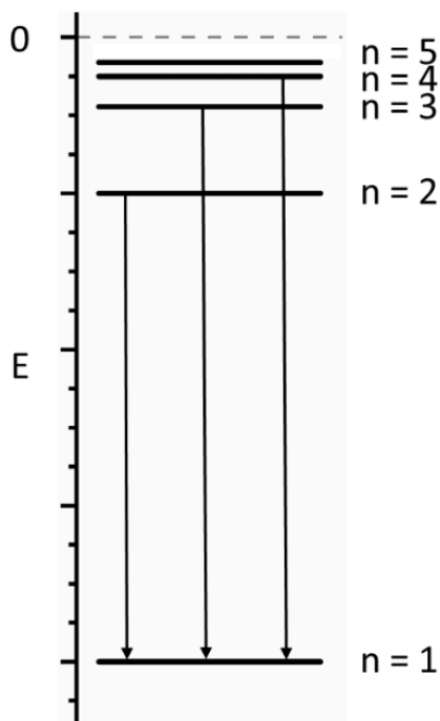


# 2024 WUCT: Individual Exam

This exam consists of 7 questions and is worth 100 points. You will complete this exam individually. You will have 1 hour to take the exam. The only allowed resources for this exam are a calculator and the provided equation sheet. You may NOT use any other notes or books. You must show your work and box your final answer to receive credit for a problem. NOTE: If you get the answer to an early part of a question incorrect but later use that answer for a subsequent part of the question, you can still earn full credit for those subsequent parts. Please write your answer in the designated space on the answer sheet. If you need additional space for a problem, you may use the blank scratch page at the end of the exam. Make sure to clearly indicate in the problem's designated space where the rest of your work can be found. Any work anywhere other than the exam or the scratch page will not be graded. Dark pencil or pen is preferred.

## **Problem #1: (11 points)**

The energy states of hydrogen-like atoms, that is, atoms containing one electron, can be represented by diagrams like the one below. Each horizontal line represents one energy state. The energies can be calculated by the following equation:  $E_n = (-2.18 \times 10^{-18} \text{ J}) \frac{z^2}{n^2}$



a. Why can't an atom of  $\text{Al}^{3+}$  be represented by this diagram? **(1 point)**

$\text{Al}^{3+}$  has **more than one electron. (+1 point)**

b. How does the distance between the horizontal lines change as you move from low to high energy? Why? **(2 points)**

Distance between the lines gets **shorter (+1 point)**

Energy is proportional to  $1/n^2$ , so as  $n$  increases, the magnitude of  $E$  decreases, but by a **smaller amount each time (+1 point)**

c. The arrows depict energy transitions between states, where a photon can either be emitted or absorbed. The three transitions depicted are the  $n=4$  to  $n=1$  transition, the  $n=3$  to  $n=1$  transition, and the  $n=2$  to  $n=1$  transition. If an electron in  $\text{Be}^{3+}$  ion transitions from the  $n=4$  to the  $n=1$  state, what is the wavelength of the photon emitted in nanometers? **(2 points)**

$$\Delta E_n = (-2.18 \times 10^{-18} \text{ J}) (4^2) \left( \frac{1}{1^2} - \frac{1}{4^2} \right) = -3.27 \times 10^{-17} \text{ J} \text{ (+1 point)}$$

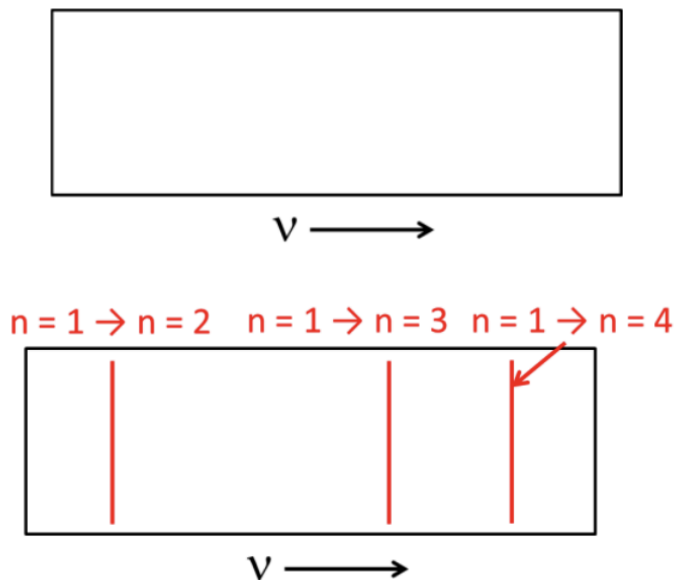
$$\Delta E_n = \frac{hc}{\lambda} = 3.27 \times 10^{-17} \text{ J}$$

$$\lambda = 6.07 \times 10^{-9} \text{ m} = 6.07 \text{ nm} \text{ (+1 point)}$$

**+1 point for correct substitution into the  $\Delta E_n$  equation ( $z = 4$  and  $\frac{1}{1^2} - \frac{1}{4^2}$ , not the other way around) (note: the value of  $\Delta E_n$  does not have to be correct to get this point)**

