### 6. Atomic and nuclear properties of materials

#### Table 6.1. Revised May 2000 by D.E. Grom (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.

<table>
<thead>
<tr>
<th>Material</th>
<th>$Z$</th>
<th>$A$</th>
<th>$(Z/A)$</th>
<th>Nuclear * collision interaction length $\lambda_1$ (g/cm$^2$)</th>
<th>Nuclear ** interaction length $\lambda_2$ (g/cm$^2$)</th>
<th>$dE/dx_{\min}$ ** (MeV/g/cm$^2$)</th>
<th>Radiation length $\gamma$ * (g/cm$^2$) cm</th>
<th>Density $\xi$ (g/cm$^3$)</th>
<th>Liquid boiling point (n - 1) x $10^6$</th>
<th>Refractive index $n$</th>
<th>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.</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$ gas</td>
<td>1</td>
<td>2</td>
<td>0.99212</td>
<td>43.3 50.8</td>
<td>(4.103) 61.28 d (731000) (0.00838) (0.0899)</td>
<td>(139.2)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>H$_2$ liquid</td>
<td>1</td>
<td>2</td>
<td>0.99212</td>
<td>43.3 50.8</td>
<td>4.854 61.28 d 866 0.0708</td>
<td>20.39 1.112</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>D$_2$</td>
<td>1</td>
<td>2</td>
<td>2.0140</td>
<td>45.7 54.7</td>
<td>(2.052) 122.4 724 0.169 (0.179)</td>
<td>23.65 1.128 [138]</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>He</td>
<td>2</td>
<td>4</td>
<td>4.002602</td>
<td>49.9 65.1</td>
<td>(1.937) 94.32 756 0.1249 (0.1786)</td>
<td>4.224 1.024 [34.9]</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Li</td>
<td>3</td>
<td>6</td>
<td>6.941</td>
<td>54.0 73.4</td>
<td>1.639 82.76 155 0.534</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Be</td>
<td>4</td>
<td>9.012182</td>
<td>55.8 75.2</td>
<td>1.594 65.19 35.28 1.848</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

#### Notation

- $Z$: atomic number
- $A$: atomic mass number
- $\lambda_1$, $\lambda_2$: nuclear collision and interaction lengths
- $dE/dx_{\min}$: minimum energy loss per unit mass
- $\gamma$: radiation length
- $\xi$: density
- Liquid boiling point: $(n - 1) x 10^6$
- Refractive index

