CHAPTER 11

Tables

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Understanding the properties of matter

by Michael de Podesta.

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- G. W. C. Kaye and T. H. Laby, *Tables of Physical and Chemical Constants*: 14th, 15th and 16th Editions, published by Longman (Harlow) in the UK and Wiley (New York) in the USA. This is referred to as *Kaye & Laby* in the text.
- Weast *CRC Handbook of Chemistry and Physics:* 65th *Edition* [also known as the 'Rubber Bible'], published by Chemical Rubber Publishing Company (Chicago, Ill)
- John Emsley, *The Elements*, published by Clarendon Press / Oxford University Press (Oxford).

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Table 11.1 Thermal data for the elements: the melting and boiling temperatures in kelvin, and the enthalpies of fusion (melting) and vaporisation. The data refer to standard atmospheric pressure unless otherwise stated. Two elements – arsenic and carbon – which sublime when heated at atmospheric pressure. These are discussed in §11.7 on the solid ⇒ gas transition, and their the enthalpies of fusion and vaporisation are estimated from studies at high pressure.

Z	Name	Atomic weight	Density (kg m^{-3})	Melting point (K)	Boiling point (K)	Enthalpy of fusion (kJ mol^{-1})	Enthalpy of vaporisation (kJ mol^{-1})
1	Hydrogen	1.008	89	14.01	20.28	0.12	0.46
2	Helium	4.003	120	0.95	4.216	0.021	0.082
3	Lithium	6.941	533	453.7	1620	4.6	134.7
4	Beryllium	9.012	1846	1551	3243	9.8	308.8
5	Boron	10.81	2466	2365	3931	22.2	538.9
6	Carbon	12.01	2266	Sublimes at ≈ 3700		105	710.9
7	Nitrogen	14.01	1035	63.15	77.4	0.72	5.577
8	Oxygen	16	1460	54.36	90.188	0.444	6.82
9	Fluorine	19	1140	53.48	85.01	5.1	6.548
10	Neon	20.18	1442	24.56	27.1	0.324	1.1736
11	Sodium	22.99	966	371	1156.1	2.64	89.04
12	Magnesium	24.31	1738	922	1363	9.04	128.7
13	Aluminium	26.98	2698	933.5	2740	10.67	293.72
14	Silicon	28.09	2329	1683	2628	39.6	383.3
15	Phosphorous	30.97	1820	317.3	553	2.51	51.9
16	Sulphur	32.06	2086	386	717.82	1.23	9.62
17	Chlorine	35.45	2030	172	239.18	6.41	20.403
18	Argon	39.95	1656	83.8	87.29	1.21	6.53
19	Potassium	39.1	862	336.8	1047	2.4	77.53
20	Calcium	40.08	1530	1112	1757	9.33	149.95
21	Scandium	44.96	2992	1814	3104	15.9	304.8
22	Titanium	47.9	4508	1933	3560	20.9	428.9
23	Vanadium	50.94	6090	2160	3650	17.6	458.6
24	Chromium	52	7194	2130	2945	15.3	348.78
25	Manganese	54.94	7473	1517	2235	14.4	219.7
26	Iron	55.85	7873	1808	3023	14.9	351
27	Cobalt	58.93	8800	1768	3143	15.2	382.4
28	Nickel	58.7	8907	1726	3005	17.6	371.8
29	Copper	63.55	8933	1356.6	2840	13	304.6
30	Zinc	65.38	7135	692.73	1180	6.67	115.3
31	Gallium	69.72	5905	302.93	3676	5.59	256.1
32	Germanium	72.59	5323	1210.6	3103	34.7	334.3
33	Arsenic	74.92	5776	Sublimes at 886		27.7	31.9
34	Selenium	78.96	4808	490	958.1	5.1	26.32
35	Bromine	79.9	3120	265.9	331.93	10.8	30
36	Krypton	83.8	3000	116.6	120.85	1.64	9.05
37	Rubidium	85.47	1533	312.2	961	2.2	69.2
38	Strontium	87.62	2583	1042	1657	6.16	138.91
39	Yttrium	88.91	4475	1795	3611	17.2	393.3
40	Zirconium	91.22	6507	2125	4650	23	581.6
41	Niobium	92.91	8578	2741	5015	27.2	696.6
42	Molybdenum	95.94	10222	2890	4885	27.6	594.1

