4. The Elements

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This chapter provides tables of the physical and physicochemical properties of the elements. Emphasis is given to properties of the elements in the condensed state. The tables are structured according to the Periodic Table of the Elements. Most of the tables deal with the properties of elements of one particular group (column) of the Periodic Table. Only the elements of the first period (hydrogen and helium), the lanthanides, and the actinides are arranged according to the periods (rows) of the Periodic Table. This synoptic representation is intended to provide an immediate overview of the trends in the data for chemically related elements.

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W. Martienssen, H. Warlimont (Eds.), *Springer Handbook of Materials Data*, https://doi.org/10.1007/978-3-319-69743-7_4

4.1 How to Use this Chapter

To find properties of a specific element or group of elements, start from one of Tables 4.1–4.5 and proceed in one of the following ways:

1. If the *name* of the element is known, refer to Table 4.1, where an alphabetical list of the elements is given, together with the numbers of the pages where the properties of these elements can be found.
2. If you know the *chemical symbol* of the element, refer to Table 4.2, where an alphabetical list of element symbols is given, together with the numbers of the pages where the properties of the corresponding elements will be found.
3. If the *atomic number* Z of the element is known, refer to Table 4.3, where a list of the elements in order of atomic number is given, together with the numbers of the pages where the properties of these elements will be found.
4. If you know the *group of the Periodic Table* that contains the element of interest, refer to Table 4.4, which gives the numbers of the pages where the properties of the elements of each group will be found.
5. To look up the element in the *Periodic Table*, refer to Table 4.5, where the element symbol and the atomic number will be found. Then use Table 4.2 or Table 4.3 to find the numbers of the pages where the properties of the element of interest are tabulated.
6. Alternatively, one may also find the name and the chemical symbol of the element you are looking for in the alphabetic index at the end of the volume. The index again will give you the first number of those pages on which the properties of the element are described.

The data-tables corresponding to the Periodes and Groups of the Periodic Table are subdivided in the following way:

A. Atomic, ionic, and molecular properties
B. Materials data:
   a) Crystallographic properties
   b) Mechanical properties
   c) Thermal and thermodynamic properties
   d) Electronic, electromagnetic, and optical properties.
C. Allotropic and high-pressure modifications
D. Ionic radii.

4.2 Description of Properties Tabulated

4.2.1 Parts A of the Tables

The properties tabulated in parts A of the tables concern the atomic, ionic, and molecular properties of the elements:

- The relative atomic mass, or atomic weight, A.
- The abundance in the lithosphere and in the sea.
- The atomic radius: the radius r_{cov} for single covalent bonding (after Pauling), the radius r_{met} for metallic bonding with a coordination number of 12 (after Pauling), the radius r_{vdW} for van der Waals bonding (after Bondi), and, for some elements, the radius r_{os} of the outer-shell orbital are given.
- The completely and partially occupied electron shells in the atom.
- The symbol for the electronic ground state.
- The electronic configuration.
- The oxidation states.
- The electron affinity.
- The electronegativity X_A (after Allred and Rochow).
- The first, second, third, and fourth ionization energies and the standard electrode potential E^0.
- The internuclear distance in the molecule.
- The dissociation energy of the molecule.

4.2.2 Parts B of the Tables

Parts B of the tables contain data on the macroscopic properties of the elements. Most of the data concern the condensed phases. If not indicated otherwise, the data in this section apply to the standard state of the element, that is, they are valid at standard temperature and pressure (STP, $T = 298.15\,\mathrm{K}$ and $p = 100\,\mathrm{kPa} = 1\,\mathrm{bar}$). For those elements which are stable in the gas phase at STP, data are given for the macroscopic properties in the gas phase.

The quantities describing the physical and physicochemical properties of materials can be divided into two classes. The first class contains all those quantities which are not directly connected with external (generalized) forces, these quantities have well-defined values even in the absence of external forces. Some

examples are the electronic ground-state configuration of the atom, the coordination number in the crystallized state and the surface tension in the liquid state. The second class contains those quantities which describe the response of the material to externally applied (generalized) forces F. Such a force might be a mechanical stress field, an electric or magnetic field, a field gradient, or a temperature gradient. The response of the material to the external force might be observed via a suitable observable O, such as a mechanical strain, an electric current density, a dielectric polarization, a magnetization, or a heat current density. Assuming homogeneous conditions, the dependence of the observable O on the force F can be used to define material-specific parameters χ, which are also called physical properties of the material. Some examples are the elastic moduli or compliance constants, the electrical conductivity, the dielectric constant, the magnetic susceptibility, and the thermal conductivity.

In the *linear-response* regime, that is, under weak external forces F, these parameters χ are considered as being independent of the strength of the forces. The dependence of an observable O on a force F is then the simple proportionality

$$O = \chi F \,. \tag{4.1}$$

For strong external fields, the dependence of the response on the strength of the forces can be expressed by a power expansion in the forces, which then – in addition to the linear parameters χ – defines *nonlinear field-dependent* materials properties $\chi^{(\mathrm{nl})}(F)$, where

$$\chi^{(\mathrm{nl})}(F) = \chi + \chi^{(1)}F + \cdots \,. \tag{4.2}$$

In general, the class of materials properties that describe the response to externally applied forces have *tensor* character. The *rank* of the property tensor χ depends on the rank of the external force F and that of the observable O considered. In the case of Ohm's law, $\boldsymbol{j} = \boldsymbol{\sigma}\boldsymbol{E}$, in which the current density $\boldsymbol{j}$ and the electric field strength $\boldsymbol{E}$ are vectors, the conductivity tensor $\boldsymbol{\sigma}$ is of rank 2; in the case of the generalized Hooke's law, $\boldsymbol{\varepsilon} = \mathbf{s}\boldsymbol{\sigma}$, the strain tensor '' and the stress tensor $\boldsymbol{\sigma}$ both are of rank 2, so that the elastic compliance tensor $\mathbf{s}$ is of rank 4. A vector can be considered as a tensor of rank 1, and a scalar, correspondingly, as a tensor of rank 0. A second-rank tensor, such as the electrical conductivity $\boldsymbol{\sigma}$, in general has nine components in three-dimensional (3-D) space; a tensor of rank n in general has 3^n components in three-dimensional space. *Symmetry*, however, of both the underlying crystal lattice and the physical phenomenon (for example, action = reaction), may reduce the number of independent nonvanishing components in the tensor. The tensor components reflect the crystal symmetry by being invariant under those orthogonal transformations which are elements of the point group of the crystal. In cubic crystals, for example, physical properties described by tensors of rank 2 are characterized by only one nonvanishing tensor component. Therefore cubic crystals are isotropic with respect to their electrical conductivity, their heat conductivity, and their dielectric properties.

Subdivisions B(a) of the Tables

These parts deal with the *crystallographic properties*. Here you will find the crystal system and the Bravais lattice in which the element is stable in its standard state; the structure type in which the element crystallizes; the lattice constants $a, b, c, \alpha, \beta, \gamma$ (symmetry reduces the number of independent lattice constants); the space group; the Schoenflies symbol; the *Strukturbericht* type; the Pearson symbol; the number A of atoms per cell; the coordination number; and the shortest interatomic distance between atoms in the solid state and in the liquid state.

Basic concepts of crystallography are explained in Chap. 3.

Subdivisions B(b) of the Tables

These parts cover the *mechanical properties*. At the top of the table, you will find the density of the material in the solid state (ϱ_s) and in the liquid state (ϱ_l), and the molar volume V_mol in the solid state. Here, one mole is the amount of substance which contains as many elementary particles (atoms or molecules) as there are atoms in 0.012 kg of the carbon isotope with a relative atomic mass of 12. This number of particles is called *Avogadro's number* and is approximately equal to 6.022×10^{23}. The next three rows present the viscosity η, the surface tension, and its temperature dependence, in the liquid state. The next properties are the coefficient of linear thermal expansion α and the sound velocity, both in the solid and in the liquid state. A number of quantities are tabulated for the presentation of the elastic properties. For isotropic materials, we list the volume compressibility $\kappa = -(1/V)(\mathrm{d}V/\mathrm{d}P)$, and in some cases also its reciprocal value, the bulk modulus (or compression modulus); the elastic modulus (or Young's modulus) E; the shear modulus G; and the Poisson number (or Poisson's ratio) μ. Hooke's law, which expresses the linear relation between the strain ε and the stress σ in terms of Young's modulus, reads $\sigma = E\varepsilon$. For monocrystalline materials, the components of the elastic compliance tensor $\mathbf{s}$ and the components of the elastic stiffness tensor $\mathbf{c}$ are given. The elastic compliance tensor $\mathbf{s}$ and the elastic stiffness tensor $\mathbf{c}$ are

both defined by the generalized forms of Hooke's law, $\boldsymbol{\sigma} = \mathbf{c}\boldsymbol{\varepsilon}$ and $\boldsymbol{\varepsilon} = \mathbf{s}\boldsymbol{\sigma}$. At the end of the list, the tensile strength, the Vickers hardness, and the Mohs hardness are given for some elements.

Subdivisions B(c) of the Tables

The *thermal and thermodynamic properties* are tabulated in these subdivisions of the tables. The properties tabulated are:

- The thermal conductivity, λ.
- The molar heat capacity at constant pressure, c_p.
- The standard entropy S^0, that is, the molar entropy of the element at 298.15 K and 100 kPa.
- The enthalpy difference $H_{298} - H_0$, that is, the difference between the molar enthalpies of the element at 298.15 and at 0 K.
- The melting temperature, T_m.
- The molar enthalpy change ΔH_m and molar entropy change ΔS_m at the melting temperature.
- The relative volume change $\Delta V_m = (V_l - V_s)/V_l$ on melting.
- The boiling temperature, T_b.
- The molar enthalpy change ΔH_b of boiling, and, for some elements, the molar enthalpy of sublimation.

In addition, the critical temperature T_c, the critical pressure p_c, the critical density ϱ_c, the triple-point temperature T_{tr}, and the triple-point pressure p_{tr} are given for some elements. For the element helium, the table also contains data for the λ point, at which liquid helium passes from the normal-fluid phase helium I (above the λ point) to the superfluid phase helium II (below the λ point), for ^{4}He and ^{3}He.

Throughout the chapter, temperature is measured in units of Kelvin (K), the unit of thermodynamic temperature. 1 K is defined as the fraction 1/273.16 of the thermodynamic temperature of the triple point of water. To convert data given in kelvin into degrees Celsius (°C), the following equation can be used

$$T(^\circ\mathrm{C}) = [T\,(\mathrm{K}) - 273.15\,\mathrm{K}]\;(^\circ\mathrm{C/K})\,.$$

This can be expressed in words as follows: the Celsius scale is shifted towards higher temperatures by 273.15 K relative to the kelvin scale, such that the temperature 273.15 K becomes 0 °C and the temperature 0 K becomes −273.15 °C. To convert data given in kelvin into degrees fahrenheit (°F), the following equation can be used

$$T(^\circ\mathrm{F}) = \left(\frac{9}{5}\right)[T(\mathrm{K}) - 273.15\,\mathrm{K}]\;(^\circ\mathrm{F/K}) + 32\,^\circ\mathrm{F}\,.$$

This can be expressed approximately in words as follows: the Fahrenheit scale is shifted relative to the kelvin scale and also differs by a scaling so that its degrees are smaller than those of the kelvin scale by nearly a factor of 2.

Subdivisions B(d) of the Tables

These subdivisions of the tables present data on the *electronic, electromagnetic, and optical properties* of the elements. Data are given for:

- The electrical resistivity ρ_s in the solid state, and its temperature and pressure dependence.
- The electrical resistivity ρ_l in the liquid state, and the resistivity ratio ρ_l/ρ_s at the melting temperature.
- The critical temperature T_{cr} and critical field strength H_{cr} for superconductivity.
- The electronic band gap ΔE.
- The Hall coefficient R, together with the range of magnetic field strength B over which it was measured.
- The thermoelectric coefficient.
- The electronic work function.
- The thermal work function.
- The intrinsic charge carrier concentration.
- The electron and hole mobilities.
- The static dielectric constant ε of the element in the solid state, and in some cases also in the liquid state.
- The molar magnetic susceptibility χ_{mol} and the mass magnetic susceptibility χ_{mass} of the element in the solid state, and in some cases also in the liquid state. The susceptibilities are given in the definitions of both the SI system and the cgs system (see below).
- The refractive index n in the solid and liquid states.

The magnetic susceptibility is the parameter that describes the response of the material to an externally applied magnetic field H, as measured by the observable magnetization M, in the linear regime, via $M = \chi H$. Three different forms of the term *magnetization* are in use, depending on the specific application:

- The volume magnetization M_{vol}, equal to the magnetic dipole moment divided by the volume of the sample.
- The molar magnetization, or magnetization related to the number of particles, M_{mol}, equal to the magnetic dipole moment divided by the number of particles measures in moles.
- The mass magnetization M_{mass}, equal to the magnetic dipole moment divided by the mass of the sample.

Correspondingly, there are three different magnetic susceptibilities. The *volume susceptibility* χ_{vol} is a dimensionless number because in this case M and H are both measured in the same units, namely A/m in the SI system and gauss in the cgs system. The dimensionless character of χ_{vol} might be the reason why, in physics textbooks, mostly only this susceptibility is mentioned. The other two susceptibilities, the *molar susceptibility* χ_{mol} and the *mass susceptibility* χ_{mass}, are more useful for practical applications. In both the SI system and the cgs system, the molar susceptibility is measured in units of $\mathrm{cm}^3/\mathrm{mol}$, and the mass susceptibility is measured in units of cm^3/g. In this Handbook, data are given for the molar and mass susceptibilities.

Although susceptibilities have the same dimensions in the SI and cgs systems, the numerical values in the cgs system are smaller than those in the SI system by a factor of 4π. This is due to the different definitions of the quantities dipole moment and magnetization in the two systems. The difference can be seen most clearly in the general relations between the magnetization M and the field strengths B and H in the two systems. In the SI system, this relation reads $B = \mu_0(H + M)$, whereas in the cgs system, it reads $B = H + 4\pi M$. Because of this difference, the magnetic-susceptibility data in Sect. 4.5 are given for both the SI and the cgs definitions.

4.2.3 Parts C of the Tables

Parts C of the tables present crystallographic data for allotropic and high-pressure modifications of the elements. The left-hand columns contain data for allotropic modifications that are stable at a pressure of 100 kPa over the temperature ranges indicated, and the right-hand columns contain data for modifications stable at higher pressures as indicated. The modifications stable at 100 kPa are denoted by Greek letters in front of the chemical symbol of the element (normally starting with α for the modification stable over the lowest temperature range), and the high-pressure modifications are denoted by Roman numerals after the chemical symbol. In these parts of the tables, RT stands for *room temperature*, and RTP stands for *room temperature and standard pressure*, i. e., 100 kPa.

4.2.4 Parts D of the Tables

Parts D of the tables contain data on *ionic radii* determined from crystal structures. The first row lists the elements, and the second row lists the positive and negative ions for which data are given. The remaining rows give the ionic radii of these ions for the most common coordination numbers.

4.3 Sources

Most of the data presented here have been taken from Landolt–Börnstein [4.1]. Additional data have been taken from the D'Ans–Lax series [4.2] and the *CRC Handbook of Chemistry and Physics* [4.3].

4.4 Tables of the Elements in Different Orders

Table 4.1 The elements ordered by their names

Element	Symbol	Atomic number	Element	Symbol	Atomic number	Element	Symbol	Atomic number
Actinium	Ac	89	Hafnium	Hf	72	Praseodymium	Pr	59
Aluminum	Al	13	Hassium	Hs	108	Promethium	Pm	61
Americium	Am	95	Helium	He	2	Protactinium	Pa	91
Antimony	Sb	51	Holmium	Ho	67	Radium	Ra	88
Argon	Ar	18	Hydrogen	H	1	Radon	Rn	86
Arsenic	As	33	Indium	In	49	Rhenium	Re	75
Astatine	At	85	Iodine	I	53	Rhodium	Rh	45
Barium	Ba	56	Iridium	Ir	77	Roentgenium	Rg	111
Berkelium	Bk	97	Iron	Fe	26	Rubidium	Rb	37
Beryllium	Be	4	Krypton	Kr	36	Ruthenium	Ru	44
Bismuth	Bi	83	Lanthanum	La	57	Rutherfordium	Rf	104
Bohrium	Bh	107	Lawrencium	Lr	103	Samarium	Sm	62
Boron	B	5	Lead	Pb	82	Scandium	Sc	21
Bromine	Br	35	Lithium	Li	3	Seaborgium	Sg	106
Cadmium	Cd	48	Livermorium	Lv	116	Selenium	Se	34
Calcium	Ca	20	Lutetium	Lu	71	Silicon	Si	14
Californium	Cf	98	Magnesium	Mg	12	Silver	Ag	47
Carbon	C	6	Manganese	Mn	25	Sodium	Na	11
Cerium	Ce	58	Meitnerium	Mt	109	Strontium	Sr	38
Cesium	Cs	55	Mendelevium	Md	101	Sulfur	S	16
Chlorine	Cl	17	Mercury	Hg	80	Tantalum	Ta	73
Chromium	Cr	24	Molybdenum	Mo	42	Technetium	Tc	43
Cobalt	Co	27	Moscovium	Mc	115	Tellurium	Te	52
Copernicium	Cn	112	Neodymium	Nd	60	Tennessine	Ts	117
Copper	Cu	29	Neon	Ne	10	Terbium	Tb	65
Curium	Cm	96	Neptunium	Np	93	Thallium	Tl	81
Darmstadtium	Ds	110	Nickel	Ni	28	Thorium	Th	90
Dubnium	Db	105	Nihonium	Nh	113	Thulium	Tm	69
Dysprosium	Dy	66	Niobium	Nb	41	Tin	Sn	50
Einsteinium	Es	99	Nitrogen	N	7	Titanium	Ti	22
Erbium	Er	68	Nobelium	No	102	Tungsten	W	74
Europium	Eu	63	Oganesson	Og	118	Uranium	U	92
Fermium	Fm	100	Osmium	Os	76	Vanadium	V	23
Flerovium	Fl	114	Oxygen	O	8	Xenon	Xe	54
Fluorine	F	9	Palladium	Pd	46	Ytterbium	Yb	70
Francium	Fr	87	Phosphorus	P	15	Yttrium	Y	39
Gadolinium	Gd	64	Platinum	Pt	78	Zinc	Zn	30
Gallium	Ga	31	Plutonium	Pu	94	Zirconium	Zr	40
Germanium	Ge	32	Polonium	Po	84			
Gold	Au	79	Potassium	K	19			

Table 4.2 The elements ordered by their chemical symbols

Element	Symbol	Atomic number	Element	Symbol	Atomic number	Element	Symbol	Atomic number
Actinium	Ac	89	Germanium	Ge	32	Polonium	Po	84
Silver	Ag	47	Hydrogen	H	1	Praseodymium	Pr	59
Aluminum	Al	13	Helium	He	2	Platinum	Pt	78
Americium	Am	95	Mercury	Hg	80	Plutonium	Pu	94
Argon	Ar	18	Hafnium	Hf	72	Radium	Ra	88
Arsenic	As	33	Holmium	Ho	67	Rubidium	Rb	37
Astatine	At	85	Hassium	Hs	108	Rhenium	Re	75
Gold	Au	79	Iodine	I	53	Rutherfordium	Rf	104
Boron	B	5	Indium	In	49	Roentgenium	Rg	111
Barium	Ba	56	Iridium	Ir	77	Rhodium	Rh	45
Beryllium	Be	4	Potassium	K	19	Radon	Rn	86
Bohrium	Bh	107	Krypton	Kr	36	Ruthenium	Ru	44
Bismuth	Bi	83	Lanthanum	La	57	Sulfur	S	16
Berkelium	Bk	97	Lithium	Li	3	Antimony	Sb	51
Bromine	Br	35	Lawrencium	Lr	103	Scandium	Sc	21
Carbon	C	6	Lutetium	Lu	71	Selenium	Se	34
Calcium	Ca	20	Livermorium	Lv	116	Seaborgium	Sg	106
Cadmium	Cd	48	Moscovium	Mc	115	Silicon	Si	14
Cerium	Ce	58	Mendelevium	Md	101	Samarium	Sm	62
Californium	Cf	98	Magnesium	Mg	12	Tin	Sn	50
Chlorine	Cl	17	Manganese	Mn	25	Strontium	Sr	38
Curium	Cm	96	Molybdenum	Mo	42	Tantalum	Ta	73
Copernicium	Cn	112	Meitnerium	Mt	109	Terbium	Tb	65
Cobalt	Co	27	Nitrogen	N	7	Technetium	Tc	43
Chromium	Cr	24	Sodium	Na	11	Tellurium	Te	52
Cesium	Cs	55	Niobium	Nb	41	Thorium	Th	90
Copper	Cu	29	Neodymium	Nd	60	Titanium	Ti	22
Dubnium	Db	105	Neon	Ne	10	Thallium	Tl	81
Darmstadtium	Ds	110	Nihonium	Nh	113	Thulium	Tm	69
Dysprosium	Dy	66	Nickel	Ni	28	Tennessine	Ts	117
Erbium	Er	68	Nobelium	No	102	Uranium	U	92
Einsteinium	Es	99	Neptunium	Np	93	Vanadium	V	23
Europium	Eu	63	Oxygen	O	8	Tungsten	W	74
Fluorine	F	9	Oganesson	Og	118	Xenon	Xe	54
Flerovium	Fl	114	Osmium	Os	76	Yttrium	Y	39
Iron	Fe	26	Phosphorus	P	15	Ytterbium	Yb	70
Fermium	Fm	100	Protactinium	Pa	91	Zinc	Zn	30
Francium	Fr	87	Lead	Pb	82	Zirconium	Zr	40
Gallium	Ga	31	Palladium	Pd	46			
Gadolinium	Gd	64	Promethium	Pm	61			

Table 4.3 The elements ordered by their atomic numbers

Element	Symbol	Atomic number	Element	Symbol	Atomic number	Element	Symbol	Atomic number
Hydrogen	H	1	Niobium	Nb	41	Thallium	Tl	81
Helium	He	2	Molybdenum	Mo	42	Lead	Pb	82
Lithium	Li	3	Technetium	Tc	43	Bismuth	Bi	83
Beryllium	Be	4	Ruthenium	Ru	44	Polonium	Po	84
Boron	B	5	Rhodium	Rh	45	Astatine	At	85
Carbon	C	6	Palladium	Pd	46	Radon	Rn	86
Nitrogen	N	7	Silver	Ag	47	Francium	Fr	87
Oxygen	O	8	Cadmium	Cd	48	Radium	Ra	88
Fluorine	F	9	Indium	In	49	Actinium	Ac	89
Neon	Ne	10	Tin	Sn	50	Thorium	Th	90
Sodium	Na	11	Antimony	Sb	51	Protactinium	Pa	91
Magnesium	Mg	12	Tellurium	Te	52	Uranium	U	92
Aluminum	Al	13	Iodine	I	53	Neptunium	Np	93
Silicon	Si	14	Xenon	Xe	54	Plutonium	Pu	94
Phosphorus	P	15	Cesium	Cs	55	Americium	Am	95
Sulfur	S	16	Barium	Ba	56	Curium	Cm	96
Chlorine	Cl	17	Lanthanum	La	57	Berkelium	Bk	97
Argon	Ar	18	Cerium	Ce	58	Californium	Cf	98
Potassium	K	19	Praseodymium	Pr	59	Einsteinium	Es	99
Calcium	Ca	20	Neodymium	Nd	60	Fermium	Fm	100
Scandium	Sc	21	Promethium	Pm	61	Mendelevium	Md	101
Titanium	Ti	22	Samarium	Sm	62	Nobelium	No	102
Vanadium	V	23	Europium	Eu	63	Lawrencium	Lr	103
Chromium	Cr	24	Gadolinium	Gd	64	Rutherfordium	Rf	104
Manganese	Mn	25	Terbium	Tb	65	Dubnium	Db	105
Iron	Fe	26	Dysprosium	Dy	66	Seaborgium	Sg	106
Cobalt	Co	27	Holmium	Ho	67	Bohrium	Bh	107
Nickel	Ni	28	Erbium	Er	68	Hassium	Hs	108
Copper	Cu	29	Thulium	Tm	69	Meitnerium	Mt	109
Zinc	Zn	30	Ytterbium	Yb	70	Darmstadtium	Ds	110
Gallium	Ga	31	Lutetium	Lu	71	Roentgenium	Rg	111
Germanium	Ge	32	Hafnium	Hf	72	Copernicium	Cn	112
Arsenic	As	33	Tantalum	Ta	73	Nihonium	Nh	113
Selenium	Se	34	Tungsten	W	74	Flerovium	Fl	114
Bromine	Br	35	Rhenium	Re	75	Moscovium	Mc	115
Krypton	Kr	36	Osmium	Os	76	Livermorium	Lv	116
Rubidium	Rb	37	Iridium	Ir	77	Tennessine	Ts	117
Strontium	Sr	38	Platinum	Pt	78	Oganesson	Og	118
Yttrium	Y	39	Gold	Au	79			
Zirconium	Zr	40	Mercury	Hg	80			

Table 4.4 The elements ordered according to the Periodic Table

							Tables
Elements of the first period							**4.6–4.11**
1 Hydrogen	1 Deuterium	1 Tritium	2 Helium-4	2 Helium-3			
Elements of Group IA							**4.12–4.18**
3 Lithium	11 Sodium	19 Potassium	37 Rubidium	55 Cesium	87 Francium		
Elements of Group IB							**4.19–4.24**
29 Copper	47 Silver	79 Gold	111 Roentgenium				
Elements of Group IIA							**4.25–4.31**
4 Beryllium	12 Magnesium	20 Calcium	38 Strontium	56 Barium	88 Radium		
Elements of Group IIB							**4.32–4.38**
30 Zinc	48 Cadmium	80 Mercury	112 Copernicium				
Elements of Group IIIA							**4.39–4.45**
5 Boron	13 Aluminum	31 Gallium	49 Indium	81 Thallium	113 Nihonium		
Elements of Group IIIB							**4.46–4.52**
21 Scandium	39 Yttrium	57 Lanthanum	89 Actinium				
Elements of Group IVA							**4.53–4.59**
6 Carbon	14 Silicon	32 Germanium	50 Tin	82 Lead	114 Flerovium		
Elements of Group IVB							**4.60–4.66**
22 Titanium	40 Zirconium	72 Hafnium	104 Rutherfordium				
Elements of Group VA							**4.67–4.73**
7 Nitrogen	15 Phosphorus	33 Arsenic	51 Antimony	83 Bismuth	115 Moscovium		
Elements of Group VB							**4.74–4.79**
23 Vanadium	41 Niobium	73 Tantalum	105 Dubnium				
Elements of Group VIA							**4.80–4.86**
8 Oxygen	16 Sulfur	34 Selenium	52 Tellurium	84 Polonium	116 Livermorium		
Elements of Group VIB							**4.87–4.93**
24 Chromium	42 Molybdenum	74 Tungsten	106 Seaborgium				
Elements of Group VIIA							**4.94–4.100**
9 Fluorine	17 Chlorine	35 Bromine	53 Iodine	85 Astatine	117 Tennessine		
Elements of Group VIIB							**4.101–4.107**
25 Manganese	43 Technetium	75 Rhenium	107 Bohrium				
Elements of Group VIIIA							**4.108–4.113**
10 Neon	18 Argon	36 Krypton	54 Xenon	86 Radon	118 Oganesson		
Elements of Group VIII(1)							**4.114–4.120**
26 Iron	44 Ruthenium	76 Osmium	108 Hassium				
Elements of Group VIII(2)							**4.121–4.127**
27 Cobalt	45 Rhodium	77 Iridium	109 Meitnerium				
Elements of Group VIII(3)							**4.128–4.133**
28 Nickel	46 Palladium	78 Platinum	110 Darmstadtium				
Lanthanides							**4.134–4.140**
58 Cerium	59 Praseodymium	60 Neodymium	61 Promethium	62 Samarium	63 Europium	64 Gadolinium	
65 Terbium	66 Dysprosium	67 Holmium	68 Erbium	69 Thulium	70 Ytterbium	71 Lutetium	
Actinides							**4.141–4.147**
90 Thorium	91 Protactinium	92 Uranium	93 Neptunium	94 Plutonium	95 Americium	96 Curium	
97 Berkelium	98 Californium	99 Einsteinium	100 Fermium	101 Mendelevium	102 Nobelium	103 Lawrencium	

Table 4.5 Periodic Table of the elements

Periodic Table of the Elements

18 VIIIA	IUPAC Notation CAS Notation
2 He	Atomic number Element symbol
	Unstable nuclei

Main Groups

1 IA	2 IIA	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA	Shells
1 H							2 He	K
3 Li	4 Be	5 B	6 C	7 N	8 O	9 F	10 Ne	K–L
11 Na	12 Mg	13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	K–L–M
19 K	20 Ca	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	–L–M–N
37 Rb	38 Sr	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	–M–N–O
55 Cs	56 Ba	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn	–N–O–P
87 Fr	88 Ra	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og	–O–P–Q

Subgroups

3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIII (1)	9 VIII (2)	10 VIII (3)	11 IB	12 IIB	Shells
21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	–L–M–N
39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	–M–N–O
57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	–N–O–P
89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	–O–P–Q

Lanthanides (Shells –N–O–P)

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu

Actinides (Shells –O–P–Q)

90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

4.5 Data

4.5.1 Elements of the First Period

Table 4.6 Elements of the first period (hydrogen and helium). Part A : Atomic, ionic, and molecular properties

Element name	**Hydrogen**			**Helium**			
Special name	**Hydrogen**	**Deuterium**	**Tritium**	**Helium 4**	**Helium 3**		
Chemical symbol	**H**	**^{2}H or D**	**^{3}H or T**	**^{4}He**	**^{3}He**		
Atomic number Z	**1**	**1**	**1**	**2**	**2**	**Units**	**Remarks**
Characteristics			Radioactive				
Half-life			12.32			y	
Relative atomic mass A (atomic weight)	[1.00784; 1.00811]	2.014101(8)	3.01605	4.002602(2)			
Abundance in lithosphere	1400×10^{-6}	1.4×10^{-4}		4.2×10^{-7}			Mass ratio
Abundance in sea	110×10^{-3}						Mass ratio
Atomic radius r_{cov}	30					pm	Covalent radius
Atomic radius r_{met}				140		pm	Metallic radius, CN[a] = 12
Atomic radius r_{vdW}	140			140		pm	van der Waals radius
Electron shells	K	K	K	K	K		
Electronic ground state	$^2S_{1/2}$	$^2S_{1/2}$	$^2S_{1/2}$	$^1S_0$	$^1S_0$		
Electronic configuration	$1s^1$	$1s^1$	$1s^1$	$1s^2$	$1s^2$		
Oxidation states	1−, 1+						
Electron affinity	0.754			0.19		eV	
Electronegativity χ_A	2.20			3.20			Allred and Rochow
1st ionization energy	13.59844			24.58741		eV	
2nd ionization energy				54.41778		eV	
Standard electrode potential E^0	0.00000					V	Reaction $2H^+ + 2e^- = H_2$
Molecular form in gaseous state	H_2						
Internuclear distance	74.166					pm	
Dissociation energy in molecule	4.475					eV	Extrapolated to $T = 0$ K

[a] Coordination number

Table 4.7 Elements of the first period (hydrogen and helium). Part B(a): Crystallographic properties (for allotropic and high-pressure modifications, Table 4.11)

Element name	**Hydrogen**			**Helium**			
Special name	**Hydrogen**	**Deuterium**	**Tritium**	**Helium 4**	**Helium 3**		
Chemical symbol	**H**	**^{2}H or D**	**^{3}H or T**	**^{4}He**	**^{3}He**		
Atomic number Z	**1**	**1**	**1**	**2**	**2**	**Units**	**Remarks**
State	H_2 at 4.2 K			At 1.5 K			
Crystal system, Bravais lattice	hex			hex			
Structure type	Mg			Mg			
Lattice constant a	377.1			357.7		pm	
Lattice constant c	615.6			584.2			
Space group	$P6_3/mmc$			$P6_3/mmc$			
Schoenflies symbol	D^4_{6h}			D^4_{6h}			
Strukturbericht type	A3			AQ3			
Pearson symbol	hP2			hP2			
Number A of atoms per cell	2			2			
Coordination number	12			12			
Shortest interatomic distance, solid				357		pm	

Table 4.8 Elements of the fist period (hydrogen and helium). Part B(b): Mechanical properties

Element name	Hydrogen			Helium			
Special name	Hydrogen	Deuterium	Tritium	Helium 4	Helium 3		
Chemical symbol	H	^{2}H or D	^{3}H or T	^{4}He	^{3}He		
Atomic number Z	1	1	1	2	2	Units	Remarks
State	H_2	D_2					
Density ϱ, liquid		0.162	0.260			g/cm^3	Near T_m
Density ϱ, gas	0.0899×10^{-3}	0.0032[a]	0.0031[a]	0.1785×10^{-3}		g/cm^3	At 273 K[b]
Molar volume V_{mol}, gas	13.26			32.07		cm^3/mol	
Viscosity η, gas	8.67					mPa s	At 293 K, 101 kPa
Sound velocity, gas	1237			969 (STP)		m/s	STP
Sound velocity, liquid	1340					m/s	At T_m, 12 MHz
Elastic modulus E	0.2			0.1		GPa	Solid state, estimated
Elastic compliance s_{11}	2930 (4.2 K)	1400 (4.2 K)		$+226 \times 10^3$ (1.6 K)	$+202 \times 10^3$ (0.4 K)	1/TPa	
Elastic compliance s_{33}	2000 (4.2 K)	995 (4.2 K)					
Elastic compliance s_{44}	9090 (4.2 K)	4350 (4.2 K)		$+46 \times 10^3$ (1.6 K)	$+108 \times 10^3$ (0.4 K)	1/TPa	
Elastic compliance s_{12}	−1240 (4.2 K)	−490 (4.2 K)		-107×10^3 (1.6 K)	-91.6×10^3 (0.4 K)	1/TPa	
Elastic compliance s_{13}	−166 (4.2 K)	−81 (4.2 K)					
Elastic stiffness c_{11}	0.042 (4.2 K)	0.82 (4.2 K)		$+31.1 \times 10^{-3}$ (1.6 K)	$+20.0 \times 10^{-3}$ (0.4 K)	GPa	
Elastic stiffness c_{33}	0.51 (4.2 K)	1.02 (4.2 K)					
Elastic stiffness c_{44}	0.11 (4.2 K)	0.23 (4.2 K)		$+21.7 \times 10^{-3}$ (1.6 K)	$+9.2 \times 10^{-3}$ (0.4 K)	GPa	
Elastic stiffness c_{12}	0.18 (4.2 K)	0.29 (4.2 K)		$+28.1 \times 10^{-3}$ (1.6 K)	16.4×10^{-3} (0.4 K)	GPa	
Elastic stiffness c_{13}	0.05 (4.2 K)						
Solubility in water α_W	0.0178[b]			0.0086			

[a] At 25 K; [b] 101.3 kPa H_2 pressure

Table 4.9 Elements of the first period (hydrogen and helium). Part B(c): Thermal and thermodynamic properties

Element name	Hydrogen			Helium			
Special name	Hydrogen	Deuterium	Tritium	Helium 4	Helium 3		
Chemical symbol	H	^{2}H or D	^{3}H or T	^{4}He	^{3}He		
Atomic number Z	1	1	1	2	2	Units	Remarks
State	H_2 gas			He gas			
Thermal conductivity λ	0.171			143.0×10^{-3}		W/(m K)	At 300 K
Molar heat capacity c_p	14.418			20.786		J/(mol K)	At 298 K
Standard entropy S^0	130.680			126.152		J/(mol K)	At 298 K and 100 kPa
Enthalpy difference $H_{298} - H_0$	8.4684			6.1965		kJ/mol	At 298 K
Melting temperature T_m	13.81	18.65	20.65	0.95[a]		K	
Enthalpy change ΔH_m	0.12			0.021		kJ/mol	
Boiling temperature T_b	20.30	23.65	25.05	4.215	3.2	K	
Enthalpy change ΔH_b	0.46			0.082		kJ/mol	
Sublimation enthalpy	0.376			0.060		kJ/mol	At 0 K
Critical temperature T_c	33.2	38.55	39.95	5.23		K	
Critical pressure p_c	1.297	1.645		0.229		MPa	
Critical density ϱ_c	0.03102			69.3×10^{-3}		g/cm^3	
Triple-point temperature T_{tr}	14.0			[b]		K	
Triple-point pressure p_{tr}	7.2					kPa	
λ point				2.184	0.0027	K	

