Name _____ Teams ID # _____

Team Name _____

2025 WUCT: Teams Exam

April 5th, 2025
2:15 p.m. – 3:15 p.m.

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

Teams ID

⑨⑨⑨⑨⑨⑨
⑧⑧⑧⑧⑧⑧
⑦⑦⑦⑦⑦⑦
⑥⑥⑥⑥⑥⑥
⑤⑤⑤⑤⑤⑤
④④④④④④
③③③③③③
②②②②②②
①①①①①①
⓪⓪⓪⓪⓪⓪

1 HOUR will be allowed for the exam. The examination contains **6** questions on **25** numbered pages, including the last **SCRATCH PAGE**.

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

Exam Points Breakdown:

1. (19 pts)
2. (16 pts)
3. (16 pts)
4. (19 pts)
5. (15 pts)
6. (15 pts)
Total Points: (100 pts)

2025 WUCT: Team Exam

This exam consists of 6 questions and is worth 100 points. You will complete this exam as a team. 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: *(19 points)*

Water is known as the "universal solvent" in biochemistry because a wide spectrum of solutes can be readily dissolved in water. However, for species that are hard to dissolve in water, we need to use equilibrium to determine the accurate amount a chemical will dissolve. This question will start from solubility calculation in aqueous solution. Then we will explore how water changes when organic compounds dissolve, and discuss the limited solubility of organic compounds in water using thermodynamic data.

a. List one characteristic of the species that are soluble in water. ***(1 point)***

---

b. Write the expression for the solubility equilibrium constant K_{sp} of $Zn(OH)_2$. ***(1 point)***

c. If the K_{sp} for $Zn(OH)_2$ is 3.00×10^{-16}, calculate the concentration of OH^- ions in water, assuming nothing is dissolved in the water initially. ***(3 points)***

d. Assume 1.0 M of NaOH is added to water before the experiment begins. How would this affect the solubility of $Zn(OH)_2$? Explain by showing calculations. ***(5 points)***

When working with organic materials, water can be tricky to deal with because most organic molecules do not dissolve in water and will form immiscible layers instead. The following table provides thermodynamics data for dissolving some organic compounds in water at 303 K, based on Mirgorod's work (2014).

Hydro-carbon	ΔG°_s, kJ/mol	$-\Delta H^\circ_h$, kJ/mol	$-\Delta S^\circ_h$, J/(mol K)	$-\Delta H^\circ_{ph.tr}$, kJ/mol
Butane	–	26.0	176.3	5.0
Pentane	28.6	28.4	188.7	4.9
Hexane	32.5	31.5	197.7	4.8

e. Calculate the equilibrium constant K of dissolving pentane in water at 303 K, using the provided ΔG_s° (change in standard Gibbs free energy of dissolution) values in the table. ***(2 points)***

f. Sketch how water molecules and a pentane molecule interact when pentane is added to water. Represent pentane as a sphere (draw only one pentane molecule) and include approximately five water molecules around it to illustrate their interaction. Draw each water molecule with its bent molecular structure, clearly showing the hydrogen (H) atoms and oxygen (O) atoms. Label the pentane molecule to distinguish it from the water molecules. ***(2 points)***

g. Refer solely to the ΔS_h° (change in standard entropy of hydrophobic hydration) value provided in the table (Note that the table lists $-\Delta S_h^\circ$, not ΔS_h°): Is dissolving pentane in water entropically favorable? Then, explain why the ΔS_h° value makes sense, focusing on how the presence of pentane affects the arrangement and mobility of water molecules. ***(4 points)***

h. Based on the table, how can you make dissolving pentane in water more energetically favorable? Assume ΔS_h° & ΔH° are constant across all temperatures. (No calculations needed) ***(1 point)***

Problem #2: ***(16 points)***

In the nuclear model of the atom, electrons are assumed to revolve around a fixed nucleus. Classically, since the electrons are constantly accelerating, they should eventually lose all the energy and spiral into the nucleus. Bohr, however, makes the assumption that the angular momentum of the electrons must be quantized, allowing the nuclear model to work and enabling us to calculate the orbital energies and radii for one-electron systems.