Z	Name	Atomic weight	Density (kg m^{-3})	Melting point (K)	Boiling point (K)	Enthalpy of fusion (kJ mol^{-1})	Enthalpy of vaporisation (kJ mol^{-1})
43	Technetium	97	11496	2445	5150	23.81	585.22
44	Ruthenium	101.1	12360	2583	4173	23.7	567.8
45	Rhodium	102.9	12420	2239	4000	21.55	495.4
46	Palladium	106.4	11995	1825	3413	17.2	393.3
47	Silver	107.9	10500	1235.1	2485	11.3	255.1
48	Cadmium	112.4	8647	594.1	1038	6.11	99.87
49	Indium	114.8	7290	429.32	2353	3.27	226.4
50	Tin	118.7	7285	505.12	2543	7.2	290.4
51	Antimony	121.7	6692	903.9	1908	20.9	67.91
52	Tellurium	127.6	6247	722.7	1263	13.5	50.63
53	Iodine	126.9	4953	386.7	457.5	15.27	41.67
54	Xenon	131.3	3560	161.3	166.1	3.1	12.65
55	Caesium	132.9	1900	301.6	951.6	2.09	65.9
56	Barium	137.3	3594	1002	1910	7.66	150.9
57	Lanthanum	138.9	6174	1194	3730	10.04	399.6
58	Cerium	140.1	6711	1072	3699	8.87	313.8
59	Praseodymium	140.9	6779	1204	3785	11.3	332.6
60	Neodymium	144.2	7000	1294	3341	7.113	283.7
61	Promethium	145	7220	1441	3000	12.6	—
62	Samarium	150.4	7536	1350	2064	10.9	191.6
63	Europium	152	5248	1095	1870	10.5	175.7
64	Gadolinium	157.2	7870	1586	3539	15.5	311.7
65	Terbium	158.9	8267	1629	3396	16.3	391
66	Dysprosium	162.5	8531	1685	2835	17.2	293
67	Holmium	164.9	8797	1747	2968	17.2	251
68	Erbium	167.3	9044	1802	3136	17.2	292.9
69	Thulium	168.9	9325	1818	2220	18.4	247
70	Ytterbium	173	6966	1097	1466	9.2	159
71	Lutetium	175	9842	1936	3668	19.2	428
72	Hafnium	178.5	13276	2503	5470	25.5	661.1
73	Tantalum	180.9	16670	3269	5698	31.4	753.1
74	Tungsten	183.9	19254	3680	5930	35.2	799.1
75	Rhenium	186.2	21023	3453	5900	33.1	707.1
76	Osmium	190.2	22580	3327	5300	29.3	627.6
77	Iridium	192.2	22550	2683	4403	26.4	563.6
78	Platinum	195.1	21450	2045	4100	19.7	510.5
79	Gold	197	19281	1337.6	3080	12.7	324.4
80	Mercury	200.6	13546	234.28	629.73	2.331	59.15
81	Thallium	204.4	11871	576.6	1730	4.31	162.1
82	Lead	207.2	11343	600.65	2013	5.121	179.4
83	Bismuth	209	9803	544.5	1833	10.48	179.1
84	Polonium	209	9400	527	1235	10	100.8
85	Astatine	210	—	575	610	23.8	—
86	Radon	222	4400	202	211.4	2.7	19.1
87	Francium	223	—	300	950	—	—
88	Radium	226	5000	973	1413	7.15	136.8
89	Actinium	227	10060	1320	3470	14.2	293

