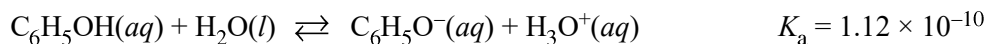


AP[®] CHEMISTRY
2016 SCORING GUIDELINES

Question 4



Phenol is a weak acid that partially dissociates in water, according to the equation above.

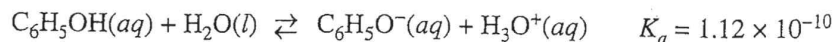
(a) What is the pH of a 0.75 M $\text{C}_6\text{H}_5\text{OH}(aq)$ solution?

$K_a = \frac{[\text{C}_6\text{H}_5\text{O}^-][\text{H}_3\text{O}^+]}{[\text{C}_6\text{H}_5\text{OH}]}$ $1.12 \times 10^{-10} = \frac{x^2}{(0.75 - x)} \quad \text{Assume that } x \ll 0.75.$ $x^2 = 8.4 \times 10^{-11}$ $x = \sqrt{8.4 \times 10^{-11}}$ $x = 9.2 \times 10^{-6} \text{ M}$ $\text{pH} = -\log[\text{H}^+] = -\log(9.2 \times 10^{-6}) = 5.04$	<p>1 point is earned for a correct setup and calculation of $[\text{H}^+]$.</p> <p>1 point is earned for the correct setup and calculation of pH based on a correct setup for the $[\text{H}^+]$ calculation.</p>
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(b) For a certain reaction involving $\text{C}_6\text{H}_5\text{OH}(aq)$ to proceed at a significant rate, the phenol must be primarily in its deprotonated form, $\text{C}_6\text{H}_5\text{O}^-(aq)$. In order to ensure that the $\text{C}_6\text{H}_5\text{OH}(aq)$ is deprotonated, the reaction must be conducted in a buffered solution. On the number scale below, circle each pH for which more than 50 percent of the phenol molecules are in the deprotonated form ($\text{C}_6\text{H}_5\text{O}^-(aq)$). Justify your answer.

<p>Numbers 10 through 14 should be circled.</p> <p>When $\text{pH} > \text{p}K_a$, the deprotonated form will predominate. $\text{p}K_a = -\log(1.12 \times 10^{-10}) = 9.95$, therefore at pH 10 and above, $[\text{C}_6\text{H}_5\text{O}^-] > [\text{C}_6\text{H}_5\text{OH}]$.</p>	<p>1 point is earned for circling 10–14.</p> <p>1 point is earned for the justification.</p>
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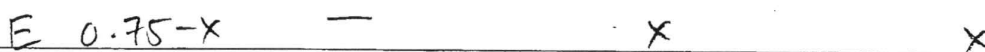
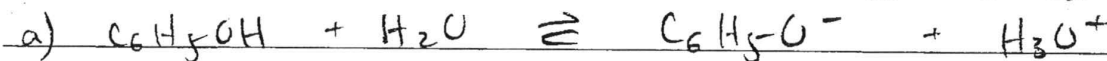
1 2 3 4 5 6 7 8 9 10 11 12 13 14



4. Phenol is a weak acid that partially dissociates in water according to the equation above.

- (a) What is the pH of a 0.75 M $\text{C}_6\text{H}_5\text{OH}(aq)$ solution?
- (b) For a certain reaction involving $\text{C}_6\text{H}_5\text{OH}(aq)$ to proceed at a significant rate, the phenol must be primarily in its deprotonated form, $\text{C}_6\text{H}_5\text{O}^-(aq)$. In order to ensure that the $\text{C}_6\text{H}_5\text{OH}(aq)$ is deprotonated, the reaction must be conducted in a buffered solution. On the number scale below, circle each pH for which more than 50 percent of the phenol molecules are in the deprotonated form ($\text{C}_6\text{H}_5\text{O}^-(aq)$). Justify your answer.

1 2 3 4 5 6 7 8 9 10 11 12 13 14



$$1.12 \times 10^{-10} = \frac{x^2}{0.75-x} \qquad x \ll 0.75 \text{ because } K_a \text{ is very small}$$

$$1.12 \times 10^{-10} = \frac{x^2}{0.75}$$

$$x^2 = 8.4 \times 10^{-11}$$

$$x = 9.2 \times 10^{-6} = [\text{H}^+]$$

$$\text{pH} = -\log(9.2 \times 10^{-6}) = 5.04$$

$$\text{b) } \text{pH} = \text{p}K_a + \log \frac{[\text{A}^-]}{[\text{HA}]} \qquad \text{when } \frac{[\text{A}^-]}{[\text{HA}]} > 1, \text{ A}^- > 50\%$$

$$\text{pH} = \text{p}K_a \text{ when } \frac{[\text{A}^-]}{[\text{HA}]} = 1$$

$$= -\log(1.12 \times 10^{-10}) = 9.951$$

$$\text{when } \frac{[\text{A}^-]}{[\text{HA}]} > 1, \text{ pH} > \text{p}K_a$$

$$\text{pH} > 9.951$$

$$\text{pH} = 10, 11, 12, 13, 14$$

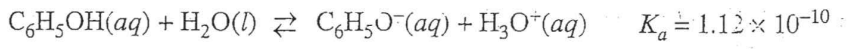
$$\text{when } [\text{C}_6\text{H}_5\text{O}^-] = [\text{C}_6\text{H}_5\text{OH}], \text{ pH} = \text{p}K_a = 9.951.$$

$$\text{For any solution where } [\text{C}_6\text{H}_5\text{O}^-] > [\text{C}_6\text{H}_5\text{OH}].$$

ADDITIONAL PAGE FOR ANSWERING QUESTION 4

$\text{pH} > \text{pK}_a$. In basic solutions with $\text{pH} > \text{pK}_a$,
the equilibrium is shifted to the left enough so
that $[\text{C}_6\text{H}_5\text{O}^-] > [\text{C}_6\text{H}_5\text{OH}]$.

