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The Natural Abundance of Isotopes of Stable Elements[†]

J. R. WHITE* AND A. E. CAMERON**

Clinton Engineer Works, Tennessee Eastman Corporation, Oak Ridge, Tennessee

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The natural isotopic abundances of the following elements have been determined by mass spectrometric techniques:

Lithium	Copper	Tin
Magnesium	Selenium	Antimony
Silicon	Bromine	Tellurium
Potassium	Strontium	Tantalum
Calcium	Zirconium	Tungsten
Chromium	Silver	Rhenium
Iron	Cadmium	Thallium
Nickel	Indium	Lead

Different masses were focused by variation of the magnetic flux in Nier-type, 60° mass spectrometers. Ion currents were measured potentiometrically. Each measurement represents at least 15 determinations. Many measurements are averages of series with different spectrometers and ion sources. From available packing fraction data and these abundances the chemical atomic weights have been computed.

INTRODUCTION

THE determinations of the natural isotopic abundance of the 24 elements here described were made in connection with the program of separation of these isotopes in the electromagnetic process pilot plant operated by the Clinton Engineer Works, Tennessee Eastman Corporation. The measurements were made to check the values in the literature and to serve as pathfinding experiments for measurements of separated isotopes. In some cases these are repetitions of previous determinations, but were usually made by somewhat different techniques. In several cases the only previous data were those

obtained by mass spectrographic determinations involving photometry of a photographic plate.

EXPERIMENTAL

The measurements were made with two 60° mass spectrometers built in the Clinton Engineer Works, Tennessee Eastman Corporation laboratory specifically for this work. These instruments were of the type developed by Professor A. O. C. Nier of the University of Minnesota and his co-workers. Each instrument was the equivalent of two, since one set of electronic controls was associated with two vacuum and magnet assemblies. The instruments embodied improvements resulting from three years of intensive use and development of equipment of this type.

The hard solder used in assembling the tubes and in attaching the envelopes contained no cadmium, zinc, or other volatile metals, so that

[†] This work was done under contract W-7401-Eng. 23.

* Present address: Socony-Vacuum Oil Company, Inc., Research and Development Department, Paulsboro, New Jersey.

** Present address: Distillation Products, Inc., 755 Ridge Road West, Rochester, New York.

background was not introduced by these elements. Three-stage, self-fractionating diffusion pumps with Octoil-S produced an ultimate vacuum of approximately 10^{-7} millimeters of mercury. Liquid nitrogen traps were used to prevent hydrocarbon background arising from traces of pump oil. The ion sources were variously fabricated from nichrome V, platinum-iridium alloy, copper, and tantalum. Of these materials the platinum-iridium alloy appeared to be least attacked by corrosive gases. Tantalum introduced a tantalum and tantalum-halide spectrum which was troublesome in some measurements. The sample vapor was ionized by electrons of between 30 and 75 volts energy, and the ions so formed were focused and accelerated through a potential drop of 1900 volts. Ions were also produced by thermionic evaporation from a tungsten filament. Mass positions were identified by reading the output voltage of a rotating coil fluxmeter driven by a synchronous motor. The coil was rotated in the magnet gap and the output obtained through the two-segment commutator was filtered and read with a slide-wire potentiometer.

The selection of the ion beams was made exclusively by variation of the magnetic flux to avoid disturbing the voltages applied to the ion source. The ion currents from the collector plate behind the receiver slit were measured by introducing voltage from a calibrated precision potentiometer between ground and the 4×10^{10} ohm grid resistor in the input of the FP-54 electrometer. The electrometer and galvanometer were used as a null indicator and no reliance upon linearity of response of other than the grid resistor was then necessary. The galvanometer zero was observed by applying deflecting voltage to a source element so as to prevent the ion beam from passing through the tube. Residual galvanometer deflections were converted to potentiometer readings by interpolation factors determined experimentally.

The element or compound used for measurements of this kind must be volatile below 1500°C . Small samples must be readily prepared, free from other elements which are isobaric with the substance to be determined, or which give rise to complex or multiply-charged ions isobaric with the ions to be measured. The compound should not be so hygroscopic that it requires handling

totally in a desiccated atmosphere. It must give an abundant ion in a mass region in which there is no background interference in the tube. The material should preferably sublime since evaporation from the liquid phase is more likely to lead to distillation fractionation because of the difference in weight of the various isotopes. Fluorides are particularly useful for measurements of this type since the step-wise ionization which occurs permits readings to be made at a number of different mass positions. Most fluorides are not, however, sufficiently volatile.

Samples which were volatile at room temperature, such as tungsten hexafluoride, were admitted to the ionizing region of the tube through a controllable capillary leak and a glass or metal sample line. Materials like selenium metal were handled with an external heating furnace and a large bore heated sample line passing into the tube. For other materials it was necessary to provide a small furnace which could be mounted above the ion source so that the substance could be distilled into the ionization region. These furnaces were supported from the ground glass cap on the source envelope and were isolated from the ionization region by a platinum screen to prevent electrostatic disturbance of the electron beam. Furnaces constructed of Vycor and tantalum and heated with platinum or tungsten elements were necessary for many of the compounds. A thermocouple was mounted in the furnace to permit a rough check upon the temperature of distillation.

