General Chemistry

IJSO Theory mock test

Solutions

Problem 1. Chemistry in a Tea Shop (3.00 points)

Part A. Tea Shop Thermochemistry (1.50 points)

A1. Calculate the molar enthalpy of solution (H_{sol}) of glucose in kJ/mol based on the observation.

(0.75 points)

Calculation:

$Q = mc\Delta t = -168J$

(0.25 points)

$M(C_6H_{12}O_6) = 180$

(0.10 points)

10g glucose….168J

180g…………x J, so x = 3024J, $H_{sol} = 3.02\frac{kJ}{mol}$

(0.40 points)

H_{sol} = $\mathbf{3.02\frac{kJ}{mol}}$

A2. Find the molality of the glucose solution Ravi prepared

(0.25 points)

Calculation:

$M(C_6H_{12}O_6) = 180$

The number of moles of glucose is $n = \frac{10}{180} = 0.056mol$

(0.10 points)

$m = \frac{0.056}{0.2} = 0.28\ mol/kg$

(0.15 points)

m = **0.28 mol/kg**

A3. If Ravi's solution freezes at $-0.52°C$, find the cryoscopic constant of water.

(0.50 points)

Pure water freezes at $0°C$, so the freezing point depression is equal to $0.52°C = 0.52K$

(0.10 points)

$K_f = \frac{\Delta T}{m} = 1.857 \frac{K \cdot kg}{mol}$

(0.40 points)

$K_f = \mathbf{1.857} \frac{\mathbf{K \cdot kg}}{\mathbf{mol}}$

Part B. The Chemistry of Acidity in Tea (0.50 points)

B1. Assuming tannic acid is a monoprotic weak acid with a Ka value of 4×10^{-6}, calculate the pH of the solution at 0.0010 mol/L.

(0.50 points)

Calculation:

$[H^+] = \sqrt{K_a c} = \sqrt{4 \times 10^{-6} \cdot 0.001} = 6.32 \times 10^{-5}$

(0.30 points)

$pH = -\log[H^+] = 4.2$

(0.20 points)

pH = **4.2**

Part C. Tea Sugar Sweetening (1.00 points)

C1. Calculate the mass of sugar Ravi needs to add.

(0.30 points)

Calculation:

The mass of the tea is 1500g. After adding x grams of sugar, the mass will be 1500+x.

Using the concentration, $\frac{x}{1500+x} = \frac{6}{100}$. Solving for x, we get x = 95.7g

Mass of sugar = **95.7g**

C2. If Ravi adds only 50 g of sugar, what will be the molar concentration of the sugar in the tea?

(0.70 points)

Calculation:

The molar mass of sucrose is $M = 342$

(0.20 points)

The number of moles of sugar is $n = \frac{50}{342} = 0.146\text{mol}$

(0.20 points)

The molar concentration is the number of moles of sugar per volume of tea, so we have $c = \frac{0.146}{1.5} = 0.097\text{M}$

(0.30 points)

Molar concentration = **0.097M**

Problem 2. Identification of Compounds (10.00 points)

Part A. Formula of a Salt (3.35 points)

A1. Identify substances **A**, **B**, **C** and **D**

(1.80 points)

Calculation:

B: element with the highest electronegativity ⇒ fluorine (F) ⇒ diatomic molecule ⇒ F_2

C: yellow-green gas with a pungent smell ⇒ chlorine (Cl) ⇒ diatomic molecule ⇒ Cl_2.

Reaction 1: $A + F_2 \rightarrow Cl_2$ + other products => the anion in A is Cl^-, so $A = XCl_n$

For compound D, let us consider we have 100g of substance:

Ag: 63.16 g → 63.16 / 107.9 = 0.585 mol

N: 8.19 g → 8.19 / 14 = 0.585 mol

O: 28.65 g → 28.65 / 16 = 1.79 mol

Thus, the molar ratio between the elements is 1:1:3, so D has the chemical formula $AgNO_3$.

At the endpoint, 34.2mL of $AgNO_3$ are consumed, so $n = 0.00342$ mol

The reaction taking place is $Ag^+ + Cl^- \rightarrow AgCl\downarrow$, so $n(Cl^-) = 0.00342$mol (in the 10mL sample). In the entire 100mL, $n(Cl^-) = 0.0342$mol

Since A = XCl_n, $n(A) = \frac{0.0342}{n}$ mol

The molar mass of A is $M(A) = \frac{2g}{n(A)} = \frac{2n}{0.0342} = 58.48n$

To get the atomic mass of X, we subtract the mass of chlorine (35.45n) and we get that $A(X) = 23.03n \approx A_{Na}$, so X = Na, A = NaCl. For other values of n, we don't get any other possible solutions.

