

6.13: Thermodynamic

Thermodynamic

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Thermodynamic Values for Select Compounds

at 298.15 K.

Species	$\Delta_f H^\circ$ (kJ/mol)	S° (J K ⁻¹ mol ⁻¹)	$\Delta_f G^\circ$ (kJ/mol)
Aluminum			
Al(s)	0	28.275	0
Al ³⁺ (aq)	-531	-321.7	-485
AlCl ₃ (s)	-704.2	110.67	-628.8
Al ₂ O ₃ (s, corundum)	-1675.7	50.92	-1582.3
Argon			
Ar(g)	0	154.843	0
Ar(aq)	-12.1	59.4	16.4
Barium			
BaCl ₂ (s)	-858.6	123.68	-810.4
BaO(s)	-553.5	70.42	-525.1
BaSO ₄ (s)	-1473.2	132.2	-1362.2
BaCO ₃ (s)	-1216.3	112.1	85.35
Beryllium			
Be(s)	0	9.5	0
Be(OH) ₂ (s)	-902.5	51.9	-815
Bromine			
Br(g)	111.884	175.022	82.396
Br ₂ (l)	0	152.231	0
Br ₂ (g)	30.907	245.463	3.110
Br ₂ (aq)	-2.59	130.5	3.93
Br ⁻ (aq)	-121.55	82.4	-103.96
BrCl(g)	14.64	240.10	-0.98
BrF ₃ (g)	-255.6	292.53	-229.43
HBr(g)	-36.40	198.695	-53.45
Calcium			
Ca(s)	0	41.42	0
Ca(g)	178.2	158.884	144.3
Ca ²⁺ (g)	1925.9	—	—
Ca ²⁺ (aq)	-542.83	-53.1	-553.58
CaC ₂ (s)	-59.8	69.96	-64.9
CaCO ₃ (s, calcite)	-1206.92	92.9	-1128.79
CaCl ₂ (s)	-795.8	104.6	-748.1
CaF ₂ (s)	-1219.6	68.87	-1167.3
CaH ₂ (s)	-186.2	42	-147.2
CaO(s)	-635.09	39.75	-604.03

Species	$\Delta_f H^\circ$ (kJ/mol)	S° (J K ⁻¹ mol ⁻¹)	$\Delta_f G^\circ$ (kJ/mol)
CaS(s)	-482.4	56.5	-477.4
Ca(OH) ₂ (s)	-986.09	83.39	-898.49
Ca(OH) ₂ (aq)	-1002.82	-74.5	-868.07
CaSO ₄ (s)	-1434.11	106.7	-1321.79
Carbon			
C(s, graphite)	0	5.74	0
C(s, diamond)	1.895	2.377	2.9
C(g)	716.682	158.096	671.257
CCl ₄ (l)	-135.44	216.4	-65.21
CCl ₄ (g)	-102.9	309.85	-60.59
CHCl ₃ (l)	-134.47	201.7	-73.66
CHCl ₃ (g)	-103.14	295.71	-70.34
CH ₄ (g, methane)	-74.81	186.264	-50.72
C ₂ H ₂ (g, ethyne)	226.73	200.94	209.2
C ₂ H ₄ (g, ethene)	52.26	219.56	68.15
C ₂ H ₆ (g, ethane)	-84.68	229.6	-32.82
C ₃ H ₈ (g, propane)	-103.8	269.9	-23.49
C ₄ H ₁₀ (g, butane)	-126.148	310.227	-16.985
C ₆ H ₆ (l, benzene)	49.03	172.8	124.5
C ₆ H ₁₄ (l, hexane)	-198.782	296.018	-4.035
C ₈ H ₁₈ (g, octane)	-208.447	466.835	16.718
C ₈ H ₁₈ (l, octane)	-249.952	361.205	6.707
CH ₃ OH(l, methanol)	-238.66	126.8	-166.27
CH ₃ OH(g, methanol)	-200.66	239.81	-161.96
CH ₃ OH(aq, methanol)	-245.931	133.1	-175.31
C ₂ H ₅ OH(l, ethanol)	-277.69	160.7	-174.78
C ₂ H ₅ OH(g, ethanol)	-235.1	282.7	-168.49
C ₂ H ₅ OH(aq, ethanol)	-288.3	148.5	-181.64
C ₆ H ₁₂ O ₆ (s, glucose)	-1274.4	235.9	-917.2
CH ₃ COO ⁻ (aq)	-486.01	86.6	-369.31
CH ₃ COOH(aq)	-485.76	178.7	-396.46
CH ₃ COOH(l)	-484.5	159.8	-389.9
CO(g)	-110.525	197.674	-137.168
CO ₂ (g)	-393.509	213.74	-394.359
H ₂ CO ₃ (aq)	-699.65	187.4	-623.08
HCO ₃ ⁻ (aq)	-691.99	91.2	-586.77
CO ₃ ²⁻ (aq)	-677.14	-56.9	-527.81
HCOO ⁻ (aq)	-425.55	92.0	-351.0
HCOOH(aq)	-425.43	163	-372.3
HCOOH(l)	-424.72	128.95	-361.35
CS ₂ (g)	117.36	237.84	67.12
CS ₂ (l)	89.70	151.34	65.27

