Supplementary Information for:

Simultaneous switching of two different CO_2-switchable amines in the same solution

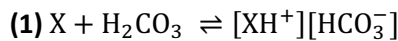Matthew Sanger[a], Daniel Barker[a], and Philip G. Jessop[a,*]

Contents:

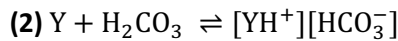## 1. Assumptions and equations used in the derivations

Assumptions made during equation derivations:
- There are two bases X and Y
- Both bases are infinitely water soluble in their neutral and bicarbonate salt form
- The pH never rises high enough to involve significant amounts of carbonate anions
- For derivations the subscript "aq" will be dropped for simplicity
- Solutions under CO_2 are assumed to be completely saturated with gas

The formula for bicarbonate salt formation with base X and Y is:

$$\textbf{(1)} \ X + H_2CO_3 \ \rightleftharpoons \ [XH^+][HCO_3^-]$$
$$\text{And}$$
$$\textbf{(2)} \ Y + H_2CO_3 \ \rightleftharpoons \ [YH^+][HCO_3^-]$$

The two bases X and Y have K_{aH} values shown below:

$$\textbf{(3)} \ K_X = \frac{[X]_{aq}[H_3O^+]_{aq}}{[XH^+]_{aq}}$$

$$\textbf{(4)} \ K_Y = \frac{[Y]_{aq}[H_3O^+]_{aq}}{[YH^+]_{aq}}$$

The two bases have nominal concentration in solution as described by:

The initial concentration of base X and Y can be defined by:

$$\textbf{(5)} \ [X]_0 = [X] + [XH^+] = \frac{K_X[XH^+]}{[H_3O^+]} + [XH^+] = [XH^+]\left(1 + \frac{K_X}{[H_3O^+]}\right)$$
$$\text{and}$$
$$\textbf{(6)} \ [Y]_0 = [Y] + [YH^+] = \frac{K_X[YH^+]}{[H_3O^+]} + [YH^+] = [YH^+]\left(1 + \frac{K_Y}{[H_3O^+]}\right)$$

We also know that the water dissociation constant is:

$$\textbf{(7)} \ K_W = [H_3O^+][OH^-]$$

2. Derivation of the equation for [H₃O⁺] with two bases in solution under air

The charge balance equation of these solutions can be given as:

$$\textbf{(8)} \ [XH^+] + [YH^+] + [H_3O^+] = [OH^-]$$

Substituting in the terms from equations 5, 6 and 7 we get:

$$\textbf{(9)} \ \frac{[X]_0}{1+K_X/[H_3O^+]} + \frac{[Y]_0}{1+K_Y/[H_3O^+]} + [H_3O^+] = K_W/[H_3O^+]$$

Multiplying and rearranging the terms to one side give the equation:

$$\textbf{(10)} \ 0 = [H_3O^+]^4 + (K_X + K_Y + [Y]_0 + [X]_0)[H_3O^+]^3 + (K_Y[X]_0 + K_X[Y]_0 + K_XK_Y - K_W)[H_3O^+]^2 -$$
$$(K_WK_X + K_WK_Y)[H_3O^+] - K_WK_XK_Y$$

3. Derivation of the equation for [H₃O⁺] with two bases in solution under CO₂

Two more general equations are required for the determination of $[H_3O^+]$ in solution when CO_2 is present: the apparent dissociation of CO_2 in water to bicarbonate:

$$\textbf{(11)} \ K_{a1}^* = \frac{[H_3O^+][HCO_3^-]}{[H_2CO_3]} + [CO_2]$$

And Henry's constant for the dissolution of CO_2 in water:

$$\textbf{(12)} \ K_H = \frac{([H_2CO_3]+[CO_2])}{P_{CO2}}$$

Combining the two equations gives:

$$\textbf{(13)} \ [HCO_3^-] = \frac{K_{a1}^* K_H P_{CO2}}{[H_3O^+]}$$

With bicarbonate present in solution under an atmosphere of CO_2 the new charge balance of the two base solution in water can be given as:

$$\textbf{(14)} \ [H_3O^+] + [XH^+] + [YH^+] = [OH^-] + [HCO_3^-]$$

Substituting in terms from equations 5, 6, 7 and 13 gives us the new formulae:

$$\textbf{(15)} \ [H_3O^+] + \frac{[H_3O^+][X]_0}{([H_3O^+]+K_X)} + \frac{[H_3O^+][Y]_0}{([H_3O^+]+K_Y)} = \frac{K_W}{[H_3O^+]} + \frac{K_{a1}^* K_H P_{CO2}}{[H_3O^+]}$$

