

## 6. ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS

**Table 6.1.** Revised May 2000 by D.E. Groom (LBNL). Gases are evaluated at 20°C and 1 atm (in parentheses) or at STP [square brackets]. Densities and refractive indices without parentheses or brackets are for solids or liquids, or are for cryogenic liquids at the indicated boiling point (BP) at 1 atm. Refractive indices are evaluated at the sodium D line. Data for compounds and mixtures are from Refs. 1 and 2. Further materials and properties are given in Ref. 3.

| Material                                                                                              | $Z$ | $A$        | $\langle Z/A \rangle$ | Nuclear<br>collision<br>length $\lambda_T$<br>{g/cm <sup>2</sup> } | Nuclear <sup>a</sup><br>interaction<br>length $\lambda_I$<br>{g/cm <sup>2</sup> } | $dE/dx _{\min}^b$<br>$\left\{ \frac{\text{MeV}}{\text{g/cm}^2} \right\}$ | Radiation length <sup>c</sup><br>$X_0$<br>{g/cm <sup>2</sup> } {cm} | Density<br>{g/cm <sup>3</sup> }<br>{g/ℓ}<br>for gas | Liquid<br>boiling<br>point at<br>1 atm(K) | Refractive<br>index $n$<br>(( $n-1$ )×10 <sup>6</sup><br>for gas) |
|-------------------------------------------------------------------------------------------------------|-----|------------|-----------------------|--------------------------------------------------------------------|-----------------------------------------------------------------------------------|--------------------------------------------------------------------------|---------------------------------------------------------------------|-----------------------------------------------------|-------------------------------------------|-------------------------------------------------------------------|
| H <sub>2</sub> gas                                                                                    | 1   | 1.00794    | 0.99212               | 43.3                                                               | 50.8                                                                              | (4.103)                                                                  | 61.28 <sup>d</sup> (731000)                                         | (0.0838)[0.0899]                                    |                                           | [139.2]                                                           |
| H <sub>2</sub> liquid                                                                                 | 1   | 1.00794    | 0.99212               | 43.3                                                               | 50.8                                                                              | 4.034                                                                    | 61.28 <sup>d</sup>                                                  | 0.0708                                              | 20.39                                     | 1.112                                                             |
| D <sub>2</sub>                                                                                        | 1   | 2.0140     | 0.49652               | 45.7                                                               | 54.7                                                                              | (2.052)                                                                  | 122.4                                                               | 0.169[0.179]                                        | 23.65                                     | 1.128 [138]                                                       |
| He                                                                                                    | 2   | 4.002602   | 0.49968               | 49.9                                                               | 65.1                                                                              | (1.937)                                                                  | 94.32                                                               | 0.1249[0.1786]                                      | 4.224                                     | 1.024 [34.9]                                                      |
| Li                                                                                                    | 3   | 6.941      | 0.43221               | 54.6                                                               | 73.4                                                                              | 1.639                                                                    | 82.76                                                               | 0.534                                               |                                           | —                                                                 |
| Be                                                                                                    | 4   | 9.012182   | 0.44384               | 55.8                                                               | 75.2                                                                              | 1.594                                                                    | 65.19                                                               | 1.848                                               |                                           | —                                                                 |
| C                                                                                                     | 6   | 12.011     | 0.49954               | 60.2                                                               | 86.3                                                                              | 1.745                                                                    | 42.70                                                               | 2.265 <sup>e</sup>                                  |                                           | —                                                                 |
| N <sub>2</sub>                                                                                        | 7   | 14.00674   | 0.49976               | 61.4                                                               | 87.8                                                                              | (1.825)                                                                  | 37.99                                                               | 0.8073[1.250]                                       | 77.36                                     | 1.205 [298]                                                       |
| O <sub>2</sub>                                                                                        | 8   | 15.9994    | 0.50002               | 63.2                                                               | 91.0                                                                              | (1.801)                                                                  | 34.24                                                               | 1.141[1.428]                                        | 90.18                                     | 1.22 [296]                                                        |
| F <sub>2</sub>                                                                                        | 9   | 18.9984032 | 0.47372               | 65.5                                                               | 95.3                                                                              | (1.675)                                                                  | 32.93                                                               | 1.507[1.696]                                        | 85.24                                     | [195]                                                             |
| Ne                                                                                                    | 10  | 20.1797    | 0.49555               | 66.1                                                               | 96.6                                                                              | (1.724)                                                                  | 28.94                                                               | 1.204[0.9005]                                       | 27.09                                     | 1.092 [67.1]                                                      |
| Al                                                                                                    | 13  | 26.981539  | 0.48181               | 70.6                                                               | 106.4                                                                             | 1.615                                                                    | 24.01                                                               | 2.70                                                |                                           | —                                                                 |
