Development of Teaching Materials on Spontaneity of Chemical Reactions: Solid Divalent Metals with Aqueous Divalent Metal Cations using Theoretical and Microscale Experimental Approach

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Development of Teaching Materials by Handmade Well Plates

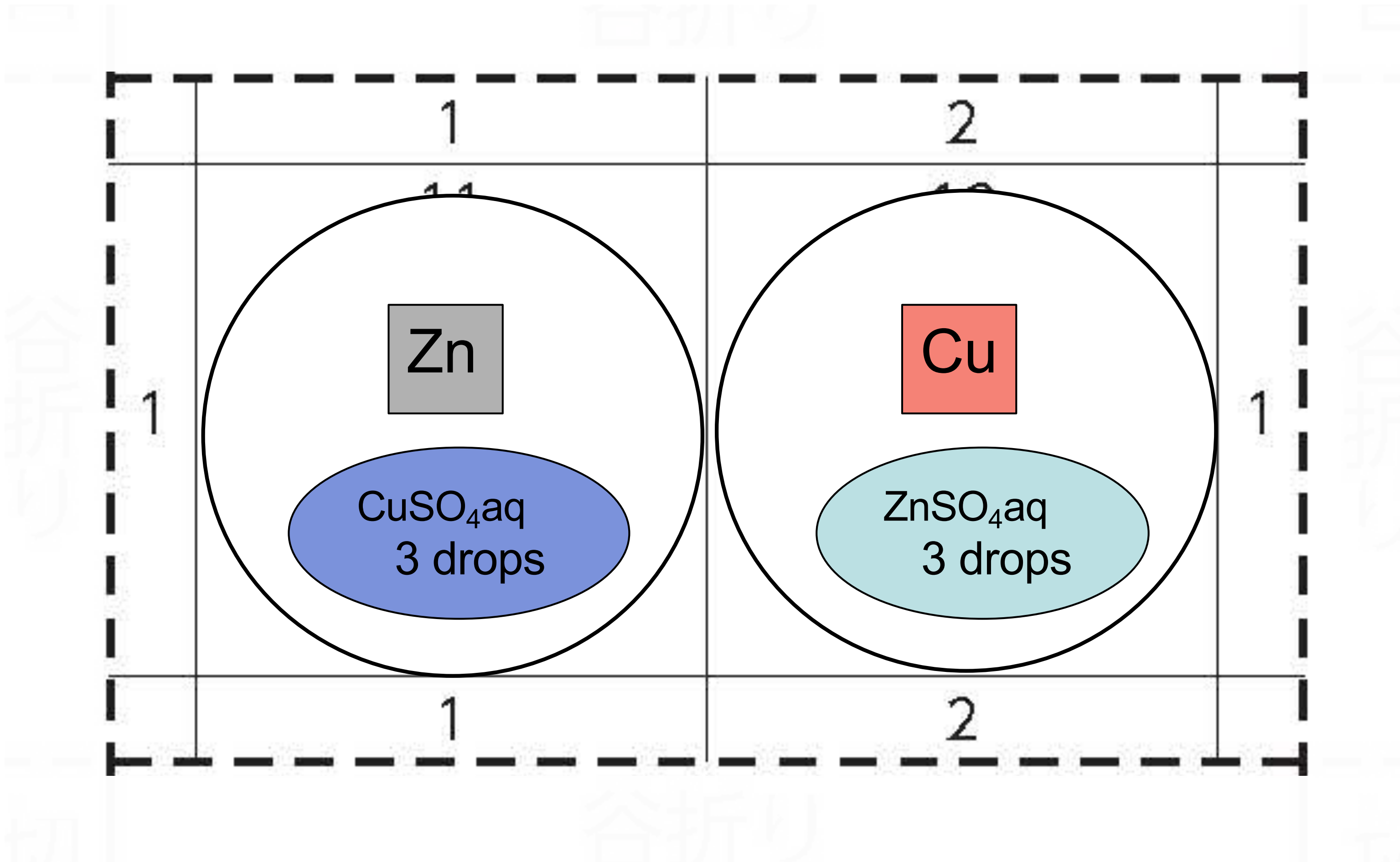
Solid Divalent Metal M
+ Aqueous Divalent Metal Cation N^{2+}