Multiplying and rearranging the rems to one side gives the final equation:

$$(16)\ 0 = [H_3O^+]^4 + (K_X + K_Y + [X]_0 + [Y]_0)[H_3O^+]^3 + (K_XK_Y + K_Y[X]_0 + K_X[Y]_0 - K_W - K_{a1}^*K_HP_{CO2})[H_3O^+]^2 - (K_WK_X + K_WK_Y + K_{a1}^*K_HP_{CO2}K_X + K_{a1}^*K_HP_{CO2}K_Y)[H_3O^+] - K_{a1}^*K_HP_{CO2}K_XK_Y - K_WK_XK_Y$$

4. Derivation of the equation for % protonation of bases X and Y

The fraction of base X that is protonated can be written as:

$$(17)\ \text{Fraction protonated} = \frac{[XH^+]}{[X]_0}$$

Substituting in the term from equation 5 gives:

$$(18)\ \text{Fraction protonated} = \frac{[XH^+]}{([X]+[XH^+])}$$

Substituting in the terms from equation 3 gives:

$$(19)\ \text{Fraction protonated} = \frac{[X][H_3O^+]}{K_X([X]+[X][H_3O^+]/K_X)}$$

Multiplying and collecting like terms gives:

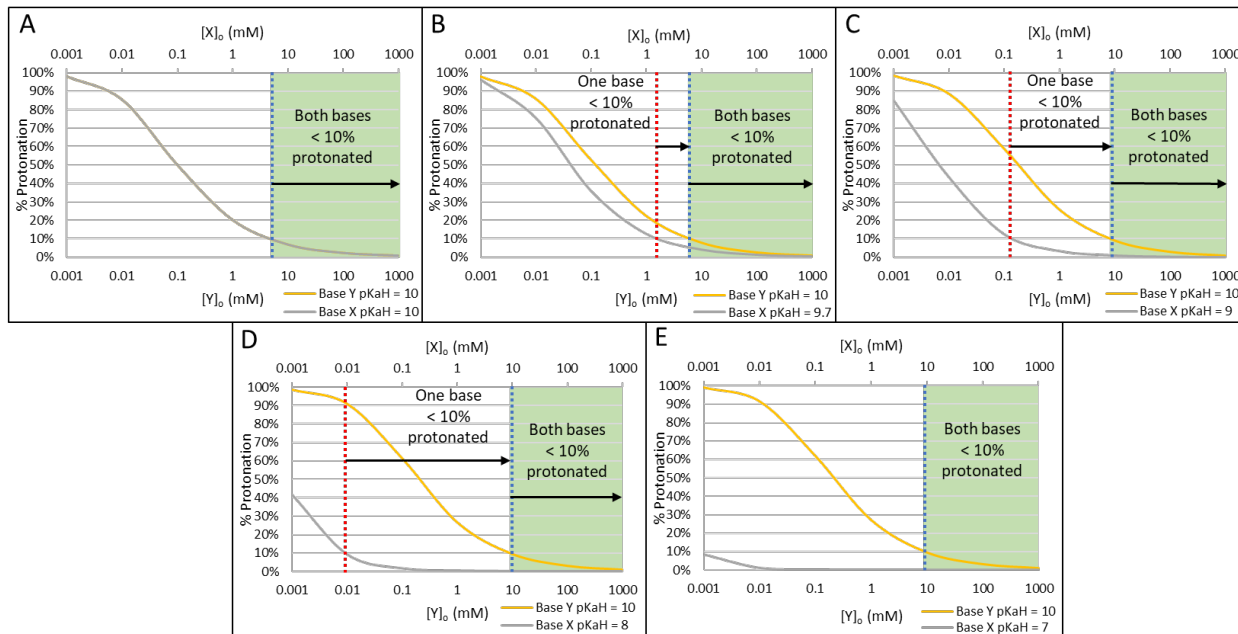$$(20)\ \text{Fraction protonated} = \frac{[H_3O^+]}{(K_X+[H_3O^+])}$$

Given as a percentage:

$$(21)\ \text{Percent protonated base X} = \frac{[H_3O^+]}{(K_X+[H_3O^+])} \times 100\%$$

Similarly for base Y:

$$(22)\ \text{Percent protonated base Y} = \frac{[H_3O^+]}{(K_Y+[H_3O^+])} \times 100\%$$

