

## APPENDIX A. PROPERTIES OF THE ELEMENTS

Table 1 lists atomic weights, densities, melting and boiling points, critical points, ionization potentials, specific heats. Data were taken from the 75th edition of the *CRC Handbook of Chemistry and Physics*<sup>1</sup>. Atomic weights apply to elements as they exist naturally on earth, or, in the cases of thorium and protactinium, to the isotopes which have the longest half-lives. Values in parentheses are the mass numbers for the longest lived isotopes of some of the radioactive elements. Specific heats are given for the elements at 25°C. Densities for solids and liquids are given at 25°C, unless otherwise indicated by a superscript temperature (in °C); densities for the gaseous elements are for the liquids at their boiling points.

The solar system elemental abundances (atomic %) in Table 2 are from the compilation of Anders and Grevesse<sup>2</sup>, and are based on meteorite and solar wind data. The elemental abundances in the earth's crust and in the sea represent the median values of reported measurements.<sup>1,3,4,5</sup> The concentrations of the less abundant elements may vary with location by several orders of magnitude.

Table 1. Chemical Properties

| Z  | El | Name       | Atomic Weight (a.m.u.)  | Density (g/cm <sup>3</sup> ) | Melting point (°C) | Boiling point (°C) | Critical point (°C) | Ionization potential (eV) | Specific heat (J/g K)         |
|----|----|------------|-------------------------|------------------------------|--------------------|--------------------|---------------------|---------------------------|-------------------------------|
| 1  | H  | Hydrogen   | 1.00794 <sup>7</sup>    | 0.0708                       | -259.34            | -252.87            | -240.18             | 13.598                    | 14.304                        |
| 2  | He | Helium     | 4.002602 <sup>2</sup>   | 0.124901                     | -272.2             | -268.93            | -267.96             | 24.587                    | 5.193                         |
| 3  | Li | Lithium    | 6.941 <sup>2</sup>      | 0.534                        | 180.5              | 1342               |                     | 5.392                     | 3.582                         |
| 4  | Be | Beryllium  | 9.012182 <sup>3</sup>   | 1.85                         | 1287               | 2471               |                     | 9.323                     | 1.825                         |
| 5  | B  | Boron      | 10.811 <sup>5</sup>     | 2.37                         | 2075               | 4000               |                     | 8.298                     | 1.026 <sup>amorphous</sup>    |
| 6  | C  | Carbon     | 12.011 <sup>1</sup>     | 2.2670 <sup>15°</sup>        | 4492 <sup>t</sup>  | 3825 <sup>s</sup>  |                     | 11.260                    | 0.709 <sup>graphite</sup>     |
| 7  | N  | Nitrogen   | 14.00674 <sup>7</sup>   | 0.807                        | -210.00            | -195.79            | -146.94             | 14.534                    | 1.040                         |
| 8  | O  | Oxygen     | 15.9994 <sup>3</sup>    | 1.141                        | -218.79            | -182.95            | -118.56             | 13.618                    | 0.918                         |
| 9  | F  | Fluorine   | 18.9984032 <sup>9</sup> | 1.50                         | -219.62            | -188.12            | -129.02             | 17.423                    | 0.824                         |
| 10 | Ne | Neon       | 20.1797 <sup>6</sup>    | 1.204                        | -248.59            | -246.08            | -228.7              | 21.565                    | 1.030                         |
| 11 | Na | Sodium     | 22.989768 <sup>6</sup>  | 0.97                         | 97.72              | 883                |                     | 5.139                     | 1.228                         |
