

2025 WUCT: Wacky Element Exam

This exam consists of 6 questions and is worth 100 points. You will complete this exam as a pair. 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: (17 points)

Tin is a post-transition metal on the periodic table. One of its unique properties is that Tin has two forms, α form (αSn) and β form (βSn), which can interconvert. Both of these two forms have unique properties. α form is brittle and can serve as a semiconductor, while β form is more malleable (stretchable) and is a conductor. The phenomenon of β form converting into α form is known as “tin pest.”

- a. Using the data in the table below, explain why the conversion from the β form to the α form is exothermic. *Hint: The formation of water by reacting H_2 and O_2 is a highly exothermic reaction because a stronger bond is formed. For this question, think about what characteristics a stronger bond has. (3 points)*

Substance	Interatomic Distance (Å)
βSn	3.03
αSn	2.79

- (1) **Interatomic distance** ($2.79 \text{ \AA} < 3.03 \text{ \AA}$) in the product is **smaller** than that in the starting material **(+1 point)**
- (2) Shorter bond length corresponds to larger bond strength **(+1 point)**,
- (3) This conversion is exothermic due to the formation of stronger bonds **(+1 point)**.

+1 points for comparing the interatomic distance

+1 point for stating the fact that shorter bond length indicates a stronger bond

+1 point for correct implication (i.e. the exothermic nature of the reaction) from closer interatomic distance

- b. Scientists theorized the change in concentration of $\alpha S n$ in this reaction over time can be expressed as $\frac{d[\alpha S n]}{dt} = k[\alpha S n][\beta S n]$. Based on this expression, provide the unit of the rate constant k below. For this question, use molarity (M) as the concentration unit and second (s) as the time unit. **(1 point)**

$M^{-1}s^{-1}$

+1 point if the unit provided is correct, no explanation is required

- c. By referring to the rate expression given in part b, explain why scientists would be surprised to discover that the half-life of βSn is directly proportional to $[\beta Sn]_0$ (the initial concentration of βSn). (2 points)

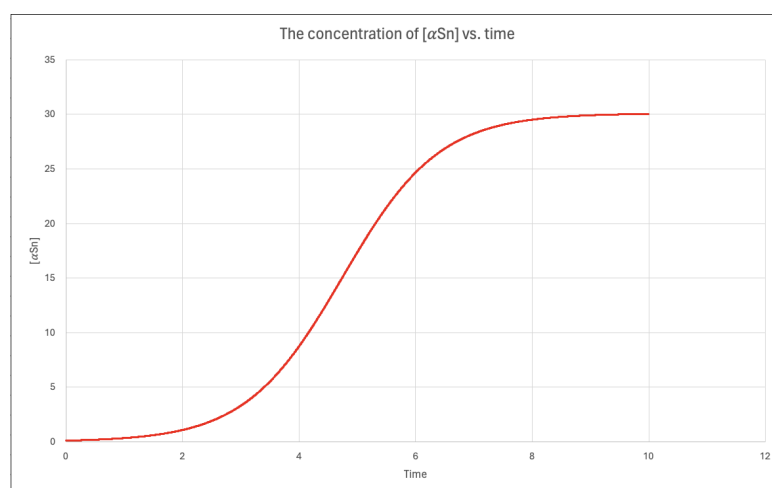
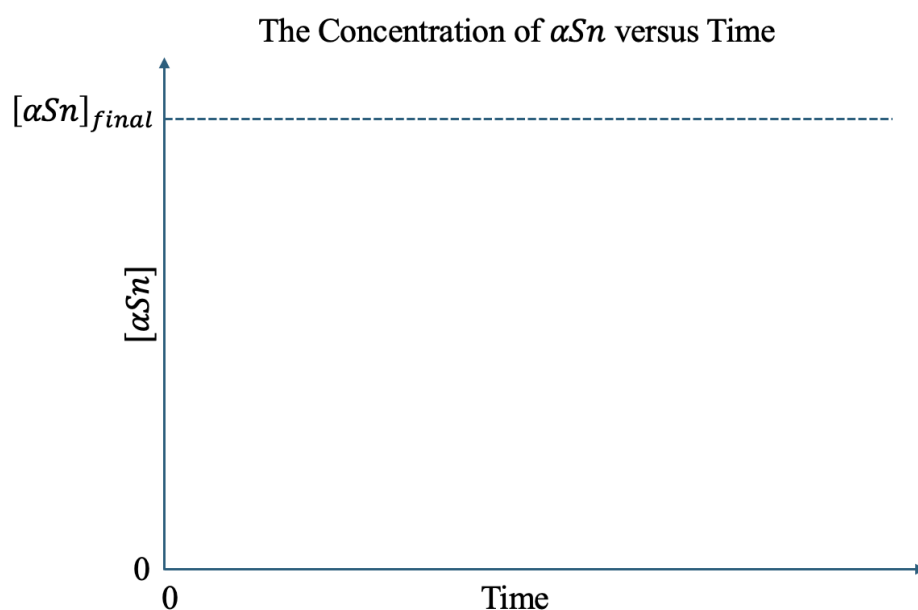
According to the expression above, this reaction is supposed to follow **second-order kinetics (+1 point)**, which means the half-life of a species should be **inversely proportional** to its initial concentration, not directly (**+1 point**). However, if this behavior was not observed, that means this interaction does not fit into a second-order kinetic interaction.