**5. Example graphs of predicted percent protonation of bases X and Y under air and CO₂ at different ΔpK_{aH}**

SI Figure 1. Predicted percent protonation of bases X and Y under air at different ΔpK_{aH}. A) 0 B) 0.3 C) 1 D) 2 and E) 3. Here, the basicity pK_X of the weaker base is allowed to vary but the basicity pK_Y of the stronger base remains fixed at 10. In the shaded area both bases are < 10% protonated under air, meeting criterion #1 for effective switching.
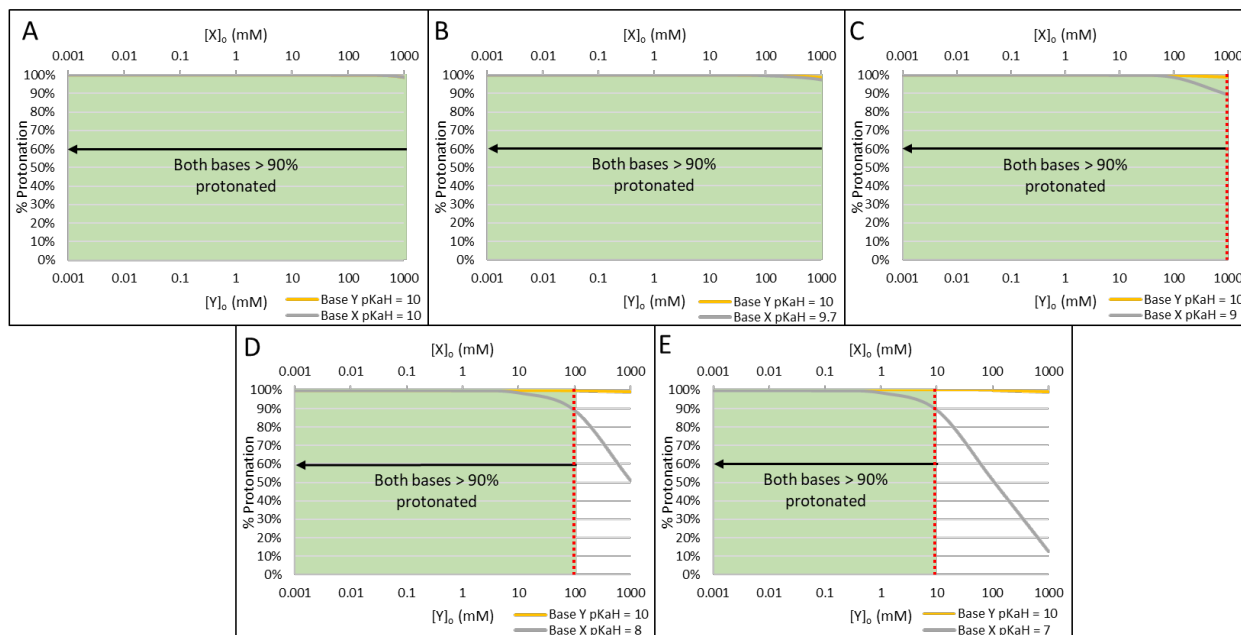
SI Figure 2. Predicted percent protonation of bases X and Y under an atmosphere of CO_2 at different ΔpK_{aH}, A) 0 B) 0.3 C) 1 D) 2 and E) 3. Here, the basicity pK_X of the weaker base is allowed to vary but the basicity pK_Y of the stronger base remains fixed at 10. In the shaded area both bases are > 90% protonated under an atmosphere of CO_2, meeting criterion #2 for effective switching.
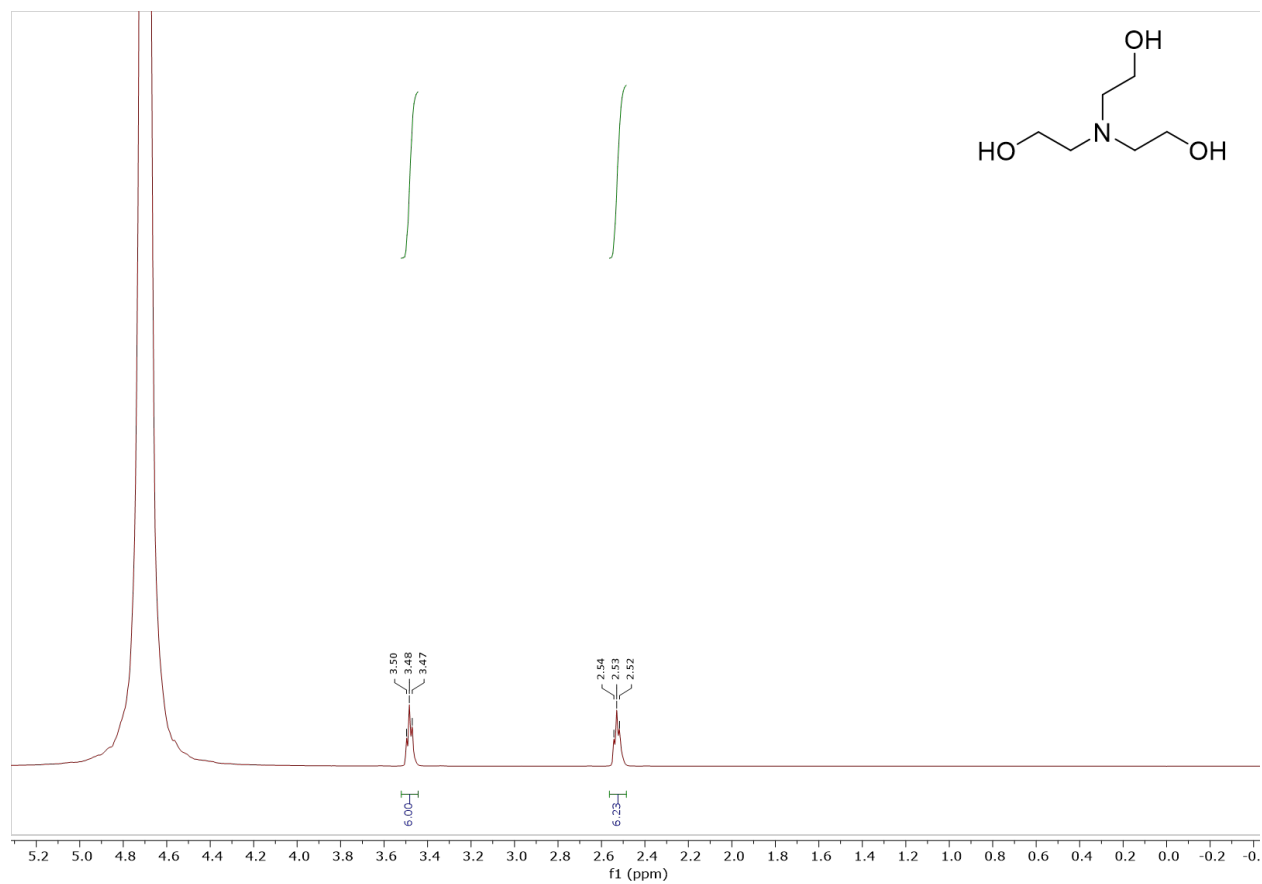