**+1 point for correct value of  $\lambda$  (either in meters or nanometers)**

- d. This information can be translated to a line diagram, where vertical lines represent the frequency of the energy emitted. Sketch these transitions on the line spectrum below. (2 points)



+1 point for three lines sketched and labeled in the correct order (2 → 1 on the left, 4 → 1 on the right) (note: the transitions go the opposite direction than what's in the picture (2 → 1, 3 → 1, 4 → 1))

+1 point for the lines getting closer together

- e. In experiments known as photoelectric effect experiments, EM radiation is used to emit electrons from a metal surface. If a photon with an energy of  $4.78 \times 10^{-17} \text{ J}$  was used to eject an electron from potassium metal, at what speed will the resulting electron have? The work function for potassium is 2.24 eV. (3 points)

$$2.24 \text{ eV} \times \frac{1.602 \times 10^{-19} \text{ J}}{1 \text{ eV}} = 3.59 \times 10^{-19} \text{ J}$$

$$KE = \Delta E_n - \phi = 4.78 \times 10^{-17} \text{ J} - 3.59 \times 10^{-19} \text{ J} = 4.7441 \times 10^{-17} \text{ J} \text{ (+1 point)}$$

$$KE = \frac{1}{2}mv^2 = 4.7441 \times 10^{-17} \text{ J} \text{ (+1 point)}$$

$$v = 1.02 \times 10^7 \text{ m/s} \text{ (+1 point)}$$

+1 point for the correct KE in J from the difference between  $E_{ph}$  and the work function

+1 point for relating KE and speed with the equation  $KE = \frac{1}{2}mv^2$

+1 point for the correct velocity in m/s

- f. Suppose the intensity of light is increased, what will change about the ejected electrons?  
*(1 point)*

**More electrons will be ejected (+1 point)**

- g. Suppose the frequency of light is increased, what will change about the ejected electrons?  
*(1 point)*

**The electrons ejected will have a higher speed (+1 point)**

**Problem #2: (11 points)**

The Downs Cell is an electrolytic cell used for the commercial preparation of liquid sodium metal.

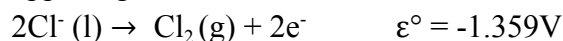
- a. What is the defining feature of electrolytic cells? (2 points)

An **external voltage** must be supplied which forces **current to flow in the non-spontaneous direction**.

**+1 point for mentioning external voltage**

**+1 point for mentioning current flow in non spontaneous direction**

- b. The half reactions happening in this cell are:



Give the balanced overall reaction occurring in the cell. (1 point)



- c. Give the change in potential in the cell. (1 point)

$$\varepsilon_{red}^\circ - \varepsilon_{ox}^\circ = -1.359\text{V} - 2.714\text{V} = -4.073\text{V} \text{ (+1 point)}$$

- d. Which of the following power sources would be able to power the cell? Circle all that apply. (2 points)

- i. 9 volt battery (+1 point)
- ii. AA (1.5V) battery
- iii. Phone (3.7V) battery
- iv. Laptop (10.8V) battery (+1 point)

**Answers depend on the value obtained for part (c) - any battery voltage larger than the absolute value of the one reported for part (c) should be considered correct - this part has a maximum of 2 possible points**

**If part (c) is left blank, points can still be obtained for part (d) for correctly circling (i) and (iv)**

- e. Define the terms anode and cathode and identify the reaction occurring at each in the Downs Cell. **(3 points)**

The **anode** is the electrode where **oxidation** occurs and the **cathode** is the electrode where **reduction** occurs. **(+1 point)**

In the Downs Cell, at the **anode**, **chlorine** ions are being **oxidized**. **(+1 point)**

At the **cathode**, **sodium** ions are being **reduced**. **(+1 point)**

- f. Calcium is often added to reduce the temperature needed to keep the mixture liquid. Its half cell reaction is:



Why doesn't the calcium react when added to the Downs Cell described above? **(1 point)**

The **reduction potential of calcium (-2.87V) is lower** than that of sodium (-2.714V), so **sodium will be selectively reduced**. **(+1 point)**

- g. What would happen to the calcium ions if all the sodium ions were used up in the cell and a 4.1V battery was being used? **(1 point)**

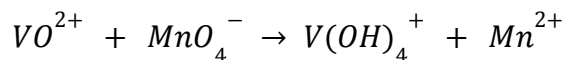
Nothing, there would be insufficient voltage to reduce the calcium ions. **(+1 point)**

For calcium:  $\varepsilon_{red}^{\circ} - \varepsilon_{ox}^{\circ} = -1.359\text{V} - 2.87\text{V} = -4.229\text{V}$

**(note: calculation does not need to be shown to receive full credit)**

**Problem #3: (19 points)**

Use the following redox reaction to answer the questions below. Round all numerical answers to three decimal places. Work must be shown to support your answers for all parts of this question.