[a] At 2.6 MPa; [b] He does not have a triple point

Table 4.10 Elements of the first period (hydrogen and helium). Part B(d): Electronic, electromagnetic, and optical properties

Element name	**Hydrogen**			**Helium**			
Special name	**Hydrogen**	**Deuterium**	**Tritium**	**Helium 4**	**Helium 3**		
Chemical symbol	**H**	**^{2}H or D**	**^{3}H or T**	**^{4}He**	**^{3}He**		
Atomic number Z	**1**	**1**	**1**	**2**	**2**	**Units**	**Remarks**
State	H_2 gas			He gas			
Characteristics	Light gas			Noble gas			
Dielectric constant $(\varepsilon - 1)$, gas	$+264 \times 10^{-6}$			$+68 \times 10^{-6}$			At 273 K
Dielectric constant ε, liquid	1.225			1.048 (3.15 K)			At 20.30 K
Dielectric constant ε, solid							
Molar magnetic susceptibility χ_{mol}, gas (SI system)	-50.1×10^{-6}			-25.4×10^{-6}		cm^3/mol	At 295 K
Molar magnetic susceptibility χ_{mol}, gas (cgs system)	-3.99×10^{-6}			-2.02×10^{-6}		cm^3/mol	At 295 K
Mass magnetic susceptibility χ_{mass}, liquid (SI system)	-68.4×10^{-6}					cm^3/mol	At 20.3 K
Mass magnetic susceptibility χ_{mass}, liquid (cgs system)	-5.44×10^{-6}					cm^3/mol	At 20.3 K
Mass magnetic susceptibility χ_{mass}, gas (SI system)	-25×10^{-6}			-5.9×10^{-6}		cm^3/g	At 295 K
Refractive index $(n - 1)$, gas	132×10^{-6}			36×10^{-6}			At 273.15 K, 101×10^5 Pa, $\lambda = 589.3$ nm
Refractive index n, liquid	1.112			1.026 (3.7 K)			$\lambda = 589.3$ nm

Table 4.11 Elements of the first period (hydrogen and helium). Part C: Allotropic and high-pressure modifications

Element name	**Hydrogen**		**Helium**			
Modification	**α-H (H_2)**	**β-H (H_2)**	**α-He**	**β-He**	**γ-He**	**Units**
Crystal system, Bravais lattice	cub, fc	hex, cp	hex, cp	cub, fc	cub, bc	
Structure type	Cu	Mg	Mg	Cu	W	
Lattice constant a	533.4	377.1	357.7	4240	4110	pm
Lattice constant c		615.6	584.2			pm
Space group	$Fm\bar{3}m$	$P6_3/mmc$	$P6_3/mmc$	$Fm\bar{3}m$	$Im\bar{3}m$	
Schoenflies symbol	O_h^5	D_{6h}^4	D_{6h}^4	O_h^5	O_h^9	
Strukturbericht type	A1	A3	A3	A1	A2	
Pearson symbol	cF4	hP2	hP2	cF4	cI2	
Number A of atoms per cell	4	2	2	4	2	
Coordination number	12	12	12	12	8	
Shortest interatomic distance, solid			357	300	356	pm
Range of stability	< 1.25 K	< 13.81 K	< 0.95 K	1.6 K; 0.125 GPa	1.73 K; 0.03 GPa	

Table 4.12 Elements of Group IA (chemically active species (CAS) notation), or Group 1 (new International Union of Pure and Applied Chemistry (IUPAC) notation). Part A: Atomic, ionic, and molecular properties (see Table 4.18 for ionic radii)

Element name **Chemical symbol** **Atomic number Z**	**Lithium** **Li** **3**	**Sodium** **Na** **11**	**Potassium** **K** **19**	**Rubidium** **Rb** **37**	**Cesium** **Cs** **55**	**Francium** **Fr** **87**	**Units**	**Remarks**
Characteristics						Radioactive		
Relative atomic mass A (atomic weight)	[6.938; 6.997]	22.98976928(2)	39.0983(1)	85.4678(3)	132.90545196(6)	[223]		
Abundance in lithosphere	65×10^{-6}	$28\,300\times10^{-6}$	$25\,900\times10^{-6}$	280×10^{-6}	3.2×10^{-6}			Mass ratio
Abundance in sea	0.18×10^{-6}	$10\,770\times10^{-6}$	380×10^{-6}	0.12×10^{-6}	4×10^{-10}			Mass ratio
Atomic radius r_{cov}	123	157	203	216	253		pm	Covalent radius
Atomic radius r_{met}	156	192	238	250	272		pm	Metallic radius, CN = 12
Atomic radius r_{os}	158.6	171.3	216.2	228.7	251.8	244.7	pm	Outer-shell orbital radius
Atomic radius r_{vdW}	180	230	280	244	262		pm	van der Waals radius
Electron shells	KL	KLM	–LMN	–MNO	–NOP	–OPQ		
Electronic ground state	$^2S_{1/2}$	$^2S_{1/2}$	$^2S_{1/2}$	$^2S_{1/2}$	$^2S_{1/2}$	$^2S_{1/2}$		
Electronic configuration	[He] $2s^1$	[Ne] $3s^1$	[Ar] $4s^1$	[Kr] $5s^1$	[Xe] $6s^1$	[Rn] $7s^1$		
Oxidation states	1+	1+	1+	1+	1+	1+		
Electron affinity	0.618	0.548	0.501	0.486	0.472	0.46	eV	
Electronegativity χ_A	0.97	1.01	0.91	0.89	0.86	(0.86)		Allred and Rochow
1st ionization energy	5.39172	5.13908	4.34066	4.17713	3.89390	4.0727	eV	
2nd ionization energy	75.64018	47.2864	31.63	27.285	23.15745		eV	
3rd ionization energy	122.45429	71.6200	45.806	40			eV	
4th ionization energy		98.91	60.91	52.6			eV	
Standard electrode potential E^0	−3.040	−2.71	−2.931	−2.98	−2.92		V	Reaction type $Li^+ + e^- = Li$

Table 4.13 Elements of Group IA (CAS notation), or Group 1 (new IUPAC notation). Part B(a): Crystallographic properties (see Table 4.17 for allotropic and high-pressure modifications)

Element name **Chemical symbol** **Atomic number *Z***	**Lithium** **Li** **3**	**Sodium** **Na** **11**	**Potassium** **K** **19**	**Rubidium** **Rb** **37**	**Cesium** **Cs** **55**	**Francium** **Fr** **87**	**Units**	**Remarks**
Modification	β-Li	β-Na				Cs-I		
Crystal system, Bravais lattice	cub, bc	cub, bc	cub, bc	cub, bc	cub, bc			
Structure type	W	W	W	W	W			
Lattice constant *a*	350.93	420.96	532.1	570.3	614.1		pm	
Space group	$Im\bar{3}m$	$Im\bar{3}m$	$Im\bar{3}m$	$Im\bar{3}m$	$Im\bar{3}m$			
Schoenflies symbol	O_h^9	O_h^9	O_h^9	O_h^9	O_h^9			
Strukturbericht type	A2	A2	A2	A2	A2			
Pearson symbol	cI2	cI2	cI2	cI2	cI2			
Number *A* of atoms per cell	2	2	2	2	2			
Coordination number	8	8	8	8	8			
Shortest interatomic distance, solid	303	371	462	487	524		pm	
Shortest interatomic distance, liquid				497 (313 K)			pm	

Table 4.14 Elements of Group IA (CAS notation), or Group 1 (new IUPAC notation). Part B(b): Mechanical properties

Element name **Chemical symbol** **Atomic number Z**	**Lithium** **Li** **3**	**Sodium** **Na** **11**	**Potassium** **K** **19**	**Rubidium** **Rb** **37**	**Cesium** **Cs** **55**	**Francium** **Fr** **87**	**Units**	**Remarks**
Density ϱ, solid	0.532	0.970	0.862	1.532	1.87	2.410	g/cm^3	
Density ϱ, liquid	0.508 (453 K)	0.927	0.827	1.470	1.847		g/cm^3	Near T_m
Molar volume V_{mol}	13.00	23.68	45.36	55.79	70.96	9.25	cm^3/mol	
Viscosity η, liquid	0.566 (473 K)	0.565 (416 K)	0.64	0.52			mPa s	
Surface tension, liquid Temperature coefficient	0.396	0.193 -0.05×10^{-3}	0.116 -0.06×10^{-3}	0.092	0.060 -0.046×10^{-3}		N/m N/(m K)	
Coefficient of linear thermal expansion α	56×10^{-6}	70.6×10^{-6}	83×10^{-6}	90×10^{-6}	97×10^{-6}		1/K	At 298 K
Sound velocity, liquid		2395 (371 K)		1260	967		m/s	At T_m, at 12 MHz
Sound velocity, solid, transverse	2820	1620	1230	770	590		m/s	
Sound velocity, solid, longitudinal	6030	3310	2600	1430	1090		m/s	
Compressibility κ	8.93×10^{-5}	13.4×10^{-5}	23.7×10^{-5}	33.0×10^{-5}	0.75×10^{-5}		1/MPa	Volume compressibility
Elastic modulus E	11.5	6.80	3.52	2.35	1.69		GPa	
Shear modulus G	4.24	2.94	1.28	0.91	0.65		GPa	
Poisson number μ	0.36	0.34	0.35	0.29	0.30			
Elastic compliance s_{11}	315	549	1339	1330	1190 (280 K)		1/TPa	
Elastic compliance s_{44}	104	233	526	625	690 (280 K)		1/TPa	
Elastic compliance s_{12}	−144	−250	−620	−600	−450 (280 K)		1/TPa	
Elastic stiffness c_{11}	13.4	7.59	3.69	2.96	1.60 (280 K)		GPa	
Elastic stiffness c_{44}	9.6	4.30	1.90	1.60	1.44 (280 K)		GPa	
Elastic stiffness c_{12}	11.3	6.33	3.18	2.44	0.99 (280 K)		GPa	
Tensile strength	0.6						MPa	
Vickers hardness				0.37	0.15			
Mohs hardness	0.6							

Table 4.15 Elements of Group IA (CAS notation), or Group 1 (new IUPAC notation). Part B(c): Thermal and thermodynamic properties

Element name **Chemical symbol** **Atomic number Z**	**Lithium** **Li** **3**	**Sodium** **Na** **11**	**Potassium** **K** **19**	**Rubidium** **Rb** **37**	**Cesium** **Cs** **55**	**Francium** **Fr** **87**	**Units**	**Remarks**
Thermal conductivity λ	84.7	141	102.4	58.2	35.9		W/(m K)	At 300 K
Molar heat capacity c_p	24.77	28.24	29.58	31.062	32.18		J/(mol K)	At 298 K
Standard entropy S^0	29.120	51.300	64.680	76.776	85.230	101.00	J/(mol K)	At 298 K and 100 kPa
Enthalpy difference $H_{298} - H_0$	4.6320	6.4600	7.0880	7.4890	7.7110	10.000	kJ/mol	
Melting temperature T_m	453.69	370.87	336.86	312.47	301.59	300	K	
Enthalpy change ΔH_m	3.0000	2.5970	2.3208	2.1924	2.0960		kJ/mol	
Entropy change ΔS_m	6.612	7.002	6.890	7.016	6.950		J/(mol K)	
Relative volume change ΔV_m	0.0151	0.027	0.0291	0.0228	0.0263			$(V_l - V_s)/V_l$ at T_m
Boiling temperature T_b	1620	1156	1040	970	947	950 (estimated)	K	
Enthalpy change ΔH_b	147.7	99.2	79.1	75.7	67.7		kJ/mol	
Critical temperature T_c		2500	2280		2010		K	
Critical pressure p_c		25.3	16.1		11.3		MPa	
Critical density ϱ_c		0.210	0.190		0.410		g/cm^3	

Table 4.16 Elements of Group IA (CAS notation), or Group 1 (new IUPAC notation). Part B(d): Electronic, electromagnetic, and optical properties

Element name **Chemical symbol** **Atomic number *Z***	**Lithium** **Li** **3**	**Sodium** **Na** **11**	**Potassium** **K** **19**	**Rubidium** **Rb** **37**	**Cesium** **Cs** **55**	**Francium** **Fr** **87**	**Units**	**Remarks**
Characteristics	Very reactive metal	Reactive metal	Soft, reactive metal	Soft, reactive metal	Alkali metal	Alkali metal		
Electrical resistivity ρ_s	85.5	42	61	116	188		nΩ m	Solid, at 293 K
Temperature coefficient	48.9×10^{-4}	54.6×10^{-4}	67.3×10^{-4}	63.7×10^{-4}	50.3×10^{-4}		1/K	Solid
Pressure coefficient	-2.1×10^{-9}	-38.3×10^{-9}	-69.7×10^{-9}	-62.9×10^{-9}	0.5×10^{-9}		1/hPa	Solid
Electrical resistivity ρ_l	240 at T_m		129.7	220	367		nΩ m	Liquid
Resistivity ratio at T_m	1.68	1.44	1.56	1.612	1.66			ρ_l/ρ_s at T_m
Hall coefficient R^a	-1.70×10^{-10}	-2.1×10^{-10}	-4.2×10^{-10}	-5.92×10^{-10}	-7.8×10^{-10}		$m^3/(A\,s)$	At 300 K
Thermoelectric coefficient	14.37		12	−8.26	0.2		μV/K	
Electronic work function	2.28	2.75	2.30	2.05	1.94		V	
Thermal work function	2.39		2.15	2.13	1.87		V	
Molar magnetic susceptibility χ_{mol}, solid (SI)	178×10^{-6}	201×10^{-6}	261×10^{-6}	214×10^{-6}	364×10^{-6}		cm^3/mol	At 295 K
Molar magnetic susceptibility χ_{mol}, solid (cgs)	14.2×10^{-6}	16×10^{-6}	20.8×10^{-6}	17×10^{-6}	29×10^{-6}		cm^3/mol	At 295 K
Mass magnetic susceptibility χ_{mass}, solid (SI)	25.6×10^{-6}	8.8×10^{-6}	6.7×10^{-6}	2.49×10^{-6}	2.8×10^{-6}		cm^3/g	At 295 K
Mass magnetic susceptibility χ_{mass}, liquid (SI)					2.6×10^{-6}		cm^3/g	
Refractive index n, solid		4.22	0.024 (134 nm)					$\lambda = 589.3$ nm
Refractive index n, liquid		0.0045						$\lambda = 589.3$ nm

[a] $B = 1-3$ T

Table 4.17 Elements of Group IA (CAS notation), or Group 1 (new IUPAC notation). Part C: Allotropic and high-pressure modifications

Element	Lithium			Sodium		Cesium			
Modification	α-Li	β-Li	γ-Li	α-Na	β-Na	Cs-I	Cs-II	Cs-III	Units
Crystal system, Bravais lattice	hex, cp	cub, bc	cub, fc	hex, cp	cub, bc	cub, bc	cub, fc	cub, fc	
Structure type	Mg	W	Cu	Mg	W	W	Cu	Cu	
Lattice constant *a*	311.1	309.3		376.7	420.96	614.1	598.4	580.0	pm
Lattice constant *c*	509.3			615.4					
Space group	$P6_3/mmc$	$Im\bar{3}m$	$Fm\bar{3}m$	$P6_3/mmc$	$Im\bar{3}m$	$Im\bar{3}m$	$Fm\bar{3}m$	$Fm\bar{3}m$	
Schoenflies symbol	D_{6h}^4	O_h^9	O_h^5	D_{6h}^4	O_h^9	O_h^9	O_h^5	O_h^5	
Strukturbericht type	A3	A2	A1	A3	A2	A2	A1	A1	
Pearson symbol	hP2	cI2	cF4	hP2	cI2	cI2	cF4	cF4	
Number *A* of atoms per cell	2	2	4	2	2	2	4	4	
Coordination number	6 + 6	8	12	12	8	8	12	12	
Shortest interatomic distance, solid	310	303	310	377	371	524	457	410	pm
Range of stability	< 72 K	RT		< 36 K	RT	RTP	> 2.37 GPa	> 4.22 GPa	

Table 4.18 Elements of Group IA (CAS notation), or Group 1 (new IUPAC notation). Part D: Ionic radii (determined from crystal structures)

Element	Lithium	Sodium	Potassium	Rubidium	Cesium	Francium	
Ion	Li^+	Na^+	K^+	Rb^+	Cs^+	Fr^+	
Coordination number							Units
4	59	99	137				pm
6	76	102	138	152	167	180	pm
8	92	118	151	161	174		pm
9		124					pm
10				166	181		pm
12		139	164	172	188		pm

Table 4.19 Elements of Group IB (CAS notation), or Group 11 (new IUPAC notation). Part A: Atomic, ionic, and molecular properties (see Table 4.24 for ionic radii)

Element name **Chemical symbol** **Atomic number *Z***	**Copper** **Cu** **29**	**Silver** **Ag** **47**	**Gold** **Au** **79**	**Roentgenium** **Rg** **111**	**Units**	**Remarks**
Relative atomic mass A_r (atomic weight)	63.546(3)	107.8682(2)	196.966569(5)			
Abundance in lithosphere	70×10^{-6}	2.0×10^{-6}	3×10^{-9}			Mass ratio
Abundance in sea	5×10^{-10}	4×10^{-11}	4×10^{-12}			Mass ratio
Atomic radius r_{cov}	117	134	134		pm	Covalent radius
Atomic radius r_{met}	128	144	144		pm	Metallic radius, CN = 12
Atomic radius r_{vdW}	140	170	170		pm	van der Waals radius
Electron shells	–LMN	–MNO	–NOP			
Electronic ground state	$^2S_{1/2}$	$^2S_{1/2}$	$^2S_{1/2}$			
Electronic configuration	[Ar] $3d^{10}4s^1$	[Kr] $4d^{10}5s^1$	[Xe] $4f^{14}5d^{10}6s^1$	[Rn] $5f^{14}6d^{10}7s^1$		
Oxidation states	2+, 1+	1+	3+, 1+			
Electron affinity	1.24	1.30	2.309		eV	
Electronegativity χ_A	1.75	1.42		(1.42)		Allred and Rochow
1st ionization energy	7.72638	7.57624	9.22567		eV	
2nd ionization energy	20.29240	21.49	20.5		eV	
3rd ionization energy	36.841	34.83			eV	
4th ionization energy	57.38				eV	
Standard electrode potential E^0	+0.521	+0.7996	+1.692		V	Reaction type $Cu^+ + e^- = Cu$
	+0.342				V	Reaction type $Cu^{2+} + 2e^- = Cu$
	+0.153				V	Reaction type $Cu^{2+} + e^- = Cu^+$
			+1.498		V	Reaction type $Au^{3+} + 3e^- = Au$
			+1.401		V	Reaction type $Au^{3+} + 2e^- = Au^+$

Table 4.20 Elements of Group IB (CAS notation), or Group 11 (new IUPAC notation). Part B(a): Crystallographic properties

Element name **Chemical symbol** **Atomic number *Z***	**Copper** **Cu** **29**	**Silver** **Ag** **47**	**Gold** **Au** **79**	**Roentgenium** **Rg** **111**	**Units**	**Remarks**
Crystal system, Bravais lattice	cub, fc	cub, fc	cub, fc			
Structure type	Cu	Cu	Cu			
Lattice constant *a*	361.49	408.61	407.84		pm	At 298 K
Space group	$Fm\bar{3}m$	$Fm\bar{3}m$	$Fm\bar{3}m$			
Schoenflies symbol	O_h^5	O_h^5	O_h^5			
Strukturbericht type	A1	A1	A1			
Pearson symbol	cF4	cF4	cF4			
Number *A* of atoms per cell	4	4	4			
Coordination number	12	12	12			
Shortest interatomic distance, solid	255.6	288	288		pm	At 293 K
Shortest interatomic distance, liquid	257 (1363 K)				pm	

Table 4.21 Elements of Group IB (CAS notation), or Group 11 (new IUPAC notation). Part B(b): Mechanical properties

Element name Chemical symbol Atomic number Z	Copper Cu 29	Silver Ag 47	Gold Au 79	Roentgenium Rg 111	Units	Remarks
Density ϱ, solid	8.960	10.50	19.30	$\geq 19\,282$	g/cm^3	
Density ϱ, liquid	8.000	9.345	17.300		g/cm^3	
Molar volume V_{mol}	7.09	10.27	10.19		cm^3/mol	
Viscosity η, liquid	3.36	3.62	5.38		mPa s	At T_m
Surface tension, liquid	1.300	0.923	1.128		N/m	
Temperature coefficient	-0.18×10^{-3}	-0.13×10^{-3}	-0.10×10^{-3}		N/(m K)	
Coefficient of linear thermal expansion α	16.5×10^{-6}	19.2×10^{-6}	14.16×10^{-6}		1/K	At 298 K
Sound velocity, solid, transverse	2300	1690	1190		m/s	
Sound velocity, solid, longitudinal	4760	3640	3280		m/s	
Compressibility κ	0.702×10^{-5}	0.95×10^{-5}	0.563×10^{-5}		1/MPa	Volume compressibility
Elastic modulus E	128	80.0	78.0		GPa	
Shear modulus G	46.8	29.5	26.0		GPa	
Poisson number μ	0.34	0.38	0.42			
Elastic compliance s_{11}	15.0	23.0	23.4		1/TPa	
Elastic compliance s_{44}	13.3	22.0	23.8		1/TPa	
Elastic compliance s_{12}	−6.3	−9.8	−10.8		1/TPa	
Elastic stiffness c_{11}	169	122	191		GPa	
Elastic stiffness c_{44}	75.3	45.5	42.2		GPa	
Elastic stiffness c_{12}	122	92	162		GPa	
Tensile strength	209	125	110		MPa	At 293 K
Vickers hardness	369	251	216			At 293 K

Table 4.22 Elements of Group IB (CAS notation), or Group 11 (new IUPAC notation). Part B(c): Thermal and thermodynamic properties

Element name Chemical symbol Atomic number Z	Copper Cu 29	Silver Ag 47	Gold Au 79	Roentgenium Rg 111	Units	Remarks
Thermal conductivity λ	1401	429	317		W/(m K)	At 300 K
Molar heat capacity c_p	24.443	25.36	25.42		J/(mol K)	At 298 K
Standard entropy S^0	33.150	42.551	47.488		J/(mol K)	At 298 K and 100 kPa
Enthalpy difference $H_{298}-H_0$	5.0040	5.7446	6.0166		kJ/mol	
Melting temperature T_m	1357.77	1234.93	1337.33		K	
Enthalpy change ΔH_m	13.263	11.297	12.552		kJ/mol	
Entropy change ΔS_m	9.768	9.148	9.386		J/(mol K)	
Relative volume change	+0.0415	0.038	0.051			$(V_l-V_s)/V_l$ at T_m
Boiling temperature T_b	2843	2436	3130		K	
Enthalpy change ΔH_b	300.7	250.6	334.4		kJ/mol	

Table 4.23 Elements of Group IB (CAS notation), or Group 11 (new IUPAC notation). Part B(d): Electronic, electromagnetic, and optical properties. There is no Part C, because no allotropic or high-pressure modifications are known

Element name **Chemical symbol** **Atomic number *Z***	**Copper** **Cu** **29**	**Silver** **Ag** **47**	**Gold** **Au** **79**	**Roentgenium** **Rg** **111**	**Units**	**Remarks**
Characteristics	Metal	Noble metal	Noble metal	Transition metal		
Electrical resistivity ρ_s	16.78	147	20.5		nΩ m	At 293 K
Temperature coefficient	43.8×10^{-4}	43×10^{-4}	40.2×10^{-4}		1/K	
Pressure coefficient	-1.86×10^{-9}	-3.38×10^{-9}	-2.93×10^{-9}		1/hPa	
Electrical resistivity ρ_l	21.5		312		nΩ m	
Resistivity ratio	2.07		2.28			ρ_l/ρ_s at T_m
Hall coefficient R	-0.536×10^{-10}	-0.84×10^{-10}	-0.704×10^{-10}		$m^3/(A\,s)$	$B = 0.3$–2.2 T, 298 K
Thermoelectric coefficient	1.72	1.42	1.72		μV/K	
Electronic work function	4.65	4.26	5.1		V	
Thermal work function	4.39	4.31	4.25		V	
Molar magnetic susceptibility χ_{mol}, solid (SI)	-68.6×10^{-6}	-245×10^{-6}	-352×10^{-6}		cm^3/mol	At 295 K
Molar magnetic susceptibility χ_{mol}, solid (cgs)	-5.46×10^{-6}	-19.5×10^{-6}	-28×10^{-6}		cm^3/mol	At 295 K
Mass magnetic susceptibility χ_{mass}, solid (SI)	-1.081×10^{-6}	-2.27×10^{-6}	-1.78×10^{-6}		cm^3/g	At 295 K
Mass magnetic susceptibility χ_{mass}, liquid (SI)	-1.2×10^{-6}	-2.83×10^{-6}	-2.16×10^{-6}		cm^3/g	

Table 4.24 Elements of Group IB (CAS notation), or Group 11 (new IUPAC notation). Part D: Ionic radii (determined from crystal structures)

Element **Ion** **Coordination number**	**Copper** **Cu^+**	 **Cu^{2+}**	**Silver** **Ag^+**	 **Ag^{2+}**	**Gold** **Au^+**	 **Au^{3+}**	**Roentgenium** **Rg**	**Units**
2	46							pm
4	60	57	100	79		64		pm
6	77	73	115	94	137	85		pm
8			128					pm

Table 4.25 Elements of Group IIA (CAS notation), or Group 2 (new IUPAC notation). Part A: Atomic, ionic, and molecular properties (see Table 4.31 for ionic radii)

Element name **Chemical symbol** **Atomic number *Z***	**Beryllium** **Be** **4**	**Magnesium** **Mg** **12**	**Calcium** **Ca** **20**	**Strontium** **Sr** **38**	**Barium** **Ba** **56**	**Radium** **Ra** **88**	**Units**	**Remarks**
Characteristics						Radioactive		
Relative atomic mass A (atomic weight)	9.0121831(5)	[24.304, 24.307]	40.078(4)	87.62(1)	137.327(7)	[226]		
Abundance in lithosphere	6×10^{-6}	$20\,900\times10^{-6}$	$26\,300\times10^{-6}$	150×10^{-6}	430×10^{-6}			Mass ratio
Abundance in sea	6×10^{-13}	1290×10^{-6}	412×10^{-6}	8.0×10^{-6}	2×10^{-9}			Mass ratio
Atomic radius r_{cov}	89	136	174	191	198		pm	Covalent radius
Atomic radius r_{met}	112	160	197	215	224	230	pm	Metallic radius, CN = 12
Atomic radius r_{vdW}		170					pm	van der Waals radius
Electron shells	KL	KLM	–LMN	–MNO	–NOP	–OPQ		
Electronic ground state	$^1S_0$	$^1S_0$	$^1S_0$	$^1S_0$	$^1S_0$	$^1S_0$		
Electronic configuration	[He] $2s^2$	[Ne] $2s^2$	[Ar] $4s^2$	[Kr] $5s^2$	[Xe] $6s^2$	[Rn] $7s^2$		
Oxidation states	2+	2+	2+	2+	2+	2+		
Electron affinity	Not stable	Not stable	0.0246	0.048	0.15		eV	
Electronegativity χ_A	1.47	1.23	1.04	0.99	0.97	(0.97)		Allred and Rochow
1st ionization energy	9.32263	7.64624	6.11316	5.69484	5.21170	5.27892	eV	
2nd ionization energy	18.21116	15.03528	11.87172	11.03013	10.00390	10.14716	eV	
3rd ionization energy	153.89661	80.1437	50.9131	42.89			eV	
4th ionization energy	217.71865	109.2655	67.27	57			eV	
Standard electrode potential E^0	−1.847	−2.372	−2.868	−2.89	−2.90		V	Reaction type $Be^{2+} + 2e^- = Be$

Table 4.26 Elements of Group IIA (CAS notation), or Group 2 (new IUPAC notation). Part B(a): Crystallographic properties (see Table 4.30 for allotropic and high-pressure modifications)

Element name **Chemical symbol** **Atomic number *Z***	**Beryllium** **Be** **4**	**Magnesium** **Mg** **12**	**Calcium** **Ca** **20**	**Strontium** **Sr** **38**	**Barium** **Ba** **56**	**Radium** **Ra** **88**	**Units**	**Remarks**
Modification	α-Be		α-Ca	α-Sr				
Crystal system, Bravais lattice	hex	hex	cub, fc	cub, fc	cub, bc	cub, bc		
Structure type	Mg	Mg	Cu	Cu	W	W		
Lattice constant a	228.57	320.93	558.84	608.4	502.3	514.8	pm	
Lattice constant c	358.39	521.07					pm	
Space group	$P6_3/mmc$	$P6_3/mmc$	$Fm\bar{3}m$	$Fm\bar{3}m$	$Im\bar{3}m$	$Im\bar{3}m$		
Schoenflies symbol	D_{6h}^4	D_{6h}^4	D_h^5	D_h^5	D_h^9	D_h^9		
Strukturbericht type	A3	A3	A1	A1	A2	A2		
Pearson symbol	hP2	hP2	cF4	cF4	cI2	cI2		
Number A of atoms per cell	2	2	4	4	2	2		
Coordination number	12	$6+6$	12	12	8	8		
Shortest interatomic distance, solid	222	319	393	430	434	446	pm	

Table 4.27 Elements of Group IIA (CAS notation), or Group 2 (new IUPAC notation). Part B(b): Mechanical properties

Element name **Chemical symbol** **Atomic number Z**	**Beryllium** **Be** **4**	**Magnesium** **Mg** **12**	**Calcium** **Ca** **20**	**Strontium** **Sr** **38**	**Barium** **Ba** **56**	**Radium** **Ra** **88**	**Units**	**Remarks**
Density ϱ, solid	1.85	1.74	1.55	2.60	3.50	5.000	g/cm^3	
Density ϱ, liquid	1.420 (1770 K)	1.590	1.365	2.375	3.325		g/cm^3	
Molar volume V_{mol}	4.88	13.98	25.86	34.50	38.21	45.2	cm^3/mol	
Viscosity η, liquid		1.23	1.06				mPa s	
Surface tension γ, liquid Temperature coefficient	1.1 (1770 K)	0.563 (954 K)	0.361 -0.068×10^3	0.303	0.276 −0.095	0.45	N/m N/(m K)	
Coefficient of linear thermal expansion α	11.5×10^{-6}	26.1×10^{-6}	22×10^{-6}	23×10^{-6}	20.7×10^{-6}	20.2×10^{-6}	1/K	
Sound velocity, solid, transverse	8330	3170	2210	1520	1160		m/s	
Sound velocity, solid, longitudinal	12 720	5700	4180	2780	2080		m/s	
Compressibility κ	0.765×10^{-5}	2.88×10^{-5}	5.73×10^{-5}[a]	7.97×10^{-5}	10.0×10^{-5}		1/MPa	Volume compressibility
Elastic modulus E	286	44.4	19.6[a]	15.7	12.8	13.2[b]	GPa	
Shear modulus G	133	16.9	7.85[a]	6.03	4.84		GPa	
Poisson number μ	0.12	0.28	0.31[a]	0.28	0.28			
Elastic compliance s_{11}	3.45	22.0	104	218	157		1/TPa	
Elastic compliance s_{33}	2.87	19.7					1/TPa	
Elastic compliance s_{44}	6.16	60.9	71	135	105		1/TPa	
Elastic compliance s_{12}	−0.28	−7.8	−42	−90	−61		1/TPa	
Elastic compliance s_{13}	−0.05	−5.0					1/TPa	
Elastic stiffness c_{11}	292	59.3	22.8	10.94	12.6		GPa	
Elastic stiffness c_{33}	349	61.5					GPa	
Elastic stiffness c_{44}	163	16.4	14	7.41	9.5		GPa	
Elastic stiffness c_{12}	24	25.7	16.0	7.69	8.0		GPa	
Elastic stiffness c_{13}	6	21.4					GPa	
Tensile strength	228−352	90					GPa	
Vickers hardness	1670		130	140	42			
Brinell hardness	1060−1300	300−500						At 293 K

[a] At 348 K
[b] Estimated

Table 4.28 Elements of Group IIA (CAS notation), or Group 2 (new IUPAC notation). Part B(c): Thermal and thermodynamic properties

Element name **Chemical symbol** **Atomic number *Z***	**Beryllium** **Be** **4**	**Magnesium** **Mg** **12**	**Calcium** **Ca** **20**	**Strontium** **Sr** **38**	**Barium** **Ba** **56**	**Radium** **Ra** **88**	**Units**	**Remarks**
Thermal conductivity λ	200	171	200	35.3	18.4	18.6	W/(m K)	
Molar heat capacity c_p	16.44	24.895	25.940	26.4	28.09		J/(mol K)	At 298 K
Standard entropy S^0	9.500	32.671	41.588	55.694	62.500	69.000	J/(mol K)	At 298 K and 100 kPa
Enthalpy difference $H_{298} - H_0$	1.9500	4.9957	5.7360	6.5680	6.9100	7.2000	kJ/mol	
Melting temperature T_m	1560.0	923.00	1115.0	1050.0	1000.0	969.00	K	
Enthalpy change ΔH_m	7.8950	8.4768	8.5395	7.4310	7.1190	7.7000	kJ/mol	
Entropy change ΔS_m	5.061	9.184	7.659	7.077	7.119	7.946	J/(mol K)	
Relative volume change ΔV_m		0.042	0.047					$(V_l - V_s)/V_l$ at T_m
Boiling temperature T_b	2741	1366	1773	1685	2118		K	
Enthalpy change ΔH_b	291.58	127.4	153.6	137.19	141.5	136.7	kJ/mol	

Table 4.29 Elements of Group IIA (CAS notation), or Group 2 (new IUPAC notation). Part B(d): Electronic, electromagnetic, and optical properties

Element name **Chemical symbol** **Atomic number *Z***	**Beryllium** **Be** **4**	**Magnesium** **Mg** **12**	**Calcium** **Ca** **20**	**Strontium** **Sr** **38**	**Barium** **Ba** **56**	**Radium** **Ra** **88**	**Units**	**Remarks**
Characteristics	Light metal	Light metal	Metal	Soft metal	Soft metal	Metal		
Electrical resistivity ρ_s	28	39.4	31.6	303	500		nΩ m	At RT
Temperature coefficient	90.0×10^{-4}	41.2×10^{-4}	41.7×10^{-4}	38.2×10^{-4}	64.9×10^{-4}		1/K	
Pressure coefficient	-1.6×10^{-9}	-4.7×10^{-9}	15.2×10^{-9}	5.56×10^{-9}	-3.0×10^{-9}		1/hPa	
Electrical resistivity ρ_l	27.4						nΩ m	
Resistivity ratio		1.78						ρ_l/ρ_s at T_m
Hall coefficient R	2.4×10^{-10}	-0.83×10^{-10}					$m^3/(A\,s)$	At 300 K, $B = 1$ T
Thermoelectric coefficient		−0.4	−8.2				μV/K	
Electronic work function	4.98	3.97	2.87	2.74	2.56		V	
Thermal work function	3.37	3.46	2.76	2.35	2.29		V	
Molar magnetic susceptibility χ_{mol}, solid (SI)	-113×10^{-6}	165×10^{-6}	503×10^{-6}	1.16×10^{-3}	259×10^{-6}		cm^3/mol	At 295 K
Molar magnetic susceptibility χ_{mol}, solid (cgs)	-9.0×10^{-6}	13.1×10^{-6}	40.0×10^{-6}	92.0×10^{-6}	20.6×10^{-6}		cm^3/mol	At 295 K
Mass magnetic susceptibility χ_{mass}, solid (SI)	-13×10^{-6}	6.8×10^{-6}	14×10^{-6}	13.2×10^{-6}	1.9×10^{-6}		cm^3/g	At 295 K
Refractive index n, solid		0.37						$\lambda = 589$ nm

Table 4.30 Elements of Group IIA (CAS notation), or Group 2 (new IUPAC notation). Part C: Allotropic and high-pressure modifications