| Si                                                                                                    | 14  | 28.0855    | 0.49848               | 70.6                                                               | 106.0                                                                             | 1.664                                                                    | 21.82                                                               | 2.33                                                |                                           | 3.95                                                              |
| Ar                                                                                                    | 18  | 39.948     | 0.45059               | 76.4                                                               | 117.2                                                                             | (1.519)                                                                  | 19.55                                                               | 1.396[1.782]                                        | 87.28                                     | 1.233 [283]                                                       |
| Ti                                                                                                    | 22  | 47.867     | 0.45948               | 79.9                                                               | 124.9                                                                             | 1.476                                                                    | 16.17                                                               | 4.54                                                |                                           | —                                                                 |
| Fe                                                                                                    | 26  | 55.845     | 0.46556               | 82.8                                                               | 131.9                                                                             | 1.451                                                                    | 13.84                                                               | 7.87                                                |                                           | —                                                                 |
| Cu                                                                                                    | 29  | 63.546     | 0.45636               | 85.6                                                               | 134.9                                                                             | 1.403                                                                    | 12.86                                                               | 8.96                                                |                                           | —                                                                 |
| Ge                                                                                                    | 32  | 72.61      | 0.44071               | 88.3                                                               | 140.5                                                                             | 1.371                                                                    | 12.25                                                               | 5.323                                               |                                           | —                                                                 |
| Sn                                                                                                    | 50  | 118.710    | 0.42120               | 100.2                                                              | 163                                                                               | 1.264                                                                    | 8.82                                                                | 7.31                                                |                                           | —                                                                 |
| Xe                                                                                                    | 54  | 131.29     | 0.41130               | 102.8                                                              | 169                                                                               | (1.255)                                                                  | 8.48                                                                | 2.953[5.858]                                        | 165.1                                     | [701]                                                             |
| W                                                                                                     | 74  | 183.84     | 0.40250               | 110.3                                                              | 185                                                                               | 1.145                                                                    | 6.76                                                                | 0.35                                                |                                           | —                                                                 |
| Pt                                                                                                    | 78  | 195.08     | 0.39984               | 113.3                                                              | 189.7                                                                             | 1.129                                                                    | 6.54                                                                | 0.305                                               |                                           | —                                                                 |
| Pb                                                                                                    | 82  | 207.2      | 0.39575               | 116.2                                                              | 194                                                                               | 1.123                                                                    | 6.37                                                                | 0.56                                                |                                           | —                                                                 |
| U                                                                                                     | 92  | 238.0289   | 0.38651               | 117.0                                                              | 199                                                                               | 1.082                                                                    | 6.00                                                                | ≈0.32                                               | ≈18.95                                    | —                                                                 |
| Air, (20°C, 1 atm.), [STP]                                                                            |     |            | 0.49919               | 62.0                                                               | 90.0                                                                              | (1.815)                                                                  | 36.66                                                               | [30420] (1.205)[1.2931]                             | 78.8                                      | (273) [293]                                                       |
| H <sub>2</sub> O                                                                                      |     |            | 0.55509               | 60.1                                                               | 83.6                                                                              | 1.991                                                                    | 36.08                                                               | 36.1                                                | 1.00                                      | 373.15                                                            |
| CO <sub>2</sub> gas                                                                                   |     |            | 0.49989               | 62.4                                                               | 89.7                                                                              | (1.819)                                                                  | 36.2                                                                | [18310]                                             | [1.977]                                   | [410]                                                             |