+1 point for correctly identifying that the rate expression in part (b) implies second-order kinetics

+1 point for correctly relating the theoretical half-life with the order of the reaction identified (even if second order was not identified, earning this partial credit is still possible)

The kinetics of an autocatalytic reaction can change with time. Usually, autocatalytic reactions speed up as final products accumulate. Therefore, the production of the final product will usually start slow and then increase at an accelerating rate. The reaction between αSn and βSn is an example of an autocatalytic reaction.

- d. Based on the previous statement, draw a **qualitative** diagram representing the concentration of αSn versus time on the axis provided below. (4 points)

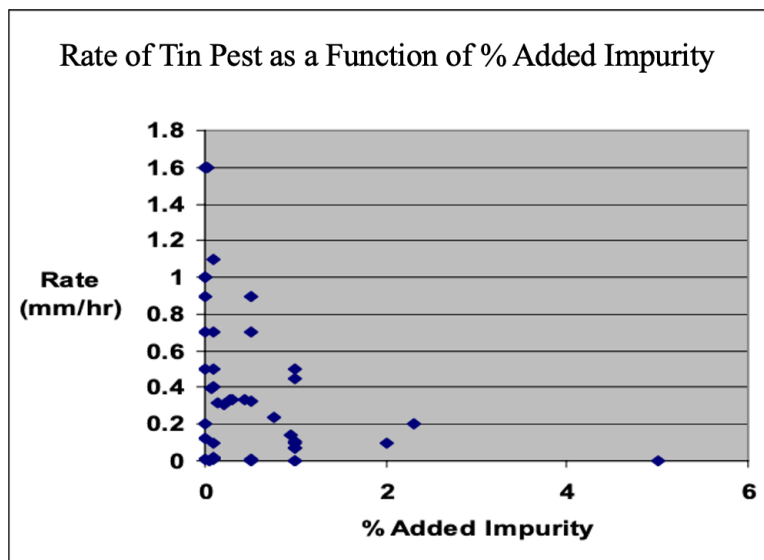


+1.5 points if the rate is slow at the beginning, $[\alpha Sn]$ can start from 0 or a small non-zero value (Will show later that $[\alpha Sn]$ cannot start at 0, but both answers are accepted here.)

+1.5 points if the rate increases sharply in the middle (i.e. having a much greater slope than the initial phase)

+0.5 points for showing that rate slows down, $[\alpha Sn]$ asymptotically approaches a maximum value at the end (sketch is qualitative, so tick marks/numerical values are not required in actual drawing.)

