2024

AP® Chemistry

Sample Student Responses and Scoring Commentary

Inside:

Free-Response Question 3

☑ Scoring Guidelines

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Question 3: Long Answer — 10 points

(a)	For the correct answer: $Ag(s)$ __0__ $Ag_2S(s)$ __+1__	**1 point**
(b) (i)	For a valid explanation: *Silver and copper have similar radii, so the alloy would be substitutional versus interstitial.*	**1 point**
(ii)	For a valid explanation: *Silver has more occupied electron shells* $(n = 5)$ *than copper* $(n = 4)$*; the electrons in the fifth shell experience weaker Coulombic attractions and are farther away from the nucleus.*	**1 point**
	Total for part (b)	**2 points**
(c)	For the correct calculated mass of Ag_2S (may be implicit): $409.21\text{ g} - 398.94\text{ g} = 10.27\text{ g}$	**1 point**
	For the correct calculated moles of Ag: $10.27\text{ g} \times \frac{1\text{ mol }Ag_2S}{247.80\text{ g }Ag_2S} \times \frac{2\text{ mol Ag}}{1\text{ mol }Ag_2S} = 0.08289\text{ mol Ag}$	**1 point**
	Total for part (c)	**2 points**
(d) (i)	For the correct balanced equation (state symbols not required): $4\ Rh^{3+}(aq) + 6\ H_2O(l) \rightarrow 4\ Rh(s) + 3\ O_2(g) + 12\ H^+(aq)$	**1 point**
(ii)	For the correct calculated value, consistent with part (d)(i): $E^\circ_{cell} = +0.80\text{ V} - 1.23\text{ V} = -0.43\text{ V}$	**1 point**
(iii)	For a correct explanation, consistent with part (d)(ii): E°_{cell} *is negative, which means the reaction is not thermodynamically favorable.*	**1 point**
	Total for part (d)	**3 points**
(e)	For the correct calculated value of moles of electrons (may be implicit): $2.8\text{ g Rh} \times \frac{1\text{ mol Rh}}{102.9\text{ g Rh}} \times \frac{3\text{ mol }e^-}{1\text{ mol Rh}} = 0.082\text{ mol }e^-$	**1 point**
	For the correct calculated value of time: $0.082\text{ mol }e^- \times \frac{96{,}485\text{ C}}{1\text{ mol }e^-} \times \frac{1\text{ second}}{2.0\text{ C}} = 3900\text{ seconds}$	**1 point**
	Total for part (e)	**2 points**
	Total for question 3	**10 points**

Question 3

Begin your response to QUESTION 3 on this page.

3. Sterling silver is an alloy that is commonly used to make jewelry and consists of 92.5% silver and 7.5% other metals, such as copper, by mass. Over time, the alloy can form a tarnish of $Ag_2S(s)$ when it reacts with hydrogen sulfide, as represented by the following equation.

$$2\,Ag(s) + H_2S(g) \rightarrow Ag_2S(s) + H_2(g)$$

(a) What are the oxidation numbers of silver in $Ag(s)$ and $Ag_2S(s)$?

$Ag(s)$ 0 $Ag_2S(s)$ +1

(b) The following table contains the atomic radii for silver and copper.

Element	Silver (Ag)	Copper (Cu)
Atomic radius (pm)	165	145

(i) Explain why sterling silver is better classified as a substitutional alloy than as an interstitial alloy.

The atomic radius of Ag and Cu are similar in size. A substitutional alloy contains metals of similar atomic radii.

(ii) Using principles of atomic structure and Coulomb's law, explain why silver has a larger atomic radius than copper does.

Silver contains electrons in a higher energy level (4d) than copper (3d). ~~These~~ Silver's electrons are a greater distance from the nucleus than copper's and have a weaker force attracting to the nucleus ($F \propto 1/r^2$) ↳ Coulomb's Law. ~~as well as less penetration~~

Thus, the atomic radius of silver atoms are larger than copper.

Question 3

Continue your response to QUESTION 3 on this page.

The Ag_2S tarnish on sterling silver can be removed until only sterling silver remains. A student weighs a tarnished sterling silver sample both before and after removing the $Ag_2S(s)$ (molar mass 247.80 g / mol) and records the data in the following table.