| 12 | Mg | Magnesium  | 24.3050 <sup>6</sup>    | 1.74                         | 650                | 1090               |                     | 7.646                     | 1.023                         |
| 13 | Al | Aluminum   | 26.981539 <sup>5</sup>  | 2.70                         | 660.32             | 2519               |                     | 5.986                     | 0.897                         |
| 14 | Si | Silicon    | 28.0855 <sup>3</sup>    | 2.3296                       | 1414               | 3265               |                     | 8.152                     | 0.705                         |
| 15 | P  | Phosphorus | 30.973762 <sup>4</sup>  | 1.82                         | 44.15              | 277                | 721                 | 10.487                    | 0.769 <sup>white</sup>        |
| 16 | S  | Sulfur     | 32.066 <sup>6</sup>     | 2.067                        | 115.21             | 444.60             | 1041                | 10.360                    | 0.710 <sup>orthorhombic</sup> |
| 17 | Cl | Chlorine   | 35.4527 <sup>9</sup>    | 1.56                         | -101.5             | -34.04             | 143.8               | 12.968                    | 0.479                         |
| 18 | Ar | Argon      | 39.948 <sup>1</sup>     | 1.396                        | -189.35            | -185.85            | -122.28             | 15.760                    | 0.520                         |
| 19 | K  | Potassium  | 39.0983 <sup>1</sup>    | 0.89                         | 63.38              | 759                |                     | 4.341                     | 0.757                         |
| 20 | Ca | Calcium    | 40.078 <sup>4</sup>     | 1.54                         | 842                | 1484               |                     | 6.113                     | 0.647                         |
| 21 | Sc | Scandium   | 44.955910 <sup>9</sup>  | 2.99                         | 1541               | 2830               |                     | 6.561                     | 0.568                         |
| 22 | Ti | Titanium   | 47.867 <sup>1</sup>     | 4.5                          | 1668               | 3287               |                     | 6.828                     | 0.523                         |
| 23 | V  | Vanadium   | 50.9415 <sup>1</sup>    | 6.0                          | 1910               | 3407               |                     | 6.746                     | 0.489                         |
| 24 | Cr | Chromium   | 51.9961 <sup>6</sup>    | 7.15                         | 1907               | 2671               |                     | 6.767                     | 0.449                         |
| 25 | Mn | Manganese  | 54.93805 <sup>1</sup>   | 7.3                          | 1246               | 2061               |                     | 7.434                     | 0.479                         |
| 26 | Fe | Iron       | 55.845 <sup>2</sup>     | 7.875                        | 1538               | 2861               |                     | 7.902                     | 0.449                         |
| 27 | Co | Cobalt     | 58.93320 <sup>1</sup>   | 8.86                         | 1495               | 2927               |                     | 7.881                     | 0.421                         |
| 28 | Ni | Nickel     | 58.6934 <sup>2</sup>    | 8.912                        | 1455               | 2913               |                     | 7.640                     | 0.444                         |
| 29 | Cu | Copper     | 63.546 <sup>3</sup>     | 8.933                        | 1084.62            | 2562               |                     | 7.726                     | 0.385                         |