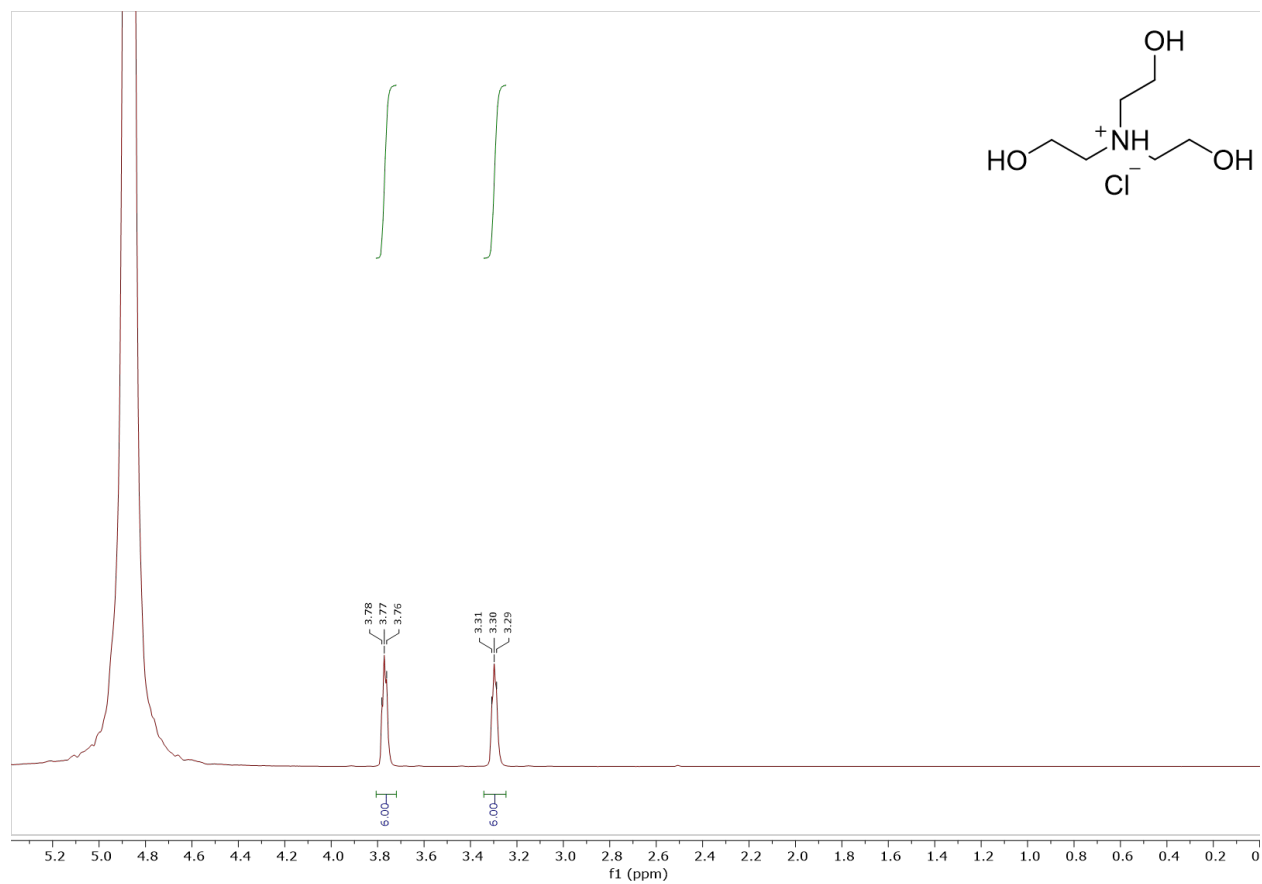**6. Example ^1H NMR spectra of MM, TEA in KOH and HCl**
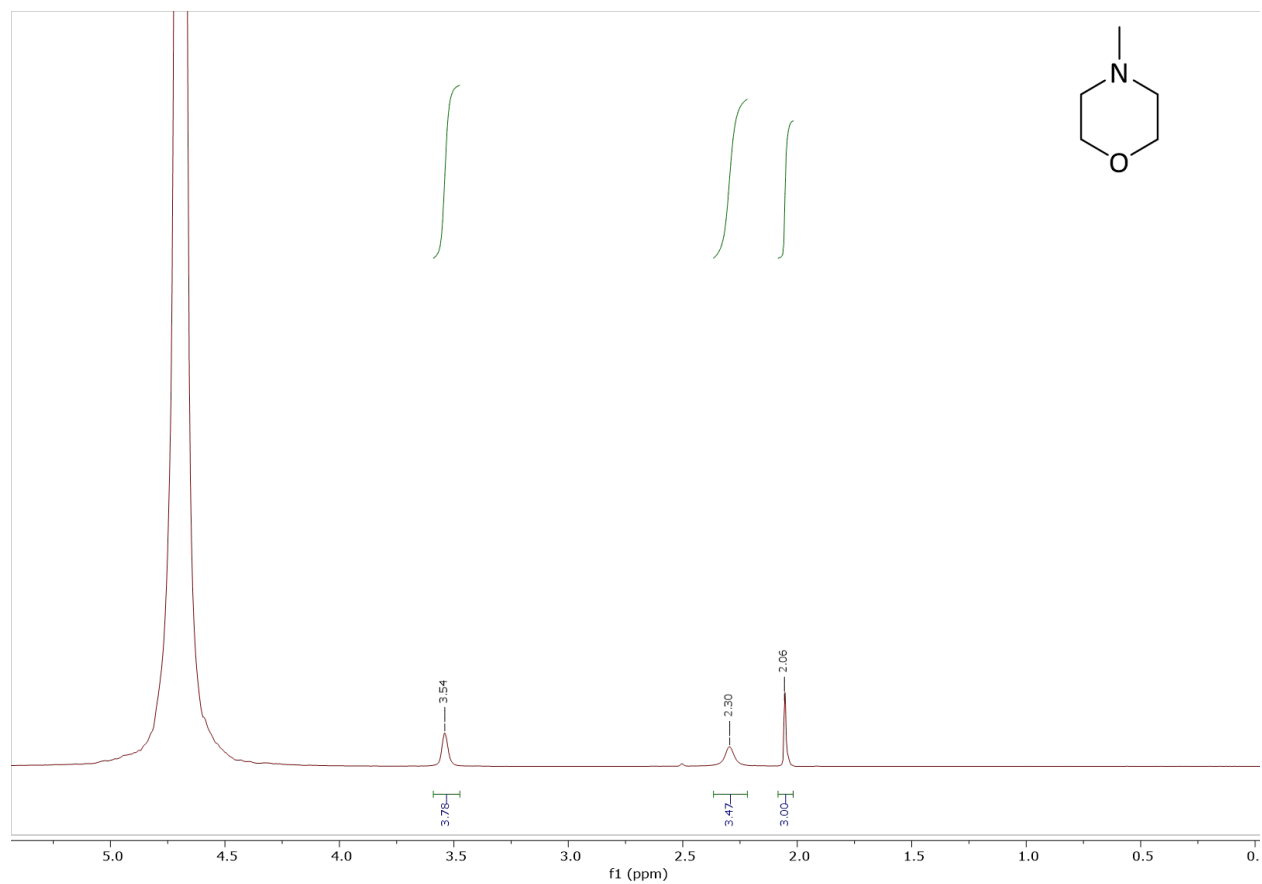
SI Figure 3. ^{1}H NMR spectrum of MM in 1 M KOH solution (500 MHz, H$_2$O, d6-DMSO). This was used to determine the chemical shifts of completely deprotonated MM.
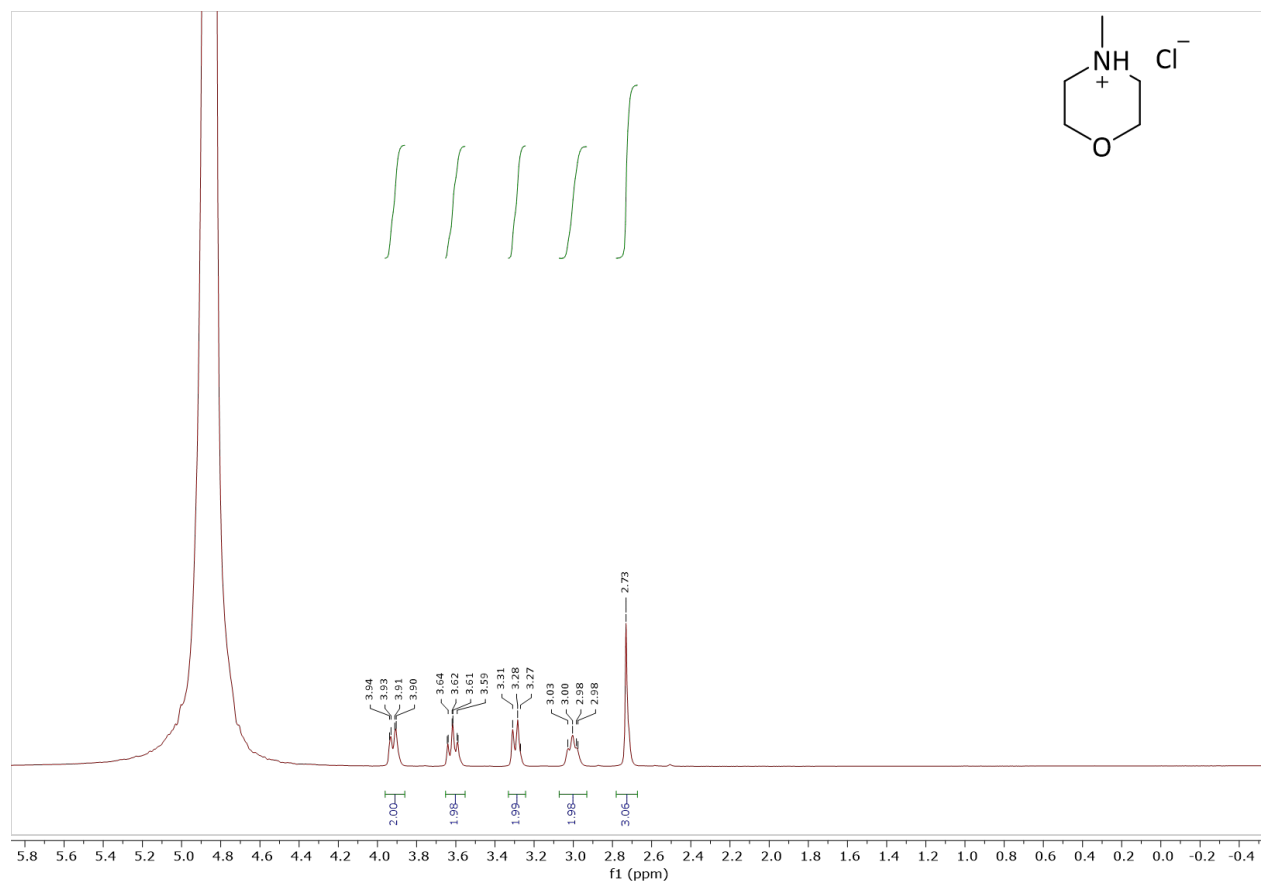
SI Figure 4. ^{1}H NMR spectrum of MM in 1 M HCl solution (500 MHz, H_2O, d6-DMSO). This was used to determine the chemical shifts of completely protonated MM.