	Before Tarnish Removal	After Tarnish Removal
Mass	409.21 g	398.94 g

(c) Assuming that only $Ag_2S(s)$ is removed, calculate the number of moles of silver atoms removed.

409.21 − 398.94

$= 10.27 \text{ g } Ag_2S \times \frac{1 \text{ mol } Ag_2S}{247.80 \text{ g } Ag_2S} \times \frac{2 \text{ mol Ag}}{1 \text{ mol } Ag_2S} =$ 0.08289 mol Ag removed

Rhodium plating is a process used to protect sterling silver from tarnishing. This involves electroplating (depositing) solid rhodium, Rh(*s*), onto the surface of the metal from an acidified solution of $Rh_2(SO_4)_3(aq)$. Oxygen gas is produced during this process.

(d) A table of half-reactions related to the overall reaction is provided.

Half-Reaction	$E°$ (V)
$Rh^{3+}(aq) + 3e^- \rightarrow Rh(s)$	+0.80
$O_2(g) + 4H^+(aq) + 4e^- \rightarrow 2H_2O(l)$	+1.23

$4Rh^{3+} + 12e^- \rightarrow 4Rh(s)$

$6H_2O \rightarrow 3O_2 + 12H^+ + 12e^-$

(i) Write the balanced net ionic equation for plating Rh(*s*) from the acidified $Rh_2(SO_4)_3(aq)$ solution.

$4Rh^{3+}(aq) + 6H_2O(l) \rightarrow 4Rh(s) + 3O_2(g) + 12H^+(aq)$

(ii) Calculate the value of $E°_{cell}$ for the reaction in part (d)(i).

$E°_{cell} = E°_{oxid} + E°_{red}$

$= -1.23 + 0.80$

$E°_{cell} = -0.43$ V

Question 3

Continue your response to **QUESTION 3** on this page.

(iii) Based on your answer to part (d)(ii), explain why this process requires the use of an external power source.

The E°cell is negative so the reaction is thermodynamically unfavorable since ΔG > 0 by ΔG = −nFE°. To make E°cell positive, and favorable external voltage must be added.

(e) Calculate the length of time, in seconds, required to plate 2.8 g of Rh(*s*) onto a piece of sterling silver if 2.0 C / s of current is applied.

$$\frac{2.8 \text{ g Rh}}{} \left| \frac{1 \text{ mol Rh}}{102.91 \text{ g Rh}} \right| \frac{3 \text{ mol } e^-}{1 \text{ mol Rh}} \left| \frac{96,485 \text{ C}}{1 \text{ mol } e^-} \right| \frac{1 \text{ s}}{2.0 \text{ C}}$$

2 sf

~3900 s

Question 3

Begin your response to QUESTION 3 on this page.

3. Sterling silver is an alloy that is commonly used to make jewelry and consists of 92.5% silver and 7.5% other metals, such as copper, by mass. Over time, the alloy can form a tarnish of $Ag_2S(s)$ when it reacts with hydrogen sulfide, as represented by the following equation.

$$2\overset{0}{Ag}(s) + H_2S(g) \rightarrow \overset{+1\ -2}{Ag_2S}(s) + H_2(g)$$

(a) What are the oxidation numbers of silver in $Ag(s)$ and $Ag_2S(s)$?

$Ag(s)$ 0 $Ag_2S(s)$ +1

(b) The following table contains the atomic radii for silver and copper.

Element	Silver (Ag)	Copper (Cu)
Atomic radius (pm)	165	145

(i) Explain why sterling silver is better classified as a substitutional alloy than as an interstitial alloy.

Sterling silver is consisted of silver and another element, an interstieal alloy is pure and an example would be pure silver.

(ii) Using principles of atomic structure and Coulomb's law, explain why silver has a larger atomic radius than copper does.

According to atomic structure, atomic radius of silver is greater than copper because silver is one group lower (larger) than copper, therefore it has one extra electron shell and will have a greater atomic radius than copper.

Question 3

Continue your response to QUESTION 3 on this page.

The Ag_2S tarnish on sterling silver can be removed until only sterling silver remains. A student weighs a tarnished sterling silver sample both before and after removing the $Ag_2S(s)$ (molar mass 247.80 g / mol) and records the data in the following table.