0.40p for B, C, D each and 0.60p for A, regardless of the method used. -0.20 points if only the n = 1 case is considered.

Chemical formulas:

A = ……………………………………**NaCl**…………………..…………………………..

B = ……………………………………$\mathbf{F_2}$………………………………………………..

C = ……………………………………$\mathbf{Cl_2}$…………...……………………………………..

D = …………………………………$\mathbf{AgNO_3}$………………………………………………..

A2. Write the balanced equations of reactions 1, 2 and 3

(0.75 points)

Reaction 1:

$$\mathbf{2NaCl + F_2 \rightarrow 2NaF + Cl_2}$$

Reaction 2:

$$\mathbf{NaCl + AgNO_3 \rightarrow AgCl + NaNO_3}$$

Reaction 3:

$$\mathbf{2AgNO_3 + K_2CrO_4 \rightarrow Ag_2CrO_4 + 2KNO_3}$$

Only 0.40p for unbalanced reactions. Counterions may be omitted.

A3. For each of the substances specify if it's ionic, covalent polar or covalent nonpolar

(0.60 points)

Tick the right answer:

	Ionic	Covalent Polar	Covalent Nonpolar
Compound A	**X**		
Compound B			**X**
Compound C			**X**
Compound D	**X**		

Part B. Substances Taking Part in a Redox Reaction (6.65 points)

B1. Write the chemical formulas of compounds A-G

(2.75 points)

Chemical formulas:

A = $\mathbf{HgCl_2}$ (0.30 points)

B = $\mathbf{H_2O_2}$ (0.55 points)

C = **KOH** (0.45 points)

D = **Hg** (0.30 points)

E = $\mathbf{O_2}$ (0.35 points)

F = **KCl** (0.40 points)

G = $\mathbf{H_2O}$ (0.40 points)

Using the clues, D = Hg, B = H_2O_2, C = KOH. Now that we know D = Hg, using the clue for A, we can figure out A = $HgCl_2$. Now, we have all reactants figured out. E is one of the main gases in the Earth's atmosphere, so either oxygen or nitrogen. Since no reactant contains nitrogen, E = O_2. Looking at the elements present in the reactants, but also at the clue for G, we figure out G = H_2O. Now we're only left with F. Since potassium and chloride ions are present in the reactants, but in no product, F contains both. The most logical compound is F = KCl

B2. Write the balanced equation of the reaction and the equations of the oxidation and reduction half-reactions

(1.50 points)

Calculation:

Reaction can be balanced using redox method. Full marks are awarded even without the method shown. If reactions are correct but oxidation and reduction are swapped, 1.00p. 0.50p per correct balanced reaction

Balanced reaction: $\mathbf{HgCl_2 + H_2O_2 + 2KOH \rightarrow Hg + O_2 + 2KCl + 2H_2O}$

Oxidation: $\mathbf{Hg^{2+} + 2e^- \rightarrow Hg}$

Reduction: $\mathbf{H_2O_2 + 2HO^- \rightarrow O_2 + 2H_2O + 2e^- or\ O^{-1} \rightarrow O^0 + e^-}$

B3. What mass of water ($\rho = 1\frac{g}{cm^3}$) is used to dilute the 10mL of solution S1 to obtain the required solution S2.

(1.00 points)

Calculation:

The number of moles of H_2O_2 is $\frac{2.71\times10^{23}}{6.022\times10^{23}} = 0.45\text{mol}$. Since the volume is 1L, the concentration of S1 is 0.45M

(0.30 points)

$c_{1,2}$ are the concentrations (0.45M and 0.1M), while $V_{1,2}$ are the volumes (10mL and an unknown one)

$c_1V_1 = c_2V_2 \Longrightarrow V_2 = \frac{c_1}{c_2}V_1 = 45\text{mL}$

The volume of water to be added is $V_2 - V_1 = 35\text{mL}$

(0.60 points)

The mass of water is $35\text{mL} \cdot 1\frac{g}{mL} = 35g$

(0.10 points)

Mass of water = **35g**

B4. If the reaction has a 85% yield, what volume of solution S2 is used to obtain the desired amount of metal D.