GO ON TO THE NEXT PAGE.



4. Phenol is a weak acid that partially dissociates in water according to the equation above.

- (a) What is the pH of a 0.75 M $C_6H_5OH(aq)$ solution?
- (b) For a certain reaction involving $C_6H_5OH(aq)$ to proceed at a significant rate, the phenol must be primarily in its deprotonated form, $C_6H_5O^-(aq)$. In order to ensure that the $C_6H_5OH(aq)$ is deprotonated, the reaction must be conducted in a buffered solution. On the number scale below, circle each pH for which more than 50 percent of the phenol molecules are in the deprotonated form ($C_6H_5O^-(aq)$). Justify your answer:

1 2 3 4 5 6 7 8 9 10 11 12 13 14

a) R $C_6H_5OH + H_2O \rightleftharpoons C_6H_5O^- + H_3O^+$

I	0.75	0	0
C	-x	+x	+x
E	0.75	x	x

$$\frac{x^2}{0.75} = 1.12 \times 10^{-10}$$

$$x = 9.16 \times 10^{-6}$$

$$-\log(9.16 \times 10^{-6}) = 5.04$$

pH = 5.04

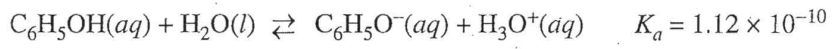
$$-\log[H_3O^+] = -\log\left(\frac{[A^-][H_3O^+]}{[HA]}\right) = \log\left(\frac{[A^-]}{[HA]}\right)$$

b) $pH = -\log pK_a - \log\left(\frac{[A^-]}{[HA]}\right)$

$pH = 9.95 - \log\left(\frac{[A^-]}{[HA]}\right)$ concentration of

According to this formula, whenever A^- (the deprotonated acid, or $C_6H_5O^-$) is larger than the concentration of HA, the pH will be below the pKa, or 9.95. As such, all pH's 9 or below will have a higher concentration of $C_6H_5O^-$ than C_6H_5OH .

4C



4. Phenol is a weak acid that partially dissociates in water according to the equation above.

- (a) What is the pH of a 0.75 M $C_6H_5OH(aq)$ solution?
- (b) For a certain reaction involving $C_6H_5OH(aq)$ to proceed at a significant rate, the phenol must be primarily in its deprotonated form, $C_6H_5O^-(aq)$. In order to ensure that the $C_6H_5OH(aq)$ is deprotonated, the reaction must be conducted in a buffered solution. On the number scale below, circle each pH for which more than 50 percent of the phenol molecules are in the deprotonated form ($C_6H_5O^-(aq)$). Justify your answer.

1 2 3 4 5 6 7 8 9 10 11 12 13 14

~~@ pH = -log[0.75 M]~~
~~pH = 0.125~~
~~pH = pKa + log $\frac{[A^-]}{[HA]}$~~
~~pH = 9.95 + 0~~
pH = 9.95

(b) ~~deprotonated~~ \rightarrow more electrons there are more products than reactants when the solution is more basic because $[A^-] > [HA]$ so $\log \frac{[A^-]}{[HA]} > 0$ which gets added to the pKa making it more basic and greater than the original pH of 9.95.

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AP[®] CHEMISTRY
2016 SCORING COMMENTARY

Question 4

Overview

Question 4 explored students' knowledge of weak acid equilibrium conditions in aqueous solution and conjugate acid/base relationships in a buffered solution. Students were given two scenarios involving solutions of phenol, $C_6H_5OH(aq)$. In part (a) students were to calculate the pH of a 0.75 M solution of phenol given the K_a value for this weak acid. In part (b) students were asked to select pH values of a buffered solution that would ensure more than 50% of the phenol was in its deprotonated form, $C_6H_5O^-(aq)$.

Sample: 4A

Score: 4

In part (a) 1 point was earned for setting up and correctly calculating $[H^+]$, and 1 point was earned for setting up and correctly calculating the pH. In part (b) 1 point was earned for circling numbers 10–14, and 1 point was earned for a justification that clearly describes buffers with a greater concentration of conjugate base than conjugate acid corresponding to a $pH > pK_a$.

Sample: 4B

Score: 3

In part (a) 1 point was earned for setting up and correctly calculating $[H^+]$, and 1 point was earned for setting up and correctly calculating the pH. In part (b) no point was earned for circling numbers 1–9; however, 1 point was earned for a justification consistent with the circled numbers. The student makes a sign error using the Henderson-Hasselbalch equation and matches the increasing concentration of conjugate base with a *decreasing* pH.

Sample: 4C

Score: 2

In part (a) neither of the two possible points were earned; the student calculates $[H^+]$ incorrectly and bases the calculation of pH on an incorrect application of the Henderson-Hasselbalch equation. In part (b) 1 point was earned for circling numbers 10–14, and 1 point was earned for a consistent justification that describes the increase of conjugate base concentration and increased base/acid ratio when $pH > pK_a$.