SI Figure 5. ^{1}H NMR spectrum of TEA in 1 M KOH solution (500 MHz, H_2O, d6-DMSO). This was used to determine the chemical shifts of completely deprotonated TEA.

SI Figure 6. ^{1}H NMR spectrum of TEA in 1 M HCl solution (500 MHz, H_2O, d6-DMSO). This was used to determine the chemical shifts of completely protonated TEA.
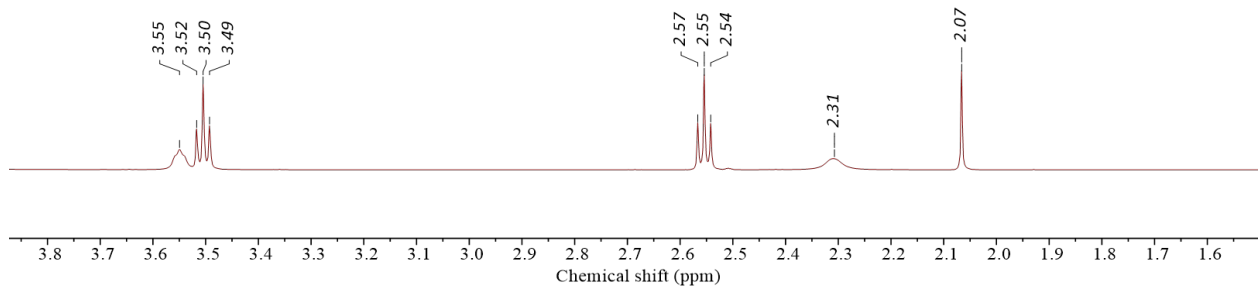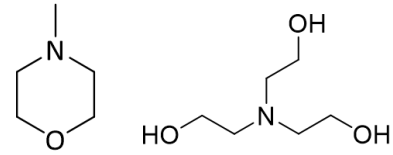
7. Example ^{1}H NMR spectra of ΔpK_{aH} = 0.47 solution at equal 0.1 M concentrations under air and under CO$_2$

