

## Supplementary Information

# Modelling the Behaviour of Switchable Hydrophilicity Solvents

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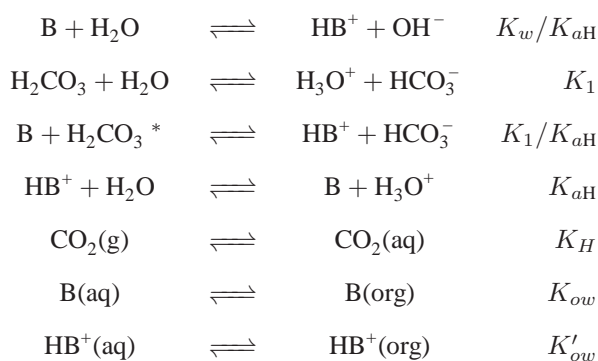
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## 1 Abbreviations & Variables

$n_{B,tot}$	- Total moles of base in the system
$n_{B,aq}$	- Moles of base in the aqueous phase
$n_{B,org}$	- Moles of base in the organic phase
$n_{HB^+,aq}$	- Moles of protonated base in the aqueous phase
$n_{HB^+,org}$	- Moles of protonated base in the organic phase
$[B]_{aq}$	- Molar concentration of base in the aqueous phase
$[B]_{org}$	- Molar concentration of base in the organic phase
$[HB^+]_{aq}$	- Molar concentration of base in the aqueous phase
$[HB^+]_{org}$	- Molar concentration of base in the organic phase
$P$	- Mole fraction of protonated base to total amount of base in the system
$D$	- Distribution coefficient of the base (neutral and protonated) in a 1-octanol/water system
$K_{ow}$	- Partition coefficient of the neutral base in a 1-octanol/water system
$K'_{ow}$	- Partition coefficient of the protonated base in a 1-octanol/water system
$V_{aq}$	- Volume of the aqueous layer in the system
$V_{org}$	- Volume of the organic layer in the system
$V_{(rat)}$	- The volume ratio of the aqueous and organic layers
$V_B$	- Volume of base in the system
$\rho$	- Density of the base
$M$	- Molecular weight of the base
$K_1$	- Acid dissociation constant of carbonic acid
$K_H$	- Henry's law constant for CO <sub>2</sub>
$pK_{aH}$	- Dissociation constant of the protonated base
SHS	- Switchable hydrophilicity solvent
$Z$	- An SHS mapping parameter for the 2-liquid system
$\Omega$	- An SHS mapping parameter for the 3-liquid system

## 2 Reaction equations



\* The concentration of H<sub>2</sub>CO<sub>3</sub> includes both carbonic acid and hydrated dissolved CO<sub>2</sub>.

### 3 Derivations

#### 3.1 Concentration of protonated base

##### 3.1.1 Before addition of CO<sub>2</sub>

$$[\text{H}_3\text{O}^+] + [\text{HB}^+] = [\text{OH}^-]$$

$$[\text{H}_3\text{O}^+] + [\text{HB}^+] = K_w/[\text{H}_3\text{O}^+]$$

$$[\text{H}_3\text{O}^+]^2 + [\text{HB}^+][\text{H}_3\text{O}^+] = K_w$$

Because  $K_{aH} = [\text{H}_3\text{O}^+][\text{B}]/[\text{HB}^+]$  then

$$\left(\frac{[\text{HB}^+]}{[\text{B}]K_{aH}^{-1}}\right)^2 + \frac{[\text{HB}^+]^2}{[\text{B}]K_{aH}^{-1}} = K_w$$

$$[\text{HB}^+]^2 \left(\frac{1}{([\text{B}]K_{aH}^{-1})^2} + \frac{1}{[\text{B}]K_{aH}^{-1}}\right) = K_w$$

$$\frac{[\text{HB}^+]^2}{[\text{B}]K_{aH}^{-1}} \left(\frac{1}{[\text{B}]K_{aH}^{-1}} + 1\right) = K_w$$

$$\frac{[\text{HB}^+]^2}{([\text{B}]K_{aH}^{-1})^2} (1 + [\text{B}]K_{aH}^{-1}) = K_w$$

$$\therefore [\text{HB}^+] = [\text{B}]K_{aH}^{-1} \sqrt{\frac{K_w}{1 + [\text{B}]K_{aH}^{-1}}}$$