Element	Beryllium		Calcium		Strontium				
Modification	α-Be	β-Be	α-Ca	γ-Ca	α-Sr	β-Sr	γ-Sr	Sr-II	Units
Crystal system, Bravais lattice	hex, cp	cub, bc	cub, fc	cub, bc	cub, fc	hex, cp	cub, bc	cub, bc	
Structure type	Mg	W	Cu	W	Cu	Mg	W	W	
Lattice constant *a*	228.57	255.15	558.84	448.0	608.4	428	487	443.7	pm
Lattice constant *c*	358.39					705			pm
Space group	$P6_3/mmc$	$Im\bar{3}m$	$Fm\bar{3}m$	$Im\bar{3}m$	$Fm\bar{3}m$	$P6_3/mmc$	$Im\bar{3}m$	$Im\bar{3}m$	
Schoenflies symbol	D_{6h}^4	O_h^9	O_h^5	O_h^9	O_h^5	D_{6h}^4	O_h^9	O_h^9	
Strukturbericht type	A3	A2	A1	A2	A1	A3	A2	A2	
Pearson symbol	hP2	cI2	cF4	cI2	cF4	hP2	cI2	cI2	
Number *A* of atoms per cell	2	2	4	2	4	2	2	2	
Coordination number	12	8	12	8	12	12	8	8	
Shortest interatomic distance, solid	222	221	393	388	430		422		pm
Range of stability	RT	> 1523 K	RT	> 1010 K	RT	> 486 K	> 878 K	> 3.5 GPa	

Table 4.31 Elements of Group IIA (CAS notation), or Group 2 (new IUPAC notation). Part D: Ionic radii (determined from crystal structures)

Element	Beryllium	Magnesium	Calcium	Strontium	Barium	Radium	
Ion	Be^{2+}	Mg^{2+}	Ca^{2+}	Sr^{2+}	Ba^{2+}	Ra^{2+}	
Coordination number							Units
4	27	57					pm
6	45	72	100	118	135		pm
8		89	112	126	142	148	pm
10			123	136			pm
12			134	144	161	170	pm

Table 4.32 Elements of Group IIB (CAS notation), or Group 12 (new IUPAC notation). Part A: Atomic, ionic, and molecular properties (see Table 4.38 for ionic radii)

Element name **Chemical symbol** **Atomic number *Z***	**Zinc** **Zn** **30**	**Cadmium** **Cd** **48**	**Mercury** **Hg** **80**	**Copernicium** **Cn** **112**	**Units**	**Remarks**
Relative atomic mass A (atomic weight)	65.38(2)	112.411(8)	200.592(3)			
Abundance in lithosphere	80×10^{-6}	0.18×10^{-6}	0.5×10^{-6}			Mass ratio
Abundance in sea	4.9×10^{-9}	1×10^{-10}	3×10^{-11}			Mass ratio
Atomic radius r_{cov}	125	141	144		pm	Covalent radius
Atomic radius r_{met}	134	149	162		pm	Metallic radius, CN = 12
Atomic radius r_{vdW}	140	160	150		pm	van der Waals radius
Electron shells	–LMN	–MNO	–NOP			
Electronic ground state	$^1S_0$	$^1S_0$	$^1S_0$			
Electronic configuration	[Ar] $3d^{10}4s^2$	[Kr] $4d^{10}5s^2$	[Xe] $4f^{14}5d^{10}6s^2$	[Rn] $5f^{14}6d^{10}7s^2$		
Oxidation states	2+	2+	2+, 1+			
Electron affinity	Not stable	Not stable	Not stable		eV	
Electronegativity χ_A	1.66	1.46	(1.44)			Allred and Rochow
1st ionization energy	9.39405	8.99367	10.43750		eV	
2nd ionization energy	17.96440	16.90832	18.756		eV	
3rd ionization energ	39.723	37.48	34.2		eV	
4th ionization energy	59.4				eV	
Standard electrode potential E^0			+0.7973		V	Reaction type $Hg^{2+} + 2e^- = 2Hg$
	−0.7618	−0.403			V	Reaction type $Cu^{2+} + 2e^- = Cu$

Table 4.33 Elements of Group IIB (CAS notation), or Group 12 (new IUPAC notation). Part B(a): Crystallographic properties (see Table 4.37 for allotropic and high-pressure modifications)

Element name **Chemical symbol** **Atomic number *Z***	**Zinc** **Zn** **30**	**Cadmium** **Cd** **48**	**Mercury** **Hg** **80**	**Copernicium** **Cn** **112**	**Units**	**Remarks**
Modification			α-Hg			
Crystal system, Bravais lattice	hex	hex	trig, R			
Structure type	Mg	Mg	α-Hg			
Lattice constant a	266.44	297.88	300.5 (225 K)		pm	At 298 K
Lattice constant c	494.94	561.67			pm	At 298 K
Lattice angle α			70.53 (225 K)		deg	
Space group	$P6_3/mmc$	$P6_3/mmc$	$R\bar{3}m$			
Schoenflies symbol	D^4_{6h}	D^4_{6h}	D^5_{3d}			
Strukturbericht type	A3	A3	A 10			
Pearson symbol	hP2	hP2	hR1			
Number A of atoms per cell	2	2	1			
Coordination number	6 + 6	6 + 6	6 + 6			
Shortest interatomic distance, solid	266	297	299 (at 234 K)		pm	At 293 K

Table 4.34 Elements of Group IIB (CAS notation), or Group 12 (new IUPAC notation). Part B(b): Mechanical properties

Element name Chemical symbol Atomic number Z	Zinc Zn 30	Cadmium Cd 48	Mercury Hg 80	Copernicium Cn 112	Units	Remarks
Density ϱ, solid	7.14	8.65			g/cm^3	
Density ϱ, liquid	6.570	8.02	13.53 (25 °C)	$\geq$ 13.5336	g/cm^3	
Molar volume V_{mol}	9.17	13.00	14.81		cm^3/mol	
Viscosity η, liquid	2.95	2.29	1.55		mPa s	At T_m
Surface tension, liquid	0.816	0.564	0.476		N/m	
Temperature coefficient	0.25×10^{-3}	0.39×10^{-3}	-0.20×10^{-3}		N/(m K)	
Coefficient of linear thermal expansion α	25.0×10^{-6}	29.8×10^{-6}	18.1		1/K	At 298.15 K
Sound velocity, liquid	2790	2200[a]	1451		m/s	12 MHz[a]
Sound velocity, solid, transverse	2290	1690			m/s	
Sound velocity, solid, longitudinal	3890	2980			m/s	
Compressibility κ	1.65×10^{-5}	2.14×10^{-5}	3.77×10^{-5}		1/MPa	Volume compressibility
Elastic modulus E	92.7	62.3	25		GPa	
Shear modulus G	34.3	24.5			GPa	
Poisson number μ	0.29	0.30				
Elastic compliance s_{11}	8.22	12.4	154 (83 K)		1/TPa	
Elastic compliance s_{33}	27.7	34.6	45 (83 K)		1/TPa	
Elastic compliance s_{44}	25.3	53.1	151 (83 K)		1/TPa	
Elastic compliance s_{12}	0.60	−1.2	−119 (83 K)		1/TPa	
Elastic compliance s_{13}	−7.0	−9.1	−21 (83 K)		1/TPa	
Elastic compliance s_{14}			−100 (83 K)		1/TPa	
Elastic stiffness c_{11}	165	114.1	36.0 (83 K)		GPa	
Elastic stiffness c_{33}	61.8	49.9	50.5 (83 K)		GPa	
Elastic stiffness c_{44}	39.6	19.0	12.9 (83 K)		GPa	
Elastic stiffness c_{12}	31.1	41.0	28.9 (83 K)		GPa	
Elastic stiffness c_{13}	50.0	40.3	30.3 (83 K)		GPa	
Elastic stiffness c_{14}			4.7 (83 K)		GPa	
Tensile strength	20−40	71			MPa	293 K
Brinell hardness	280−330	180−230				

[a] At 594 K

Table 4.35 Elements of Group IIB (CAS notation), or Group 12 (new IUPAC notation). Part B(c): Thermal and thermodynamic properties

Element name Chemical symbol Atomic number Z	Zinc Zn 30	Cadmium Cd 48	Mercury Hg 80	Copernicium Cn 112	Units	Remarks
State	Solid	Solid	Liquid	Liquid		
Thermal conductivity λ	121	96.8	8.34		W/(m K)	At 300 K
Molar heat capacity c_p	25.44	25.98	27.983		J/(mol K)	At 298 K
Standard entropy S^0	41.631	51.800	75.900		J/(mol K)	At 298 K and 100 kPa
Enthalpy difference $H_{298} - H_0$	5.6570	6.2470	9.3420		kJ/mol	
Melting temperature T_m	692.68	594.22	234.32		K	
Enthalpy change ΔH_m	7.3220	6.1923	2.2953		kJ/mol	
Entropy change ΔS_m	10.571	10.421	9.796		J/(mol K)	
Relative volume change	0.0730	0.0474	0.037			$(V_l - V_s)/V_l$ at T_m
Boiling temperature T_b	1180	1040	629		K	
Enthalpy change ΔH_b	115.3	97.40	59.2		kJ/mol	
Critical temperature T_c			1750		K	
Critical pressure p_c			167		MPa	
Critical density ϱ_c			5.700		g/cm^3	

Table 4.36 Elements of Group IIB (CAS notation), or Group 12 (new IUPAC notation). Part B(d): Electronic, electromagnetic, and optical properties

Element name **Chemical symbol** **Atomic number *Z***	**Zinc** **Zn** **30**	**Cadmium** **Cd** **48**	**Mercury** **Hg** **80**	**Copernicium** **Cn** **112**	**Units**	**Remarks**
Characteristics	Ductile metal	Soft metal	Noble metal			
Electrical resistivity ρ_s Temperature coefficient Pressure coefficient	54.3 41.7×10^{-4} -6.3×10^{-9}	68 46.2×10^{-4} -7.32×10^{-9}			nΩ m 1/K 1/hPa	At 293 K
Electrical resistivity ρ_l	326	337	958 (298 K)		nΩ m	
Resistivity ratio	2.1	1.97	3.74–4.94			ρ_l/ρ_s at T_m
Superconducting critical temperature T_{crit}	0.88	0.55	4.15 K		K	α-Hg
Superconducting critical field H_{crit}	53	30	412		Oe	α-Hg
Hall coefficient R	0.63×10^{-10}	0.589×10^{-10}	-0.73×10^{-10}		$m^3/(A\,s)$	$B = 0.3$–2.2 T At 298 K
Thermoelectric coefficient	2.9	2.8	−3.4		μV/K	
Electronic work function	4.22	4.04			V	
Thermal work function	3.74	3.92			V	
Molar magnetic susceptibility χ_{mol}, solid (SI)	-115×10^{-6}	-248×10^{-6}	-303×10^{-6} (234 K)		cm^3/mol	At 295 K
Molar magnetic susceptibility χ_{mol}, solid (cgs)	-9.15×10^{-6}	-19.7×10^{-6}	-24.1×10^{-6} (234 K)		cm^3/mol	At 295 K
Molar magnetic susceptibility χ_{mol}, liquid (SI)			-421×10^{-6}		cm^3/mol	At 295 K
Molar magnetic susceptibility χ_{mol}, liquid (cgs)			-33.5×10^{-6}		cm^3/mol	At 295 K
Mass magnetic susceptibility χ_{mass}, solid (SI)	-1.38×10^{-6}	-2.21×10^{-6}			cm^3/g	At 295 K
Mass magnetic susceptibility χ_{mass}, liquid (SI)	-1.32×10^{-6}	-1.83×10^{-6}			cm^3/g	
Refractive index $(n-1)$, gas			$+1882\times10^{-6}$ (Hg_2 vapor)			
Refractive index n, solid	1.19 (λ = 550 nm)	1.8 (578 nm)				

Table 4.37 Elements of Group IIB (CAS notation), or Group 12 (new IUPAC notation). Part C: Allotropic and high-pressure modifications

Element / **Modification**	**Mercury** **α-Hg**	**β-Hg**	**Units**
Crystal system, Bravais lattice	trig, R	tetr	
Structure type	α-Hg	In	
Lattice constant *a*	300.5 (225 K)	399.5	pm
Lattice constant *c*		282.5	pm
Lattice angle α	70.53 (225 K)		
Space group	$R\bar{3}m$	$I4/mmm$	
Schoenflies symbol	D_{3d}^{5}	D_{4h}^{17}	
Strukturbericht type	A10		
Pearson symbol	hR1	tI2	
Number *A* of atoms per cell	1	2	
Coordination number	6 + 6	2 + 8	
Shortest interatomic distance, solid	299	283	pm
Range of stability	< 234.2 K	77 K, high pressure	

Table 4.38 Elements of Group IIB (CAS notation), or Group 12 (new IUPAC notation). Part D: Ionic radii (determined from crystal structures)

Element / **Ion** / **Coordination number**	**Zinc** Zn^{2+}	**Cadmium** Cd^{2+}	**Mercury** Hg^{+}	Hg^{2+}	**Units**
2				69	pm
4	60	78		96	pm
6	74	95	119	102	pm
8	90	110		114	pm
12		131			pm

Table 4.39 Elements of Group IIIA (CAS notation), or Group 13 (new IUPAC notation). Part A: Atomic, ionic, and molecular properties (see Table 4.45 for ionic radii)

Element name **Chemical symbol** **Atomic number *Z***	**Boron** **B** **5**	**Aluminum** **Al** **13**	**Gallium** **Ga** **31**	**Indium** **In** **49**	**Thallium** **Tl** **81**	**Nihonium** **Nh** **113**	**Units**	**Remarks**
Relative atomic mass A (atomic weight)	[10.806; 10.821]	26.9815385(7)	69.723(1)	114.818(1)	[204.382; 204.385]			
Abundance in lithosphere	10×10^{-6}	$81\,300\times10^{-6}$	15×10^{-6}	0.06×10^{-6}	0.3×10^{-6}			Mass ratio
Abundance in sea	4.4×10^{-6}	0.002×10^{-6}	3×10^{-11}	1×10^{-13}	1×10^{-11}			Mass ratio
Atomic radius r_{cov}	81	125	125	150	155		pm	Covalent radius
Atomic radius r_{met}	89	143	153	167	170		pm	Metallic radius, CN=12
Atomic radius r_{vdW}		205	190	190	200		pm	van der Waals radius
Electron shells	KL	KLM	–LMN	–MNO	–NOP			
Electronic ground state	$^2P_{1/2}$	$^2P_{1/2}$	$^2P_{1/2}$	$^2P_{1/2}$	$^2P_{1/2}$			
Electronic configuration	[He] $2s^22p^1$	[Na] $3s^23p^1$	[Ar] $3d^{10}4s^24p^1$	[Kr] $4d^{10}5s^25p^1$	[Xe] $4f^{14}5d^{10}6s^26p^1$			
Oxidation states	3+	3+	3+	3+	3+, 1+			
Electron affinity	0.277	0.441	0.3	0.3	0.2		eV	
Electronegativity χ_A	2.01	1.47	1.82	1.49	1.44			Allred and Rochow
1st ionization energy	8.29803	5.98577	5.99930	5.78636	6.10829		eV	
2nd ionization energy	25.15484	18.82856	20.5142	18.8698	20.428		eV	
3rd ionization energy	37.93064	28.44765	30.71	28.03	29.83		eV	
4th ionization energy	259.37521	119.992	64	54			eV	
Standard electrode potential E^0					−0.336		V	Reaction type $Tl^+ + e^- = Tl$
		−1.662	−0.560	−0.338			V	Reaction type $Al^{3+} + 3e^- = Al$
					+1.252		V	Reaction type $Tl^{3+} + 2e^- = Tl^+$

Table 4.40 Elements of Group IIIA (CAS notation), or Group 13 (new IUPAC notation). Part B(a): Crystallographic properties (see Table 4.44 for allotropic and high-pressure modifications)

Element name **Chemical symbol** **Atomic number *Z***	**Boron** **B** **5**	**Aluminum** **Al** **13**	**Gallium** **Ga** **31**	**Indium** **In** **49**	**Thallium** **Tl** **81**	**Nihonium** **Nh** **113**	**Units**	**Remarks**
Modification	β-B	α-Al	α-Ga					
Crystal system, Bravais lattice	trig, R	cub, fc	orth, C	tetr, I	hex			
Structure type	β-B	Cu	α-Ga	In	Mg			
Lattice constant a		361.49	451.92	459.90	345.63		pm	
Lattice constant b			765.86				pm	
Lattice constant c			452.58	494.70	552.63		pm	
Space group	$R\bar{3}m$	$Fm\bar{3}m$	$Cmca$	$I4/mmm$	$P6_3/mmc$			
Schoenflies symbol	D_{3d}^5	O_h^5	D_{2h}^{18}	D_{4h}^{17}	D_{6h}^4			
Strukturbericht type		A1	A11	A6	A3			
Pearson symbol	hR105	cF4	oC8	tI2	hP2			
Number A of atoms per cell	105	4	8	2	2			
Coordination number		12	$1+2+2+2$	$4+8$				
Shortest interatomic distance, solid	162–192	286	247	325			pm	

Table 4.41 Elements of Group IIIA (CAS notation), or Group 13 (new IUPAC notation). Part B(b): Mechanical properties

Element name **Chemical symbol** **Atomic number Z**	**Boron** **B** **5**	**Aluminum** **Al** **13**	**Gallium** **Ga** **31**	**Indium** **In** **49**	**Thallium** **Tl** **81**	**Nihonium** **Nh** **113**	**Units**	**Remarks**
Density ϱ, solid	2.46	2.70	5.91	7.31	11.85		g/cm^3	
Density ϱ, liquid		2.39	6.200	6.990	11.29		g/cm^3	At T_m
Molar volume V_{mol}	4.62	10.00	11.81	15.71	17.24		cm^3/mol	
Viscosity η, liquid		1.38	1.70	1.65			mPa s	At T_m
Surface tension γ, liquid Temperature coefficient		0.860 -0.135×10^{-3}	0.718	0.556 -0.09×10^{-3}	0.447 -0.07×10^{-3}		N/m N/(m K)	At T_m
Coefficient of linear thermal expansion α	5×10^{-6}	23.03×10^{-6}	18.3×10^{-6}	33×10^{-6}	28×10^{-6}		1/K	
Sound velocity, liquid		4650	2740	2215			m/s	At 12 MHz
Sound velocity, solid, transverse		3130	750	710	480		m/s	
Sound velocity, solid, longitudinal		6360	3030	2460	1630		m/s	
Compressibility κ	0.539×10^{-5}	1.33×10^{-5}	1.96×10^{-5}	2.70×10^{-5}	3.41×10^{-5}		1/MPa	Volume compressibility
Elastic modulus E	178[a]	70.2	9.81	10.6	7.89		GPa	
Shear modulus G		27.8	6.67	3.68	2.67		GPa	
Poisson number μ		0.34	0.47	0.45	0.45			
Elastic compliance s_{11}		16.0	12.2	148.8	104		1/TPa	
Elastic compliance s_{22}			14.0				1/TPa	
Elastic compliance s_{33}			8.49	196.2	31.1		1/TPa	
Elastic compliance s_{44}		35.3	28.6	153.7	139		1/TPa	
Elastic compliance s_{55}			23.9				1/TPa	
Elastic compliance s_{66}			24.8	83.2			1/TPa	
Elastic compliance s_{12}		−5.8	−4.4	−46.0	−83		1/TPa	
Elastic compliance s_{13}			−1.7	−94.5	−11.6		1/TPa	
Elastic compliance s_{23}			−2.4				1/TPa	
Elastic stiffness c_{11}	467	108	100	45.1	41.9		GPa	
Elastic stiffness c_{22}			90.2				GPa	
Elastic stiffness c_{33}	473		135	44.6	54.9		GPa	

Table 4.41 (continued)

Element name Chemical symbol Atomic number Z	Boron B 5	Aluminum Al 13	Gallium Ga 31	Indium In 49	Thallium Tl 81	Nihomium Nh 113	Units	Remarks
Elastic stiffness c_{44}	198	28.3	35.0	6.51	7.20		GPa	
Elastic stiffness c_{55}			41.8				GPa	
Elastic stiffness c_{66}			40.3	12.0			GPa	
Elastic stiffness c_{12}	241	62	37	40.0	36.6		GPa	
Elastic stiffness c_{13}			33	41.0	29.9		GPa	
Elastic stiffness c_{23}			31				GPa	
Elastic stiffness c_{14}	15.1						GPa	
Tensile strength	16–24[b]	90–100			8.9		MPa	
Vickers hardness	49 000	167			9			At 293 K
Brinell hardness				0.9				
Mohs hardness	9.3		1.5–2.5					

[a] Estimated
[b] Amorphous

Table 4.42 Elements of Group IIIA (CAS notation), or Group 13 (new IUPAC notation). Part B(c): Thermal and thermodynamic properties

Element name Chemical symbol Atomic number Z	Boron B 5	Aluminum Al 13	Gallium Ga 31	Indium In 49	Thallium Tl 81	Nihonium Nh 113	Units	Remarks
State	Crystalline							
Thermal conductivity λ	27.0	237	33.5	81.6	46.1		W/(m K)	
Thermal conductivity (liquid) λ_l		90					W/(m K)	At T_m
Molar heat capacity c_p	11.20	24.392	26.15	26.732	26.32		J/(mol K)	At 298 K
Standard entropy S^0	5.900	28.300	40.727	57.650	64.300		J/(mol K)	At 298 K and 100 kPa
Enthalpy difference $H_{298} - H_0$	1.2220	4.5400	5.5720	6.6100	6.832		kJ/mol	
Melting temperature T_m	2348.00	933.47	302.91	429.75	577.00		K	
Enthalpy change ΔH_m	50.200	10.7110	5.5898	3.2830	4.1422		kJ/mol	
Entropy change ΔS_m	21.380	11.474	18.454	7.639	7.179		J/(mol K)	
Volume change ΔV_m		0.065	−0.034	0.025	0.0323			$(V_l - V_s)/V_l$ at T_m
Boiling temperature T_b	4138	2790	2478	2346	1746		K	
Enthalpy change ΔH_b	480.5	294.0	258.7	231.45	164.1		kJ/mol	

Table 4.43 Elements of Group IIIA (CAS notation), or Group 13 (new IUPAC notation). Part B(d): Electronic, electromagnetic, and optical properties

Element name **Chemical symbol** **Atomic number Z**	**Boron** **B** **5**	**Aluminum** **Al** **13**	**Gallium** **Ga** **31**	**Indium** **In** **49**	**Thallium** **Tl** **81**	**Nihonium** **Nh** **113**	**Units**	**Remarks**
Characteristics	Semi conductor	Light metal	Soft metal	Soft metal	Soft metal, toxic	Transition metal		
Electrical resistivity ρ_s Temperature coefficient Pressure coefficient	6500×10^{9} [a]	25.0 46×10^{-4} -4.06×10^{-9}	136 39.6×10^{-4} -2.47×10^{-9}	80.0 49.0×10^{-4} -12.2×10^{-9}	150 51.7×10^{-4} -3.4×10^{-9}		nΩ m 1/K 1/hPa	At 300 K[a]
Electrical resistivity ρ_l		200	258	331	740		nΩ m	
Resistivity ratio at T_m		1.64	1.9	2.18				ρ_l/ρ_s at T_m
Superconducting critical temperature T_{cr}		1.2	1.09	3.4	2.4		K	
Superconducting critical field H_{cr}		99	51	293	171		Oe	
Electronic band gap ΔE	1.5						eV	
Electronic work function	4.79	4.28	4.35	4.08	4.05		V	
Thermal work function	5.71	3.74	4.12	4.0	3.76		V	
Intrinsic charge carrier concentration	$+5\times10^{14}$						$1/cm^3$	At 430 K
Electron mobility	1						$cm^2/(V\,s)$	
Hole mobility	55						$cm^2/(V\,s)$	
Hall coefficient R		-0.343×10^{-10}	-0.63×10^{-10}	-0.24×10^{-10}	0.240×10^{-10}		$m^3/(A\,s)$	$B = 1.0-1.8$ T 300 K
Thermoelectric coefficient		−0.6		2.4	0.4		μV/K	
Dielectric constant ε, solid	13 (0.5 MHz)							
Molar magnetic susceptibility χ_{mol}, solid (SI)	-84.2×10^{-6}	207×10^{-6}	-271×10^{-6}	-128×10^{-6}	-628×10^{-6}		cm^3/mol	At 295 K
Molar magnetic susceptibility χ_{mol}, solid (cgs)	-6.7×10^{-6}	16.5×10^{-6}	-21.6×10^{-6}	-10.2×10^{-6}	-50.0×10^{-6}		cm^3/mol	At 295 K
Mass magnetic susceptibility χ_{mass}, solid (SI)		$+7.9\times10^{-6}$	-3.9×10^{-6}	-1.4×10^{-6}	-3.13×10^{-6}		cm^3/g	At 295 K
Mass magnetic susceptibility χ_{mass}, liquid (SI)					-1.72×10^{-6}		cm^3/g	At T_m
Refractive index n, solid	3.2 ($\lambda = 1\,\mu m$)							

[a] At 300 K

Table 4.44 Elements of Group IIIA (CAS notation), or Group 13 (new IUPAC notation). Part C: Allotropic and high-pressure modifications

Element	Aluminum		Gallium			Thallium			
Modification	α-Al	β-Al	α-Ga	β-Ga	γ-Ga	α-Tl	β-Tl	γ-Tl	Units
Crystal system, Bravais lattice	cub, fc	hex, cp	orth, C	tetr	orth	hex, cp	cub, bc	cub, fc	
Structure type	Cu	Mg	α-Ga	In	γ-Ga	Mg	W	Cu	
Lattice constant a	404.96	269.3	451.92	280.8	1059.3	345.63	387.9		pm
Lattice constant b			765.86		1352.3				pm
Lattice constant c		439.8	452.58	445.8	520.3	552.63			pm
Space group	$Fm\bar{3}m$	$P6_3/mmc$	$Cmca$	$I4/mmm$	$Cmcm$	$P6_3/mmc$	$Im\bar{3}m$	$Fm\bar{3}m$	
Schoenflies symbol	O_h^5	D_{6h}^4	D_{2h}^{18}		D_{2h}^{17}	D_{6h}^4	O_h^9	O_h^5	
Strukturbericht type	A1	A3	A11	A6		A3	A2	A1	
Pearson symbol	cF4	hP2	oC8	tI2	oC40	hP2	cI2	cF4	
Number A of atoms per cell	4	2	8	2	40	2	2	4	
Coordination number	12	12	1 + 2 + 2 + 2	4 + 8			8	12	
Shortest interatomic distance, solid	286		247	281	260–308		336		
Range of stability	RTP	> 20.5 GPa	RTP	> 1.2 GPa	220 K, > 3.0 GPa	RTP	> 503 K	High pressure	

Table 4.45 Elements of Group IIIA (CAS notation), or Group 13 (new IUPAC notation). Part D: Ionic radii (determined from crystal structures)

Element	Aluminum	Gallium	Indium	Thallium		
Ion	Al^{3+}	Ga^{3+}	In^{3+}	Tl^{+}	Tl^{3+}	
Coordination number						Units
4	39	47	62		75	pm
5	48					pm
6	54	62	80	150	89	pm
8				159	98	pm
12				170		pm

Table 4.46 Elements of Group IIIB (CAS notation), or Group 3 (new IUPAC notation). Part A: Atomic, ionic, and molecular properties (see Table 4.52 for ionic radii)

Element name **Chemical symbol** **Atomic number *Z***	**Scandium** **Sc** **21**	**Yttrium** **Y** **39**	**Lanthanum** **La** **57**	**Actinium** **Ac** **89**	**Units**	**Remarks**
Characteristics				Radioactive		
Relative atomic mass A (atomic weight)	44.955908(5)	88.90584(2)	138.9055(2)	[227]		
Abundance in lithosphere	5×10^{-6}	28.1×10^{-6}	18.3×10^{-6}			Mass ratio
Abundance in sea	6×10^{-13}	3×10^{-12}	3×10^{-12}			Mass ratio
Atomic radius r_{cov}	144	162	169		pm	Covalent radius
Atomic radius r_{met}	166	178	187	188	pm	Metallic radius, CN = 12
Electron shells	–LMN	–MNO	–NOP	–OPQ		
Electronic ground state	$^2D_{3/2}$	$^2D_{3/2}$	$^2D_{3/2}$	$^2D_{3/2}$		
Electronic configuration	[Ar] $3d^14s^2$	[Kr] $4d^15s^2$	[Xe] $5d^16s^2$	[Rn] $6d^17s^2$		
Oxidation states	3+	3+	3+	3+		
Electron affinity	0.188	0.307	0.5		eV	
Electronegativity χ_A	1.20	1.11	1.08	(1.00)		Allred and Rochow
1st ionization energy	6.56144	6.217	5.5770	5.17	eV	
2nd ionization energy	12.79967	12.24	11.060	12.1	eV	
3rd ionization energy	24.75666	20.52	19.1773		eV	
4th ionization energy	73.4894	60.597	49.95		eV	
Standard electrode potential E^0			−2.522		V	Reaction type $La^{3+} + 3e^- = La$

Table 4.47 Elements of Group IIIB (CAS notation), or Group 3 (new IUPAC notation). Part B(a): Crystallographic properties (see Table 4.51 for allotropic and high-pressure modifications)

Element name **Chemical symbol** **Atomic number *Z***	**Scandium** **Sc** **21**	**Yttrium** **Y** **39**	**Lanthanum** **La** **57**	**Actinium** **Ac** **89**	**Units**	**Remarks**
Modification	α-Sc	α-Y	α-La			
Crystal system, Bravais lattice	hex	hex	hex			
Structure type	Mg	Mg	α-La			
Lattice constant a	330.88	364.82	377.40		pm	
Lattice constant c	526.80	573.18	1217.1		pm	
Space group	$P6_3/mmc$	$P6_3/mmc$	$P6_3/mmc$			
Schoenflies symbol	D^4_{6h}	D^4_{6h}	D^4_{6h}			
Strukturbericht type	A3	A3	A3′			
Pearson symbol	hP2	hP2	hP4			
Number A of atoms per cell	2	2	4			
Coordination number	12	6 + 6	12			
Shortest interatomic distance, solid	166		364		pm	

Table 4.48 Elements of Group IIIB (CAS notation), or Group 3 (new IUPAC notation). Part B(b): Mechanical properties

Element name **Chemical symbol** **Atomic number *Z***	**Scandium** **Sc** **21**	**Yttrium** **Y** **39**	**Lanthanum** **La** **57**	**Actinium** **Ac** **89**	**Units**	**Remarks**
Density ϱ, solid	2.989	4.50	6.70	10.07	g/cm^3	
Molar volume V_{mol}	15.04	19.89	22.60		cm^3/mol	
Surface tension, liquid	0.9	0.9	0.71		N/m	
Coefficient of linear thermal expansion α	10.0×10^{-6}	10.6×10^{-6}	4.9×10^{-6}		1/K	
Sound velocity, solid, transverse		2420	1540		m/s	
Sound velocity, solid, longitudinal		4280	2770		m/s	
Compressibility κ	2.22×10^{-5}	2.62×10^{-5}	3.96×10^{-5}		1/MPa	Volume compressibility
Elastic modulus E	75.2	66.3	39.2	25[a]	GPa	
Shear modulus G	29.7	25.5	14.9		GPa	
Poisson number μ	0.28	0.27	0.28			
Elastic compliance s_{11}	12.5	15.4	51.7[b]		1/TPa	
Elastic compliance s_{33}	10.6	14.4			1/TPa	
Elastic compliance s_{44}	36.1	41.1	55.7[b]		1/TPa	
Elastic compliance s_{12}	−4.3	−5.1	−19.2[b]		1/TPa	
Elastic compliance s_{13}	−2.2	−2.7			1/TPa	
Elastic stiffness c_{11}	99.3	77.9	34.5[b]		GPa	
Elastic stiffness c_{33}	107	76.9			GPa	
Elastic stiffness c_{44}	27.7	24.3	18.0[b]		GPa	
Elastic stiffness c_{12}	39.7	29.2	20.4[b]		GPa	
Elastic stiffness c_{13}	29.4	20			GPa	
Tensile strength	256	250–380			MPa	
Vickers hardness	350	40	491			

[a] Estimated
[b] For lanthanum in its metastable fcc phase at room temperature

Table 4.49 Elements of Group IIIB (CAS notation), or Group 3 (new IUPAC notation). Part B(c): Thermal and thermodynamic properties

Element name **Chemical symbol** **Atomic number *Z***	**Scandium** **Sc** **21**	**Yttrium** **Y** **39**	**Lanthanum** **La** **57**	**Actinium** **Ac** **89**	**Units**	**Remarks**
Thermal conductivity λ	15.8	17.2	13.5		W/(m K)	
Molar heat capacity c_p	25.52	26.53	27.11	27.2	J/(mol K)	At 298 K
Standard entropy S^0	34.644	44.788	56.902	62.000	J/(mol K)	At 298 K and 100 kPa
Enthalpy difference $H_{298}-H_0$	5.2174	5.9835	6.6651	6.7000	kJ/mol	
Melting temperature T_m	1814.00	1795.15	1193.00	1323.00	K	
Enthalpy change ΔH_m	14.0959	11.3942	6.1965	12.000	kJ/mol	
Entropy change ΔS_m	7.771	6.347	5.194	9.070	J/(mol K)	
Relative volume change ΔV_m			0.006			$(V_l-V_s)/V_l$ at T_m
Boiling temperature T_b	3104	3611	3730	3473	K	
Enthalpy change ΔH_b	314.2	363.3	413.7	293	kJ/mol	

Table 4.50 Elements of Group IIIB (CAS notation), or Group 3 (new IUPAC notation). Part B(d): Electronic, electromagnetic, and optical properties

Element name Chemical symbol Atomic number Z	Scandium Sc 21	Yttrium Y 39	Lanthanum La 57	Actinium Ac 89	Units	Remarks
Characteristics	Soft metal	Reactive metal	Very reactive metal			
Electrical resistivity ρ_s Temperature coefficient Pressure coefficient	505 28.2×10^{-4}	550 27.1×10^{-4}	540 21.8×10^{-4} -1.7×10^{-9}		nΩ m 1/K 1/hPa	At RT
Electrical resistivity ρ_l			1350		nΩ m	
Superconducting critical temperature T_{crit}			5.0		K	
Superconducting critical field H_{crit}						
Hall coefficient R	-0.67×10^{-10}	-0.770×10^{-10}	-0.8×10^{-10}		$m^3/(A\,s)$	At 293 K, $B = 0.5-1.0$ T
Thermoelectric coefficient	−3.6	2.2			μV/K	
Electronic work function	3.5	3.1	3.5		V	
Thermal work function	3.23	3.07	3.3		V	
Molar magnetic susceptibility χ_{mol}, solid (SI)	3710×10^{-6}	2359×10^{-6}	$+1205\times10^{-6}$		cm^3/mol	At 295 K
Molar magnetic susceptibility χ_{mol}, solid (cgs)	295×10^{-6}	188×10^{-6}	$+95.9\times10^{-6}$		cm^3/mol	At 295 K
Mass magnetic susceptibility χ_{mass}, solid (SI)	88×10^{-6}	27.0×10^{-6}	$+11\times10^{-6}$		cm^3/g	

Table 4.51 Elements of Group IIIB (CAS notation), or Group 3 (new IUPAC notation). Part C: Allotropic and high-pressure modifications

Element	Scandium		Yttrium		Lanthanum				
Modification	α-Sc	β-Sc	α-Y	β-Y	α-La	β-La	γ-La	β′-La	Units
Crystal system, Bravais lattice	hex, cp	cub, bc	hex, cp	cub, bc	hex	cub, fc	cub, bc	cub, fc	
Structure type	Mg	W	Mg	W	α-La	Cu	W	Cu	
Lattice constant a	330.88		364.82		377.40	530.45	426.5	517	pm
Lattice constant c	526.80		573.18		1217.1				pm
Space group	$P6_3/mmc$	$Im\bar{3}m$	$P6_3/mmc$	$Im\bar{3}m$	$P6_3/mmc$	$Fm\bar{3}m$	$Im\bar{3}m$	$Fm\bar{3}m$	
Schoenflies symbol	D_{6h}^4	O_h^9	D_{6h}^4	O_h^9	D_{6h}^4	O_h^5	O_h^9	O_h^5	
Strukturbericht type	A3	A2	A3	A2	A3′	A1	A2	A1	
Pearson symbol	hP2	cI2	hP2	cI2	hP4	cF4	cI2	cF4	
Number A of atoms per cell	2	2	2	2	4	4	2	4	
Coordination number	12	8	6 + 6	8	12	12	8	12	
Shortest interatomic distance, solid				356	374	375	369		pm
Range of stability	RT	> 1607 K	RT	> 1752 K	RTP	> 613 K	> 1141 K	> 2.0 GPa	

