2018

AP Chemistry

Sample Student Responses and Scoring Commentary

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Question 3

Answer the following questions relating to Fe and its ions, Fe^{2+} and Fe^{3+}.

(a) Write the ground-state electron configuration of the Fe^{2+} ion.

$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^6$ OR $[Ar]\ 3d^6$	1 point is earned for a correct electron configuration.

Ion	Ionic Radius (pm)
Fe^{2+}	92
Fe^{3+}	79

(b) The radii of the ions are given in the table above. Using principles of atomic structure, explain why the radius of the Fe^{2+} ion is larger than the radius of the Fe^{3+} ion.

Both ions have the same nuclear charge; however, the greater number of electrons in the outermost shell of Fe^{2+} results in greater electron-electron repulsion within that shell, leading to a larger radius.	1 point is earned for a valid explanation

(c) Fe^{3+} ions interact more strongly with water molecules in aqueous solution than Fe^{2+} ions do. Give one reason for this stronger interaction, and justify your answer using Coulomb's law.

Coulomb's law: $F \propto \frac{q_1\,q_2}{r^2}$ (need not be explicitly stated) In comparison to the Fe^{2+} ion, the Fe^{3+} ion has a higher charge. OR The smaller size of Fe^{3+} allows it to get closer to a water molecule.	1 point is earned for a valid explanation

A student obtains a solution that contains an unknown concentration of $Fe^{2+}(aq)$. To determine the concentration of $Fe^{2+}(aq)$ in the solution, the student titrates a sample of the solution with $MnO_4^-(aq)$, which converts $Fe^{2+}(aq)$ to $Fe^{3+}(aq)$, as represented by the following equation.

$$5\ Fe^{2+}(aq) + MnO_4^-(aq) + 8\ H^+(aq) \rightarrow 5\ Fe^{3+}(aq) + Mn^{2+}(aq) + 4\ H_2O(l)$$

(d) Write the balanced equation for the half-reaction for the oxidation of $Fe^{2+}(aq)$ to $Fe^{3+}(aq)$.

$Fe^{2+}(aq) \rightarrow Fe^{3+}(aq) + e^-$	1 point is earned for the correct half-reaction.

Question 3 (continued)

(e) The student titrates a 10.0 mL sample of the $Fe^{2+}(aq)$ solution. Calculate the value of $[Fe^{2+}]$ in the solution if it takes 17.48 mL of added 0.0350 M $KMnO_4(aq)$ to reach the equivalence point of the titration.

$17.48\text{ mL} \times \frac{0.0350\text{ mol KMnO}_4}{1000\text{ mL}} = 0.000612\text{ mol KMnO}_4$ $0.000612\text{ mol KMnO}_4 \times \frac{5\text{ mol Fe}^{2+}}{1\text{ mol KMnO}_4} = 0.003059\text{ mol Fe}^{2+}$ $\frac{0.003059\text{ mol Fe}^{2+}}{0.0100\text{ L}} = 0.306\ M\text{ Fe}^{2+}$	1 point is earned for calculating the number of moles of $KMnO_4$ (may be implicit) 1 point is earned for the correct concentration of $Fe^{2+}(aq)$.

To deliver the 10.0 mL sample of the $Fe^{2+}(aq)$ solution in part (e), the student has the choice of using one of the pieces of glassware listed below.

- 25 mL buret
- 25 mL graduated cylinder
- 25 mL beaker
- 25 mL volumetric flask

(f) Explain why the 25 mL volumetric flask would be a poor choice to use for delivering the required volume of the $Fe^{2+}(aq)$ solution.

The volumetric flask is designed to contain only 25.00 mL precisely.	1 point is earned for a valid explanation.

Question 3 (continued)

In a separate experiment, the student is given a sample of powdered Fe(*s*) that contains an inert impurity. The student uses a procedure to oxidize the Fe(*s*) in the sample to $Fe_2O_3(s)$. The student collects the following data during the experiment.

Mass of Fe(*s*) with inert impurity	6.724 g
Mass of $Fe_2O_3(s)$ produced	7.531 g

(g) Calculate the number of moles of Fe in the $Fe_2O_3(s)$ produced.

$7.531 \text{ g } Fe_2O_3 \times \frac{1 \text{ mol } Fe_2O_3}{159.70 \text{ g } Fe_2O_3} = 0.04716 \text{ mol } Fe_2O_3$ $0.04716 \text{ mol } Fe_2O_3 \times \frac{2 \text{ mol Fe}}{1 \text{ mol } Fe_2O_3} = 0.09431 \text{ mol Fe}$	1 point is earned for correct calculation.

(h) Calculate the percent by mass of Fe in the original sample of powdered Fe(*s*) with the inert impurity.