Species	$\Delta_f H^\circ$ (kJ/mol)	S° (J K ⁻¹ mol ⁻¹)	$\Delta_f G^\circ$ (kJ/mol)
COCl ₂ (g)	-218.8	283.53	-204.6
Cesium			
Cs(s)	0	85.23	0
Cs ⁺ (g)	457.964	—	—
CsCl(s)	-443.04	101.17	-414.53
Chlorine			
Cl(g)	121.679	165.198	105.68
Cl ⁻ (g)	-233.13	—	—
Cl ⁻ (aq)	-167.159	56.5	-131.228
Cl ₂ (g)	0	223.066	0
Cl ₂ (aq)	-23.4	121	6.94
HCl(g)	-92.307	186.908	-95.299
HCl(aq)	-167.159	56.5	-131.228
ClO ₂ (g)	102.5	256.84	120.5
Cl ₂ O(g)	80.3	266.21	97.9
ClO ⁻ (aq)	-107.1	42.0	-36.8
HClO(aq)	-120.9	142	-79.9
ClF ₃ (g)	-163.2	281.61	-123.0
Chromium			
Cr(s)	0	23.77	0
Cr ₂ O ₃ (s)	-1139.7	81.2	-1058.1
CrCl ₃ (s)	-556.5	123	-486.1
Copper			
Cu(s)	0	33.15	0
CuO(s)	-157.3	42.63	-129.7
CuCl ₂ (s)	-220.1	108.07	-175.7
CuSO ₄ (s)	-771.36	109	-661.8
Fluorine			
F ₂ (g)	0	202.78	0
F(g)	78.99	158.754	61.91
F ⁻ (g)	-255.39	—	—
F ⁻ (aq)	-332.63	-13.8	-278.79
HF(g)	-271.1	173.779	-273.2
HF(aq, un-ionized)	-320.08	88.7	-296.82
HF(aq, ionized)	-332.63	-13.8	-278.79
Hydrogen†			
H ₂ (g)	0	130.684	0
H ₂ (aq)	-4.2	57.7	17.6
HD(g)	0.318	143.801	-1.464
D ₂ (g)	0	144.960	0
H(g)	217.965	114.713	203.247
H ⁺ (g)	1536.202	—	—