Lengthy evacuation was necessary to remove background spectra from the tube and to free the sample from volatile impurities. The tube was baked at about 200°C by furnaces wound on the envelopes. It was frequently necessary to spend three to five days in pumping to reduce the background to a usable level.

Background ion contributions not associated with instrumental resolution could be reduced to a level such that these contributions to the abundances of the principal ions being measured were orders of magnitude less than the abundance deviations reported. However, particularly when employing corrosive halide gases, background ions frequently rendered critical examination for unreported isotopes infeasible. Accord-

ingly, only for lithium, zirconium, tantalum and rhenium are these examinations reported.

Each measurement series reported below represents between 15- and 300-ratio determinations. Many measurements are an average of several series of determinations with different spectrometers and ion sources. In the case of elements having more than two isotopes, measurements were made between a principal isotope and each of the other isotopes. Where the packing fraction data are accurately known and these abundance measurements are thought to make significant contributions, the computed chemical weights are given.

DISCUSSION

The discrepancy between observers is not any greater than that between instruments in cases where the measurements were made by identical techniques. The residual discrepancy may probably be ascribed to mass discrimination occurring in the ion lenses in the source. Reversal of the magnetic field in the ionization region, operation with widely varied voltages applied to the source elements, and variations in collector geometry and secondary electron suppression make it probable that this discrimination is a function of the actual structural geometry of the source, rather than being caused by conditions which can be varied or differences in instrument geometry. The measurements of copper are a good example.

It has been assumed that the most probable ion abundance results from averaging of the measurements from a variety of ion sources and instruments and assigning equal weight to each instrument and ion-source structural variation. Only where several series of different determinations have been averaged may the average deviations tabulated be regarded as indexing the uncertainty in the abundances reported. In all other data an uncertainty of one percent of the specific ion abundance tabulated appears likely for abundances above two percent. For abundances between two percent and 0.05 percent, the uncertainty may be regarded as increasing from one percent to fifteen percent.

Measurements on any one spectrometer and ion source agreed much more closely than is indicated for the agreement between measurements on different instruments and ion sources.

It is accordingly possible to use differential techniques in estimating enhanced tracer samples whose enhancement may be less than the expected instrument-to-instrument variation.

Lithium

Previous measurements of the abundance of the lithium isotopes have, for the most part, utilized the thermionic properties of the lithium salts for the production of ions. Some uncertainty was introduced by the correction for the free evaporation of ions with a large percentile mass difference.¹⁻⁸ For the measurements reported here, lithium aluminum chloride (LiAlCl₄) was distilled from a Pyrex glass retort into the ionizing region where it was bombarded by 75-volt electrons. The retort was separated from the platinum-iridium ionizing case by a platinum gauze screen. The distillation of the heavy molecule, LiAlCl₄, reduced the effects caused by the mass difference between the lithium isotopes. Measurements were made on the Li⁺ ion. Three different series of determinations are represented. (See Table I.)

TABLE I. Relative abundance of Li isotopes.

Mass	5	6	7	8
Mole percent	<10 ⁻⁵	7.30	92.70	<10 ⁻⁵
Average deviation		±0.04	±0.04	
	Ratio Li ⁷ /Li ⁶			
This measurement				12.7 ± 0.07
Morand ^a				14.9
Bainbridge ^b				11.28
Aston ^c				11.0
Harnwell and Bleakney ^d				8.4
Brewer ^{e,g}				11.60 to 12.52
Hoff Lu ^f				12.29
McKellar ^h				8.57

^a See reference 1.

^b See reference 2.

^c See reference 3.

^d See reference 4.

^e See references 5-7.

^f See reference 8.

^g A. K. Brewer, *Ind. Eng. Chem.* **30**, 893 (1938); A. K. Brewer and O. Baudisch, *J. Am. Chem. Soc.* **59**, 1578 (1937); A. K. Brewer, *Phys. Rev.* **49**, 867 (1937).

^h A. McKellar and F. A. Jenkins, *Dominion Astrophys. Obs. Victoria, Pub.* **7**, 155 (1939).

¹ M. Morand, *Comptes rendus* **182**, 460 (1926); *Ann. de physique* **7**, 164 (1927).

² K. T. Bainbridge, *J. Franklin Inst.* **212**, 317 (1931).

³ F. W. Aston, *Proc. Roy. Soc.* **A134**, 574 (1931).

⁴ G. P. Harnwell and W. Bleakney, *Phys. Rev.* **45**, 117 (1934).

⁵ A. K. Brewer and P. D. Kueck, *Phys. Rev.* **46**, 894 (1934).

⁶ A. K. Brewer, *Phys. Rev.* **47**, 571 (1935).

⁷ A. K. Brewer, *J. Chem. Phys.* **4**, 350 (1936).

⁸ Hoff Lu, *Phys. Rev.* **53**, 845 (1938).

TABLE II. Relative abundance of Mg isotopes.

Mass	24	25	26
This measurement mole percent	78.60	10.11	11.29
Average deviation	± 0.13	± 0.05	± 0.08
Dempster; ^a electron ionization of Mg metal vapor	77.4	11.5	11.1

^a A. J. Dempster, Phys. Rev. **18**, 421 (1921).

TABLE III. Relative abundance of Si isotopes.