Z	Name	Atomic weight	Density (kg m^{-3})	Melting point (K)	Boiling point (K)	Enthalpy of fusion (kJ mol^{-1})	Enthalpy of vaporisation (kJ mol^{-1})
90	Thorium	232	11725	2023	5060	19.2	543.9
91	Protactinium	231	15370	2113	4300	16.7	481
92	Uranium	238	19050	1405	4018	15.5	422.6
93	Neptunium	237	20250	913	4175	9.46	336.6
94	Plutonium	244	19840	914	3505	2.8	343.5
95	Americium	243	13670	1267	2880	14.4	238.5

Table 11.2 Thermal data for the various substances: the melting and boiling temperatures in kelvin, and the enthalpies of fusion (melting) and vaporisation. The data refer to standard atmospheric pressure unless otherwise stated and (s) indicates that the substance sublimes rather than boils and the melting temperature is obtained under pressure. (*) indicates a large discrepancy of ± 20 K amongst data from different sources.

Substance		MW	Density (kg m^{-3})	Melting point (K)	Boiling point (K)	Enthalpy of fusion (kJ mol^{-1})	Enthalpy of vaporisation (kJ mol^{-1})
Acetic acid	CH_3COOH	60	1049	289.75	391.1	11.535	—
Acetone	CH_3COCH_3	58	787	177.8	329.3	5.691	—
Aniline	C_6H_7N	93	1026	266.85	457.6	10.555	—
Benzene	C_6H_6	78	877	278.65	353.2	9.951	—
Chloroform	$CHCl_3$	119	—	209.55	334.4	8.800	—
Cyclohexane	C_6H_{10}	82	779	279.65	353.8	2.630	—
Ethyl acetate	$C_4H_8O_2$	88	—	189.55	350.2	10.481	—
Methanol	CH_3OH	32	791	179.25	337.7	3.177	—
Ethanol	C_2H_5OH	46	789	155.85	351.5	5.021	—
Propan-1-ol	C_3H_7OH	60	804	146.65	370.3	5.195	—
Propan-2-ol	C_3H_7OH	60	786	—	—	—	—
Butan-1-ol	C_4H_9OH	74	810	183.65	390.35	9.282	—
Butan-2-ol	C_4H_9OH	74	808	298.55	372.65	6.786	—
Toluene	C_7H_8	92	867	178.15	383.8	6.851	—
Lithium fluoride	LiF	25.9	2635	1118	1949	—	—
Lithium chloride	LiCl	42.39	2068	878	1620(*)	—	—
Lithium bromide	LiBr	86.9	3464	823	1538	—	—
Sodium chloride	NaF	42.0	2558	1266	1968	—	—
Sodium fluoride	NaCl	58.4	2165	1074	1686	—	—
Sodium bromide	NaBr	102.9	3203	1020	1663	—	—
Potassium fluoride	KF	58.1	2480	1131	1778	—	—
Potassium chloride	KCl	74.6	1984	1043	1273(s)	—	—
Potassium bromide	KBr	119.0	2750	1007	1708	—	—
Carbon dioxide	CO_2	44	—	216.55	194.7	—	—
Carbontetrachloride	CCl_4	154	1632	—	—	—	—
Carbon disulphide	CS_2	76	1293	162.35	319.6	4.395	—
Carbon monoxide	CO	28	—	74.15	81.7	—	—
Water	H_2O	18	998	273.15	373.15	5.994	40.608

Table 11.3 Comparison of $N_A \Delta E_e$ with the experimental value of the latent heat of vaporisation L. The final column shows the ratio of these two quantities $N_A \Delta E_e / L$. The values of ΔE_e are drawn from Table 9.12.

