.902 953 6(37) u	7.68(7)
^{118}Sn	117.901 606 6(37) u	24.22(11)
^{119}Sn	118.903 310 2(37) u	8.58(4)
^{120}Sn	119.902 199 0(37) u	32.59(10)
^{122}Sn	121.903 440(4) u	4.63(3)
^{124}Sn	123.905 271(5) u	5.79(5)

In its 1961 Report (0.1a) the Commission recommended A_r(Sn) = 118.69 based on chemical-ratio determinations by Baxter and Starkweather (50.1); Briscoe (50.2); and Brauner and Krepelka (50.3). From these measurements, with current values of the atomic weights of the other elements involved (0.1j), the following atomic weights for tin are derived: A_r(Sn) = 118.691, 118.686 and 118.701, respectively. In 1969 (0.1c) the Commission assessed the uncertainty to be U_r(Sn) = 0.03.

Even in 1961 the Commission was aware that three mass-spectrometric determinations had been made which yield slightly higher atomic-weight values. However, tin has ten stable isotopes, the largest number of all elements. The isotopic-composition measurements therefore involve an unusually large number of experimentally determined ratios each subject to uncertainty. The Commission therefore preferred the chemically determined values. This viewpoint was reconfirmed during the years until in 1983 the Commission (0.1j) was able to consider the first calibrated mass-spectrometric measurement by Devillers et al. (50.4) who used double spiking with two samples highly enriched in ^{116}Sn and ^{122}Sn. The difficulty of the high ionization potential of tin is overcome by the use of electrodeposited tin onto a rhenium-ribbon side filament in a thermal-ionization mass spectrometer. The authors obtain A_r(Sn) = 118.709 93(220) and demonstrate good agreement with seven previous abundance measurements after correcting those uncalibrated measurements linearly by mass for isotope fractionation. The Commission in 1983 (0.1j) therefore changed the basis for the standard atomic weight of tin to mass spectrometry and the value to A_r(Sn) = 118.710(7) with the knowledge that natural variability is very small (50.5).

References

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(50.2) Briscoe, H. V. A., J. Chem. Soc., 107, 63 (1915).

(50.3) Brauner, B., and Krepelka, J. Am. Chem. Soc., 42, 917, 925 (1920).

(50.4) Devillers, C., Lecomte, T., and Hagemann, R., Int. J. Mass Spectrom. Ion Phys., 50, 205 (1983).

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$_{51}$Sb ANTIMONY (STIBIUM)

A_r(Sb) = 121.75(3)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{121}Sb	120.903 823 7(38) u	57.3(9)
^{123}Sb	122.904 222(4) u	42.7(9)

In its 1961 Report (0.1a) the Commission recommended A_r(Sb) = 121.75 based on chemical measurements by Willard and McAlpine (51.1), Hönigschmid et al. (51.2), Weatherill (51.3) and Krishnaswami (51.4). With current values of the other atomic weights (0.1j) these measurements yield the following results from the listed comparisons:

$SbBr_3/3Ag$ = 1.117 704	A_r(Sb) = 121.778	(51.1)
$SbBr_3/3AgBr$ = 0.641 682	A_r(Sb) = 121.758	(51.1)
$SbCl_3/3Ag$ = 0.704 88	A_r(Sb) = 121.743	(51.2)
$SbCl_3/3AgCl$ = 0.530 53	A_r(Sb) = 121.750	(51.2)
$SbBr_3/3Ag$ = 1.116 99	A_r(Sb) = 121.751	(51.2)
$SbBr_3 3AgBr$ = 0.641 67	A_r(Sb) = 121.751	(51.2)
$SbCl_3/3Ag$ = 0.704 864	A_r(Sb) = 121.738	(51.3)
$SbBr_3/3AgBr$ = 0.641 659	A_r(Sb) = 121.745	(51.4)

Giving these determinations equal weight leads to an average value for A_r(Sb) = 121.751. The Commission in 1961 (0.1a) was aware of what has remained the sole measurement of the isotopic composition of antimony by mass spectroscopy published by White and Cameron (51.5). With current nuclidic-mass data by Wapstra and Bos (0.2e) that measurement yields A_r(Sb) = 121.759 in good agreement with the chemical value.

The corresponding values calculated in 1961 (0.1a) provided the Commission with an average chemical value of A_r(Sb) = 121.750 and for the mass-spectrometric determination A_r(Sb) = 121.76. The chemical value was evidently given slight preference in the tabulated value of A_r(Sb) = 121.75 for which in 1969 (0.1c) the Commission assigned a U_r(Sb) = 0.03. These values have remained unchanged since. With only two isotopes, antimony may be a good candidate for a second, perhaps superior mass-spectrometric determination.

References

(51.1) Willard, H. H., and McAlpine, R. K., J. Am. Chem. Soc., 43, 797 (1921).

(51.2) Hönigschmid, O., Zintl, E., and Linhard, M., Z. Anorg. Allg. Chem., 136, 257 (1924).

(51.3) Weatherill, P. F., J. Am. Chem. Soc., 46, 2437 (1924).

(51.4) Krishnaswami, K. R., J. Chem. Soc. II, 2534 (1927).

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$_{52}$Te TELLURIUM

A_r(Te) = 127.60(3)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{120}Te	119.904 021(23) u	0.096(2)
^{122}Te	121.903 055(5) u	2.60(1)
^{123}Te	122.904 278(4) u	0.908(3)
^{124}Te	123.902 825(4) u	4.816(8)
^{125}Te	124.904 435(4) u	7.14(1)
^{126}Te	125.903 310(4) u	18.95(1)
^{128}Te	127.904 464(4) u	31.69(2)
^{130}Te	129.906 229(5) u	33.80(2)

Annotation Code: g

The Commission Report in 1961 (0.1a) recommended A_r(Te) = 127.60 based on the chemical-ratio determinations by Hönigschmid and his collaborators (52.1) to (52.3). In 1969 (0.1c), the Commission assessed U_r(Te) to 0.03. Recalculations of the chemical ratios with current values of the other atomic weights involved (0.1j) yields the following results from the listed comparisons:

$TeBr_4/4Ag$ = 1.036 49	A_r(Te) = 127.601	(52.1)
$TeBr_4/4AgBr$ = 0.595 426	A_r(Te) = 127.602	(52.1)
$Ag_2Te/2Ag$ = 1.591 45	A_r(Te) = 127.597	(52.2)

$TeCl_4/4Ag = 0.624\ 425$ $A_r(Te) = 127.610$ (52.3)

$TeCl_4/4AgCl = 0.469\ 960$ $A_r(Te) = 127.612$ (52.3)

Giving these chemical determinations equal weight yields $A_r(Te) = 127.604$.

Already in 1961, the Commission noted the mass-spectrometric measurements of Williams and Yuster (52.4), and White and Cameron (52.5), which average to a higher atomic-weight value: $A_r(Te) = 127.63$. More recent isotope abundance measurements by Smith et al. (52.6) coupled with latest nuclidic-mass data (0.2e) gave a value lower than that from the chemical determinations. That value, $A_r(Te) = 127.586$, was invariant within experimental precision for six tellurium mineral sources. In the absence of calibrated mass-spectrometric measurements, the value of $A_r(Te) = 127.60(3)$ has been retained for the standard atomic weight of tellurium.

^{123}Te, ^{128}Te, and ^{130}Te are radioactive; the minor isotope ^{123}Te has a long life-life of $1.3(4) \times 10^{13}$a (0.6) and transforms to $^{123}_{51}$Sb without significantly affecting either element's atomic weight even in geologic time. The major isotopes, ^{128}Te and ^{130}Te have the enormously long half-lives of more than 10^{24} a and 10^{21}a (0.6). They suffer double β^- decay causing a detectable anomaly for xenon in tellurium-bearing minerals.

References

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$_{53}$I IODINE

$A_r(I) = 126.9045(1)$

Nuclide	Nuclidic Mass	Atom Percent in Element
^{127}I	126.904 477(5) u	100.00

The Commission in 1961 (0.1a) proposed for the atomic weight of iodine $A_r(I) = 126.9044$ based on nuclidic-mass data by Everling et al. (0.2a). The Commission had a preview of the revision of this data in a paper by Wapstra and Gove (0.2d) that had been accepted for publication prior to the Commission meeting in 1969 (0.1c). Presumably it was the new value for the mass of $^{127}I = 126.904\ 47$ u that led the Commission there to adopt the change to $A_r(I) = 126.9045(1)$ without documenting the reasoning in the 1969 Report (0.1c). However, the new value also is in agreement with Wapstra and Bos (0.2e), who in this latest published compilation of nuclidic-mass data, give for ^{127}I the mass quoted above.