Mass	28	29	30
This measurement mole percent	92.16	4.71	3.13
Average deviation	± 0.06	± 0.03	± 0.04
McKellar; ^a photometry of SiN	89.6	6.2	4.2
Inghram; ^b electron ionization of SiF ₄	92.28	4.67	3.05
Williams and Yuster; ^c electron ionization of SiF ₄	92.27	4.68	3.05
Ney and McQueen; ^d electron ionization of SiF ₄	92.24	4.69	3.07

^a A. McKellar, Phys. Rev. **45**, 761 (1934).

^b M. G. Inghram, Bull. Am. Phys. Soc. **21**-3, Sp-1 (1946).

^c D. Williams and P. Yuster, Phys. Rev. **69**, 556 (1946).

^d E. P. Ney and J. H. McQueen, Phys. Rev. **69**, 41 (1946).

This abundance ratio with the masses of Li⁶=6.01670 and Li⁷=7.01799 calculated by Allison⁹ or the masses Li⁶=6.01682 and Li⁷=7.0178₄ calculated by Smith¹⁰ yields a chemical atomic weight for lithium of 6.943. The international value is 6.940. A physical to chemical scale conversion factor of 1.000275 has been employed in this and subsequent calculations.

Magnesium

Magnesium metal was distilled from a Vycor retort into a platinum-iridium ionizing case. The retort was heated by a platinum resistance furnace. Ionization was produced by slow electrons and measurements were made on the Mg⁺ ion. Three different series of determinations were conducted.

Measurements were made also by distilling magnesium acetyl acetonate. These were found to be unreliable because of interference at masses 24, 25, and 26 and the absence of a complex ion containing magnesium useful for analysis. The interfering ions were presumed to be C₂⁺, C₂H⁺, and C₂H₂⁺. No compound was found which could be used for the determination of separated

⁹ S. K. Allison, Phys. Rev. **55**, 624 (1939).

¹⁰ N. M. Smith, Jr., Phys. Rev. **56**, 548 (1939).

samples. The metal could not be prepared readily in micro-quantity. (See Table II.)

These abundance data taken with the isotopic masses Mg²⁴=23.99189, Mg²⁵=24.99277 and Mg²⁶=25.99062 computed by Pollard¹¹ yield a chemical atomic weight of 24.31. The present international value is 24.32.

Silicon

Silicon tetrafluoride vapor, produced by the action of fluorine on hot Pyrex glass, was subjected to slow electron bombardment. Measurements were made with ionizing cases of tantalum and of copper. All measurements were made on the SiF₃⁺ ion. A total of 61 different determinations, representing about 800 ratio measurements for each isotope pair, using five different instruments, has been performed. In computing the average, each instrument has been given equal weight. (See Table III.)

Using either Aston's¹² packing fraction value of -4.90 for Si²⁸ or Pollard's¹¹ computed values, Si²⁸=27.98639, Si²⁹=28.98685, and Si³⁰=29.98294,

TABLE IV. Abundance ratios of K isotopes.

	Ratio K ³⁹ /K ⁴¹	Ratio K ⁴⁰ /K ³⁹
This measurement	13.66 \pm 0.1	
Brewer and Kueck; ^a thermionic	13.88 \pm 0.4	
Nier; ^b electron ionization of K metal vapor	13.96 \pm 0.1	1/8600
Bondy, Johansen and Popper; ^c thermionic	16.2	
Manley; ^d magnetic moment separation of molecular beam	13.4 \pm 0.5	
Bondy and Vanicek; ^e thermionic	14.0	
Brewer; ^f thermionic (plant ash)	12.63 to 14.32	
Brewer; ^f thermionic (sea water)	14.2	
Brewer; ^f thermionic (mineral)	14.11 to 14.6	
		1/8300
Brewer; ^g thermionic	—	
Paul and Pahl ^h	13.96 \pm 0.1	
Cook; ⁱ thermionic	14.12 \pm 0.28	

^a See reference 5.

^b A. O. Nier, Phys. Rev. **48**, 283 (1935).

^c H. Bondy, G. Johansen and K. Popper, Zeits. f. Physik **95**, 46 (1935).

^d J. H. Manley, Phys. Rev. **49**, 921 (1936).

^e H. Bondy and V. Vanicek, Zeits. f. Physik **101**, 186 (1936).

^f A. K. Brewer, J. Am. Chem. Soc. **58**, 365 (1936).

^g A. H. Brewer, Phys. Rev. **48**, 640 (1935).

See also:

A. K. Brewer and O. Bandisch, J. Am. Chem. Soc., **59**, 1578 (1937).

A. K. Brewer, Ind. Eng. Chem. **30**, 893 (1938).

A. K. Brewer, J. Am. Chem. Soc. **61**, 1597 (1939); *ibid.* **59**, 869 (1937).

^h W. Paul and M. Pahl, Naturwiss. **32**, 228 (1944).

ⁱ K. L. Cook, Phys. Rev. **64**, 278 (1943).

¹¹ E. Pollard, Phys. Rev. **57**, 1186 (1940).

¹² F. W. Aston, Nature **138**, 1094 (1936); Mass Spectra and Isotopes (1933).

TABLE V. Relative abundance of Ca isotopes.

