AP® CHEMISTRY
2012 SCORING GUIDELINES

Question 6
(9 points)

In a laboratory experiment, Pb and an unknown metal Q were immersed in solutions containing aqueous ions of unknown metals Q and X. The following reactions summarize the observations.

Observation 1: $Pb(s) + X^{2+}(aq) \rightarrow Pb^{2+}(aq) + X(s)$
Observation 2: $Q(s) + X^{2+}(aq) \rightarrow$ no reaction
Observation 3: $Pb(s) + Q^{2+}(aq) \rightarrow Pb^{2+}(aq) + Q(s)$

(a) On the basis of the reactions indicated above, arrange the three metals, Pb, Q, and X, in order from least reactive to most reactive on the lines provided below.

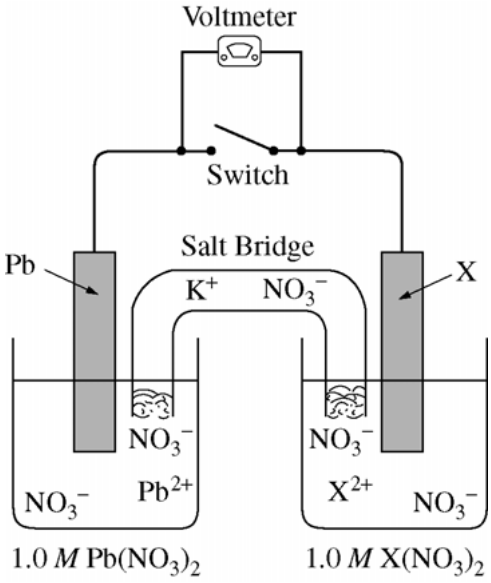
_____Q_____ , _____X_____ , _____Pb_____

least reactive metal most reactive metal

Q, X, Pb	2 points are earned for the correctly ordered relationship. (1 point earned for Q, Pb, X or X, Q, Pb)

Question 6 (continued)

The diagram below shows an electrochemical cell that is constructed with a Pb electrode immersed in 100. mL of 1.0 *M* $Pb(NO_3)_2(aq)$ and an electrode made of metal X immersed in 100. mL of 1.0 *M* $X(NO_3)_2(aq)$. A salt bridge containing saturated aqueous KNO_3 connects the anode compartment to the cathode compartment. The electrodes are connected to an external circuit containing a switch, which is open. When a voltmeter is connected to the circuit as shown, the reading on the voltmeter is 0.47 V. When the switch is closed, electrons flow through the switch from the Pb electrode toward the X electrode.



(b) Write the equation for the half-reaction that occurs at the anode.

$Pb(s) \rightarrow Pb^{2+}(aq) + 2\ e^-$	1 point is earned for the correct equation.

(c) The value of the standard potential for the cell, $E°$, is 0.47 V.

(i) Determine the standard reduction potential for the half-reaction that occurs at the cathode.

$E^\circ_{cell} = E^\circ_{cathode} - E^\circ_{anode}$ $E^\circ_{cathode} = E^\circ_{cell} + E^\circ_{anode}$ $E^\circ_{cathode} = 0.47 + (-0.13) = 0.34$ V	1 point is earned for the calculated reduction potential with mathematical justification.

Question 6 (continued)

(ii) Determine the identity of metal X.

The metal is copper.	1 point is earned for identification of the metal.

(d) Describe what happens to the mass of each electrode as the cell operates.

The mass of the Pb electrode decreases and the mass of the Cu electrode increases.	1 point is earned for both descriptions.

(e) During a laboratory session, students set up the electrochemical cell shown above. For each of the following three scenarios, choose the correct value of the cell voltage and justify your choice.

(i) A student bumps the cell setup, resulting in the salt bridge losing contact with the solution in the cathode compartment. Is V equal to 0.47 or is V equal to 0? Justify your choice.

V = 0 V. The transfer of ions through the salt bridge will stop. A charge imbalance between the half-cells will prevent electrons from flowing through the wire.	1 point is earned for the correct choice with an appropriate explanation.