M, N = Cu, Zn and Mg

$$M(s) + N^{2+}(aq) \rightarrow M^{2+}(aq) + N(s)$$

- $Zn(s)/Cu^{2+}(aq)$, $Cu(s)/Zn^{2+}(aq)$
- $Mg(s)/Zn^{2+}(aq)$, $Zn(s)/Mg^{2+}(aq)$
- $Mg(s)/Cu^{2+}(aq)$, $Cu(s)/Mg^{2+}(aq)$

Microscale Experiments 1



Microscale Experiments 4

$Zn(s)/Cu^{2+}aq$ $Cu(s)/Zn^{2+}aq$

\+ –

$Mg/Zn^{2+}aq$ $Zn/Mg^{2+}aq$

\+ –

$Mg/Cu^{2+}aq$ $Cu/Mg^{2+}aq$

\+ –

+: Reacted

–: Not Reacted

Theoretical 2

ΔH°, ΔG° and ΔS°

$$\Delta H^\circ = \Sigma \nu_p \Delta_f H_p^\circ - \Sigma \nu_r \Delta_f H_r^\circ$$

$$\Delta G^\circ = \Sigma \nu_p \Delta_f G_p^\circ - \Sigma \nu_r \Delta_f G_r^\circ$$

$$\Delta S^\circ = \Sigma \nu_p S_p^\circ - \Sigma \nu_r S_r^\circ$$

$\Delta_f H_i^\circ$: Standard Enthalpy of Formation
$\Delta_f G_i^\circ$: Standard Gibbs Energy of Formation
S_i° : Standard Entropy
ν_i : Stoichiometric Coefficient
$i = p, r$: Each Product and Reactant, respectively

Ref: *CRC Handbook of Chemistry and Physics*, 100th, CRC Press, 2019 (Data Sources)

Theoretical 3

	ΔH^o/kJ·mol^{-1}	ΔG^o/kJ·mol^{-1}	ΔS^o/J·K^{-1}·mol^{-1}
Zn(s)/Cu^{2+}(aq)	-218.7	-212.6	-20.9
Cu(s)/Zn^{2+}(aq)	218.7	212.6	20.9
Mg(s)/Zn^{2+}(aq)	-313.0	-307.7	-17.1
Zn(s)/Mg^{2+}(aq)	313.0	307.7	17.1
Mg(s)/Cu^{2+}(aq)	-531.7	-520.3	-38.0
Cu(s)/Mg^{2+}(aq)	531.7	520.3	38.0

$\Delta G^o < 0$ ⇨ Reactions progress.

$\Delta G^o > 0$ ⇨ Reactions do not progress.

$\Delta H^o < 0$ ⇨ Driving Force (Exothermic).

Theoretical 4

Ideal solution model

$N^{2+}(aq) \rightarrow M^{2+}(aq)$ $(\because \Delta_f G_{M(s)}^\circ = \Delta_f G_{N(s)}^\circ = 0)$, $a_i = x_i$

$$G = (1\ \mathrm{mol} - \alpha)\,\Delta_f G_{N^{2+}}^\circ + \alpha\,\Delta_f G_{M^{2+}}^\circ$$
$$+ RT[(1\ \mathrm{mol} - \alpha)\ln(1 - \alpha/\mathrm{mol}) + \alpha \ln(\alpha/\mathrm{mol})]$$
$$= G^\circ + RT[(1\ \mathrm{mol} - \alpha)\ln(1 - \alpha/\mathrm{mol}) + \alpha \ln(\alpha/\mathrm{mol})]$$