There is little information in the literature on the hypothetical presence in normal sources of iodine of nuclides other than ^{127}I. Leland (53.1) finds the upper limit of presence of ^{129}I in normal iodine as 3×10^{-4} atom percent. It is a β^- emitter with a half-life of $1.6(1) \times 10^7$a (0.6) too short for the survival in terrestrial iodine of significant amounts of this nuclide from primordial material. If present in normal iodine in the concentration determined by Leland to be the upper limit, it would increase $A_r(I)$ by six in the ninth significant figure, more than one order of magnitude below the level of significance for the atomic-weight value as quoted.

Reference

(53.1) Leland, W. T., Phys. Rev. **76**, 992 (1949).

$_{54}$Xe XENON

A_r(Xe) = 131.29(3)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{124}Xe	123.906 12(15) u	0.10(1)
^{126}Xe	125.904 281(9) u	0.09(1)
^{128}Xe	127.903 530 8(17) u	1.91(3)
^{129}Xe	128.904 780 1(21) u	26.4(6)
^{130}Xe	129.903 509 5(17) u	4.1(1)
^{131}Xe	130.905 076(5) u	21.2(4)
^{132}Xe	131.904 148(5) u	26.9(5)
^{134}Xe	133.905 395(8) u	10.4(2)
^{136}Xe	135.907 219(9) u	8.9(1)

Annotation Codes: g and m

In its 1961 Report (0.1a) the Commission recommended A_r(Xe) = 131.30 based on the isotopic-abundance measurements of Nier (54.1) and the masses reported by Halsted (54.2). The Commission recognized that this calculation was "slightly in error" and noted that with the same abundances and using the masses reported by Everling et al. (0.2a) the correct calculated value was nearer to A_r(Xe) = 131.29. Despite the fact that the tabulated value was believed to be not the optimum value the Commission in 1969 (0.1c) estimated that the uncertainty U_r(Xe) was no greater than 0.01.

In 1979 the Commission (0.1h) corrected the above-mentioned error and recommended A_r(Xe) = 131.29(3). This is the first of only two instances after 1969 in which the Commission has increased the assigned uncertainty of a recommended atomic weight.

The production of ^{129}Xe from the now extinct $^{129}_{53}$I; that of ^{131}Xe and ^{136}Xe from spontaneous fission of $^{238}_{92}$U and extinct $^{244}_{94}$Pu; that of ^{128}Xe and ^{130}Xe from double β^- decay of $^{128}_{52}$Te and ^{130}Te; and mantle-source xenon explain many reported measurements of minor occurrences of xenon of anomalous composition. The Tables of Standard Atomic Weights therefore carry the "g" annotation for xenon (see also reference (2.9)).

References

(54.1) Nier, A. O., Phys. Rev., 79, 450 (1950).

(54.2) Halsted, R. E., Phys. Rev., 88, 666 (1952).

$_{55}$Cs CAESIUM

A_r(Cs) = 132.9054(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{133}Cs	132.905 433(9) u	100.00

The Commission Report in 1961 (0.1a) proposed A_r(Cs) = 132.905 based on nuclidic-mass data by Everling et al. (0.2a). The Commission also quoted experimental evidence from the literature that the upper limits for the hypothetical existence of any other stable or quasi-stable nuclides of caesium are very low. On re-examination of the literature we estimate the uncertainty in A_r(Cs) so introduced to be at most $+1.2 \times 10^{-4}$ or -5.5×10^{-5}.

When assessing the reliability of data, the Commission in 1969 (0.1c) decided to add one significant figure. A_r(Cs) thus became equal to 132.9055(1) but, on the basis of Wapstra and Gove's revision of nuclidic-mass data (0.2d), had to be adjusted in 1971 (0.1d) to 132.9054(1). This last value is the present IUPAC standard atomic weight for caesium. It is consistent with Wapstra and Bos (0.2e) who in the most recently published compilation give the nuclidic mass as quoted above.

$_{56}$Ba BARIUM

$\underline{A}_r$(Ba) = 137.33(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{130}Ba	129.906 277(13) u	0.106(2)
^{132}Ba	131.905 042(11) u	0.101(2)
^{134}Ba	133.904 490(9) u	2.417(27)
^{135}Ba	134.905 668(8) u	6.592(18)
^{136}Ba	135.904 556(8) u	7.854(39)
^{137}Ba	136.905 816(8) u	11.23(4)
^{138}Ba	137.905 236(7) u	71.70(7)

Annotation Code: g

In 1961, the Commission (0.1a) recommended the value of $\underline{A}_r$(Ba) = 137.34 for the atomic weight of barium. This value was based firstly on a recalculation of Hönigschmid and Sachtleben's measurement (56.1), who converted barium perchlorate to barium chloride. They compared both salts to each other, to silver and silver chloride. Their results can be averaged with current atomic weights of the other elements involved (0.1j) to $\underline{A}_r$(Ba) = 137.341. The Commission in 1961 secondly based the recommended atomic weight on isotopic abundance measurements by Nier (56.2) and Thode (56.3) using nuclidic masses reported by Everling et al. (0.2a). In 1969, after reevaluating the uncertainties associated with the works cited above, the Commission (0.1c) recommended a value of $\underline{U}_r$(Ba) = 0.03.

In 1975, the Commission (0.1f) reviewed once again all the older chemical and all significant mass-spectrometric measurements, including more recent measurements of the isotopic composition that were not available for the earlier assessment (56.4) to (56.7). Using current nuclidic-mass data (0.21), all these mass-spectrometric measurements are in the tight range $\underline{A}_r$(Ba) = 137.326 to 137.339. Eugster et al. (56.6) calibrated their measurements by a double-spike technique giving $\underline{A}_r$(Ba) = 137.327. These authors as well as De Laeter and Date (56.7) reported no variation of isotopic composition in a range of terrestrial and meteoritic samples. With this evidence, the Commission recommended the lower mass-spectrometric value with a smaller uncertainty, $\underline{A}_r$(Ba) = 137.33(1).

References

(56.1) Hönigschmid, O., and Sachtleben, R., Z. Anorg. Allg. Chem., 178, 1 (1929).

(56.2) Nier, A. O., Phys. Rev., 54, 275 (1938).

(56.3) Thode, H., G., Priv. Comm. cited in Nucl. Data Tables, K. Way, editor (1959), Supt. of Documents, U.S. Government Printing Office, Washington, DC.

(56.4) Rider, B. F., Peterson, J. P., Jr., and Ruiz, C. P., General Electric Comp. Rep. GEAP-4008 (1962).

(56.5) Umemoto, S., J. Geophys. Res., 67, 375 (1962).

(56.6) Eugster, O., Tera, F., and Wasserburg, G. J., J. Geophys. Res., 74, 3897 (1969).

(56.7) De Laeter, J. R., and Date, R., Int. J. Mass Spectrom. Ion Phys., 12, 455 (1973).

$_{57}$La LANTHANUM

$\underline{A}_r$(La) = 138.9055(3)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{138}La	137.907 114(7) u	0.09(1)
^{139}La	138.906 355(6) u	99.91(1)

Annotation Code: g

In its 1961 Report (0.1a) the Commission recommended value $\underline{A}_r$(La) = 138.91 based on the recalculation of two chemical determinations and the average of two mass-spectrometric determinations, by Inghram et al. (57.1) and White et al. (57.2) using the nuclidic-mass data by Everling et al. (0.2a). In 1969 the Commission (0.1c) recommended $\underline{A}_r$(La) = 138.9055(3) based upon the same determinations but bearing in mind that two additional digits were justified in view of the small influence any mass discrimination could have on the atomic weight of this nearly mononuclidic element. In effect the chemical determinations were no longer considered significant.

In the absence of new calibrated mass-spectrometric measurements as well as of a study of possible natural variations the Commission did not see sufficiently convincing reasons to make any further change.