(ii) A student spills a small amount of 0.5 M $Na_2SO_4(aq)$ into the compartment with the Pb electrode, resulting in the formation of a precipitate. Is V less than 0.47 or is V greater than 0.47 ? Justify your choice.

V > 0.47 V. The sulfate ion will react with the Pb^{2+} ion to form a precipitate. This results in a thermodynamically favored anode half-cell reaction and hence a larger potential difference. The choice may also be justified using the Nernst equation. $E_{cell} = E^{\circ}_{cell} - \left(\frac{RT}{nF}\right)\ln\frac{[Pb^{2+}]}{[Cu^{2+}]}$ Decreasing the $[Pb^{2+}]$ will increase the cell voltage.	1 point is earned for the correct choice with an appropriate explanation.

(iii) After the laboratory session is over, a student leaves the switch closed. The next day, the student opens the switch and reads the voltmeter. Is V less than 0.47 or is V equal to 0.47? Justify your choice.

V < 0.47 V. Over time, $[Pb^{2+}]$ increases and $[Cu^{2+}]$ decreases, making both half-cell reactions less thermodynamically favorable. The choice may also be justified using the Nernst equation. Increasing $[Pb^{2+}]$ and decreasing $[Cu^{2+}]$ decreases the cell voltage. The choice may also be justified by stating that the voltage is zero as a result of the establishment of equilibrium.	1 point is earned for the correct choice with an appropriate explanation.

6. In a laboratory experiment, Pb and an unknown metal Q were immersed in solutions containing aqueous ions of unknown metals Q and X. The following reactions summarize the observations.

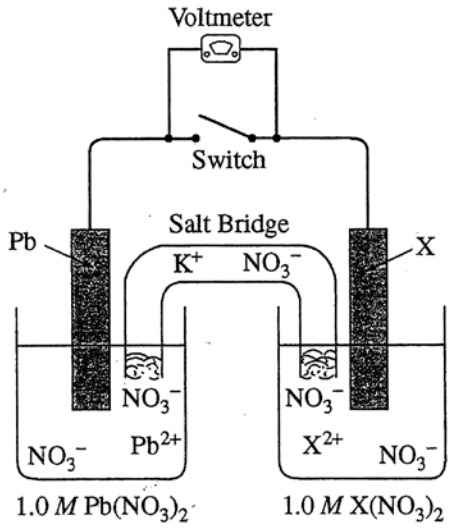
Observation 1: $Pb(s) + X^{2+}(aq) \rightarrow Pb^{2+}(aq) + X(s)$
Observation 2: $Q(s) + X^{2+}(aq) \rightarrow$ no reaction
Observation 3: $Pb(s) + Q^{2+}(aq) \rightarrow Pb^{2+}(aq) + Q(s)$

(a) On the basis of the reactions indicated above, arrange the three metals, Pb, Q, and X, in order from least reactive to most reactive on the lines provided below.

Q , X , Pb

least reactive metal most reactive metal

The diagram below shows an electrochemical cell that is constructed with a Pb electrode immersed in 100. mL of 1.0 *M* $Pb(NO_3)_2(aq)$ and an electrode made of metal X immersed in 100. mL of 1.0 *M* $X(NO_3)_2(aq)$. A salt bridge containing saturated aqueous KNO_3 connects the anode compartment to the cathode compartment. The electrodes are connected to an external circuit containing a switch, which is open. When a voltmeter is connected to the circuit as shown, the reading on the voltmeter is 0.47 V. When the switch is closed, electrons flow through the switch from the Pb electrode toward the X electrode.



(b) Write the equation for the half-reaction that occurs at the anode.

(c) The value of the standard potential for the cell, $E°$, is 0.47 V.

(i) Determine the standard reduction potential for the half-reaction that occurs at the cathode.

(ii) Determine the identity of metal X.

(d) Describe what happens to the mass of each electrode as the cell operates.

6A2

(e) During a laboratory session, students set up the electrochemical cell shown above. For each of the following three scenarios, choose the correct value of the cell voltage and justify your choice.

(i) A student bumps the cell setup, resulting in the salt bridge losing contact with the solution in the cathode compartment. Is V equal to 0.47 or is V equal to 0 ? Justify your choice.