Substance	ΔE_e(J) $\times 10^{-21}$	$N_A \Delta E_e$ (kJ mol^{-1})	L (kJ mol^{-1})	$N_A \Delta E_e / L$
Copper	486	292.7	300.5	0.97
Silver	403	242.7	255.06	0.95
Gold	516	310.7	324.43	0.96
Aluminium	447	269.2	290.8	0.92
Tin	436	262.6	290.37	0.90
Helium	0.13	0.078	0.08	0.98
Neon	3.23	1.95	1.77	1.10
Argon	10.8	6.50	6.52	0.99
Krypton	17.2	10.36	9.03	1.15
Xenon	24.4	14.69	12.64	1.16

Table 11.4 The critical parameters of various substances discussed in Chapter 6 and Chapter 8. P_C,V_C and T_C are the critical pressure, molar volume and temperature. Z_C is the *compression factor* which is discussed in §11.5.3. The next column gives the density at the critical point, calculated from the molecular mass and V_C. This may be compared with the density of the substance in the liquid state well away from T_C. For the inorganic substances where the liquid density data is not available, the solid density has been used instead The final column gives the ratio of the density at the critical point to that at a temperature well below the critical point.

Substance	P_C (MPa)	V_C ($\times 10^{-6}$ m^3 mol^{-1})	T_C (K)	$Z_C = P_C V_C/RT_C$	Critical Density (kg m^{-3})	Liquid Density (kgm^{-3})	Density Ratio
Methanol, CH_3OH	8.09	118	512.6	0.224	271	791	0.343
Ethanol, C_2H_5OH	6.14	167	513.9	0.240	275	789	0.349
Propan-1-ol , C_3H_7OH	5.17	219	536.8	0.254	274	804	0.340
Acetic acid, $C_2H_4O_2$	5.79	171	594.5	0.200	351	1049	0.334
Acetone, C_3H_6O	4.7	213	508.1	0.237	272	787	0.346
Aniline, C_6H_7N	5.3	274	698.9	0.250	339	1026	0.330
Benzene, C_6H_6	4.9	254	562.2	0.266	307	879	0.349
Bromoethane, C_2H_5Br	6.23	215	503.8	0.320	507	1456	0.348
Chloroform, $CHCl_3$	5.5	240	536.4	0.296	500	1498	0.333
Cyclohexane, C_6H_{10}	4.02	308	553.4	0.269	266	941.6	0.282
Ethyl acetate, $C_4H_8O_2$	3.83	286	523.2	0.252	287	900.6	0.319
Toluene, C_7H_8	4.11	320	591.8	0.267	288	868.8	0.331
Carbon monoxide, CO	3.50	93.1	133	0.295	300.75	—	—
Carbon dioxide, CO_2	7.38	94.0	304.2	0.274	468.09	—	—
Carbon disulphide, CS_2	7.9	173	552	0.298	439.31	1263	0.348
Carbon tetrachloride, CCl_4	4.56	276	556.4	0.272	550.72	1604	0.343
Hydrogen, H_2	1.294	65.5	32.99	0.309	30.534	89	0.343
Nitrogen, N_2	3.39	90.1	126.2	0.291	310.77	1035	0.300
Oxygen, O_2	5.08	78	154.8	0.308	410.26	1460	0.281
Chlorine, Cl_2	7.71	124	417	0.276	572.58	2030	0.282
Bromine, Br_2	10.3	135	584	0.287	1185.2	3120	0.380
Helium, He	0.229	58	5.2	0.307	68.966	120	0.575
Neon, Ne	2.73	41.7	44.4	0.309	479.62	1442	0.333
Argon, Ar	4.86	75.2	150.7	0.292	531.91	1656	0.321
Krypton, Kr	5.50	92.3	209.4	0.292	910.08	3000	0.303
Xenon, Xe	5.88	119	289.7	0.291	1100.8	3560	0.309
Radon, Rn	6.3	—	377		—	4400	
Water, H_2O	22.12	59.1	647.3	0.243	304.57	1000	0.305
Heavy water, D_2O	21.88	54.9	644.2	0.224	364.30	1100	0.331

Table 11.5 The cohesive energies U_o of the elements in units of kJ mol^{-1}. U_o is the energy required to separate the atoms of a solid at $T = 0$ K into isolated neutral atoms.