The minor isotope ^{138}La is radioactive with a half-life of 1.06(4) x 10^{11}a (0.6), with $^{138}_{56}$Ba and $^{138}_{58}$Ce as daughter nuclides. The atomic weight of all three elements remains unaffected even over geologic time periods.

References

(57.1) Inghram, M. G., Hayden, R. J., and Hess, D. C., Jr., Phys. Rev., 72, 967 (1947).

(57.2) White, F. A., Collins, T. L., Jr., and Rourke, F. M., Phys. Rev., 101, 1786 (1956).

$_{58}$Ce CERIUM

$\underline{A}_r$(Ce) = 140.12(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{136}Ce	135.907 14(5) u	0.19(1)
^{138}Ce	137.905 996(14) u	0.25(1)
^{140}Ce	139.905 442(6) u	88.48(10)
^{142}Ce	141.909 249(7) u	11.08(10)

Annotation Code: g

In its 1961 Report (0.1a) the Commission recommended $\underline{A}_r$(Ce) = 140.12 based on the average value of the mass-spectrometric measurements by Inghram et al. (58.1) and Hibbs (58.2) which were in good agreement with earlier chemical determinations. As a result the Commission in 1969 (0.1c) assessed the uncertainty $\underline{U}_r$(Ce) to be 0.01. Consideration was also given to a more recent determination by Umemoto (58.3) which with current nuclidic masses (0.2e) calculates to $\underline{A}_r$(Ce) = 140.1148 compared with 140.1048 for Inghram et al. (58.1) and 140.1245 for Hibbs (58.2). Though $\underline{A}_r$(Ce) = 140.11(2) might be a slightly better value the Commission has not seen sufficiently compelling reasons to make a change until new results are available. The above representative isotopic composition calculates to $\underline{A}_r$(Ce) = 140.1149(20) which favors the lower value and higher uncertainty without compelling a change.

^{138}Ce and ^{140}Ce are the decay products of long-lived minor isotopes $^{138}_{57}$La and $^{144}_{60}$Nd, respectively. They have a negligible effect on $\underline{A}_r$(Ce) in normal sources but add justification to the "g" annotation which also refers to the Oklo occurrence (see Part I, Section 6).

References

(58.1) Inghram, M. G., Hayden, R. J., and Hess, D. C., Jr., Phys. Rev., 72 967 (1947).

(58.2) Hibbs, R. F., U.S.A.E.C. Rep. A.E.C.U.-556 (1949).

(58.3) Umemoto, S., J. Geophys. Res., 67, 375 (1962).

$_{59}$Pr PRASEODYMIUM

$\underline{A}_r$(Pr) = 140.9077(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{141}Pr	140.907 657(6) u	100.00

The Commission Report in 1961 (0.1a) proposed for the atomic weight of praseodymium $\underline{A}_r$(Pr) = 140.907 based on nuclidic-mass data by Everling et al. (0.2a). The Commission also quoted the literature placing very low limits for the existence of other stable nuclides of this element. On re-examination of the literature we estimate the uncertainty in $\underline{A}_r$(Pr) so introduced to be about ±4 x 10^{-3}. That upper limit derived from experimental observation, is large and hardly useful. It is more meaningful to consider that praseodymium has no known radionuclides of long half-life. The existence of a stable or quasi-stable isotope must be judged to be very unlikely. The effective uncertainty should be less than the experimentally determined maximum.

On its assessment of the data, the Commission in 1969 (0.1c) added one additional decimal figure. The A_r(Pr) thus became 140.9077(1) and has remained the same since then. It is consistent with Wapstra and Bos (0.2e) who now give the nuclidic mass of ^{141}Pr quoted above.

$_{60}$Nd NEODYMIUM

A_r(Nd) = 144.24(3)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{142}Nd	141.907 731(6) u	27.13(10)
^{143}Nd	142.909 823(6) u	12.18(5)
^{144}Nd	143.910 096(6) u	23.80(10)
^{145}Nd	144.912 582(6) u	8.30(5)
^{146}Nd	145.913 126(6) u	17.19(8)
^{148}Nd	147.916 901(6) u	5.76(3)
^{150}Nd	149.920 900(6) u	5.64(3)

Annotation Code: g

In its 1961 Report (0.1a) the Commission recommended A_r(Nd) = 144.24 based on the average of the isotopic-abundance measurements of Inghram et al. (60.1) and Walker and Thode (60.2) with nuclidic masses by Everling et al. (0.2a). In 1969 the Commission (0.1c) evaluated the uncertainty U_r(Nd) to be 0.03.

Two isotopes of neodymium (^{144}Nd and ^{145}Nd) are radioactive but with half-lives so long, 2.1(4) x 10^{15} and more than 6 x 10^{16}a (0.6) respectively, that there is no measurable effect on the atomic weight comparable with the precision of the tabulated standard atomic weight. ^{143}Nd is the decay product of radioactive $^{147}_{62}$Sm. Although the resulting fluctuations of ^{143}Nd/^{144}Nd are also too small to affect A_r(Nd) they are measurable and do permit deductions to be made in geochronology (60.3) and geochemical phenomena for instance the mixing of ocean currents (60.4). For such applications precise measurements of isotopic-abundances and Sm/Nd ratios are needed such as are greatly facilitated by comparisons with standard solutions (60.5).

References

(60.1) Inghram, M. G., Hess, Jr., D. C., and Hayden, R. J., Phys. Rev., 74, 98 (1948).

(60.2) Walker, W. H., and Thode, H. G., Phys. Rev., 90, 447 (1953).

(60.3) Jacobsen, S. B., and Wasserburg, G. J., J. Geophys. Res. 84, 7411 (1979).

(60.4) Piepgras, D. J., and Wasserburg, G. J., Science, 217, 207 (1982).

(60.5) Wasserburg, G. J., Jacobsen, S. B., De Paolo, D. J., Mc Culloch, M. T., and Wen, T., Geochim. Cosmochim. Acta 45, 2311 (1981).

$_{62}$Sm SAMARIUM

A_r(Sm) = 150.36(3)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{144}Sm	143.912 009(6) u	3.1(1)
^{147}Sm	146.914 907(6) u	15.0(2)
^{148}Sm	147.914 832(6) u	11.3(1)
^{149}Sm	148.917 193(6) u	13.8(1)
^{150}Sm	149.917 285(6) u	7.4(1)

^{152}Sm	151.919 741(5) u	26.7(2)
^{154}Sm	153.922 218(6) u	22.7(2)

Annotation Code: g

In its 1961 Report (0.1a) the Commission expressed concern about disparities among several abundance measurements for samarium, while chemical measurements yielded persistently higher values. Nevertheless, the Commission retained A_r(Sm) = 150.35 — the 1955 value based on the mass spectrometry of Inghram et al. (62.1) which was even lower than the average of five mass-spectrometric measurements averaged and recalculated with nuclidic masses by Bhanot et al. (0.2b). In 1969 the Commission (0.1c) found the evidence inadequate for the precision previously implied and corrected A_r(Sm) to 150.4(1) which value included almost all chemical and mass-spectrometric data.

In 1979 the Commission (0.1h) undertook a thorough review of the literature. The chemical determinations by Hönigschmid and Hirschbold-Wittner (62.2) were found most reliable, because the purity of $SmCl_3$ was proved by x-ray fluorescence and optical-emission spectrometry. Earlier work had been subject to contamination by oxychloride as correctly pointed out by Hönigschmid and Hirschbold-Wittner (62.2). Their data, recalculated with current values of the atomic weights of the other elements involved (0.1j), yield the following results from the listed comparisons:

$SmCl_3$/3Ag = 0.793 310 A_r(Sm) = 150.359 (62.2)

$SmCl_3$/3AgCl = 0.597 068 A_r(Sm) = 150.358 (62.2)

By 1975 Lugmair et al. (62.3) had carried out more precise mass-spectrometric measurements that with current nuclidic masses (0.2e) give A_r(Sm) = 150.366. Thus the Commission in 1979 (0.1h) recommended A_r(Sm) = 150.36(3) a vindication of the 1961 value. From the previous A_r(Sm) = 150.4 this was the largest change of an atomic weight value in recent Commission history (see Part I, Table 4) although it was only 40 percent of the previously estimated uncertainty.