#### Footnotes

- *Atomic and nuclear properties of materials
- **Note for values:
- \(T\) (°C, 1 atm), [STP]
- H$_2$O
- CO$_2$ gas
- CO$_2$ solid (dry ice)
- Shielding concrete $f$
- SiO$_2$ (fused quartz)
- Dimethyl ether, (CH$_3$)$_2$O
- Methane, CH$_4$
- Ethane, C$_2$H$_6$
- Propane, C$_3$H$_8$
- Isobutane, (CH$_3$)$_2$CHCH$_3$
- Octane, liquid, CH$_3$(CH$_2$)$_{2}$CH$_3$
- Paraffin wax, CH$_3$(CH$_2$)$_{23}$CH$_3$
- Nylon, type 6
- Polycarbonate (Lexan) $j$
- Polylethylene terephthalate (Mylar) $k$
- Polylethylene $l$
- Polyimide film (Kapton) $m$
- Lucite, Plexiglas $n$
- Polystyrene, scintillator $s$
- Polytetrafluoroethylene (Teflon) $p$
- Polyvinyltoluene, scintillator $q$
- Aluminum oxide (Al$_2$O$_3$)
- Barium fluoride (BaF$_2$)
- Bismuth germaine (BGO) $r$
- Cesium iodide (CsI)
- Lithium fluoride (LiF)
- Sodium fluoride (NaF)
- Sodium iodide (NaI)
- Silica Aerogel $^s$
- NEMA G10 plate $^t$
<table>
<thead>
<tr>
<th>Material</th>
<th>Dielectric constant ($\varepsilon = \epsilon/\varepsilon_0$)</th>
<th>Young's modulus (10^6 psi)</th>
<th>Coeff. of thermal expansion [10^{-6}cm/cm°C]</th>
<th>Specific heat [cal/g°C]</th>
<th>Electrical resistivity [$\mu\Omega$cm(0°C)]</th>
<th>Thermal conductivity [cal/cm°C-sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>(253.9)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N₂</td>
<td>(548.5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>O₂</td>
<td>(495)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ne</td>
<td>(127)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td>—</td>
<td>10</td>
<td>23.9</td>
<td>0.215</td>
<td>2.65(20°C)</td>
<td>0.53</td>
</tr>
<tr>
<td>Si</td>
<td>11.9</td>
<td>16</td>
<td>2.8-7.3</td>
<td>0.162</td>
<td>—</td>
<td>0.20</td>
</tr>
<tr>
<td>Ar</td>
<td>(517)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td>—</td>
<td>28.5</td>
<td>11.7</td>
<td>0.11</td>
<td>9.71(20°C)</td>
<td>0.18</td>
</tr>
<tr>
<td>Cu</td>
<td>—</td>
<td>16</td>
<td>16.5</td>
<td>0.092</td>
<td>1.67(20°C)</td>
<td>0.94</td>
</tr>
<tr>
<td>Ge</td>
<td>16.0</td>
<td>—</td>
<td>5.75</td>
<td>0.073</td>
<td>—</td>
<td>0.14</td>
</tr>
<tr>
<td>Sn</td>
<td>—</td>
<td>6</td>
<td>20</td>
<td>0.052</td>
<td>11.5(20°C)</td>
<td>0.16</td>
</tr>
<tr>
<td>Xe</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>—</td>
<td>50</td>
<td>4.4</td>
<td>0.032</td>
<td>5.5(20°C)</td>
<td>0.48</td>
</tr>
<tr>
<td>Pt</td>
<td>—</td>
<td>21</td>
<td>8.9</td>
<td>0.032</td>
<td>9.83(0°C)</td>
<td>0.17</td>
</tr>
<tr>
<td>Pb</td>
<td>—</td>
<td>2.6</td>
<td>29.3</td>
<td>0.038</td>
<td>20.65(20°C)</td>
<td>0.083</td>
</tr>
<tr>
<td>U</td>
<td>—</td>
<td>—</td>
<td>36.1</td>
<td>0.028</td>
<td>29(20°C)</td>
<td>0.064</td>
</tr>
</tbody>
</table>


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 $\lambda^{-1} = N_A^{-1} \sum \sigma_j A_j$, where $N_A$ is Avogadro’s number and $\sigma_j$ is the weight fraction of the $j$th element in the element, compound, or mixture, $\sigma_{total}$ at 80–240 GeV for neutrons ($\approx \sigma$ for protons) from Murthy et al., Nucl. Phys. B102, 260 (1975). This scales approximately as $A^{0.77}$. $\sigma_{inelastic} = \sigma_{total} – \sigma_{elastic} – \sigma_{quasielastic}$; 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 $\sigma(\rho) \approx \sigma_0(\rho)$ 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. For 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 H₂ and D₂. For atomic H, $X_0 = 63.05$ g/cm².
d. For molecular hydrogen (deuterium). For atomic H, $X_0 = 63.047$ g cm⁻².
e. For pure graphite; industrial graphite density may vary 2.1–2.3 g/cm³.
f. Standard shielding blocks, typical composition O₂ 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/cm², 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°C; gaseous refractive index at 0°C, 546 mm pressure.
i. Nylon, Type 6, (NH(CH₂)₆CO)n
j. Polycarbonate (Lexan), (C₁₀H₁₄O₃)n
k. Polyethylene terephthalate, monomer, C₆H₄O₂
l. Polyethylene, monomer CH₂ =CH₂
m. Polymide film (Kapton), (C₂₂H₁₀N₂O₇)n
n. Polymethylmethacrylate, monomer CH₂ =C(CH₃)CO₂CH₃
o. Polystyrene, monomer C₆H₅CH=CH₂
p. Teflon, monomer CF₂ =CF₂
q. Polyvinyltoluene, monomer 2 CH₂C₆H₄CH=CH₂
r. Bismuth germanate (BGO), (Bi₂O₃)₂(GeO₂)₃
s. n(SiO₂) + 2n(H₂O) used in Cerenkov counters, $\rho$ = density in g/cm³. From M. Cantin et al., Nucl. Instrum. Methods 118, 177 (1974).
t. G10-plate, typically 60% SiO₂ and 40% epoxy.