##### 3.1.2 After addition of CO<sub>2</sub>

$$[\text{H}_3\text{O}^+] + [\text{HB}^+] = [\text{OH}^-] + [\text{HCO}_3^-]$$

$$[\text{H}_3\text{O}^+] + [\text{HB}^+] = \frac{K_w}{[\text{H}_3\text{O}^+]} + \frac{K_1[\text{H}_2\text{CO}_3]}{[\text{H}_3\text{O}^+]}$$

$$[\text{H}_3\text{O}^+] + [\text{HB}^+] = \frac{1}{[\text{H}_3\text{O}^+]} (K_w + K_1K_H P_{\text{CO}_2})$$

$$[\text{H}_3\text{O}^+]^2 + [\text{HB}^+][\text{H}_3\text{O}^+] = K_w + K_1K_H P_{\text{CO}_2}$$

$$\left(\frac{[\text{HB}^+]}{[\text{B}]K_{aH}^{-1}}\right)^2 + \frac{[\text{HB}^+]^2}{[\text{B}]K_{aH}^{-1}} = K_w + K_1K_H P_{\text{CO}_2}$$

$$[\text{HB}^+]^2 \left(\frac{1}{([\text{B}]K_{aH}^{-1})^2} + \frac{1}{[\text{B}]K_{aH}^{-1}}\right) = K_w + K_1K_H P_{\text{CO}_2}$$

$$\frac{[\text{HB}^+]^2}{[\text{B}]K_{aH}^{-1}} \left(\frac{1}{[\text{B}]K_{aH}^{-1}} + 1\right) = K_w + K_1K_H P_{\text{CO}_2}$$

$$\frac{[\text{HB}^+]^2}{([\text{B}]K_{aH}^{-1})^2} (1 + [\text{B}]K_{aH}^{-1}) = K_w + K_1K_H P_{\text{CO}_2}$$

$$\therefore [\text{HB}^+] = [\text{B}]K_{aH}^{-1} \sqrt{\frac{K_w + K_1K_H P_{\text{CO}_2}}{1 + [\text{B}]K_{aH}^{-1}}}$$

#### 3.2 Solubility

$$S = [\text{B}]_{\text{aq}} + [\text{HB}^+]_{\text{aq}}$$

$$S' = [B]_{\text{aq}} + [\text{HB}^+]_{\text{aq}}'$$

Substituting  $[\text{HB}^+]_{\text{aq}}$  from the charge balance equation,

$$S = [B]_{\text{aq}} \left( 1 + \frac{1}{K_{\text{aH}}} \sqrt{\frac{K_w}{1 + [B]_{\text{aq}} K_{\text{aH}}^{-1}}} \right)$$

Similarly, the solubility after the introduction of  $\text{CO}_2$  is given by

$$S' = [B]_{\text{aq}} \left( 1 + \frac{1}{K_{\text{aH}}} \sqrt{\frac{K_w + K_1 K_H P_{\text{CO}_2}}{1 + [B]_{\text{aq}} K_{\text{aH}}^{-1}}} \right)$$

### 3.3 Distribution coefficient

$$\begin{aligned} D &= \frac{[B]_{\text{org}} + [\text{HB}^+]_{\text{org}}}{[B]_{\text{aq}} + [\text{HB}^+]_{\text{aq}}} \\ &= \frac{\frac{[B]_{\text{org}}}{[B]_{\text{aq}}} + \frac{[\text{HB}^+]_{\text{org}}}{[B]_{\text{aq}}}}{1 + \frac{[\text{HB}^+]_{\text{aq}}}{[B]_{\text{aq}}}} \\ &= \frac{K_{\text{ow}} + \frac{[\text{HB}^+]_{\text{org}}}{[B]_{\text{aq}}}}{1 + \frac{[\text{H}_3\text{O}^+]}{K_{\text{aH}}}} \\ &= \frac{K_{\text{ow}} K_{\text{aH}} + \frac{[\text{H}_3\text{O}^+][\text{HB}^+]_{\text{org}}}{[\text{HB}^+]_{\text{aq}}}}{K_{\text{aH}} + [\text{H}_3\text{O}^+]} \\ &= \frac{K_{\text{aH}} K_{\text{ow}} + [\text{H}_3\text{O}^+] K'_{\text{ow}}}{K_{\text{aH}} + [\text{H}_3\text{O}^+]} \\ &= \frac{10^{-\text{p}K_{\text{aH}}} K_{\text{ow}} + 10^{-\text{pH}} K'_{\text{ow}}}{10^{-\text{p}K_{\text{aH}}} + 10^{-\text{pH}}} \\ &= \frac{K_{\text{ow}} + 10^{\text{p}K_{\text{aH}} - \text{pH}} K'_{\text{ow}}}{1 + 10^{\text{p}K_{\text{aH}} - \text{pH}}} \\ &= K_{\text{ow}} \left( \frac{1 + 10^{\text{p}K_{\text{aH}} - \text{pH}} K'_{\text{ow}} / K_{\text{ow}}}{1 + 10^{\text{p}K_{\text{aH}} - \text{pH}}} \right) \end{aligned}$$

$$\therefore \log D = \log K_{\text{ow}} + \log \left( 1 + 10^{\text{p}K_{\text{aH}} - \text{pH}} K'_{\text{ow}} / K_{\text{ow}} \right) - \log \left( 1 + 10^{\text{p}K_{\text{aH}} - \text{pH}} \right)$$