| CO <sub>2</sub> solid (dry ice)                                                                       |     |            | 0.49989               | 62.4                                                               | 89.7                                                                              | 1.787                                                                    | 36.2                                                                | 23.2                                                | 1.563                                     | sublimes                                                          |
| Shielding concrete <sup>f</sup>                                                                       |     |            | 0.50274               | 67.4                                                               | 99.9                                                                              | 1.711                                                                    | 26.7                                                                | 10.7                                                | 2.5                                       | —                                                                 |
| SiO <sub>2</sub> (fused quartz)                                                                       |     |            | 0.49926               | 66.5                                                               | 97.4                                                                              | 1.699                                                                    | 27.05                                                               | 12.3                                                | 2.20 <sup>g</sup>                         | 1.458                                                             |
| Dimethyl ether, (CH <sub>3</sub> ) <sub>2</sub> O                                                     |     |            | 0.54778               | 59.4                                                               | 82.9                                                                              | —                                                                        | 38.89                                                               | —                                                   | —                                         | 248.7                                                             |
| Methane, CH <sub>4</sub>                                                                              |     |            | 0.62333               | 54.8                                                               | 73.4                                                                              | (2.417)                                                                  | 46.22                                                               | [64850]                                             | 0.4224[0.717]                             | 111.7                                                             |
| Ethane, C <sub>2</sub> H <sub>6</sub>                                                                 |     |            | 0.59861               | 55.8                                                               | 75.7                                                                              | (2.304)                                                                  | 45.47                                                               | [34035]                                             | 0.509(1.356) <sup>h</sup>                 | 184.5                                                             |
| Propane, C <sub>3</sub> H <sub>8</sub>                                                                |     |            | 0.58962               | 56.2                                                               | 76.5                                                                              | (2.262)                                                                  | 45.20                                                               | —                                                   | (1.879)                                   | 231.1                                                             |
| Isobutane, (CH <sub>3</sub> ) <sub>2</sub> CHCH <sub>3</sub>                                          |     |            | 0.58496               | 56.4                                                               | 77.0                                                                              | (2.239)                                                                  | 45.07                                                               | [16930]                                             | [2.67]                                    | 261.42                                                            |
| Octane, liquid, CH <sub>3</sub> (CH <sub>2</sub> ) <sub>6</sub> CH <sub>3</sub>                       |     |            | 0.57778               | 56.7                                                               | 77.7                                                                              | 2.123                                                                    | 44.86                                                               | 63.8                                                | 0.703                                     | 398.8                                                             |
| Paraffin wax, CH <sub>3</sub> (CH <sub>2</sub> ) <sub><math>n \approx 23</math></sub> CH <sub>3</sub> |     |            | 0.57275               | 56.9                                                               | 78.2                                                                              | 2.087                                                                    | 44.71                                                               | 48.1                                                | 0.93                                      | —                                                                 |
| Nylon, type 6 <sup>i</sup>                                                                            |     |            | 0.54790               | 58.5                                                               | 81.5                                                                              | 1.974                                                                    | 41.84                                                               | 36.7                                                | 1.14                                      | —                                                                 |
| Polycarbonate (Lexan) <sup>j</sup>                                                                    |     |            | 0.52697               | 59.5                                                               | 83.9                                                                              | 1.886                                                                    | 41.46                                                               | 34.6                                                | 1.20                                      | —                                                                 |
| Polyethylene terephthlate (Mylar) <sup>k</sup>                                                        |     |            | 0.52037               | 60.2                                                               | 85.7                                                                              | 1.848                                                                    | 39.95                                                               | 28.7                                                | 1.39                                      | —                                                                 |
| Polyethylene <sup>l</sup>                                                                             |     |            | 0.57034               | 57.0                                                               | 78.4                                                                              | 2.076                                                                    | 44.64                                                               | ≈47.9                                               | 0.92–0.95                                 | —                                                                 |
| Polyimide film (Kapton) <sup>m</sup>                                                                  |     |            | 0.51264               | 60.3                                                               | 85.8                                                                              | 1.820                                                                    | 40.56                                                               | 28.6                                                | 1.42                                      | —                                                                 |