- e. In order for tin pest conversion to occur, diffusion of tin atoms is required throughout the tin solid. It is believed that immobile impurities introduced to solid tin will slow the conversion rate between α and β form. Consider the following diagram. Does the data present here support this claim? Justify your reasoning. *Note: Immobile impurities are atoms present in the structure that are neither reactants or products and are fixed in place. (3 points)*



As more impurities present in the sample, the rate of tin pest conversion is **slowed down** (decreased) (+1 point).

The tin atoms need to diffuse to rearrange, converting βSn to αSn . **Immobile impurities** present can effectively **block the diffusion routes and slow down this process** (+1 point). This will in turn **decrease the rate of conversion** (+1 point).

+1 point for identifying the correct relationship between the impurities and the rate from the graph (do not need to go too specific to relate % of the impurities with the rate.)

+1 point for correctly explaining why dormant impurities will slow down the diffusion process

+1 point for the correct conclusion

- f. Read the following statement and expression for $[\alpha Sn]$.

“Since the conversion to αSn requires expansion, the tin pest will usually nucleate at an edge, corner, or surface. The nucleation can take a very long time, but once it starts, the conversion can be rapid, causing structural failure within a short period.” (4 points)

$$[\alpha Sn] = \frac{[\alpha Sn]_0 + [\beta Sn]_0}{1 + \frac{[\beta Sn]_0}{[\alpha Sn]_0} e^{-k([\alpha Sn]_0 + [\beta Sn]_0)t}}$$

Include the following points in your justification:

1. (For the statement) How does the statement address the autocatalytic nature of this conversion? (2 points)

The statement states the initial conversion from βSn to αSn is slow. But once the **gray tin** is formed, it **will keep catalyzing the formation of itself (+1 point)**, making the conversion **very fast once a certain amount of αSn is accumulated (+1 point)**. This is the effect of speeding up the rate autocatalytically.

+1 point for stating the formation of gray tin will catalyze the reaction which produces itself

+1 point for stating the reaction will be very fast once a certain amount of αSn is accumulated because of the consistent catalytic effect gray tin brings to its own formation reaction

2. **(For the equation above)** Why is it important for the conversion to start with an initial concentration of $[\alpha S n]_0$ rather than 0? *Hint: Do not overcomplicate the equation, think about basic math! (2 points)*

It is important for the conversion to start with a non-zero $[\alpha S n]_0$, otherwise the $\frac{[\beta S n]_0}{[\alpha S n]_0}$ term in the expression of $[\alpha S n]_0$ will be **undefined (+2 points)**. This expression tells us that we need to have some $\alpha S n$ to start the conversion.

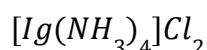
+2 points for expressing that the equation above will be undefined if $[\alpha S n]_0$ is 0

Problem #2: (19 points)

On a planet billions of lightyears away in an uncharted galaxy, space-exploring scouts have discovered what they believe to be a new element. They decided to name it intergalactium, chemical symbol Ig . They characterize this new element as a metal. Dive deeper into the properties of this new element in the following questions below.

- a. In the spaceship's laboratory, a scout grinds some of the Ig down into a solid powder. **(4 points)**

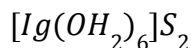
- i. This powder was then mixed in a beaker with some ammonia and potassium chloride. Using spectroscopy, the scout identified the following complex in solution:



Determine the charge of the Ig ion and circle your answer. **(1 point)**

$[Ig(NH_3)_4]Cl_2 \rightarrow [Ig(NH_3)_4]^{2+} \rightarrow$ ammonia is a neutral compound $\rightarrow Ig^{2+}$ **(+1 point)**

- ii. Some more of the powder was mixed with water and zinc sulfide. The scout identified the follow complex in solution:



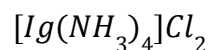
Determine the charge of the Ig ion and circle your answer. **(1 point)**