Now,

$$\frac{K'_{\text{ow}}}{K_{\text{ow}}} = 10^{\log K'_{\text{ow}} - \log K_{\text{ow}}}$$

So if we let  $\Delta \log K_{\text{ow}} = \log K_{\text{ow}} - \log K'_{\text{ow}}$ , then

$$\log D = \log K_{\text{ow}} + \log \left( 1 + 10^{\text{p}K_{\text{aH}} - \text{pH} - \Delta \log K_{\text{ow}}} \right) - \log \left( 1 + 10^{\text{p}K_{\text{aH}} - \text{pH}} \right)$$

To eliminate the pH variable, we begin in a similar way

$$\begin{aligned}
 D &= \frac{[\text{B}]_{\text{org}} + [\text{HB}^+]_{\text{org}}}{[\text{B}]_{\text{aq}} + [\text{HB}^+]_{\text{aq}}} \\
 &= \frac{\frac{[\text{B}]_{\text{org}}}{[\text{B}]_{\text{aq}}} + \frac{[\text{HB}^+]_{\text{org}}}{[\text{B}]_{\text{aq}}}}{1 + \frac{[\text{HB}^+]_{\text{aq}}}{[\text{B}]_{\text{aq}}}} \\
 &= \frac{K_{ow} + K'_{ow} \frac{[\text{HB}^+]_{\text{aq}}}{[\text{B}]_{\text{aq}}}}{1 + \frac{[\text{HB}^+]_{\text{aq}}}{[\text{B}]_{\text{aq}}}} \\
 &= \frac{(K_{ow}/K'_{ow}) + \frac{[\text{HB}^+]_{\text{aq}}}{[\text{B}]_{\text{aq}}}}{\frac{1}{K'_{ow}} \left(1 + \frac{[\text{HB}^+]_{\text{aq}}}{[\text{B}]_{\text{aq}}}\right)}
 \end{aligned}$$

$$\therefore \log D = \log \left( \frac{K_{ow}}{K'_{ow}} + \frac{[\text{HB}^+]_{\text{aq}}}{[\text{B}]_{\text{aq}}} \right) + \log(K'_{ow}) - \log \left( 1 + \frac{[\text{HB}^+]_{\text{aq}}}{[\text{B}]_{\text{aq}}} \right)$$

### 3.4 Fraction of protonation

$$\begin{aligned}
 P &= \frac{n_{\text{HB}^+, \text{org}} + n_{\text{HB}^+, \text{aq}}}{n_{\text{B}, \text{tot}}} \\
 &= \frac{[\text{HB}^+]_{\text{org}} V_{\text{org}} + [\text{HB}^+]_{\text{aq}} V_{\text{aq}}}{[\text{B}]_{\text{org}} V_{\text{org}} + [\text{B}]_{\text{aq}} V_{\text{aq}} + [\text{HB}^+]_{\text{org}} V_{\text{org}} + [\text{HB}^+]_{\text{aq}} V_{\text{aq}}} \\
 \frac{1}{P} &= 1 + \frac{[\text{B}]_{\text{aq}} V_{\text{aq}} + [\text{B}]_{\text{org}} V_{\text{org}}}{[\text{HB}^+]_{\text{aq}} V_{\text{aq}} + [\text{HB}^+]_{\text{org}} V_{\text{org}}} \\
 &= 1 + \frac{V_{\text{aq}} + V_{\text{org}}([\text{B}]_{\text{org}}/[\text{B}]_{\text{aq}})}{V_{\text{aq}}([\text{HB}^+]_{\text{aq}}/[\text{B}]_{\text{aq}}) + V_{\text{org}}([\text{HB}^+]_{\text{org}}/[\text{B}]_{\text{aq}})} \\
 &= 1 + \frac{1 + V_{\text{rat}} K_{ow}}{([\text{HB}^+]_{\text{aq}}/[\text{B}]_{\text{aq}}) + V_{\text{rat}} K'_{ow}([\text{HB}^+]_{\text{aq}}/[\text{B}]_{\text{aq}})} \\
 &= 1 + \frac{1 + V_{\text{rat}} K_{ow}}{[\text{H}_3\text{O}^+] K_{\text{aH}}^{-1} (1 + V_{\text{rat}} K'_{ow})} \\
 \therefore P &= \frac{[\text{H}_3\text{O}^+] K_{\text{aH}}^{-1} (1 + V_{\text{rat}} K'_{ow})}{[\text{H}_3\text{O}^+] K_{\text{aH}}^{-1} (1 + V_{\text{rat}} K'_{ow}) + (1 + V_{\text{rat}} K_{ow})} \\
 &= \frac{[\text{H}_3\text{O}^+] (1 + V_{\text{rat}} K'_{ow})}{[\text{H}_3\text{O}^+] (1 + V_{\text{rat}} K'_{ow}) + K_{\text{aH}} (1 + V_{\text{rat}} K_{ow})} \\
 &= \frac{[\text{H}_3\text{O}^+]}{[\text{H}_3\text{O}^+] + K_{\text{aH}} \left( \frac{1 + V_{\text{rat}} K_{ow}}{1 + V_{\text{rat}} K'_{ow}} \right)}
 \end{aligned}$$