$0.09431 \text{ mol Fe} \times \frac{55.85 \text{ g Fe}}{1 \text{ mol}} = 5.267 \text{ g Fe}$ $\frac{5.267 \text{ g Fe}}{6.724 \text{ g sample}} \times 100 = 78.33\%$	1 point is earned for correct calculation of the mass percent based on the answer to part (g).

(i) If the oxidation of the Fe(*s*) in the original sample was incomplete so that some of the 7.531 g of product was FeO(*s*) instead of $Fe_2O_3(s)$, would the calculated mass percent of Fe(*s*) in the original sample be higher, lower, or the same as the actual mass percent of Fe(*s*)? Justify your answer.

The calculated mass percent of Fe would be lower than the actual mass percent of Fe. A sample that contains any FeO (rather than Fe_2O_3) will have a higher actual mass percent of Fe than a completely oxidized sample would have. Therefore, when the moles of Fe are calculated (assuming all the mass of the sample is Fe_2O_3) the calculated number of moles of Fe, and hence the calculated mass percent of Fe, will be lower.	1 point is earned for the correct answer and a valid explanation.

PAGE FOR ANSWERING QUESTION 3

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(a) $1s^2 2s^2 2p^6 3s^2 3p^6 3d^6$

(b) The Fe^{2+} ion contains more electrons, thus more repulsion occurs between the electrons, increasing the space they occupy. Fe^{3+} has less electrons and thus less repulsion as well as having the same nuclear charge pulling in fewer electrons.

(c) Fe^{3+} ions have a higher charge than Fe^{2+} and therefore will more strongly attract the negative dipoles on water molecules. In addition, their smaller ionic radius means the attractive positive charge will be closer to the H_2O molecule, furthering the attractive forces.

(d) $Fe^{2+} \longrightarrow Fe^{3+} + e^-$

(e) $\frac{.0350 \text{ mol } KMnO_4}{1 L} = \frac{x \text{ mol}}{.01748 L} = 6.12 \times 10^{-4} \text{ mol } KMnO_4 \cdot \frac{5 \text{ mol } Fe^{2+}}{1 \text{ mol } MnO_4^-} = 0.00306 \text{ mol } Fe^{2+}$

$\frac{0.00306 \text{ mol } Fe^{2+}}{0.01 L} = \boxed{0.306 M\ Fe^{2+}}$

(f) The volumetric flask only takes a reading at 25 mL, thus when using it you cannot tell when the inside volume of solution has reached 10 mL. In addition, it does not measure to a decimal place, as with a beaker, further limiting its use.

(g) $7.531 g\ Fe_2O_3 \cdot \frac{1 \text{ mol}}{159.70 g\ Fe_2O_3} \cdot \frac{2 \text{ mol } Fe}{1 \text{ mol } Fe_2O_3} = \boxed{0.0943 \text{ mol } Fe}$

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ⓗ $0.0943\text{ mol Fe} \cdot \frac{55.85\text{ g Fe}}{1\text{ mol Fe}} = \frac{5.27\text{ g Fe}}{6.724\text{ g}} \times 100\% = \boxed{78.3\%}$

ⓘ The calculated mass percent would be lower as FeO has a lower molar mass than Fe_2O_3 and therefore increases the moles of iron present when calculated. With simply Fe_2O_3 being assumed to be produced, the moles of iron are reduced due to the differences in molar mass

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a) $[Ar]\,3d^6$

b) The ionic radius of Fe^{2+} is larger than the ionic radius of Fe^{3+}, because Fe^{2+} has 1 more electron that exerts repulsive forces on the rest of the electron cloud. Also, in Fe^{3+} there are 3 less electrons compared to its nuclear charge (compared to 2 less in Fe^{2+}), so the electron cloud is more strongly attracted to the nucleus.

c) Fe^{3+} ions interact more strongly with H_2O because they have a greater charge, e.g.

$$F = \frac{kq_1q_2}{r^2} \qquad \frac{k(3)(1)}{r^2} > \frac{k(2)(1)}{r^2}$$

d) $Fe^{2+}_{(aq)} \longrightarrow Fe^{3+}_{(aq)} + e^-$

e) $M = \frac{mol}{L}$ $\quad$ $mol = (.0350M)(17.48mL \times \frac{1L}{1000mL}) = 6.12 \times 10^{-4}$ moles $KMnO_4$

6.12×10^{-4} moles $KMnO_4 \times \frac{1\,mole\,MnO_4^-}{1\,mole\,KMnO_4} \frac{5\,mole\,Fe^{2+}}{1\,mole\,MnO_4^-} = .00306$ moles Fe^{2+}

$M = \frac{mol}{L} = .00306\,moles / (10.0mL \times \frac{1L}{1000mL})$

$[Fe^{2+}] = \boxed{.306\,M}$

f) The 25mL volumetric flask will be too large to accurately measure 10.0mL of the solution, and a buret is a better choice for measuring volumes in a titration.