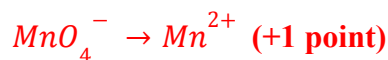


- a. Assign oxidation states to each of the elements in the bottom row of the table. (2 points)

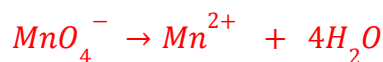
$VO^{2+}$		+	$MnO_4^{-}$		→	$V(OH)_4^{+}$			+	$Mn^{2+}$
V	O		Mn	O		V	O	H		Mn
+4	-2		+7	-2		+5	-2	+1		2+

(+0.25 points each)

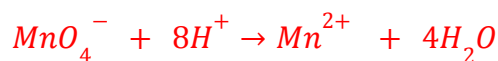
- b. Balance the REDUCTION half reaction in basic medium. (4 points)



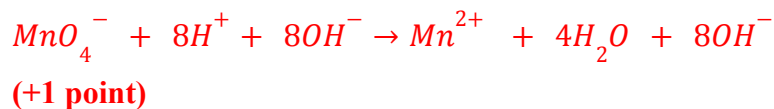
Reduction half reaction



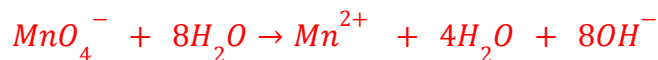
Balance the O's



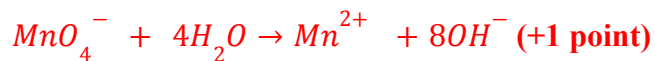
Balance the H's



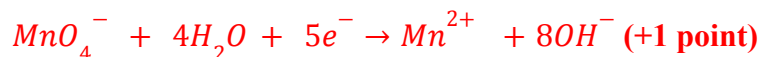
Add the hydroxide to get rid of the  $H^{+}$



Combine  $H^{+}$  and  $OH^{-}$  to form water

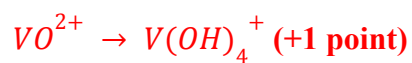


Cancel out as many waters as possible on both sides

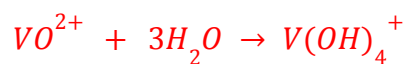


Balance the charges with electrons

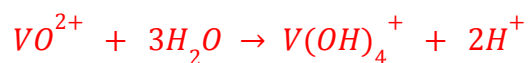
c. Balance the OXIDATION half reaction in basic medium. (4 points)



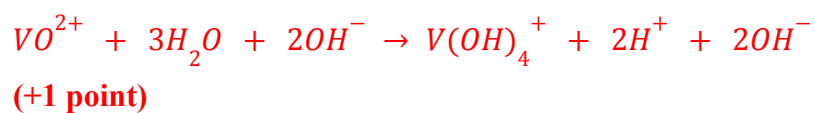
Oxidation half reaction



Balance the O's



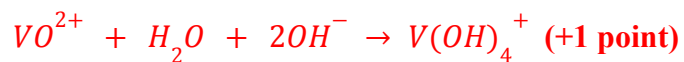
Balance the H's



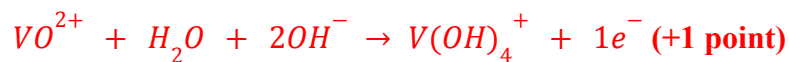
Add the hydroxide to get rid of the  $H^+$



Combine  $H^+$  and  $OH^-$  to form water



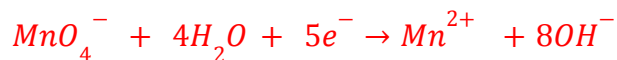
Cancel out as many waters as possible on both sides



Balance the charges with electrons



d. Write out the fully balanced redox reaction. (2 points)

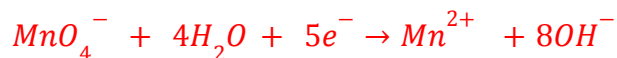


Balanced reduction half reaction



Balanced oxidation half reaction multiplied by 5 to balance the electrons

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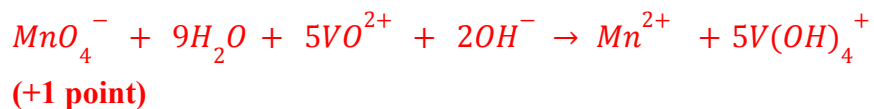
Rewrite