a. The energy of the second excited state for a one-electron ion is -37.78 eV. Identify the ion (include both the element symbol and the ionic charge). ***(4 points)***

b. Considering a one-electron beryllium ion (Be^{3+}), calculate the energy emitted (in eV) when the electron transitions from the $n = 4$ to the $n = 3$ state. Round your answer to three decimal places. ***(2 points)***

c. Calculate the wavelength (in nm) of a photon emitted during an electronic transition that releases 16.528 eV of energy. Round your answer to the nearest integer. ***(1 point)***

d. A metal is irradiated with light that has a wavelength of 100 nm. Knowing that the ejected electron has a kinetic energy of 10 eV, calculate the work function of the metal (in eV, and round to the second decimal place). ***(3 points)***

e. Using the kinetic energy of the electrons given in part d (10 eV), calculate the momentum p (in $kg \cdot \frac{m}{s}$) and the de Broglie wavelength λ (in pm) of the ejected electron. Hint: $p = mv = \sqrt{2m \times (\frac{1}{2}mv^2)}$ ***(3 points)***

f. Since electrons behave as circular standing waves around the nucleus, an integer number of complete wavelengths must fit around the circumference of the orbit, which gives us the equation $2\pi r = n\lambda$, where n=1,2,3,4… If this electron is in the first Bohr orbit (n=1) of the Be^{3+}, calculate the velocity of the electron. ***(3 points)***

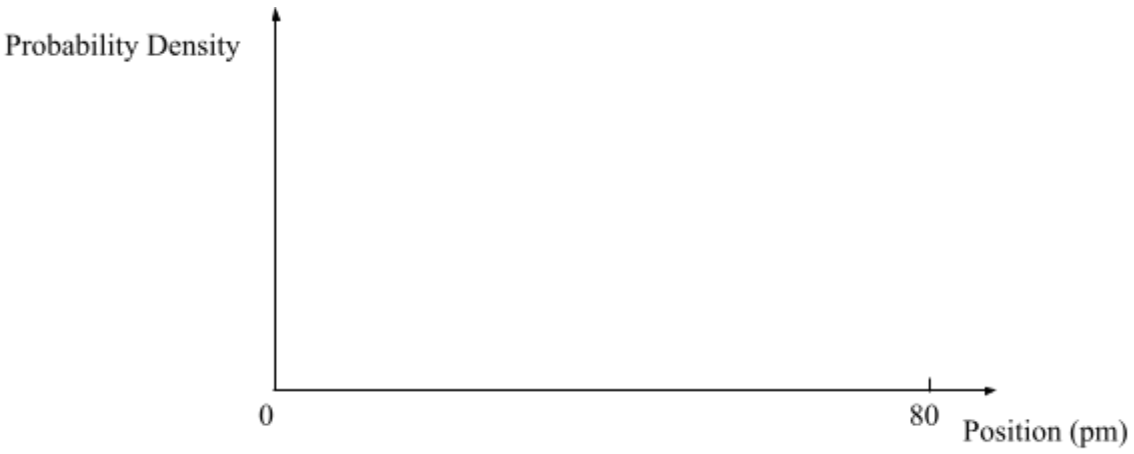
Problem #3: ***(16 points)***

The Particle-in-a-box (PIB) model is a foundational quantum mechanics model describing a particle confined within an infinitely high potential, and the potential energy within the box is assumed to be zero. The wave function of a particle in a one-dimensional box is given by: $\psi_n(x) = \sqrt{\frac{2}{L}}\, sin(\frac{n\pi x}{L})$, where L is the length of the box, and n is the quantum number.