$[Ig(OH_2)_6]S_2 \rightarrow$ sulfur ions have a 2- charge $\rightarrow [Ig(OH_2)_6]^{4+} \rightarrow$ water is a neutral compound $\rightarrow Ig^{4+}$ **(+1 point)**

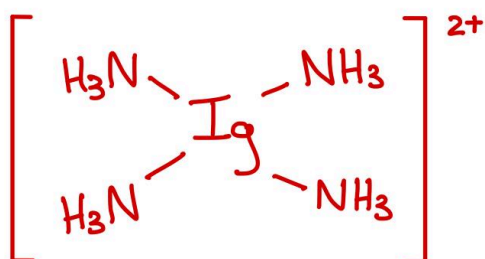
- iii. Based on your answers to the previous parts a(i) and a(ii), what specific family on the periodic table must Ig be in? (e.g. alkali metal, alkaline earth metal, transition metal, etc.) Justify your answer in 1 sentence. **(2 points)**

Ig must be a **transition metal (+1 point)**, as it can **stably exist in multiple oxidation states (+1 point)**.

- b. Answer the following with respect to the coordination complex discussed in part a(i).
(3 points)



- i. Draw the Lewis Structure of the **cation** of this coordination complex. Include all lone pairs around the ligands. Assume there are no lone pairs around the central atom. Label the overall charge of the species. (2 points)



+1 point for attaching 4 identical ligands around the central metal and having no lone pairs on any of the ligands

+1 point for labeling the Lewis structure with the correct charge (2+)

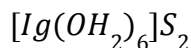
Note: students do not necessarily have to put the structure in brackets this way for full credit

Note: students do not need to draw the ligands in any specific arrangement

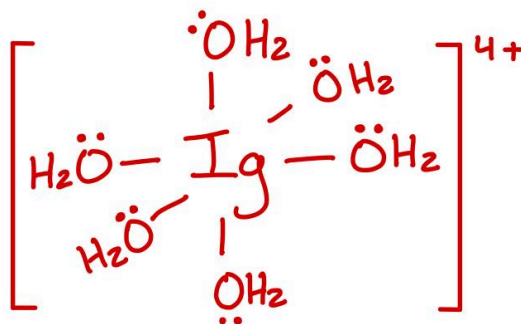
- ii. Using VSEPR Theory, what is the name of the molecular geometry that best describes the *Ig* ion? (1 point)

Tetrahedral (+1 point)

- c. Answer the following with respect to the coordination complex discussed in part a(ii). (3 points)



- i. Draw the Lewis Structure of the **cation** of this coordination complex. Include all lone pairs around the ligands. Assume there are no lone pairs around the central atom. Label the overall charge of the species. (2 points)



+1 point for attaching 6 identical ligands around the central metal and having one lone pair on each ligand

+1 point for labeling the Lewis structure with the correct charge (4+)

Note: students do not necessarily have to put the structure in brackets this way for full credit

Note: students do not need to draw the ligands in any specific arrangement (i.e. octahedral)

- ii. Using VSEPR Theory, what is the name of the molecular geometry that best describes the *Ig* ion in the $[Ig(OH_2)_6]S_2$ complex? (1 point)

Octahedral (+1 point)

- d. Answer the following questions regarding periodic trends: (2 points)

- i. Assuming both elements are present in the same period of the periodic table, fill in the blank by circling your answer: (1 point)

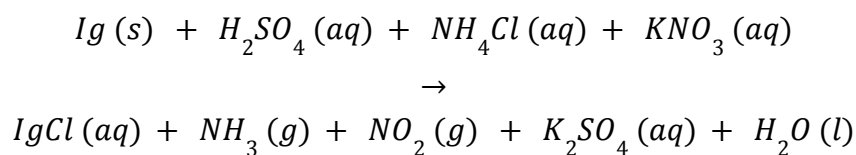
Ig has a/the **larger** smaller same atomic radius than/as *Rn*.