Rewrite multiplied by 5

+-----

Add them together



Cancel matching species on opposite sides

e. If 175 mL of a 0.35 M  $\text{KMnO}_4$  solution and 225 mL of a 3.45 M  $\text{VO}^{2+}$  solution are combined, what are the new concentrations of each relevant species (those given in the initial unbalanced redox reaction)? (2 points)

Molarity of mixed  $\text{MnO}_4^-$ :

$$M_1 V_1 = M_2 V_2$$

$$M_2 = \frac{M_1 V_1}{V_2}$$

$$M_2 = \frac{(0.35 \text{ M})(0.175 \text{ L})}{(0.400 \text{ L})} = 0.1531 \text{ M (+1 point)}$$

Molarity of mixed  $\text{VO}^{2+}$ :

$$M_1 V_1 = M_2 V_2$$

$$M_2 = \frac{M_1 V_1}{V_2}$$

$$M_2 = \frac{(3.45 \text{ M})(0.225 \text{ L})}{(0.400 \text{ L})} = 1.9406 \text{ M (+1 point)}$$

- f. What is the limiting reactant of the reaction described in (e)? Show all necessary work. (3 points)

Moles of  $MnO_4^-$ :

$$mol = ML = (0.1531 M)(0.400 L) = 0.06124 mol$$

OR

$$mol = ML = (0.35 M)(0.175 L) = 0.06125 mol \text{ (+1 point)}$$

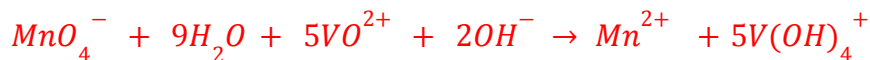
Moles of  $VO^{2+}$ :

$$mol = ML = (1.9406 M)(0.400 L) = 0.77624 mol$$

OR

$$mol = ML = (3.45 M)(0.225 L) = 0.77625 mol \text{ (+1 point)}$$

Determining the limiting reactant:

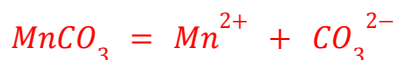


$$0.06124 mol MnO_4^- \times \frac{1 mol Mn^{2+}}{1 mol MnO_4^-} = 0.06124 mol Mn^{2+}$$

$$0.77624 mol VO^{2+} \times \frac{1 mol Mn^{2+}}{5 mol VO^{2+}} = 0.155248 mol Mn^{2+}$$

Limiting Reactant:  $MnO_4^-$  (+1 point)

- g.  $MnCO_3$  is a naturally occurring mineral that is typically produced industrially. It is pale pink and water insoluble. How many grams of  $MnCO_3$  solid could be produced (in grams) from the reaction? Hint: assume all the  $Mn^{2+}$  from parts (e) and (f) are converted into  $MnCO_3$ . (2 points)



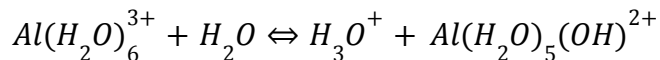
$$0.06124 mol Mn^{2+} \times \frac{1 mol MnCO_3}{1 mol Mn^{2+}} \times \frac{114.9469 g MnCO_3}{1 mol MnCO_3} = 7.0393 g MnCO_3$$

+1 point for using the moles of  $Mn^{2+}$

+1 point for correct numerical answer

**Problem #4: (13 points)**

A metal-aquo complex like  $Al(H_2O)_6^{3+}$  will undergo an acid-base reaction within its aqueous solution. Use the chemical equation below to answer parts a, b, and c.



- a. Identify the acid, base, conjugate acid, and conjugate base. (1 point)

Acid:  $Al(H_2O)_6^{3+}$

Base:  $H_2O$

Conjugate Acid:  $H_3O^+$

Conjugate Base:  $Al(H_2O)_5(OH)^{2+}$

**+1 point for completely correct answer, no partial credit**

- b. Suppose the  $K_a$  value of  $Al(H_2O)_6^{3+}$  is  $1.4 \times 10^{-5}$  what will the  $pK_b$  value of its conjugate base be? (At 25°C) (2 points)

$$K_b = \frac{K_w}{K_a} = \frac{1.0 \times 10^{-14}}{1.4 \times 10^{-5}} = 7.14285714 \times 10^{-10} \text{ (+1 point)}$$

$$pK_b = -\log K_b = 9.146128036 \text{ (+1 point)}$$

**+1 point for correct use of Kw equation**

**+1 point for correct final answer**

- c. If there's a 250 mL aqueous solution containing only 1.6 mol of  $Al(H_2O)_6^{3+}$  initially, what will the pH value of the solution be after the equilibrium is established. (Remember: the  $K_a$  value of  $Al(H_2O)_6^{3+}$  is small) **(2 points)**

$$[Al(H_2O)_6^{3+}] = \frac{1.6 \text{ mol}}{0.25L} = 6.4 \text{ M}$$

$$[H_3O^+] = 0.009465728 \text{ M}$$

$$pH = -\log[H_3O^+] = 2.023845979$$

**+1 point for correct  $[Al(H_2O)_6^{3+}]$  and  $[H_3O^+]$**

**+1 point for correct final answer**

- d. If given that the structure of  $Al(H_2O)_6^{3+}$  is **octahedral**, using the hybridization theory, what would be the hybridization state of the central Aluminum (ex.: sp, sp<sup>2</sup>, sp<sup>3</sup>, etc.)? Also, what are the atomic orbitals used to produce the hybridized orbitals? **(2 points)**