Mass	40	42	43	44	46	48
This measurement; thermal evaporation	Mole percent 96.92	0.64	0.132	2.13	0.0032	0.179
Average deviation	±0.03	±0.01	±0.004	±0.04	—	±0.001
Nier; ^a electron ionization of metal vapor	96.97	0.64	0.145	2.06	0.0033	0.185
Aston ^b photometry	96.76	0.77	0.17	2.30	—	—

^a A. O. Nier, Phys. Rev. **53**, 282 (1938).
^b F. W. Aston, Nature **133**, 684 (1934); Proc. Roy. Soc. **A149**, 396 (1935).

TABLE VI. Relative abundance of Cr isotopes.

Mass	50	52	53	54
This measurement mole percent	4.31	83.76	9.55	2.38
Average deviation	±0.04	±0.14	±0.09	±0.02
Aston; ^a photometry	4.9	81.6	10.4	3.1
Nier; ^b thermal evaporation from metal	4.49	83.78	9.43	2.30

^a F. W. Aston, Proc. Roy. Soc. **A130**, 306 (1931).
^b A. O. Nier, Phys. Rev. **55**, 1143 (1939).

these abundances permit computation of a chemical atomic weight of 28.08₈. The present international value is 28.06.

Potassium

Potassium aluminum chloride, prepared by the Chemical Development Group of the Clinton Engineer Works, Tennessee Eastman Corporation, was distilled into an ionizing case constructed of platinum-iridium alloy. Measurements were made on the K⁺ ion. The traces of calcium which were present in the sample made exact measurement of the concentration of the mass 40 isotope impossible. (See Table IV.)

From either Aston's¹² or Bainbridge's¹³ packing fraction data the packing fraction of potassium is about -7.0. Hahn, Flügge, and Mattauch¹⁴ report -6. From transmutation data Pollard¹¹ has calculated K³⁹=38.97518 and K⁴¹=40.9739 corresponding to packing fractions of -6.37. Combining these latter with the abundance ratio of this measurement yields a chemical weight of 39.10 for potassium. The present international value is 39.096.

¹³ K. T. Bainbridge, Phys. Rev. **43**, 424 (1933).

¹⁴ O. Hahn, S. Flügge, and J. Mattauch, Ber. **73A**, 1 (1940).

Calcium

Calcium ions were produced by thermal evaporation from a tungsten filament coated with calcium oxide. Measurements were made upon the Ca⁺ ion. These measurements compare very favorably with those which were made by Nier by electron ionization of calcium metal vapor. (See Table V.)

Selecting a packing fraction of -6.3 in accord with that reported by Hahn, Flügge, and Mattauch,¹⁴ -6.2, and the mass, K⁴¹=40.9725 to 40.9739, computed by Davidson,¹⁵ permits computation of a chemical weight of 40.08 from the data in Table V. The international value is 40.08.

Chromium

Chromium trichloride (CrCl₃) was distilled from a tungsten, platinum, Vycor retort assembly into the tantalum metal electron ionization source. Cr⁺ ion abundances were measured. (See Table VI.)

TABLE VII. Relative abundance of Fe isotopes.

Mass	54	56	57	58
This measurement mole percent	5.81	91.64	2.21	0.34
Average deviation	±0.01	±0.02	±0.01	±0.01
Aston; ^a photometry	6.5	90.7	2.8	—
Nier; ^b electron ionization of Fe metal vapor	6.0	91.6	2.1	0.28
Valley; ^c electron ionization of Fe metal vapor	5.83	91.7	2.16	0.31
deGier and Zeeman; ^d photometry	6.5	90.2	2.8	0.5

^a F. W. Aston, Nature **133**, 684 (1934); Proc. Roy. Soc. **A149**, 396 (1935).

^b A. O. Nier, Phys. Rev. **55**, 1143 (1939).

^c G. E. Valley and H. H. Anderson, Phys. Rev. **59**, 113 (1941).

^d J. deGier and P. Zeeman, Proc. Akad. Sci. Amsterdam **38**, 959 (1935).

TABLE VIII. Relative abundance of Ni isotopes.

Mass	58	60	61	62	64
This measurement mole percent	67.76	26.16	1.25	3.66	1.16
Average deviation	±0.22	±0.66	±0.03	±0.01	±0.20
Aston; ^a photometry	67.5	27.0	1.7	3.7	?
Straus; ^b oscillating spark Faraday collector	62.8	29.5	1.7	4.7	1.3
Valley; ^c electron bombardment of Ni vapor	67.4	26.7	1.2	3.8	0.88
Lub ^d	68.0	27.2	0.1	3.8	0.9

^a F. W. Aston, Proc. Roy. Soc. **A130**, 306 (1931).

^b H. A. Straus, Phys. Rev. **59**, 430 (1941).

^c G. E. Valley, Phys. Rev. **59**, 836 (1941).

^d W. A. Lub, Proc. Acad. Sci. Amsterdam **42**, 253 (1939).

¹⁵ W. L. Davidson, Jr., Phys. Rev. **57**, 244 (1940).

TABLE IX. Relative abundance of Cu⁶³ isotope.

	Mole percent Cu ⁶³
This measurement	68.94±0.19*
Ewald; ^a photometry	70.16±0.27
Dempster; ^b oscillating spark Faraday collector	69.04±0.29
Duckworth and Hoge; ^c photometry	69.48±0.16

* Maximum value for any series, 69.41. Minimum value for any series, 68.62.