SI Figure 7. ^{1}H NMR spectrum of MM and TEA in equal concentrations under air. (500 MHz, H$_2$O, d6-DMSO). This was used to determine the chemical shifts of MM and TEA under air so that a % protonation calcution could be performed.
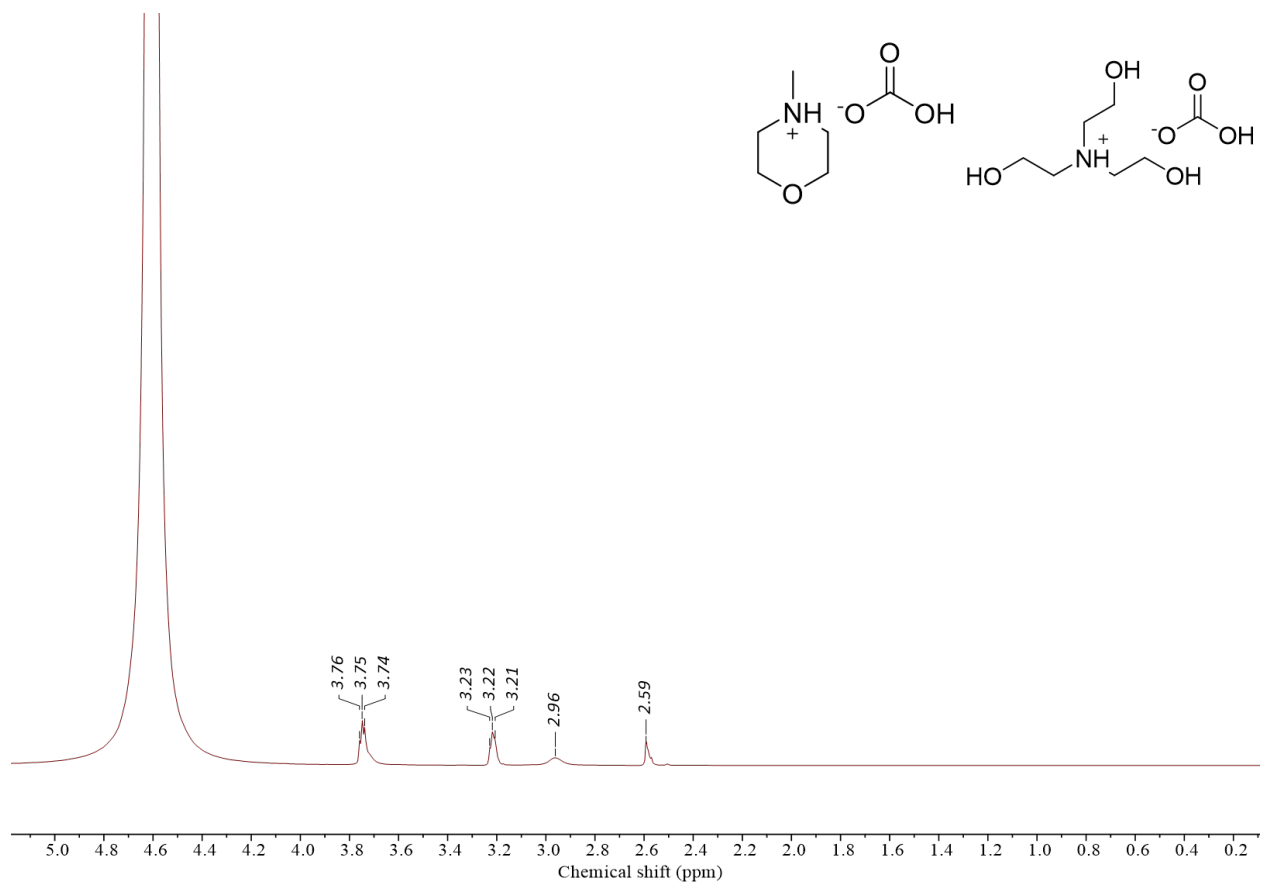
SI Figure 8. ^{1}H NMR spectrum of MM and TEA in equal concentrations under CO_2. (500 MHz, H_2O, d6-DMSO). This was used to determine the chemical shifts of MM and TEA under CO_2 so that a % protonation calcution could be perfromed.

