# Acid-Base Equilibria

## Section 91 – Bronsted-Lowry Acids and Bases

91-1 Write an equation that shows $NH_3$ acting as a base in aqueous solution. What is the conjugate acid of $NH_3$?

**Solution**

$NH_3(aq) + H_2O(l) \rightleftharpoons NH_4^+(aq) + OH^-(aq)$

The conjugate acid is the ammonium ion, $NH_4^+$.

91-2 Write equations that show $H_2PO_4^-$ acting both as an acid and as a base in aqueous solution. For each equation, indicate the conjugate acid/base pairs.

**Solution**

As a base: $H_2PO_4^-(aq) + H_2O(l) \rightleftharpoons H_3PO_4(aq) + OH^-(aq)$;
Base **acid** conjugate acid **conjugate base**

as an acid: $H_2PO_4^-(aq) + H_2O(aq) \rightleftharpoons HPO_4^{2-}(aq) + H_3O^+(aq)$
**acid** Base **conjugate base** conjugate acid

91-3 Show by suitable net ionic equations that each of the following species can act as a Brønsted-Lowry acid in aqueous solution:

(a) $H_3O^+$
(b) $HCl$
(c) $CH_3CO_2H$
(d) $NH_4^+$
(e) $HSO_4^-$

**Solution**

(a) $H_3O^+(aq) \rightleftharpoons H^+(aq) + H_2O(l)$;
(b) $HCl(l) \rightarrow H^+(aq) + Cl^-(aq)$;
(c) $CH_3CO_2H(aq) \rightleftharpoons H^+(aq) + CH_3CO_2^-(aq)$;
(d) $NH_4^+(aq) \rightleftharpoons H^+(aq) + NH_3(aq)$;
(e) $HSO_4^-(aq) \rightleftharpoons H^+(aq) + SO_4^{2-}(aq)$

91-4 Show by suitable net ionic equations that each of the following species can act as a Brønsted-Lowry acid.

(a) $HNO_3$
(b) $PH_4^+$
(c) $H_2S$

(d) $CH_3CH_2COOH$
(e) $H_2PO_4^-$

**Solution**

In a Brønsted-Lowry acid, the acid must supply an $H^+$.

(a) $HNO_3(aq) \rightarrow H^+(aq) + NO_3^-(aq)$;

(b) $PH_4^+(aq) \rightarrow H^+(aq) + PH_3(aq)$;

Note: the phosphonium ion, $PH_4^+$, is a strong acid, and will completely dissociate in water to form phosphine, $PH_3$. Phosphine is a toxic, flammable gas. There are important applications that use phosphine but it is very dangerous to work with. Thus, the phosphonium ion is not listed in our table of "common acids".

(c) $H_2S(aq) \rightleftharpoons H^+(aq) + HS^-(aq)$;

(d) $C_2H_5CO_2H(aq) \rightleftharpoons H^+(aq) + C_2H_5CO_2^-(aq)$;

(e) $H_2PO_4^-(aq) \rightleftharpoons H^+(aq) + HPO_4^{2-}(aq)$;

91-5 Show by suitable net ionic equations that each of the following species can act as a Brønsted-Lowry base in aqueous solution:

(a) $H_2O$
(b) $OH^-$
(c) $NH_3$
(d) $CN^-$
(e) $S^{2-}$
(f) $H_2PO_4^-$

**Solution**

(a) $H_2O(l) + H^+(aq) \rightleftharpoons H_3O^+(aq)$;

(b) $OH^-(aq) + H^+(aq) \rightleftharpoons H_2O(l)$;

(c) $NH_3(aq) + H^+(aq) \rightleftharpoons NH_4^+(aq)$;

(d) $CN^-(aq) + H^+(aq) \rightleftharpoons HCN(aq)$;

(e) $S^{2-}(aq) + H^+(aq) \rightleftharpoons HS^-(aq)$;

(f) $H_2PO_4^-(aq) + H^+(aq) \rightleftharpoons H_3PO_4(aq)$

91-6 Show by suitable net ionic equations that each of the following species can act as a Brønsted-Lowry base:

(a) $HS^-$
(b) $PO_4^{3-}$
(c) $NH_2^-$
(d) $C_2H_5OH$
(e) $O^{2-}$
(f) $H_2PO_4^-$

**Solution**

In a Brønsted-Lowry base, the base must accept an $H^+$.

(a) $HS^- + H^+ \rightleftharpoons H_2S$;
(b) $PO_4{}^{3-} + H^+ \rightleftharpoons HPO_4{}^{2-}$;
(c) $NH_2{}^- + H^+ \rightleftharpoons NH_3$
(d) $C_2H_5OH + H^+ \rightleftharpoons C_2H_5OH_2{}^+$;
(e) $O^{2-} + H^+ \rightleftharpoons OH^-$;
(f) $HPO_4{}^{2-} + H^+ \rightleftharpoons H_2PO_4{}^-$

91-7 What is the conjugate acid of each of the following? What is the conjugate base of each?
(a) $OH^-$
(b) $H_2O$
(c) $HCO_3{}^-$
(d) $NH_3$
(e) $HSO_4{}^-$
(f) $H_2O_2$
(g) $HS^-$
(h) $H_5N_2{}^+$

**Solution**

Note that to form the conjugate acid, you just add an $H^+$; to form the conjugate base you remove an $H^+$. Be careful to balance the charge.