Table 4.52 Elements of Group IIIB (CAS notation), or Group 3 (new IUPAC notation). Part D: Ionic radii (determined from crystal structures)

Element Ion Coordination number	Scandium Sc^{3+}	Yttrium Y^{3+}	Lanthanum La^{3+}	Actinium Ac^{3+}	Units
6	75	90	103	112	pm
8	87	102	116		pm
9		108			pm
10			127		pm
12			136		pm

Table 4.53 Elements of Group IVA (CAS notation), or Group 14 (new IUPAC notation). Part A: Atomic, ionic, and molecular properties (see Table 4.59 for ionic radii)

Element name **Chemical symbol** **Atomic number Z**	**Carbon** **C** **6**	**Silicon** **Si** **14**	**Germanium** **Ge** **32**	**Tin** **Sn** **50**	**Lead** **Pb** **82**	**Flerovium** **Fl** **114**	**Units**	**Remarks**
Relative atomic mass A (atomic weight)	[12.0096; 12.0116]	[28.084; 28.086]	72.630(8)	118.710(7)	207.2(1)			
Abundance in lithosphere	320×10^{-6}	$277\,200\times10^{-6}$	7×10^{-6}	40×10^{-6}	16×10^{-6}			Mass ratio
Abundance in sea	28×10^{-6}	2×10^{-6}	5×10^{-11}	1×10^{-11}	3×10^{-11}			Mass ratio
Atomic radius r_{cov}	77	117	122	140	154		pm	Covalent radius
Atomic radius r_{met}	91	132	137	220	175		pm	Metallic radius, CN=12
Atomic radius r_{vdW}	170	210	234	158	200		pm	van der Waals radius
Electron shells	KL	KLM	–LMN	–MNO	–NOP			
Electronic ground state	$^3P_0$	$^3P_0$	$^3P_0$	$^3P_0$	$^3P_0$			
Electronic configuration	$1s^2 2s^2 2p^2$	[Ne] $3s^2 3p^2$	[Ar] $3d^{10} 4s^2 4p^2$	[Kr] $4d^{10} 5s^2 5p^2$	[Xe] $4f^{14} 5d^{10} 6s^2 6p^2$	[Rn] $5f^{14} 6d^{10} 7s^2 7p^2$		
Oxidation states	4+, 4−, 2+	4+	4+	4+, 2+	4+, 2+			
Electron affinity	1.26	1.39	1.23	1.11	0.364		eV	
Electronegativity χ_A	2.50	1.74	2.02	1.72	1.55			Allred and Rochow
1st ionization energy	11.26030	8.15169	7.900	7.34381	7.41666		eV	
2nd ionization energy	24.38332	16.34585	15.93462	14.63225	15.0322		eV	
3rd ionization energy	47.8878	33.49302	34.2241	30.50260	31.9373		eV	
4th ionization energy	64.4939	45.14181	45.7131	40.73502	42.32		eV	
5th ionization energy	392.087	166.767	93.5	72.28	68.8		eV	
Standard electrode potential E^0				−0.137 +0.151	−0.126		V V	Reaction type $Sn^{2+} + 2e^- = Sn$ Reaction type $Sn^{4+} + 2e^- = Sn^{2+}$

Table 4.54 Elements of Group IVA (CAS notation), or Group 14 (new IUPAC notation). Part B(a): Crystallographic properties (see Table 4.58 for allotropic and high-pressure modifications)

Element name **Chemical symbol** **Atomic number *Z***	**Carbon** **C** **6**		**Silicon** **Si** **14**	**Germanium** **Ge** **32**	**Tin** **Sn** **50**	**Lead** **Pb** **82**	**Flerovium** **Fl** **114**	**Units**	**Remarks**
Modification	Diamond	Graphite			β-Sn[a], white tin, Sn-I				
Crystal system, Bravais lattice	cub	hex	cub, fc	cub, fc	tetr, I	cub, fc			
Structure type	Diamond	C	Diamond	Diamond	β-Sn	Cu			
Lattice constant a	356.71	246.12	543.102 (22.5 °C)	565.9(1) RT	581.97 (300 K)	495.02		pm	
Lattice constant c		670.90			317.49			pm	
Space group	$Fd3m$	$P6_3/mmc$	$Fd3m$	$Fd3m$	$I4_1/amd$	$Fm3m$			
Schoenflies symbol	O_h^7	D_{6v}^4	O_h^7	O_h^7	D_{4h}^{19}	O_h^5			
Strukturbericht type		A9	A4	A4	A5	A1			
Pearson symbol		hP4	cF8	cF8	tI4	cF4			
Number A of atoms per cell	8	4	8	8	4	4			
Coordination number	4	3	4	4		12			
Shortest interatomic distance, solid	154.45	142.10 335.45	235	244	302	349		pm pm	Graphite, within layers Graphite, between layers
Range of stability	RT, > 60 GPa	RTP							

[a] At ambient pressure Sn crystallizes in the diamond structure (gray tin, α-Sn) and below 17 °C in the β-tin structure (white tin, β-Sn, Sn-I) at room temperature. If it is alloyed with In or Hg, the simple hexagonal γ-Sn structure is observed

Table 4.55 Elements of Group IVA (CAS notation), or Group 14 (new IUPAC notation). Part B(b): Mechanical properties

Element name **Chemical symbol** **Atomic number Z**	**Carbon** **C** **6**		**Silicon** **Si** **14**	**Germanium** **Ge** **32**	**Tin** **Sn** **50**	**Lead** **Pb** **82**	**Flerovium** **Fl** **114**	**Units**	**Remarks**
Modification	Diamond	Graphite			β-Sn (white)				
Density ϱ, solid	3.513	2.266	2.33	5.32	7.30	11.4	$\geq$ 11.342	g/cm^3	At 293 K
Density ϱ, liquid			2.525	5.500	6.978	10.678		g/cm^3	
Molar volume V_{mol}	3.42	5.3	12.06	13.64	16.24	18.26		cm^3/mol	
Viscosity η, liquid			2.0		2.71	1.67		mPa s	
Surface tension γ, liquid Temperature coefficient			0.735 -0.5×10^{-3}	0.650 -0.20×10^{-3}	0.545 -0.075×10^{-3}	0.470 -0.26×10^{-3}		N/m N/(m K)	
Coefficient of linear thermal expansion α	1.06×10^{-6}	1.9×10^{-6} [a]	2.56×10^{-6}	5.57×10^{-6}	21.2×10^{-6}	29.1×10^{-6}		1/K	At 293 K
Sound velocity, liquid					2270	1790		m/s	At T_m, 12 MHz
Sound velocity, solid, transverse			5845	2420	1650	710		m/s	At 298 K
Sound velocity, solid, longitudinal	11 220	3450	8433	4580	3300	2050		m/s	
Compressibility κ	2.25×10^{-6}	1.56×10^{-6}	10.2×10^{-6}	13.4×10^{-6}	18.3×10^{-6}	23.7×10^{-6}		1/MPa	Volume compressibility
Bulk modulus B_0	444		98.0	74.9	56.6			GPa	At 295 K
Elastic modulus E	545		112	79.9	52.9	15.8		GPa	
Shear modulus G			80.5	29.6	19.9	5.54		GPa	
Poisson number μ				0.34	0.33	0.44			
Elastic compliance s_{11}	0.951	0.98	7.73	9.73	41.6	93.7		1/TPa	
Elastic compliance s_{33}		27.5			14.9			1/TPa	
Elastic compliance s_{44}	1.732	250	12.7	14.9	45.6	68.0		1/TPa	
Elastic compliance s_{66}					42.8			1/TPa	
Elastic compliance s_{12}	−0.0987	−0.16	−2.15	−2.64	31.2	−43.0		1/TPa	
Elastic compliance s_{13}		−0.33			4.6			1/TPa	
Elastic stiffness c_{11}	1079	1060	165.6	129	72.30	48.8		GPa	At 300 K
Elastic stiffness c_{33}		36.5			88.40			GPa	At 300 K
Elastic stiffness c_{44}	578	4	79.6	67.1	22.03	14.8		GPa	At 300 K
Elastic stiffness c_{66}					24.00			GPa	At 300 K
Elastic stiffness c_{12}	124.5	180	63.9	48.3	59.40	41.4		GPa	At 300 K
Elastic stiffness c_{13}		15			35.78			GPa	At 300 K
Tensile strength			690			700		MPa	
Vickers hardness			2350			39			
Mohs hardness	10								

[a] At 298 K, parallel to layer planes. The corresponding value perpendicular to the layer planes is 2.9×10^{-6} 1/K

Table 4.56 Elements of Group IVA (CAS notation), or Group 14 (new IUPAC notation). Part B(c): Thermal and thermodynamic properties

Element name **Chemical symbol** **Atomic number *Z***	**Carbon** **C** **6**		**Silicon** **Si** **14**	**Germanium** **Ge** **32**	**Tin** **Sn** **50**	**Lead** **Pb** **82**	**Flerovium** **Fl** **114**	**Units**	**Remarks**
Modification	Diamond	Graphite			β-Sn (white)				
Thermal conductivity λ	1000–2320	5.7[a] 1960[b]	83.7	58.6	66.6	35.2		W/(m K) W/(m K)	At 300 K At 300 K
Molar heat capacity c_p	6.11	8.519	20.00	33.347	27.17	26.51		J/(mol K)	At 298 K
Standard entropy S^0	2.360	5.742	18.810	31.090	51.180	64.800		J/(mol K)	At 298 K and 100 kPa
Enthalpy difference $H_{298} - H_0$	0.5188	1.0540	3.2170	4.6360	6.3230	6.8700		kJ/mol	
Melting temperature T_m		4765.30	1687.00	1211.0	505.08	600.61		K	
Enthalpy change ΔH_m		117.3690	50.208	36.9447	7.01940	4.7739		kJ/mol	
Entropy change ΔS_m		24.630	29.762	30.498	14.243	7.948		J/(mol K)	
Relative volume change ΔV_m			−0.10	−0.054	0.028	0.032			$(V_l - V_s)/V_l$ at T_m
Boiling temperature T_b		3915	3505	3107	2876	2019		K	
Enthalpy change ΔH_b		710.9	383.3	331	295.8	177.58		kJ/mol	
Transformation temperature	1900–2100							K	Transforms to graphite

[a] Perpendicular to layer planes
[b] Parallel to layer planes

Table 4.57 Elements of Group IVA (CAS notation), or Group 14 (new IUPAC notation). Part B(d): Electronic, electromagnetic, and optical properties

Element name **Chemical symbol** **Atomic number *Z***	**Carbon** **C** **6**		**Silicon** **Si** **14**	**Germanium** **Ge** **32**	**Tin** **Sn** **50**	**Lead** **Pb** **82**	**Flerovium** **Fl** **114**	**Units**	**Remarks**
Modification	Diamond	Graphite			β-Sn (white)				
Characteristics	Very hard insulator	Soft conductor	Hard semiconductor	Semiconductor	Ductile metal	Soft metal	Semimetal		
Electrical resistivity ρ_s Temperature coefficient Pressure coefficient	10^{11}	1.4×10^{-5}		0.45	110×10^{-9} 46.5×10^{-4} -9.2×10^{-9}	192×10^{-9} 42.8×10^{-4} -12.5×10^{-9}		Ω m 1/K 1/hPa	At 293 K
Electrical resistivity ρ_l				710				nΩ m	
Resistivity ratio				0.071		1.94			ρ_l/ρ_s at T_m
Superconducting critical temperature T_{crit}					3.72	7.2		K	
Superconducting critical field H_{crit}					309	803		Oe	
Hall coefficient R^a		-487×10^{-10}	-100	0.1	0.041×10^{-10}	0.09×10^{-10}		$m^3/(A\,s)$	At 300 K
Thermoelectric coefficient		11.06		302.5	0.1	-0.1		$\mu V/K$	
Electronic band gap ΔE Temperature dependence	5.4		1.107 -2.3×10^{-4}	0.6642				eV eV/K	At 300 K At 300 K
Electronic work function		4.81	4.95	5.0	4.42	4.25		V	
Thermal work function		4.00	4.1	4.56	4.11	3.83		V	
Electron mobility	1800		1900	3800				$cm^2/(V\,s)$	
Hole mobility	1400		480	1820				$cm^2/(V\,s)$	
Dielectric constant ε, static, solid	5.68		11.7[b]	16.0					
Dielectric constant ε, high-frequency, solid	5.9(1)		12.0	16	24				
Molar magnetic susceptibility χ_{mol}, solid[c] (SI)	-74.1×10^{-6}	-75.4×10^{-6}	-39.2×10^{-6}	-146×10^{-6}	-470×10^{-6}	-289×10^{-6}		cm^3/mol	At 295 K
Molar magnetic susceptibility χ_{mol}, solid[c] (cgs)	-5.88×10^{-6}	-6.0×10^{-6}	-3.12×10^{-6}	-11.6×10^{-6}	-37.4×10^{-6}	-23×10^{-6}		cm^3/mol	At 295 K
Mass magnetic susceptibility χ_{mass}, solid (SI)	-6.17×10^{-6}	-6.3×10^{-6}	-1.8×10^{-6}	-1.328×10^{-6}	-3.3×10^{-6}	-1.39×10^{-6}		cm^3/g	At 295 K
Mass magnetic susceptibility χ_{mass}, liquid (SI)					-4.4×10^{-6}			cm^3/g	
Refractive index n, solid	2.4173		4.24	4.00 (25 μm)	1.0	2.01			$\lambda = 589$ nm
Refractive index n, liquid					1.7				

[a] $B = 1.0-1.6$ T; [b] At 11 K and 1 MHz; [c] The values for Sn apply to gray Sn

Table 4.58 Elements of Group IVA (CAS notation), or Group 14 (new IUPAC notation). Part C: Allotropic and high-pressure modifications

Element	**Silicon**				**Germanium**				**Tin**			**Lead**		
Modification	**α-Si**	**β-Si**	**γ-Si**	**δ-Si**	**α-Ge**	**β-Ge**	**γ-Ge**	**δ-Ge**	**α-Sn (gray tin)**	**β-Sn (white tin)**	**γ-Sn**	**Pb I**	**Pb II**	**Units**
Crystal system, Bravais lattice	cub, fc	tetr	cub	hex	cub, fc	tetr	tetr	cub, bc	cub, fc	tetr, I	tetr	cub, fc	hex, cp	
Structure type	Diamond	β-Sn		α-La	Diamond	β-Sn		γ-Si	Diamond	β-Sn	In	Cu	Mg	
Lattice constant a	543.06	468.6	636	380	565.74	488.4	593	692	648.92	583.16	370	495.02	326.5	pm
Lattice constant c		258.5		628		269.2	698			318.15	337		538.7	pm
Space group	$Fd\bar{3}m$	$I4_1/amd$	$Im3m$	$P6_3/mmc$	$Fd\bar{3}m$	$I4_1/amd$	$P4_32_12$	$Im\bar{3}m$	$Fd\bar{3}m$	$I4_1/amd$		$Fm\bar{3}m$	$P6_3/mmc$	
Schoenflies symbol	O_h^7	D_{4h}^{19}	O_h^9	D_{6v}^4	O_h^7	D_{4h}^{19}	D_4^8		O_h^7	D_{4h}^{19}		O_h^5	D_{6h}^4	
Strukturbericht type	A4	A5		A3′	A4	A5			A4	A5		A1	A3	
Pearson symbol	cF8	tI4	cI16	hP4	cF8	tI4	tP12	cI16	c8	tI4	tI2	cF4	hP2	
Number A of atoms per cell	8	4		4	8	4	12	16	8	4	2	4	2	
Coordination number	4	4 + 2			4	4 + 2	4 + 2 + 2		4			12		
Shortest interatomic distance, solid	235	243			245	253	249		281	302		349		
Range of stability	RTP	> 9.5 GPa	> 16.0 GPa	[a]	RTP	> 12.0 GPa	[b]	> 12.0 GPa	< 291 K	RT	> 9 GPa	RTP	> 10.3 GPa	

[a] Decompressed β-Si
[b] Decompressed β-Ge

Table 4.59 Elements of Group IVA (CAS notation), or Group 14 (new IUPAC notation). Part D: Ionic radii (determined from crystal structures)

Element Ion Coordination number	Carbon C^{4+}	Silicon Si^{4+}	Germanium Ge^{2+}	 Ge^{4+}	Tin Sn^{4+}	Lead Pb^{2+}	 Pb^{4+}	Units
4	15	26		39	55		65	pm
6	16	40	73	53	69	119	78	pm
8					81	129	94	pm
10						140		pm
12						149		pm

Table 4.60 Elements of Group IVB (CAS notation), or Group 4 (new IUPAC notation). Part A: Atomic, ionic, and molecular properties (see Table 4.66 for ionic radii)

Element name Chemical symbol Atomic number Z	Titanium Ti 22	Zirconium Zr 40	Hafnium Hf 72	Rutherfordium Rf 104	Units	Remarks
Characteristics				Radioactive		
Relative atomic mass A (atomic weight)	47.867(1)	91.224(2)	178.49(2)	[261]		
Abundance in lithosphere	4400×10^{-6}	220×10^{-6}	4.5×10^{-6}			Mass ratio
Abundance in sea	1×10^{-9}	3×10^{-11}	7×10^{-12}			Mass ratio
Atomic radius r_{cov}	132	145	144		pm	Covalent radius
Atomic radius r_{met}	147	160	156		pm	Metallic radius, CN = 12
Electron shells	–LMN	–MNO	–NOP	–OPQ		
Electronic ground state	$^3F_2$	$^3F_2$	$^3F_2$	$^3F_2$		
Electronic configuration	[Ar] $3d^2 4s^2$	[Kr] $4d^2 5s^2$	[Xe] $4f^{14} 5d^2 6s^2$			
Oxidation states	4+, 3+	4+	4+			
Electron affinity	0.079	0.426	near 0		eV	
Electronegativity χ_A	1.32	1.22	(1.23)			Allred and Rochow
1st ionization energy	6.8282	6.63390	6.82507		eV	
2nd ionization energy	13.5755	13.13	14.9		eV	
3rd ionization energy	27.4917	22.99	23.3		eV	
4th ionization energy	43.2672	34.34	33.33		eV	
Standard electrode potential E^0	−1.630	−1.553[a]			V	Reaction type $Ti^{2+} + 2e^- = Ti$
	−0.368				V	Reaction type $Ti^{3+} + e^- = Ti^{2+}$
	−0.04				V	Reaction type $Ti^{4+} + e^- = Ti^{3+}$

[a] Reaction type $ZrO_2 + 4H^+ + 4e^- = Zr + 2H_2O$

Table 4.61 Elements of Group IVB (CAS notation), or Group 4 (new IUPAC notation). Part B(a): Crystallographic properties (see Table 4.65 for allotropic and high-pressure modifications)

Element name **Chemical symbol** **Atomic number *Z***	**Titanium** **Ti** **22**	**Zirconium** **Zr** **40**	**Hafnium** **Hf** **72**	**Rutherfordium** **Rf** **104**	**Units**	**Remarks**
Modification	α-Ti	α-Zr	α-Hf			
Crystal system, Bravais lattice	hex	hex	hex			
Structure type	Mg	Mg	Mg			
Lattice constant a	295.03	323.17	319.46		pm	
Lattice constant c	468.36	514.76	505.11		pm	
Space group	$P6_3/mmc$	$P6_3/mmc$	$P6_3/mmc$			
Schoenflies symbol	D^4_{6h}	D^4_{6h}	D^4_{6h}			
Strukturbericht type	A3	A3	A3			
Pearson symbol	hP2	hP2	hP2			
Number A of atoms per cell	2	2	2			
Coordination number	12	6 + 6	12			
Shortest interatomic distance, solid	291		318		pm	

Table 4.62 Elements of Group IVB (CAS notation), or Group 4 (new IUPAC notation). Part B(b): Mechanical properties

Element name **Chemical symbol** **Atomic number *Z***	**Titanium** **Ti** **22**	**Zirconium** **Zr** **40**	**Hafnium** **Hf** **72**	**Rutherfordium** **Rf** **104**	**Units**	**Remarks**
Density ϱ, solid	4.50	6.49	13.10		g/cm^3	
Density ϱ, liquid	4.110	5.80	12.00		g/cm^3	
Molar volume V_{mol}	10.55	14.02	13.41		cm^3/mol	
Surface tension, liquid	1.65	1.48	1.63		N/m	Near T_m
Temperature coefficient	0.26×10^{-3}	-0.2×10^{-3}	-0.21×10^{-3}		N/(m K)	
Coefficient of linear thermal expansion α	8.35×10^{-6}	5.78×10^{-6}	5.9×10^{-6}		1/K	
Sound velocity, solid, transverse	2920	1950	2000		m/s	
Sound velocity, solid, longitudinal	6260	4360	3671		m/s	
Compressibility κ	0.779×10^{-5}	1.08×10^{-5}	0.80×10^{-5}		1/MPa	Volume compressibility
Elastic modulus E	102	68.0	138		GPa	
Shear modulus G	37.3	24.8	53.0		GPa	
Poisson number μ	0.35	0.37	0.29			
Elastic compliance s_{11}	9.69	10.1	7.16		1/TPa	
Elastic compliance s_{33}	6.86	8.0	6.13		1/TPa	
Elastic compliance s_{44}	21.5	30.1	18.0		1/TPa	
Elastic compliance s_{12}	−4.71	−4.0	−2.48		1/TPa	
Elastic compliance s_{13}	−1.82	−2.4	−1.57		1/TPa	
Elastic stiffness c_{11}	160	144	181		GPa	
Elastic stiffness c_{33}	181	166	197		GPa	
Elastic stiffness c_{44}	46.5	33.4	55.7		GPa	
Elastic stiffness c_{12}	90	74	77		GPa	
Elastic stiffness c_{13}	66	67	66		GPa	
Tensile strength	235	150–450	400		MPa	
Vickers hardness	2000–3500	903	1760			

Table 4.63 Elements of Group IVB (CAS notation), or Group 4 (new IUPAC notation). Part B(c): Thermal and thermodynamic properties

Element name **Chemical symbol** **Atomic number Z**	**Titanium** **Ti** **22**	**Zirconium** **Zr** **40**	**Hafnium** **Hf** **72**	**Rutherfordium** **Rf** **104**	**Units**	**Remarks**
Modification		α-Zr				
Thermal conductivity λ	21	22.7	23.0		W/(m K)	
Molar heat capacity c_p	25.02	25.36	25.3		J/(mol K)	At 298 K
Standard entropy S^0	30.720	39.181	43.560		J/(mol K)	At 298 K and 100 kPa
Enthalpy difference $H_{298} - H_0$	4.8240	5.5663	5.8450		kJ/mol	
Melting temperature T_m	1941.00	2127.85	2506.00		K	
Enthalpy change ΔH_m	14.1460	20.9978	27.1960		kJ/mol	
Entropy change ΔS_m	7.288	9.868	10.852		J/(mol K)	
Volume change ΔV_m						$(V_l - V_s)/V_l$ at T_m
Boiling temperature T_b	3631	4203	4963		K	
Enthalpy change ΔH_b	410.0	561.3	575.5		kJ/mol	

Table 4.64 Elements of Group IVB (CAS notation), or Group 4 (new IUPAC notation). Part B(d): Electronic, electromagnetic, and optical properties

Element name **Chemical symbol** **Atomic number Z**	**Titanium** **Ti** **22**	**Zirconium** **Zr** **40**	**Hafnium** **Hf** **72**	**Rutherfordium** **Rf** **104**	**Units**	**Remarks**
Modification		α-Zr				
Characteristics	Hard, light metal	Resistant metal	Metal			
Electrical resistivity ρ_s	390	410	296		nΩ m	At 293 K
Temperature coefficient	54.6×10^{-4}	44.0×10^{-4}	44×10^{-4}		1/K	
Pressure coefficient	-1.118×10^{-9}	0.33×10^{-9}	-0.87×10^{-9}		1/hPa	
Superconducting critical temperature T_{crit}	0.39	0.55	0.35		K	
Superconducting critical field H_{crit}	100	47			Oe	
Hall coefficient R	-1.2×10^{-10}	0.212×10^{-10}	0.43×10^{-10}		$m^3/(A\,s)$	At 300 K, $B = 0.4$–2.8 T
Electronic work function	4.31	4.05	3.9		V	
Thermal work function	4.16	4.12	3.53		V	
Molar magnetic susceptibility χ_{mol}, solid (SI)	1898×10^{-6}	1508×10^{-6}	892×10^{-6}		cm^3/mol	At 295 K
Molar magnetic susceptibility χ_{mol}, solid (cgs)	151×10^{-6}	120×10^{-6}	71×10^{-6}		cm^3/mol	At 295 K
Mass magnetic susceptibility χ_{mass}, solid (SI)	40.1×10^{-6}	16.8×10^{-6}	5.3×10^{-6}		cm^3/g	At 295 K

Table 4.65 Elements of Group IVB (CAS notation), or Group 4 (new IUPAC notation). Part C: Allotropic and high-pressure modifications

Element	Titanium		Zirconium		Hafnium			
Modification	α-Ti	β-Ti	α-Zr	β-Zr	α-Hf	β-Hf	Hf-II	Units
Crystal system, Bravais lattice	hex, cp	cub, bc	hex, cp	cub, bc	hex, cp	cub, bc	hex	
Structure type	Mg	W	Mg	W	Mg	W		
Lattice constant *a*	295.03	330.65	323.17	360.9	319.46	361.0		pm
Lattice constant *c*	468.36		514.76		505.11			pm
Space group	$P6_3/mmc$	$Im\bar{3}m$	$P6_3/mmc$	$Im\bar{3}m$	$P6_3/mmc$	$Im\bar{3}m$		
Schoenflies symbol	D_{6h}^4	O_h^9	D_{6h}^4	O_h^9	D_{6h}^4	O_h^9		
Strukturbericht type	A3	A2	A3	A2	A3	A2		
Pearson symbol	hP2	cI2	hP2	cI2	hP2	cI2		
Number *A* of atoms per cell	2	2	2	2	2	2		
Coordination number	12	8	6 + 6	8	12	8		
Shortest interatomic distance, solid	291	286		313	318	313		
Range of stability	RT	> 1173 K	RT	> 1138 K	RTP	> 2268 K	> 38.8 GPa	

Table 4.66 Elements of Group IVB (CAS notation), or Group 4 (new IUPAC notation). Part D: Ionic radii (determined from crystal structures)

Element	Titanium			Zirconium	Hafnium	
Ion	Ti^{2+}	Ti^{3+}	Ti^{4+}	Zr^{4+}	Hf^{4+}	
Coordination number						Units
4			42	59	58	pm
6	86	67	61	72	71	pm
8			74	84	83	pm
9				89		pm

Table 4.67 Elements of Group VA (CAS notation), or Group 15 (new IUPAC notation). Part A: Atomic, ionic, and molecular properties (see Table 4.73 for ionic radii)

Element name **Chemical symbol** **Atomic number *Z***	**Nitrogen** **N** **7**	**Phosphorus** **P** **15**	**Arsenic** **As** **33**	**Antimony** **Sb** **51**	**Bismuth** **Bi** **83**	**Moscovium** **Mc** **115**	**Units**	**Remarks**
Relative atomic mass A (atomic weight)	[14.00643; 14.00728]	30.973761998(5)	74.921595(6)	121.760(1)	208.98040(1)			
Abundance in lithosphere	20×10^{-6}	1200×10^{-6}	5×10^{-6}	0.2×10^{-6}	0.2×10^{-6}			Mass ratio
Abundance in sea	150×10^{-6}	0.06×10^{-6}	3.7×10^{-9}	2.4×10^{-10}	2×10^{-11}			Mass ratio
Atomic radius r_{cov}	70	110	121	141	146		pm	Covalent radius
Atomic radius r_{met}	92	128	139	159	182		pm	Metallic radius, CN = 12
Atomic radius r_{vdW}	155	190	200	220	240		pm	van der Waals radius
Electron shells	KL	KLM	–LMN	–MNO	–NOP			
Electronic ground state	$^4S_{3/2}$	$^4S_{3/2}$	$^4S_{3/2}$	$^4S_{3/2}$	$^4S_{3/2}$			
Electronic configuration	[He] $2s^2 2p^3$	[Ne] $3s^2 3p^3$	[Ar] $3d^{10} 4s^2 4p^3$	[Kr] $4d^{10} 5s^2 5p^3$	[Xe] $4f^{14} 5d^{10} 6s^2 6p^3$			
Oxidation states	5+, 3+, 3−	5+, 3+, 3−	5+, 3+, 3−	5+, 3+, 3−	5+, 3+			
Electron affinity	Not stable	0.747	0.81	1.046	0.946		eV	
Electronegativity χ_A	3.07	2.06	2.20	1.82	(1.67)			Allred and Rochow
1st ionization energy	14.53414	10.48669	9.8152	8.64	7.289		eV	
2nd ionization energy	29.6013	19.7694	18.633	16.53051	16.69		eV	
3rd ionization energy	47.44924	30.2027	28.351	25.3	25.56		eV	
4th ionization energy	77.4735	51.4439	50.13	44.2	45.3		eV	
5th ionization energy	97.8902	65.0251	62.63	56	56.0		eV	
6th ionization energy	552.0718	220.421	127.6	108	88.3		eV	

Table 4.68 Elements of Group VA (CAS notation), or Group 15 (new IUPAC notation). Part B(a): Crystallographic properties (see Table 4.72 for allotropic and high-pressure modifications)

Element name Chemical symbol Atomic number Z	Nitrogen N 7	Phosphorus P 15	Arsenic As 33	Antimony Sb 51	Bismuth Bi 83	Moscovium Mc 115	Units	Remarks
State	N_2, 4.2 K	P, black						
Crystal system, Bravais lattice	cub, sc	orth, C	trig, R	trig, R	trig, R			
Structure type	α-N	P, black	α-As	α-As	α-As			
Lattice constant a	565.9	331.36	413.20	450.65	474.60		pm	
Lattice constant b		1047.8					pm	
Lattice constant c		43 763					pm	
Lattice angle α			54.12	57.11	57.23		deg	
Space group	*Pa*3	*Cmca*	$R\bar{3}m$	$R\bar{3}m$	$R\bar{3}m$			
Schoenflies symbol	T_h^6	D_{2h}^{18}	D_{3d}^5	D_{3d}^5	D_{3d}^5			
Strukturbericht type		A11	A7	A7	A7			
Pearson symbol	cP8	oC8	hR2	hR2	hR2			
Number A of atoms per cell	4×2	8	2	2	2			
Coordination number		$2 + 1$	3	3	3			
Shortest interatomic distance, solid		222	252	291	307		pm	

Table 4.69 Elements of Group VA (CAS notation), or Group 15 (new IUPAC notation). Part B(b): Mechanical properties

Element name Chemical symbol Atomic number Z	Nitrogen N 7	Phosphorus P 15	Arsenic As 33	Antimony Sb 51	Bismuth Bi 83	Moscovium Mc 115	Units	Remarks
State	N_2 gas	P, black						
Density ϱ, solid		2.690	5.72	6.68	9.80		g/cm^3	
Density ϱ, liquid					10.05		g/cm^3	
Density ϱ, gas	1.2506×10^{-3}						g/cm^3	At 273 K
Molar volume V_{mol}	13.65		12.95	18.20	21.44		cm^3/mol	
Viscosity η, gas	18.9						$\mu Pa\,s$	At 323 K
Viscosity η, liquid				1.50	1.65		mPa s	Near T_m
Surface tension γ, liquid				0.384	0.376		N/m	
Coefficient of linear thermal expansion α			4.7×10^{-6}	8.5×10^{-6}	13.4×10^{-6}		1/K	
Sound velocity, gas	336.9						m/s	
Sound velocity, liquid	929 (70 K)				1635		m/s	
Sound velocity, solid, transverse				1800	1140		m/s	
Sound velocity, solid, longitudinal				3140	2298		m/s	
Compressibility κ				2.6×10^{-5}	2.86×10^{-5}		1/MPa	Volume compressibility
Elastic modulus E	1.2[a,b]	30.4[b]	22	54.4	34.0		GPa	
Shear modulus G				20.6	12.8		GPa	
Poisson number μ				0.25	0.33			
Elastic compliance s_{11}			46.71	16.1	26.0		1/TPa	
Elastic compliance s_{33}			202.9	29.9	42.0		1/TPa	
Elastic compliance s_{44}			44.91	38.9	114		1/TPa	
Elastic compliance s_{12}			36.94	−6.1	−7.9		1/TPa	
Elastic compliance s_{13}			−88.2	−6.2	−11.9		1/TPa	
Elastic compliance s_{14}			1.80	−12.3	−21.2		1/TPa	

Table 4.69 (continued)

Element name Chemical symbol Atomic number Z	Nitrogen N 7	Phosphorus P 15	Arsenic As 33	Antimony Sb 51	Bismuth Bi 83	Moscovium Mc 115	Units	Remarks
State	N_2 gas	P, black						
Elastic stiffness c_{11}		73.9	123.6	101	63.4		GPa	
Elastic stiffness c_{22}		277					GPa	
Elastic stiffness c_{33}	53.7	53.7	59.1	44.9	37.9		GPa	
Elastic stiffness c_{44}		15.6	22.6	39.5	11.5		GPa	
Elastic stiffness c_{55}		11.5					GPa	
Elastic stiffness c_{66}		56.7					GPa	
Elastic stiffness c_{12}			19.7	32.2	24.5		GPa	
Elastic stiffness c_{13}			62.3	27.6	24.9		GPa	
Elastic stiffness c_{14}			−4.16	21.8	7.3		GPa	
Brinell hardness					200			
Mohs hardness			3.5					
Solubility in water α_W, 293 K	0.01557							α_W = vol (gas)/vol (water)

[a] Solid
[b] Estimated

Table 4.70 Elements of Group VA (CAS notation), or Group 15 (new IUPAC notation). Part B(c): Thermal and thermodynamic properties

Element name Chemical symbol Atomic number Z	Nitrogen N 7	Phosphorus P 15	Arsenic As 33	Antimony Sb 51	Bismuth Bi 83	Moscovium Mc 115	Units	Remarks
State	N_2 gas	P, white[a]	α-As					
Thermal conductivity λ	0.02598		50.0	25.9	7.87		W/(m K)	
Molar heat capacity c_p	14.560	23.824	24.65	25.23	25.52		J/(mol K)	At 298 K
Standard entropy S^0	191.611	41.090	35.689	45.522	56.735		J/(mol K)	At 298 K and 100 kPa
Enthalpy difference $H_{298} - H_0$	8.6692	5.3600	5.1170	5.8702	6.4266		kJ/mol	
Melting temperature T_m	63.1458	317.30	1090.00	903.78	544.55		K	
Enthalpy change ΔH_m	0.720	0.6590	24.4429	19.8740	11.2968		kJ/mol	
Entropy change ΔS_m		2.077	22.425	21.990	20.745		J/(mol K)	
Volume change ΔV_m			0.10	−0.008	−0.33			$(V_l - V_s)/V_l$ at T_m
Boiling temperature T_b	77.35	550		1860	1837		K	
Enthalpy change ΔH_b	5.577	51.9	34.8	165.8	174.1		kJ/mol	
Critical temperature T_c	126.25		1089				K	
Critical pressure p_c	3.40		36				MPa	
Critical density ϱ_c	0.311						g/cm^3	
Triple-point temperature T_{tr}	63.14						K	
Triple-point pressure p_{tr}	12.5						kPa	

[a] In Landolt–Börnstein, Group IV, Vol. 19A, Part 1 [4.4], the white form of phosphorus has been chosen as the reference phase for all phosphides because the more stable red form is difficult to characterize

Table 4.71 Elements of Group VA (CAS notation), or Group 15 (new IUPAC notation). Part B(d): Electronic, electromagnetic, and optical properties

