10. ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS

Table 10.1. Table revised June 1994. Gases are evaluated at 20°C, 1 atm, (in parentheses) or at STP [square brackets].

Material	Z	A	Nuclear[a] total cross section σ_T [barn]	Nuclear[b] inelastic cross section σ_I [barn]	Nuclear[c] collision length λ_T [g/cm^2]	Nuclear[c] interaction length λ_I [g/cm^2]	$dE/dx\|_{\rm min}$[d] $\left[\frac{\rm MeV}{\rm g/cm^2}\right]$ () is for gas	Radiation length[e] X_0 [g/cm^2]	Radiation length[e] X_0 [cm] () is for gas	Density[f] [g/cm^3] () is for gas [g/ℓ]	Refractive index n[f] () is $(n-1)\times10^6$ for gas
H_2 gas	1	1.01	0.0387	0.033	43.3	50.8	(4.103)	61.28	865	(0.0838)[0.090]	[140]
H_2 (B.C., 26K)	1	1.01	0.0387	0.033	43.3	50.8	4.045	61.28	865	0.0708	1.112
D_2	1	2.01	0.073	0.061	45.7	54.7	(2.052)	122.6	757	0.162[0.177]	1.128
He	2	4.00	0.133	0.102	49.9	65.1	(1.937)	94.32	755	0.125[0.178]	1.024[35]
Li	3	6.94	0.211	0.157	54.6	73.4	1.639	82.76	155	0.534	—
Be	4	9.01	0.268	0.199	55.8	75.2	1.594	65.19	35.3	1.848	—
C	6	12.01	0.331	0.231	60.2	86.3	1.745	42.70	18.8	2.265[g]	—
N_2	7	14.01	0.379	0.265	61.4	87.8	(1.825)	37.99	47.0	0.808[1.25]	1.205[300]
O_2	8	16.00	0.420	0.292	63.2	91.0	(1.801)	34.24	30.0	1.14[1.43]	1.22[266]
Ne	10	20.18	0.507	0.347	66.1	96.6	(1.724)	28.94	24.0	1.207[0.900]	1.092[67]
Al	13	26.98	0.634	0.421	70.6	106.4	1.615	24.01	8.9	2.70	—
Si	14	28.09	0.660	0.440	70.6	106.0	1.664	21.82	9.36	2.33	—
Ar	18	39.95	0.868	0.566	76.4	117.2	(1.519)	19.55	14.0	1.40[1.782]	1.233[283]
Ti	22	47.88	0.995	0.637	79.9	124.9	1.476	16.17	3.56	4.54	—
Fe	26	55.85	1.120	0.703	82.8	131.9	1.451	13.84	1.76	7.87	—
Cu	29	63.55	1.232	0.782	85.6	134.9	1.403	12.86	1.43	8.96	—
Ge	32	72.59	1.365	0.858	88.3	140.5	1.371	12.25	2.30	5.323	—
Sn	50	118.69	1.967	1.21	100.2	163	1.264	8.82	1.21	7.31	—
Xe	54	131.29	2.120	1.29	102.8	169	(1.255)	8.48	2.77	3.057[5.858]	[705]
W	74	183.85	2.767	1.65	110.3	185	1.145	6.76	0.35	19.3	—
Pt	78	195.08	2.861	1.708	113.3	189.7	1.129	6.54	0.305	21.45	—
Pb	82	207.19	2.960	1.77	116.2	194	1.123	6.37	0.56	11.35	—
U	92	238.03	3.378	1.98	117.0	199	1.082	6.00	≈0.32	≈18.95	—
Air, (20°C, 1 atm.), [STP]					62.0	90.0	(1.815)	36.66	[30420]	(1.205)[1.29]	(273)[293]
H_2O					60.1	84.9	1.991	36.08	36.1	1.00	1.33
CO_2					62.4	90.5	(1.819)	36.2	[18310]	[1.977]	[410]
Shielding concrete[h]					67.4	99.9	1.711	26.7	10.7	2.5	—
Borosilicate glass (Pyrex)[i]					66.2	97.6	1.695	28.3	12.7	2.23	1.474
SiO_2 (fused quartz)					67.0	99.2	1.70[j]	27.05	12.3	2.20[k]	1.458
Methane (CH_4)					54.7	74.0	(2.417)	46.5	[64850]	0.423[0.717]	[444]
Ethane (C_2H_6)					55.73	75.71	(2.304)	45.66	[34035]	0.509(1.356)[ℓ]	(1.038)[ℓ]
Propane (C_3H_8)					—	—	(2.262)	—	—	(1.879)	
Isobutane ($(CH_3)_2CHCH_3$)					56.3	77.4	(2.239)	45.2	[16930]	[2.67]	[1900]
Octane, liquid ($CH_3(CH_2)_6CH_3$)					—	—	2.123	—	—	0.703	
Paraffin wax ($CH_3(CH_2)_nCH_3$, $\langle n\rangle \approx 25$)					—	—	2.087	—	—	0.93	
Nylon, type 6					—	—	1.974	—	—	1.14	
Polycarbonate (Lexan)					—	—	1.886	—	—	1.200	
Polyethylene terephthlate (Mylar) ($C_5H_4O_2$)					60.2	85.7	1.848	39.95	28.7	1.39	—
Polyethylene (monomer $CH_2=CH_2$)					56.9	78.8	2.076	44.8	≈47.9	0.92–0.95	—
Polyimide film (Kapton)					—	—	1.820	—	—	1.420	
Polymethylmethacralate (Lucite, Plexiglas) (monomer ($CH_2=C(CH_3)CO_2CH_3$))					59.2	83.6	1.929	40.55	≈34.4	1.16–1.20	≈1.49
Polystyrene, scintillator (monomer $C_6H_5CH=CH_2$)					58.4	82.0	1.936	43.8	42.4	1.032	1.581
Polytetrafluoroethylene (Teflon) (monomer $CF_2=CF_2$)					—	—	1.671	—	—	2.20	
Polyvinyltolulene, scintillator (monomer 2-$CH_3C_6H_4CH=CH_2$)					—	—	1.956	—	—	1.032	
Barium fluoride (BaF_2)					92.1	146	1.303	9.91	2.05	4.89	1.56
Bismuth germanate (BGO) ($Bi_4Ge_3O_{12}$)					97.4	156	1.251	7.98	1.12	7.1	2.15
Cesium iodide (CsI)					—	—	1.243	—	—	4.51	
Lithium fluoride (LiF)					62.00	88.24	1.614	39.25	14.91	2.632	1.392
Sodium fluoride (NaF)					66.78	97.57	1.69	29.87	11.68	2.558	1.336
Sodium iodide (NaI)					94.8	152	1.305	9.49	2.59	3.67	1.775
Silica Aerogel[m]					65.5	95.7	1.83	29.85	≈150	0.1–0.3	1.0+0.25ρ
NEMA G10 plate[n]					62.6	90.2	1.87	33.0	19.4	1.7	—