$i = N^{2+}(aq)$, $M^{2+}(aq)$, a_i : Activity, x_i : Mole Fraction

G : Gibbs Energy Change including Mixing

G°: Standard Gibbs Energy Change without Mixing

α : Extent of Reaction (0 mol $\leq \alpha \leq$ 1 mol)

$\Delta_f G_i^\circ$: Standard Gibbs Energy of Formation

R : Gas Constant, T : Absolute Temperature

Theoretical 5

$$\Delta G = \left(\frac{\partial G}{\partial \alpha}\right)_{T,P}$$

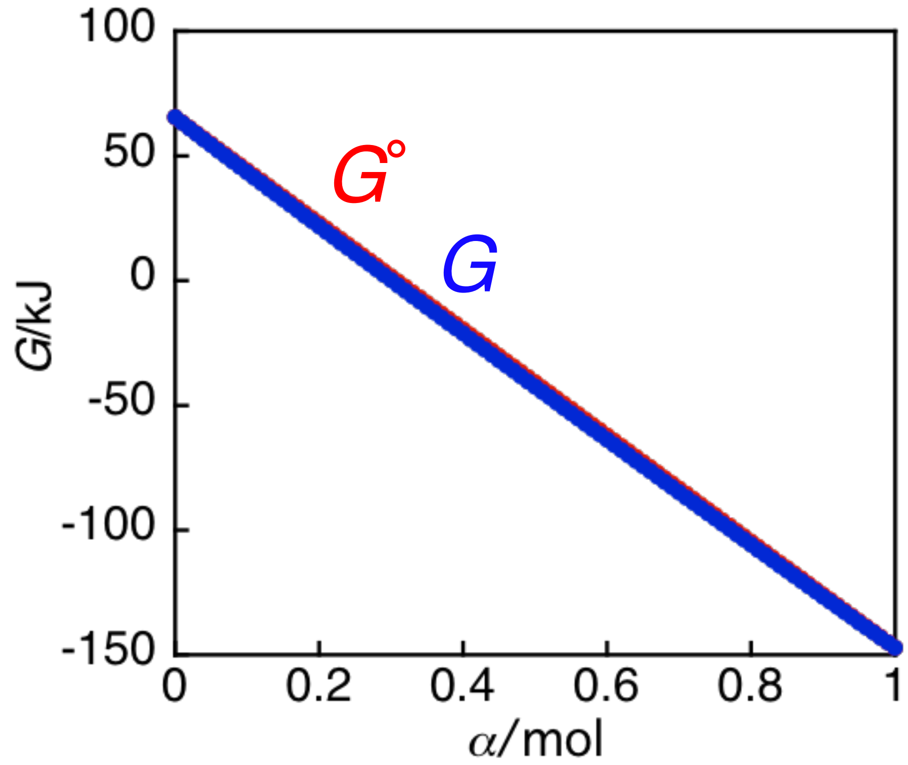
$$= -\Delta_f G_{N2+}^\circ + \Delta_f G_{M2+}^\circ + RT \ln [(\alpha/\text{mol})/(1 - \alpha/\text{mol})]$$