Z	Element	U_o (kJ mol^{-1})	Z	Element	U_o (kJ mol^{-1})	Z	Element	U_o (kJ mol^{-1})
1	Hydrogen	—	32	Germanium	372	63	Europium	179
2	Helium	—	33	Arsenic	285.3	64	Gadolinium	400
3	Lithium	158	34	Selenium	237	65	Terbium	391
4	Beryllium	320	35	Bromine	118	66	Dysprosium	294
5	Boron	561	36	Krypton	11.2	67	Holmium	302
6	Carbon	711	37	Rubidium	82.2	68	Erbium	317
7	Nitrogen	474	38	Strontium	166	69	Thulium	233
8	Oxygen	251	39	Yttrium	422	70	Ytterbium	154
9	Fluorine	81	40	Zirconium	603	71	Lutetium	428
10	Neon	1.92	41	Niobium	730	72	Hafnium	621
11	Sodium	107	42	Molybdenum	658	73	Tantalum	782
12	Magnesium	145	43	Technetium	661	74	Tungsten	859
13	Aluminium	327	44	Ruthenium	650	75	Rhenium	775
14	Silicon	446	45	Rhodium	554	76	Osmium	788
15	Phosphorous	331	46	Palladium	376	77	Iridium	670
16	Sulphur	275	47	Silver	284	78	Platinum	564
17	Chlorine	135	48	Cadmium	112	79	Gold	368
18	Argon	7.74	49	Indium	243	80	Mercury	65
19	Potassium	90.1	50	Tin	303	81	Thallium	182
20	Calcium	178	51	Antimony	265	82	Lead	196
21	Scandium	376	52	Tellurium	211	83	Bismuth	210
22	Titanium	468	53	Iodine	107	84	Polonium	144
23	Vanadium	512	54	Xenon	15.9	85	Astatine	—
24	Chromium	395	55	Caesium	77.6	86	Radon	18.5
25	Manganese	282	56	Barium	183	87	Francium	—
26	Iron	413	57	Lanthanum	431	88	Radium	160
27	Cobalt	424	58	Cerium	417	89	Actinium	410
28	Nickel	428	59	Praseodymium	357	90	Thorium	598
29	Copper	336	60	Neodymium	328	91	Protactinium	—
30	Zinc	130	61	Promethium	—	92	Uranium	536
31	Gallium	271	62	Samarium	206			

Table 11.6 The equilibrium vapour pressure (Pa) of water substance above the solid or liquid surface as a function of temperature. The shaded data on the liquid corresponds to data taken on supercooled water.

T (°C)	Solid	Liquid	T (°C)	Solid	Liquid
–90	0.009	—	–15	165.5	191.50
–80	0.053	—	–14	181.5	208.03
–70	0.258	—	–13	198.7	225.50
–60	1.077	—	–12	217.6	244.57
–50	3.940	—	–11	238.0	264.98
–40	12.88	—	–10	260.0	286.58
–30	38.12	—	–9	284.2	310.18
–29	42.27	—	–8	310.2	335.26
–28	46.80	—	–7	338.3	362.06
–27	51.87	—	–6	368.7	390.86
–26	57.34	—	–5	401.8	421.80
–25	63.47	—	–4	437.4	454.74
–24	70.14	—	–3	475.8	489.81
–23	77.34	—	–2	517.4	527.55
–22	85.34	—	–1	562.4	567.83
–21	94.01	—	0	610.6	610.6
–20	103.4	—	1	—	656.9
–19	113.8	—	2	—	706.0
–18	125.2	—	3	—	758.1
–17	137.5	—	4	—	813.6
–16	151.0	—	5	—	872.5
			6	—	935.2
			7	—	1002
			8	—	1073
			9	—	1148
			10	—	1228.1
			11	—	1312.7
			12	—	1402.6
			13	—	1497.7
			14	—	1598.5
			15	—	1705.3

Table 11.7 The melting, boiling and triple-point temperatures of various substances. The T_{tr} values are often known extremely accurately. The T_M and T_B values are typically known to within ≈ 10 mK.

Substance	T_M **(K)**	T_{Tr} **(K)**	T_B **(K)**
Oxygen	54.35	54.3584	90.188
Nitrogen	63.15	63.150	77.352
Argon	83.75	83.8058	87.29
Water	273.15	273.16	373.15