<sup>1</sup> *Handbook of Chemistry and Physics*, 75th edition, D.R. Lide, editor, CRC Press, Boca Raton, FL (1995).

<sup>2</sup> E. Anders and N. Grevesse, *Geochimica et Cosmochimica Acta* **53**, 197 (1989).

<sup>3</sup> *CRC Practical Handbook of Physical Properties of Rocks and Minerals*, R.S. Carmichael, editor, CRC Press, Boca Raton, FL (1989).

<sup>4</sup> I. Bodek *et al*, *Environmental Inorganic Chemistry*, Pergamon Press, New York (1988).

<sup>5</sup> A.B. Ronov and A.A. Yaroshevsky, "Earth's Crust Geochemistry", in the *Encyclopedia of Geochemistry and Environmental Sciences*, R.W. Fairbridge, editor, Van Nostrand, New York (1969).

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| Z  | El | Name         | Atomic Weight (a.m.u.) | Density (g/cm <sup>3</sup> ) | Melting point (°C) | Boiling point (°C) | Critical point (°C) | Ionization potential (eV) | Specific heat (J/g K)  |
|----|----|--------------|------------------------|------------------------------|--------------------|--------------------|---------------------|---------------------------|------------------------|
| 30 | Zn | Zinc         | 65.39 2                | 7.134                        | 419.53             | 907                |                     | 9.394                     | 0.388                  |
| 31 | Ga | Gallium      | 69.723 1               | 5.91                         | 29.76              | 2204               |                     | 5.999                     | 0.371                  |
| 32 | Ge | Germanium    | 72.61 2                | 5.323                        | 938.25             | 2833               |                     | 7.900                     | 0.320                  |
| 33 | As | Arsenic      | 74.92159 2             | 5.776 <sup>26°</sup>         | 817 <sup>t</sup>   | 614 <sup>s</sup>   | 1400                | 9.815                     | 0.329                  |
| 34 | Se | Selenium     | 78.96 3                | 4.809 <sup>26°</sup>         | 221                | 685                | 1493                | 9.752                     | 0.321                  |
| 35 | Br | Bromine      | 79.904 1               | 3.11                         | -7.2               | 58.8               | 315                 | 11.814                    | 0.226                  |
| 36 | Kr | Krypton      | 83.80 1                | 2.418                        | -157.36            | -153.22            | -63.74              | 14.000                    | 0.248                  |
| 37 | Rb | Rubidium     | 85.4678 3              | 1.53                         | 39.31              | 688                |                     | 4.177                     | 0.363                  |
| 38 | Sr | Strontium    | 87.62 1                | 2.64                         | 777                | 1382               |                     | 5.695                     | 0.301                  |
| 39 | Y  | Yttrium      | 88.90585 2             | 4.47                         | 1526               | 3336               |                     | 6.217                     | 0.298                  |
| 40 | Zr | Zirconium    | 91.224 2               | 6.52                         | 1855               | 4409               |                     | 6.634                     | 0.278                  |
| 41 | Nb | Niobium      | 92.90638 2             | 8.57                         | 2477               | 4744               |                     | 6.759                     | 0.265                  |
| 42 | Mo | Molybdenum   | 95.94 1                | 10.2                         | 2623               | 4639               |                     | 7.092                     | 0.251                  |
| 43 | Tc | Techneium    | [98]                   | 11                           | 2157               | 4265               |                     | 7.28                      |                        |
| 44 | Ru | Ruthenium    | 101.07 2               | 12.1                         | 2334               | 4150               |                     | 7.361                     | 0.238                  |
| 45 | Rh | Rhodium      | 102.90550 3            | 12.4                         | 1964               | 3695               |                     | 7.459                     | 0.243                  |
| 46 | Pd | Palladium    | 106.42 1               | 12.0                         | 1554.9             | 2963               |                     | 8.337                     | 0.244                  |
| 47 | Ag | Silver       | 107.8682 2             | 10.501                       | 961.78             | 2162               |                     | 7.576                     | 0.235                  |
| 48 | Cd | Cadmium      | 112.411 8              | 8.69                         | 321.07             | 767                |                     | 8.994                     | 0.232                  |
| 49 | In | Indium       | 114.818 3              | 7.31                         | 156.60             | 2072               |                     | 5.786                     | 0.233                  |
| 50 | Sn | Tin          | 118.710 7              | 7.287 <sup>26°</sup>         | 231.93             | 2602               |                     | 7.344                     | 0.228 <sup>white</sup> |
| 51 | Sb | Antimony     | 121.760 1              | 6.685 <sup>26°</sup>         | 630.63             | 1587               |                     | 8.64                      | 0.207                  |
| 52 | Te | Tellurium    | 127.60 3               | 6.232                        | 449.51             | 988                |                     | 9.010                     | 0.202                  |
| 53 | I  | Iodine       | 126.90447 3            | 4.93 <sup>20°</sup>          | 113.7              | 184.4              | 546                 | 10.451                    | 0.145                  |
| 54 | Xe | Xenon        | 131.29 2               | 2.953                        | -111.75            | -108.04            | 16.58               | 12.130                    | 0.158                  |