	Before Tarnish Removal	After Tarnish Removal
Mass	409.21 g	398.94 g

5 sig figs.

(c) Assuming that only $Ag_2S(s)$ is removed, calculate the number of moles of silver atoms removed.

409.21 g - 398.94 g = 10.27 g $Ag_2S(s)$

$\frac{10.27 g}{247.8 g/mol}$ = 0.04144 mol $Ag_2S(s)$

Rhodium plating is a process used to protect sterling silver from tarnishing. This involves electroplating (depositing) solid rhodium, Rh(*s*), onto the surface of the metal from an acidified solution of $Rh_2(SO_4)_3(aq)$. Oxygen gas is produced during this process.

(d) A table of half-reactions related to the overall reaction is provided.

4Rh(s) → 4Rh³⁺ + 12e⁻

Half-Reaction	$E°$ (V)		
$Rh^{3+}(aq) + 3e^- \rightarrow Rh(s)$	+0.80	× 4	(−0.8)
3$O_2(g)$ + 12 4 $H^+(aq)$ + 12 ~~4~~ e^- → 6 2 $H_2O(l)$	+1.23	× 3	

2 sig figs.

(i) Write the balanced net ionic equation for plating Rh(*s*) from the acidified $Rh_2(SO_4)_3(aq)$ solution.

$4Rh(s) + 3O_2(g) + 12H^+(aq) \rightarrow 4Rh^{3+}(s) + 6H_2O(l)$

(ii) Calculate the value of $E°_{cell}$ for the reaction in part (d)(i).

$E°_{cell}$ = 1.23 − 0.8 = **0.43 V**

Question 3

Continue your response to **QUESTION 3** on this page.

(iii) Based on your answer to part (d)(ii), explain why this process requires the use of an external power source.

- Part (d)(ii) tells us that this is a galvanic cell, a galvanic cell requires an external power source.

(e) Calculate the length of time, in seconds, required to plate 2.8 g of Rh(*s*) onto a piece of sterling silver if 2.0 C / s of current is applied.

$2.8g \times \frac{1 \text{ mol Rh}}{103 g} \times \frac{12 \text{ mol } e^-}{4 \text{ mol Rh}} \times \frac{96485 \text{ Col}}{1 \text{ mole}^-} = 7868.68 \text{ Col}$

$I = \frac{q}{t}$

$2.0 \text{ Col/s} = \frac{7868.68}{t}$

$t = 3934.34$ secs

$\approx$ 3900 s

Question 3

Begin your response to QUESTION 3 on this page.

3. Sterling silver is an alloy that is commonly used to make jewelry and consists of 92.5% silver and 7.5% other metals, such as copper, by mass. Over time, the alloy can form a tarnish of $Ag_2S(s)$ when it reacts with hydrogen sulfide, as represented by the following equation.

$$2\,Ag(s) + H_2S(g) \rightarrow Ag_2S(s) + H_2(g)$$

(a) What are the oxidation numbers of silver in $Ag(s)$ and $Ag_2S(s)$?

$Ag(s)$ 2 $Ag_2S(s)$ 0

(b) The following table contains the atomic radii for silver and copper.

Element	Silver (Ag)	Copper (Cu)
Atomic radius (pm)	165	145

(i) Explain why sterling silver is better classified as a substitutional alloy than as an interstitial alloy.

Its better classified as a substitutional alloy because it has a larger atomic radius and it can oxidize,

(ii) Using principles of atomic structure and Coulomb's law, explain why silver has a larger atomic radius than copper does.

Silver has a larger atomic radius than Copper does because Silver has more electron Shells, meaning that the radius between the nucleus and the outer most electrons is more

Question 3

Continue your response to **QUESTION 3** on this page.

The Ag_2S tarnish on sterling silver can be removed until only sterling silver remains. A student weighs a tarnished sterling silver sample both before and after removing the $Ag_2S(s)$ (molar mass 247.80 g / mol) and records the data in the following table.

	Before Tarnish Removal	After Tarnish Removal
Mass	409.21 g	398.94 g

(c) Assuming that only $Ag_2S(s)$ is removed, calculate the number of moles of silver atoms removed.