Hybridization state:  $d^2 sp^3$  **(+1 point)**

The atomic orbitals in aluminum used to produce the hybridized orbitals:

1×3s orbital, 3×3p orbitals, and 2×3d orbitals **(+1 point)**

- e. There are many other similar molecules like  $Al(H_2O)_6^{3+}$ . Another example of a metal-aquo complex is  $Fe(H_2O)_6^{3+}$ .

- i. Write an electron configuration for Fe. **(1 point)**

$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^6$  **(+1 point)**

- ii. If given that the structure of  $Fe(H_2O)_6^{3+}$  is also octahedral, identify the atomic orbitals used to form the hybridized orbitals of the central iron. (2 points)

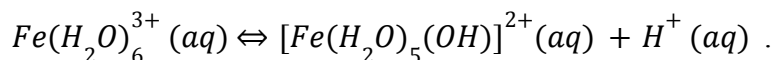
The atomic orbitals used to produce the hybridized orbitals:

1×4s orbital, 3×4p orbitals, and 2×4d orbitals (+2 points)

+1 point for the correct number of atomic orbitals (6 total)

+1 point for the correct atomic orbitals

- f. When you dissolve a compound that contains an iron (III) ion into the water, the color of the solution is determined by multiple complexes that are related to the iron (III) ion. One of the major complexes that determines the color of the solution is  $[Fe(H_2O)_5(OH)]^{2+}$  which is formed through the following reaction:



Knowing that  $Fe(H_2O)_6^{3+}$  has a **light, pale** violet color, and  $[Fe(H_2O)_5(OH)]^{2+}$  has an **orange** color. Explain why the solution containing iron (III) ions shows a color of yellow (when diluted) and orange (when concentrated). How will the color of the solution change if the concentration of  $Fe(H_2O)_6^{3+}$  increases? (3 points)

The solution containing iron (III) shows a color of yellow and orange because the color of the  $[Fe(H_2O)_5(OH)]^{2+}$  ion masks the color of  $Fe(H_2O)_6^{3+}$ . (+1 point)

If the concentration of  $Fe(H_2O)_6^{3+}$  increases, according to **Le Chatelier Principle**, the equilibrium will shift to the right which causes more  $[Fe(H_2O)_5(OH)]^{2+}$  being produced, so the solution will have a **more concentrated orange color**.

+1 point for the first statement or that the  $[Fe(H_2O)_5(OH)]^{2+}$  is present in a higher concentration

+1 point for stating the solution will be a more concentrated orange color

+1 point for mentioning Le Chatelier Principle

**Problem #5: (12 points)**

The following molecule, Compound D, is deficient in Parkinson's Disease patients. One of the major hurdles of treating Parkinson's Disease is transporting Compound D into the brain due to the Blood Brain Barrier, a semipermeable layer of endothelial cells that blocks access to many different solutes.

- a. Compound D has 62.5% C, 7.21% H, 9.10% N, and 20.8% O. It has a molar mass of 153.18 g/mol. Write the molecular formula for compound D. **(4 points)**

For 100 g of Compound D (Dopamine):

$$62.5 \text{ g C} \times \frac{1 \text{ mol C}}{12.011 \text{ g C}} = 5.20 \text{ mol C}$$

$$7.21 \text{ g H} \times \frac{1 \text{ mol H}}{1.008 \text{ g H}} = 7.15 \text{ mol H}$$

$$9.10 \text{ g N} \times \frac{1 \text{ mol N}}{14.01 \text{ g N}} = 0.65 \text{ mol N}$$

$$20.8 \text{ g O} \times \frac{1 \text{ mol O}}{15.999 \text{ g O}} = 1.30 \text{ mol O} \quad \text{(+1 point)}$$

$$5.20 \text{ mol C} / 0.65 = 8 \text{ C}$$

$$7.21 \text{ mol H} / 0.65 = 11 \text{ H}$$

$$0.65 \text{ mol N} / 0.65 = 1 \text{ N}$$

$$1.30 \text{ mol O} / 0.65 = 2 \text{ O} \quad \text{(+2 points)}$$

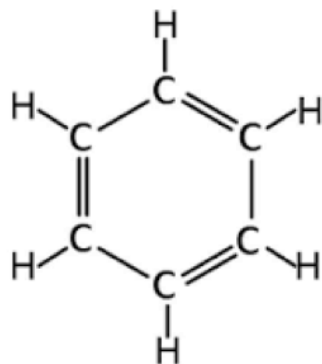
Compound D (dopamine) formula:  $C_8H_{11}NO_2$  (+1 point)