Element name **Chemical symbol** **Atomic number Z**	**Nitrogen** **N** **7**	**Phosphorus** **P** **15**	**Arsenic** **As** **33**	**Antimony** **Sb** **51**	**Bismuth** **Bi** **83**	**Moscovium** **Mc** **115**	**Units**	**Remarks**
State	N_2 gas	P, black						
Characteristics	Gas	Semiconductor	Semiconductor	Semimetal	Brittle metal	Semimetal		
Electrical resistivity ρ_s Temperature coefficient Pressure coefficient			260 42×10^{-4}	370 51.1×10^{-4} 6.0×10^{-9}	1068 45.4×10^{-4} 15.2×10^{-9}		nΩ m 1/K 1/hPa	Solid, at RT
Electrical resistvity ρ_l				1135	1280			Liquid
Resistivity ratio				0.61	0.43			ρ_l/ρ_s at T_m
Electronic band gap ΔE Temperature coefficient		0.57 8×10^{-4}	1.14				eV eV/K	At 300 K
Electronic work function			4.79	4.56	4.36		V	
Thermal work function			5.71	4.08	4.28		V	
Electron mobility		220					$cm^2/(V\,s)$	
Hole mobility		350					$cm^2/(V\,s)$	
Hall coefficient R			0.45×10^{-7}	0.27×10^{-7}	-6.33×10^{-7}		$m^3/(A\,s)$	$B = 0.4-1.0$ T
Thermoelectric coefficient				35	−70		μV/K	
Dielectric constant $(\varepsilon-1)$, gas	580×10^{-6}							At 293 K
Dielectric constant ε, liquid	1.45							At 74.8 K
Dielectric constant ε, solid			11.2 (optical)					
Molar magnetic susceptibility χ_{mol}, (SI)	-151×10^{-6}	a,b	-70.4×10^{-6}[c]	-1244×10^{-6}	-3520×10^{-6}		cm^3/mol	At 295 K
Molar magnetic susceptibility χ_{mol}, (cgs)	-12.0×10^{-6}	a,b	-5.60×10^{-6}[c]	-99×10^{-6}	-280.1×10^{-6}		cm^3/mol	At 295 K
Mass magnetic susceptibility χ_{mass}, (SI)	-5.4×10^{-6}		-3.9×10^{-6}	-10×10^{-6}	-16.8×10^{-6}		cm^3/g	At 295 K
Refractive index $(n-1)$, gas	297×10^{-6}							589.3 nm
Refractive index n, liquid	1.929 (78 K)							589.3 nm
Refractive index n, solid			3.35 (0.8 μm)					

[a] White P: Molar magnetic susceptibility: -26.7×10^{-6} (cgs) and -335×10^{-6} (SI) cm^3/mol
[b] Red P: Molar magnetic susceptibility: -20.8×10^{-6} (cgs) and -261×10^{-6} (SI) cm^3/mol
[c] Yellow As: Molar magnetic susceptibility: -292×10^{-6} (SI) and -23.2×10^{-6} (cgs) cm^3/mol

Table 4.72 Elements of Group VA (CAS notation), or Group 15 (new IUPAC notation). Part C: Allotropic and high-pressure modifications

Element	Nitrogen			Arsenic		Antimony				Bismuth						
Modification	α-N	β-N	γ-N	α-As	ε-As	Sb-I	Sb-II	Sb-III	Sb-IV	α-Bi	β-Bi	γ-Bi	δ-Bi	ε-Bi	ζ-Bi	Units
Crystal system, Bravais lattice	cub, P	hex	tetr	trig, R	orth	trig, R	cub	hex, cp	mon	trig, R	mon	mon			cub, bc	
Structure type	α-N	La		As	α-Ga	α-As		Mg		α-As					W	
Lattice constant *a*	565.9	404.6	395.7	413.20	362	450.65	299.2	337.6	556	474.60		605			3800	pm
Lattice constant *b*					1085				404			420				pm
Lattice constant *c*		662.9	510.1		448			534.1	422			465				pm
Lattice angle α				54.12		57.11				57.23						deg
Lattice angle β									86.0							deg
Space group	$Pa\bar{3}$	$P6_3/mmc$	$P4_2/mnm$	$R\bar{3}m$	$Cmca$	$R\bar{3}m$	$Pm3m$	$P6_3/mmc$		$R\bar{3}m$	$C2/m$				$Im\bar{3}m$	
Schoenflies symbol	T_h^6	D_{6v}^4	D_{4h}^{12}	D_{3d}^5	D_{2h}^{18}	D_{3d}^5	O_h^1	D_{6h}^4		D_{3d}^5	C_{2h}^3				O_h^9	
Strukturbericht type		A9		A7	A11	A7				A7					A2	
Pearson symbol	cP8	hP4	tP4	hR2	oC8	hR2	cP1	A3		hR2	mC4	mP3			cI2	
Number *A* of atoms per cell	4 × 2	4	4	2	8	2	1	hP2		2	4	3			2	
Coordination number		3		3		3		2		3						
Shortest interatomic distance, solid				252		291				307						pm
Range of stability	< 20 K	> 35.6 K	20 K, > 3.3 GPa		> 721 K	RTP	> 5.0 GPa	> 7.5 GPa	14.0 GPa	RTP	> 0.28 GPa	> 3.0 GPa	> 4.3 GPa	> 6.5 GPa	> 9.0 GPa	

Table 4.73 Elements of Group VA (CAS notation), or Group 15 (new IUPAC notation). Part D: Ionic radii (determined from crystal structures)

Element	Nitrogen		Phosphorus	Arsenic		Antimony		Bismuth		
Ion	N^{3+}	N^{5+}	P^{5+}	As^{3+}	As^{5+}	Sb^{3+}	Sb^{5+}	Bi^{3+}	Bi^{5+}	
Coordination number										Units
4			17		34	76				pm
5								96		pm
6	16	13	38	58	46	76	60	103	76	pm
8								117		pm

Table 4.74 Elements of Group VB (CAS notation), or Group 5 (new IUPAC notation). Part A: Atomic, ionic, and molecular properties (see Table 4.79 for ionic radii)

Element name	Vanadium	Niobium	Tantalum	Dubnium		
Chemical symbol	V	Nb	Ta	Db		
Atomic number Z	23	41	73	105	Units	Remarks
Relative atomic mass A (atomic weight)	50.9415(1)	92.90637(2)	180.94788(2)	[262]		
Abundance in lithosphere	150×10^{-6}	20×10^{-6}	2.1×10^{-6}			Mass ratio
Abundance in sea	2.5×10^{-9}	1×10^{-11}	2×10^{-12}			Mass ratio
Atomic radius r_{cov}	122	134	134		pm	Covalent radius
Atomic radius r_{met}	135	147	147		pm	Metallic radius, CN = 12
Electron shells	–LMN	–MNO	–NOP	–OPQ		
Electronic ground state	$^4F_{3/2}$	$^6D_{1/2}$	$^4F_{3/2}$			
Electronic configuration	[Ar] $3d^3 4s^2$	[Kr] $4d^4 5s^1$	[Xe] $4f^{14} 5d^3 6s^2$			
Oxidation states	5+, 4+, 3+, 2+	5+, 3+	5+			
Electron affinity	0.525	0.893	0.322		eV	
Electronegativity χ_A	1.45	1.23	(1.33)			Allred and Rochow
1st ionization energy	6.7463	6.75885	7.89		eV	
2nd ionization energy	14.66	14.32			eV	
3rd ionization energy	29.311	25.04			eV	
4th ionization energy	46.709	38.3			eV	
5th ionization energy	65.282	50.55			eV	
Standard electrode potential E^0	−1.175				V	Reaction type $V^{2+} + 2e^- = V$
	−0.255				V	Reaction type $V^{3+} + e^- = V^{2+}$

Table 4.75 Elements of Group VB (CAS notation), or Group 5 (new IUPAC notation). Part B(a): Crystallographic properties

Element name **Chemical symbol** **Atomic number *Z***	**Vanadium** **V** **23**	**Niobium** **Nb** **41**	**Tantalum** **Ta** **73**	**Dubnium** **Db** **105**	**Units**	**Remarks**
Crystal system, Bravais lattice	cub, bc	cub, bc	cub, bc			
Structure type	W	W	W			
Lattice constant a	302.38	330.07	330.31		pm	
Space group	$Im\bar{3}m$	$Im\bar{3}m$	$Im\bar{3}m$			
Schoenflies symbol	O_h^9	O_h^9	O_h^9			
Strukturbericht type	A2	A2	A2			
Pearson symbol	cI2	cI2	cI2			
Number A of atoms per cell	2	2	2			
Coordination number	8	8	8			
Shortest interatomic distance, solid	263	285	285		pm	

Table 4.76 Elements of Group VB (CAS notation), or Group 5 (new IUPAC notation). Part B(b): Mechanical properties

Element name **Chemical symbol** **Atomic number *Z***	**Vanadium** **V** **23**	**Niobium** **Nb** **41**	**Tantalum** **Ta** **73**	**Dubnium** **Db** **105**	**Units**	**Remarks**
Density ϱ, solid	5.80	8.35	16.60		g/cm^3	
Density ϱ, liquid	5.55	7.830	15.00		g/cm^3	
Molar volume V_{mol}	8.34	10.84	10.87		cm^3/mol	
Surface tension, liquid Temperature coefficient	1.95 0.3×10^{-3}	2.0 -0.24×10^{-3}	2.15 -0.25×10^{-3}		N/m N/(m K)	
Coefficient of linear thermal expansion α	8.3×10^{-6}	7.34×10^{-6}	6.64×10^{-6}		1/K	300 K
Sound velocity, solid, transverse	2780	2100	2900		m/s	
Sound velocity, solid, longitudinal	6000	4900	4100		m/s	
Compressibility κ	0.63×10^{-5}	0.56×10^{-5}	0.465×10^{-5}		1/MPa	Volume compressibility
Elastic modulus E	127	104	185		GPa	
Shear modulus G	46.6	59.5	64.7		GPa	
Poisson number μ	0.36	0.38	0.35			
Elastic compliance s_{11}	6.75	6.56	6.89		1/TPa	
Elastic compliance s_{44}	23.2	35.2	12.1		1/TPa	
Elastic compliance s_{12}	−2.31	−2.29	−2.58		1/TPa	
Elastic stiffness c_{11}	230	245	264		GPa	
Elastic stiffness c_{44}	43.1	28.4	82.6		GPa	
Elastic stiffness c_{12}	120	132	158		GPa	
Vickers hardness	630	70–250 (HV 10)	80–300 (HV 10)			At 293 K

Table 4.77 Elements of Group VB (CAS notation), or Group 5 (new IUPAC notation). Part B(c): Thermal and thermodynamic properties

Element name Chemical symbol Atomic number Z	Vanadium V 23	Niobium Nb 41	Tantalum Ta 73	Dubnium Db 105	Units	Remarks
Thermal conductivity λ	30.7	59.0	60.7		W/(m K)	At 300 K
Molar heat capacity c_p	24.90	24.69	25.30		J/(mol K)	At 298 K
Standard entropy S^0	30.890	36.270	41.472		J/(mol K)	At 298 K and 100 kPa
Enthalpy difference $H_{298} - H_0$	4.5070	5.2200	5.6819		kJ/mol	
Melting temperature T_m	2183.00	2750.00	3290.00		K	
Enthalpy change ΔH_m	21.5000	30.0000	36.5682		kJ/mol	
Entropy change ΔS_m	9.849	10.909	11.115		J/(mol K)	
Relative volume change ΔV_m						$(V_l - V_s)/V_l$ at T_m
Boiling temperature T_b	3690	5017	5778		K	
Enthalpy change ΔH_b	451.8	683.2	743.1		kJ/mol	

Table 4.78 Elements of Group VB (CAS notation), or Group 5 (new IUPAC notation). Part B(d): Electronic, electromagnetic, and optical properties. There is no Part C, because no allotropic or high-pressure modifictions are known

Element name Chemical symbol Atomic number Z	Vanadium V 23	Niobium Nb 41	Tantalum Ta 73	Dubnium Db 105	Units	Remarks
Electrical resistivity ρ_s	248	152	125		nΩ m	At RT
Temperature coefficient	39.0×10^{-4}	25.8×10^{-4}	38.2×10^{-4}		1/K	
Pressure coefficient	-1.6×10^{-9}	-1.37×10^{-9}	-1.62×10^{-9}		1/hPa	
Superconducting critical temperature T_{crit}	5.3	9.13	4.49		K	
Superconducting critical field H_{crit}	1020	1980	830		Oe	
Hall coefficient R	0.82×10^{-10}	0.88×10^{-10}	1.01×10^{-10}		$m^3/(A\,s)$	At 273 K, $B = 0.5$–2.9 T
Thermoelectric coefficient			−5.0		μV/K	
Electronic work function	4.3	4.3	4.3		V	
Thermal work function	4.09	3.99	4.25		V	
Molar magnetic susceptibility χ_{mol}, solid, (SI)	3581×10^{-6}	2614×10^{-6}	1935×10^{-6}		cm^3/mol	At 295 K
Molar magnetic susceptibility χ_{mol}, solid, (cgs)	285×10^{-6}	208×10^{-6}	154×10^{-6}		cm^3/mol	At 295 K
Mass magnetic susceptibility χ_{mass}, solid, (SI)	62.8×10^{-6}	27.6×10^{-6}	10.7×10^{-6}		cm^3/g	At 295 K

Table 4.79 Elements of Group VB (CAS notation), or Group 5 (new IUPAC notation). Part D: Ionic radii (determined from crystal structures)

Element Ion Coordination number	Vanadium V^{2+}	 V^{3+}	 V^{4+}	 V^{5+}	Niobium Nb^{3+}	 Nb^{4+}	 Nb^{5+}	Tantalum Ta^{3+}	 Ta^{4+}	 Ta^{5+}	Units
4				36			48				pm
5			53	46							pm
6	79	64	58	54	72	68	64	72	68	64	pm
8			72		79		74				pm

Table 4.80 Elements of Group VIA (CAS notation), or Group 16 (new IUPAP notation). Part A: Atomic, ionic and molecular properties (see Table 4.86 for ionic radii)

Element name **Chemical symbol** **Atomic number Z**	**Oxygen** **O** **8**	**Sulfur** **S** **16**	**Selenium** **Se** **34**	**Tellurium** **Te** **52**	**Polonium** **Po** **84**	**Livermorium** **Lv** **116**	**Units**	**Remarks**
Characteristics					Radioactive			
Relative atomic mass A (atomic weight)	[15.99903; 15.99977]	[32.059; 32.076]	78.971(8)	127.60(3)	[209]			
Abundance in lithosphere	$464\,000 \times 10^{-6}$	520×10^{-6}	0.09×10^{-6}	2×10^{-9}				Mass ratio
Abundance in sea	$880\,000 \times 10^{-6}$	905×10^{-6}	2×10^{-10}					Mass ratio
Atomic radius r_{cov}	66	104	117	137	146		pm	Covalent radius
Atomic radius r_{met}		127	140	160	176		pm	Metallic radius, CN = 12
Atomic radius r_{vdW}	150	185	200	220				van der Waals radius
Electron shells	KL	KLM	–LMN	–MNO	–NOP			
Electronic ground state	$^3P_2$	$^3P_2$	$^3P_2$	$^3P_2$	$^3P_2$			
Electronic configuration	[He] $2s^2 2p^4$	[Ne] $3s^2 3p^4$	[Ar] $3d^{10} 4s^2 4p^4$	[Kr] $4d^{10} 5s^2 5p^4$	[Xe] $4f^{14} 5d^{10} 6s^2 6p^4$	[Rn] $5f^{14} 6d^{10} 7s^2 7p^4$		
Oxidation states	2−	6+, 4+, 2+, 2−	6+, 4+, 2+, 2−	6+, 4+, 2+, 2−	4+, 2+			
Electron affinity	1.46 −8.75	2.08 −5.51	2.08	1.97	1.9		eV eV	Reaction type $O + e^- = O^-$ Reaction type $O^- + e^- = O^{2-}$
Electronegativity χ_A	3.50	2.44	2.48	2.01	(1.76)			Allred and Rochow
1st ionization energy	13.61806	10.36001	9.75238	9.0096	8.41671		eV	
2nd ionization energy	35.11730	23.3379	21.19	18.6			eV	
3rd ionization energy	54.9355	34.79	30.8204	27.96			eV	
4th ionization energy	77.41353	47.222	42.9450	37.41			eV	
Standard electrode potential E^0		−0.476	−0.924	−1.143 +0.568	 +0.56		V V V	Reaction type $Te^{2-} = Te + 2e^-$ Reaction type $Po^{3+} + 3e^- = Po$ Reaction type $Te^{4+} + 4e^- = Te$

Table 4.81 Elements of Group VIA (CAS notation), or Group 16 (new IUPAC notation). Part B(a): Crystallographic properties (see Table 4.85 for allotropic and high-pressure modifications)

Element name Chemical symbol Atomic number Z	Oxygen O 8	Sulfur S 16	Selenium Se 34	Tellurium Te 52	Polonium Po 84	Livermorium Lv 116	Units	Remarks
State	α-O, $T < 23$ K	S_8, α-S	Gray Se, chains		α-Po			
Crystal system, Bravais lattice	mon, C	orth, F	hex	hex	cub, sc			
Structure type	α-O	α-S	γ-Se	γ-Se	α-Po			
Lattice constant a	540.3	1046.4	436.55	445.61	336.6		pm	
Lattice constant b	342.9	1286.60					pm	
Lattice constant c	508.6	2448.60	495.76	592.71			pm	
Lattice angle γ	132.53						deg	
Space group	$C2/m$	$Fddd$	$P3_121$	$P3_121$	$Pm3m$			
Schoenflies symbol	C_{2h}^3	D_{2h}^{24}	D_3^4	D_3^4	O_h^1			
Strukturbericht type		A16	A8	A8	A_h			
Pearson symbol	mC4	oF128	hP3	hP3	cP1			
Number A of atoms per cell	2×2	128	3	3	1			
Coordination number		2	2	$2 + 4$	6			
Shortest interatomic distance, solid		204	237	283	337		pm	

Table 4.82 Elements of Group VIA (CAS notation), or Group 16 (new IUPAC notation). Part B(b): Mechanical properties

Element name Chemical symbol Atomic number Z	Oxygen O 8	Sulfur S 16	Selenium Se 34	Tellurium Te 52	Polonium Po 84	Livermorium Lv 116	Units	Remarks
State	O_2 gas	α-S	Gray Se					
Density ϱ, solid		2.037	4.79	6.24	9.40	≥ 9.32	g/cm^3	At 293 K
Density ϱ, liquid		1.819	3.990	5.797			g/cm^3	
Density ϱ, gas	1.429×10^{-3}						g/cm^3	
Molar volume V_{mol}	8.00	15.49	16.48	20.45	22.4		cm^3/mol	
Viscosity η, gas	19.5						μPa s	
Viscosity η, liquid		11.5	1260				mPa s	At T_m
Surface tension, liquid		0.061	0.106	0.186			N/m	At T_m
Coefficient of linear thermal expansion α		74.33×10^{-6}	36.9×10^{-6}	16.75×10^{-6}	23×10^{-6}		1/K	
Sound velocity, gas	336.95 (70 K)						m/s	
Sound velocity, liquid	1079 (70 K)						m/s	
Compressibility κ		13.0×10^{-5}	11.6×10^{-5}	4.8×10^{-5}			1/MPa	Volume compressibilty
Elastic modulus E		17.8[a]	58.0	47.1	26[a]		GPa	
Shear modulus G			6.46	16.7			GPa	
Poisson number μ			0.45	0.23				
Elastic compliance s_{11}	1280[b]	74.6					1/TPa	
Elastic compliance s_{22}		111					1/TPa	
Elastic compliance s_{33}		75.4					1/TPa	
Elastic compliance s_{44}	3640[b]	121					1/TPa	
Elastic compliance s_{55}		234					1/TPa	

Table 4.82 (continued)

Element name Chemical symbol Atomic number Z	Oxygen O 8	Sulfur S 16	Selenium Se 34	Tellurium Te 52	Polonium Po 84	Livermorium Lv 116	Units	Remarks
Elastic compliance s_{66}		229					1/TPa	
Elastic compliance s_{12}	−570[b]	−13.1					1/TPa	
Elastic compliance s_{13}		−7.1					1/TPa	
Elastic compliance s_{23}		−45.8					1/TPa	
Elastic stiffness c_{11}	2.60[b]	14.22					GPa	
Elastic stiffness c_{22}		12.68					GPa	
Elastic stiffness c_{33}		18.30					GPa	
Elastic stiffness c_{44}	0.275[b]	8.27					GPa	
Elastic stiffness c_{55}		4.28					GPa	
Elastic stiffness c_{66}		4.37					GPa	
Elastic stiffness c_{12}	2.06[b]	2.99					GPa	
Elastic stiffness c_{13}		3.14					GPa	
Elastic stiffness c_{23}		7.95					GPa	
Tensile strength				10.8−12.25			MPa	
Brinell hardness				250				
Mohs hardness			2.0					
Solubility in water α_W^c	0.0310							At 293 K and 1013 hPa

[a] Estimated
[b] γ-Oxygen, $T = 54.4$ K
[c] α_W = vol (gas)/vol (water)

Table 4.83 Elements of Group VIA (CAS notation), or Group 16 (new IUPAC notation). Part B(c): Thermal and thermodynamic properties

Element name Chemical symbol Atomic number Z	Oxygen O 8	Sulfur S 16	Selenium Se 34	Tellurium Te 52	Polonium Po 84	Livermorium Lv 116	Units	Remarks
State	O_2 gas	α-S	α-Se	α-Te	α-Po			
Thermal conductivity λ	0.0245	0.269	2.48	1.7	20		W/(m K)	At STP
Molar heat capacity c_p	14.690	22.70	25.04	25.73			J/(mol K)	At 298 K
Standard entropy S^0	205.147	32.070	41.966	49.221	62.000		J/(mol K)	At 298 K and 100 kPa
Enthalpy difference $H_{298} - H_0$	8.6800	4.4120	5.5145	6.0800	6.700		kJ/mol	
Melting temperature T_m	54.361	388.36	494	722.66	527.00		K	
Enthalpy change ΔH_m	0.444	1.7210	6.6944	17.3760	10.000		kJ/mol	
Entropy change ΔS_m		4.431	13.551	24.045	18.975		J/(mol K)	
Relative volume change ΔV_m		0.515	+0.168	0.05				$(V_l - V_s)/V_l$ at T_m
Boiling temperature T_b	90.18	882	958	1261	1335		K	
Enthalpy change ΔH_b	6.2	9.62	90	104.6	100.8		kJ/mol	
Critical temperature T_c	154.58		1863				K	
Critical pressure p_c	5.4		38				MPa	
Critical density ϱ_c	0.419						g/cm^3	
Triple-point temperature T_{tr}	54.4						K	
Triple-point pressure p_{tr}	1.52						hPa	

Table 4.84 Elements of Group VIA (CAS notation), or Group 16 (new IUPAC notation). Part B(d): Electronic, electromagnetic, and optical properties

Element name **Chemical symbol** **Atomic number *Z***	**Oxygen** **O** **8**	**Sulfur** **S** **16**	**Selenium** **Se** **34**	**Tellurium** **Te** **52**	**Polonium** **Po** **84**	**Livermorium** **Lv** **116**	**Units**	**Remarks**
State	O_2 gas		Gray Se					
Characteristics		Solid insulator	Semiconductor	Semiconductor	Volatile metal	Semimetal		
Electrical resistivity ρ_s			100	1–50			MΩ m	At RT
Electrical resistivity ρ_l			20	6.0 μΩ m			MΩ m	
Resistivity ratio at T_m			1.0	0.048–0.091				
Hall coefficient R				0.24×10^{-10}			$m^3/(A\,s)$	At 298 K
Thermoelectric coefficient				400			μV/K	
Electronic band gap ΔE Temperature coefficient		3.6 -6.8×10^{-4}	1.79 -9×10^{-4}	0.33			eV eV/K	
Electronic work function			5.9	4.95			V	
Thermal work function			4.72	4.73			V	
Electron mobility				1100			$cm^2/(V\,s)$	
Hole mobility				560			$cm^2/(V\,s)$	
Dielectric constant $(\varepsilon - 1)$, gas	525×10^{-6}							At 373 K
Dielectric constant ε, liquid	1.505							At 81 K
Dielectric constant ε, solid			8.5 ($\lambda = 3.3$ cm)	5.0 $\parallel c$ 2.2 $\perp c$				
Molar magnetic susceptibility χ_{mol}(SI)	$43\,341 \times 10^{-6}$ [a]	-195×10^{-6}	-314×10^{-6}	-478×10^{-6}			cm^3/mol	At 295 K
Molar magnetic susceptibility χ_{mol} (cgs)	3449×10^{-6} [b]	-15.5×10^{-6}	-25×10^{-6}	-38×10^{-6}			cm^3/mol	At 295 K
Mass magnetic susceptibility χ_{mass} (SI)	1.34×10^{-6} [c]	-6.09×10^{-6}	-4.0×10^{-6}	-3.9×10^{-6}			cm^3/g	At 295 K
Mass magnetic susceptibility χ_{mass}, liquid (SI)				-0.6×10^{-6}			cm^3/g	
Refractive index $(n - 1)$, gas	270.6×10^{-6}							$\lambda = 589.3$ nm
Refractive index n, liquid	1.221 (92 K)							$\lambda = 589.3$ nm
Refractive index n, solid			4.0					$\lambda = 589.3$ nm

[a] Liquid O_2, 90 K, 96 748 cm^3/mol; solid O_2, 54 K, 128 177 cm^3/mol; [b] Liquid O_2, 90 K, 7699 cm^3/mol; solid O_2, 54 K, 10 200 cm^3/mol; [c] At 280 K

Further remarks

Liquid O_3 has a molar magnetic susceptibility of 84.2×10^{-6} cm^3/mol (SI) and 6.7×10^{-6} cm^3/mol (cgs). The values given for the molar magnetic susceptibility χ_{mol} of sulfur apply to rhombic sulfur. The corresponding values for monoclinic sulfur are -187×10^{-6} cm^3/mol (SI) and -14.9×10^{-6} cm^3/mol (cgs)

Table 4.85 Elements of Group VIA (CAS notation), or Group 16 (new IUPAC notation). Part C: Allotropic and high-pressure modifications

Element	Oxygen			Selenium			Tellurium			Polonium		
Modification	α-O	β-O	γ-O	γ-Se	α-Se	β-Se	α-Te	β-Te	γ-Te	α-Po	β-Po	Units
Crystal system, Bravais lattice	mon, C	trig, R	cub, P	hex	mon	mon	hex	trig, R	trig, R	cub, P	trig, R	
Structure type	α-O	α-As	γ-O	γ-Se			γ-Se	α-As	α-Hg	α-Po	α-Hg	
Lattice constant a	540.3	421.0	683	436.55	905.4	1501.8	445.61	469	300.2	336.6	337.3	pm
Lattice constant b	342.9				908.3	1471.3						pm
Lattice constant c	508.6			495.76	233.6	887.9	592.71					pm
Lattice angle α		46.27						53.30	103.3		98.08	deg
Lattice angle γ	132.53				90.82	93.6						deg
Space group	$C2/m$	$R\bar{3}m$	$Pm\bar{3}m$	$P3_121$	$P2_1/m$	$P2_1/b$	$P3_121$	$R\bar{3}m$	$R\bar{3}m$	$Pm\bar{3}m$	$R\bar{3}m$	
Schoenflies symbol	C_{2h}^3	D_{3d}^5	O_h^3	D_3^4	C_{2h}^2	C_{2h}^5	D_3^4	D_{3d}^5	D_{3d}^5	O_h^1	D_{3d}^5	
Strukturbericht type		A7	A15	A8			A8	A7	A10	A_h	A10	
Pearson symbol	mC4	hR2	cP16	hP3		mP32	hP3	hR2	hR1	cP1	hR1	
Number A of atoms per cell	2×2	2	16	3		32	3	2	1	1	1	
Coordination number				2	2	2	$2+4$			6	6	
Shortest interatomic distance, solid				237	233–235	233–236	283			337	337	
Range of stability	< 23 K	> 23.9 K	> 43.6 K	RT	RT	RT	RTP	> 2 GPa	> 7.0 GPa	RTP	> 327 K	
Characteristics				Gray, Se chains	Red, Se_8 rings	Red, Se_8 rings						

Table 4.86 Elements of Group VIA (CAS notation), or Group 16 (new IUPAC notation). Part D: Ionic radii (determined from crystal structures)

Element	Oxygen	Sulfur			Selenium			Tellurium			Polonium	
Ion	O^{2-}	S^{2-}	S^{4+}	S^{6+}	Se^{2-}	Se^{4+}	Se^{6+}	Te^{2-}	Te^{4+}	Te^{6+}	Po^{4+}	
Coordination number												Units
2	121											pm
4				12			28		66	43		pm
6	140	184	37	29	198	50	42	221	97	56	97	pm
8	142											pm

Table 4.87 Elements of Group VIB (CAS notation), or Group 6 (new IUPAC notation). Part A: Atomic, ionic, and molecular properties (see Table 4.93 for ionic radii)

Element name	Chromium	Molybdenum	Tungsten	Seaborgium		
Chemical symbol	Cr	Mo	W	Sg		
Atomic number Z	24	42	74	106	Units	Remarks
Characteristics				Radioactive		
Relative atomic mass A (atomic weight)	51.9961(6)	95.95(1)	183.84(1)			
Abundance in lithosphere	200×10^{-6}	2.3×10^{-6}	1×10^{-6}			Mass ratio
Abundance in sea	3×10^{-10}	0.01×10^{-6}	1×10^{-10}			Mass ratio
Atomic radius r_{cov}	118	130	130		pm	Covalent radius
Atomic radius r_{met}	129	140	141		pm	Metallic radius, CN = 12
Electron shells	–LMN	–MNO	–NOP	–OPQ		
Electronic ground state	$^7S_3$	$^7S_3$	$^5D_0$			
Electronic configuration	[Ar] $3d^5 4s^1$	[Kr] $4d^5 5s^1$	[Xe] $4f^{14} 5d^4 6s^2$			
Oxidation states	6+, 3+, 2+	6+, 5+, 4+, 3+, 2+, 1+, 2−	6+, 5+, 4+, 3+, 2+, 1−, 2−			
Electron affinity	0.666	0.748	0.815		eV	
Electronegativity χ_A	1.56	1.30	(1.40)			Allred and Rochow
1st ionization energy	6.76664	7.09243	7.98		eV	
2nd ionization energy	16.4857	16.16			eV	
3rd ionization energy	30.96	27.13			eV	
4th ionization energy	49.16	46.4			eV	
Standard electrode potential E^0	−0.913				V	Reaction type $Cr^{2+} + 2e^- = Cr$
	−0.744	−0.2			V	Reaction type $Cr^{3+} + 3e^- = Cr$
	−0.407				V	Reaction type $Cr^{3+} + e^- = Cr^{2+}$

Table 4.88 Elements of Group VIB (CAS notation), or Group 6 (new IUPAC notation). Part B(a): Crystallographic properties (see Table 4.92 for allotropic and high-pressure modifications)

Element name **Chemical symbol** **Atomic number *Z***	**Chromium** **Cr** **24**	**Molybdenum** **Mo** **42**	**Tungsten** **W** **74**	**Seaborgium** **Sg** **106**	**Units**	**Remarks**
Crystal system, Bravais lattice	cub, bc	cub, bc	cub, bc			
Structure type	W	W	W			
Lattice constant a	288.47	314.70	316.51		pm	
Space group	$Im\bar{3}m$	$Im\bar{3}m$	$Im\bar{3}m$			
Schoenflies symbol	O_h^9	O_h^9	O_h^9			
Strukturbericht type	A2	A2	A2			
Pearson symbol	cI2	cI2	cI2			
Number A of atoms per cell	2	2	2			
Coordination number	8	8	8			
Shortest interatomic distance, solid	249	272	273		pm	

Table 4.89 Elements of Group VIB (CAS notation), or Group 6 (new IUPAC notation). Part B(b): Mechanical properties

Element name **Chemical symbol** **Atomic number *Z***	**Chromium** **Cr** **24**	**Molybdenum** **Mo** **42**	**Tungsten** **W** **74**	**Seaborgium** **Sg** **106**	**Units**	**Remarks**
Density ϱ, solid	7.19	10.220	19.30		g/cm^3	
Density ϱ, liquid	6.460		17.60		g/cm^3	
Molar volume V_{mol}	7.23	9.39	9.53		cm^3/mol	
Surface tension, liquid Temperature coefficient	1.6	2.25 -0.3×10^{-3}	2.31 -0.29×10^{-3}		N/m N/(m K)	
Coefficient of linear thermal expansion α	6.2×10^{-6}	5.35×10^{-6}	4.31×10^{-6}		1/K	300 K
Sound velocity, solid, transverse	3980	3350	2870		m/s	
Sound velocity, solid, longitudinal	6850	6250	5180		m/s	
Compressibility κ	0.78×10^{-5}	0.338×10^{-5}	0.28×10^{-5}		1/MPa	Volume compressibility
Elastic modulus E	145	330	407		GPa	
Shear modulus G	71.6	123	152		GPa	
Poisson number μ	0.31	0.31	0.28			
Elastic compliance s_{11}	3.05	2.63	2.45		1/TPa	
Elastic compliance s_{44}	9.98	9.20	6.24		1/TPa	
Elastic compliance s_{12}	−0.49	−0.68	−0.69		1/TPa	
Elastic stiffness c_{11}	348	465	523		GPa	
Elastic stiffness c_{44}	100.0	109	160		GPa	
Elastic stiffness c_{12}	67	163	203		GPa	
Tensile strength	Strongly dependent on microstructure					
Vickers hardness	1060	160–400 (HV 10)	360–600 (HV 30)			

Table 4.90 Elements of Group VIB (CAS notation), or Group 6 (new IUPAC notation). Part B(c): Thermal and thermodynamic properties

Element name Chemical symbol Atomic number Z	Chromium Cr 24	Molybdenum Mo 42	Tungsten W 74	Seaborgium Sg 106	Units	Remarks
Thermal conductivity λ	93.7	142	164		W/(m K)	At 293 K
Molar heat capacity c_p	23.44	23.932	24.27		J/(mol K)	At 298 K
Standard entropy S^0	23.543	28.560	32.618		J/(mol K)	At 298 K and 100 kPa
Enthalpy difference $H_{298} - H_0$	4.0500	4.5890	4.9700		kJ/mol	
Melting temperature T_m	2180.00	2893	3693		K	
Enthalpy change ΔH_m	21.0040	37.4798	52.3137		kJ/mol	
Entropy change ΔS_m	9.635	12.942	14.158		J/(mol K)	
Relative volume change ΔV_m						$(V_l - V_s)/V_l$ at T_m
Boiling temperature T_b	2952	4952	5828		K	
Enthalpy change ΔH_b	344.3	582.2	806.8		kJ/mol	
Critical temperature T_c		11 000			K	
Critical pressure p_c		540			MPa	
Critical density ϱ_c		2.630			g/cm^3	

Table 4.91 Elements of Group VIB (CAS notation), or Group 6 (new IUPAC notation). Part B(d): Electronic, electromagnetic, and optical properties

Element name Chemical symbol Atomic number Z	Chromium Cr 24	Molybdenum Mo 42	Tungsten W 74	Seaborgium Sg 106	Units	Remarks
Electrical resistivity ρ_s	127	52	54.9		nΩ m	At 293 K
Temperature coefficient	30.1×10^{-4}	43.3×10^{-4}	51×10^{-4}		1/K	
Pressure coefficient	-17.3×10^{-9}	-1.29×10^{-9}	-1.333×10^{-9}		1/hPa	
Superconducting critical temperature T_{crit}		0.92	0.005		K	
Superconducting critical field H_{crit}		98			Oe	
Hall coefficient R	3.63×10^{-10}	1.26×10^{-10}	0.856×10^{-10}		m^3/(A s)	$B = 0.5$–2.0 T, $T = 293$ K
Thermoelectric coefficient		5.9	1.5		μV/K	
Electronic work function	4.5	4.39	4.54		eV	
Thermal work function	4.6	4.26	4.50		V	
Molar magnetic susceptibility χ_{mol} (SI)	2099×10^{-6}	905×10^{-6}	666×10^{-6}		cm^3/mol	At 295 K
Molar magnetic susceptibility χ_{mol} (cgs)	167×10^{-6}	72×10^{-6}	53×10^{-6}		cm^3/mol	At 295 K
Mass magnetic susceptibility χ_{mass} (SI)	44×10^{-6}	12×10^{-6}	4.0×10^{-6}		cm^3/g	At 295 K