| Lucite, Plexiglas <sup>n</sup>                                                                        |     |            | 0.53937               | 59.3                                                               | 83.0                                                                              | 1.929                                                                    | 40.49                                                               | ≈34.4                                               | 1.16–1.20                                 | ≈1.49                                                             |
| Polystyrene, scintillator <sup>o</sup>                                                                |     |            | 0.53768               | 58.5                                                               | 81.9                                                                              | 1.936                                                                    | 43.72                                                               | 42.4                                                | 1.032                                     | 1.581                                                             |
| Polytetrafluoroethylene (Teflon) <sup>p</sup>                                                         |     |            | 0.47992               | 64.2                                                               | 93.0                                                                              | 1.671                                                                    | 34.84                                                               | 15.8                                                | 2.20                                      | —                                                                 |
| Polyvinyltolulene, scintillator <sup>q</sup>                                                          |     |            | 0.54155               | 58.3                                                               | 81.5                                                                              | 1.956                                                                    | 43.83                                                               | 42.5                                                | 1.032                                     | —                                                                 |
| Aluminum oxide (Al <sub>2</sub> O <sub>3</sub> )                                                      |     |            | 0.49038               | 67.0                                                               | 98.9                                                                              | 1.647                                                                    | 19.27                                                               | 4.85                                                | 3.97                                      | 1.761                                                             |
| Barium fluoride (BaF <sub>2</sub> )                                                                   |     |            | 0.42207               | 92.0                                                               | 145                                                                               | 1.303                                                                    | 9.91                                                                | 2.05                                                | 4.89                                      | 1.56                                                              |
| Bismuth germanate (BGO) <sup>r</sup>                                                                  |     |            | 0.42065               | 98.2                                                               | 157                                                                               | 1.251                                                                    | 7.97                                                                | 1.12                                                | 7.1                                       | 2.15                                                              |
| Cesium iodide (CsI)                                                                                   |     |            | 0.41569               | 102                                                                | 167                                                                               | 1.243                                                                    | 8.39                                                                | 1.85                                                | 4.53                                      | 1.80                                                              |
| Lithium fluoride (LiF)                                                                                |     |            | 0.46262               | 62.2                                                               | 88.2                                                                              | 1.614                                                                    | 39.25                                                               | 14.91                                               | 2.632                                     | 1.392                                                             |
| Sodium fluoride (NaF)                                                                                 |     |            | 0.47632               | 66.9                                                               | 98.3                                                                              | 1.69                                                                     | 29.87                                                               | 11.68                                               | 2.558                                     | 1.336                                                             |
| Sodium iodide (NaI)                                                                                   |     |            | 0.42697               | 94.6                                                               | 151                                                                               | 1.305                                                                    | 9.49                                                                | 2.59                                                | 3.67                                      | 1.775                                                             |
| Silica Aerogel <sup>s</sup>                                                                           |     |            | 0.52019               | 64                                                                 | 92                                                                                | 1.83                                                                     | 29.83                                                               | ≈150                                                | 0.1–0.3                                   | 1.0+0.25ρ                                                         |
| NEMA G10 plate <sup>t</sup>                                                                           |     |            |                       | 62.6                                                               | 90.2                                                                              | 1.87                                                                     | 33.0                                                                | 19.4                                                | 1.7                                       | —                                                                 |

| Material       | Dielectric<br>constant ( $\kappa = \epsilon/\epsilon_0$ )<br>( ) is $(\kappa-1)\times 10^6$<br>for gas | Young's<br>modulus<br>[ $10^6$ psi] | Coeff. of<br>thermal<br>expansion<br>[ $10^{-6}\text{cm/cm-}^\circ\text{C}$ ] | Specific<br>heat<br>[cal/g- $^\circ\text{C}$ ] | Electrical<br>resistivity<br>[ $\mu\Omega\text{cm}(@^\circ\text{C})$ ] | Thermal<br>conductivity<br>[cal/cm- $^\circ\text{C-sec}$ ] |
|----------------|--------------------------------------------------------------------------------------------------------|-------------------------------------|-------------------------------------------------------------------------------|------------------------------------------------|------------------------------------------------------------------------|------------------------------------------------------------|
| H <sub>2</sub> | (253.9)                                                                                                | —                                   | —                                                                             | —                                              | —                                                                      | —                                                          |