**+1 point for correctly determining the number of moles of each of the elements**

**+2 points for dividing each of the number of moles by the smallest number of moles (moles of N)**

**+1 point for the correct final empirical formula**

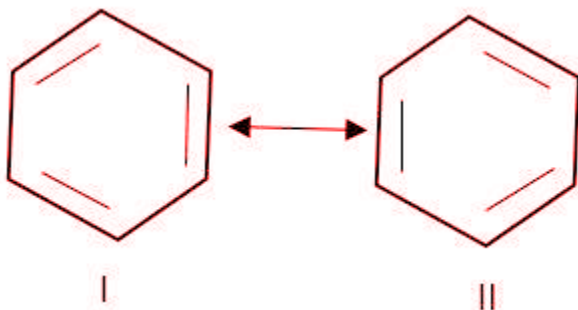
- b. The structure of an organic molecule similar to Compound D is given below. This molecule is called Compound B.



What is the hybridization of the carbons in the ring? Hint: they all have the same one. (1 point)

$sp^2$  (+1 point)

- c. Draw any resonance structures for Compound B. (2 points)



+1 point for each resonance structure

Note: both points can be obtained if the student draws one correct hybrid resonance structure with dashed lines around the inside of the ring at every bond

- d. The Gibbs Free Energy of formation of Compound B is -113.90 kJ/mol. Calculate the equilibrium constant (K) at 298.15 K. (2 points)

$$\Delta G = -RT \ln K \text{ (+1 point)}$$

$$-113.90 \text{ kJ/mol} = -8.3145 \text{ JK}^{-1} \text{ mol}^{-1} \times 298.15 \text{ K} \times \ln(K)$$

$$K = 9.0018 \times 10^{19} \text{ (+1 point)}$$

+1 point for the correct equation

+1 point for the correct unitless final answer (note: to report K with units is conceptually incorrect)

- e. The enthalpy of formation of Compound B is -292.75 kJ/mol. Calculate the entropy of formation of the compound. (2 points)

$$\Delta G = \Delta H - T\Delta S \text{ (+1 point)}$$

$$-113.90 \text{ kJ/mol} = -292.75 \text{ kJ/mol} - 298.15 \text{ K} \Delta S$$

$$\Delta S = -599.86 \text{ J/mol} = -0.59986 \text{ kJ/mol} \text{ (+1 point)}$$

+1 point for the correct equation

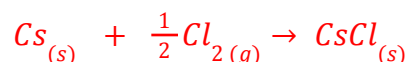
+1 point for the correct final answer (may report in either J/mol or kJ/mol)



**Problem #6: (16 points)**

The ionic compound cesium chloride has the formula CsCl. In this question, you will try to determine the heat of formation of CsCl using given thermodynamic data.

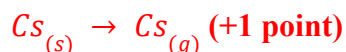
- a. The heat of formation of a compound is defined to be the enthalpy change of producing one mole of that compound from its constituent elements, all in their most stable states under standard temperature and pressure. For CsCl, write out the chemical equation that describes this process, INCLUDING physical states. **(1 point)**



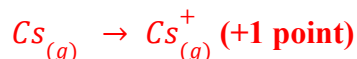
**+1 point for the correct equation (note: the coefficients must be as shown here, with only one mole of CsCl(s) produced by the definition of a heat of formation reaction)**

- b. Hess's law can be used to predict the enthalpy change of this reaction by following a different path from reactants to products. As long as this new path starts and ends with the same compounds, it should give an accurate value for the enthalpy of the overall reaction. The steps in the new path are described below. Under each statement, write out the physical/chemical equation describing that step, INCLUDING physical states.

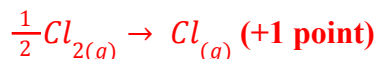
- i. To start, turn 1 mole of  $\text{Cs}_{(s)}$  into  $\text{Cs}_{(g)}$  **(1 point)**



- ii. Then, remove one electron each from this 1 mole of  $\text{Cs}_{(g)}$  **(1 point)**



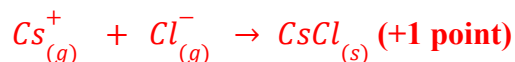
- iii. Then, split  $\text{Cl}_{2(g)}$  into 1 mole of Cl **(1 point)**



- iv. Add an electron to each of this 1 mole of Cl atoms (**1 point**)



- v. Bring together the gas-phase Cs ions and Cl ions (one mole of each) to form 1 mole of CsCl<sub>(s)</sub> (**1 point**)



- c. The enthalpies of the above processes are given below. Under each enthalpy value given, write the Roman numeral (i, ii, iii, iv, or v) of the reaction from the previous problem that describes that enthalpy value. If any enthalpy value does not describe an above process, write NONE.