| 55 | Cs | Cesium       | 132.90543 5            | 1.93                         | 28.44              | 671                |                     | 3.894                     | 0.242                  |
| 56 | Ba | Barium       | 137.327 7              | 3.62                         | 727                | 1897               |                     | 5.212                     | 0.204                  |
| 57 | La | Lanthanum    | 138.9055 2             | 6.15                         | 920                | 3455               |                     | 5.577                     | 0.195                  |
| 58 | Ce | Cerium       | 140.115 4              | 8.16                         | 799                | 3424               |                     | 5.539                     | 0.192                  |
| 59 | Pr | Praseodymium | 140.90765 3            | 6.77                         | 931                | 3510               |                     | 5.464                     | 0.193                  |
| 60 | Nd | Neodymium    | 144.24 3               | 7.01                         | 1016               | 3066               |                     | 5.525                     | 0.190                  |
| 61 | Pm | Promethium   | [145]                  | 7.26                         | 1042               | 3000               |                     | 5.55                      |                        |
| 62 | Sm | Samarium     | 150.36 3               | 7.52                         | 1072               | 1790               |                     | 5.644                     | 0.197                  |
| 63 | Eu | Europium     | 151.965 9              | 5.24                         | 822                | 1596               |                     | 5.670                     | 0.182                  |
| 64 | Gd | Gadolinium   | 157.25 3               | 7.90                         | 1314               | 3264               |                     | 6.150                     | 0.236                  |
| 65 | Tb | Terbium      | 158.92534 3            | 8.23                         | 1359               | 3221               |                     | 5.864                     | 0.182                  |
| 66 | Dy | Dysprosium   | 162.50 3               | 8.55                         | 1411               | 2561               |                     | 5.939                     | 0.173                  |
| 67 | Ho | Holmium      | 164.93032 3            | 8.80                         | 1472               | 2694               |                     | 6.022                     | 0.165                  |
| 68 | Er | Erbium       | 167.26 3               | 9.07                         | 1529               | 2862               |                     | 6.108                     | 0.168                  |
| 69 | Tm | Thulium      | 168.93421 3            | 9.32                         | 1545               | 1946               |                     | 6.184                     | 0.160                  |
| 70 | Yb | Ytterbium    | 173.04 3               | 6.90                         | 824                | 1194               |                     | 6.254                     | 0.155                  |
| 71 | Lu | Lutetium     | 174.967 1              | 9.84                         | 1663               | 3393               |                     | 5.426                     | 0.154                  |
| 72 | Hf | Hafnium      | 178.49 2               | 13.3                         | 2233               | 4603               |                     | 6.825                     | 0.144                  |
| 73 | Ta | Tantalum     | 180.9479 1             | 16.4                         | 3017               | 5458               |                     | 7.89                      | 0.140                  |
| 74 | W  | Tungsten     | 183.84 1               | 19.3                         | 3422               | 5555               |                     | 7.98                      | 0.132                  |
| 75 | Re | Rhenium      | 186.207 1              | 20.8                         | 3186               | 5596               |                     | 7.88                      | 0.137                  |
| 76 | Os | Osmium       | 190.23 3               | 22.5                         | 3033               | 5012               |                     | 8.7                       | 0.130                  |
| 77 | Ir | Iridium      | 192.217 3              | 22.5                         | 2446               | 4428               |                     | 9.1                       | 0.131                  |
| 78 | Pt | Platinum     | 195.08 3               | 21.46                        | 1768.4             | 3825               |                     | 9.0                       | 0.133                  |
| 79 | Au | Gold         | 196.96654 3            | 19.282                       | 1064.18            | 2856               |                     | 9.226                     | 0.129                  |
| 80 | Hg | Mercury      | 200.59 2               | 13.5336                      | -38.83             | 356.73             | 1477                | 10.438                    | 0.140                  |
| 81 | Tl | Thallium     | 204.3833 2             | 11.8                         | 304                | 1473               |                     | 6.108                     | 0.129                  |
| 82 | Pb | Lead         | 207.2 1                | 11.342                       | 327.46             | 1749               |                     | 7.417                     | 0.129                  |
| 83 | Bi | Bismuth      | 208.98037 3            | 9.807                        | 271.40             | 1564               |                     | 7.289                     | 0.122                  |
| 84 | Po | Polonium     | [209]                  | 9.32                         | 254                |                    |                     | 8.417                     |                        |
| 85 | At | Astatine     | [210]                  |                              | 302                |                    |                     |                           |                        |