| He             | (64)                                                                                                   | —                                   | —                                                                             | —                                              | —                                                                      | —                                                          |
| Li             | —                                                                                                      | —                                   | 56                                                                            | 0.86                                           | 8.55(0°)                                                               | 0.17                                                       |
| Be             | —                                                                                                      | 37                                  | 12.4                                                                          | 0.436                                          | 5.885(0°)                                                              | 0.38                                                       |
| C              | —                                                                                                      | 0.7                                 | 0.6–4.3                                                                       | 0.165                                          | 1375(0°)                                                               | 0.057                                                      |
| N <sub>2</sub> | (548.5)                                                                                                | —                                   | —                                                                             | —                                              | —                                                                      | —                                                          |
| O <sub>2</sub> | (495)                                                                                                  | —                                   | —                                                                             | —                                              | —                                                                      | —                                                          |
| Ne             | (127)                                                                                                  | —                                   | —                                                                             | —                                              | —                                                                      | —                                                          |
| Al             | —                                                                                                      | 10                                  | 23.9                                                                          | 0.215                                          | 2.65(20°)                                                              | 0.53                                                       |
| Si             | 11.9                                                                                                   | 16                                  | 2.8–7.3                                                                       | 0.162                                          | —                                                                      | 0.20                                                       |
| Ar             | (517)                                                                                                  | —                                   | —                                                                             | —                                              | —                                                                      | —                                                          |
| Ti             | —                                                                                                      | 16.8                                | 8.5                                                                           | 0.126                                          | 50(0°)                                                                 | —                                                          |
| Fe             | —                                                                                                      | 28.5                                | 11.7                                                                          | 0.11                                           | 9.71(20°)                                                              | 0.18                                                       |
| Cu             | —                                                                                                      | 16                                  | 16.5                                                                          | 0.092                                          | 1.67(20°)                                                              | 0.94                                                       |
| Ge             | 16.0                                                                                                   | —                                   | 5.75                                                                          | 0.073                                          | —                                                                      | 0.14                                                       |
| Sn             | —                                                                                                      | 6                                   | 20                                                                            | 0.052                                          | 11.5(20°)                                                              | 0.16                                                       |
| Xe             | —                                                                                                      | —                                   | —                                                                             | —                                              | —                                                                      | —                                                          |
| W              | —                                                                                                      | 50                                  | 4.4                                                                           | 0.032                                          | 5.5(20°)                                                               | 0.48                                                       |
| Pt             | —                                                                                                      | 21                                  | 8.9                                                                           | 0.032                                          | 9.83(0°)                                                               | 0.17                                                       |
| Pb             | —                                                                                                      | 2.6                                 | 29.3                                                                          | 0.038                                          | 20.65(20°)                                                             | 0.083                                                      |
| U              | —                                                                                                      | —                                   | 36.1                                                                          | 0.028                                          | 29(20°)                                                                | 0.064                                                      |

1. R.M. Sternheimer, M.J. Berger, and S.M. Seltzer, Atomic Data and Nuclear Data Tables **30**, 261–271 (1984).
2. S.M. Seltzer and M.J. Berger, Int. J. Appl. Radiat. **33**, 1189–1218 (1982).
3. D.E. Groom, N.V. Mokhov, and S.I. Striganov, “Muon stopping-power and range tables,” Atomic Data and Nuclear Data Tables, to be published (2000).
4. S.M. Seltzer and M.J. Berger, Int. J. Appl. Radiat. **35**, 665 (1984) and <http://physics.nist.gov/PhysRefData/Star/Text/contents.html>.