- i. Electron Affinity of chlorine atom: -349 kJ/mol (**1 point**)

iv

- ii. Heat of sublimation of cesium metal:  $7.82 \times 10^4$  J/mol (**1 point**)

i

- iii. First ionization energy of cesium metal: 375.7 kJ/mol (**1 point**)

ii

- iv. Lattice energy of CsCl<sub>(s)</sub>: -633 kJ/mol (**1 point**)

v

- v. Bond energy of Cl<sub>2(g)</sub> gas: 243 kJ/mol (**1 point**)

iii

d. Calculate the enthalpy of formation of CsCl. (2 points)

$$\Delta H = -349 \frac{\text{kJ}}{\text{mol}} + 78.2 \frac{\text{kJ}}{\text{mol}} + 375.7 \frac{\text{kJ}}{\text{mol}} - 633 \frac{\text{kJ}}{\text{mol}} + \frac{1}{2} (243 \frac{\text{kJ}}{\text{mol}})$$

$$\Delta H = -406.6 \frac{\text{kJ}}{\text{mol}}$$

+1 point for taking half of the value given for the bond energy of Cl<sub>2</sub>

+1 point for the correct final answer

e. You decide to prepare some CsCl using cesium metal and chlorine gas. You start with 1.37 grams of cesium metal (132.91 g/mol) and 0.008 L of chlorine gas (at 1 atm, 273 K, 22.4 M). Determine the limiting reagent in this case **and** calculate the theoretical yield (in grams) for CsCl. (3 points)

$$n(\text{Cs}) = \frac{1.37\text{g}}{132.91\text{g/mol}} \approx 0.0103\text{ mol}$$

$$n(\text{Cl}_2) = 0.008\text{ L} \times 22.4\text{ mol/L} = 0.1792\text{ mol} \quad (+1\text{ point})$$

Cesium metal is the limiting reagent. (+1 point)

$$n(\text{CsCl}) = n(\text{Cs}) = 0.0103\text{ mol}$$

$$m(\text{CsCl}) = 0.0103\text{ mol} \times 168.363\text{ g/mol} \approx 1.735\text{ g} (+1\text{ point})$$

+1 point for showing the calculations for finding the moles of each reactant

+1 point for determining that the limiting reagent is cesium metal

+1 for the correct theoretical yield

**Problem #7: (18 points)**

Acid rain occurs when compounds such as sulfur dioxide (SO<sub>2</sub>) and nitrogen oxides (NO<sub>x</sub>) are released into the atmosphere and fall back down to the ground through precipitation.

- a. Investigate the following properties of nitrogen gas (N<sub>2</sub>).
- i. Draw the Lewis structure of N<sub>2</sub> and indicate non-zero formal charges, if any. (2 points)



No formal charges

**+1 point for the correct Lewis structure (triple bond, one lone pair on each nitrogen)**

**+1 point for no formal charges**

- ii. State the VSEPR molecular shape, polarity, and N-N bond angle (3 points)

Shape: Linear (+1 point)

Polarity: Nonpolar (+1 point)

N-N Bond Angle: 180° (+1 point)

- iii. If multiple N<sub>2</sub> molecules are placed in the same container, what would the dominating intermolecular interactions be? No justification is required. (1 point)

Dispersion forces / London dispersion forces / Instantaneous dipole - induced dipole forces / Van der Waals forces

- b. Nitrogen gas will not react with oxygen gas unless in conditions of high temperature. Based on the Lewis structure, predict the reasoning for this. *(2 points)*

Nitrogen gas has a very stable structure due to its triple bond, which means it has a **high bond strength**. Therefore, it will take **a lot of energy to break the bond** to get the nitrogen to be able to react.