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| Z   | El | Name          | Atomic Weight (a.m.u.) | Density (g/cm <sup>3</sup> ) | Melting point (°C) | Boiling point (°C) | Critical point (°C) | Ionization potential (eV) | Specific heat (J/g K) |
|-----|----|---------------|------------------------|------------------------------|--------------------|--------------------|---------------------|---------------------------|-----------------------|
| 86  | Rn | Radon         | [222]                  | 4.4                          | -71                | -61.7              | 104                 | 10.749                    | 0.094                 |
| 87  | Fr | Francium      | [223]                  |                              | 27                 |                    |                     |                           |                       |
| 88  | Ra | Radium        | [226]                  | 5                            | 700                |                    |                     | 5.279                     |                       |
| 89  | Ac | Actinium      | [227]                  | 10.07 <sup>a</sup>           | 1051               | 3198               |                     | 5.17                      |                       |
| 90  | Th | Thorium       | 232.0381 <sup>1</sup>  | 11.72                        | 1750               | 4788               |                     | 6.08                      | 0.113                 |
| 91  | Pa | Protactinium  | 231.03588 <sup>2</sup> | 15.37 <sup>a</sup>           | 1572               |                    |                     | 5.89                      |                       |
| 92  | U  | Uranium       | 238.0289 <sup>1</sup>  | ≈18.95                       | 1135               | 4131               |                     | 6.194                     | 0.116                 |
| 93  | Np | Neptunium     | [237]                  | 20.25 <sup>20°</sup>         | 644                |                    |                     | 6.266                     |                       |
| 94  | Pu | Plutonium     | [244]                  | 19.84                        | 640                | 3228               |                     | 6.06                      |                       |
| 95  | Am | Americium     | [243]                  | 13.69 <sup>20°</sup>         | 1176               |                    |                     | 5.993                     |                       |
| 96  | Cm | Curium        | [247]                  | 13.51 <sup>a</sup>           | 1345               |                    |                     | 6.02                      |                       |
| 97  | Bk | Berkelium     | [247]                  | 14 <sup>b</sup>              | 1050               |                    |                     | 6.23                      |                       |
| 98  | Cf | Californium   | [251]                  |                              | 900                |                    |                     | 6.30                      |                       |
| 99  | Es | Einsteinium   | [252]                  |                              | 860                |                    |                     | 6.42                      |                       |
| 100 | Fm | Fermium       | [257]                  |                              | 1527               |                    |                     | 6.50                      |                       |
| 101 | Md | Mendelevium   | [258]                  |                              | 827                |                    |                     | 6.58                      |                       |
| 102 | No | Nobelium      | [259]                  |                              | 827                |                    |                     | 6.65                      |                       |
| 103 | Lr | Lawrencium    | [260]                  |                              | 1627               |                    |                     |                           |                       |
| 104 | Rf | Rutherfordium | [261]                  |                              |                    |                    |                     |                           |                       |
| 105 | Db | Dubnium       | [262]                  |                              |                    |                    |                     |                           |                       |
| 106 | Sg | Seaborgium    | [263]                  |                              |                    |                    |                     |                           |                       |
| 107 | Bh | Bohrium       | [264]                  |                              |                    |                    |                     |                           |                       |
| 108 | Hs | Hassium       | [267]                  |                              |                    |                    |                     |                           |                       |
| 109 | Mt | Meitnerium    | [268]                  |                              |                    |                    |                     |                           |                       |
| 110 | ?? | Element-110   | [271]                  |                              |                    |                    |                     |                           |                       |
| 111 | ?? | Element-111   | [272]                  |                              |                    |                    |                     |                           |                       |

<sup>a</sup>Calculated<sup>b</sup>Estimated<sup>t</sup>Critical temperature<sup>s</sup>Sublimation temperature