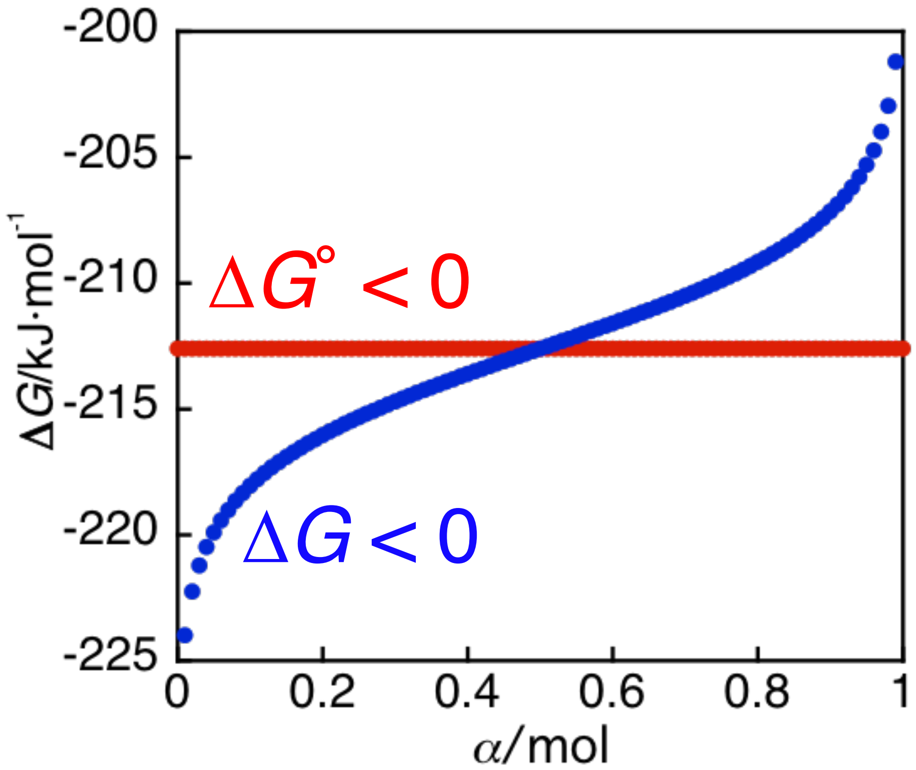
$$= \Delta G^\circ + RT \ln [(\alpha/\text{mol})/(1 - \alpha/\text{mol})]$$

$\Delta_f G_i^\circ$: Standard Gibbs Energy of Formation
ΔG : Gibbs Energy Change including Mixing
ΔG° : Standard Gibbs Energy Change without Mixing
α : Extent of Reaction（0 mol $\leq \alpha \leq$ 1 mol）

Theoretical 6

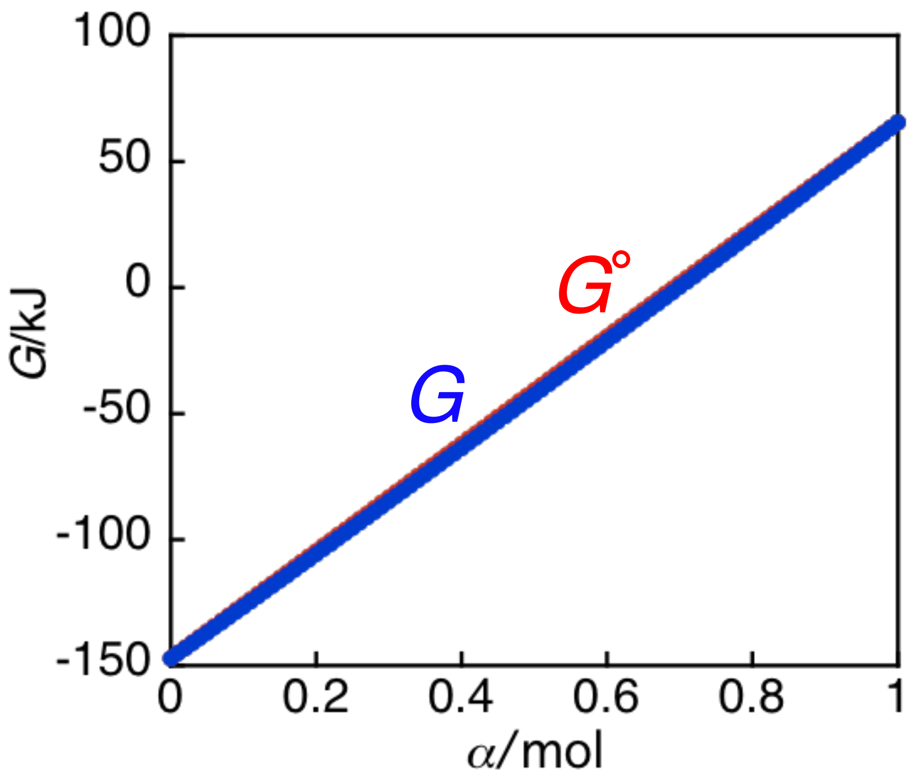
Zn(s) + Cu^{2+}(aq)