^a H. Ewald, Zeits. f. Physik **122**, 487 (1944).

^b A. J. Dempster, Report for February, 1946, CP-3445.

^c H. E. Duckworth and B. J. Hoge, Phys. Rev. **71**, 212 (1947).

TABLE X. Relative abundance of Se isotopes.

Mass	74	76	77	78	80	82
This measurement; SeF ₆ mole percent	0.86	9.08	7.51	23.54	50.02	8.99
Se	0.88	8.95	7.65	23.51	49.62	9.39
Mean	0.87	9.02	7.58	23.52	49.82	9.19
Average deviation	±0.01	±0.07	±0.07	±0.02	±0.20	±0.20
Aston; ^a photometry	0.9	9.5	8.3	24.0	48.0	9.3

^a See reference 24.

With either Aston's¹⁶ packing fraction, -8.18 ± 0.15 or that of Hahn, Flügge, and Mattauch,¹⁴ 7.9 ± 0.2 the chemical weight computed from these abundances becomes 52.00. The international chemical weight is presently 52.01.

Iron

Ferrous chloride (FeCl₂) was distilled from a Pyrex glass retort into the electron ionizing case of the platinum-iridium ion source. Fe⁺ ion abundances were measured. Two series of determinations are represented. (See Table VII.)

Dempster¹⁷ gives -7.0 ± 0.4 as the packing fraction for iron; Flügge and Mattauch¹⁸ list -7.15 ± 0.30 ; while Okuda *et al.*¹⁹ report Fe⁵⁶ = -7.7 . Selection of a mean -7.3 permits calcu-

TABLE XI. Relative abundance of Br isotopes.

Mass	79	81
This measurement mole percent	50.51	49.49
Average deviation	±0.06	±0.06
Blewett ^a	50.6	49.4
Williams and Yuster ^b	50.52	49.48

^a J. P. Blewett, Phys. Rev. **49**, 900 (1935).

^b D. Williams and P. Yuster, Phys. Rev. **69**, 556 (1946).

¹⁶ F. W. Aston, Nature **141**, 1096 (1938).

¹⁷ A. J. Dempster, Phys. Rev. **53**, 64 (1938).

¹⁸ S. Flügge and J. Mattauch, Ber. d.d. chem. Ges. **76**, 1 (1943).

¹⁹ T. Okuda, K. Ogata, K. Aoki, and Y. Sugawara, Phys. Rev. **58**, 578 (1940).

TABLE XII. Relative abundance of Sr isotopes.

Mass	84	86	87	88
This measurement mole percent	0.55	9.75	6.96	82.74
Average deviation	±0.01	±0.04	±0.01	±0.06
Sampson and Bleakney ^a	0.5	9.6	7.5	82.4
Nier; ^b electron ionization of Sr metal vapor	0.56	9.86	7.02	82.56

^a M. B. Sampson and W. Bleakney, Phys. Rev. **50**, 456 (1936).

^b A. O. Nier, Phys. Rev. **54**, 275 (1938).

lation of a chemical weight of 55.85₆ from these abundance observations. The international value is 55.85.

Nickel

Nickelous chloride (NiCl₂) was distilled from a tungsten, platinum, Vycor retort assembly into the ionizing region of the tantalum metal electron bombardment source. The abundances of Ni⁺ and NiCl⁺ ions were measured.

A number of determinations of different samples of chloride yielded similar ratio behavior in all mass positions save 64. Prolonged distillation resulted in some upward shift in the ratios with respect to 64. An average of four series of determinations after prolonged distillation yields the following. Mass 64 abundance is least certain. It is probable that the abundance lies between the 0.88 percent reported by Valley and 1.16 percent. (See Table VIII.)

Employing the packing fractions, Ni⁵⁸ = 6.97

TABLE XIII. Relative abundance of Zr isotopes.

Mass	90	91	92	94	96
This measurement:					
Zr ⁺ mole percent	51.51	11.27	17.14	17.30	2.78
ZrF ₄ ⁺	51.40	11.19	17.09	17.50	2.82
Average	51.46	11.23	17.11	17.40	2.80
Aston; ^a photometry of photographic plate	48	11.5	22	17	1.5

^a F. W. Aston, Nature **133**, 684 (1934); Proc. Roy. Soc. **A149**, 396 (1935).

TABLE XIV. Relative abundance of Ag isotopes.

Mass	107	109
This measurement mole percent	51.35	48.65
Average deviation	±0.07	±0.07
Aston; ^a photometry	52.5	47.5
Paul ^b	51.92	48.08

^a F. W. Aston, Nature **133**, 684 (1934); Proc. Roy. Soc. **A149**, 396 (1935).

^b W. Pauli, Naturwiss. **31**, 419 (1943).

TABLE XV. Relative abundance of Cd isotopes.

Mass	106	108	110	111	112	113	114	116
This measurement mole percent	1.22	0.98	12.35	12.78	24.00	12.30	28.75	7.63
Average deviation	± 0.01	± 0.01	± 0.04	± 0.04	± 0.10	± 0.04	± 0.20	± 0.04
Aston; ^a photometry	1.5	1.0	15.2	15.2	21.8	14.9	23.7	5.9
Nier; ^b electron ionization of Cd metal vapor	1.4	1.0	12.8	13.0	24.2	12.3	28.0	7.3

^a F. W. Aston, *Nature*, **133**, 684 (1934); *Proc. Roy. Soc.* **A149**, 396 (1935).