  - a.  $\sigma_T$ ,  $\lambda_T$  and  $\lambda_I$  are energy dependent. Values quoted apply to high energy range, where energy dependence is weak. Mean free path between collisions ( $\lambda_T$ ) or inelastic interactions ( $\lambda_I$ ), calculated from  $\lambda^{-1} = N_A \sum w_j \sigma_j / A_j$ , where  $N$  is Avogadro's number and  $w_j$  is the weight fraction of the  $j$ th element in the element, compound, or mixture.  $\sigma_{\text{total}}$  at 80–240 GeV for neutrons ( $\approx \sigma$  for protons) from Murthy *et al.*, Nucl. Phys. **B92**, 269 (1975). This scales approximately as  $A^{0.77}$ .  $\sigma_{\text{inelastic}} = \sigma_{\text{total}} - \sigma_{\text{elastic}} - \sigma_{\text{quasielastic}}$ ; for neutrons at 60–375 GeV from Roberts *et al.*, Nucl. Phys. **B159**, 56 (1979). For protons and other particles, see Carroll *et al.*, Phys. Lett. **80B**, 319 (1979); note that  $\sigma_I(p) \approx \sigma_I(n)$ .  $\sigma_I$  scales approximately as  $A^{0.71}$ .
  - b. For minimum-ionizing muons (results are very slightly different for other particles). Minimum  $dE/dx$  from Ref. 3, using density effect correction coefficients from Ref. 1. For electrons and positrons see Ref. 4. Ionization energy loss is discussed in Sec. 23.
  - c. From Y.S. Tsai, Rev. Mod. Phys. **46**, 815 (1974);  $X_0$  data for all elements up to uranium are given. Corrections for molecular binding applied for H<sub>2</sub> and D<sub>2</sub>. For atomic H,  $X_0 = 63.05$  g/cm<sup>2</sup>.
  - d. For molecular hydrogen (deuterium). For atomic H,  $X_0 = 63.047$  g cm<sup>-2</sup>.
  - e. For pure graphite; industrial graphite density may vary 2.1–2.3 g/cm<sup>3</sup>.
  - f. Standard shielding blocks, typical composition O<sub>2</sub> 52%, Si 32.5%, Ca 6%, Na 1.5%, Fe 2%, Al 4%, plus reinforcing iron bars. The attenuation length,  $\ell = 115 \pm 5$  g/cm<sup>2</sup>, is also valid for earth (typical  $\rho = 2.15$ ), from CERN–LRL–RHEL Shielding exp., UCRL–17841 (1968).
  - g. For typical fused quartz. The specific gravity of crystalline quartz is 2.64.
  - h. Solid ethane density at  $-60^\circ\text{C}$ ; gaseous refractive index at  $0^\circ\text{C}$ , 546 mm pressure.
  - i. Nylon, Type 6,  $(\text{NH}(\text{CH}_2)_5\text{CO})_n$
  - j. Polycarbonate (Lexan),  $(\text{C}_{16}\text{H}_{14}\text{O}_3)_n$
  - k. Polyethylene terephthalate, monomer,  $\text{C}_5\text{H}_4\text{O}_2$
  - l. Polyethylene, monomer  $\text{CH}_2=\text{CH}_2$
  - m. Polyimide film (Kapton),  $(\text{C}_{22}\text{H}_{10}\text{N}_2\text{O}_5)_n$
  - n. Polymethylmethacrylate, monomer  $\text{CH}_2=\text{C}(\text{CH}_3)\text{CO}_2\text{CH}_3$
  - o. Polystyrene, monomer  $\text{C}_6\text{H}_5\text{CH}=\text{CH}_2$
  - p. Teflon, monomer  $\text{CF}_2=\text{CF}_2$
  - q. Polyvinyltoluene, monomer  $2\text{-CH}_3\text{C}_6\text{H}_4\text{CH}=\text{CH}_2$
  - r. Bismuth germanate (BGO),  $(\text{Bi}_2\text{O}_3)_2(\text{GeO}_2)_3$
  - s.  $n(\text{SiO}_2) + 2n(\text{H}_2\text{O})$  used in Čerenkov counters,  $\rho$  = density in g/cm<sup>3</sup>. From M. Cantin *et al.*, Nucl. Instrum. Methods **118**, 177 (1974).
  - t. G10-plate, typically 60% SiO<sub>2</sub> and 40% epoxy.