409.21 - 398.94 = 10.27 g removed   10.27 / 247.8 ⇒

0.04144 mol removed

Rhodium plating is a process used to protect sterling silver from tarnishing. This involves electroplating (depositing) solid rhodium, $Rh(s)$, onto the surface of the metal from an acidified solution of $Rh_2(SO_4)_3(aq)$. Oxygen gas is produced during this process.

(d) A table of half-reactions related to the overall reaction is provided.

Half-Reaction	$E°$ (V)
$Rh^{3+}(aq) + 3e^- \rightarrow Rh(s)$	+0.80
$O_2(g) + 4H^+(aq) + 4e^- \rightarrow 2H_2O(l)$	+1.23
$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$	−1.23

(i) Write the balanced net ionic equation for plating $Rh(s)$ from the acidified $Rh_2(SO_4)_3(aq)$ solution.

$Rh^{3+}_{(aq)} + 3e^- + 2H_2O(l) \rightarrow Rh_{(s)} + O_{2(g)} + 4H^+ + 4e^-$

$4Rh^{3+}_{(aq)} + 12e^- + 8H_2O_{(l)} \rightarrow 3Rh_{(s)} + 3O_{2(g)} + 12H^+ + 12e^-$

(ii) Calculate the value of $E°_{cell}$ for the reaction in part (d)(i).

0.8 − −1.23 = 2.03

$E°_{cell} = 2.03$

Question 3

Continue your response to **QUESTION 3** on this page.

(iii) Based on your answer to part (d)(ii), explain why this process requires the use of an external power source.

Since E°_{cell} is positive that means it needs to be able to gain energy from an external power source.

(e) Calculate the length of time, in seconds, required to plate 2.8 g of Rh(*s*) onto a piece of sterling silver if 2.0 C / s (amp) of current is applied.

$$2.8\text{ g Rh} \times \frac{1\text{ mol Rh}}{102.91\text{ g Rh}} \times \frac{96500\text{ C}}{1\text{ mol}} \times \frac{1\text{ sec}}{2.0\text{ C}} =$$

1300 seconds

GO ON TO THE NEXT PAGE.

Question 3

Note: Student samples are quoted verbatim and may contain spelling and grammatical errors.

Overview

Question 3 presents students with a sequence of items regarding the structure, composition, and electroplating of sterling silver.

Part (a) requires students to assign oxidation numbers to silver as elemental Ag(*s*) and in the binary compound $Ag_2S(s)$. The intent was for respondents to apply the generally accepted rules for determining oxidation numbers to the silver atoms in these substances (Learning Objective TRA-2.A/4.7.A, Skill 1.A from the *AP Chemistry Course and Exam Description*).

Part (b)(i) requires students to use the provided atomic radii of the primary constituents of sterling silver to justify the classification of this alloy as substitutional rather than interstitial. The intent was for respondents to recognize that for atoms with radii as similar as those for Ag and Cu, a substitutional alloy is the appropriate category (SAP-3.D/2.4.A, 4.C).

Part (b)(ii) requires students to use principles of atomic structure and Coulomb's law to explain why silver has a larger atomic radius than copper. The intent was for respondents to recognize that atomic size is largely a function of the occupied principal energy level, *n*, and that one additional value of occupied levels ($5s$, $4d$) for Ag than for Cu ($4s$, $3d$) means that electrons in the larger shells experience weaker Coulombic attractions due to their increased distance from the nucleus. This, combined with the increased Coulombic interelectron repulsions in Ag, results in silver having the larger atomic radius (SAP-2.A/1.7.A, 4.A).

Part (c) requires students to calculate the number of moles of Ag atoms in a layer of Ag_2S tarnish given masses of a sample of sterling silver before and after the sulfide was removed. The intent was for respondents to first recognize that the difference of these masses was the mass of Ag_2S tarnish, and then perform a stoichiometric conversion from the mass of Ag_2S to moles Ag present in the compound (SPQ-1.A/1.1.A, SPQ-4.A/4.5.A, 5.F).

Part (d)(i) requires students to write a balanced net ionic equation for plating Rh(*s*) from acidified $Rh_2(SO_4)_3(aq)$ given two applicable half-reactions. The intent was for respondents to correctly identify which reduction half-reaction to reverse and then appropriately combine it with the remaining reduction half-reaction to create a balanced net ionic equation (TRA-2.C/4.9.A, 5.E).