^b A. O. Nier, *Phys. Rev.* **50**, 1041 (1936).

± 0.07 , $\text{Ni}^{60} = -8.37 \pm 0.06$, $\text{Ni}^{61} = -7.5 \pm 0.3$, $\text{Ni}^{62} = -8.14 \pm 0.06$, and $\text{Ni}^{64} = -8.22 \pm 0.09$ of Okuda *et al.*,²⁰ which are in fair accord with Aston's¹⁶ $\text{Ni}^{58} = -8.35$, the chemical weight is calculated as 58.71. The international weight is 58.69.

Copper

This element has been very extensively investigated by distillation of cuprous chloride (Cu_2Cl_2) from a Pyrex glass retort into the electron region of a variety of sources constructed of platinum-iridium and tantalum. In all, 21 series of determinations, representing about 300 ratio measurements, have been conducted under a variety of measurement conditions. Four different spectrometers have been used in this work. Cuprous chloride was obtained from four different suppliers. Cu^+ and CuCl^+ ion abundances were measured. (See Table IX.)

With a packing fraction of -6.9 ± 0.2 measured by Dempster,¹⁷ the chemical atomic weight of copper becomes 63.56 in good accord with the older international chemical weight, 63.57, and slightly higher than the recent determination of Hönigschmidt and Johansen,²¹ 63.542, now accepted in the 1947 international table. With Flügge and Mattauch's²² packing fraction of -8.13 ± 0.10 or Duckworth's²³ packing fraction of -7.92 ± 0.25 the computed chemical weight becomes 63.55.

Selenium

Selenium was measured using both the metal and the hexafluoride. Selenium metal was dis-

²⁰ T. Okuda, K. Ogata, H. Kuroda, S. Shima, and S. Shindo, *Phys. Rev.* **59**, 104 (1941).

²¹ O. Hönigschmidt and Th. Johansen, *Naturwiss.* **31**, 548 (1943).

²² S. Flügge and J. Mattauch, *Physik. Zeits.* **44**, 181 (1943).

²³ H. E. Duckworth, *Phys. Rev.* **62**, 19 (1942).

tilled into a platinum-iridium metal electron ionization source. A tantalum metal ion source was used for the selenium hexafluoride measurements. The Se^+ ion formed from the metal and the SeF_5^+ ion formed from the hexafluoride were measured. (See Table X.)

Aston²⁴ reports a packing fraction of -7.3 for Se^{80} with a large uncertainty. Flügge and Mattauch¹⁸ list -7.1 . With either the chemical weight of selenium computed from these abundance data is 78.99; the international chemical weight is 78.96.

Bromine

Silver bromide has been distilled from a high temperature Vycor retort into a tantalum electron bombardment ion source. Br^+ and HBr^+ ion abundances have been measured. (See Table XI.)

Aston¹⁶ indicates a packing fraction for bromine of -7.4 while Flügge and Mattauch¹⁸ list -7.1 . Either leads to a computed chemical atomic weight of 79.91 for bromine; the international weight is 79.916.

Strontium

Metallic strontium was distilled into the electron ionization region of a tantalum metal ion source. The abundances of Sr^+ ions were measured. (See Table XII.)

TABLE XVI. Relative abundance of In isotopes.

Mass	113	115
This measurement mole percent	4.23	95.77
Average deviation	± 0.03	± 0.03
Aston; ^a photometry	4.5	95.5
Sampson and Bleakney; ^b thermal ionization	4.5	95.5

^a F. W. Aston, *Nature*, **133**, 684 (1934); *Proc. Roy. Soc.* **A149**, 396 (1935).

^b M. B. Sampson and W. Bleakney, *Phys. Rev.* **50**, 456 (1936).

²⁴ F. W. Aston, *Proc. Roy. Soc.* **A132**, 487 (1931).

TABLE XVII. Relative abundance of Sn isotopes.

Mass	112	114	115	116	117	118	119	120	122	124
This measurement mole percent	0.90	0.61	0.35	14.07	7.54	23.98	8.62	33.03	4.78	6.11
Average deviation	± 0.003	± 0.01	± 0.006	± 0.08	± 0.03	± 0.03	± 0.003	± 0.12	± 0.01	± 0.006
Aston; ^a photometry	1.1	0.8	0.4	15.5	9.1	22.5	9.8	28.5	5.5	6.8

^a F. W. Aston, Proc. Roy. Soc. A115, 506 (1927).

Flügge and Mattauch¹⁸ adopt a packing fraction for strontium of -7.0 . A value of -6.3 may be deduced from Dempster's²⁵ packing fraction curve. The former leads to a computed chemical weight of 87.62 while the latter leads to 87.63; the accepted international weight is 87.63.

Zirconium

Ions were formed by 50-volt electron bombardment of vapors of zirconium tetrachloride ($ZrCl_4$) and zirconium tetrafluoride (ZrF_4). Zr^+ ions formed in the tetrachloride bombardment, and ZrF_3^+ ions formed in the tetrafluoride bombardment, were measured. Masses 88, 89, 93, 95, 97, 98, and 99 are each not greater than 1/5000 of the total zirconium ion abundance. (See Table XIII.)