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g) $7.531\,g\ Fe_2O_3 \times \frac{1\,mole\ Fe_2O_3}{159.70\,g} \times \frac{2\,moles\ Fe}{1\,mole\ Fe_2O_3} = \boxed{.09431\,moles\ Fe}$

$2(55.85) + 3(16.00) = 159.70\,g$

h) $.09431\,moles\ Fe \times \frac{55.85\,g}{1\,mole\ Fe} = 5.267\,g\ Fe$

$\frac{5.267\,g}{6.724\,g} \times 100\% = \boxed{78.33\%}$

i) The calculated mass perent of Fe would be higher than the actual mass percent, because there is one Fe for every mole of FeO, instead of two for every mole of Fe_2O_3.

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a $1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^4$

b The effective nucler charge of the valance electrons is greater for Fe^{+3} ions as they have less of the postive charge of the nucleus to share amoung the valance electrons. Thus, the valance electrons are more closer making the radii of Fe^{+3} smaller

c Fe^{+3} has a stronger net charge meaning it would more likely reaction with other species with negative charges compared to Fe^{+2}. From $\frac{qq}{r}$ of Coulumb's law, we see that a stronger charge for Fe^{+3} (q) and and smaller distance (r) means greater attraction.

d. $1Fe^{+2}_{(aq)} \rightarrow 1Fe^{+3}_{(aq)} + 1e^-$

e $$\frac{17.48\ mL}{10.0 mL\ Fe^{+2}} \cdot \frac{1L}{1000mL} \cdot \frac{0.0350\ mol\ KMnO_4}{1L} \cdot \frac{5 mol\ Fe^{+2}}{1\ mol\ KMnO_4} \cdot \frac{1000 mL\ Fe^{+2}}{1\ L\ Fe^{+2}} = 0.306\ M$$

f The flask has no specific markings to determine to 17.48 mL needed for the solution.

g $$7.531g\ Fe_2O_3 \cdot \frac{1mol\ Fe_2O_3}{159.70g\ Fe_2O_3} \cdot \frac{2\ mol\ Fe}{1mol\ Fe_2O_3}$$

$$= \boxed{0.09431\ mol\ Fe}$$

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h From g: 0.09431 mol Fe $\cdot \frac{55.85\text{ g Fe}}{1\text{ mol Fe}}$ = 5.267 g Fe

$\frac{5.267\text{ g Fe}}{6.724\text{ g Fe Impure}} \cdot 100\% = \boxed{78.33\%\text{ Fe}}$

i The calculated percent mass would be lower than the actual percent mass. This is FeO has less of a mole ration of $\frac{Fe}{O}$ and thus some Fe ~~mass~~ would be accounted as O mass in calculations of the moles of Fe. This in turn caused Fe mass to decrease and the percent mass to decrease as well.

AP® CHEMISTRY
2018 SCORING COMMENTARY

Question 3

Overview

This question used the properties and reactions of iron and iron ions to assess students' mastery of atomic structure and reaction stoichiometry. It dealt broadly with qualitative and quantitative connections between experimental observations and atomic/molecular/bulk structure. Students were asked in parts (a) through (c) to use principles of atomic structure to predict the electron configuration of Fe^{2+} (LO 1.19; SP 6.4) and explain differences in its ionic radius (LO 1.19; SP 6.4) and the strength of its Coulombic interaction with water molecules in comparison to Fe^{3+} (LO 1.10; SP 6.1). Part (d) asked students to write a balanced half-reaction for the oxidation of Fe^{2+} to Fe^{3+} (LO 3.13; SP 5.1), and then part (e) had them calculate $[Fe^{2+}]$ based upon the results of a redox titration (LO 3.9; SP 4.2, 5.1). The students then needed to justify in part (f) why a 25 mL volumetric flask would be a poor choice for dispensing 10.00 mL of Fe^{2+} solution (LO 3.9; SP 4.2, 5.1). The students were asked in part (g) in a separate experiment to calculate the number of moles of Fe present in a sample containing an inert impurity (LO 1.4; SP 7.1) and then in part (h) to determine the percent by mass of Fe present in the original sample (LO 1.2; SP 2.2). Part (i) was an error analysis question that probed students' understanding of the impact of an incomplete oxidation reaction on the quantitative outcome of the experiment (LO 1.2; SP 2.2).

