Name _____ Individual ID # _____

Team Name _____

2024 WUCT: Individual Exam

April 6th, 2024
9:45 a.m. – 10:45 a.m.

Please fill in the numbers of your 6-digit individual ID:

Individual ID

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1 HOUR will be allowed for the exam. The examination contains **7** questions on **23** numbered pages, including the last **SCRATCH PAGE**.

TURN IN THE ENTIRE EXAM (INCLUDING THE SCRATCH PAGE) WHEN YOU ARE FINISHED!

Exam Points Breakdown:

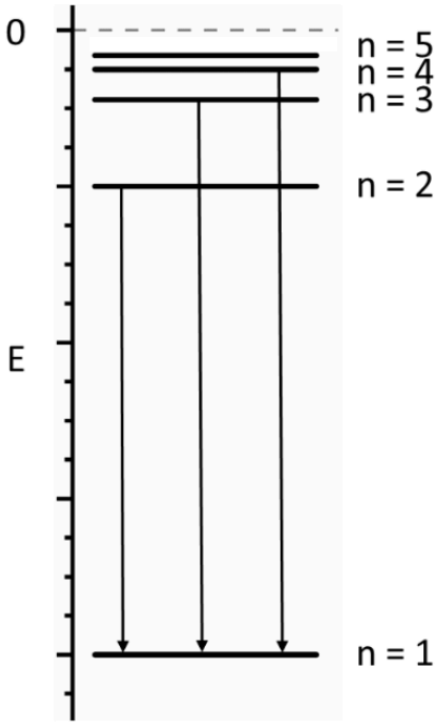
1. (11 pts)
2. (11 pts)
3. (19 pts)
4. (13 pts)
5. (12 pts)
6. (16 pts)
7. (18 pts)
Total Points: (100 pts)

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: $E_n = (-2.18 \times 10^{-18} J)\frac{z^2}{n^2}$

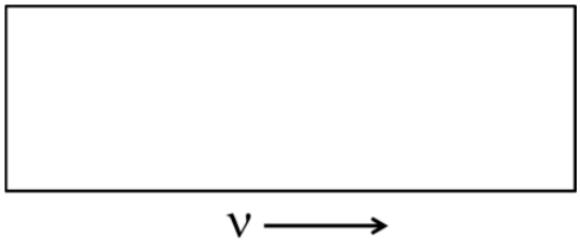


a. Why can't an atom of Al^{3+} be represented by this diagram? ***(1 point)***

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

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 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)***

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)***



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 $4.78 \times 10^{-17}\ J$ 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)***

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

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

b. The half reactions happening in this cell are:

$2Cl^-(l) \rightarrow Cl_2(g) + 2e^-$ $\quad \varepsilon° = -1.359V$

$Na(l) \rightarrow Na^+(l) + e^-$ $\quad \varepsilon° = 2.714V$

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

c. Give the change in potential in the cell. ***(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
ii. AA (1.5V) battery
iii. Phone (3.7V) battery
iv. Laptop (10.8V) battery

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

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

$$Ca^{2+} + 2e^- \rightarrow Ca \qquad \varepsilon^\circ = -2.87V$$

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

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.

$$VO^{2+} + MnO_4^- \rightarrow V(OH)_4^+ + Mn^{2+}$$

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

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

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

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

e. If 175 mL of a 0.35 M $KMnO_4$ solution and 225 mL of a 3.45 M VO^{2+} solution are combined, what are the new concentrations of each relevant species (those given in the initial unbalanced redox reaction)? ***(2 points)***

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

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)***

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.

$$Al(H_2O)_6^{3+} + H_2O \Leftrightarrow H_3O^+ + Al(H_2O)_5(OH)^{2+}$$

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

Acid: _____

Base: _____

Conjugate Acid: _____

Conjugate Base: _____

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

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)***

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^2, sp^3, etc.)? Also, what are the atomic orbitals used to produce the hybridized orbitals? ***(2 points)***

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)***

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)***

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:

$$Fe(H_2O)_6^{3+}(aq) \Leftrightarrow [Fe(H_2O)_5(OH)]^{2+}(aq) + H^+(aq) \ .$$

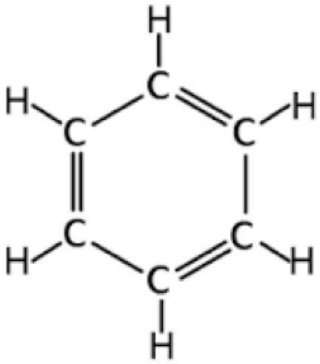
Knowing that $Fe(H_2O)_6^{3+}$ has a **light**, **pale** violet color, and $[Fe(H_2O)_5(OH)]^{2+}$ has an **orange** color. Explain why the solution containing iron (III) ions shows a color of yellow (when diluted) and orange (when concentrated). How will the color of the solution change if the concentration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

<u>Problem #5</u>: *(12 points)*

The following molecule, Compound D, is deficient in Parkison'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)***

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)***

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

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)***

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

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)***

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 $Cs_{(s)}$ into $Cs_{(g)}$ ***(1 point)***

   ii. Then, remove one electron each from this 1 mole of $Cs_{(g)}$ ***(1 point)***

   iii. Then, split $Cl_{2(g)}$ 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 $CsCl_{(s)}$ ***(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)***

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

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

iv. Lattice energy of $CsCl_{(s)}$: -633 kJ/mol ***(1 point)***

v. Bond energy of $Cl_{2(g)}$ gas: 243 kJ/mol ***(1 point)***

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

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)***

Problem #7: *(18 points)*

Acid rain occurs when compounds such as sulfur dioxide (SO_2) and nitrogen oxides (NO_x) are released into the atmosphere and fall back down to the ground through precipitation.

a. Investigate the following properties of nitrogen gas (N_2).

i. Draw the Lewis structure of N_2 and indicate non-zero formal charges, if any. ***(2 points)***

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

Shape: _____

Polarity: _____

N-N Bond Angle: _____

iii. If multiple N_2 molecules are placed in the same container, what would the dominating intermolecular interactions be? No justification is required. ***(1 point)***

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)***

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)***

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

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)***

$$CaCO_3 + 2HNO_3 \rightarrow Ca(NO_3)_2 + H_2O + CO_2$$

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)***

$$2HNO_3 + Mg \rightarrow Mg(NO_3)_2 + H_2$$

Scratch Paper