Table 4.92 Elements of Group VIB (CAS notation), or Group 6 (new IUPAC notation). Part C: Allotropic and high-pressure modifications

Element	Chromium		
Modification	α-Cr	α′-Cr	Units
Crystal system, Bravais lattice	cub, bc	cub, bc	
Structure type	W	W	
Lattice constant *a*	288.47	288.2	pm
Space group	$Im\bar{3}m$	$Im\bar{3}m$	
Schoenflies symbol	O_h^9	O_h^9	
Strukturbericht type	A2	A2	
Pearson symbol	cI2	cI2	
Number *A* of atoms per cell	2	2	
Coordination number	8	8	
Shortest interatomic distance, solid	249		
Range of stability	RTP	High pressure	

Table 4.93 Elements of Group VIB (CAS notation), or Group 6 (new IUPAC notation). Part D: Ionic radii (determined from crystal structures)

Element	Chromium				Molybdenum				Tungsten			
Ion	Cr^{2+}	Cr^{3+}	Cr^{4+}	Cr^{6+}	Mo^{3+}	Mo^{4+}	Mo^{5+}	Mo^{6+}	W^{4+}	W^{5+}	W^{6+}	
Coordination number												Units
4			41	26			46	41			42	pm
5											51	pm
6	73	62	55	44	69	65	61	59	66	62	60	pm
7								73				pm

Table 4.94 Elements of Group VIIA (CAS notation), or Group 17 (new IUPAC notation). Part A: Atomic, ionic, and molecular properties (see Table 4.100 for ionic radii)

Element name **Chemical symbol** **Atomic number Z**	**Fluorine** **F** **9**	**Chlorine** **Cl** **17**	**Bromine** **Br** **35**	**Iodine** **I** **53**	**Astatine** **At** **85**	**Tennessine** **Ts** **117**	**Units**	**Remarks**
Characterization					Radioactive			
Relative atomic mass A (atomic weight)	18.998403163(6)	[35.446; 35.457]	[79.901, 79.907]	126.90447(3)	[210]			
Abundance in lithosphere	800×10^{-6}	480×10^{-6}	2.5×10^{-6}	0.3×10^{-6}				Mass ratio
Abundance in sea	1.3×10^{-6}	$18\,800\times10^{-6}$	67×10^{-6}	0.06×10^{-6}				Mass ratio
Atomic radius r_{cov}	64	99	114	133	145		pm	Covalent radius
Atomic radius r_{vdW}	150–160	175	200	210			pm	van der Waals radius
Electron shells	KL	KLM	–LMN	–MNO	–NOP			
Electronic ground state	$^2P_{3/2}$	$^2P_{3/2}$	$^2P_{3/2}$	$^2P_{3/2}$	$^2P_{3/2}$			
Electronic configuration	[He] $2s^2 2p^5$	[Ne] $3s^2 3p^5$	[Ar] $3d^{10}4s^2 4p^5$	[Kr] $4d^{10}5s^2 5p^5$	[Xe] $4f^{14}5d^{10}6s^2 6p^5$			
Oxidation states		1+, 3+, 5+, 7+, 1–, 3–, 5–, 7–						
Electron affinity	3.40	3.61	3.36	3.06	2.8		eV	Reaction type $F + e^- = F^-$
Electronegativity χ_A	4.10	2.83	2.74	2.21	(1.90)			Allred and Rochow
1st ionization energy	17.42282	12.96764	11.81381	10.45126			eV	
2nd ionization energy	34.97082	23.814	21.8	19.1313			eV	
3rd ionization energy	62.7084	39.61	36	33			eV	
4th ionization energy	87.1398	53.4652	47.3				eV	
Standard electrode potential E^0	+2.866	+1.358	+1.066	+0.536			V	Reaction type $2Cl^- = Cl_2 + 2e^-$
Molecular form in gaseous state	F_2	Cl_2	Br_2	I_2				
Internuclear distance in molecule		198.8					pm	
Dissociation energy		2.475		1.5417			eV	Extrapolated to $T = 0$ K

Table 4.95 Elements of Group VIIA (CAS notation), or Group 17 (new IUPAC notation). Part B(a): Crystallographic properties (see Table 4.99 for allotropic and high-pressure modifications)

Element name **Chemical symbol** **Atomic number *Z***	**Fluorine** **F** **9**	**Chlorine** **Cl** **17**	**Bromine** **Br** **35**	**Iodine** **I** **53**	**Astatine** **At** **85**	**Tennessine** **Ts** **117**	**Units**	**Remarks**
State	F_2, < 45.6 K	Cl_2, 113 K	Br_2, 123 K	I_2				
Crystal system, Bravais lattice	mon, C	orth, C	orth, C	orth, C				
Structure type				Ga				
Lattice constant a	550	624	668	726.8			pm	
Lattice constant b	328	448	449	479.7			pm	
Lattice constant c	728	826	874	979.7			pm	
Lattice angle β	102.17						deg	
Space group	$C2/m$	$Cmca$	$Cmca$	$Cmca$				
Schoenflies symbol	C_{2h}^3	D_{2h}^{18}	D_{2h}^{18}	D_{2h}^{18}				
Strukturbericht type	C34	A11	A11	A11				
Pearson symbol	mC6	oC8	oC8	oC8				
Number A of atoms per cell	6	2×4	2×4	2×4				
Coordination number	1	1	1	1				
Shortest interatomic distance, solid	149	198.0	227	269			pm	

Table 4.96 Elements of Group VIIA (CAS notation), or Group 17 (new IUPAC notation). Part B(b): Mechanical properties

Element name **Chemical symbol** **Atomic number *Z***	**Fluorine** **F** **9**	**Chlorine** **Cl** **17**	**Bromine** **Br** **35**	**Iodine** **I** **53**	**Astatine** **At** **85**	**Tennessine** **Ts** **117**	**Units**	**Remarks**
State	F_2, gas	Cl_2, gas	Br_2, crystalline	I_2, crystalline				
Density ϱ, solid				4.92			g/cm^3	
Density ϱ, liquid			3.119 (293 K)					
Density ϱ, gas	1.696×10^{-3}	3.17×10^{-3}					g/cm^3	At 273 K, 1 bar
Molar volume V_{mol}	18.05	17.46	19.73	25.74			cm^3/mol	
Viscosity η, gas	209.3×10^2						µPa s	
Viscosity η, liquid			0.916 (299 K)	2.27			mPa s	
Surface tension, liquid			0.0441 (286 K)	0.0557			N/m	
Sound velocity, gas	336 (375 K)	206					m/s	STP
Elastic compliance s_{11}				328			1/TPa	
Elastic compliance s_{22}				103			1/TPa	
Elastic compliance s_{33}				132			1/TPa	
Elastic compliance s_{44}				303			1/TPa	
Elastic compliance s_{55}				67.7			1/TPa	
Elastic compliance s_{66}				170			1/TPa	
Elastic compliance s_{12}				−97			1/TPa	
Elastic compliance s_{13}				−173			1/TPa	
Elastic compliance s_{23}				49			1/TPa	
Elastic stiffness c_{11}			11.5				GPa	
Elastic stiffness c_{22}			13.5				GPa	
Elastic stiffness c_{33}			25.0				GPa	
Elastic stiffness c_{44}			3.30				GPa	
Elastic stiffness c_{55}			14.8				GPa	
Elastic stiffness c_{66}			5.88				GPa	
Elastic stiffness c_{12}			4.50				GPa	
Elastic stiffness c_{13}			13.5				GPa	
Elastic stiffness c_{23}			0.93				GPa	

Table 4.97 Elements of Group VIIA (CAS notation), or Group 17 (new IUPAC notation). Part B(c): Thermal and thermodynamic properties

Element name **Chemical symbol** **Atomic number Z**	**Fluorine** **F** **9**	**Chlorine** **Cl** **17**	**Bromine** **Br** **35**	**Iodine** **I** **53**	**Astatine** **At** **85**	**Tennessine** **Ts** **117**	**Units**	**Remarks**
State	F_2, gas	Cl_2, gas	Br_2, liquid	I_2, crystalline	At_2, crystalline			
Thermal conductivity λ	2.43×10^{-2}	9.3×10^{-3}		0.4	1.7		W/(m K)	STP
Molar heat capacity c_p	15.66	16.974	37.84	27.21			J/(mol K)	At 298 K
Standard entropy S^0	202.789	223.079	152.210	116.139	54.000		J/(mol K)	At 298 K and 100 kPa
Enthalpy difference $H_{298} - H_0$	8.8250	9.1810		13.1963	13.4000		kJ/mol	
Melting temperature T_m	53.48	172.18	265.90	386.75	575		K	
Enthalpy change ΔH_m		6.41	10.8	15.5172	23.8		kJ/mol	
Entropy change ΔS_m				40.122	40.0		J/(mol K)	
Volume change ΔV_m								$(V_l - V_s)/V_l$ at T_m
Boiling temperature T_b	84.95	239.1	332.3	458.4			K	
Enthalpy change ΔH_b		20.40	29.56	41.96	91		kJ/mol	
Critical temperature T_c	144.3	417		819			K	
Critical pressure p_c	5.22	7.98					MPa	
Critical density ϱ_c	0.630	0.573					g/cm^3	
Triple-point temperature T_{tr}	55	162					K	
Triple-point pressure p_{tr}	0.221	1.39					kPa	
Solubility in water[a]		4.610						At 273 K and 101 kPa

[a] m^3 gas/m^3 water

Table 4.98 Elements of Group VIIA (CAS notation), or Group 17 (new IUPAC notation). Part B(d): Electronic, electromagnetic, and optical properties

Element name **Chemical symbol** **Atomic number *Z***	**Fluorine** **F** **9**	**Chlorine** **Cl** **17**	**Bromine** **Br** **35**	**Iodine** **I** **53**	**Astatine** **At** **85**	**Tennessine** **Ts** **117**	**Units**	**Remarks**
State	F_2, gas	Cl_2, gas	Br_2, liquid	I_2, crystalline				
Characteristics	Yellow gas, very reactive	Yellow-green gas	Liquid halogen	Solid semi-conductor				
Electronic work function				2.8			eV	
Dielectric constant ε, liquid	1.517 (83.2 K)	2.15 (213 K)						
Molar magnetic susceptibility χ_{mol}, gas (SI)			-924				cm^3/mol	
Molar magnetic susceptibility χ_{mol}, gas (cgs)			-73.5×10^{-6}				cm^3/mol	
Molar magnetic susceptibility χ_{mol}, liquid (SI)		-508×10^{-6}	-709				cm^3/mol	
Molar magnetic susceptibility χ_{mol}, liquid (cgs)		-40.4×10^{-6}	-56.4×10^{-6}				cm^3/mol	
Molar magnetic susceptibility χ_{mol}, solid (SI)				-1131×10^{-6}			cm^3/mol	
Molar magnetic susceptibility χ_{mol}, solid (cgs)				-90×10^{-6}			cm^3/mol	
Mass magnetic susceptibility χ_{mass}, solid (SI)		-7.2×10^{-6}	-11.1×10^{-6}	-4.40×10^{-6}			cm^3/g	
Refractive index $(n-1)$, gas[a]	206×10^{-6}	773×10^{-6}						At 273 K and 101 kPa
Refractive index n, liquid[a]		1.367[b]	1.659					

[a] $\lambda = 589$ nm
[b] At 92 K, $\varrho = 1.330\,g/cm^3$

Table 4.99 Elements of Group VIIA (CAS notation), or Group 17 (new IUPAC notation). Part C: Allotropic and high-pressure modifications

Element **Modification**	**Fluorine** **α-F (F_2)**	**β-F**	**Units**
Crystal system, Bravais lattice	mon, C	cub, P	
Structure type		γ-O	
Lattice constant a	550	667	pm
Lattice constant b	328		pm
Lattice constant c	728		pm
Lattice angle γ	102.17		deg
Space group	$C2/m$	$Pm\bar{3}m$	
Schoenflies symbol	C_{2h}^3	O_h^3	
Strukturbericht type	C34	A15	
Pearson symbol	mC6	cP16	
Number A of atoms per cell	6	16	
Coordination number	1		
Shortest interatomic distance, solid	149		pm
Range of stability	< 45.6 K	> 45.6 K	

Table 4.100 Elements of Group VIIA (CAS notation), or Group 17 (new IUPAC notation). Part D: Ionic radii (determined from crystal structures)

Element	Fluorine		Chlorine			Bromine			Iodine			
Ion	F^-	F^{7+}	Cl^-	Cl^{5+}	Cl^{7+}	Br^-	Br^{5+}	Br^{7+}	I^-	I^{5+}	I^{7+}	
Coordination number												Units
3				12			31			44		pm
3					8			25			42	pm
6	133	8	181			196		39	220	95	53	pm

Table 4.101 Elements of Group VIIB (CAS notation), or Group 7 (new IUPAC notation). Part A: Atomic, ionic, and molecular properties (see Table 4.107 for ionic radii)

Element name	Manganese	Technetium	Rhenium	Bohrium		
Chemical symbol	Mn	Tc	Re	Bh		
Atomic number Z	25	43	75	107	Units	Remarks
Characteristics		Radioactive				
Relative atomic mass A (atomic weight)	54.938044(3)	[98]	186.207(1)			
Abundance in lithosphere	1000×10^{-6}		1×10^{-9}			Mass ratio
Abundance in sea	2×10^{-10}					Mass ratio
Atomic radius r_{cov}	118	127	128		pm	Covalent radius
Atomic radius r_{met}	137	137	137		pm	Metallic radius, CN = 12
Electron shells	–LMN	–MNO	–NOP	–OPQ		
Electronic ground state	$^6S_{5/2}$	$^6S_{5/2}$	$^6S_{5/2}$			
Electronic configuration	[Ar] $3d^5 4s^2$	[Kr] $4d^5 5s^2$	[Xe] $4f^{14} 5d^5 6s^2$			
Oxidation states	7+, 6+, 4+, 3+, 2+	7+	7+, 6+, 4+, 2+, 1−			
Electron affinity	Not stable	0.55	0.15		eV	Reaction type $Tc + e^- = Tc^-$
Electronegativity χ_A	1.60	1.36	(1.46)			Allred and Rochow
1st ionization energy	7.43402	7.28	7.88		eV	
2nd ionization energy	15.63999	15.26			eV	
3rd ionization energy	33.668	29.54			eV	
4th ionization energy	51.2				eV	
Standard electrode potential E^0	−1.185				V	Reaction type $Mn^{2+} + 2e^- = Mn$

Table 4.102 Elements of Group VIIB (CAS notation), or Group 7 (new IUPAC notation). Part B(a): Crystallographic properties (see Table 4.106 for allotropic and high-pressure modifications)

Element name	Manganese	Technetium	Rhenium	Bohrium		
Chemical symbol	Mn	Tc	Re	Bh		
Atomic number Z	25	43	75	107	Units	Remarks
State	α-Mn					
Crystal system, Bravais lattice	cub, bc	hex	hex			
Structure type	α-Mn	Mg	Mg			
Lattice constant a	892.19	273.8	276.08		pm	
Lattice constant c		439.4	445.80		pm	
Space group	$Im\bar{3}m$	$P6_3/mmc$	$P6_3/mmc$			
Schoenflies symbol	T_d^3	D_{6h}^4	D_{6h}^4			
Strukturbericht type	A12	A3	A3			
Pearson symbol	cI58	hP2	hP2			
Number A of atoms per cell	58	2	2			
Coordination number		12	12			
Shortest interatomic distance, solid	226–293	274			pm	

Table 4.103 Elements of Group VIIB (CAS notation), or Group 7 (new IUPAC notation). Part B(b): Mechanical properties

Element name Chemical symbol Atomic number Z	Manganese Mn 25	Technetium Tc 43	Rhenium Re 75	Bohrium Bh 107	Units	Remarks
Density ϱ, solid	7.470	11.50	21.00		g/cm^3	
Density ϱ, liquid	6.430		18.80		g/cm^3	
Molar volume V_{mol}	7.38	8.6	8.86		cm^3/mol	
Surface tension, liquid Temperature coefficient	1.10 0		2.65 -0.34×10^{-3}		N/m N/(m K)	
Coefficient of linear thermal expansion α	23×10^{-6}	8.06×10^{-6}	6.63×10^{-6}		1/K	
Sound velocity, solid, transverse	3280	50.6	2930		m/s	
Sound velocity, solid, longitudinal	5560	3270	5360		m/s	
Compressibility κ	0.716×10^{-5}	3.22×10^{-5}	0.264×10^{-5}		1/MPa	Volume compressibility
Elastic modulus E	196	407	520		GPa	At 293 K
Shear modulus G	79.4	162	180		GPa	
Poisson number μ	0.24	0.26	0.26			
Elastic compliance s_{11}		3.2	2.11		1/TPa	
Elastic compliance s_{33}		2.9	1.70		1/TPa	
Elastic compliance s_{44}		5.7	6.21		1/TPa	
Elastic compliance s_{12}		−1.1	−0.80		1/TPa	
Elastic compliance s_{13}		−0.9	−0.40		1/TPa	
Elastic stiffness c_{11}		433	616		GPa	
Elastic stiffness c_{33}		470	683		GPa	
Elastic stiffness c_{44}		177	161		GPa	
Elastic stiffness c_{12}		199	273		GPa	
Elastic stiffness c_{13}		199	206		GPa	
Tensile strength		0.40–0.74	1.16		GPa	
Vickers hardness	9.81	1.510	2.45–8.00			

Table 4.104 Elements of Group VIIB (CAS notation), or Group 7 (new IUPAC notation). Part B(c): Thermal and thermodynamic properties

Element name Chemical symbol Atomic number Z	Manganese Mn 25	Technetium Tc 43	Rhenium Re 75	Bohrium Bh 107	Units	Remarks
State	α-Mn					
Thermal conductivity λ	29.7	185	71.2		W/(m K)	
Molar heat capacity c_p	26.28		25.31		J/(mol K)	At 298 K
Standard entropy S^0	32.220	32.985	36.482		J/(mol K)	At 298 K and 100 kPa
Enthalpy difference $H_{298}-H_0$	4.9957		5.3330		kJ/mol	
Melting temperature T_m	1519.00	2430.01	3458.00		K	
Transition	δ–liquid	α–liquid	α–liquid			
Enthalpy change ΔH_m	12.9089	33.2912	34.0750		kJ/mol	
Entropy change ΔS_m	8.498	13.700	9.854		J/(mol K)	
Relative volume change ΔV_m	0.017					$(V_l-V_s)/V_l$ at T_m
Boiling temperature T_b	2335	4538	5869		K	
Enthalpy change ΔH_b	226.7	592.9	714.8		kJ/mol	
Critical temperature T_c			2090		K	
Critical pressure p_c			14.5		MPa	
Critical density ϱ_c			0.320		g/cm^3	

Table 4.105 Elements of Group VIIB (CAS notation), or Group 7 (new IUPAC notation). Part B(d): Electronic, electromagnetic, and optical properties

Element name Chemical symbol Atomic number Z	Manganese Mn 25	Technetium Tc 43	Rhenium Re 75	Bohrium Bh 107	Units	Remarks
Characteristics	Brittle metal	Metal	Metal			
Electrical resistivity ρ_s Temperature coefficient Pressure coefficient	1380 5.0×10^{-4} -3.54×10^{-9}	1510	172 44.8×10^{-4}		nΩ m 1/K 1/hPa	At RT
Electrical resistivity ρ_l	400				nΩ m	
Resistivity ratio at T_m	0.61					
Superconducting critical temperature T_{crit}			1.70		K	
Superconducting critical field H_{crit}			198		Oe	
Hall coefficient R	0.84×10^{-10}		3.15×10^{-10}		$m^3/(A\,s)$	At 297 K, $B = 0.5-5.0$ T
Electronic work function	4.08		About 5.0		V	
Thermal work function	3.91		4.96		V	
Molar magnetic susceptibility χ_{mol} (SI)	6421×10^{-6}	1445×10^{-6}	842×10^{-6}		cm^3/mol	At 295 K
Molar magnetic susceptibility χ_{mol} (cgs)	511×10^{-6}	115×10^{-6}	67×10^{-6}		cm^3/mol	At 295 K
Mass magnetic susceptibility χ_{mass} (SI)	121×10^{-6}	31×10^{-6}	4.56×10^{-6}		cm^3/g	At 295 K

Table 4.106 Elements of Group VIIB (CAS notation), or Group 7 (new IUPAC notation). Part C: Allotropic and high-pressure modifications

Element Modification	Manganese α-Mn	β-Mn	γ-Mn	δ-Mn	Units
Crystal system, Bravais lattice	cub, bc	cub, P	cub, fc	cub, bc	
Structure type	α-Mn	β-Mn	Cu	W	
Lattice constant a	892.19	631.52	386.24	308.06	pm
Lattice constant c					pm
Space group	$Im\bar{3}m$	$P4_132$	$Fm\bar{3}m$	$Im\bar{3}m$	
Schoenflies symbol	T_d^3	O'	O_h^5	O_h^9	
Strukturbericht type	A12	A13	A1	A2	
Pearson symbol	cI58	cP20	cF4	cI2	
Number A of atoms per cell	58	20	4	2	
Coordination number			12	8	
Shortest interatomic distance, solid	226–293		273	267	pm
Range of stability	RTP	> 1000 K	> 1368 K	> 1408 K	

Table 4.107 Eleents of Group VIIB (CAS notation), or Group 7 (new IUPAC notation). Part D: Ionic radii (determined from crystal structures)

Element Ion Coordination number	Manganese Mn^{2+}	Mn^{3+}	Mn^{4+}	Mn^{5+}	Mn^{6+}	Mn^{7+}	Technetium Tc^{4+}	Rhenium Re^{4+}	Re^{5+}	Re^{6+}	Re^{7+}	Units
4	66		39	33	26	25					38	pm
6	83	58	53				65	63	58	55		pm
8	96											pm

Table 4.108 Elements of Group VIIIA (CAS notation), or Group 18 (new IUPAC notation). Part A: Atomic, ionic, and molecular properties

Element name **Chemical symbol** **Atomic number Z**	**Neon** **Ne** **10**	**Argon** **Ar** **18**	**Krypton** **Kr** **36**	**Xenon** **Xe** **54**	**Radon** **Rn** **86**	**Oganesson** **Og** **118**	**Units**	**Remarks**
Characteristics					Radioactive			
Relative atomic mass A (atomic weight)	20.1797(6)	39.948(1)	83.80(1)	131.29(2)	[222]			
Atomic radius r_{cov}	(69)	(97)	110	130			pm	Covalent radius
Atomic radius r_{met}	154	188	202	216	240		pm	Metallic radius, CN = 12
Atomic radius r_{vdW}	160	188	200	220	240		pm	van der Waals radius
Electron shells	KL	KLM	–LMN	–MNO	–NOP			
Electronic ground state	$^1S_0$	$^1S_0$	$^1S_0$	$^1S_0$	$^1S_0$			
Electronic configuration	[He] $2s^2 2p^6$	[Ne] $3s^2 3p^6$	[Ar] $3d^{10} 4s^2 4p^6$	[Kr] $4d^{10} 5s^2 5p^6$	[Xe] $4f^{14} 5d^{10} 6s^2 6p^6$	[Rn] $5f^{14} 6d^{10} 7s^2 7p^6$		
Electron affinity	Not stable	Not stable	Not stable	Not stable	Not stable		eV	Reaction type $He + e^- = He^-$
Electronegativity χ_A	5.10	3.30	3.10	2.40	(2.06)			Allred and Rochow
1st ionization energy	21.56454	15.75962	13.99961	12.12987	10.74850		eV	
2nd ionization energy	40.96328	27.62967	24.35985	21.20979			eV	
3rd ionization energy	63.45	40.74	36.950	32.1230			eV	
4th ionization energy	97.12	59.81	52.5				eV	

Table 4.109 Elements of Group VIIIA (CAS notation), or Group 18 (new IUPAC notation). Part B(a): Crystallographic properties (see Table 4.112 for allotropic and high-pressure modifications)

Element name **Chemical symbol** **Atomic number Z**	**Neon** **Ne** **10**	**Argon** **Ar** **18**	**Krypton** **Kr** **36**	**Xenon** **Xe** **54**	**Radon** **Rn** **86**	**Oganesson** **Og** **118**	**Units**	**Remarks**
State	At 4.2 K	At 4.2 K	At 4.2 K	At 4.2 K				
Crystal system, Bravais lattice	cub, fc	cub, fc	cub, fc	cub, fc				
Structure type	Cu	Cu	Cu	Cu				
Lattice constant a	446.22	531.2	564.59	613.2			pm	
Space group	$Fm\bar{3}m$	$Fm\bar{3}m$	$Fm\bar{3}m$	$Fm\bar{3}m$				
Schoenflies symbol	O_h^5	O_h^5	O_h^5	O_h^5				
Strukturbericht type	A1	A1	A1	A1				
Pearson symbol	cF4	cF4	cF4	cF4				
Number A of atoms per cell	4	4	4	4				
Coordination number	12	12	12	12				
Shortest interatomic distance, solid	320	383	405	441			pm	

Table 4.110 Elements of Group VIIIA (CAS notation), or Group 18 (new IUPAC notation). Part B(b): Mechanical properties

Element name Chemical symbol Atomic number Z	Neon Ne 10	Argon Ar 18	Krypton Kr 36	Xenon Xe 54	Radon Rn 86	Oganesson Og 118	Units	Remarks
Characterics	Noble gas	Noble gas	Noble gas	Noble gas	Noble gas	Noble gas		
Density ϱ, solid		1.736 (40 K)					g/cm^3	
Density ϱ, gas	0.8994×10^{-3}		3.7493×10^{-3}	5.8971×10^{-3}	9.73×10^{-3}		g/cm^3	At 273 K
Molar volume V_{mol}	13.97		29.68	37.09	50.5		cm^3/mol	
Viscosity η, gas	29.8	21	23.4	21.2			$\mu Pa\,s$	At 293 K
Sound velocity, gas	461	308	213	168			m/s	At STP
Sound velocity, liquid		855 (85 K)					m/s	
Elastic modulus E	1.0	1.6	1.8				GPa	Low temperature, estimated values
Elastic compliance s_{11}	1020 (4.7 K)	593 (80 K)	618 (115 K)	690 (160.5 K)			1/TPa	
Elastic compliance s_{44}	1000 (4.7 K)	1073 (80 K)	744 (115 K)	708 (160.5 K)			1/TPa	
Elastic compliance s_{12}	−370 (4.7 K)	−205 (80 K)	−226 (115 K)	−271 (160.5 K)			1/TPa	
Elastic stiffness c_{11}	1.69 (4.7 K)	2.77 (80 K)	2.85 (115 K)	2.93 (160.5 K)			GPa	
Elastic stiffness c_{44}	1.00 (4.7 K)	0.98 (80 K)	1.35 (115 K)	1.41 (160.5 K)			GPa	
Elastic stiffness c_{12}	0.97 (4.7 K)	1.37 (80 K)	1.60 (115 K)	1.89 (160.5 K)			GPa	
Solubility in water α_W	0.010	0.0340	0.059	0.108				At 293 K, α_W = vol(gas)/vol(water)

Table 4.111 Elements of Group VIIIA (CAS notation), or Group 18 (new IUPAC notation). Part B(c): Thermal and thermodynamic properties

Element name Chemical symbol Atomic number Z	Neon Ne 10	Argon Ar 18	Krypton Kr 36	Xenon Xe 54	Radon Rn 86	Oganesson Og 118	Units	Remarks
State	Ne gas	Ar gas	Kr gas	Xe gas	Rn gas			
Thermal conductivity λ	49.3×10^{-3}	18.0×10^{-3}	9.49×10^{-3}	5.1×10^{-3}	3.64×10^{-3}		W/(m K)	
Molar heat capacity c_p	20.786	20.87	20.786	20.744	20.786		J/(mol K)	At 298.15 K
Standard entropy S^0	146.328	154.842	164.085	169.575	176.234		J/(mol K)	At 298.15 K and 100 kPa
Enthalpy difference $H_{298} - H_0$	6.1965	6.1965	6.1965	6.1970	6.1970		kJ/mol	At 298.15 K
Melting temperature T_m	24.563	83.8	115.765	161.391	202		K	
Transition	α–liquid	α–liquid		α–liquid	α–liquid			
Enthalpy change ΔH_m	27.0	1.21	1.64	3.10	2.7		kJ/mol	
Boiling temperature T_b	27.10	87.30	119.80	165.03	211		K	
Enthalpy change ΔH_b	0.324	6.3	9.05	12.65	18.1		kJ/mol	
Critical temperature T_c	44.0	150.75	209.4	289.74			K	
Critical pressure p_c	2.75	4.86	5.50	5.840			MPa	
Critical density ϱ_c	0.4835	0.307	0.9085	1.105			g/cm^3	
Triple-point temperature T_{tr}	24.5	83.85	115.95	161.25			K	
Triple-point pressure p_{tr}	43.3	68.75	73.19	81.6			kPa	

Table 4.112 Elements of Group VIIIA (CAS notation), or Group 18 (new IUPAC notation). Part B(d): Electronic, electromagnetic, and optical properties

Element name	**Neon**	**Argon**	**Krypton**	**Xenon**	**Radon**	**Oganrsson**		
Chemical symbol	**Ne**	**Ar**	**Kr**	**Xe**	**Rn**	**Og**		
Atomic number Z	**10**	**18**	**36**	**54**	**86**	**118**	**Units**	**Remarks**
State	Ne gas	Ar gas	Kr gas	Xe gas	Rn gas			
Dielectric constant $\varepsilon - 1$, gas	130×10^{-6}	545×10^{-6}	7×10^{-6}	1238×10^{-6}				At STP
Dielectric constant ε, liquid		1.516 (89 K)						
Molar magnetic susceptibility χ_{mol}, gas (SI)	-87.5×10^{-6}	-243×10^{-6}	-364×10^{-6}	-572×10^{-6}			cm^3/mol	At 295 K
Molar magnetic susceptibility χ_{mol}, gas (cgs)	-6.96×10^{-6}	-19.3×10^{-6}	-29.0×10^{-6}	-45.5×10^{-6}			cm^3/mol	At 295 K
Mass magnetic susceptibility χ_{mass}, gas (SI)	-4.2×10^{-6}	-6.16×10^{-6}	-4.32×10^{-6}	-4.20×10^{-6}			cm^3/g	At 293 K
Refractive index $(n-1)$, gas	7.25×10^{-6}	281×10^{-6}		706×10^{-6}				$\lambda = 589.3$ nm
Refractive index n, liquid		1.233 (84 K)						$\lambda = 589.3$ nm

Table 4.113 Elements of Group VIIIA (CAS notation), or Group 18 (new IUPAC notation). Part C: Allotropic and high-pressure modifications. There is no Part D, because no data on ionic radii are available

Element	**Argon**		
Modification	**α-Ar**	**β-Ar**	**Units**
Crystal system, Bravais lattice	cub, fc	hex, cp	
Structure type	Cu	Mg	
Lattice constant a	531.2	376.0	pm
Lattice constant c		614.1	pm
Space group	$Fm\bar{3}m$	$P6_3/mmc$	
Schoenflies symbol	O_h^5	D_{6h}^4	
Strukturbericht type	A1	A3	
Pearson symbol	cF4	hP2	
Number A of atoms per cell	4	2	
Coordination number	12	12	
Shortest interatomic distance, solid	383		pm
Range of stability	< 83.8 K	> 83.8 K	

Table 4.114 Elements of Group VIII(1) (CAS notation), or Group 8 (new IUPAC notation). Part A: Atomic, ionic, and molecular properties (see Table 4.119 for ionic radii)

Element name **Chemical symbol** **Atomic number *Z***	**Iron** **Fe** **26**	**Ruthenium** **Ru** **44**	**Osmium** **Os** **76**	**Hassium** **Hs** **108**	**Units**	**Remarks**
Relative atomic mass A (atomic weight)	55.845(2)	101.07(2)	190.23(3)			
Abundance in lithosphere	$50\,000 \times 10^{-6}$					Mass ratio
Abundance in sea	2×10^{-9}					Mass ratio
Atomic radius r_{cov}	116	125	126		pm	Covalent radius
Atomic radius r_{met}	126	132.5	134		pm	Metallic radius, CN = 12
Electron shells	–LMN	–MNO	–NOP	–OPQ		
Electronic ground state	$^5D_4$	$^5F_5$	$^5D_4$			
Electronic configuration	$[Ar]\ 3d^6 4s^2$	$[Kr]\ 4d^7 5s^1$	$[Xe]\ 4f^{14} 5d^6 6s^2$			
Oxidation states	3+, 2+	8+, 6+, 4+, 3+, 2+	8+, 6+, 4+, 3+, 2+			
Electron affinity	0.151	1.05	1.1		eV	Reaction type $Fe + e^- = Fe^-$
Electronegativity χ_A	1.64	1.42	(1.52)			Allred and Rochow
1st ionization energy	7.9024	7.36050	8.7		eV	
2nd ionization energy	16.1878	16.76			eV	
3rd ionization energy	30.652	28.47			eV	
4th ionization energy	54.8				eV	
5th ionization energy	75.0				eV	
Standard electrode potential E^0	−0.447				V	Reaction type $Fe^{2+} + 2e^- = Fe$
	−0.037				V	Reaction type $Fe^{3+} + 3e^- = Fe$
	+0.771				V	Reaction type $Fe^{3+} + e^- = Fe^{2+}$

Table 4.115 Elements of Group VIII(1) (CAS notation), or Group 8 (new IUPAC notation). Part B(a): Crystallographic properties (see Table 4.118 for allotropic and high-pressure modifications)

Element name **Chemical symbol** **Atomic number *Z***	**Iron** **Fe** **26**	**Ruthenium** **Ru** **44**	**Osmium** **Os** **76**	**Hassium** **Hs** **108**	**Units**	**Remarks**
Modification	α-Fe					
Crystal system, Bravais lattice	cub, bc	hex	hex			
Structure type	W	Mg	Mg			
Lattice constant a	286.65	270.53	273.48		pm	
Lattice constant c		428.14	439.13		pm	
Space group	$Im\bar{3}m$	$P6_3/mmc$	$P6_3/mmc$			
Schoenflies symbol	O_h^9	D_{6h}^4	D_{6h}^4			
Strukturbericht type	A2	A3	A3			
Pearson symbol	cI2	hP2	hP2			
Number A of atoms per cell	2	2	2			
Coordination number	8	6 + 6	6 + 6			
Shortest interatomic distance, solid	248	265	267		pm	

Table 4.116 Elements of Group VIII(1) (CAS notation), or Group 8 (new IUPAC notation). Part B(b): Mechanical properties

Element name **Chemical symbol** **Atomic number *Z***	**Iron** **Fe** **26**	**Ruthenium** **Ru** **44**	**Osmium** **Os** **76**	**Hassium** **Hs** **108**	**Units**	**Remarks**
Density ϱ, solid	7.86	12.20	22.4		g/cm^3	
Density ϱ, liquid	7.020	10.90	20.100		g/cm^3	
Molar volume V_{mol}	7.09	8.14	8.43		cm^3/mol	
Viscosity η, liquid	5.53				mPa s	
Surface tension, liquid Temperature coefficient	1.65	2.25 -0.31×10^{-3}	2.5 -0.33×10^{-3}		N/m N/(m K)	
Coefficient of linear thermal expansion α	12.3×10^{-6}	9.1×10^{-6}	6.1×10^{-6}		1/K	
Sound velocity, solid, transverse	3220	3740	3340		m/s	
Sound velocity, solid, longitudinal	5920	6530	5480		m/s	
Compressibility κ	0.56×10^{-5}	0.331×10^{-5}	0.261×10^{-5}		1/MPa	Volume compressibility
Elastic modulus E	211	432	559		GPa	
Shear modulus G	80.4	173	223		GPa	
Poisson number μ	0.29	0.25	0.25			
Elastic compliance s_{11}	7.67	2.09			1/TPa	
Elastic compliance s_{33}		1.82			1/TPa	
Elastic compliance s_{44}	8.57	5.53			1/TPa	
Elastic compliance s_{12}	−2.83	−0.58			1/TPa	
Elastic compliance s_{13}		−0.41			1/TPa	
Elastic stiffness c_{11}	230	563			GPa	
Elastic stiffness c_{33}		624			GPa	
Elastic stiffness c_{44}	117	181			GPa	
Elastic stiffness c_{12}	135	188			GPa	
Elastic stiffness c_{13}		168			GPa	
Tensile strength	193–206[a]	540			MPa	
Vickers hardness	608[a]	$2–5\times10^3$	800			