Sample: 3A
Score: 10

This response earned 10 out of 10 possible points. Each part is worth 1 point with the exception of part (e), which is worth 2 points. In part (a) the response correctly provides the electron configuration for iron ($1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^2\ 3d^6$) minus its valence electrons ($4s^2$) to become Fe^{2+}: $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^6$. In part (b) the response addresses the idea that Fe^{2+} has one more electron than does Fe^{3+}, leading to more electron-electron repulsion and an increase in the amount of space occupied. In part (c) the response earned the point. Although Coulomb's Law (the magnitude of the attractive force varies directly with the product of the opposite charges and indirectly with the square of the distance between the attracting particles) is not directly cited, the response deals with the magnitude of the charge ("Fe^{3+} ions have a higher charge than Fe^{2+}, and therefore will more strongly attract the negative dipoles on water molecules") AND the distance ("smaller ionic radius means the attractive positive charge will be closer to the H_2O molecule"). In other words the smaller ionic radius of the Fe^{3+} allows for a closer approach to the water molecule. In part (d) the response reduces the balanced oxidation half-reaction, $5\ Fe^{2+} \rightarrow 5\ Fe^{3+} + 5\ e^-$, to become the simpler $Fe^{2+} \rightarrow Fe^{3+} + e^-$, and the point was earned. Both points were earned in part (e). The student correctly multiplies the molarity (mol L^{-1}) by the volume 0.01748 L (switched to liters to make the volume units agree and cancel) to find the number of moles of potassium permanganate. The student multiplies the number of moles of permanganate by 5 to find the number of moles of Fe^{2+} and then divides by the volume of Fe^{2+} cations in L to determine molarity. The response earned 1 point in part (f) for indicating why the 25 mL volumetric flask would be an unsuitable choice for the task of measuring a 10.0 mL sample of Fe^{2+} solution. The flask has no mark for 10.0 mL and has only one etched line on its neck to allow precise measurement of 25.00 mL. The point was earned in part (g). The response includes a conversion of mass of oxidized iron to moles of Fe_2O_3 (by dividing by its molar mass, 159.70) and then to moles of iron by multiplying by the appropriate stoichiometric ratio. The resulting answer should be 0.09431 mol Fe. The response, 0.0943, is within the significant figure tolerance (4 SF $\pm$1 SF). The response earned 1 point in part (h) for correctly converting the number of moles of iron from part (g) to mass (in grams) of iron. That mass is then compared to the mass of the iron with impurity and converted to a mass percent. In part (i) the answer "lower" is selected from a choice list of higher, lower, or the same, and the justification earned 1 point.

Question 3 (continued)

Sample: 3B
Score: 8

This response earned 8 out of 10 possible points. In part (a) 1 point was earned because the response includes a correct form of the electron configuration (using a noble gas core) for the Fe^{2+} cation. In part (b) 1 point was earned for an explanation that Fe^{2+} has one more electron than Fe^{3+} does; therefore, there is more electron-electron repulsion to expand the ionic radius. In part (c) the response earned 1 point because it includes the idea that Fe^{3+} has a greater positive charge to interact more strongly with H_2O in accordance with Coulomb's Law. In part (d) the response includes an identification of the correct oxidation half-reaction and earned 1 point. In part (e) the response includes a calculation of the correct number of moles of permanganate anion. That value was then used with the stoichiometric ratio to find the number of moles of Fe^{2+} and divided by the volume in liters to determine molarity (*M*). This earned 2 points. In part (f) no point was earned. The response incorrectly states that the 25 mL volumetric flask will be too large to accurately measure 10.0 mL. In part (g) the response earned 1 point because it includes the correctly calculated moles of iron, expressed to the correct number of significant figures. In part (h) the response earned 1 point for correctly calculating the mass percent of iron in the sample of iron powder containing an inert impurity. In part (i) the response incorrectly states that the calculated mass percentage would be higher, and therefore earned no point.

Sample: 3C
Score: 6

This response earned 6 out of 10 possible points. In part (a) no point was earned because the response incorrectly removes 3*d* electrons from the iron atom to form Fe^{2+}, rather than valence 4*s* electrons. In part (b) no points were earned because the response neglects the electron-electron repulsion of more electrons in the Fe^{2+} cation. In part (c) 1 point was earned because the response indicates that Fe^{3+} has a stronger net charge than Fe^{2+} to interact with negative species, like the oxygen end of the polar water molecule. In part (d) 1 point was earned because the response identifies the correct oxidation half-reaction. In part (e) the response earned 2 points because it calculates the correct number of moles of permanganate anion, implicitly uses the correct stoichiometric ratio, and divides by the volume in liters to determine molarity (*M*). In part (f) no point was earned because a volumetric flask does have one marking to indicate a predetermined volume, in this case 25 mL. The response earned 1 point in part (g) because the student correctly calculates the number of moles of Fe_2O_3 implicitly, and then calculates the number of moles of elemental iron. The response earned 1 point in part (h) because the student uses the number of moles of Fe from part (g), converts those moles to the mass of iron, and compares that result to the mass of the impure iron powder to express a mass percent. In part (i) no point was earned because there is an incorrect assumption about the ratio of iron to oxygen in the oxidized sample.