Species	$\Delta_f H^\circ$ (kJ/mol)	S° (J K ⁻¹ mol ⁻¹)	$\Delta_f G^\circ$ (kJ/mol)
H ⁺ (aq)	0	0	0
OH ⁻ (aq)	-229.994	-10.75	-157.244
H ₂ O(l)	-285.83	69.91	-237.129
H ₂ O(g)	-241.818	188.825	-228.572
H ₂ O ₂ (l)	-187.78	109.6	-120.35
H ₂ O ₂ (aq)	-191.17	143.9	-134.03
HO ₂ ⁻ (aq)	-160.33	23.8	-67.3
HDO(l)	-289.888	79.29	-241.857
D ₂ O(l)	-294.600	75.94	-243.439
Iodine			
I ₂ (s)	0	116.135	0
I ₂ (g)	62.438	260.69	19.327
I ₂ (aq)	22.6	137.2	16.40
I(g)	106.838	180.791	70.25
I ⁻ (g)	-197	—	—
I ⁻ (aq)	-55.19	111.3	-51.57
I ₃ ⁻ (aq)	-51.5	239.3	-51.4
HI(g)	26.48	206.594	1.70
HI(aq, ionized)	-55.19	111.3	-51.57
IF(g)	-95.65	236.17	-118.51
ICl(g)	17.78	247.551	-5.46
ICl(l)	-23.89	135.1	-13.58
IBr(g)	40.84	258.773	3.69
ICl ₃ (s)	-89.5	167.4	-22.29
Iron			
Fe(s)	0	27.78	0
FeO(s, wustite)	-266.27	57.49	-245.12
Fe ₂ O ₃ (s, hematite)	-824.2	87.4	-742.2
Fe ₃ O ₄ (s, magnetite)	-1118.4	146.4	-1015.4
FeCl ₂ (s)	-341.79	117.95	-302.3
FeCl ₃ (s)	-399.49	142.3	-344
FeS ₂ (s, pyrite)	-178.2	52.93	-166.9
Fe(CO) ₅ (l)	-774	338.1	-705.3
Lead			
Pb(s)	0	64.81	0
PbCl ₂ (s)	-359.41	136	-314.1
PbO(s, yellow)	-217.32	68.7	-187.89
PbS(s)	-100.4	91.2	-98.7
PbSO ₄ (s)	-919.94	148.57	-813.14
PbCl ₄ (l)	-329.3	—	—
PbO ₂ (s)	-277.4	68.6	-217.33
Lithium			

Species	$\Delta_f H^\circ$ (kJ/mol)	S° (J K ⁻¹ mol ⁻¹)	$\Delta_f G^\circ$ (kJ/mol)
Li(s)	0	29.12	0
Li ⁺ (g)	685.783	—	—
LiOH(s)	-484.93	42.8	-438.95
LiOH(aq)	-508.48	2.8	-450.58
LiCl(s)	-408.701	59.33	-384.37
Magnesium			
Mg(s)	0	32.68	0
Mg ²⁺ (aq)	-466.85	-138.1	-454.8
MgCl ₂ (g)	-400.4	—	—
MgCl ₂ (s)	-641.32	89.62	-591.79
MgCl ₂ (aq)	-801.15	-25.1	-717.1
MgO(s)	-601.70	26.94	-569.43
Mg(OH) ₂ (s)	-924.54	63.18	-833.51
MgS(s)	-346	50.33	-341.8
MgSO ₄ (s)	-1284.9	91.6	-1170.6
MgCO ₃ (s)	-1095.8	65.7	-1012.1
Mercury			
Hg(l)	0	76.02	0
HgCl ₂ (s)	-224.3	146	-178.6
HgO(s, red)	-90.83	70.9	-58.539
HgS(s, red)	-58.2	82.4	-50.6
Nickel			
Ni(s)	0	29.87	0
NiO(s)	-239.7	37.99	-211.7
NiCl ₂ (s)	-305.332	97.65	-259.032
Nitrogen			
N ₂ (g)	0	191.61	0
N ₂ (aq)	-10.8	—	—
N(g)	472.704	153.298	455.53
NH ₃ (g)	-46.11	192.45	-16.45
NH ₃ (aq)	-80.29	111.3	-26.50
NH ₄ ⁺ (aq)	-132.51	113.4	-79.31
N ₂ H ₄ (l)	50.63	121.21	149.34
NH ₄ Cl(s)	-314.43	94.6	-202.87
NH ₄ Cl(aq)	-299.66	169.9	-210.52
NH ₄ NO ₃ (s)	-365.56	151.08	-183.87
NH ₄ NO ₃ (aq)	-339.87	259.8	-190.56
NO(g)	90.25	210.761	86.55
NO ₂ (g)	33.18	240.06	51.31
N ₂ O(g)	82.05	219.85	104.20
N ₂ O ₄ (g)	9.16	304.29	97.89
N ₂ O ₄ (l)	-19.50	209.2	97.54

Species	$\Delta_f H^\circ$ (kJ/mol)	S° (J K ⁻¹ mol ⁻¹)	$\Delta_f G^\circ$ (kJ/mol)
NOCl(g)	51.71	261.69	66.08
HNO ₃ (ℓ)	-174.10	155.60	-80.71
HNO ₃ (g)	-135.06	266.38	-74.72
HNO ₃ (aq)	-207.36	146.4	-111.25
NO ₃ ⁻ (aq)	-205.0	146.4	-108.74
NF ₃ (g)	-124.7	260.73	-83.2
Oxygen†			
O ₂ (g)	0	205.138	0
O ₂ (aq)	-11.7	110.9	16.4
O(g)	249.170	161.055	231.731
O ₃ (g)	142.7	238.93	163.2
OH ⁻ (aq)	-229.994	-10.75	-157.244
Phosphorus			
P ₄ (s, white)	0	164.36	0
P ₄ (s, red)	-70.4	91.2	-48.4
P(g)	314.64	163.193	278.25
PH ₃ (g)	5.4	310.23	13.4
PCl ₃ (g)	-287.0	311.78	-267.8
PCl ₃ (ℓ)	-319.7	217.1	-272.3
PCl ₅ (s)	-443.5	—	—
P ₄ O ₁₀ (s)	-2984.0	228.86	-2697.7
H ₃ PO ₄ (s)	-1279	110.5	-1119.1
Potassium			
K(s)	0	64.18	0
KF(s)	-567.27	66.57	-537.75
KCl(s)	-436.747	82.59	-409.14
KCl(aq)	-419.53	159.0	-414.49
KBr(s)	-393.798	95.90	-380.66
KI(s)	-327.900	106.32	-324.892
KClO ₃ (s)	-397.73	143.1	-296.25
KOH(s)	-424.764	78.9	-379.08
KOH(aq)	-482.37	91.6	-440.5
Silicon			
Si(s)	0	18.83	0
SiBr ₄ (ℓ)	-457.3	277.8	-443.8
SiC(s)	-65.3	16.61	-62.8
SiCl ₄ (g)	-657.01	330.73	-616.98
SiH ₄ (g)	34.3	204.62	56.9
SiF ₄ (g)	-1614.94	282.49	-1572.65
SiO ₂ (s, quartz)	-910.94	41.84	-856.64
Silver			
Ag(s)	0	42.55	0

Species	$\Delta_f H^\circ$ (kJ/mol)	S° (J K ⁻¹ mol ⁻¹)	$\Delta_f G^\circ$ (kJ/mol)
Ag ⁺ (aq)	105.579	72.68	77.107
Ag ₂ O(s)	-31.05	121.3	-11.2
AgCl(s)	-127.068	96.2	-109.789
AgI(s)	-61.84	115.5	-66.19
AgN ₃ (s)	620.60	99.22	591.0
AgNO ₃ (s)	-124.39	140.92	-33.41
AgNO ₃ (aq)	-101.8	219.2	-34.16
Sodium			
Na(s)	0	51.21	0
Na(g)	107.32	153.712	76.761
Na ⁺ (g)	609.358	—	—
Na ⁺ (aq)	-240.12	59.0	-261.905
NaF(s)	-573.647	51.46	-543.494
NaF(aq)	-572.75	45.2	-540.68
NaCl(s)	-411.153	72.13	-384.138
NaCl(g)	-176.65	229.81	-196.66
NaCl(aq)	-407.27	115.5	-393.133
NaBr(s)	-361.062	86.82	-348.983
NaBr(aq)	-361.665	141.4	-365.849
NaI(s)	-287.78	98.53	-286.06
NaI(aq)	-295.31	170.3	-313.47
NaOH(s)	-425.609	64.455	-379.484
NaOH(aq)	-470.114	48.1	-419.15
NaClO ₃ (s)	-365.774	123.4	-262.259
NaHCO ₃ (s)	-950.81	101.7	-851.0
Na ₂ CO ₃ (s)	-1130.68	134.98	-1044.44
Na ₂ SO ₄ (s)	-1387.08	149.58	-1270.16
Sulfur			
S(s, monoclinic)	0.33	—	—
S(s, rhombic)	0	31.80	0
S(g)	278.805	167.821	238.250
S ²⁻ (aq)	33.1	-14.6	85.8
S ₂ Cl ₂ (g)	-18.4	331.5	-31.8
SF ₆ (g)	-1209	291.82	-1105.3
SF ₄ (g)	-774.9	292.03	-731.3
H ₂ S(g)	-20.63	205.79	-33.56
H ₂ S(aq)	-39.7	121	-27.83
HS ⁻ (aq)	-17.6	62.8	12.08
SO ₂ (g)	-296.830	248.22	-300.194
SO ₃ (g)	-395.72	256.76	-371.06
SOCl ₂ (g)	-212.5	309.77	-198.3
SO ₄ ²⁻ (aq)	-909.27	20.1	-744.53

Species	$\Delta_f H^\circ$ (kJ/mol)	S° (J K ⁻¹ mol ⁻¹)	$\Delta_f G^\circ$ (kJ/mol)
H ₂ SO ₄ (l)	-813.989	156.904	-690.003
H ₂ SO ₄ (aq)	-909.27	20.1	-744.53
HSO ₄ ⁻ (aq)	-887.34	131.8	-755.91
Tin			
Sn(s, white)	0	51.55	0
Sn(s, gray)	-2.09	44.14	0.13
SnCl ₂ (s)	-325.1	—	—
SnCl ₄ (l)	-511.3	258.6	-440.1
SnCl ₄ (g)	-471.5	365.8	-432.2
SnO ₂ (s)	-580.7	52.3	-519.6
Titanium			
Ti(s)	0	30.63	0
TiCl ₄ (l)	-804.2	252.34	-737.2
TiCl ₄ (g)	-763.2	354.9	-726.7
TiO ₂ (s)	-939.7	49.92	-884.5
Uranium			
U(s)	0	50.21	0
UO ₂ (s)	-1084.9	77.03	-1031.7
UO ₃ (s)	-1223.8	96.11	-1145.9
UF ₄ (s)	-1914.2	151.67	-1823.3
UF ₆ (g)	-2147.4	377.9	-2063.7
UF ₆ (s)	-2197.0	227.6	-2068.5
Zinc			
Zn(s)	0	41.63	0
ZnCl ₂ (s)	-415.05	111.46	-369.398
ZnO(s)	-348.28	43.64	-318.3
ZnS(s, sphalerite)	-205.98	57.7	-201.29

From Wagman, D. D., Evans, W. H., Parker, V. B., Schumm, R. H., Halow, I., Bailey, S. M., Churney, K. L., and Nuttall, R., Journal of Physical and Chemical Reference Data, Vol. 11, Suppl. 2, 1982.

[†]Many hydrogen-containing and oxygen-containing compounds are listed only under other elements.

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