From Dempster's²⁵ packing fraction curve a value of about -6.0 is obtained for the isotopes of zirconium. Flügge and Mattauch¹⁸ list -6.75 . These abundance data reduce to a chemical atomic weight of 91.24 with the former value and of 91.23 with the latter value; the accepted international chemical weight is 91.22.

Silver

Silver chloride was distilled from a Vycor and platinum retort into the platinum-iridium electron bombardment source. Ag^+ ion abundances were measured. Two series of determinations are represented. With Dempster's¹⁷ packing fraction value of -4.93 ± 0.5 , the chemical atomic weight

TABLE XVIII. Relative abundance of Sb isotopes.

Mass	121	123
This measurement mole percent	57.25	42.75
Average deviation	± 0.03	± 0.03
Aston; ^a photometry	56.0	44.0

^a F. W. Aston, Proc. Roy. Soc. A132, 492 (1931).

²⁵ A. J. Dempster, Phys. Rev. 53, 869 (1938).

is calculated as 107.89, in excellent agreement with the international chemical value of 107.880. (See Table XIV.)

Cadmium

Anhydrous cadmium chloride ($CdCl_2$) was distilled into the ionizing case of a tantalum metal ion source. Cd^+ ion abundances were measured. (See Table XV.)

The packing fractions for the cadmium isotopes have been deduced as about -5.0 from Dempster's²⁵ curve. Flügge and Mattauch¹⁸ list -5.3 . With either value the computed chemical weight of cadmium becomes 112.44 as contrasted with an international value of 112.41.

Indium

Indium trichloride ($InCl_3$) was vaporized and subjected to electron bombardment in a platinum-iridium metal ion source. In^+ ion abundances were measured. An average of three series of determinations yields the values shown in Table XVI.

Flügge and Mattauch¹⁸ assign a packing fraction of -5.1 for the isotopes of indium. Dempster's²⁵ curve indicates an essentially similar value. With these abundances the chemical weight of indium is calculated as 114.83; the international chemical value is 114.76.

Tin

Anhydrous stannous chloride ($SnCl_2$) was volatilized and ionized by electron impact. Metal parts were constructed of platinum-iridium alloy. Sn^+ ion abundances were measured. Three series of determinations yield an average of the values shown in Table XVII.

Using Aston's²⁶ packing fraction, -5.8 , for the mass 118 and 120 isotopes of tin, the computed

²⁶ F. W. Aston, Proc. Roy. Soc. A163, 391 (1937).

TABLE XIX. Relative abundance of Te isotopes.

Mass	120	122	123	124	125	126	128	130
Metal* mole percent	0.092	2.32	0.88	4.51	6.99	18.53	32.57	34.11
Hexafluoride	0.091	2.49	0.89	4.63	7.01	18.72	31.72	34.46
Average deviation TeF ₆	±0.001	±0.02	±0.02	±0.05	±0.01	±0.04	±0.01	±0.09
Bainbridge; ^a photometry	—	2.9	1.6	4.5	6.0	19.0	32.8	33.1
Aston; ^b photometry	—	—	—	—	6.6	20.9	36.1	36.4
Williams and Yuster; ^c electron ionization of TeF ₆	0.090	2.43	0.85	4.59	6.97	18.70	31.85	34.5

* Distillation of Te metal; Te⁺ ion abundance.
^a K. T. Bainbridge, Phys. Rev. **39**, 1021 (1932).
^b F. W. Aston, Proc. Roy. Soc. **A132**, 487 (1931).
^c D. Williams and P. Yuster, Phys. Rev. **69**, 556 (1946).

chemical weight becomes 118.75. With Graves's²⁷ packing fraction, -4.56, or Dempster's²⁵ value of -5.0±0.5 for the 116 and 118 isotopes and -4.5±0.5 for the 122 and 124 isotopes, the computed chemical weight is 118.76. The present international value is 118.70.

Antimony

Metallic antimony was volatilized and ionized by electron bombardment. Sb⁺ ion abundances were measured. (See Table XVIII.)

Flügge and Mattauch¹⁸ indicate a packing fraction of -4.8 for the isotopes of antimony. From Dempster's²⁵ data on tin a value nearer -4.5 may be inferred. Either figure leads to a chemical weight computed from these abundances of 121.77; the international value is 121.76.

Tellurium

Tellurium hexafluoride was admitted to the electron flux region of the ion source through a controllable capillary leak. TeF₅⁺ and TeF₂⁺ ion abundances were measured. Tellurium metal has also been distilled from a Vycor, platinum retort into a tantalum ion source. The ion sources were constructed of tantalum and of copper. Five series of 24 determinations are represented in the hexafluoride data. (See Table XIX.)

Aston²⁴ has indicated a rough packing fraction value for tellurium of 5±2. Flügge and Mattauch¹⁸ list -4.5, while Dempster's²⁵ curve suggests -4.5 to -4.0 over the range of ten mass units. Adopting this latter permits computation of a chemical atomic weight of 127.64 for tellurium; the international chemical weight is 127.61.

²⁷ A. C. Graves, Phys. Rev. **55**, 863 (1939).