CITATION: L. Montanet *et al.*, Physical Review **D50**, 1173 (1994) and 1995 off-year partial update for the 1996 edition available on the PDG WWW pages (URL: `http://pdg.lbl.gov/`)

Material	Dielectric constant ($\kappa = \epsilon/\epsilon_0$) () is ($\kappa$–1)$\times 10^6$ for gas	Young's modulus [10^6 psi]	Coeff. of thermal expansion [10^{-6}cm/cm-°C]	Specific heat [cal/g-°C]	Electrical resistivity [$\mu\Omega$cm(@°C)]	Thermal conductivity [cal/cm-°C-sec]
H_2	(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_2	(548.5)	—	—	—	—	—
O_2	(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

σ_T, σ_I, λ_T, and λ_I are energy dependent. Values quoted apply to high energy range given in footnote *a* or *b*, where energy dependence is weak.

a. σ_{total} at 80–240 GeV for neutrons ($\approx \sigma$ for protons) from Murthy *et al.*, Nucl. Phys. **B92**, 269 (1975). This scales approximately as $A^{0.77}$.

b. $\sigma_{\text{inelastic}} = \sigma_{\text{total}} - \sigma_{\text{elastic}} - \sigma_{\text{quasielastic}}$; 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 $\sigma_I(p) \approx \sigma_I(n)$. σ_I scales approximately as $A^{0.71}$.

c. Mean free path between collisions (λ_T) or inelastic interactions (λ_I), calculated from $\lambda = A/(N \times \sigma)$, where N is Avogadro's number.

d. For minimum-ionizing heavy particles (muons, pions, protons, *etc.*). Minimum dE/dx calculated in 1994, using density effect correction coefficients from R. M. Sternheimer, M. J. Berger, and S. M. Seltzer, Atomic Data and Nuclear Data Tables **30**, 261–271 (1984). For electrons and positrons see S.M. Seltzer and M.J. Berger, Int. J. Appl. Radiat. **35**, 665–676 (1984). Ionization energy loss is discussed in Sec. 14.

e. From Y.S. Tsai, Rev. Mod. Phys. **46**, 815 (1974); X_0 data for all elements up to uranium may be found here. Corrections for molecular binding applied for H_2 and D_2. Parentheses refer to gaseous form at STP (0°C, 1 atm.).

f. Values for solids, or the liquid phase at boiling point, except as noted. Refractive index given for sodium D line.

g. For pure graphite; industrial graphite density may vary 2.1–2.3 g/cm^3.

h. Standard shielding blocks, typical composition O_2 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^2, is also valid for earth (typical $\rho = 2.15$), from CERN–LRL–RHEL Shielding exp., UCRL–17841 (1968).

i. Main components: 80% SiO_2 + 12% B_2O_3 + 5% Na_2O.

j. Calculated using Sternheimer's density effect parameterization for $\rho = 2.32$ g cm^{-3}. Actual value may be slightly lower.

k. For typical fused quartz. The specific gravity of crystalline quartz is 2.64.

ℓ. Solid ethane density at −60°C; gaseous refractive index at 0°C, 546 mm pressure.

m. $n(SiO_2) + 2n(H_2O)$ used in Čerenkov counters, ρ = density in g/cm^3. From M. Cantin *et al.*, Nucl. Instr. and Meth. **118**, 177 (1974).

n. G10-plate, typical 60% SiO_2 and 40% epoxy.