(0.70 points)

Calculation:

We want to obtain 5.025/200.59 = 0.025mol of Hg, which, from the reaction stoichiometry, requires 0.025mol of H_2O_2. However, since the yield is 85%, we actually need $0.025 \cdot \frac{100}{85} = 0.03\text{mol of } H_2O_2$

(0.50 points, 0.30 points if yield is not used)

The volume of S2 is just 0.03mol/0.1M = 0.3L

(0.20 points)

Volume of solution = **0.3L**

B5. For the experiment described, 100mL of solution S3 containing substance C were stoichiometrically necessary. Find the pH of solution S3.

(0.70 points)

Calculation:

From the reaction stoichiometry, the number of moles of KOH is twice that of Hg, so $n(KOH) = 0.05mol$. However, using the yield, we get $0.05 \cdot \frac{100}{85} = 0.059mol$

(0.30 points, 0.10 points if yield isn't used)

The concentration of solution S3 is $c = \frac{0.059}{0.1} = 0.59M$. Since KOH is a strong base, $[HO^-] = 0.59M$

(0.20 points)

$pOH = -\log[HO^-] = 0.23$

pH = 14 – pOH = 13.77

(0.20 points)

pH = **13.77**

Extra space for problem 2:

Problem 3. Mineral Water (5.50 points)

A. In the following text, choose the right word from each pair of bolded words:

(0.30 points)

Circle the correct word:

> The solution to be analyzed is a **supersaturated/saturated** solution, a metastable (unstable) state, in which the solute concentration exceeds the theoretical limit and any small disturbance may cause it to **crystalize/dissolve**. To get the solution to a state where this is no longer a problem, the solution is **heated/cooled** and all analysis is performed at this temperature.

B. Choose which technique could have been used for the determination of calcium:

(0.20 points)

Tick the right answer:

Acid-base titration (based on the acid-base properties of calcium hydroxide)	
Redox titration (based on transformations between oxidation states of calcium)	
Complexonometric titration (based on the formation of a calcium complex)	**X**
Argentometry (based on the formation of a silver-calcium precipitate)	

C. Calculate the total molar concentration of phosphorus in the solution.

(0.75 points)

Calculation:

The number of moles of phosphorus is equal to the number of moles of ammonium phosphomolybdate.

The molar mass of the phosphomolybdate is $\mathrm{M} = 1874$

(0.20 points)

Part C continuation:

The number of moles is $\frac{16.89\times10^{-3}}{1874} = 9 \times 10^{-6}$

(0.35 points)

The molar concentration is $\frac{9\times10^{-6}}{10^{-2}} = 9 \times 10^{-4}\text{mol/L}$

(0.20 points)

Phosphorus concentration = $\mathbf{9 \times 10^{-4}mol/L}$

D. Using the acidity constants formulas, find the expressions of all phosphate system ions (dihydrogen phosphate, monohydrogen phosphate and neutral phosphate) in terms of acidity constants, the concentration of protons and the concentration of phosphoric acid.

(1.00 points)

Calculation:

Using the first acidity constant:

$[H_2PO_4^-] = \frac{k_{a1}}{[H^+]}[H_3PO_4]$

(0.30 points)

Using the second acidity constant:

$[HPO_4^{2-}] = \frac{k_{a2}}{[H^+]}[H_2PO_4^-] = \frac{k_{a1}k_{a2}}{[H^+]^2}[H_3PO_4]$

(0.40 points)

Similarly, $[PO_4^{3-}] = \frac{k_{a1}k_{a2}k_{a3}}{[H^+]^3}[H_3PO_4]$

(0.30 points)

$[H_2PO_4^-] = \frac{\mathbf{k_{a1}}}{\mathbf{[H^+]}}\mathbf{[H_3PO_4]}$

$[HPO_4^{2-}] = \frac{\mathbf{k_{a1}k_{a2}}}{\mathbf{[H^+]^2}}\mathbf{[H_3PO_4]}$

$[PO_4^{3-}] = \frac{\mathbf{k_{a1}k_{a2}k_{a3}}}{\mathbf{[H^+]^3}}\mathbf{[H_3PO_4]}$

E. Using results in parts C and D, find the values of the molar concentrations of phosphoric acid, dihydrogen phosphate, monohydrogen phosphate and neutral phosphate.