Tantalum

Ta⁺, TaF⁺, TaF₂⁺, TaF₃⁺, TaF₄⁺, and TaF₅⁺ ions have been formed by admitting uranium hexafluoride to an ionizing case constructed of tantalum metal. Tantalum may be regarded as simple; no other isotopes greater than one part in ten thousand of the principal mass, 181, are present.

Tungsten

Tungsten hexafluoride (WF₆) was admitted through a controllable capillary leak into the electron ionization case of ion sources constructed of tantalum and copper. WF₅⁺ ion abundances were measured. Four series of 27 determinations have been averaged. (See Table XX.)

Computation of chemical weight from reported or deduced packing fractions of 0.0²⁴, +0.6¹⁸, and +1.8²⁵ leads to values of 183.84, 183.85, and 183.87, respectively. The international chemical weight is 183.92.

Rhenium

The hemi-heptoxide of rhenium (Re₂O₇) has been distilled into the electron flux region of an ion source constructed of platinum-iridium. Re⁺ ion abundances have been measured. The rhen-

TABLE XX. Relative abundance of W isotopes.

Mass	180	182	183	184	186
This measurement mole percent	0.126	26.31	14.28	30.64	28.64
Average deviation	±0.006	±0.03	±0.01	±0.03	±0.01
Aston; ^a photometry	0.2	22.6	17.3	30.1	29.8
Inghram; ^b electron ionization of WF ₆	0.122	25.77	14.24	30.68	29.17
Williams and Yuster; ^c electron ionization of hexacarbonyl	0.135	26.41	14.40	30.64	28.41

^a F. W. Aston, Proc. Roy. Soc. **A132**, 492 (1931).
^b M. B. Inghram, Bull. Am. Phys. Soc. **21-3**, Sp-1 (1946).
^c D. Williams and P. Yuster, Phys. Rev. **69**, 556 (1946).

TABLE XXI. Relative abundance of Rh isotopes.

Mass	180-184	185	186	187	188-190
This measurement mole percent	<10 ⁻⁴	37.07	<10 ⁻⁴	62.93	<10 ⁻⁴
Average deviation		±0.06		±0.06	
Aston; ^a photometry		38.2		61.8	

^a See reference 24.

TABLE XXII. Relative abundance of Tl isotopes.

Mass	203	205
This measurement mole percent	29.46	70.54
Average deviation	±0.05	±0.05
Schuler and Keyston ^a	30.31	69.69
Nier; ^b electron ionization of Tl vapor	29.1	70.9
Aston; ^c photometry	29.43	70.57

^a H. Schuler and J. E. Keyston, *Zeits. f. Physik* **70**, 1-2, 1 (1931).

^b A. O. Nier, *Phys. Rev.* **54**, 275 (1938).

^c See Ref. 3.

ium was obtained from Dr. G. E. Boyd of the Clinton Laboratories, Monsanto Chemical Company.

Assuming a packing fraction of +1.0²⁴, the computed chemical atomic weight becomes 186.22. The international value is 186.31. (See Table XXI.)

Thallium

The metal was distilled from a Pyrex glass retort into a platinum-iridium ion source. Ionization was by slow electron bombardment. Measurements were made upon the Tl⁺ ion. These measurements and those of Nier have been corrected for the free evaporation of the metal vapor from the liquid phase. The correction factor is (205/203)^{1/2} = 1.005. (See Table XXII.)

With a packing fraction of +2.0 deduced from Dempster's²⁵ curve or a value of +2.65 reported by Flüge and Mattauch¹⁸ the corresponding chemical atomic weights of thallium computed from these abundance measurements are 204.40

TABLE XXIII. Relative abundance of Pb isotopes.

Mass	204	206	207	208
This measurement mole percent	1.37	25.15	21.11	52.38
Average deviation	±0.02	±0.04	±0.04	±0.10
Aston; ^a photometry	1.5	28.3	20.1	50.1
Nier; ^b electron ionization of Pbl vapor Great Bear Lake Galena	1.5	23.5	22.7	52.3*
Rose and Stranathan ^c	0.8	26.3	21.3	51.5
Mattauch ^d	1.15	24.55	21.35	52.95

^a F. W. Aston, *Proc. Roy. Soc.* **A140**, 535 (1933).

^b A. O. Nier, *Phys. Rev.* **53**, 680; *J. Am. Chem. Soc.* **60**, 1571 (1938).

* Variation with source of lead, A. O. Nier, R. W. Thompson, and B. F. Murphey, *Phys. Rev.* **60**, 112 (1941).

^c J. L. Rose and R. K. Stranathan, *Phys. Rev.* **49**, 916 (1936).

^d J. Mattauch, *Naturwiss.* **25**, 763 (1937).

and 204.41 respectively; the international chemical atomic weight is 204.39.

Lead

Lead chloride (PbCl₂) was distilled into the electron flux region of ion sources constructed of platinum-iridium. Pb⁺ and PbCl⁺ ion abundances were measured. Nier and Hanson's²⁸ data for the 35/37 chlorine isotope ratio have been used for correction. The samples were assumed to be common lead of unspecified source. (See Table XXIII.)

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²⁸ A. O. Nier and E. E. Hanson, *Phys. Rev.* **50**, 722 (1936).