Two of the isotopes, ^{147}Sm and ^{148}Sm, are α-emitters with very long half-lives of 1.06(1) x 10^{11}a and 7(3) x 10^{15}a (0.6) respectively. ^{148}Sm is also the decay product of $^{152}_{64}$Gd a very minor isotope also with a very long half-life. The discovery of ^{146}Sm, an α-emitter with a half-life of 1.03(5) x 10^{8}a (0.6), as a very minor component of naturally occurring samarium, was predictable (see Part I, Section 11). None of these facts can appreciably influence A_r(Sm) even over geologic time intervals. The applications to geochronology and geochemical phenomena are mentioned in the preceding section on neodymium.

References

(62.1) Inghram, M. C., Hayden, R. J., and Hess, D. C., see Seaborg, G. T., and Perlman, I., Rev. Mod. Phys., 20, 585 (1948).

(62.2) Hönigschmid, O., and Hirschbold-Wittner, Fr., Z. Phys. Chem., 189A, 38 (1941).

(62.3) Lugmair, C. W., Scheinin, N. B., and Marti, K., Proc. Lunar Sci. Conf., 6th, Goechim. Cosmochim. Acta Suppl., 6, 2, 1419 (1975).

$_{63}$Eu EUROPIUM

A_r(Eu) = 151.96(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{151}Eu	150.919 860(6) u	47.8(5)
^{153}Eu	152.921 243(6) u	52.2(5)

Annotation Code: g

In its 1961 Report (0.1a) the Commission recommended the atomic weight of europium A_r(Eu) = 151.96 based on the mass-spectrometric determinations by Hess (63.1) and Collins et al. (63.2) and nuclidic masses by Bhanot et al. (0.2b). Owing to the fact that europium has only two isotopes, the Commission in 1969 (0.1c) assessed U_r(Eu) at 0.01, that is less than, say, U_r(Gd). Since that time other confirmatory isotopic-composition measurements have become available (63.3), but none was a calibrated measurement. Natural variability has not been studied and reported in the literature. The Commission therefore does not see compelling reasons for changing the earlier values of A_r(Eu) and U_r(Eu).

References

(63.1) Hess, D. C., Jr., Phys. Rev., 74, 773 (1948).

(63.2) Collins, T. L., Rourke, F. M., and White, F. A., Phys. Rev., 105, 196 (1957).

(63.3) Holliger, P., and Devillers, C., Earth, Planet Sci. Lett., 52, 76 (1981).

$_{64}$Gd GADOLINIUM

A_r(Gd) = 157.25(3)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{152}Gd	151.919 803(6) u	0.20(1)
^{154}Gd	153.920 876(6) u	2.18(3)
^{155}Gd	154.922 629(6) u	14.80(5)
^{156}Gd	155.922 130(6) u	20.47(4)
^{157}Gd	156.923 967(6) u	15.65(3)
^{158}Gd	157.924 111(6) u	24.84(12)
^{160}Gd	159.927 061(6) u	21.86(4)

Annotation Code: g

In 1961 the Commission (0.1a) recommended for the value of the atomic weight of gadolinium A_r(Gd) = 157.25. This value was based on the average of the isotopic-abundance measurements of Hess (64.1) and Leland (64.2) using nuclidic masses reported by Bhanot et al. (0.2b). In 1969, after reevaluating the uncertainties associated with the determinations cited above, the Commission (0.1c) recommended a value of A_r(Gd) = 157.25(3).

The most recent isotopic-abundance measurements of Eugster et al. (64.3) and Holliger and Devillers, (64.4) are considered superior, but when used with nuclidic masses by Wapstra and Bos (0.2e) do not present a compelling argument for a change in the recommended values for A_r(Gd) or U_r(Gd). However, the best estimate of A_r(Gd) would currently be lower by 0.01.

^{152}Gd is an α-emitter with a very long half-life in excess of 10^{14} years. Within the life time of the earth this radioactivity will not have affected the atomic weight to the precision here quoted.

References

(64.1) Hess, Jr., D. C., Phys. Rev., 74, 773 (1948).

(64.2) Leland, W. T., Phys. Rev., 77, 634 (1950).

(64.3) Eugster, O., Tera, F., Burnett, B. S., and Wasserburg, G. J., J. Geophys. Res., 75, 2753 (1970).

(64.4) Holliger, P., and Devillers, C., Earth Planet. Sci. Lett., 52, 76 (1981).

$_{65}$Tb TERBIUM

A_r(Tb) = 158.9254(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{159}Tb	158.925 350(6) u	100.00

The Commission Report in 1961 (0.1a) proposed for the atomic weight of terbium A_r(Tb) = 158.924 based on nuclidic-mass data by Everling et al. (0.2a). The Commission also quoted experimental evidence from the literature which indicated that the upper limits for the hypothetical existence of other stable or quasi-stable isotopes of terbium were very low. On re-examination of the literature we estimate that the experimentally determined uncertainty in A_r(Tb) so introduced is as high as $+1.6 \times 10^{-3}$ or -2.8×10^{-4}. However, other arguments lead to far lower estimates of that uncertainty (see Part I, Section 7).

A revision of the nuclidic-mass data was considered by the Commission in 1969, although the relevant publication by Wapstra and Gove (0.2d) was finalized later. However, the publication had been accepted in a refereed journal prior to the Commission meeting in July 1969 (0.1c). The acceptance of the new value thus conformed to Commission policy. The $\underline{A}_r$(Tb) value thus became equal to 158.9254(1), and has remained the same since then. Wapstra and Bos (0.2e) now give the nuclidic mass of ^{159}Tb as quoted above.

$_{66}$Dy DYSPROSIUM

$\underline{A}_r$(Dy) = 162.50(3)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{156}Dy	155.924 287(9) u	0.06(1)
^{158}Dy	157.924 412(7) u	0.10(1)
^{160}Dy	159.925 203(6) u	2.34(5)
^{161}Dy	160.926 939(6) u	18.9(1)
^{162}Dy	161.926 805(6) u	25.5(2)
^{163}Dy	162.928 737(6) u	24.9(2)
^{164}Dy	163.929 183(6) u	28.2(2)

Annotation Code: g

In its 1961 Report (0.1a) the Commission recommended $\underline{A}_r$(Dy) = 162.50 based on the mass-spectrometric determination by Inghram et al. (66.1) and nuclidic masses by Bhanot et al. (0.2b). In 1969 the Commission (0.1c) assessed $\underline{U}_r$(Dy) as 0.03. In the absence of new calibrated spectrometric measurements as well as due to lack of a study of natural variability the Commission finds no compelling reason to make any change in these values. Several confirmatory determinations of isotopic composition are now available as for instance those published by Holliger and Devillers (66.2).

References

(66.1) Inghram, M. G., Hayden, R. J., and Hess, D. C., Jr., Phys. Rev., 75, 693 (1949).

(66.2) Holliger, P., and Devillers, C., Earth Planet. Sci. Lett., 52, 76 (1981).

$_{67}$Ho HOLMIUM

$\underline{A}_r$(Ho) = 164.9304(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{165}Ho	164.930 332(6) u	100.00

The Commission Report in 1961 (0.1a) proposed $\underline{A}_r$(Ho) = 164.930 for the atomic weight of holmium. This number was based on nuclidic-mass data by Bhanot et al. (0.2b). The Commission also quoted experimental evidence from the literature which indicated that the upper limits for the hypothetical existence of other stable isotopes of holmium were low. On re-examination of the literature we estimate that the experimentally determined uncertainty in $\underline{A}_r$(Ho) so introduced is $+2.2 \times 10^{-3}$ or -6.4×10^{-3}. However, other arguments lead to far lower estimates of that uncertainty (see Part I, Section 7).

Based on an assessment of the data, the Commission in 1969 (0.1c) added one figure of decimal. The $\underline{A}_r$(Ho) value thus became 164.9303(1). However, the revision of nuclidic-mass data by Wapstra and Gove (0.2d) led the Commission in 1971 (0.1d) to revise $\underline{A}_r$(Ho) to 164.9304. That value has remained unchanged since then. However, Wapstra and Bos (0.2e) in the most recently published compilation give the nuclidic mass of ^{165}Ho as quoted above which favors return to the 1969 value of $\underline{A}_r$(Ho). Unpublished information had thrown some doubt upon the new value. The Commission in 1977 (0.1g) therefore, decided to await confirmation of the new value before again changing $\underline{A}_r$(Ho). The most recent unpublished information does not sustain the above-mentioned doubt. Nevertheless, the Commission in 1983 (0.1j) decided to postpone the minor change in $\underline{A}_r$(Ho) pending the expected publication of an up-dated nuclidic-mass table and a Commission policy decision on rounding-off fluctuations in "best" values for the mononuclidic elements while avoiding frequent changes of virtually no significance in the Table of Standard Atomic Weights.