(1.50 points)

Calculation:

$[H_3PO_4] + [H_2PO_4^-] + [HPO_4^{2-}] + [PO_4^{3-}] = 9 \times 10^{-4} \Longrightarrow$

$[H_3PO_4]\left(1 + \frac{k_{a1}}{[H^+]} + \frac{k_{a1}k_{a2}}{[H^+]^2} + \frac{k_{a1}k_{a2}k_{a3}}{[H^+]^3}\right) = 9 \times 10^{-4} \Longrightarrow [H_3PO_4] \times 1.71 \times 10^5 = 9 \times 10^{-4} \Longrightarrow [H_3PO_4] = 5.26 \times 10^{-9}\text{M}$

(0.60 points)

Using the formulas from part D: $[H_2PO_4^-] = 4.90 \times 10^{-4}\text{M}$; $[HPO_4^{2-}] = 4.08 \times 10^{-4}\text{M}$; $[PO_4^{3-}] = 2.41 \times 10^{-9}\text{M}$

(3×0.30 points)

$[H_3PO_4] = \mathbf{5.26 \times 10^{-9}M}$

$[H_2PO_4^-] = \mathbf{4.90 \times 10^{-4}M}$

$[HPO_4^{2-}] = \mathbf{4.08 \times 10^{-4}M}$

$[PO_4^{3-}] = \mathbf{2.41 \times 10^{-9}M}$

F. Through calculations, determine which of the following compounds will precipitate when the solution is brought back to 25°C.

(1.75 points)

Calculation:

$[HO^-] = 10^{-(14-pH)} = 1.32 \times 10^{-7}$

$Q(Ca(OH)_2) = [Ca^{2+}][HO^-]^2 = 8.71 \times 10^{-18} < K_s \Longrightarrow$ doesn't precipitate

(0.65 points)

Part F continuation:

$Q(Ca_3(PO_4)_2) = [Ca^{2+}]^3[PO_4^{3-}]^2 = 7.26 \times 10^{-28} < K_s \Longrightarrow$ doesn't precipitate

(0.55 points)

$Q(CaHPO_4) = [Ca^{2+}][HPO_4^{-}] = 2.04 \times 10^{-7} > K_s \Longrightarrow$ precipitates

(0.55 points)

Tick the compounds that will precipitate:

$Ca(OH)_2$	
$Ca_3(PO_4)_2$	
$CaHPO_4$	**X**

If any of the results is wrong due to an error in a previous part, but the method is correct, full marks are awarded to avoid double penalties.

Extra space for problem 3:

Problem 4. Chemistry in a Parallel Universe (4.25 points)

Part A. Stable Elements (0.50 points)

Write the chemical symbol of the element which is the lightest element with a stable valance shell structure.

(0.50 points)

Chemical symbol - ………………………………**Li**………………………………..

Because electrons can now have 3 spin states, each orbital will be able to accommodate 3 electrons. So the lightest element with a stable valence shell structure must only have one shell because it is the lightest and must be occupied by 3 electrons because it needs to be stable. The chemical element that has 3 electrons is Lithium (Li).

Part B. Properties of Aluminum (1.30 points)

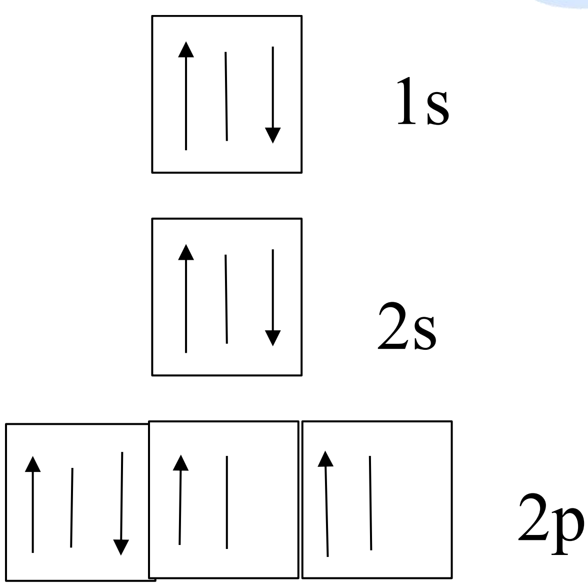
B1. Using the given rules, draw the electron structure of aluminum

(1.00 points)

Structure:

In this parallel universe, the s subshell can have 3 electrons, the p subshell can have 9, so the new electronic distribution of aluminum would be

$$^{13}\mathrm{Al}: 1s^3, 2s^3, 2p^7$$



Only 0.50 points if Hund's rule is not respected.
Full marks if the last two 2p orbitals have any other combination of electron spins (up+down/down+null).

B2. Using the drawn electron structure, what element from our Universe does aluminum in the imaginary Universe resemble the most? Tick the right answer.