8. Example calculation for % protonation under air and under CO_2

Table 1. Chemical shifts of MM and TEA in KOH, HCl, under air and under CO_2. MM and TEA were used to prepare the 0.5 Δpk_{aH} solution.

Amine	Chemical shift in KOH (ppm)	Chemical shift in HCl (ppm)	Chemical shift under Air (ppm)	Chemical shift under CO_2 (ppm)
MM	2.06	2.74	2.07	2.59
TEA	2.53	3.30	2.56	3.21

$$\% \text{ Protonation} = \frac{ppm_{obs} - ppm_{KOH}}{ppm_{HCl} - ppm_{KOH}} \times 100\%$$

Under Air

% protonation of MM

$$\% \text{ Protonation} = \frac{2.07 - 2.06}{2.74 - 2.06} \times 100\% = 0.015\% \approx 0\%$$

% protonation of TEA

$$\% \text{ Protonation} = \frac{2.56 - 2.53}{3.30 - 2.53} \times 100\% = 3.89\% \approx 4\%$$

Under CO_2

% protonation of MM

$$\% \text{ Protonation} = \frac{2.59 - 2.06}{2.74 - 2.06} \times 100\% = 77.9\% \approx 78\%$$

% protonation of TEA

$$\% \text{ Protonation} = \frac{3.21 - 2.53}{3.30 - 2.53} \times 100\% = 88.3\% \approx 88\%$$

9. Materials

4-Methylmorphine (MM, 99%), 3-diethylamino-1-propanol (DEAP, 99%), Triethanolamine (TEA, ≥99.0%), 2-(dimethylamino) ethanol (DMAE, 99%) were purchased from Sigma-Milipore and used as received. Deionized water was filtered through a Milipore® Filtration system containing a Synergy Pak® filtration cartridge. CO_2 gas (3.0) was purchased from Linde Canada and used as received.

10. Experimental Methods

Solution Preparation

To prepare a solution, the stronger and weaker amines were weighed out separately. Using an Eppendorf pipette, Millipore® water (15 mL) was measured and added to one of the amines. The amine was dissolved and then transferred to the other amine via the Eppendorf pipette. Different concentrations categories were prepared: equal concentrations of stronger and weaker amine, 10x excess of stronger amine, and 10x excess of weaker amine. Each of the 4 Δpk_{aH} pairs were made at each different concentration in triplicate resulting in 36 different solutions. CO_2 was bubbled through the solutions via a stainless steel needle for 4 h to saturate the solution with CO_2.

Analysis methods

The pH of each solution was analyzed by Thermo Scientific Orion 2-Star Benchtop pH meter that was calibrated using pH 4, 7, and 10 buffer solutions. The % protonation of solution was determined by ^{1}H NMR spectroscopy using a Bruker NEO-500 MHz NMR. Test solutions were added directly to the NMR tube and then 50 µL of deuterated dimethyl sulfoxide (d6-DMSO) was added as a locking solvent.