a. A particle in a one-dimensional box has a wave function of $\psi(x) = \psi_n(x)$. Given that this wave function has four nodes (a node is where the wavefunction is zero and changes signs), and the distance between two nearby nodes is 20 pm, determine the length of the box L and the quantum number n. ***(2 points)***

b. Sketch the probability density distribution function $\left|\psi_n(x)\right|^2$ for a particle confined to a one-dimensional box of length 80 pm in the n=4 state. Additionally, sketch the probability density distribution function for the next energy state $\left|\psi_{n+1}(x)\right|^2$. Clearly indicate the position of the nodes in your drawing. Assume that the box starts at x = 0 pm and ends at x=80 pm. ***(4 points)***

$\left|\psi_n(x)\right|^2$:



$\left|\psi_{n+1}(x)\right|^2$:

c. What is the probability of finding the particle in part b (in the n=4 state) in the region 20 pm $\leq x \leq$ 70 pm? ***(1 point)***

d. Calculate the total energy of the particle (in J) in part b (in the n=4 state). Assume that the particle is an electron. ***(2 points)***

e. Knowing that an electron can be described as a standing de Broglie wave in a one-dimensional particle-in-a-box model, calculate its lowest allowed velocity in a one-dimensional box of length 2×10^{-13} m. ***(4 points)***

f. Consider a modified model where the potential energy at the walls and outside the box is not infinitely large but instead has a finite value V_0. This adjustment allows the particle to have non-zero probability of being found outside the box. Describe qualitatively how this change would affect the probability distribution graphs you sketched in part b. Focus on how the probability varies across the available positions, without requiring precise mathematical details or exact function shapes. ***(1 point)***

g. If $V_0 = 5 \times 10^{-15} J$ and the particle's total energy is $4 \times 10^{-26} J$, discuss why this scenario is problematic from a classical perspective. ***(2 points)***

Problem #4: *(19 points)*

Molecular orbital theory (MOT) is a theory used to describe the distribution of electrons over a molecule by looking at the interactions between atomic orbitals. In this theory, *n* atomic orbitals interact to form *n* molecular orbitals.

a. Briefly describe how the energy levels for bonding and antibonding molecular orbitals compare to one another. ***(1 point)***

_____

_____

b. To understand MOT, one must first look at the different characteristics of each atom and then molecule. The four quantum numbers used to describe these characteristics are n, l, m_l, and m_s.

   i. What does each quantum number determine? What are their possible values? ***(4 points)***

n:

l:

m_l:

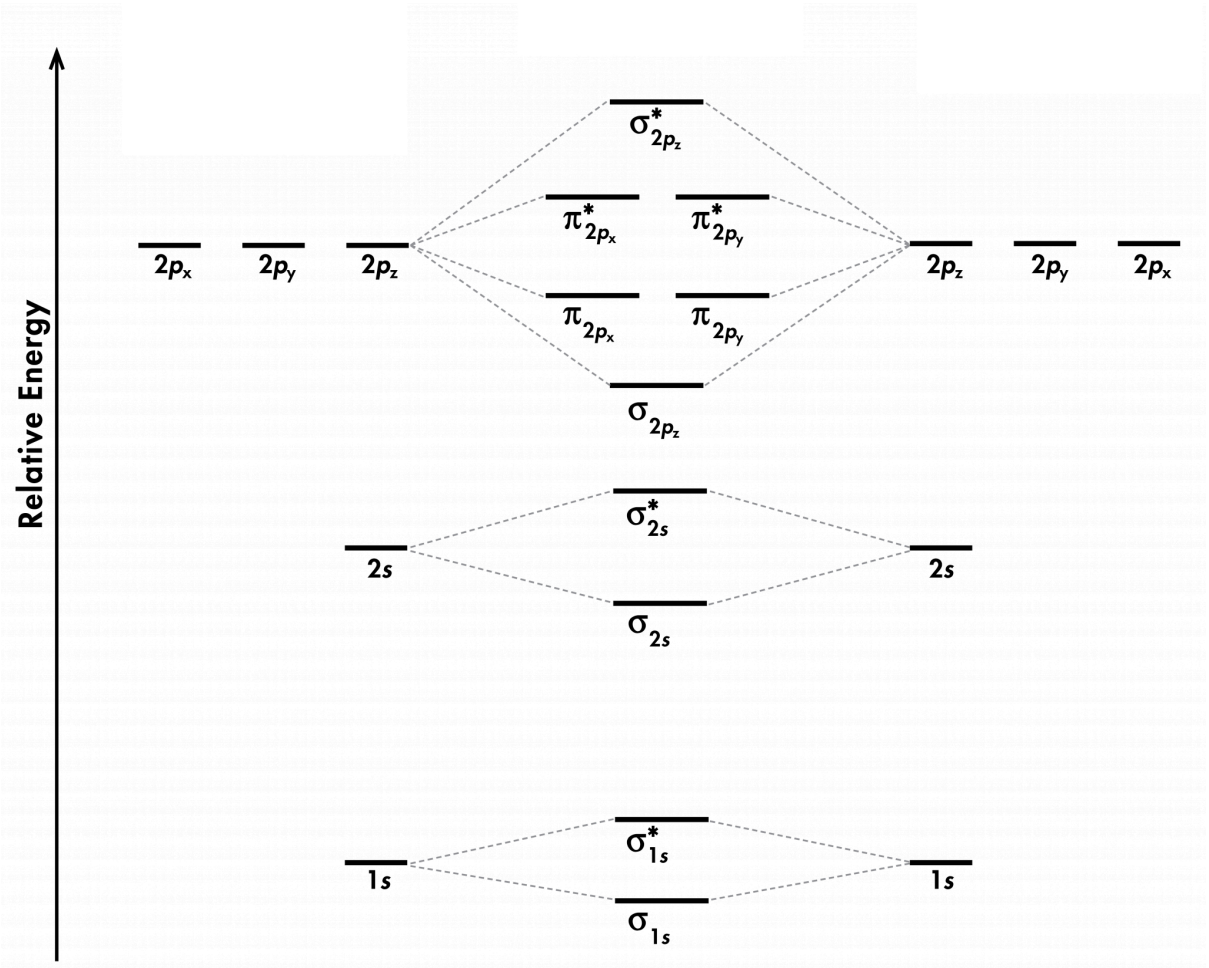
m_s:

ii. Fill in the chart below. ***(5 points)***

Set of Quantum Numbers	Allowed? (yes or no)	If not allowed, list a valid set of quantum numbers by changing **one** of the quantum numbers in the original set.
$(0, 0, 0, +\frac{1}{2})$		
$(3, 3, -2, +\frac{1}{2})$		
$(6, 4, -1, -\frac{1}{2})$		
$(2, 0, -1, -\frac{1}{2})$		
$(4, 1, 0, +\frac{1}{2})$		

c. To develop a better understanding of MOT, you are assigned to study the molecule O_2. ***(6 points)***

i. Fill in the molecular orbital diagram below for O_2. Make sure that you fill in the electrons for both the atomic orbitals and the molecular orbitals. ***(2 points)***