**+1 point for relating the triple bond to bond strength**

**+1 point for relating bond strength to ability to react**

- c. Nitrogen monoxide, on the other hand, reacts readily in the presence of oxygen to produce nitrogen dioxide, which then reacts with water to produce both nitrous and nitric acid. Write two separate balanced equations describing this process (one for the production of nitrogen dioxide, one for the production of nitrous and nitric acid). State symbols are not necessary. Hint: these are irreversible reactions. *(2 points)*

Production of nitrogen dioxide:  $2NO + O_2 \rightarrow 2NO_2$  **(+1 point)**

Production of Nitrous and Nitric Acid:  $H_2O + 2NO_2 \rightarrow HNO_2 + HNO_3$  **(+1 point)**

**Note: full credit can be received if the coefficients are a constant multiple of the ones shown here**

- d. Nitrous acid is considered a weak acid. What would be the pOH of a 0.75 M nitrous acid solution, given that its  $K_a = 7.2 \times 10^{-4}$ ? Use an ICE table and show all of your work. (4 points)

	$HNO_2$	+	$H_2O$	$\leftrightarrow$	$H_3O^+$	+	$NO_2^-$
I	0.75 M				0		0
C	-x				+x		+x
E	0.75 - x				x		x

$$K_a = [H_3O^+][NO_2^-] / [HNO_2]$$

$$7.2 \times 10^{-4} = \frac{(x)(x)}{0.75 - x} \text{ (+1 point)}$$

Quadratic Formula: (+1 point)

$$(7.2 \times 10^{-4})(0.75 - x) = x^2$$

$$5.4 \times 10^{-4} - (7.2 \times 10^{-4})x = x^2$$

$$x^2 + (7.2 \times 10^{-4})x - (5.4 \times 10^{-4}) = 0$$

$$a = 1$$

$$b = 7.2 \times 10^{-4}$$

$$c = -5.4 \times 10^{-4}$$

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} = \frac{-(7.2 \times 10^{-4}) \pm \sqrt{(7.2 \times 10^{-4})^2 - 4(1)(-5.4 \times 10^{-4})}}{2(1)}$$

$$x = 0.02288$$

$$x = -0.2360$$

Therefore, the logical x is  $x = 0.02288$  (+1 point)

$$[H_3O^+] = 0.02288 \text{ M}$$

$$pH = -\log[H_3O^+] = -\log[0.02288] = 1.64$$

$$pOH = 14 - pH = 14 - 1.64 = 12.36 \text{ (+1 point)}$$

+1 point for the correct expression with  $K_a$

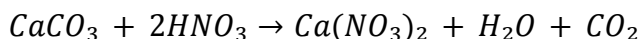
+1 point for using the quadratic formula

+1 point for the correct x value

+1 point for the correct final pH

Note: the student can have any acid and any conjugate base written down and still receive full credit (i.e. no credit is awarded for the chemical equation or the species used)

- e. Nitric acid from acid rain is known to dissolve limestone (calcium carbonate) upon reaction. If a 0.05 mL raindrop with 0.005 M nitric acid hits a 1 gram limestone pebble, what is the volume of the gas produced (in liters), assuming standard temperature and pressure conditions? Use the following chemical equation. (2 points)



Find the limiting reagent:

Molar mass of calcium carbonate is 100.1 g/mol

$$0.05 \text{ mL} \times 0.005 \text{ mol HNO}_3/1000 \text{ mL} \times 1 \text{ mol CO}_2/2 \text{ mol HNO}_3 = 1.25 \times 10^{-7} \text{ mol CO}_2$$

$$1 \text{ g} \times 1 \text{ mol}/100.1 \text{ g CaCO}_3 \times 1 \text{ mol CO}_2/1 \text{ mol CaCO}_3 = 0.01 \text{ mol CO}_2$$

Therefore  $\text{HNO}_3$  is the limiting reagent and  $1.25 \times 10^{-7} \text{ mol CO}_2$  is produced. (+1 point)

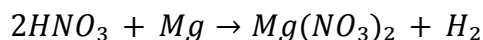
At STP, 1 mol of gas occupies 22.4 L of volume

$$1.25 \times 10^{-7} \text{ mol CO}_2 \times 22.4 \text{ L}/1 \text{ mol} = 2.8 \times 10^{-6} \text{ L CO}_2 \text{ (+1 point)}$$

**+1 point for determining that the limiting reagent is  $\text{HNO}_3$**

**+1 point for the correct final volume of  $\text{CO}_2$**

- f. One way to combat the effects of acid rain is to utilize a “buffer” such as magnesium. What is the minimum amount of grams of magnesium needed to neutralize the raindrop described in Part E? Use the following chemical equation. (2 points)



The minimum amount of grams Mg will be the exact amount that will completely react with all the  $\text{HNO}_3$ .

$$0.05 \text{ mL} \times \frac{0.005 \text{ mol HNO}_3}{1000 \text{ mL}} \times \frac{1 \text{ mol Mg}}{2 \text{ mol HNO}_3} = 1.25 \times 10^{-7} \text{ mol Mg (+1 point)}$$

$$1.25 \times 10^{-7} \text{ mol Mg} \times \frac{24.31 \text{ g Mg}}{1 \text{ mol Mg}} = 3.04 \times 10^{-6} \text{ g Mg (+1 point)}$$

**+1 point for solving for the moles of Mg**

**+1 point for the correct final mass of Mg in grams**

## Scratch Paper