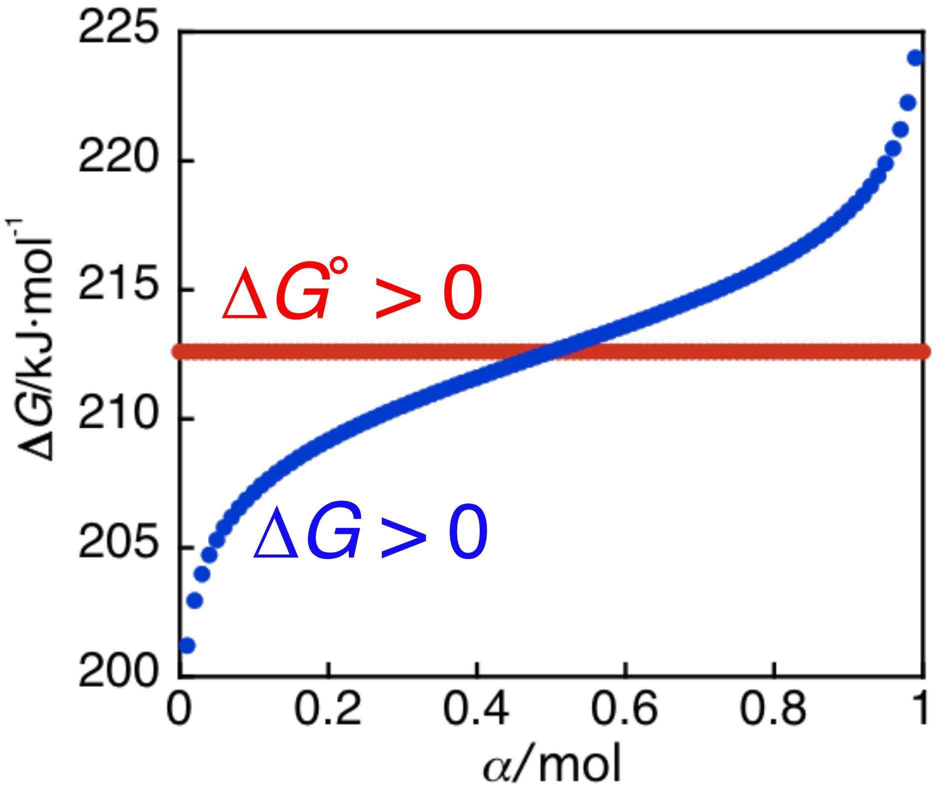




Theoretical 7

$Cu(s) + Zn^{2+}(aq)$





Theoretical 8

at Chemical Equilibrium,

$\Delta G = \Delta G^\circ + RT \ln [(\alpha_e/\text{mol})/(1 - \alpha_e/\text{mol})] = 0$

$\therefore \Delta G^\circ = -RT \ln [(\alpha_e/\text{mol})/(1 - \alpha_e/\text{mol})] = -RT \ln K$

α_e : Extent of Reaction at Chemical Equilibrium
(0 mol $\leq \alpha \leq$ 1 mol)

K : Equilibrium Constant

Conclusions

The microscale experiment teaching materials on the reactions of solid divalent metals [Cu(s), Zn(s) and Mg(s)] with aqueous divalent metal cations [Cu^{2+}(aq), Zn^{2+}(aq) and Mg^{2+}(aq)] have been developed using low-cost handmade well plates.

The $\Delta G°$ values obtained from thermo-dynamical calculations are consistent with the results of microscale experiments.