(ii) A student spills a small amount of 0.5 *M* $Na_2SO_4(aq)$ into the compartment with the Pb electrode, resulting in the formation of a precipitate. Is V less than 0.47 or is V greater than 0.47 ? Justify your choice.

(iii) After the laboratory session is over, a student leaves the switch closed. The next day, the student opens the switch and reads the voltmeter. Is V less than 0.47 or is V equal to 0.47 ? Justify your choice.

(b) $Pb \rightarrow Pb^{2+} + 2e^-$

(c) i. $\mathcal{E}^\circ_{cell} = \mathcal{E}^\circ_{red} + \mathcal{E}^\circ_{ox}$ $\quad \mathcal{E}^\circ_{ox} = .13\ V$

$\mathcal{E}^\circ_{red} = .47\ V - .13\ V = \boxed{.34\ V}$

ii. Cu

(d) The mass of Pb (the anode) decreases because Pb is oxidized and forms Pb^{2+} ions in solution, while the mass of Cu (at the cathode) increases because Cu^{2+} is reduced to form more Cu metal.

(e) i. V=0 because the salt bridge is necessary to balance the charge. Without the salt bridge, e^- can't flow through the circuit, and therefore, the voltage is zero.

ii. $Pb^{2+} + SO_4^{2-} \rightarrow PbSO_4$ V is greater than .47 because $[Pb^{2+}]$ is reduced by the formation of the precipitate, so to form more Pb^{2+}, more oxidation occurs at the anode, and more electrons are sent to the cathode, increasing the voltage.

iii. V is less than .47 because the reaction has been going for a long time and the cell is getting closer to equilibrium, at which point, no voltage will be detected and the cell will be dead.

6. In a laboratory experiment, Pb and an unknown metal Q were immersed in solutions containing aqueous ions of unknown metals Q and X. The following reactions summarize the observations.

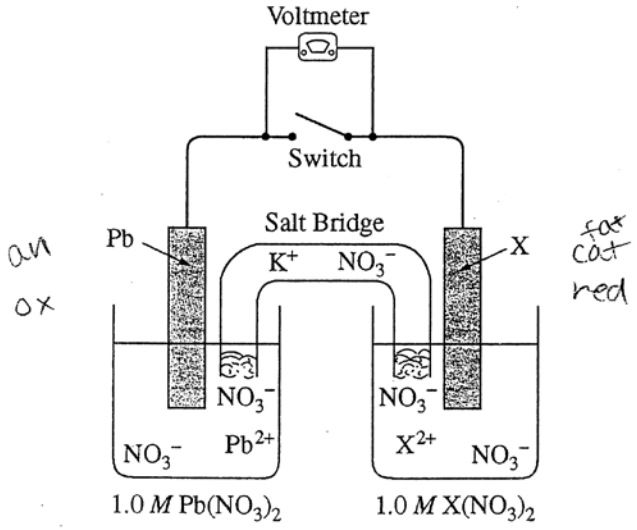
Observation 1: $Pb(s) + X^{2+}(aq) \rightarrow Pb^{2+}(aq) + X(s)$
Observation 2: $Q(s) + X^{2+}(aq) \rightarrow$ no reaction
Observation 3: $Pb(s) + Q^{2+}(aq) \rightarrow Pb^{2+}(aq) + Q(s)$

(a) On the basis of the reactions indicated above, arrange the three metals, Pb, Q, and X, in order from least reactive to most reactive on the lines provided below.

Q , X , Pb

least reactive metal most reactive metal

The diagram below shows an electrochemical cell that is constructed with a Pb electrode immersed in 100. mL of 1.0 *M* $Pb(NO_3)_2(aq)$ and an electrode made of metal X immersed in 100. mL of 1.0 *M* $X(NO_3)_2(aq)$. A salt bridge containing saturated aqueous KNO_3 connects the anode compartment to the cathode compartment. The electrodes are connected to an external circuit containing a switch, which is open. When a voltmeter is connected to the circuit as shown, the reading on the voltmeter is 0.47 V. When the switch is closed, electrons flow through the switch from the Pb electrode toward the X electrode.



(b) Write the equation for the half-reaction that occurs at the anode.