(0.30 points)

Neon	
Calcium	
Chlorine	
Sulfur	**X**

In this parallel universe, aluminum needs to receive two more electrons to become stable, which resembles **sulfur** in our universe, that also needs to receive two electrons to fill its outermost layer and, therefore, become stable.

Part C. More Chemical Properties (1.20 points)

C1. Give an example of an element which, in this imaginary Universe, would be a monovalent metal

(0.60 points)

Element = ……………………….**Be/S/Co**…………..…………………………

The main aspect that defines a monovalent metal is that it has one valence electron (except for the case of just one electron, since that would be hydrogen). Possible electronic structures of a monovalent metal would be:

$1s^3\ 2s^1$ (Berilium)

$1s^3 2s^3 2p^9 3s^1$ (Z = 16: Sulfur)

$1s^3 2s^3 2p^9 3s^2 3p^9 4s^1$ (Z=27: Cobalt)

C2. Give an example of an element, which, on this imaginary Universe, would be a divalent nonmetal

(0.60 points)

Element = ……………………………**Al/Mn/In**……………………………………

Divalent non-metals must receive two electrons in order to have a stable electronic configuration, and their last electron must be on the p subshell. Some possibilities are:

$1s^3 2s^3 2p^7$ (Z=13: Aluminum)

$1s^3 2s^3 2p^9 3s^3 3p^7$(Z=25: Manganese)

$1s^3 2s^3 2p^9 3s^3 3p^9 4s^3 3d^{15} 4p^7$(Z=49: Indium)

Part D. The Periodic Table (1.25 points)

D1. How many periods and how many groups does the periodic table of the imaginary Universe have?

Hint: In the imaginary periodic table, the f-block is added as an extension under the table just like in our Universe

(0.75 points)

Calculation:

Because the heaviest known element is still the one with a full 7p subshell, the number of periods remains unchanged, since it depends on the number of layers, and the maximum is still 7.

The number of groups on our is 18, and it can be calculated by adding up the number of electrons that occupy the s subshell (2), the d subshell (10), and the p subshell (6) (the f subshell is not added because it is added as an extension). On this new universe, the number of electrons that occupy the s subshell is 3, the p subshell is 9, and the d subshell is 15, so the number of groups would be

$$3 + 15 + 9 = 27$$

Number of periods = **7 (0.25 points)**

Number of groups = **27 (0.50 points)**

Full marks are awarded for the values, even if there is no explanation given.

D2. How many elements are there in the s-block of the periodic table in the imaginary Universe?

(0.50 points)

Calculation:

The s subshell can be occupied by 3 electrons, so the s block would have 3 columns (groups), and the number of rows (periods) would still be 7, so there would be a total of $7 \times 3 = 21$ elements on the s-block. (Or 20 if you exclude the element that plays a similar role to helium)

Number of s-block elements = **21/20**

Full marks are awarded just for the value, even if there is no explanation.

Problem 5. Electrochemical Cells (7.25 points)

Part A. Redox Reactions (0.75 points)

A1. Write the strongest reducing agent among those in the table.

(0.25 points)

Strongest reducing agent = **Zn**

The strongest reducing agent is the species with the highest oxidation potential

A2. Write the chemical reaction of fluorine and water.

(0.50 points)

Chemical reaction equation:

$$\mathbf{2F_2 + 2H_2O \rightarrow 4HF + O_2}$$

Part B. A Simple Electrochemical Cell (1.00 points)

B1. Write its symbol.

(0.50 points)

Symbol:

$$(+)\mathbf{Ag|Ag_2O, H^+||Zn^{2+}|Zn}(-)$$

B2. Calculate the standard cell potential, E^0_{cell}

(0.50 points)

Calculation:

$E^0_{cell} = E^0(Ag) - E^0(Zn) = 1.10V$

E^0_{cell} = **+1.10V**

Part C. More Analysis of a Lead Battery (3.60 points)

C1. Calculate the potential of reaction (2).