$_{68}$Er ERBIUM

$A_r(\mathrm{Er}) = 167.26(3)$

Nuclide	Nuclidic Mass	Atom Percent in Element
^{162}Er	161.928 787(6) u	0.14(1)
^{164}Er	163.929 211(6) u	1.61(1)
^{166}Er	165.930 305(6) u	33.6(2)
^{167}Er	166.932 061(6) u	22.95(13)
^{168}Er	167.932 383(6) u	26.8(2)
^{170}Er	169.935 476(6) u	14.9(1)

In its 1961 Report (0.1a) the Commission recommended $A_r(\mathrm{Er}) = 167.26$ based on the isotope-abundance measurements by Hayden et al. (68.1) and Leland (68.2), and the nuclidic masses by Bhanot et al. (0.2b). In 1969 the Commission (0.1c) assessed $U_r(\mathrm{Er})$ at 0.03.

Despite a new confirmatory isotopic-composition measurement by Holliger and Devillers (68.3) the Commission does not see a sufficiently convincing reason to make a change in the precision or value of $A_r(\mathrm{Er})$.

References

(68.1) Hayden, R. J., Hess, D. C., Jr., and Inghram, M. G., Phys. Rev., 77, 299 (1950).

(68.2) Leland, W. T., Phys. Rev., 76, 634 (1950).

(68.3) Holliger, P., and Devillers, C., Earth Planet. Sci. Lett., 52, 76 (1981).

$_{69}$Tm THULIUM

$A_r(\mathrm{Tm}) = 168.9342(1)$

Nuclide	Nuclidic Mass	Atom Percent in Element
^{169}Tm	168.934 225(6) u	100.00

The Commission Report in 1961 (0.1a) proposed for the atomic weight of thulium $A_r(\mathrm{Tm}) = 168.934$ based on nuclidic-mass data by Bhanot et al. (0.2b).

A search by Collins et al. (69.1) for minor stable or quasi-stable isotopes of thulium has found none and placed the upper limit of their existence so low that they could only affect the atomic weight in the ninth significant figure.

When it assessed the reliability of the data, the Commission in 1969 (0.1c) added one decimal figure. The $A_r(\mathrm{Tm})$ value thus became 168.9342(1) and has remained unchanged since then. It is consistent with Wapstra and Bos (0.2e) who in the most recently published compilation give the nuclidic mass of ^{169}Tm as quoted above.

Reference

(69.1) Collins, T. L., Rourke, F. M., and White, F. A., Phys. Rev., 105, 196 (1957).

$_{70}$Yb YTTERBIUM

$A_r(\mathrm{Yb}) = 173.04(3)$

Nuclide	Nuclidic Mass	Atom Percent in Element
^{168}Yb	167.933 908(7) u	0.13(1)
^{170}Yb	169.934 774(6) u	3.05(5)
^{171}Yb	170.936 338(6) u	14.3(2)
^{172}Yb	171.936 393(6) u	21.9(3)
^{173}Yb	172.938 222(6) u	16.12(18)

^{174}Yb	173.938 873(6) u	31.8(4)
^{176}Yb	175.942 576(6) u	12.7(1)

The atomic weight of ytterbium has been taken as 173.04 since 1934. This value was reconfirmed in the 1961 Commission Report (0.1a). However, from that time onwards, A_r(Yb) was no longer based on chemical but on mass-spectrometric data by Hayden et al. (70.1) and by Leland (70.2). The uncertainty of U_r(Yb) = ±0.03 was assigned in 1969 (0.1c) and has also remained unchanged since.

A number of mass-spectrometric determinations of the isotopic composition of ytterbium are referenced below (70.1) to (70.5). McCulloch et al. (70.4) showed that the isotopic composition of eight meteoritic and four terrestrial samples were identical within experimental errors to a laboratory standard.

References

(70.1) Hayden, R. J., Hess, D. C., and Inghram, M. G., Phys. Rev., 75, 322 (1949).
(70.2) Leland, W. T., Phys. Rev., 77, 634 (1950).
(70.3) Collins, T. L., Rourke, F. M., and White, F. A., Phys. Rev., 105, 196 (1957).
(70.4) McCulloch, M. T., Rosman, K. J. R., and De Laeter, J. R., Geochim. Cosmochim. Acta., 41, 1703 (1977).
(70.5) Hollinger, P. and Devillers, C., Earth Planet. Sci. Lett., 52, 76 (1981).

$_{71}$Lu LUTETIUM

A_r(Lu) = 174.967(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{175}Lu	174.940 785(6) u	97.41(2)
^{176}Lu	175.942 694(6) u	2.59(2)

Annotation Code: g

In its 1961 Report (0.1a) the Commission recommended A_r(Lu) = 174.97 based on the mass-spectrometric determinations by Hayden et al. (71.1) and Collins et al. (71.2). The Commission noted the close agreement with the chemical determination of Hönigschmid and Wittner (71.3) after recalculation on the A_r(^{12}C) = 12 scale. In 1969 the Commission assessed the uncertainty U_r(Lu) as 0.01 (0.1c).

Then, in 1977 (0.1g), the Commission took note of a new isotope-abundance determination by McCulloch et al. (71.4) which was deemed more accurate, but, like its predecessors, it was not calibrated. Nevertheless, as a result the more precise A_r(Lu) = 174.967(3) was recommended. Moreover, in 1981 the Commission (0.1i) was able to reduce the uncertainty from U_r(Lu) = 0.003 to 0.001. This change was justified because another abundance determination by Holliger and Devillers (71.5) agreed very well with earlier measurements. Besides, it was pointed out that the predominance of one isotope coupled with the small mass difference between the isotopes reduces the effect of a small unrecognized mass-discrimination effect in the determination of the isotopic composition. McCullough et al. (71.4) had found no significant variability for lutetium from different sources.

The minor isotope, ^{176}Lu, is radioactive with a half-life of 3.57(14) x 10^{10}a (71.6). In consequence A_r(Lu) will change comparably with the current uncertainty in only about 500 million years. At Oklo (see Part I, Section 6) the ^{176}Lu/^{175}Lu ratio has been used (71.5) as a sensitive measure of the average equilibrium temperature of the neutrons at the time of the nuclear reactions. The occurrence at this site of almost pure (99.7 atom percent) isotope ^{175}Lu (71.5) justifies the annotation "g".

References

(71.1) Hayden, R. J., Hess, D. C., Jr., and Inghram, M. G., Phys. Rev., 77, 299 (1950).
(71.2) Collins, T. L., Rourke, F. M., and White, F. A., Phys. Rev., 105, 196 (1957).
(71.3) Hönigschmid, O., and Wittner, F., Z. Anorg. Allg. Chem., 240, 284 (1939).
(71.4) McCulloch, M. T., De Laeter, J. R., and Rosman, K. J. R., Earth and Planet. Sci. Lett., 28, 308 (1976).

(71.5) Holliger, P., and Devillers, C., Earth Planet. Sci. Lett., 52, 76 (1981).

(71.6) Patchett, P. J., Geochim. Cosmochim. Acta, 47, 81 (1983).

$_{72}$Hf HAFNIUM

$A_r(\mathrm{Hf}) = 178.49(3)$

Nuclide	Nuclidic Mass	Atom Percent in Element
^{174}Hf	173.940 065(8) u	0.162(2)
^{176}Hf	175.941 420(6) u	5.206(4)
^{177}Hf	176.943 233(6) u	18.606(3)
^{178}Hf	177.943 710(6) u	27.297(3)
^{179}Hf	178.945 827(6) u	13.629(5)
^{180}Hf	179.946 561(6) u	35.100(6)

In its 1961 Report (0.1a) the Commission recommended $A_r(\mathrm{Hf}) = 178.49$ based on abundance measurements by Hibbs (72.1), Reynolds (72.2), White et al. (72.3), and nuclidic masses by Bhanot et al. (0.2b). In 1969 (0.1c) the Commission assessed $U_r(\mathrm{Hf}) = 0.03$.

In the absence of new calibrated mass-spectrometric measurements as well as of a study of possible natural variations, the Commission did not since that time see sufficiently convincing reasons for making any other change.

The minor isotope, ^{174}Hf is an α-emitter with the very long half-life of $2.0(4) \times 10^{15}$a (0.5). It does not affect A_r(Hf) even in a geologic time frame. However ^{176}Hf is the principal product of $^{176}_{71}$Lu decay so that small but detectable variations in ^{176}Hf abundance with geologic age and lutetium association do occur. They are overshadowed by larger uncertainties in the absolute value for A_r(Hf), which, however, does not preclude their use in geochronology (0.9).

References

(72.1) Hibbs, R. F., U.S.A.E.C. Rep. AECU-556 (1949).

(72.2) Reynolds, J. H., Phys. Rev., 90, 1047 (1953).

(72.3) White, F. A., Collins, T. L., Jr., and Rourke, F. M., Phys. Rev., 101, 1786 (1956).

$_{73}$Ta TANTALUM

$A_r(\mathrm{Ta}) = 180.9479(1)$

Nuclide	Nuclidic Mass	Atom Percent in Element
^{180}Ta	179.947 489(14) u	0.012(2)
^{181}Ta	180.948 014(7) u	99.988(2)

In its 1961 Report (0.1a) the Commission recommended $A_r(\mathrm{Ta}) = 180.948$, based upon the isotope-abundance measurements by White et al. (73.1) and Palmer (73.2) and the nuclidic masses of Bhanot et al. (0.2b). In 1969 the Commission (0.1c) increased the precision of A_r(Ta) to 180.9479 recognizing the element as one whose atomic weight could be stated very precisely because of a predominant isotope. At that time U_r(Ta) was assessed at 0.03, but lowered to 0.01 in 1979 (0.1h). Mass discrimination in the abundance measurements could have only a very minor effect when applied to an isotope of very low abundance and minimum mass difference. Possible natural variability, which remains to be investigated, and the nuclidic masses introduce the other factors contributing to the uncertainty.

The minor isotope, ^{180}Ta, is radioactive with a very long half-life of more than about 10^{13}a (0.6). It is the last quasi-stable isotope to be discovered (73.1). Its interest is heightened by the discovery (73.3) that it is not the ground-state isomer as discussed in Part I, Section 7.

References

(73.1) White, F. A., Collins, T. L., Jr., and Rourke, F. M., Phys. Rev., 97, 566 (1955) and 101, 1786 (1956).

(73.2) Palmer, G. H., J. Nucl. Energy, 7, 1 (1958).

(73.3) Sharma, K. S., Ellis, R. J., Derenchuk, V. P., Barber, R. C., and Duckworth, H. E., Phys. Lett., 91B2, 211 (1980).

$_{74}$W WOLFRAM (TUNGSTEN)

A_r(W) = 183.85(3)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{180}W	179.946 727(8) u	0.13(3)
^{182}W	181.948 225(7) u	26.3(2)
^{183}W	182.950 245(7) u	14.3(1)
^{184}W	183.950 953(7) u	30.67(15)
^{186}W	185.954 377(7) u	28.6(2)

In 1961 the Commission (0.1a) recommended the value of A_r(W) = 183.85 for the atomic weight of tungsten. This value was based on the average of the isotopic-abundance measurements by Williams and Yuster (74.1), Mattauch and Scheld (74.2), White and Cameron (74.3), and Hibbs (74.4) using nuclidic masses reported by Bhanot et al. (0.2b).

In 1969 after evaluating the uncertainties associated with the measurements cited above, the Commission (0.1c) assigned a value of U_r(W) = 0.03. In the absence of calibrated mass-spectrometric measurements the Commission continues to be concerned with a discrepancy in the atomic-weight value with earlier chemical determinations which yield higher values around A_r(W) = 183.90 as for instance in Hönigschmid and Menn (74.5).

References

(74.1) Williams, D., and Yuster, P., Phys. Rev., 69, 556 (1946).

(74.2) Mattauch, J., and Scheld, H., Z. Naturforsch., 3a, 105 (1948).

(74.3) White, J. R., and Cameron, A. E., Phys. Rev., 74, 991 (1948).

(74.4) Hibbs, R. F., U.S.A.E.C. Rep. AECU-556 (1949).

(74.5) Hönigschmid, O., and Menn, W., Z. Anorg. Allg. Chem., 229, 49 (1936).

$_{75}$Re RHENIUM

A_r(Re) = 186.207(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{185}Re	184.952 977(7) u	37.40(2)
^{187}Re	186.955 765(7) u	62.60(2)

In its 1961 Report (0.1a) the Commission recommended for the atomic weight of rhenium A_r(Re) = 186.2 based on the abundance measurements by White and Cameron (75.1) and the nuclidic-mass data reported by Bhanot et al. (0.2b).

The Commission in 1975 (0.1f) recommended as new value A_r(Re) = 186.207(1) based on the superior calibrated measurements by Gramlich et al. (75.2). These authors detected no isotopic-composition variations in sources of natural rhenium.

^{187}Re is radioactive, decaying to $^{187}_{76}$Os with a half-life of 4.3(5) x 10^{10}a (0.6). Thus it will take a billion years for the abundance of that isotope to decline by appreciably more than the uncertainty in its present value. However, the anomalies caused in the isotopic composition of some osmium occurrences are of geophysical interest as described in the following section on osmium.

References

(75.1) White, J. R., and Cameron, A. E., Phys. Rev., 74, 991 (1948).

(75.2) Gramlich, J. W., Murphy, T. J., Garner, E. L., and Shields, W. R., J. Res. Natl. Bur. Stand. (U.S.), 77A, 691 (1973).

$_{76}$Os OSMIUM

A_r(Os) = 190.2(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{184}Os	183.952 514(7) u	0.02(1)
^{186}Os	185.953 852(7) u	1.58(10)
^{187}Os	186.955 762(7) u	1.6(1)
^{188}Os	187.955 850(7) u	13.3(2)
^{189}Os	188.958 156(7) u	16.1(3)
^{190}Os	189.958 455(7) u	26.4(4)
^{192}Os	191.961 487(8) u	41.0(3)

Annotation Code: g

In 1961, the Commission (0.1a) recommended A_r(Os) = 190.2. This value was based on the isotopic-abundance measurement of Nier (76.1) using nuclidic masses reported by Bhanot et al. (0.2b).

In 1969, after re-evaluating the uncertainties associated with the work cited above, the Commission (0.1c) recommended U_r(Os) = 0.1. This is the highest absolute uncertainty in the Table of Standard Atomic Weights, equaled by U_r(Pb) for which element, however, this results from natural variability not applicable to osmium. The determination of osmium isotopic abundances by high-resolution CO_2-laser saturation spectroscopy (76.2) is most welcome, but does not yet appear to have been applied to a point at which a new value for A_r(Os) can be derived.

One of the minor isotopes, ^{186}Os is radioactive with a very long half-life of 2.0(11) x 10^{15}a (0.6). It suffers a decay into stable $^{182}_{74}$W. It does not affect A_r(Os) even over geologic time. ^{187}Os is the stable daughter nuclide of β^-active $^{187}_{75}$Re. As a result, osmium occurs with anomalous atomic weight as a trace element in rhenium-bearing rocks. The "g" annotation is thereby justified.

The isotope ratio ^{187}Os/^{186}Os is more sensitive to enrichment from ^{187}Re decay than the atomic weight. Very high values of that ratio are typical of marine manganese nodules. Less high values were found in the Cretaceous/Tertiary boundary (76.3) where they seem to confirm the theory of asteroid or comet impact to explain the mass extinction of fauna on earth. The same ^{187}Os/^{186}Os ratio is used in geology for dating deposits (e.g. molybdenites) high in rhenium to osmium ratio (0.9).

References

(76.1) Nier, A. O., Phys. Rev., 52, 885 (1937).

(76.2) Schieder, R., Sorgalla, K. H., and Herr, W., Radiochim. Acta, 28, 109 (1981).

(76.3) Luck, J. M., and Turekian, K. K., Science, 222, 613 (1983).