Part (d)(ii) requires students to calculate the value of E°_{cell} for the reaction in part (d)(i). The intent was for respondents to correctly manipulate E° values from the provided half-reactions to obtain the value of E°_{cell} that is consistent with the equation written in part (d)(i) (ENE-6.B/9.9.A, 5.F).

Part (d)(iii) requires students to explain the need for an external power source for this electroplating process based on the E°_{cell} derived in part (d)(ii). The intent was that respondents recognize that the negative E°_{cell} value indicates that the electrolytic process is thermodynamically unfavorable and therefore a power source would be required for the reaction to occur (ENE-6.B/9.9.A, 6.D).

Question 3 (continued)

Part (e) requires students to use a given current and mass of plated Rh(*s*) to calculate the time required for the plating to occur. The intent was for respondents to correctly use the number of moles of electrons consistent with the process detailed in part (d)(i) to calculate the time required for the reaction to occur. The correct number of significant figures was required in this part (ENE-6.D/9.11.A, 5.F).

Sample: 3A
Score: 10

This response earned 10 points. The point for part (a) was earned for correctly indicating the oxidation numbers for silver in both the element and in Ag_2S. In part (b)(i) the point was earned for correctly explaining that sterling silver is a substitutional alloy due to the similar radii of the Ag and Cu atoms. The point for (b)(ii) was earned by indicating that the additional occupied energy level in Ag atoms relative to Cu atoms, as well as the resulting reduction in Coulombic attraction, account for silver's larger atomic radius. The first point in part (c) was earned for correctly determining the mass of Ag_2S removed and the second point was earned for correctly converting this quantity to moles of Ag. The response to part (d)(i) earned a point for a correct balanced equation for the deposition of Rh metal under the given conditions. Part (d)(ii) earned the point for calculating the E°_{cell} corresponding to part (d)(i). In part (d)(iii) the point was earned for correctly relating the negative E°_{cell} from part (d)(ii) to a thermodynamically unfavorable reaction that would therefore require an external power source. Part (e) earned both points, 1 point for the correct calculation of moles of electrons (implicit in the overall calculation) and 1 point for the correct length of time expressed to the correct number of significant figures.

Sample: 3B
Score: 6

This response earned 6 points. The point for part (a) was earned for correctly indicating the oxidation numbers for silver in both the element and in Ag_2S. In part (b)(i) the point was not earned; the response classifies sterling silver as an interstitial alloy without justification. The point for part (b)(ii) was earned for indicating that the extra electron shell in Ag atoms relative to Cu atoms accounts for silver's larger atomic radius. The first point in part (c) was earned for correctly determining the mass of Ag_2S removed but the second point was not earned because the stoichiometric ratio is not applied to calculate the moles of Ag_2S. The response to part (d)(i) did not earn a point because the balanced equation is reversed. However, part (d)(ii) earned the point for calculating the E°_{cell} consistent with the reversed reaction in part (d)(i). In part (d)(iii) the point was not earned for incorrectly stating that a galvanic cell requires an external power source. Part (e) earned both points, 1 for the correct calculation of moles of electrons (implicit in the overall calculation) and 1 for the correct time expressed to the correct number of significant figures.

Question 3 (continued)

Sample: 3C
Score: 3

This response earned 3 points. The point for part (a) was not earned because the oxidation numbers given for elemental Ag and Ag_2S are both incorrect. In part (b)(i) the point was not earned for claiming that classification as a substitutional alloy is due to silver's larger radius. The point for part (b)(ii) was earned for indicating that "more electron shells" in Ag atoms relative to Cu atoms accounts for silver's larger atomic radius. The first point in part (c) was earned for correctly determining the mass of Ag_2S removed but the second point was not earned because the calculation does not account for the 2 moles of Ag per mole of Ag_2S. The response to part (d)(i) did not earn the point because the equation is not balanced. Part (d)(ii) did not earn the point for calculating an $E°_{cell}$ inconsistent with the equation in part (d)(i). In part (d)(iii) the point was not earned because the response incorrectly associates the positive $E°_{cell}$ from part (d)(ii) to the need for an external power source. Part (e) did not earn the first point because the calculation omits the necessary factor of 3 moles of electrons per mole of Rh; however, the second point was earned for a consistent calculation of time, expressed to the correct number of significant figures.