## 4 Measuring the solubility of CyNMe<sub>2</sub> in aqueous solutions of [CyNMe<sub>3</sub>]I

Four samples of distilled water (average of 5 g accurate to 0.1 mg) were placed in 20 mL vials. To each vial, an average of 0.0, 450.0, 900.0, and 1350.0 mg of N,N,N-trimethylcyclohexylammonium iodide salt ([CyNMe<sub>3</sub>]I, a white powder) was added to make 0.0000, 0.3343, 0.6686 and 1.0030 M aqueous solutions, respectively. N,N-dimethylcyclohexylamine (CyNMe<sub>2</sub>) was then added to each solution until a biphasic mixture was observed. It should be noted that this biphasic mixture could not be attained for salt solutions with concentrations greater than 1.0 M. The mixtures were stirred for 30 min and allowed to settle for 3 h at which point it was assumed that equilibrium had been established. A sample from each aqueous layer was taken (450.0 mg average) and placed in a 50 mL volumetric flask. Acetophenone (20.0 μL) was added

to each flask as an internal standard and then each flask was filled with HPLC-grade methanol to the 50 mL mark. These samples were then analyzed by gas chromatography with flame-ionization detection (GC-FID). The weight of CyNMe<sub>2</sub> was calculated by a calibration curve of weight ratio (of acetophenone to CyNMe<sub>2</sub>) to peak area ratio (of acetophenone to CyNMe<sub>2</sub>). This was repeated in triplicate.

## 5 Measuring $\Delta \log K_{ow}$

CyNMe<sub>2</sub> (averaging 450.0 mg) was added to a mixture of water (averaging 5.0000 g) and 1-octanol (averaging 4.5000 g) at room temperature. The mixture was stirred for 30 min and was left to settle for 3 h. The pH of the aqueous layer was then measured. A sample of the aqueous layer (500.0 mg average) was drawn from the mixture and placed in a 50 mL volumetric flask. Acetophenone (20.0  $\mu$ L) was added as an internal standard. The solution was diluted to the mark with HPLC-grade methanol and analyzed by GC-FID. The weight of CyNMe<sub>2</sub> was calculated by a calibration curve of weight ratio (of acetophenone to CyNMe<sub>2</sub>) to peak area ratio (of acetophenone to CyNMe<sub>2</sub>).

Another mixture of CyNMe<sub>2</sub>, water, and 1-octanol was prepared and the pH was measured after CO<sub>2</sub> was bubbled through the system for 1 h under 101.3 kPa. Again, a sample from the aqueous layer (100.0 mg average) was taken and treated with excess base (to deprotonate the ammonium salt). Acetophenone (20  $\mu$ L) was added and the sample was diluted with methanol to the 50 mL mark. A smaller sample size was used to avoid saturating the GC column with the amine analyte.

Three more mixtures were prepared as described above. Glycolic acid was added to each mixture in 0.500, 1.00, and 2.00 mol equivalents to CyNMe<sub>2</sub>, respectively. Glycolic acid was chosen because its conjugate base is more stable than the bicarbonate anion and yet similar in size and hydrogen-bonding ability. The pH of each aqueous layer was measured. A 100.0 mg sample from each aqueous layer was taken and acetophenone (20.0  $\mu$ L) was added. The sample was treated with base, diluted with methanol to the 50 mL mark, and analyzed by GC-FID.

Finally, another mixture was prepared and treated with NaOH (1.00 mol equivalent to CyNMe<sub>2</sub>). The pH of the aqueous layer was measured and 500.0 mg of the aqueous layer was analyzed by GC-FID as described above.

Each sample was prepared in triplicate. This procedure was repeated with toluene in place of 1-octanol.