$_{77}$Ir IRIDIUM

A_r(Ir) = 192.22(3)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{191}Ir	190.960 603(7) u	37.3(5)
^{193}Ir	192.962 942(7) u	62.7(5)

In its 1961 Report (0.1a) the Commission recommended for the atomic weight of iridium

$\underline{A}_r$(Ir) = 192.2 which was based on two mass-spectrometric determinations by Sampson and Bleakney (77.1) and Baldock (77.2), and on nuclidic masses by Bhanot et al. (0.2b). In 1969 the Commission (0.1c) recommended the present value of $\underline{A}_r$(Ir) = 192.22(3) based on a closer uncertainty analysis of the above-mentioned mass-spectrometric determinations.

In the absence of calibrated mass-spectrometric measurements and lacking a study of possible natural variations, the Commission does not see compelling reasons for making any other change.

References

(77.1) Sampson, M. P., and Bleakney, W., Phys. Rev., 50, 732 (1936).

(77.2) Baldock, R., Oak Ridge Natl. Rep. ORNL 1719 (1954).

$_{78}$Pt PLATINUM

$\underline{A}_r$(Pt) = 195.08(3)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{190}Pt	189.959 937(23) u	0.01(1)
^{192}Pt	191.961 049(7) u	0.79(5)
^{194}Pt	193.962 679(7) u	32.9(5)
^{195}Pt	194.964 785(6) u	33.8(5)
^{196}Pt	195.964 947(6) u	25.3(5)
^{198}Pt	197.967 879(21) u	7.2(2)

In its 1961 Report the Commission (0.1a) confirmed the previously recommended atomic weight of platinum $\underline{A}_r$(Pt) = 195.09 based on the determinations of the isotopic composition of this element using mass spectrometry by Inghram et al. (78.1) and White et al. (78.2) with nuclidic masses by Bhanot et al. (0.2b). The uncertainty of $\underline{U}_r$(Pt) = 0.03 was assigned by the Commission in 1969 (0.1c). In 1979 the Commission (0.1h) corrected a small computational error by which $\underline{A}_r$(Pt) was amended to 195.08(3), the current value.

The minor isotope, ^{190}Pt, is radioactive with a very long half-life of 6.9(6) x 10^{11}a (0.6). It does not affect the atomic weight of platinum even over geologic time.

References

(78.1) Inghram, M. G., Hess, D. C., Jr., and Hayden, R. J., Argonne Natl. Lab. Rep. ANL-4012 (1947); cited in Nucl. Data Tables (1959).

(78.2) White, F. A., Collins, T. L., and Rourke, F. M., Phys. Rev., 101, 1786 (1956).

$_{79}$Au GOLD

$\underline{A}_r$(Au) = 196.9665(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{197}Au	196.966 560(6) u	100.00

The Commission Report in 1961 (0.1a) proposed $\underline{A}_r$(Au) = 196.967 from nuclidic-mass data by Bhanot et al. (0.2b). On examination of the literature in 1974 we estimate that the uncertainty in $\underline{A}_r$(Au) introduced by the hypothetical presence of a long-lived, but yet undiscovered isotope is at most +2.9 x 10^{-5} or -1.2 x 10^{-5}.

When it assessed the reliability of the data, the Commission in 1969 (0.1c) decided to add one figure of decimal. The $\underline{A}_r$(Au) value thus became equal to 196.9665(1). However, Wapstra and Bos (0.2e) in the most recent published compilation assess the nuclidic mass of ^{197}Au as quoted above. This value suggests a rounding-off change in the seventh significant figure for $\underline{A}_r$(Au). By subsequent unpublished analysis, the previous value is now believed to be better. Therefore, the prior condition for making a change, namely a cogent reason for believing a new published value is reliable and superior, does not exist. Wapstra himself strongly endorses that conclusion. In a private communication to Commission members he explains how old measurements of mercury isotopes had been used with unjustified confidence in the least-squares adjustment for all masses of heavier nuclides (0.2e). They had introduced a systematic error of about 30 μu. This happens to make a noticeable difference in standard atomic-weight values only in the fourth (last) decimal rounding for gold. It is fortunate therefore that the Commission had disregarded the change which is almost certain to be reversed at the next revision of the nuclidic masses.

$_{80}$Hg MERCURY

$\underline{A}_r(\text{Hg}) = 200.59(3)$

Nuclide	Nuclidic Mass	Atom Percent in Element
^{196}Hg	195.965 812(10) u	0.14(10)
^{198}Hg	197.966 760(6) u	10.02(7)
^{199}Hg	198.968 269(6) u	16.84(11)
^{200}Hg	199.968 316(6) u	23.13(11)
^{201}Hg	200.970 293(6) u	13.22(11)
^{202}Hg	201.970 632(6) u	29.80(14)
^{204}Hg	203.973 481(7) u	6.85(5)

The Commission Report in 1961 (0.1a) proposed $\underline{A}_r(\text{Hg}) = 200.59$ based on the chemical determination by Hönigschmid et al. (80.1), to which in 1969 the Commission assigned an uncertainty $\underline{U}_r(\text{Hg}) = 0.03$ (0.1c).

Recalculation of the chemical ratios (80.1) based on current values of the other atomic weights involved (0.1j) yields the following results from the listed comparisons:

$HgCl_2/2Ag = 1.258\ 47$	$\underline{A}_r(\text{Hg}) = 200.592$	(80.1)
$HgBr_2/2Ag = 1.670\ 56$	$\underline{A}_r(\text{Hg}) = 200.593$	(80.1)

Published measurements of the isotopic composition of mercury (80.2) to (80.5) with current nuclidic masses agree remarkably despite the large number of isotopes. Resulting $\underline{A}_r(\text{Hg})$ values range only from 200.58 to 200.60. No significant variations of terrestrial sources have been reported, but Haeffner (80.6) observes isotopic separation in a mercury column by an electric current. The lighter isotopes become enriched at the anode as for gallium (see gallium section). The composition reported by Dibeler (80.5) is subject to a small unresolved uncertainty since it fails to sum to 100 percent. Wapstra in a private communication expresses his belief that all masses of mercury isotopes have published values - as quoted above - which are high by about 30 μu that is between three and five times the previously indicated uncertainty (0.2e). This change would still not affect the $\underline{A}_r(\text{Hg})$ value at the currently stated precision. The Commission has so far maintained $\underline{U}_r(\text{Hg}) = 0.03$ in recognition of the possibility of illusory agreement between the experimental $\underline{A}_r(\text{Hg})$ determinations.

References

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(80.2) Inghram, M. G., Hess, D. C. Jr., and Hayden, R. J., Phys. Rev., 71, 561 (1947).

(80.3) Hibbs, R. F., U.S.A.E.C. Rep. AECU-556 (1949).

(80.4) Nier, A. O., Phys. Rev., 79, 450 (1950).

(80.5) Dibeler, V. H., Anal. Chem., 27, 1958 (1955).

(80.6) Haeffner, E., Nature (London), 172, 4382, 775 (1953).

$_{81}$Tl THALLIUM

$\underline{A}_r(\text{Tl}) = 204.383(1)$

Nuclide	Nuclidic Mass	Atom Percent in Element
^{203}Tl	202.972 336(6) u	29.524(9)
^{205}Tl	204.974 410(5) u	70.476(9)

The Commission in 1961 (0.1a) recommended $\underline{A}_r$(Tl) = 204.37 for the atomic weight of thallium based on the chemical determinations of Hönigschmid et al. (81.0) and Hönigschmid and Striebel (81.2). After a reevaluation of the probable uncertainties in the previous work, the Commission in 1969 (0.1c) recommended $\underline{U}_r$(Tl) = 0.03.

In 1979 the Commission (0.1h) considered the calibrated measurement of Dunstan et al. (81.3) and recommended $\underline{A}_r$(Tl) = 204.383(1). These authors also reported following a comprehensive mineral survey of terrestrial material that no natural variations were found in the thallium isotopic ratio.

References

(81.1) Hönigschmid, O., Birckenbach, L., and Kothe, E., Sitzungsber. Bayer. Akad. Wiss. Jahrb., p. 179 (1922).

(81.2) Hönigschmid, O., and Striebel, H., Z. Anorg. Allg. Chem., 194, 293 (1930).

(81.3) Dunstan, L. P., Gramlich, J. W., Barnes, I. L., and Purdy, W. C., J. Res. Natl. Bur. Stand. (U.S.), 85, 1, (1980).