[a] Strongly dependent on microstructure

Table 4.117 Elements of Group VIII(1) (CAS notation), or Group 8 (new IUPAC notation). Part B(c): Thermal and thermodynamic properties

Element name Chemical symbol Atomic number Z	Iron Fe 26	Ruthenium Ru 44	Osmium Os 76	Hassium Hs 108	Units	Remarks
Modification	α-Fe					
Thermal conductivity λ	80.2	117	87.6		W/(m K)	
Molar heat capacity c_p	25.10	24.06	24.7		J/(mol K)	At 298.2 K
Standard entropy S^0	27.280	28.614	32.635		J/(mol K)	At 298.15 K and 100 kPa
Enthalpy difference $H_{298} - H_0$	4.4890	4.6024			kJ/mol	At 298.15 K
Melting temperature T_m	1811.0	2607.0	3306.0		K	
Transition	δ–liquid	α–liquid	δ–liquid			
Enthalpy change ΔH_m	13.8060	38.5890	57.8550		kJ/mol	
Entropy change ΔS_m	7.623	14.802	17.500		J/(mol K)	
Relative volume change ΔV_m	0.034					$(V_l - V_s)/V_l$ at T_m
Boiling temperature T_b	3139	4423	5285		K	
Enthalpy change ΔH_b	349.6	595.5	746		kJ/mol	

Table 4.118 Elements of Group VIII(1) (CAS notation), or Group 8 (new IUPAC notation). Part B(d): Electronic, electromagnetic, and optical properties

Element name Chemical symbol Atomic number Z	Iron Fe 26	Ruthenium Ru 44	Osmium Os 76	Hassium Hs 108	Units	Remarks
Characteristics	Soft metal	Metal	Brittle metal			
Electrical resistivity ρ_s	89	76	81		nΩ m	At RT
Temperature coefficient	65.1×10^{-4}	45.8×10^{-4}	42×10^{-4}		1/K	
Pressure coefficient	-2.34×10^{-9}	-2.48×10^{-9}			1/hPa	
Superconducting critical temperature T_{crit}		0.49	0.66		K	
Superconducting critical field H_{crit}		66	65		Oe	
Hall coefficient R	8×10^{-10}	2.2×10^{-10}			$m^3/(A\,s)$	At 300 K, $B = 4-5$ T
Thermoelectric coefficient	-51.34				μV/K	
Electronic work function	4.70	4.71			V	
Thermal work function	4.50	4.73	4.83		V	
Molar magnetic susceptibility χ_{mol} (SI)	Ferromagnetic	490	138		cm^3/mol	At 295 K
Molar magnetic susceptibility χ_{mol} (cgs)	Ferromagnetic	39	11		cm^3/mol	At 295 K
Mass magnetic susceptibility χ_{mass} (SI)	Ferromagnetic	5.37×10^{-6}	0.65×10^{-6}		cm^3/g	At 295 K

Table 4.119 Elements of Group VIII(1) (CAS notation), or Group 8 (new IUPAC notation). Part C: Allotropic and high-pressure modifications

Element Modification	Iron α-Fe	γ-Fe	δ-Fe	ε-Fe	Units
Crystal system, Bravais lattice	cub, bc	cub, fc	cub, bc	hex, cp	
Structure type	W	Cu	W	Mg	
Lattice constant a	286.65	364.67	291.35	248.5	pm
Lattice constant c				399.0	pm
Space group	$Im\bar{3}m$	$Fm\bar{3}m$	$Im\bar{3}m$	$P6_3/mmc$	
Schoenflies symbol	O_h^9	O_h^5	O_h^9	D_{6h}^4	
Strukturbericht type	A2	A1	A2	A3	
Pearson symbol	cI2	cF4	cI2	hP2	
Number A of atoms per cell	2	4	2	2	
Coordination number	8	12	8	6 + 6	
Shortest interatomic distance, solid	248	258	254	241	pm
Range of stability	RTP	> 1183 K	> 1663 K	> 13.0 GPa	

Table 4.120 Elements of Group VIII(1) (CAS notation), or Group 8 (new IUPAC notation). Part D: Ionic radii (determined from crystal structures)

Element	Iron		Ruthenium					Osmium				
Ion	Fe^{2+}	Fe^{3+}	Ru^{3+}	Ru^{4+}	Ru^{5+}	Ru^{7+}	Ru^{8+}	Os^{4+}	Os^{5+}	Os^{6+}	Os^{8+}	
Coordination number												Units
4	63	49				38	36				39	pm
6	61	55	68	62	57			63	58	55		pm
8	92	78										pm

Table 4.121 Elements of Group VIII(2) (CAS notation), or Group 9 (new IUPAC notation). Part A: Atomic, ionic, and molecular properties (see Table 4.126 for ionic radii)

Element name	Cobalt	Rhodium	Iridium	Meitnerium		
Chemical symbol	Co	Rh	Ir	Mt		
Atomic number Z	27	45	77	109	Units	Remarks
Relative atomic mass A (atomic weight)	58.933194(4)	102.90550(2)	192.217(3)			
Abundance in lithosphere	40×10^{-6}	0.001×10^{-6}	1×10^{-9}			Mass ratio
Abundance in sea	5×10^{-11}					Mass ratio
Atomic radius r_{cov}	116	125	127		pm	Covalent radius
Atomic radius r_{met}	125	134.5	136		pm	Metallic radius, CN = 12
Electron shells	–LMN	–MNO	–NOP	–OPQ		
Electronic ground state	$^4F_{9/2}$	$^4F_{9/2}$	$^4F_{9/2}$			
Electronic configuration	[Ar] $3d^7 4s^2$	[Kr] $4d^8 5s^1$	[Xe] $4f^{14} 5d^7 6s^2$			
Oxidation states	3+, 2+	4+, 3+, 2+	6+, 4+, 3+, 2+			
Electron affinity	0.662	1.14	1.57		eV	Reaction type $Co + e^- = Co^-$
Electronegativity χ_A	1.75	1.35	(1.44)			Allred and Rochow
1st ionization energy	7.8810	7.45890	9.1		eV	
2nd ionization energy	17.083	18.08			eV	
3rd ionization energy	33.50	31.06			eV	
4th ionization energy	51.3				eV	
Standard electrode potential E^0	−0.28	+0.6	+1.156		V	Reaction type $Co^{2+} + 2e^- = Co$
					V	Reaction type $Ir^{3+} + 3e^- = Ir$

Table 4.122 Elements of Group VIII(2) (CAS notation), or Group 9 (new IUPAC notation). Part B(a): Crystallographic properties (see Table 4.125 for allotropic and high-pressure modifications)

Element name	Cobalt	Rhodium	Iridium	Meitnerium		
Chemical symbol	Co	Rh	Ir	Mt		
Atomic number Z	27	45	77	109	Units	Remarks
Modifaction	ε-Co					
Crystal system, Bravais lattice	hex, cp	cub, fc	cub, fc			
Structure type	Mg	Cu	Cu			
Lattice constant a	250.71	280.32	383.91		pm	
Lattice constant c	406.94				pm	
Space group	$P6_3/mmc$	$Fm\bar{3}m$	$Fm\bar{3}m$			
Schoenflies symbol	D_{6h}^4	O_h^5	O_h^5			
Strukturbericht type	A3	A1	A1			
Pearson symbol	hP2	cF4	cF4			
Number A of atoms per cell	2	4	4			
Coordination number	6 + 6	12	12			
Shortest interatomic distance, solid	250	269	271		pm	

Table 4.123 Elements of Group VIII(2) (CAS notation), or Group 9 (new IUPAC notation). Part B(b): Mechanical properties

Element name Chemical symbol Atomic number Z	Cobalt Co 27	Rhodium Rh 45	Iridium Ir 77	Meitnerium Mt 109	Units	Remarks
Modification	ε-Co					
Density ϱ, solid	8.90	12.40	22.50		g/cm^3	
Density ϱ, liquid	7.670	10.800	20.000		g/cm^3	
Molar volume V_{mol}	6.62	8.29	8.57		cm^3/mol	
Viscosity η, liquid	4.8				mPa s	Near T_m
Coefficient of linear thermal expansion α	13.36×10^{-6}	8.40×10^{-6}	6.8×10^{-6}		1/K	
Surface tension, liquid	1.520	1.97	2.250		N/m	
Temperature coefficient	-0.92×10^{-3}	-0.3×10^{-3}	-0.31×10^{-3}		N/(m K)	
Sound velocity, solid, transverse	3000	3470	3050		m/s	
Sound velocity, solid, longitudinal	5730	6190	5380		m/s	
Compressibility κ	0.525×10^{-5}	0.350×10^{-5}	0.258×10^{-5}		1/MPa	Volume compressibility
Elastic modulus E	204	379	528		GPa	
Shear modulus G	77.3	149	209		GPa	
Poisson number μ	0.32	0.27	0.26			
Elastic compliance s_{11}	5.11	3.46	2.28		1/TPa	
Elastic compliance s_{33}	3.69				1/TPa	
Elastic compliance s_{44}	14.1	5.43	3.90		1/TPa	
Elastic compliance s_{12}	−2.37	−1.10	−0.67		1/TPa	
Elastic compliance s_{13}	−0.94				1/TPa	
Elastic stiffness c_{11}	295	413	580		GPa	
Elastic stiffness c_{33}	335				GPa	
Elastic stiffness c_{44}	71.0	184	256		GPa	
Elastic stiffness c_{12}	159	194	242		GPa	
Elastic stiffness c_{13}	111				GPa	
Tensile strength	255	951	623×10^3		MPa	
Vickers hardness	1043	1246	1760			

Table 4.124 Elements of Group VIII(2) (CAS notation), or Group 9 (new IUPAC notation). Part B(c): Thermal and thermodynamic properties

Element name Chemical symbol Atomic number Z	Cobalt Co 27	Rhodium Rh 45	Iridium Ir 77	Meitnerium Mt 109	Units	Remarks
Modification	ε-Co					
Thermal conductivity λ	100	150	147		W/(m K)	
Molar heat capacity c_p	24.811	24.98	24.98		J/(mol K)	At 298 K
Standard entropy S^0	30.040	31.556	35.505		J/(mol K)	At 298 K and 100 kPa
Enthalpy difference $H_{298}-H_0$	4.7655		5.2677		kJ/mol	
Melting temperature T_m	1768.0	2237.0	2719.0		K	
Transition	α–liquid	α–liquid	α–liquid			
Enthalpy change ΔH_m	16.200	26.5935	41.124		kJ/mol	
Entropy change ΔS_m	9.163	11.888	15.125		J/(mol K)	
Relative volume change ΔV_m		0.12				$(V_l-V_s)/V_l$ at T_m
Boiling temperature T_b	3184	3970	4701		K	
Enthalpy change ΔH_b	376.6	493.3	604.1		kJ/mol	

Table 4.125 Elements of Group VIII(2) (CAS notation), or Group 9 (new IUPAC notation). Part B(d): Electronic, electromagnetic, and optical properties

Element name **Chemical symbol** **Atomic number Z**	**Cobalt** **Co** **27**	**Rhodium** **Rh** **45**	**Iridium** **Ir** **77**	**Meitnerium** **Mt** **109**	**Units**	**Remarks**
Modification	α-Co					
Characteristics	Hard metal	Metal	Brittle metal			
Electrical resistivity ρ_s	56	43.0	47		nΩ m	At RT
Temperature coefficient	6.04×10^{-3}	4.62×10^{-3}	4.11×10^{-3}		1/K	
Pressure coefficient	-0.904×10^{-9}	-1.62×10^{-9}	-1.37×10^{-9}		1/hPa	
Electrical resistivity ρ_l	1020				nΩ m	
Resistivity ratio at T_m	1.05					
Superconducting critical temperature T_{crit}			0.14		K	
Superconducting critical field H_{crit}			77		Oe	
Hall coefficient R	360×10^{-12}	50.5×10^{-12}	31.8×10^{-12}		$m^3/(A\,s)$	At 300 K, $B = 4.5$–5.0 T
Thermoelectronic coefficient	17.5	1.0	1.2		μV/K	
Electronic work function	4.97	4.98			V	
Thermal work function	4.37	4.68	5.03		V	
Molar magnetic susceptibility χ_{mol} (SI)	Ferromagnetic	1282×10^{-6}	314×10^{-6}		cm^3/mol	At 295 K
Molar magnetic susceptibility χ_{mol} (cgs)	Ferromagnetic	102×10^{-6}	25×10^{-6}		cm^3/mol	At 295 K
Mass magnetic susceptibility χ_{mass} (SI)	Ferromagnetic	13.6×10^{-6}	1.67×10^{-6}		cm^3/g	At 295 K

Table 4.126 Elements of Group VIII(2) (CAS notation), or Group 9 (new IUPAC notation). Part C: Allotropic and high-pressure modifications

Element **Modification**	**Cobalt** **ε-Co**	**α-Co**	**Units**
Crystal system, Bravais lattice	hex, cp	cub, fc	
Structure type	Mg	Cu	
Lattice constant a	250.71	354.45	pm
Lattice constant c	406.94		pm
Space group	$P6_3/mmc$	$Fm\bar{3}m$	
Schoenflies symbol	D_{6h}^4	O_h^5	
Strukturbericht type	A3	A1	
Pearson symbol	hP2	cF4	
Number A of atoms per cell	2	4	
Coordination number	6 + 6	12	
Shortest interatomic distance, solid	250	251	pm
Range of stability	RTP	> 661 K	

Table 4.127 Elements of Group VIII(2) (CAS notation), or Group 9 (new IUPAC notation). Part D: Ionic radii (determined from crystal structures)

Element **Ion** **Coordination number**	**Cobalt** **Co^{2+}**	 **Co^{3+}**	**Rhodium** **Rh^{3+}**	 **Rh^{4+}**	 **Rh^{5+}**	**Iridium** **Ir^{3+}**	 **Ir^{4+}**	 **Ir^{5+}**	**Units**
4	56								pm
6	65	55	67	60	55	68	63	57	pm
8	90								pm

Table 4.128 Elements of Group VIII(3) (CAS notation) or Group 10 (new IUPAC notation). Part A: Atomic, ionic, and molecular properties (see Table 4.132 for ionic radii)

Element name **Chemical symbol** **Atomic number *Z***	**Nickel** **Ni** **28**	**Palladium** **Pd** **46**	**Platinum** **Pt** **78**	**Darmstadtium** **Ds** **110**	**Units**	**Remarks**
Relative atomic mass A (atomic weight)	58.6934(4)	106.42(1)	195.084(9)			
Abundance in lithosphere	100×10^{-6}	0.01×10^{-6}	5×10^{-9}			Mass ratio
Abundance in sea	1.7×10^{-9}					Mass ratio
Atomic radius r_{cov}	115	128	130		pm	Covalent radius
Atomic radius r_{met}	125	138	137		pm	Metallic radius, CN = 12
Atomic radius r_{vdW}	160	160	170–180		pm	van der Waals radius
Electron shells	–LMN	–MNO	–NOP	–OPQ		
Electronic ground state	$^3F_4$	$^1S_0$	$^3D_3$			
Electronic configuration	[Ar] $3d^8 4s^2$	[Kr] $4d^{10}$	[Xe] $4f^{14}5d^9 6s^1$			
Oxidation states	3+, 2+	4+, 2+	4+, 2+			
Electron affinity	1.16	0.562	2.13		eV	Reaction type $Ni + e^- = Ni^-$
Electronegativity χ_A	1.75	1.35	(1.44)			Allred and Rochow
1st ionization energy	7.6398	8.3369	9.0		eV	
2nd ionization energy	18.16884	19.43	18.563		eV	
3rd ionization energy	35.19	32.93			eV	
4th ionization energy	54.9				eV	
Standard electrode potential E^0	−0.257	+0.951	+1.118		V	Reaction type $Ni^{2+} + 2e^- = Ni$

Table 4.129 Elements of Group VIII(3) (CAS notation) or Group 10 (new IUPAC notation). Part B(a): Crystallographic properties

Element name **Chemical symbol** **Atomic number *Z***	**Nickel** **Ni** **28**	**Palladium** **Pd** **46**	**Platinum** **Pt** **78**	**Darmstadtium** **Ds** **110**	**Units**	**Remarks**
Crystal system, Bravais lattice	cub, fc	cub, fc	cub, fc			
Structure type	Cu	Cu	Cu			
Lattice constant a	352.41	389.01	392.33		pm	
Space group	$Fm\bar{3}m$	$Fm\bar{3}m$	$Fm\bar{3}m$			
Schoenflies symbol	O_h^5	O_h^5	O_h^5			
Strukturbericht type	A1	A1	A1			
Pearson symbol	cF4	cF4	cF4			
Number A of atoms per cell	4	4	4			
Coordination number	12	12	12			
Shortest interatomic distance, solid	249	274	277		pm	

Table 4.130 Elements of Group VIII(3) (CAS notation), or Group 10 (new IUPAC notation). Part B(b): Mechanical properties

Element name **Chemical symbol** **Atomic number *Z***	**Nickel** **Ni** **28**	**Palladium** **Pd** **46**	**Platinum** **Pt** **78**	**Darmstadtium** **D** **110**	**Units**	**Remarks**
Density ϱ, solid	8.90	12.00	21.40		g/cm^3	
Density ϱ, liquid	7.910	10.700	19.700		g/cm^3	
Molar volume V_{mol}	6.59	8.85	9.10		cm^3/mol	
Viscosity η, liquid	5.0				mPa s	
Surface tension, liquid	1.725	1.50	1.866		N/m	
Temperature coefficient	-0.98×10^{-3}	-0.22×10^{-3}	-0.17×10^{-3}		N/(m K)	
Coefficient of linear thermal expansion α	13.3×10^{-6}	11.2×10^{-6}	9.0×10^{-6}		1/K	
Sound velocity, solid, transverse	3080	1900	1690		m/s	
Sound velocity, solid, longitudinal	5810	4540	4080		m/s	
Compressibility κ	0.513×10^{-5}	0.505×10^{-5}	0.351×10^{-5}		1/MPa	Volume compressibility
Elastic modulus E	220	121	170		GPa	
Shear modulus G	78.5	43.5	60.9		GPa	
Poisson number μ	0.31	0.39	0.39			
Elastic compliance s_{11}	7.67	13.7	7.35		1/TPa	
Elastic compliance s_{44}	8.23	14.1	13.1		1/TPa	
Elastic compliance s_{12}	−2.93	−6.0	−3.08		1/TPa	
Elastic stiffness c_{11}	247	221	347		GPa	
Elastic stiffness c_{44}	122	70.8	76.5		GPa	
Elastic stiffness c_{12}	153	171	251		GPa	
Tensile strength	317		134		MPa	At 293 K
Vickers hardness	640	461	560			At 293 K

Table 4.131 Elements of Group VIII(3) (CAS notation), or Group 10 (new IUPAC notation). Part B(c): Thermal and thermodynamic properties

Element name **Chemical symbol** **Atomic number *Z***	**Nickel** **Ni** **28**	**Palladium** **Pd** **46**	**Platinum** **Pt** **78**	**Darmstadtium** **Ds** **110**	**Units**	**Remarks**
Thermal conductivity λ	83	71.8	71.6		W/(m K)	
Molar heat capacity c_p	26.07	25.98	25.85		J/(mol K)	At 298 K
Standard entropy S^0	29.796	37.823	41.631		J/(mol K)	At 298 K and 100 kPa
Enthalpy difference $H_{298}-H_0$	4.7870	5.4685	5.7237		kJ/mol	
Melting temperature T_m	1728.30	1828.0	2041.50		K	
Transition	α–liquid	α–liquid	α–liquid			
Enthalpy change ΔH_m	17.4798	16.736	22.1750		kJ/mol	
Entropy change ΔS_m	10.114	9.155	10.862		J/(mol K)	
Relative volume change ΔV_m						$(V_l-V_s)/V_l$ at T_m
Boiling temperature T_b	3157	3237	4100		K	
Enthalpy change ΔH_b	369.24	357.6	509.8		kJ/mol	

Table 4.132 Elements of Group VIII(3) (CAS notation), or Group 10 (new IUPAC notation). Part B(d): Electronic, electromagnetic, and optical properties. There is no Part C, because no allotropic or high-pressure modifications are known

Element name Chemical symbol Atomic number Z	Nickel Ni 28	Palladium Pd 46	Platinum Pt 78	Darmstadtium Ds 110	Units	Remarks
Characteristics	Ductile metal	Ductile metal	Ductile metal			
Electrical resistivity ρ_s	59.0	101	98.1		nΩ m	At RT
Temperature coefficient	69.2×10^{-4}	37.7×10^{-4}	39.6×10^{-4}		1/K	
Pressure coefficient	1.82×10^{-9}	-2.1×10^{-9}	-1.88×10^{-9}		1/hPa	
Electrical resistivity ρ_l	850				nΩ m	
Resistivity ratio at T_m	1.3					
Hall coefficient R	-60×10^{-12}	-86×10^{-12}	-24.4×10^{-12}		$m^3/(A\,s)$	At 298 K, $B = 0.3$–4.6 T
Thermoelectronic coefficient	−18	−9.54	−3.50		μV/K	
Electronic work function	5.15	5.12	5.65		V	
Thermal work function	4.60	4.99	5.30		V	
Molar magnetic susceptibility χ_{mol} (SI)	Ferromagnetic	6786×10^{-6}	2425×10^{-6}		cm^3/mol	At 295 K
Molar magnetic susceptibility χ_{mol} (cgs)	Ferromagnetic	540×10^{-6}	193×10^{-6}		cm^3/mol	At 295 K
Mass magnetic susceptibility χ_{mass} (SI)	Ferromagnetic	67.0×10^{-6}	13.0×10^{-6}		cm^3/g	At 295 K

Table 4.133 Elements of Group VIII(3) (CAS notation), or Group 10 (new IUPAC notation). Part D: Ionic radii (determined from crystal structures)

Element Ion Coordination number	Nickel Ni^{2+}	 Ni^{3+}	Palladium Pd^{2+}	 Pd^{3+}	 Pd^{4+}	Platinum Pt^{2+}	 Pt^{4+}	Units
4	49		64			60		pm
6	69	56	86	76	62	80	63	pm

Table 4.134 Lanthanides. Part A: Atomic, ionic, and molecular properties (see Table 4.139 for ionic radii)

Element name **Chemical symbol** **Atomic number *Z***	**Cerium** **Ce** **58**	**Praseodymium** **Pr** **59**	**Neodymium** **Nd** **60**	**Promethium** **Pm** **61**	**Samarium** **Sm** **62**	**Europium** **Eu** **63**	**Gadolinium** **Gd** **64**	**Units**
Characteristics				Radioactive				
Relative atomic mass *A* (atomic weight)	140.116(1)	140.90766(2)	144.242(3)	[145]	150.36(2)	151.964(1)	157.25(3)	
Abundance in lithosphere[a]	41.6×10^{-6}	5.5×10^{-6}	23.9×10^{-6}		6.5×10^{-6}	1.1×10^{-6}	6.4×10^{-6}	
Abundance in sea[a]	1×10^{-12}	6×10^{-13}	3×10^{-12}		5×10^{-14}	1×10^{-14}	7×10^{-13}	
Atomic radius r_{cov}	165	165	164	165	162	185	161	pm
Atomic radius r_{met}	182	183	182	181	180	200	179	pm
Electron shells	–NOP	–NOP	–NOP	–NOP	–NOP	–NOP	–NOP	
Electronic ground state	$^3H_4$	$^4I_{9/2}$	$^5I_4$	$^6H_{5/2}$	$^7F_0$	$^8S_{7/2}$	$^9D_2$	
Electronic configuration	[Xe] $4f^1 5d^1 6s^2$	[Xe] $4f^3 6s^2$	[Xe] $4f^4 6s^2$	[Xe] $4f^5 6s^2$	[Xe] $4f^6 6s^2$	[Xe] $4f^7 6s^2$	[Xe] $4f^7 5d^1 6s^2$	
Oxidation states	4+, 3+	4+, 3+	3+	3+	3+, 2+	3+, 2+	3+	
Electronegativity χ_A^b	(1.08)	(1.07)	(1.07)	(1.07)	(1.07)	(1.01)	1.11	
1st ionization energy	5.5387	5.464	5.5250	5.55	5.6437	5.6704	6.1500	eV
2nd ionization energy	10.85	10.55	10.73	10.90	11.07	11.241	12.09	eV
3rd ionization energy	20.198	21.624	22.1	22.3	23.4	24.92	20.63	eV
4th ionization energy	36.758	38.98	40.4	41.1	41.4	42.7	44.0	eV
Element name **Chemical symbol** **Atomic number *Z***	**Terbium** **Tb** **65**	**Dysprosium** **Dy** **66**	**Holmium** **Ho** **67**	**Erbium** **Er** **68**	**Thulium** **Tm** **69**	**Ytterbium** **Yb** **70**	**Lutetium** **Lu** **71**	**Units**
Relative atomic mass *A* (atomic weight)	158.92535(2)	162.500(1)	164.93033(2)	167.26(3)	168.93422(2)	173.045(10)	174.9668(1)	
Abundance in lithosphere[a]	1×10^{-6}	4.5×10^{-6}	1.2×10^{-6}	2.5×10^{-6}	0.2×10^{-6}	2.7×10^{-6}	0.8×10^{-6}	
Abundance in sea[a]	1×10^{-13}	9×10^{-13}	2×10^{-13}	8×10^{-13}	2×10^{-13}	8×10^{-13}	2×10^{-13}	
Atomic radius r_{cov}	159	159	158	157	156	174	156	pm
Atomic radius r_{met}	176	175	174	173	172	194	172	pm
Electron shells	–NOP	–NOP	–NOP	–NOP	–NOP	–NOP	–NOP	
Electronic ground state	$^6H_{15/2}$	$^5I_8$	$^4I_{15/2}$	$^3H_6$	$^2F_{7/2}$	$^1S_0$	$^2D_{3/2}$	
Electronic configuration	[Xe] $4f^6 6s^2$	[Xe] $4f^{10} 6s^2$	[Xe] $4f^{11} 6s^2$	[Xe] $4f^{12} 6s^2$	[Xe] $4f^{13} 6s^2$	[Xe] $4f^{14} 6s^2$	[Xe] $4f^{14} 5d^1 6s^2$	
Oxidation states	4+, 3+	3+	3+	3+	3+, 2+	3+, 2+	3+	
Electronegativity χ_A^b	(1.10)	(1.10)	(1.10)	(1.11)	(1.11)	(1.06)	(1.14)	
1st ionization energy	5.8639	5.9389	6.0216	6.1078	6.18431	6.25416	5.42585	eV
2nd ionization energy	11.52	11.67	11.80	11.93	12.05	12.1761	13.9	eV
3rd ionization energy	21.91	22.8	22.84	22.74	23.68	25.05	20.9594	eV
4th ionization energy	39.79	41.4	42.5	42.7	42.7	43.56	45.25	eV

[a] Mass ratio
[b] According to Allred and Rochow

Table 4.135 Lanthanides. Part B(a): Crystallographic properties (see Table 4.138 for allotropic and high-pressure modifications)

Element name **Chemical symbol** **Atomic number *Z***	**Cerium** **Ce** **58**	**Praseodymium** **Pr** **59**	**Neodymium** **Nd** **60**	**Promethium** **Pm** **61**	**Samarium** **Sm** **62**	**Europium** **Eu** **63**	**Gadolinium** **Gd** **64**	**Units**
Modification					α-Sm			
Crystal system, Bravais lattice	cub, fc	hex	hex	hex	hex	cub, bc	hex	
Structure type	Cu	α-La	α-La	α-La	Se	W	Mg	
Lattice constant *a*	516.10	367.21	365.82	365	362.90	458.27	363.36	pm
Lattice constant *c*		1183.26	1179.66	1165	2620.7		578.10	pm
Space group	$Fm\bar{3}m$	$P6_3/mmc$	$P6_3/mmc$	$P6_3/mmc$		$Im\bar{3}m$	$P6_3/mmc$	
Schoenflies symbol	O_h^5	D_{6h}^4	D_{6h}^4	D_{6h}^4		O_h^9	D_{6h}^4	
Strukturbericht type	A1	A3′	A3′	A3′		A2	A3	
Pearson symbol	cF4	hP4	hP4	hP4		cI2	hP2	
Number *A* of atoms per cell	4	4	4	4		2	2	
Coordination number	12	12	12	12			12	
Shortest interatomic distance, solid	364		364	362		397	360	pm
Element name **Chemical symbol** **Atomic number *Z***	**Terbium** **Tb** **65**	**Dysprosium** **Dy** **66**	**Holmium** **Ho** **67**	**Erbium** **Er** **68**	**Thulium** **Tm** **69**	**Ytterbium** **Yb** **70**	**Lutetium** **Lu** **71**	**Units**
Crystal system, Bravais lattice	hex	hex	hex	hex	hex	cub, fc	hex	
Structure type	Mg	Mg	Mg	Mg	Mg	Cu	Mg	
Lattice constant *a*	360.55	359.15	357.78	355.92	353.75	548.48	350.52	pm
Lattice constant *c*	569.66	565.01	561.78	558.50	555.40		554.94	pm
Space group	$P6_3/mmc$	$P6_3/mmc$	$P6_3/mmc$	$P6_3/mmc$	$P6_3/mmc$	$Fm\bar{3}m$	$P6_3/mmc$	
Schoenflies symbol	D_{6h}^4	D_{6h}^4	D_{6h}^4	D_{6h}^4	D_{6h}^4	O_h^5	D_{6h}^4	
Strukturbericht type	A3	A3	A3	A3	A3	A1	A3	
Pearson symbol	hP2	hP2	hP2	hP2	hP2	cF4	hP2	
Number *A* of atoms per cell	2	2	2	2	2	4	2	
Coordination number	12	12	12	12	12	12	12	
Shortest interatomic distance, solid	357	355	353	351	349	388	347	pm

Table 4.136 Lanthanides. Part B(b): Mechanical properties

Element name Chemical symbol Atomic number Z	Cerium[a] Ce 58	Praseodymium Pr 59	Neodymium Nd 60	Promethium Pm 61	Samarium Sm 62	Europium Eu 63	Gadolinium Gd 64	Units
Density ϱ, solid	6.78	6.77	7.00	6.48	7.54	5.26	7.89	g/cm^3
Density ϱ, liquid		6.609						g/cm^3
Molar volume V_{mol}	17.00	20.80	20.59	20.1	20.00	28.29	19.90	cm^3/mol
Viscosity η, liquid		0.431						mPa s
Surface tension, liquid	0.72	0.7	0.688	0.65	0.6	0.450	0.816	N/m
Coefficient of linear thermal expansion α	6.3×10^{-6}	6.79×10^{-6}	9.6×10^{-6}	11×10^{-6}	10.4×10^{-6}	32×10^{-6}	9.4×10^{-6}	1/K
Sound velocity, solid, transverse	1230	1410	1440		1290		1680	m/s
Sound velocity, solid, longitudinal	3060	2660	2720		2700		2950	m/s
Volume compressibility κ	5.06×10^{-5}	3.15×10^{-5}	2.94×10^{-5}	2.9×10^{-5}	3.27×10^{-5}	8.13×10^{-5}	2.47×10^{-5}	1/MPa
Elastic modulus E	44.1	35.2	37.9	46	53.9	18.2	56.3	GPa
Shear modulus G	12.1	13.2	14.3	18	12.7	7.8	22.4	GPa
Poisson number μ	0.25	0.31	0.31	0.28	0.35	0.17	0.26	
Elastic compliance s_{11}	62.8	26.6	23.7				18.0	1/TPa
Elastic compliance s_{33}		19.3	18.5				16.1	1/TPa
Elastic compliance s_{44}	57.8	73.6	66.5				48.1	1/TPa
Elastic compliance s_{12}	−22.3	−11.3	−9.5				−5.7	1/TPa
Elastic compliance s_{13}		−3.8	−3.9				−3.6	1/TPa
Elastic stiffness c_{11}	26.0	49.4	54.8				67.8	GPa
Elastic stiffness c_{33}		57.4	60.9				71.2	GPa
Elastic stiffness c_{44}	17.3	13.6	15.0				20.8	GPa
Elastic stiffness c_{12}	14.3	23.0	24.6				25.6	GPa
Elastic stiffness c_{13}		14.3	16.6				20.7	GPa
Tensile strengths	117	169	169	170	157		122	MPa
Vickers hardness	275	400	348		412	167	510–638	

Table 4.136 (continued)

Element name **Chemical symbol** **Atomic number Z**	**Terbium** **Tb** **65**	**Dysprosium** **Dy** **66**	**Holmium** **Ho** **67**	**Erbium** **Er** **68**	**Thulium** **Tm** **69**	**Ytterbium** **Yb** **70**	**Lutetium** **Lu** **71**	**Units**
Density ϱ, solid	8.27	8.54	8.80	9.05	9.33	6.98	9.840	g/cm^3
Density ϱ, liquid						6.292		g/cm^3
Molar volume V_{mol}	19.31	19.00	18.75	18.44	18.12	24.84	17.78	cm^3/mol
Viscosity η, liquid						0.424		mPa s
Surface tension, liquid	0.65	0.650	0.650	0.620	0.62	0.85		N/m
Coefficient of linear thermal expansion α	7.0×10^{-6}	10.0×10^{-6}	11.2×10^{-6}	9.2×10^{-6}	13.3×10^{-6}	25.0×10^{-6}	8.12×10^{-6}	1/K
Sound velocity, solid, transverse	1060	1720	1740	1810		1000		m/s
Sound velocity, solid, longitudinal	2920	2960	3040	3080		1820		m/s
Volume compressibility κ	2.40×10^{-5}	2.50×10^{-5}	2.42×10^{-5}	2.34×10^{-5}	2.42×10^{-5}	7.24×10^{-5}	2.33×10^{-5}	1/MPa
Elastic modulus E	57.5	63.1	67.1	73.3	74.0	18.4	68.4	GPa
Shear modulus G	22.8	25.5	26.7	29.6	30.4	7.16	27.1	GPa
Poisson number μ	0.26	0.24	0.26	0.24	0.27	0.28	0.27	
Elastic compliance s_{11}	17.4	16.0	15.3	14.1		89.2	14.3	1/TPa
Elastic compliance s_{33}	15.6	14.5	14.0	13.2			14.8	1/TPa
Elastic compliance s_{44}	46.0	41.2	38.6	36.4		56.4	37.3	1/TPa
Elastic compliance s_{12}	−5.2	−4.6	−4.3	−4.2		−31.9	−4.2	1/TPa
Elastic compliance s_{13}	−3.6	−3.2	−2.9	−2.6			−3.5	1/TPa
Elastic stiffness c_{11}	69.2	74.0	76.5	84.1		18.6	86.2	GPa
Elastic stiffness c_{33}	74.4	78.6	79.6	84.7			80.9	GPa
Elastic stiffness c_{44}	21.8	24.3	25.9	27.4		17.7	26.8	GPa
Elastic stiffness c_{12}	25.0	25.5	25.6	29.4		10.4	32.0	GPa
Elastic stiffness c_{13}	21.8	21.8	21.0	22.6			28.0	GPa
Tensile strength	About 122		About 132	139	About 140	72.5	139	MPa
Vickers hardness	863	544	481	589	520	206	1160	