(a) $H_2O$, $O^{2-}$;
(b) $H_3O^+$, $OH^-$;
(c) $H_2CO_3$, $CO_3{}^{2-}$;
(d) $NH_4{}^+$, $NH_2{}^-$;
(e) $H_2SO_4$, $SO_4{}^{2-}$;
(f) $H_3O_2{}^+$, $HO_2{}^-$;
(g) $H_2S$; $S^{2-}$;
(h) $H_6N_2{}^{2+}$, $H_4N_2$

91-8 What is the conjugate acid of each of the following? What is the conjugate base of each?

(a) $H_2S$
(b) $H_2PO_4{}^-$
(c) $PH_3$
(d) $HS^-$
(e) $HSO_3{}^-$
(f) $H_3O_2{}^+$
(g) $H_4N_2$
(h) $CH_3OH$

**Solution**

(a) $H_3S^+$, $HS^-$;
(b) $H_3PO_4{}^-$, $HPO_4{}^{2-}$;
(c) $PH_4{}^+$, $PH_2{}^-$;
(d) $H_2S$, $S^{2-}$;

(e) $H_2SO_3$, $SO_3^{2-}$;
(f) $H_4O_2^{2+}$, $H_2O_2$;
(g) $H_5N_2^{+}$, $H_3N_2^{-}$;
(h) $CH_3OH_2^{+}$, $CH_3O^{-}$

91-9 Identify and label the Brønsted-Lowry acid, its conjugate base, the Brønsted-Lowry base, and its conjugate acid in each of the following equations:

(a) $HNO_3 + H_2O \longrightarrow H_3O^+ + NO_3^-$

(b) $CN^- + H_2O \longrightarrow HCN + OH^-$

(c) $H_2SO_4 + Cl^- \longrightarrow HCl + HSO_4^-$

(d) $HSO_4^- + OH^- \longrightarrow SO_4^{2-} + H_2O$

(e) $O^{2-} + H_2O \longrightarrow 2OH^-$

(f) $[Cu(H_2O)_3(OH)]^+ + [Al(H_2O)_6]^{3+} \longrightarrow [Cu(H_2O)_4]^{2+} + [Al(H_2O)_5(OH)]^{2+}$

(g) $H_2S + NH_2^- \longrightarrow HS^- + NH_3$

**Solution**

The labels are Brønsted-Lowry acid = BA; its conjugate base = CB; Brønsted-Lowry base = BB; its conjugate acid = CA.

(a) $HNO_3$(BA), $H_2O$(BB), $H_3O^+$(CA),$NO_3^-$(CB);
(b) $CN^-$(BB), $H_2O$(BA), HCN(CA), $OH^-$(CB);
(c) $H_2SO_4$(BA), $Cl^-$(BB), HCl(CA), $HSO_4^-$(CB);
(d) $HSO_4^-$(BA), $OH^-$(BB), $SO_4^{2-}$(CB), $H_2O$(CA);
(e) $O^{2-}$(BB), $H_2O$(BA) $OH^-$(CB and CA);
(f) $[Cu(H_2O)_3(OH)]^+$(BB), $[Al(H_2O)_6]^{3+}$(BA), $[Cu(H_2O)_4]^{2+}$(CA), $[Al(H_2O)_5(OH)]^{2+}$(CB); (g) $H_2S$(BA), $NH_2^-$(BB), $HS^-$(CB), $NH_3$(CA)

91-10 Identify and label the Brønsted-Lowry acid, its conjugate base, the Brønsted-Lowry base, and its conjugate acid in each of the following equations:

(a) $NO_2^- + H_2O \longrightarrow HNO_2 + OH^-$

(b) $HBr + H_2O \longrightarrow H_3O^+ + Br^-$

(c) $HS^- + H_2O \longrightarrow H_2S + OH^-$

(d) $H_2PO_4^- + OH^- \longrightarrow HPO_4^{2-} + H_2O$

(e) $H_2PO_4^- + HCl \longrightarrow H_3PO_4 + Cl^-$

(f) $[Fe(H_2O)_5(OH)]^{2+} + [Al(H_2O)_6]^{3+} \longrightarrow [Fe(H_2O)_6]^{3+} + [Al(H_2O)_5(OH)]^{2+}$

(g) $CH_3OH + H^- \longrightarrow CH_3O^- + H_2$

**Solution**

The labels are Brønsted-Lowry acid = BA; its conjugate base = CB; Brønsted-Lowry base = BB; and its conjugate acid = CA.