ii. Is O_2 a paramagnetic or a diamagnetic molecule? Explain. ***(1 point)***

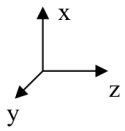
_____

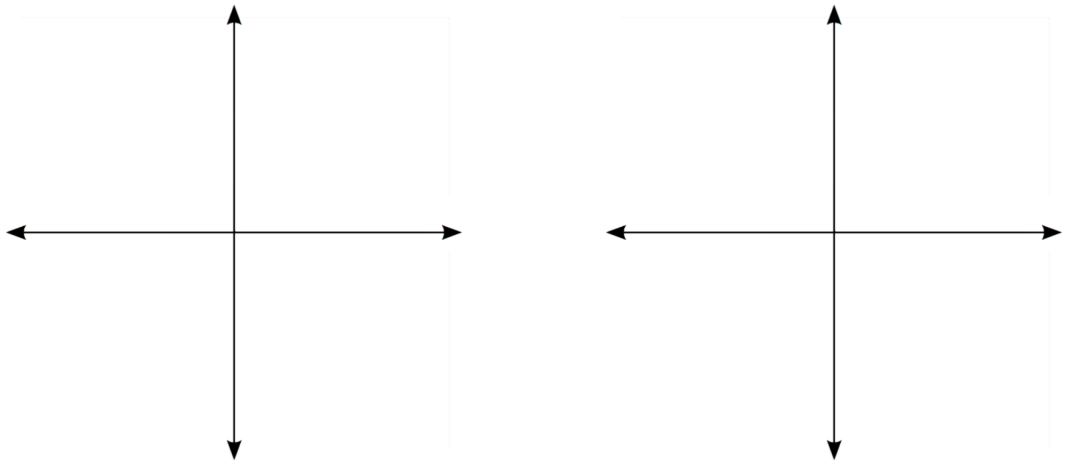
_____

iii. Using your answer from ii, determine if the following statement is true or false by circling your answer below: O_2 would be attracted to an external magnetic field. ***(1 point)***

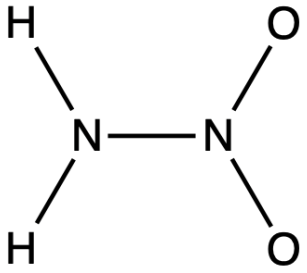
TRUE / FALSE

iv. For O_2, sketch the molecular orbitals of π_{2p_x} and $\pi^*_{2p_x}$ using the coordinate systems shown below. Note: make sure to use shading to indicate the correct phase of each lobe. ***(3 points)***





d. The Lewis structure for the molecule $H_2N_2O_2$ (shown below) is incomplete. Sketch the proper Lewis structure and any equivalent resonance forms with all the atoms (except for H) have complete octets. Please be sure to include any lone pairs and formal charges. ***(2 points)***



Problem #5: ***(15 points)***

S-AdenosylMethionine (SAM)'s family is preparing for a trip to the Andes. As a chemistry enthusiast, SAM would like to determine how much time it would take to boil an egg in his hotel. For all following questions, ignore the temperature difference due to heat conductance (assume homogeneous temperature for all parts of the system in question).

a. At sea level (1 atm), water boils at 100 degrees celsius. The process of water boiling can be represented as: $H_2O\ (l) \rightleftharpoons H_2O\ (g)$. Using $\Delta G^{o} = -RTlnK$, show why ΔG_{vap}^{o} for water at 100 ℃ is equal to 0 and explain your reasoning. (ΔG_{vap}^{o} is the change in standard Gibbs free energy for vaporization under standard conditions) ***(4 points)***

b. Atmospheric pressure decreases with elevation according to the relation:

$P\,(h) = 1\,atm \times (1 - 2.25577 \times 10^{-5} m^{-1} \cdot h)^{5.25588}$, where h is the elevation (in meters) with respect to sea level. Calculate the boiling point of water at the top of the Andes, at an elevation of 6962 m. ***(3 points)***

Given: $\Delta G_{vap}{}^{o} = 0$ and $\Delta S_{vap}{}^{o}(H_2O) = 109.1 \frac{J}{mol \cdot K}$ at 373 K. You may assume that $\Delta H_{vap}{}^{o}(H_2O)$ and $\Delta S_{vap}{}^{o}(H_2O)$ are temperature and elevation independent.

c. Thinking about the process of an egg boiling as following first-order kinetics, we can equate the amount of time it takes for the egg to be half-boiled as its half life. At sea level, it takes 5 mins in boiling water for the egg to be half boiled, but 30 mins in 80 ℃ water. Using the Arrhenius equation and assuming the Arrhenius (pre-exponential) factor A and activation energy E_a are independent of temperature and elevation, calculate the time it takes for the egg to become half-boiled at 90 ℃. ***(3 points)***

d. As a seasoned chemist, SAM is aware that the above calculations are over-simplifying the problem. In fact, we've been assuming that the pressure experienced by the liquid water is solely its vapor pressure, which is the partial pressure of water vapor. However, in reality, when boiling an egg, the water is also subject to atmospheric pressure in addition to the vapor pressure of water. To accurately determine the time required to boil an egg, we need to first explore the idea of chemical potential.