(c) The value of the standard potential for the cell, $E°$, is 0.47 V.

(i) Determine the standard reduction potential for the half-reaction that occurs at the cathode.

(ii) Determine the identity of metal X.

(d) Describe what happens to the mass of each electrode as the cell operates.

6B2.

(e) During a laboratory session, students set up the electrochemical cell shown above. For each of the following three scenarios, choose the correct value of the cell voltage and justify your choice.

(i) A student bumps the cell setup, resulting in the salt bridge losing contact with the solution in the cathode compartment. Is V equal to 0.47 or is V equal to 0 ? Justify your choice.

(ii) A student spills a small amount of 0.5 *M* $Na_2SO_4(aq)$ into the compartment with the Pb electrode, resulting in the formation of a precipitate. Is V less than 0.47 or is V greater than 0.47 ? Justify your choice.

(iii) After the laboratory session is over, a student leaves the switch closed. The next day, the student opens the switch and reads the voltmeter. Is V less than 0.47 or is V equal to 0.47 ? Justify your choice.

(b) $Pb \rightarrow Pb^{2+} + 2e^-$

(c) $0.47 = E^\circ_{red} + 0.13$

$E^\circ_{red} = 0.34\,V$

Metal X: Cu

(d) The mass of the Cu electrode increases while the mass of the Pb electrode decreases

(e) (i) V is equal to 0 because there are no longer any transfer of ions to move forward the reaction

(ii) V is less than 0.47 because the new mixture in the anode would require more voltage to transfer its electrons to the cathode.

(iii) V is equal to 0.47 because nothing has changed since the laboratory experiment is over.

6. In a laboratory experiment, Pb and an unknown metal Q were immersed in solutions containing aqueous ions of unknown metals Q and X. The following reactions summarize the observations.

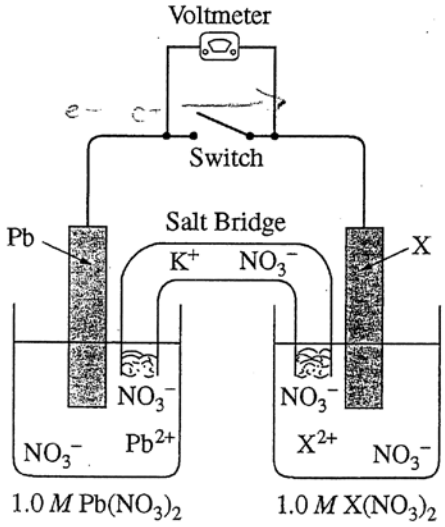
Observation 1: $Pb(s) + X^{2+}(aq) \rightarrow Pb^{2+}(aq) + X(s)$
Observation 2: $Q(s) + X^{2+}(aq) \rightarrow$ no reaction
Observation 3: $Pb(s) + Q^{2+}(aq) \rightarrow Pb^{2+}(aq) + Q(s)$

(a) On the basis of the reactions indicated above, arrange the three metals, Pb, Q, and X, in order from least reactive to most reactive on the lines provided below.

Q , Pb , X

least reactive metal most reactive metal

The diagram below shows an electrochemical cell that is constructed with a Pb electrode immersed in 100. mL of 1.0 *M* $Pb(NO_3)_2(aq)$ and an electrode made of metal X immersed in 100. mL of 1.0 *M* $X(NO_3)_2(aq)$. A salt bridge containing saturated aqueous KNO_3 connects the anode compartment to the cathode compartment. The electrodes are connected to an external circuit containing a switch, which is open. When a voltmeter is connected to the circuit as shown, the reading on the voltmeter is 0.47 V. When the switch is closed, electrons flow through the switch from the Pb electrode toward the X electrode.



Anode OX

(b) Write the equation for the half-reaction that occurs at the anode.

$Pb \rightarrow Pb^{2+} + 2e^-$ $E^\circ = .13$

(c) The value of the standard potential for the cell, E°, is 0.47 V.

$.47 = .13 + V$
$-.13 \quad -.13$
$.34 = E^\circ$

(i) Determine the standard reduction potential for the half-reaction that occurs at the cathode.

(ii) Determine the identity of metal X.

W

(d) Describe what happens to the mass of each electrode as the cell operates.