(a) $NO_2^-$ (BB), $H_2O$(BA), $HNO_2$(CA), $OH^-$(CB);
(b) HBr(BA), $H_2O$(BB), $H_3O^+$ (CA), $Br^-$(CB);
(c) $HS^-$(BB), $H_2O$(BA), $H_2S$(CA), $OH^-$(CB)$^-$;
(d) $H_2PO_4^-$ (BA), $OH^-$(BB), $HPO_4^{2-}$ (CB), $H_2O$(CA);
(e) $H_2PO_4^-$ (BB), HCl(BA), $H_3PO_4$(CA), $Cl^-$(CB);
(f) $[Fe(H_2O)_5(OH)]^{2+}$ (BB), $[Al(H_2O)_6]^{3+}$ (BA), $[Fe(H_2O)_6]^{3+}$ (CA), $[Al(H_2O)_5(OH)]^{2+}$ (CB);
(g) $CH_3OH$(BA), $H^-$(BB), $CH_3O^-$ (CB), $H_2$(CA)

91-11 What are amphiprotic species? Illustrate with suitable equations.

**Solution**

Amphiprotic species may either gain or lose a proton in a chemical reaction, thus acting as a base or an acid. An example is $H_2O$. As an acid: $H_2O(l) + NH_3(aq) \rightleftharpoons NH_4^+(aq) + OH^-(aq)$. As a base: $H_2O(l) + HCl(aq) \rightleftharpoons H_3O^+(aq) + Cl^-(aq)$

91-12 State which of the following species are amphiprotic and write chemical equations illustrating the amphiprotic character of these species:

(a) $H_2O$
(b) $H_2PO_4^-$
(c) $S^{2-}$
(d) $CO_3^{2-}$
(e) $HSO_4^-$

**Solution**

amphiprotic:

(a) $H_2O(l) + HBr(aq) \rightleftharpoons H_3O^+(aq) + Br^-(aq)$,
$H_2O(l) + CN^-(aq) \rightleftharpoons HCN(aq) + OH^-(aq)$;
(b) $H_2PO_4^-(aq) + HBr(aq) \rightleftharpoons H_3PO_4(aq) + Br^-(aq)$,
$H_2PO_4^-(aq) + OH^-(aq) \rightleftharpoons HPO_4^{2-}(aq) + H_2O(l)$;
(e) $HSO_4^-(aq) + HClO_4(aq) \rightleftharpoons H_2SO_4(aq) + ClO_4^-(aq)$,
$HSO_4^-(aq) + OH^-(aq) \rightleftharpoons SO_4^{2-}(aq) + H_2O(l)$;

not amphiprotic (neither has a proton to donate, and so cannot serve as an acid): (c) $S^{2-}$, (d) $CO_3^{2-}$

91-13 State which of the following species are amphiprotic and write chemical equations illustrating the amphiprotic character of these species.

(a) $NH_3$
(b) $HPO_4^{2-}$
(c) $Br^-$
(d) $NH_4^+$
(e) $ASO_4^{3-}$

**Solution**

Amphiprotic:

(a) $NH_3 + H_3O^+ \rightleftharpoons NH_4OH + H_2O$, $NH_3 + OCH_3{}^- \rightleftharpoons NH_2{}^- + CH_3OH$;

(b) $HPO_4{}^{2-} + OH^- \rightleftharpoons PO_4{}^{3-} + H_2O$, $HPO_4{}^{2-} + HClO_4 \rightleftharpoons H_2PO_4{}^- + ClO_4{}^-$;

not amphiprotic: (c) $Br^-$; (d) $NH_4{}^+$; (e) $AsO_4{}^{3-}$

91-14 Which of the following does not fit the definition of a Brønsted Acid?

(a) $H_3PO_4$
(b) $H_2PO_4{}^-$
(c) $H_2O$
(d) $NH_4{}^+$
(e) $CO_2$

**Solution:** A Brønsted Acid can donate a proton. All of compounds (a) – (d) have protons that they can donate in aqueous solution. $CO_2$ does not have any protons, and thus it cannot directly act as a Brønsted

91-15 Which of the following does not fit the definition of a Brønsted Base?

(a) $NH_3$
(b) $H_2O$
(c) $NH_4{}^+$
(d) $HCO_3{}^-$
(e) $CO_3{}^{2-}$

**Solution:** A Brønsted Base can accept a proton. All of the compounds except ammonium ion ($NH_4{}^+$) can accept a proton, and so ammonium ion is the only one that cannot act as a Brønsted Base.

91-16 Is the self-ionization of water endothermic or exothermic? The ionization constant for water ($K_w$) is $2.9 \times 10^{-14}$ at 40 °C and $9.3 \times 10^{-14}$ at 60 °C.

**Solution**

The equation for the self-ionization of water is

$$2H_2O(l) \rightleftharpoons H_3O^+(aq) + OH^-(aq),$$

You are given that the $K_w$ increases with increasing temperature – i.e., when more heat is available, the reaction shifts to the product side. According to Le Châtelier's principle, the system will try to resist the change (added heat), and so it will shift in the direction that uses up heat. Therefore, the reaction is endothermic.