[a] The data for the elastic behavior of cerium concern γ-cerium

Table 4.137 Lanthanides. Part B(c): Thermal and thermodynamic properties

Element name **Chemical symbol** **Atomic number Z**	**Cerium** **Ce** **58**	**Praseodymium** **Pr** **59**	**Neodymium** **Nd** **60**	**Promethium** **Pm** **61**	**Samarium** **Sm** **62**	**Europium** **Eu** **63**	**Gadolinium** **Gd** **64**	**Units**	**Remarks**
Thermal conductivity λ	11.4	12.5	16.5	17.9	13.3	13.9	10.6	W/(m K)	
Molar heat capacity c_p	26.4	27.20	27.45		29.54	27.6	37.02	J/(mol K)	At 298.2 K
Standard entropy S^0	69.454	73.931	71.086	72.00	69.496	80.793	68.089	J/(mol K)	At 298.15 K and 100 kPa
Enthalpy difference $H_{298} - H_0$	7.2802	7.4182	7.1337	7.3000	7.5730	8.0040	9.0876	kJ/mol	At 298.15 K
Melting temperature T_m	1072.0	1204.0	1289.0	1315.0	1345.0	1095.0	1586.15	K	
Transition	δ–liquid	β–liquid	β–liquid	β–liquid	γ–liquid	α–liquid	β–liquid		
Enthalpy change ΔH_m	5.4601	6.8869	7.1421	7.7000	8.6190	9.2132	9.6680	kJ/mol	
Entropy change ΔS_m	5.093	5.720	5.541	5.856	6.408	8.414	6.095	J/(mol K)	
Relative volume change ΔV_m	0.011	0.02	0.09		0.036	0.048	0.02		$(V_l - V_s)/V_l$ at T_m
Boiling temperature T_b	3699	3785	3341	3785	2064	1870	3569	K	
Enthalpy change ΔH_b	414.2	296.8	273.0		166.4	144.7	359.4	kJ/mol	
Element name **Chemical symbol** **Atomic number Z**	**Terbium** **Tb** **65**	**Dysprosium** **Dy** **66**	**Holmium** **Ho** **67**	**Erbium** **Er** **68**	**Thulium** **Tm** **69**	**Ytterbium** **Yb** **70**	**Lutetium** **Lu** **71**	**Units**	**Remarks**
Thermal conductivity λ	11.1	10.7	16.2	14	16.8	38.5	16.4	W/(m K)	
Molar heat capacity c_p	28.91	28.16	27.15	28.12	27.03	26.74	26.86	J/(mol K)	At 298.2 K
Standard entropy S^0	73.8	74.956	75.019	73.178	74.015	59.831	50.961	J/(mol K)	At 298.15 K and 100 kPa
Enthalpy difference $H_{298} - H_0$	9.4266	8.8659	7.9956	7.3923	7.3973	6.7111	6.3890	kJ/mol	At 298.15 K
Melting temperature T_m	1632	1685.15	1745.0	1802.0	1818.0	1097	1936.0	K	
Transition	β–liquid	β–liquid	β–liquid	α–liquid	α–liquid	γ–liquid	α–liquid		
Enthalpy change ΔH_m	10.1504	11.3505	11.7570	19.9033	16.8406	7.6567	18.6481	kJ/mol	
Entropy change ΔS_m	6.220	6.736	6.738	11.045	9.263	6.980	9.632	J/(mol K)	
Relative volume change ΔV_m	0.031	0.45	0.074	0.09	0.069	0.051	0.036		$(V_l - V_s)/V_l$ at T_m
Boiling temperature T_b	3496	2835	2968	3136	2220	1467	3668	K	
Enthalpy change ΔH_b	330.9	230	242.50	261.4	190.7	128.83	355.9	kJ/mol	

Table 4.138 Lanthanides. Part B(d): Electronic, electromagnetic, and optical properties

Element name **Chemical symbol** **Atomic number Z**	**Cerium** **Ce** **58**	**Praseodymium** **Pr** **59**	**Neodymium** **Nd** **60**	**Promethium** **Pm** **61**	**Samarium** **Sm** **62**	**Europium** **Eu** **63**	**Gadolinium** **Gd** **64**	**Units**	**Remarks**
Characteristics	Metal	Ductile reactive metal	Reactive metal	Metal	Metal	Soft metal very reactive	Soft metal		
Electrical resistivity ρ_s Temperature coefficient Pressure coefficient	730 9.7×10^{-4} -45.2×10^{-9}	650 17.1×10^{-4} -0.4×10^{-9}	610 21.3×10^{-4} -1.5×10^{-9}	500 28×10^{-4}	914 14.8×10^{-4} -3.57×10^{-9}	890 81.3×10^{-4}	1260 17.6×10^{-4} -4.5×10^{-9}	nΩ m 1/K 1/hPa	At RT
Electrical resistivity ρ_l		1130	1550			2440	1950	nΩ m	
Hall coefficient R	1.92×10^{-10}	0.709×10^{-10}	0.971×10^{-10}		-0.2×10^{-10}		0.95×10^{-10}	$m^3/(A\,s)$	At 293 K, $B < 1$ T
Thermoelectric coefficient	4.39							μV/K	
Electronic work function	2.88		3.2		2.7	2.5	3.1	V	
Thermal work function	2.6	2.7	3.3		3.2	2.54	3.07	V	
Molar magnetic susceptibility χ_{mol} (SI)	31.4×10^{-3}	69.5×10^{-3}	74.5×10^{-3}		16.1×10^{-3}	388×10^{-3}	2.324	cm^3/mol	At 295 K
Molar magnetic susceptibility χ_{mol} (cgs)	2.5×10^{-3}	5.53×10^{-3}	5.93×10^{-3}		1.28×10^{-3}	30.9×10^{-3}	185×10^{-3}	cm^3/mol	At 295 K
Mass magnetic susceptibility χ_{mass} (SI)	217×10^{-6}	474×10^{-6}	490×10^{-6}		106×10^{-6}	2.81×10^{-3}	14.9×10^{-3}	cm^3/g	At 295 K
Element name **Chemical symbol** **Atomic number Z**	**Terbium** **Tb** **65**	**Dysprosium** **Dy** **66**	**Holmium** **Ho** **67**	**Erbium** **Er** **68**	**Thulium** **Tm** **69**	**Ytterbium** **Yb** **70**	**Lutetium** **Lu** **71**	**Units**	**Remarks**
Characteristics	Ductile metal	Metal	Soft metal	Soft metal	Ductile metal	Ductile metal	Metal		
Electrical resistivity ρ_s Temperature coefficient Pressure coefficient	1130 11.9×10^{-4}	890 11.9×10^{-4} -2.3×10^{-9}	814 17.1×10^{-4} -2.2×10^{-9}	810 20.1×10^{-4} -27×10^{-9}	670 19.5×10^{-4} -2.6×10^{-9}	250 13×10^{-4} 9.7×10^{-9}	540 24×10^{-4} -1.31×10^{-9}	nΩ m 1/K 1/hPa	At RT
Electrical resistivity ρ_l	1930	2100	2210	2260		1080		nΩ m	
Hall coefficient R				-0.34×10^{-10}		-0.53×10^{-10}		$m^3/(A\,s)$	At 293 K, $B < 1$ T
Electronic work function							3.3	V	
Thermal work function	3.4	3.09	3.09	3.12	3.12	2.50	3.14	V	
Molar magnetic susceptibility χ_{mol} (SI)	2.136[a]	1.232[a]	916×10^{-3}	603×10^{-3}	329×10^{-3}	842×10^{-6}	2.30×10^{-3}	cm^3/mol	At 295 K
Molar magnetic susceptibility χ_{mol} (cgs)	170×10^{-3}[a]	98×10^{-3}[a]	72.9×10^{-3}	48×10^{-3}	26.2×10^{-3}	67×10^{-6}	183×10^{-6}	cm^3/mol	At 295 K
Mass magnetic susceptibility χ_{mass} (SI)	15.3×10^{-3}	8.00×10^{-3}	5.49×10^{-3}	3.33×10^{-3}	1.90×10^{-3}	4.9×10^{-6}	13×10^{-6}	cm^3/g	At 295 K

[a] The molar magnetic susceptibility is given for Tb and Dy for the α-phase [4.3]

Table 4.139 Lanthanides. Part C: Allotropic and high-pressure modifications

Element	Cerium					Praseodymium			Neodymium			
Modification	α-Ce	β-Ce	γ-Ce	α′-Ce	Ce-III	α-Pr	β-Pr	γ-Pr	α-Nd	β-Nd	γ-Nd	Units
Crystal system, Bravais lattice	cub, fc	hex	cub, fc	cub, fc	orth	hex	cub, bc	cub, fc	hex	cub, bc	cub, fc	
Structure type	Cu	α-La	Cu	Cu	α-U	α-La	W	Cu	α-La	W	Cu	
Lattice constant *a*	516.10	367.3		482		367.21	413	488	365.82	413	480	pm
Lattice constant *c*		1180.2				1183.26			1179.66			pm
Space group	$Fm\bar{3}m$	$P6_3/mmc$	$Fm\bar{3}m$	$Fm\bar{3}m$	$Cmcm$	$P6_3/mmc$	$Im\bar{3}m$	$Fm\bar{3}m$	$P6_3/mmc$	$Im\bar{3}m$	$Fm\bar{3}m$	
Schoenflies symbol	O_h^5	D_{6h}^4	O_h^5	O_h^5	D_{2h}^{17}	D_{6h}^4	O_h^9	O_h^5	D_{6h}^4	O_h^9	O_h^5	
Strukturbericht type	A1	A3′	A1	A1	A20	A3′	A2	A1	A3′	A2	A1	
Pearson symbol	cF4	hP4	cF4	cF4	oC4	hP4	cI2	cF4	hP4	cI2	cF4	
Number *A* of atoms per cell	4	4	4	4	4	4	2	4	4	2	4	
Coordination number	12	12	12	12	2 + 2 + 4 + 4	12	8	12	12	8	12	
Shortest interatomic distance, solid	364						358	345	364	358	339	pm
Range of stability	RTP	> 263 K	< 95 K	> 1.5 GPa	5.1 GPa	RTP	> 1094 K	> 4.0 GPa	RTP	> 1135 K	> 5.0 GPa	

Table 4.139 (continued)

Element	Promethium		Samarium			Gadolinium			
Modification	α-Pm	β-Pm	α-Sm	β-Sm	γ-Sm	α-Gd	β-Gd	γ-Gd	Units
Crystal system, Bravais lattice	hex	cub, bc	trig	cub, bc	hex	hex, cp	cub, bc	trig	
Structure type	α-La	W	α-Sm	W	α-La	Mg	W	α-Sm	
Lattice constant *a*	365		362.90		361.8	363.36	406	361	pm
Lattice constant *c*	1165		2620.7		1166	578.10		2603	pm
Space group	$P6_3/mmc$	$Im\bar{3}m$	$R\bar{3}m$	$Im\bar{3}m$	$P6_3/mmc$	$P6_3/mmc$	$Im\bar{3}m$	$R\bar{3}m$	
Schoenflies symbol	D_{6h}^4	O_h^9	D_{3d}^5	O_h^9	D_{6h}^4	D_{6h}^4	O_h^9	D_{3d}^5	
Strukturbericht type	A3′	A2	A7	A2	A3′	A3	A2	A7	
Pearson symbol	hP4	cI2	hR3	cI2	hP4	hP2	cI2	hR3	
Number *A* of atoms per cell	4	2	3	2	4	2	2	3	
Coordination number	12	8	12	8	12	12	8		
Shortest interatomic distance, solid	362		361	353	360	360	351		pm
Range of stability	RTP	> 1163 K	RTP	> 1190 K	> 4.0 GPa	RTP	> 1535 K	> 3.0 GPa	

Table 4.139 (continued)

Element	Terbium			Dysprosium				Holmium			
Modification	α-Tb	β-Tb	Tb-II	α-Dy	β-Dy	α′-Dy	γ-Dy	α-Ho	β-Ho	γ-Ho	Units
Crystal system, Bravais lattice	hex, cp	cub, bc	trig	hex, cp	cub, bc	orth	trig	hex, cp	cub, bc	trig	
Structure type	Mg	W	α-Sm	Mg	W		α-Sm	Mg	W	α-Sm	
Lattice constant *a*	360.55		341	359.15		359.5	343.6	357.78		334	pm
Lattice constant *b*						618.4					pm
Lattice constant *c*	569.66		2450	565.01		567.8	2483.0	561.78		2450	pm
Space group	$P6_3/mmc$	$Im\bar{3}m$	$R\bar{3}m$	$P6_3/mmc$	$Im\bar{3}m$	$Cmcm$	$R\bar{3}m$	$P6_3/mmc$	$Im\bar{3}m$	$R\bar{3}m$	
Schoenflies symbol	D^4_{6h}	O^9_h	D^5_{3d}	D^4_{6h}	O^9_h	D^{17}_{2h}	D^5_{3d}	D^4_{6h}	O^9_h	D^5_{3d}	
Strukturbericht type	A3	A2	A7	A3	A2			A3	A2	A7	
Pearson symbol	hP2	cI2	hR3	hP2	cI2	oC4	hR3	hP2	cI2	hR3	
Number *A* of atoms per cell	2	2	3	2	2	4	3	2	2	3	
Coordination number	12			12	8			12	8		
Shortest interatomic distance, solid	357			355	345			353	343		pm
Range of stability	RTP	> 1589 K	> 6.0 GPa	RTP	> 1243 K	< 86 K	> 7.5 GPa	RTP	High temperature	> 4.0 GPa	

Table 4.139 (continued)

Element	Erbium		Thulium			Ytterbium			Lutetium			
Modification	α-Er	β-Er	α-Tm	β-Tm	Tm-II	α-Yb	β-Yb	γ-Yb	α-Lu	β-Lu	Lu-II	Units
Crystal system, Bravais lattice	hex, cp	cub, bc	hex, cp	cub, bc	trig	cub, fc	cub, bc	hex, cp	hex, cp	cub, bc	trig	
Structure type	Mg	W	Mg	W	α-Sm	Cu	W	Mg	Mg	W	α-Sm	
Lattice constant *a*	355.92		353.75			548.48	444	387.99	350.52			pm
Lattice constant *c*	558.50		555.40					638.59	554.94			pm
Space group	$P6_3/mmc$	$Im\bar{3}m$	$P6_3/mmc$	$Im\bar{3}m$	$R\bar{3}m$	$Fm\bar{3}m$	$Im\bar{3}m$	$P6_3/mmc$	$P6_3/mmc$	$Im\bar{3}m$	$R\bar{3}m$	
Schoenflies symbol	D^4_{6h}	O^9_h	D^4_{6h}	O^9_h	D^5_{3d}	O^5_h	O^9_h	D^4_{6h}	D^4_{6h}	O^9_h	D^5_{3d}	
Strukturbericht type	A3	A2	A3	A2		A1	A2	A3	A3	A2		
Pearson symbol	hP2	cI2	hP2	cI2	hR3	cF4	cI2	hP2	hP2	cI2	hR3	
Number *A* of atoms per cell	2	2	2	2	3	4	2	2	2	2	3	
Coordination number	12	8	12	8		12	8	6 + 6	12	8	12	
Shortest interatomic distance, solid	351		349			388	385	388	347	385		pm
Range of stability	RTP	High temperature	RTP	High temperature	> 6.0 GPa	RTP	> 1005 K	< 270 K	RTP	> 1005 K	> 23 GPa	

Table 4.140 Lanthanides. Part D: Ionic radii (determined from crystal structures)

Element	Cerium		Praseodymium		Neodymium	Promethium	Samarium		Europium		Gadolinium	
Ion	Ce^{3+}	Ce^{4+}	Pr^{3+}	Pr^{4+}	Nd^{3+}	Pm^{3+}	Sm^{2+}	Sm^{3+}	Eu^{2+}	Eu^{3+}	Gd^{3+}	
Coordination number												Units
6	101	87	99	85	98		119	96	117	95	94	pm
8	114	97	113	96	112	109	127	108	125	107	105	pm
9					116							pm
10	125	107							135			pm
12	134	114			127			124				pm

Table 4.140 (continued)

Element	Terbium		Dysprosium		Erbium	Thulium		Ytterbium		Lutetium	
Ion	Tb^{3+}	Tb^{4+}	Dy^{2+}	Dy^{3+}	Er^{3+}	Tm^{2+}	Tm^{3+}	Yb^{2+}	Yb^{3+}	Lu^{3+}	
Coordination number											Units
6	92	76	107	91	89	101	88	102		86	pm
7						109					pm
8	104	88	119	103	100		99	114	99	97	pm
9									104		pm

Table 4.141 Actinides. Part A: Atomic, ionic, and molecular properties (see Table 4.146 for ionic radii)

Element name **Chemical symbol** **Atomic number Z**	**Thorium** **Th** **90**	**Protactinium** **Pa** **91**	**Uranium** **U** **92**	**Neptunium** **Np** **93**	**Plutonium** **Pu** **94**	**Americium** **Am** **95**	**Curium** **Cu** **96**	**Units**
Characteristics	Radioactive	Radioactive	Radioactive	Radioactive	Radioactive	Radioactive	Radioactive	
Relative atomic mass A (atomic weight)	232.0377(4)	231.03588(2)	238.0289(1)	[237]	[244]	[243]	[247]	
Abundance in lithosphere[a]	11.5×10^{-6}		4×10^{-6}					
Atomic radius r_{cov}	165		142					pm
Atomic radius r_{met}	180	164	154	150	164	173	174	pm
Electron shells	–OPQ	–OPQ	–OPQ	–OPQ	–OPQ	–OPQ	–OPQ	
Electronic ground state	$^3F_2$	$^4K_{11/2}$	$^5L_6$	$^6L_{11/2}$	$^7F_0$	$^8S_{7/2}$	$^9D_2$	
Electronic configuration	[Rn] $6d^27s^2$	[Rn] $5f^26d^17s^2$	[Rn] $5f^36d^17s2$	[Rn] $5f^46d^17s^2$	[Rn] $5f^67s^2$	[Rn] $5f^77s^2$	[Rn] $5f^76d^17s^2$	
Oxidation states	4+	5+, 4+	6+, 5+, 4+, 3+	6+, 5+, 4+, 3+	6+, 5+, 4+, 3+	6+, 5+, 4+, 3+	3+	
Electronegativity χ_A^b	(1.11)	(1.14)	(1.22)	(1.22)	(1.22)	(1.2)	(1.2)	
1st ionization energy	6.08	5.89	6.19405	6.2657	6.06	5.993	6.02	eV
2nd ionization energy	11.5							eV
3rd ionization energy	20.0							eV
4th ionization energy	28.8							eV
Standard electrode potential E^0 [c]	−1.899							V
Element name **Chemical symbol** **Atomic number Z**	**Berkelium** **Bk** **97**	**Californium** **Cf** **98**	**Einsteinium** **Es** **99**	**Fermium** **Fm** **100**	**Mendelevium** **Md** **101**	**Nobelium** **No** **102**	**Lawrencium** **Lr** **103**	**Units**
Characteristics	Radioactive	Radioactive	Radioactive	Radioactive	Radioactive	Radioactive	Radioactive	
Relative atomic mass A (atomic weight)	[247]	[251]	[252]	[257]	[258]	[259]	[262]	
Atomic radius r_{met}	170	186	186					pm
Electron shells	–OPQ	–OPQ	–OPQ	–OPQ	–OPQ	–OPQ	–OPQ	
Electronic ground state	$^6H_{15/2}$	$^5I_8$	$^5I_{15/2}$	$^3H_6$	$^2F_{7/2}$	$^1S_0$	$^2D_{5/2}$	
Electronic configuration	[Rn] $5f^97s^2$	[Rn] $5f^{10}7s^2$	[Rn] $5f^{11}7s^2$	[Rn] $5f^{12}7s^2$	[Rn] $5f^{13}7s^2$	[Rn] $5f^{14}7s^2$	[Rn] $5f^{14}6d^17s^2$	
Oxidation states	4+, 3+	3+					3+	
Electronegativity χ_A^b	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)			
1st ionization energy	6.23	6.30	6.42	6.50	6.58	6.65		eV

[a] Mass ratio
[b] According to Allred and Rochow
[c] Reaction type $Th^{4+} + 4e^- = Th$

Table 4.142 Actinides. Part B(a): Crystallographic properties (see Table 4.145 for allotropic and high-pressure modifications)

Element name **Chemical symbol** **Atomic number *Z***	**Thorium** **Th** **90**	**Protactinium** **Pa** **91**	**Uranium** **U** **92**	**Neptunium** **Np** **93**	**Plutonium** **Pu** **94**	**Americium** **Am** **95**	**Curium** **Cu** **96**	**Units**
Modification			α-U		α-Pu			
Crystal system, Bravais lattice	cub, fc	tetr, I	orth, C	orth, P	mon, P	hex	hex	
Structure type	Cu	α-Pa	α-U	α-Np	α-Pu	α-La	α-La	
Lattice constant a	508.51	394.5	285.38	666.3	618.3	346.8	349.6	pm
Lattice constant b			586.80	472.3	482.2			pm
Lattice constant c		324.2	495.57	488.7	1096.8	1124.1	1133.1	pm
Lattice angle γ					101.78			deg
Space group	$Fm3m$	$I4/mmm$	$Cmcm$	$Pnma$	$P2_1/m$	$P6_3/mmc$	$P6_3/mmc$	
Schoenflies symbol	O_h^5	D_{4h}^{17}	D_{2h}^{17}	D_{2h}^{16}	C_{2h}^2	D_{6h}^4	D_{6h}^4	
Strukturbericht type	A1	A6	A20	A_c		A3′	A3′	
Pearson symbol	cF4	tI2	oC4	oP8	mP16	hP4	hP4	
Number A of atoms per cell	4	2	4	8	16	4	4	
Coordination number	12	8 + 2	2 + 2 + 4 + 4	8 + 6		6 + 6	6 + 6	
Shortest interatomic distance, solid	360	321	276	259–335	257–278	347	349	pm
Element name **Chemical symbol** **Atomic number *Z***	**Berkelium** **Bk** **97**	**Californium** **Cf** **98**	**Einsteinium** **Es** **99**	**Fermium** **Fm** **100**	**Mendelevium** **Md** **101**	**Nobelium** **No** **102**	**Lawrencium** **Lr** **103**	**Units**
Crystal system, Bravais lattice	hex	hex	hex					
Structure type	α-La	α-La	α-La					
Lattice constant a	341.6							pm
Lattice constant c	1106.9							pm
Space group	$P6_3/mmc$	$P6_3/mmc$	$P6_3/mmc$					
Schoenflies symbol	D_{6h}^4	D_{6h}^4	D_{6h}^4					
Strukturbericht type	A3′	A3′	A3′					
Pearson symbol	hP4	hP4	hP4					
Number A of atoms per cell	4	4	4					

Table 4.143 Actinides. Part B(b): Mechanical properties

Element name **Chemical symbol** **Atomic number *Z***	**Thorium** **Th** **90**	**Protactinium** **Pa** **91**	**Uranium** **U** **92**	**Neptunium** **Np** **93**	**Plutonium** **Pu** **94**	**Americium** **Am** **95**	**Curium** **Cu** **96**	**Units**
Modification					α-Pu			
Density ϱ, solid	11.70	15.40	18.90	20.40	19.80	13.60	13.510	g/cm^3
Density ϱ, liquid	10.35		17.907		16.623			
Molar volume V_{mol}	19.80	15.0	12.56	11.71	12.3	17.78	18.3	cm^3/mol
Viscosity η, liquid					7.4			mPa s
Surface tension, liquid Temperature coefficient	1.05		1.53 -0.14×10^{-3}		0.55			N/m N/(m K)
Coefficient of linear thermal expansion α	12.5×10^{-6}	7.3×10^{-6}	12.6×10^{-6}	27.5×10^{-6}	55×10^{-6}			1/K
Sound velocity, solid, transverse	1630		1940					m/s
Sound velocity, solid, longitudinal	2850		3370					m/s
Volume compressibility κ	1.86×10^{-5}		0.785×10^{-5}					1/MPa
Elastic modulus E	78.3	76	177	68	92.7			GPa
Shear modulus G	30.8		70.6		45			GPa
Poisson number μ	0.26		0.25		0.18			
Elastic compliance s_{11}	27.4		4.91					1/TPa
Elastic compliance s_{22}			6.73					1/TPa
Elastic compliance s_{33}			4.79					1/TPa
Elastic compliance s_{44}	22.0		8.04					1/TPa
Elastic compliance s_{55}			13.6					1/TPa
Elastic compliance s_{66}			13.4					1/TPa
Elastic compliance s_{12}	−10.9		−1.19					1/TPa
Elastic compliance s_{13}			0.08					1/TPa
Elastic compliance s_{23}			−2.61					1/TPa
Elastic stiffness c_{11}	77.0		215					GPa
Elastic stiffness c_{22}			199					GPa
Elastic stiffness c_{33}			267					GPa
Elastic stiffness c_{44}	45.5		124					GPa
Elastic stiffness c_{55}			73.4					GPa
Elastic stiffness c_{66}			74.3					GPa
Elastic stiffness c_{12}	50.9		46					GPa
Elastic stiffness c_{13}			22					GPa
Elastic stiffness c_{23}			108					GPa
Tensile strength	0.219		0.585		0.525			GPa
Vickers hardness	294–687		1960		2500–2800			
Element name **Chemical symbol** **Atomic number *Z***	**Berkelium** **Bk** **97**	**Californium** **Cf** **98**	**Einsteinium** **Es** **99**	**Fermium** **Fm** **100**	**Mendelevium** **Md** **101**	**Nobelium** **No** **102**	**Lawrencium** **Lr** **103**	**Units**
Density ϱ, solid	14.790	9.310	8.840					g/cm^3
Molar volume V_{mol}	16.70	26.96	28.5					cm^3/mol

Table 4.144 Actinides. Part B(c): Thermal and thermodynamic properties

Element name **Chemical symbol** **Atomic number Z**	**Thorium** **Th** **90**	**Protactinium** **Pa** **91**	**Uranium** **U** **92**	**Neptunium** **Np** **93**	**Plutonium** **Pu** **94**	**Americium** **Am** **95**	**Curium** **Cu** **96**	**Units**	**Remarks**
Modification	α-Th	α-Pa	α-U	α-Np	α-Pu				
Thermal conductivity λ	77.0	About 47	22.0	6.3	6.74	About 10	About 10	W/(m K)	
Molar heat capacity c_p	27.32	(27.61)	27.66	29.62	32.84	25.9	(27.70)	J/(mol K)	At 298 K
Standard entropy S^0	51.800	51.882	50.200	50.459	54.461	55.396	71.965	J/(mol K)	At 298.15 K and 100 kPa
Enthalpy difference $H_{298} - H_0$	6.3500	6.4392	6.3640	6.6065	6.9023	6.4070	6.1337	kJ/mol	
Melting temperature T_m	2022.99	1844.78	1408.0	917.0	913.0	1449.0	1618.0	K	
Transition	β–liquid	β–liquid	γ–liquid	γ–liquid	ε–liquid	γ–liquid	β–liquid		
Enthalpy change ΔH_m	13.8072	12.3412	9.1420	3.1986	2.8240	14.3930	14.6440	kJ/mol	
Entropy change ΔS_m	6.825	6.690	6.493	3.488	3.093	9.933	9.051	J/(mol K)	
Relative volume change ΔV_m	0.05		0.022						$(V_l - V_s)/V_l$ at T_m
Boiling temperature T_b	5061		4407		3503	2880		K	
Enthalpy change ΔH_b	514.1	481	464.1	423.4	260.0	238.5	395.7	kJ/mol	
Element name **Chemical symbol** **Atomic number Z**	**Berkelium** **Bk** **97**	**Californium** **Cf** **98**	**Einsteinium** **Es** **99**	**Fermium** **Fm** **100**	**Mendelevium** **Md** **101**	**Nobelium** **No** **102**	**Lawrencium** **Lr** **103**	**Units**	**Remarks**
Thermal conductivity λ	About 10	About 10	About 10					W/(m K)	
Standard entropy S^0	(76.15)	80.542	89.471	87.236				J/(mol K)	At 298.15 K and 100 kPa
Melting temperature T_m	1256	1213	1133.0	1800	1100	1100	1900	K	
Transition			β–liquid						
Enthalpy change ΔH_m			9.4056	1.02				kJ/mol	
Entropy change ΔS_m			8.302					J/(mol K)	
Enthalpy of boiling ΔH_b				3.26				kJ/mol	

Table 4.145 Actinides. Part B(d): Electronic, electromagnetic, and optical properties

Element name **Chemical symbol** **Atomic number *Z***	**Thorium** **Th** **90**	**Protactinium** **Pa** **91**	**Uranium** **U** **92**	**Neptunium** **Np** **93**	**Plutonium** **Pu** **94**	**Americium** **Am** **95**	**Curium** **Cu** **96**	**Units**	**Remarks**
Characteristics	Soft metal	Toxic metal	Ductile metal	Reactive metal	Metal, very toxic	Metal	Metal, very reactive		
Electrical resistivity ρ_s Temperature coefficient Pressure coefficient	147 27.5×10^{-4} -3.4×10^{-9}	177	280 28.2×10^{-4}		1414	680 33×10^{-4}	860	nΩ m 1/K 1/Pa	At RT
Superconducting critical temperature T_{crit}	1.37							K	
Superconducting critical field H_{crit}	162							Oe	
Hall coefficient R^a	-1.2×10^{-10}		0.34×10^{-10}		0.69×10^{-6}			$m^3/(A\,s)$	
Thermoelectronic coefficient			5.0					μV/K	
Electronic work function	3.67		3.47					V	
Thermal work function	3.42	4.8	3.47					V	
Molar magnetic susceptibility χ_{mol} (SI)	1.22×10^{-3}	3.48×10^{-3}	5.14×10^{-3}	7.23×10^{-3}	6.60×10^{-3}			cm^3/mol	
Molar magnetic susceptibility χ_{mol} (cgs)	97×10^{-6}	277×10^{-6}	409×10^{-6}	575×10^{-6}	525×10^{-6}			cm^3/mol	
Mass magnetic susceptibility χ_{mol} (SI)	7.2×10^{-6}		21.6×10^{-6}		31.7×10^{-6}	50×10^{-6}		cm^3/g	
Element name **Chemical symbol** **Atomic number *Z***	**Berkelium** **Bk** **97**	**Californium** **Cf** **98**	**Einsteinium** **Es** **99**	**Fermium** **Fm** **100**	**Mendelevium** **Md** **101**	**Nobelium** **No** **102**	**Lawrencium** **Lr** **103**		
Characteristics	Metal	Metal	Metal		Metal				

[a] At 298 K, $B = 0.3-0.7$ T

Table 4.146 Actinides. Part C: Allotropic and high-pressure modifications

Element	Thorium		Protactinium		Uranium			
Modification	α-Th	β-Th	α-Pa	β-Pa	α-U	β-U	γ-U	Units
Crystal system, Bravais lattice	cub, fc	cub, bc	tetr, I	cub, bc	orth, C	tetr	cub, bc	
Structure type	Cu	W	In	W	α-U		W	
Lattice constant a	508.51	411	394.5		285.38	1075.9	352.4	pm
Lattice constant b					586.80			pm
Lattice constant c			324.2		495.57	565.4		pm
Space group	$Fm\bar{3}m$	$Im\bar{3}m$	$I4/mmm$	$Im\bar{3}m$	$Cmcm$	$P4_2/mmm$	$Im\bar{3}m$	
Schoenflies symbol	O_h^5	O_h^9	D_{4h}^{17}	O_h^9	D_{2h}^{17}	C_{2h}^{14}	O_h^9	
Strukturbericht type	A1	A2	A6	A2	A20		A2	
Pearson symbol	cF4	cI2	tI2	cI2	oC4	tP30	cI2	
Number A of atoms per cell	4	2	2	2	4	30	2	
Coordination number	12	8	8 + 2	2 + 2 + 4 + 4	2 + 2 + 4 + 4	12	8	
Shortest interatomic distance, solid	360	356	321		276	287–353	347	pm
Range of stability	RTP	> 1673 K	RTP	> 1443 K	RTP	> 935 K	> 1045 K	

Table 4.146 (continued)

Element	Neptunium			Plutonium						
Modification	α-Np	β-Np	γ-Np	α-Pu	β-Pu	γ-Pu	δ-Pu	δ′-Pu	ε-Pu	Units
Crystal system, Bravais lattice	orth, P	tetr	cub, bc	mon, P	mon	orth	cub, fc	tetr	cub, bc	
Structure type	α-Np		W				Cu	In	W	
Lattice constant a	666.3	489.6	352	618.3	928.4	315.87	463.71	332.61	570.3	pm
Lattice constant b	472.3			482.2	1046.3	576.82				pm
Lattice constant c	488.7	338.7		1096.8	785.9	1016.2		446.30		pm
Lattice angle γ				101.78	92.13					deg
Space group	$Pnma$	$P42_12$	$Im\bar{3}m$	$P2_1/m$	$I2/m$	$Fddd$	$Fm\bar{3}m$	$I4/mmm$	$Im\bar{3}m$	
Schoenflies symbol	D_{2h}^{16}	D_{4h}^{7}	O_h^9	C_{2h}^{2}	C_{2h}^{3}	D_{2h}^{24}	O_h^5	D_{4h}^{17}	O_h^9	
Strukturbericht type	A_c	A_d	A2				A1	A6	A2	
Pearson symbol	oP8	tP4	cI2	mP16	mI34	oF8	cF4	tI2	cI2	
Number A of atoms per cell	8	4	2	16	34	8	4	2	2	
Coordination number	8 + 6	8 + 6	8 + 6			4 + 2 + 4	12	4 + 8	8 + 6	
Shortest interatomic distance, solid	260–336	275–356	305	257–278	259–310	303	328	333	315	pm
Range of stability	RTP	> 553 K	> 850 K	RTP	> 395 K	> 508 K	> 592 K	> 726 K	> 744 K	

Table 4.146 (continued)

Element	Americium			Curium		
Modification	**α-Am**	**β-Am**	**γ-Am**	**α-Cm**	**β-Cm**	**Units**
Crystal system, Bravais lattice	hex	cub, fc	orth	hex	cub, fc	
Structure type	α-La	Cu	α-U	α-La	Cu	
Lattice constant *a*	346.8	489.4	306.3	349.6	438.1	pm
Lattice constant *b*			596.8			pm
Lattice constant *c*	1124.1		516.9	1133.1		pm
Space group	$P6_3/mmc$	$Fm\bar{3}m$	$Cmcm$	$P6_3/mmc$	$Fm\bar{3}m$	
Schoenflies symbol	D_{6h}^4	O_h^5	D_{2h}^{17}	D_{6h}^4	O_h^5	
Strukturbericht type	A3′	A1	A20	A3′	A1	
Pearson symbol	hP4	cF4	oC4	hP4	cF4	
Number *A* of atoms per cell	4	4	4	4	4	
Coordination number	6 + 6	12		6 + 6	12	
Shortest interatomic distance, solid	347	346		350	310	pm
Range of stability	RTP	> 878 K	> 15.0 GPa	RTP	> 1449 K	

Table 4.146 (continued)

Element	Berkelium		Californium		Einsteinium		
Modification	**α-Bk**	**β-Bk**	**α-Cf**	**β-Cf**	**α-Es**	**β-Es**	**Units**
Crystal system, Bravais lattice	hex	cub, fc	hex	cub, fc	hex	cub, fc	
Structure type	α-La	Cu	α-La	Cu	α-La	Cu	
Lattice constant *a*	341.6	499.7					pm
Lattice constant *c*	1106.9						pm
Space group	$P6_3/mmc$	$Fm\bar{3}m$	$P6_3/mmc$	$Fm\bar{3}m$	$P6_3/mmc$	$Fm\bar{3}m$	
Schoenflies symbol	D_{6h}^4	O_h^5	D_{6h}^4	O_h^5	D_{6h}^4	O_h^5	
Strukturbericht type	A3′	A1	A3′	A1	A3′	A1	
Pearson symbol	hP4	cF4	hP4	cF4	hP4	cF4	
Number *A* of atoms per cell	4	4	4	4	4	4	
Coordination number		12		12			
Shortest interatomic distance, solid		353		406			pm
Range of stability	RTP	> 1183 K		> 1213 K	RTP	> 1093 K	

Table 4.147 Actinides. Part D: Ionic radii (determined from crystal structures)

Element	Thorium	Protactinium			Uranium				Neptunium				
Ion	Th^{4+}	Pa^{3+}	Pa^{4+}	Pa^{5+}	U^{3+}	U^{4+}	U^{5+}	U^{6+}	Np^{3+}	Np^{4+}	Np^{5+}	Np^{6+}	
Coordination number													Units
2								45					pm
4								52					pm
6	94	104	90	78	103	89	76	73	101	87	75	72	pm
8	105					100		86					pm
10	113												pm
12	121					117							pm

Table 4.147 (continued)

Element	Plutonium				Americium		
Ion	Pu^{3+}	Pu^{4+}	Pu^{5+}	Pu^{6+}	Am^{3+}	Am^{4+}	
Coordination number							Units
6	100	86	74	71	98	85	pm
8					109	95	pm
Element	**Berkelium**		**Californium**		**Curium**		
Ion	**Bk^{3+}**	**Bk^{4+}**	**Cf^{3+}**	**Cf^{4+}**	**Cm^{3+}**	**Cm^{4+}**	
Coordination number							**Units**
6	96	83	95	82	97	85	pm
8		93		92		95	pm

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