The chemical potential of a substance i in a system with multiple phases is defined as:

$$\mu_i = \overline{G}_i$$

In essence, the chemical potential of substance i (μ_i) in a particular phase is equal to its molar Gibbs free energy ($\overline{G}_i$). Based on what you know, prove that for water at its boiling point (an equilibrium state), the chemical potential of the liquid phase must be equal to the chemical potential of the gaseous phase. Note: μ_i must be the same in all phases of a system for equilibrium to exist. ***(2 points)***

_____

_____

_____

_____

_____

e. The chemical potential of a liquid is related to pressure by the following equation:

$$\mu_{liquid,\,i}(T,\ P_2) = \mu_{liquid,\,i}(T,\ P_1) + \overline{V} \cdot (P_2 - P_1)$$

Using this information, calculate the corrected boiling point of water at sea level, where the atmospheric pressure is 1 atm. ***(3 points)***

Given: $P_1 = 1$ atm, $P_2 = P_1 + P_{atmospheric} = 2$ atm, $T = T_b$ (boiling point), $\overline{V}$ is the molar volume of liquid i (in this case, H_2O), $\Delta S_{vap}^{o}(H_2O) = 109.1\ J/(mol \bullet K)$, and $\Delta H_{vap}^{o}(H_2O) = 39\ kJ/mol$.

Hint: when boiling, $\mu_{liquid,\,H_2O}(T_b,\ P_2) = \mu_{gas,\,H_2O}(T_b,\ P_1)$

Problem #6: ***(15 points)***

In this question, we will explore the electron configuration of atoms, the rules behind electron filling, and the ionization of atoms.

a. Write out the full electron configuration of Cu without using noble gas abbreviation. ***(1 point)***

b. Fill in the missing information in the table below. (For the violated electron filling rules: select from Aufbau Principle, Hund's Rule, and Pauli Exclusion Principle). ***(4 points)***

Atomic Number	Electron Configuration	Ground or Excited State or Forbidden	# of unpaired electrons	Which Electron filling rules violated.
24	$[Ar]4s^2 3d^4$		0	
27		Ground		None
39	$[Kr]5s^3$		1	
53		Excited	1	

c. When forming a zinc ion (Zn^{2+}) from a zinc atom, why is the electron removed from the 4s orbital instead of the 3d orbital? Justify your answer in a few sentences. ***(2 points)***

Justification:

_____

_____

_____

_____

_____

_____

_____

_____

d. Radial wavefunctions describe the probability of finding an electron in a region of space as a function of distance from the nucleus. It is determined from the Schrödinger equation of H atom. In this question, a radial wavefunction is provided for an electron in $3s$ orbital.

$R(r) = 2 \cdot (\frac{Z}{3a_0})^{\frac{3}{2}} \cdot (1 - \frac{2Zr}{3a_0} + \frac{2(Zr)^2}{27a_0^2}) \cdot e^{-\frac{Zr}{3a_0}}$, where Z is the atomic number, and a_0 is the Bohr Radius.

i. Using the equation above and basic algebra, describe in a few sentences how the probability of finding an electron changes as the radius *r* increases.***(2 points)***

_____

_____

_____

_____

_____

_____

_____

_____

ii. In Physical Chemistry, a node is defined as a position in space where the probability of finding the electron (or particle) is zero. The probability density of finding an electron is described as $R^2(r)$ (or $|R(r)|^2$). It is known that the $3s$ orbital has 2 radial nodes. Using this information, find the positions of radial nodes for the $3s$ orbital. ***(3 points)***

e. Finally, we will come back to electron configuration. Considering that the electron configuration of Ru is $[Kr]5s^1 4d^7$, explain why the statement below is true. Make sure you include the electron configuration of Ru^+ in your explanation. ***(3 points)***

"The most probable distance of finding the highest energy valence electron in Ru is much larger than the most probable distance of finding the highest energy valence electron in Ru^+."

_____

_____

_____

_____

_____

_____

_____

_____

SCRATCH PAGE