(e) During a laboratory session, students set up the electrochemical cell shown above. For each of the following three scenarios, choose the correct value of the cell voltage and justify your choice.

(i) A student bumps the cell setup, resulting in the salt bridge losing contact with the solution in the cathode compartment. Is V equal to 0.47 or is V equal to 0 ? Justify your choice.

(ii) A student spills a small amount of 0.5 *M* $Na_2SO_4(aq)$ into the compartment with the Pb electrode, resulting in the formation of a precipitate. Is V less than 0.47 or is V greater than 0.47 ? Justify your choice.

(iii) After the laboratory session is over, a student leaves the switch closed. The next day, the student opens the switch and reads the voltmeter. Is V less than 0.47 or is V equal to 0.47 ? Justify your choice.

a.) Q, Pb, X

b.) $Pb \rightarrow Pb^{2+} + 2e^-$

c.) (i) $.47 = .13 + X$ $X = .3415$

(ii) Cu

d.) The Pb mass decreases while the X mass increases. e^-s from Pb are transfered to X & combine w/ X^{2+} to increase size of X.

e.) (i) V=0 without the salt bridge connected there will be a shortage of electrons and soon V will =0.

(ii) V less than .47V

(iii) equal to .47. With the salt bridge connected there will be a constant flow of electrons keeping the voltage at .47V

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AP® CHEMISTRY
2012 SCORING COMMENTARY

Question 6

Overview

This electrochemistry question was divided into three parts. The first component asked students to consider observations of electrochemical reactions to determine the relative reactivities of three metals: Q, X, and Pb. The second component asked students to write chemical equations and determine particular electrochemical values for an electrochemical cell. The third component asked students to predict potential difference changes and justify these changes. In part (a) students were asked to analyze observations of three equations involving three different metals and the respective ions to create a list showing the least reactive metal to the most reactive metal. In part (b) students were asked to write the half-reaction occurring at the anode in the electrochemical cell. In part (c)(i) students were asked to calculate the standard reduction potential for the half-reaction that occurs at the cathode. In part (c)(ii) students were asked to identify the unknown metal (X). A table of standard reduction potentials was provided on the exam. In part (d) students were asked what happens to the mass of each electrode. In part (e)(i) students were asked to identify the potential difference of the electrochemical cell if the salt bridge lost contact with the solution and to justify the prediction. In part (e)(ii) students were asked to identify the potential difference of the electrochemical cell if sodium sulfate solution was spilled into the anode compartment and to justify the prediction. In part (e)(iii) students were asked to identify the potential difference of the electrochemical cell after the switch had been closed approximately one day and to justify the prediction.

Sample: 6A
Score: 9

The response earned all available points. In part (a) 2 points were earned for the list Q, X, Pb. All the points were earned in parts (b), (c)(i), (c)(ii), and (d). In part (e)(i) 1 point was earned for stating that V = 0 V and giving an explanation. In part (e)(ii) 1 point was earned for stating that V > 0.47 and giving an explanation. In part (e)(iii) 1 point was earned for stating that V < 0.47 V and giving an explanation.

Sample: 6B
Score: 7

The point was not earned in part (e)(ii) because V is not less than 0.47 V. Additionally, the justification that the new mixture requires more voltage to transfer electrons does not explain this change. The point was not earned in part (e)(iii) because V is not equal to 0.47 V. Additionally, the justification indicates that no change in concentration of ions occurred, but the concentrations would change ($[Pb^{2+}]$ would increase and $[Cu^{2+}]$ would decrease) as a result of the continuous operation of the electrochemical cell.

Sample: 6C
Score: 5

In part (a) the list Q, Pb, X only partially describes the reactivity of the metals based on the equations provided in the question, so only 1 of the 2 points was earned. In part (c)(i) the correct answer earned credit despite the spurious incorrect unit. In part (e)(i) it is true that V = 0 V, but the justification indicating that a shortage of electrons occurs does not explain this change in potential energy of the electrochemical cell, so the point was not earned. The point was not earned in part (e)(ii) because V is not less than 0.47 V. The point was not earned in part (e)(iii) because V is not equal to 0.47 V.