$_{82}$Pb LEAD

$\underline{A}_r$(Pb) = 207.2(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{204}Pb	203.973 037(6) u	1.4(1)
^{206}Pb	205.974 455(5) u	24.1(1)
^{207}Pb	206.975 885(5) u	22.1(1)
^{208}Pb	207.976 641(5) u	52.4(1)

Annotation Codes: g and r

The atomic weight of lead is quite variable in nature since the three heaviest isotopes are the stable end products of the radioactive decay of uranium ($^{238}_{92}$U to ^{206}Pb; ^{235}U to ^{207}Pb) and thorium (to ^{208}Pb). Recognizing this, the Commission in 1961 (0.1a) recommended the value of 207.19 based on the chemical measurements of Baxter and Alter (82.1), Baxter et al. (82.2) and Hönigschmid et al. (82.3) and stated that "...it quite well represented the lead most likely to be encountered in normal laboratory work". As discussed in Part I, later Commission policy aims for the implied range of the tabulated (standard) atomic weights to cover all "normal" sources of an element.

In the 1969 Report (0.1c) the Commission considered the tabulation by Brown (82.4) and the work of Catanzaro et al. (82.5) showing natural variations in the atomic weight of lead ranging from 207.184 to 207.293 and recommended the value of $\underline{A}_r$(Pb) = 207.2(1). These circumstances justify the annotation "r". In addition the annotation "g" warns of the existence of abnormal sources outside the implied range.

The variability of $\underline{A}_r$(Pb) had been incontrovertibly shown by Richards (0.3a) when the chemical atomic weights were thought to be constants of nature, before the discovery of isotopes. The isotopic composition of common lead must now be regarded as a variable mixture of primeval and radiogenic components.

When an atomic-weight value of a specific sample is required to an accuracy better than the precision of the tabulated standard $\underline{A}_r$(E) value, an abundance measurement must be made. Such measurements are facilitated by comparison with a standard reference material of known abundance, such as is available from the work of Catanzaro et al. (82.5).

The decay of uranium and thorium to lead permits geological-age determinations to be made of minerals containing the heavy radioactive elements (0.9).

References

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(82.2) Baxter, G. P., Faull, J. H., and Tuemmler, F. D., J. Am. Chem. Soc., 59, 702 (1937).

(82.3) Hönigschmid, O., Sachtleben, R., and Baudrexler, H., Z. Anorg. Allg. Chem., 214, 104 (1933).

(82.4) Brown, J. S., Econ. Geol., 57, 673 (1962).

(82.5) Catanzaro, E. J., Murphy, T. J., Shields, W. R., and Garner, E. L., J. Res. Natl. Bur. Stand. (U.S.), 72A, 261 (1968).

$_{83}$Bi BISMUTH

$\underline{A}_r$(Bi) = 208.9804(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{209}Bi	208.980 388(5) u	100.00

The Commission Report in 1961 (0.1a) proposed $\underline{A}_r$(Bi) = 208.980 based on nuclidic-mass data by Everling et al. (0.2a). Leipziger (83.1) found the upper limits for the existence of stable or quasi-stable nuclides of bismuth other than ^{209}Bi to be so low that they could cause at most a change in the eighth significant figure of $\underline{A}_r$(Bi).

Assessment of the reliability of data led the Commission in 1969 (0.1c) to add one significant figure. The $\underline{A}_r$(Bi) value thus became equal to 208.9806(1), but, on the basis of Wapstra and Gove's revision of nuclidic-mass data (0.2d), was adjusted in 1971 (0.1d) to 208.9804(1). This change in IUPAC atomic weight, though small and seemingly insignificant to most chemists, is twice the previously estimated uncertainty and may dispel any impression that the Commission tends to be excessively conservative in the dissemination of reliable atomic weights. The new 1971 value of $\underline{A}_r$(Bi) has remained unchanged since then. It is consistent with Wapstra and Bos (0.2e) who in the most recently published compilation give the nuclidic mass of ^{209}Bi as quoted above.

Reference

(83.1) Leipziger, F. D., Appl. Spectros., 17, 158 (1963).

$_{90}$Th THORIUM

$\underline{A}_r$(Th) = 232.0381(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{232}Th	232.038 053 805(2515) u	100.00

Annotation Code: g

^{232}Th is an α-emitter with a half-life of 1.40(1) x 10^{10}a (0.6), decaying through a branched series to $^{208}_{82}$Pb without very long-lived intermediate nuclides. However, ^{230}Th is such a nuclide in the $^{238}_{92}$U decay series. It has a half-life of 7.54(2) x 10^{4}a (0.6), and is formed by a decay of ^{234}U with which it is in equilibrium. It has been named ionium, as if it were a distinct element, but that name is not recognized by IUPAC. ^{230}Th is not generally found in significant amounts in normal crystal sources of thorium, and for that reason thorium has been classified as a mononuclidic element. In this Review, however, this classification is based on the half-lives of the two thorium nuclides (compare Part I, Section 7). ^{230}Th is readily detected in sea water in significant but variable abundance relative to ^{232}Th.

In virtue of its long half-life, about 80 percent of the ^{232}Th present when the earth was formed survives to this time. It is reasonably abundant in the earth's crust and so we can recognize normal terrestrial occurrences with an atomic weight numerically equal to the nuclidic mass of ^{232}Th (0.1j). The Commission in 1969 (0.1c) increased the precision of $\underline{A}_r$(Th) from 232.038 to 232.0381 with an indicated uncertainty $\underline{U}_r$(Th) = 0.0001. These values have remained unchanged since.

$_{92}$U URANIUM

A_r(U) = 238.0289(1)

Nuclide	Nuclidic Mass	Atom Percent in Element
^{234}U	234.040 947 400(2556) u	0.0055(5)
^{235}U	235.043 925 247(2552) u	0.7200(12)
^{238}U	238.050 785 782(2361) u	99.2745(15)

Annotation Codes: g and m

In its 1961 Report the Commission (0.1a) recommended A_r(U) = 238.03(1) for the atomic weight of uranium based on mass-spectrometric determinations by White et al. (92.1) and those quoted by Greene et al. (92.2), with nuclidic masses by Everling et al. (0.2a). This literature included a calibrated measurement of the natural isotopic composition. The uncertainty included an allowance for up to 0.1 atom percent variation in the ^{235}U abundance, interpreted as 0.7205 ± 0.1000 atom percent. The actual variability in normal sources is found to be much smaller (see below), close to 0.1 atom percent of the abundance value, that is 0.7205 ± 0.0007 atom percent.

In 1969 the Commission (0.1c) recommended an uncertainty U_r(U) = 0.001 based on the same determinations and a more careful analysis of the variability. In 1979 (0.1h) the Commission took note of later studies of the variations of the ^{235}U abundance in normal sources by Smith and Jackson (92.3) and Cowan and Adler (92.4). One more significant digit in the standard atomic weight was now fully justified, thus leading to the present value of A_r(U) = 238.0289(1). That value applies to uranium as found in normal terrestrial sources, except as discovered in one locality in Africa (Gabon at Oklo) as described in Part I, Section 6. Much uranium is used in the nuclear-fuel cycle either enriched or depleted in ^{235}U. Atomic weights of such materials must be calculated from the experimentally determined isotopic composition. Such measurements are facilitated by comparison with a reference material of known abundance.

All uranium isotopes are α-emitters. Half-lives are: for ^{234}U: 2.454(6) x 10^5a; for ^{235}U: 7.037(11) x 10^8a; and for ^{238}U: 4.468(5) x 10^9a (0.6). The latter two are primordial with the ^{235}U abundance declining very gradually in geologic time because of its faster decay. ^{234}U itself a daughter of ^{238}U is in equilibrium established by the ratio of the half-lives. ^{235}U decays by a branched series ending with $^{207}_{82}$Pb; ^{238}U (and ^{234}U) by a similar series ending in ^{206}Pb.

References

(92.1) White, F. A., Collins, T. L., and Rourke, F. M., Phys. Rev., 90, 447 (1956).

(92.2) Greene, R. E., Kienberger, C. A., and Meservey, A. E., Nucl. Data Tables (1959).

(92.3) Smith, R. F., and Jackson, J. M., U.S.A.E.C. Rep. KY-581 (1969).

(92.4) Cowan, G. A., and Adler, H. H., Geochim. Cosmochim. Acta, 40, 1487 (1976).