Skills to Develop

- Estimate the pH of the solution due to precipitate of a metal hydroxide.
- Calculate the maximum metal ion concentration when the pH is known.
- Explain behavior of amphoteric metal hydroxides.

Most metal hydroxides are insoluble; some such as $\ce{Ca(OH)2}$, $\ce{Mg(OH)2}$, $\ce{Fe(OH)2}$, $\ce{Al(OH)3}$ etc. are sparingly soluble. However, alkali metal hydroxides $\ce{CsOH}$, $\ce{KOH}$, and $\ce{NaOH}$ are very soluble, making them strong bases. When dissolved, these hydroxides are completely ionized. Since the hydroxide concentration, $\ce{[OH-]}$, is an integrated property of the solution, the solubility of metal hydroxide depends on pH, pOH or $\ce{[OH-]}$.

Alkali metal hydroxides $\ce{LiOH}$, $\ce{NaOH}$, $\ce{KOH}$, $\ce{CsOH}$ are soluble, and their solutions are basic. Hydroxides of alkali earth metals are much less soluble. For example, quicklime ($\ce{CaO}$) reacts with water to give slaked lime, which is slightly soluble.

\[
\begin{array}{ccccl}
\ce{CaO &+ &H2O &\rightleftharpoons &Ca(OH)2} \\
\text{quicklime} & & & &\text{slaked lime (slightly soluble)}
\end{array}
\]

Milk of magnesia is $\ce{Mg(OH)2}$ ($K_{\text{sp}} = 7e-12$) suspension. In an acidic solution such as stomach juice, the following reaction takes place,

\[
\ce{Mg(OH)2 + H+ \rightleftharpoons Mg^{2+} + 2 H2O}
\]

Thus, it can neutralize excess acid in the stomach.

Example 1

Calculate the maximum concentration of $\ce{Mg^{2+}}$ in a solution which contains a buffer so that pH = 3 at 298 K.

**SOLUTION**

As usual, we write the equilibrium equation so that we can write the concentration below the formula. If we do not know the concentration, we assume it to be a variable $x$.

\[
\begin{array}{cccccc}
\ce{Mg(OH)2 &\rightleftharpoons &Mg^{2+} &+ &2 OH-} \\
& &x & &1 \times 10^{-11}
\end{array}
\]

\[K_{\text{sp}} = x (1 \times 10^{-11})^2 = 7 \times 10^{-12}\]

Solving for $x$ results in $x = 7 \times 10^{10}$.
DISCUSSION

This value certainly is too large, unrealistic.

Example 2

Calculate the pH of a saturated \(\ce{Mg(OH)_2}\) solution.

SOLUTION

We assume the concentration to be \(x\) M of \(\ce{Mg(OH)}\), and note that \(\ce{[OH^-]} = 2x\),

\[
\begin{array}{cccccc}
\ce{Mg(OH)_2} &\rightleftharpoons &\ce{Mg^{2+}} &+ &2\ \ce{OH^-} \\
& x & & 2x & \\
\end{array}
\]

\[K_{sp} = x (2x)^2 = \text{7e-12}\]

Solving for \(x\); \(x = 1.2\times10^{-4}\)

\[
\begin{align}
\ce{[OH^-]} &= \text{2.4e-4} \\
\ce{pOH} &= 3.62 \\
\mathrm{pH = 14 - 3.62 = 10.38}\]
\]

DISCUSSION

The pH of a saturated lime (\(\ce{Ca(OH)_2}\)) solution is about 10.0.

Amphoteric Hydroxides

Not all metal hydroxides behave the same way - that is precipitate as hydroxide solids. Metal hydroxides such as \(\ce{Fe(OH)_3}\) and \(\ce{Al(OH)_3}\) react with acids and bases, and they are called amphoteric hydroxide. In reality, \(\ce{Al(OH)_3}\) should be formulated as \(\ce{Al(H_2O)_3(OH)_3}\), and this neutral substance has a very low solubility. It reacts in the following way as \(\ce{[H^+]}\) increases.

\[
\begin{align}
\ce{Al(H_2O)_3(OH)_3 + H_3O^+ &\rightleftharpoons Al(H_2O)_4(OH)_2 + HOH}} \\
\ce{Al(H_2O)_4(OH)_2 + H_3O^+ &\rightleftharpoons Al(H_2O)_5(OH)^2 + H_2O}} \\
\ce{Al(H_2O)_5(OH)^2 + H_3O^+ &\rightleftharpoons Al(H_2O)_6^3 + H_2O} \\
\end{align}
\]

When the pH increases, the following reactions take place:
\[
\begin{align*}
\ce{Al(H2O)3(OH)3 + OH- &\rightleftharpoons Al(H2O)2(OH)4- + H2O} \\
\ce{Al(H2O)2(OH)4- + OH- &\rightleftharpoons Al(H2O)(OH)5^2- + H2O} \\
\ce{Al(H2O)(OH)5^2- + OH- &\rightleftharpoons Al(OH)6^3- + H2O}
\end{align*}
\]

The charged species are soluble in water. As a result, amphoteric hydroxides dissolve in acidic and basic solutions.

**Questions**

1. Assume the pH of gastric juice to be 2. Calculate the maximum \(\ce{[Mg^2+]})\).
2. Calculate the pH of a 0.10 M \(\ce{[NH3]}\) solution.
3. Calculate the maximum \(\ce{[Fe^2+]})\) in a 0.10 M \(\ce{[NH3]}\) solution. Give the value in M.
4. What are amphoteric metal hydroxides? (enter no more than one line)

**Solutions**

1. **Answer** \(\text{Mg}^{2+} = 7 \times 10^{-12} \text{ M}\)
   
   Consider...
   
   We assume the temperature to be 298 K, which is too low.

   \[
   \ce{[Mg^2+] = \frac{7 \times 10^{-12}}{(1 \times 10^{-12})^2} = ?}\]

   This value is unrealistically large. The result is correct, but meaningless.

2. **Answer** pH = 11.12
   
   Consider...

   \[
   \ce{[OH^-] = (0.1 \times 10^{-1.8 - 5})^{1/2} = 1.34 \times 10^{-3}}\]

   \[
   \ce{[H+] = \frac{10^{-14}}{1.34 \times 10^{-3}} = 7.5 \times 10^{-12}}\]

   This value is required for the calculation in next question. Better yet, remember that \(\ce{[OH^-]} = 1.34 \times 10^{-14}\).

3. **Answer** 4.4e-10 M
   
   Consider...

   \[
   \ce{[Fe^{2+}] = \frac{7.9 \times 10^{-16}}{(1.34 \times 10^{-3})^2} = ? \text{ M}}\]

   What is the value in g/L? Molar mass of \(\ce{Fe}\) is 55.8 g/mol.

4. **Answer** Metal hydroxides such as \(\ce{Fe(OH)_3}\) and \(\ce{Al(OH)_3}\) that react with acids and bases are called amphoteric hydroxide.
Contributors

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