(0.65 points)

Calculation:

Looking at the overall reaction, half-reaction 1 takes place in the given direction, while the other reaction will be the inverse of reaction 2. That means, the cell potential will be $E^0 = E_1^0 - E_2^0$

(0.55 points)

$E_2^0 = E_1^0 - E^0 = -0.46V$

(0.10 points)

E_2^0 = **-0.46V**

C2. After some time of discharge, the concentration of H^+ ions near the Pb electrode decreases from 1.0 M to 0.80 M. Assuming the rate law for the cell reaction is:

rate $= k \times [H^+]^n$ with $k = 2.5 \times 10^{-3}$ (in SI unit)

calculate:

(a) The rate of reaction at the beginning (when $[H^+]$ = 1.0 M)

(0.40 points)

Calculation:

The reaction rate is $k \times [H^+]^n = k \times 1^n = k = 2.5 \times 10^{-3}\,\frac{mol}{L\cdot s}$

Rate = $\mathbf{2.5 \times 10^{-3}\,\frac{mol}{L\cdot s}}$

(b) The order n of the reaction, if it's known that the rate at 0.80 M is 64% of the initial rate.

(1.00 points)

Calculation:

$v_0 = k \times c_0^n$

$v_1 = k \times c_1^n$

(0.30 points)

Dividing the equations, $\frac{v_1}{v_0} = \left(\frac{c_1}{c_0}\right)^n \Longrightarrow 0.8 = 0.64^n$

(0.50 points)

The solution to the equation is n = 2

(0.20 points)

n = **2**

(c) The rate of reaction when $[H^+] = 0.80$ M

(0.20 points)

Calculation:

$v = k \times [H^+]^2 = 1.6 \times 10^{-3} \frac{mol}{L \cdot s}$

Rate = $\mathbf{1.6 \times 10^{-3} \frac{mol}{L \cdot s}}$

C3. Based on your result from C2. estimate how long it will take for $[H^+]$ to fall from 1.0 M to 0.50 M. Assume no reverse reaction occurs and the rate law remains valid.

(0.60 points)

Calculation:

The integrated rate law is $\frac{1}{[H^+]} = \frac{1}{[H^+]_0} + kt$

(0.20 points)

The time is $t = \frac{1}{k}\left(\frac{1}{[H^+]} - \frac{1}{[H^+]_0}\right) = 400s$

(0.40 points)

Time = **400s**

C4. Calculate the overall enthalpy change ΔH^0_{cell}

(0.75 points)

Calculation:

$\Delta H^0_{cell} = 2\Delta H^0_f(PbSO_4) + 2\Delta H^0_f(H_2O) - \Delta H^0_f(PbO_2) - \Delta H^0_f(Pb) - 2\Delta H^0_f(H^+) - 2\Delta H^0_f(HSO_4^-)$

(0.50 points)

Numerically, $\Delta H^0_{cell} = -363\,\frac{kJ}{mol}$

ΔH^0_{cell} = $\mathbf{-363\,\frac{kJ}{mol}}$

Part D. Mass Changes in the Battery (1.90 points)

D1. Using the stoichiometry of the reaction, find the mass of lead that was oxidized

(0.40 points)

Calculation:

Two moles of electrons are transferred per mole of lead oxidized, so 5×10^{-4}mol of lead are oxidized

(0.20 points)

This corresponds to $5 \times 10^{-4} \cdot 207.2 = 0.1036\text{g}$

(0.20 points)

Mass of lead = **0.1036g**

D2. Calculate by how much the total mass (mg) of the solid phase increases

(0.75 points)

Calculation:

From the stoichiometry of the reaction, the number of moles of PbO_2 is equal to that of Pb. The mass of PbO_2 that reacted is $5 \times 10^{-4} \cdot (207.2 + 32) = 0.1196\text{g}$

(0.30 points)

The number of moles of lead sulfate which forms is double that of lead, so the mass is $10^{-3} \cdot (207.2 + 32 + 64) = 0.303\text{g}$

(0.30 points)

The increase in the mass of the solid phase is $0.303 - (0.1036 + 0.1196) = 0.0798\text{g}$

(0.15 points)

Mass increase = **0.0798g**

D3. If the actual measured increase of the total mass of the solid phase is 42mg, find the mass of lead sulfate that dissolved in water

(0.25 points)

Calculation:

The difference between the calculated mass and the given mass comes from some lead sulfate that dissolved. Its mass is $0.0798\text{g} - 42\text{mg} = 79.8\text{mg} - 42\text{mg} = 37.8\text{mg}$

Mass of lead sulfate dissolved = **37.8mg**

D4. If the reaction is performed in a 1L aqueous solution, find the solubility (mg/L) of lead sulphate

(0.30 points)

Calculation:

The solubility is just $S = \frac{m_{dissolved}}{V_{water}} = 37.8\,\frac{mg}{L}$

Solubility = $\mathbf{37.8\,\frac{mg}{L}}$

Extra space for problem 5: