Chemistry Lecture #100: Hess's Law

Hess's law states that the change in enthalpy for a chemical reaction can be found by adding two or more thermochemical equations.

For example, suppose we are given the reactions

(a). $S_{(s)} + O_{2(g)} \rightarrow SO_{2(g)}$ $\Delta H = -297$ kJ

(b). $2SO_{3(g)} \rightarrow 2SO_{2(g)} + O_2$ $\Delta H = 198$ kJ

and we want to find the ΔH for the equation

(c). $2S_{(s)} + 3O_{2(g)} \rightarrow 2SO_{3(g)}$ $\Delta H = ?$

We can add equations (a) and (b) to get the ΔH for equation (c). To do this, we need to modify equations (a) and (b) to make them look more like equation (c). We do this by multiplying and flipping the equations.

For example, equation (c) has a 2 in front of the S, while equation (a) has an implicit 1 in front of the S. So, we multiply equation (a) and its ΔH by 2 so the S matches equation (c).

(a). $S_{(s)} + O_{2(g)} \rightarrow SO_{2(g)}$ $\Delta H = -297$ kJ

becomes

(a). $2S_{(s)} + 2O_{2(g)} \rightarrow 2SO_{2(g)}$ $\Delta H = -594$ kJ

Notice that ΔH has been multiplied by 2.

Next, compare equation (b) with equation (c). Notice that $2SO_3$ is on the left side of equation (b), while it is on the right side of equation (c).

(b). $2SO_{3(g)} \rightarrow 2SO_{2(g)} + O_{2(g)}$ $\quad \Delta H = 198$

(c). $2S_{(s)} + 3O_{2(g)} \rightarrow 2SO_{3(g)}$ $\quad \Delta H = ?$

To make equation (b) match equation (c), we reverse the equation, and also change the sign of ΔH.

(b). $2SO_{3(g)} \rightarrow 2SO_{2(g)} + O_{2(g)}$ $\quad \Delta H = 198$

becomes

(b) $2SO_{2(g)} + O_{2(g)} \rightarrow 2SO_{3(g)}$ $\quad \Delta H = -198$

If we add the modified equations (a) and (b) along with their ΔH's, we get equation (c) and its ΔH.

(a). $2S_{(s)} + 2O_{2(g)} \rightarrow \cancel{2SO_{2(g)}}$ $\quad \Delta H = -594$ kJ

(b) $\cancel{2SO_{2(g)}} + O_{2(g)} \rightarrow 2SO_{3(g)}$ $\quad \Delta H = -198$ kJ

(c). $2S_{(s)} + 3O_{2(g)} \rightarrow 2SO_{3(g)}$ $\quad \Delta H = -792$ kJ

The ΔH for a reaction can also be found if you know the heat of formation ($\Delta H°_f$) of the product and reactants. The next page is a chart of thermodynamic properties which gives the heat of formation for various substances. Notice that elements have a $\Delta H°_f$ equal to zero.

Thermodynamic Properties (at 25°C and 100.000 kPa)

$\Delta H_f°$ (kJ/mol) $\Delta G_f°$ (kJ/mol) $S°$ (J/mol · K)
(concentration of aqueous solutions is 1*M*)

Substance	$\Delta H_f°$	$\Delta G_f°$	$S°$	Substance	$\Delta H_f°$	$\Delta G_f°$	$S°$
Ag(cr)	0	0	42.55	H_3PO_3(aq)	−964.4	—	—
AgCl(cr)	−127.068	−109.789	96.2	H_3PO_4(aq)	−1279.0	−1119.1	110.50
AgCN(cr)	146.0	156.9	107.19	H_2S(g)	−20.63	−33.56	205.79
Al(cr)	0	0	28.33	H_2SO_3(aq)	−608.81	−537.81	232.2
Al_2O_3(cr)	−1675.7	−1582.3	50.92	H_2SO_4(aq)	−909.27	−744.53	20.1
$BaCl_2$(aq)	−871.95	−823.21	122.6	$HgCl_2$(cr)	−224.3	−178.6	—
$BaSO_4$(cr)	−1473.2	−1362.2	132.2	Hg_2Cl_2(cr)	−265.22	−210.745	192.5
Be(cr)	0	0	9.50	Hg_2SO_4(cr)	−743.12	−625.815	200.66
BeO(cr)	−609.6	−580.3	—	I_2(cr)	0	0	116.135
Bi(cr)	0	0	56.74	K(cr)	0	0	64.18
$BiCl_3$(cr)	−379.1	−315.0	177.0	KBr(cr)	−393.798	−380.66	95.90
Bi_2S_3(cr)	−143.1	−140.6	200.4	$KMnO_4$(cr)	−837.2	−737.6	171.71
Br_2(l)	0	0	152.231	KOH(cr)	−424.764	—	—
CH_4(g)	−74.81	−50.72	186.264	LiBr(cr)	−351.213	—	—
C_2H_2(g)	+226.73	+209.20	200.94	LiOH(cr)	−484.93	−438.95	42.80
C_2H_4(g)	+52.26	+68.15	219.56	Mn(cr)	0	0	32.01
C_2H_6(g)	−84.68	−32.82	229.60	$MnCl_2$(aq)	−555.05	−490.8	38.9
CO(g)	−110.525	−137.168	197.674	$Mn(NO_3)_2$(aq)	−635.5	−450.9	218
CO_2(g)	−393.509	−394.359	213.74	MnO_2(cr)	−520.03	−465.14	53.05
CS_2(l)	+89.70	+65.27	151.34	MnS(cr)	−214.2	—	—
Ca(cr)	0	0	41.42	N_2(g)	0	0	191.61
$Ca(OH)_2$(cr)	−986.09	−898.49	—	NH_3(g)	−46.11	−16.45	192.45
Cl_2(g)	0	0	223.066	NH_4Br(cr)	−270.83	−175.2	113
Co_3O_4(cr)	−891	−774	—	NO(g)	+90.25	86.55	210.761
CoO(cr)	−237.94	−214.20	52.97	NO_2(g)	+33.18	+51.31	240.06
Cr_2O_3(cr)	−1139.7	−1058.1	81.2	N_2O(g)	+82.05	+104.20	219.85
CsCl(cr)	−443.04	−414.53	101.17	Na(cr)	0	0	51.21
Cs_2SO_4(cr)	−1443.02	−1323.58	211.92	NaBr(cr)	−361.062	—	—
CuI(cr)	−67.8	−69.5	96.7	NaCl(cr)	−411.153	−384.138	72.13
CuS(cr)	−53.1	−53.6	66.5	$NaNO_3$(aq)	−447.48	—	—
Cu_2S(cr)	−79.5	−86.2	120.9	NaOH(cr)	−425.609	—	—
$CuSO_4$(cr)	−771.36	−661.8	109	Na_2S(aq)	−447.3	—	—
F_2(g)	0	0	202.78	Na_2SO_4(cr)	−1387.08	−1270.16	149.58
$FeCl_3$(cr)	−399.49	—	—	O_2(g)	0	0	205.138
FeO(cr)	−272.0	—	—	P_4O_6(cr)	−1640.1	—	—
Fe_2O_3(cr)	−824.2	−742.2	87.40	P_4O_{10}(cr)	−2984.0	−2697.7	228.86
Fe_3O_4(cr)	−1118.4	−1015.4	146.4	$PbBr_2$(cr)	−278.7	−261.92	161.5
H(g)	+217.965	—	114.713	$PbCl_2$(cr)	−359.41	−314.10	136.0
H_2(g)	0	0	130.684	S(cr)	0	0	31.80
HBr(g)	−36.40	−53.45	198.695	SO_2(g)	−296.830	−300.194	248.22
HCl(g)	−92.307	−95.299	186.908	SO_3(g)	−454.51	−374.21	70.7
HCl(aq)	−167.159	−131.228	56.5	SrO(cr)	−592.0	−561.9	54.4
HCN(aq)	+150.6	+172.4	94.1	Ti(cr)	0	0	30.63
HCHO(g)	−108.57	−102.53	218.77	TiO_2(cr)	−939.7	−884.5	49.92
HCOOH(l)	−424.72	−361.35	128.95	TlI(cr)	−123.8	−125.39	127.6
HF(g)	−271.1	−273.2	173.779	UCl_4(cr)	−1019.2	−930.0	197.1
HI(g)	+26.48	+1.70	206.594	UCl_5(cr)	−1059	−950	242.7
H_2O(l)	−285.830	−237.129	69.91	Zn(cr)	0	0	41.63
H_2O(g)	−241.818	−228.572	188.825	$ZnCl_2$(aq)	−488.19	−409.50	0.8
H_2O_2(l)	—	−120.35	109.6	ZnO(cr)	−348.28	−318.30	43.64
H_3PO_2(l)	−595.4	—	—	$ZnSO_4$(aq)	−1063.15	−891.59	−92.0

The heat of formation for a reaction can be calculated using the formula

$\Delta H^\circ_{rxn} = \sum \Delta H^\circ_f$ (products) - $\sum \Delta H^\circ_f$ (reactants)

ΔH°_{rxn} = change in enthalpy for a reaction

$\sum \Delta H^\circ_f$ (products) = sum of the ΔH°_f of the products

$\sum \Delta H^\circ_f$ (reactants) = sum of the ΔH°_f of the reactants

Using the chart of thermodynamic properties, find the ΔH°_{rxn} for the reaction

$CH_{4(g)} + 2O_{2(g)} \rightarrow CO_{2(g)} + 2H_2O_{(l)}$ $\Delta H^\circ_{rxn} = ?$

Solution

Using the thermodynamic properties chart, list the ΔH°_f of each product and reactant.

ΔH°_f products (kJ/mole)	ΔH°_f reactants (kJ/mole)
$CO_{2(g)} = -394$	$CH_{4(g)} = -74.8$
$H_2O_{(l)} = -286 \times 2 = -572$	$O_{2(g)} = 0.0 \times 2 = 0$

Notice that the for H_2O and O_2, we multiplied the values by 2. This is because there is a 2 in front of these substances in the balanced equation.

Next, add the ΔH°_f of the products and reactants.

$\sum \Delta H^\circ_f$ (products) = $-394 + (-572) = -966$

$\sum \Delta H^\circ_f$ (reactants) = $-74.8 + 0 = -74.8$

Finally, subtract $\sum \Delta H^\circ_f$ (reactants) from $\sum \Delta H^\circ_f$ (products) to get ΔH°_{rxn}.

$\Delta H^\circ_{rxn} = \sum \Delta H^\circ_f$ (products) - $\sum \Delta H^\circ_f$ (reactants)

$\Delta H^\circ_{rxn} = -966 - (-74.8)$

$\Delta H^\circ_{rxn} = -891.2$ or -891 kJ

Thus, the combustion of one mole of $CH_{4(g)}$ produces 891 kJ of energy.