- ii. Assuming both elements are present in the same period of the periodic table, fill in the blank by circling your answer: (1 point)

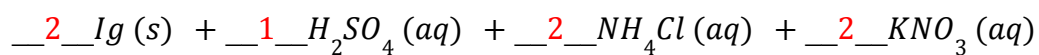
Ig has a/the **larger** smaller same electronegativity than/as *K*

- e. Balance the following chemical equation involving intergalactium:

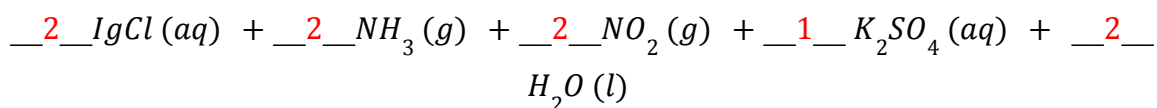
Unbalanced Equation:



Fill in the blanks below with all coefficients for balancing. Include any 1's as coefficients as well. You may use the blank space below this page to work, but only answers in the lines will be graded. (2 points)



→



+1 point for correctly balancing the reactant side

+1 point for correctly balancing the product side

f. In the lab, a scout combines the following substances to make a solution:

947 g *Ig*

7.25 L of 5.42 M H_2SO_4

6.50 L of 1.74 M KNO_3

Excess NH_4Cl

The reaction results in 1.74 mol of $K_2SO_4(aq)$ being formed. Using your balanced chemical equation from part e, determine the limiting reactant and report your answer on the line provided below. Show all work to support your answer. (5 points)

Limiting Reactant: *Ig*

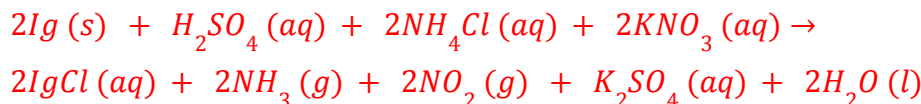
Moles of H_2SO_4 :

$$mol = ML = (5.42 M)(7.25 L) = 39.295 \text{ mol } H_2SO_4 \text{ (+1 point)}$$

Moles of KNO_3 :

$$mol = ML = (1.74 M)(6.50 L) = 11.31 \text{ mol } KNO_3 \text{ (+1 point)}$$

Determining the limiting reactant:



$$39.295 \text{ mol } H_2SO_4 \times \frac{1 \text{ mol } K_2SO_4}{1 \text{ mol } H_2SO_4} = 39.295 \text{ mol } K_2SO_4 \text{ (+1 point)}$$

$$11.31 \text{ mol } KNO_3 \times \frac{1 \text{ mol } K_2SO_4}{2 \text{ mol } KNO_3} = 5.655 \text{ mol } K_2SO_4 \text{ (+1 point)}$$

Because both H_2SO_4 and KNO_3 yield an amount of K_2SO_4 greater than that described in the problem, neither of these compounds can be the limiting reactant. The NH_4Cl is present in excess, so it cannot be the limiting reactant either. Therefore, *Ig* must be the limiting reactant by process of elimination. (+1 point)

Note (not necessary for full points): this implies that the molar mass for *Ig* is 272.13 g/mol
+1 point each for obtaining the moles of H_2SO_4 and KNO_3 (+2 points in total)

+1 point each for calculating the moles of K_2SO_4 that H_2SO_4 and KNO_3 will produce (+2 points in total)

+1 point for an analysis that gives the correct conclusion

Problem #3: (18 points)

Mercury (*Hg*) is the only metal that exists as a liquid at room temperature. This unusual property arises from its electronic structure and bonding characteristics which are influenced by relativistic effects. In this problem, you will explore how these factors contribute to mercury's unique behavior.

- a. Write the electron configuration of a mercury (*Hg*) atom in noble gas notation. **(1 point)**

$[Xe]6s^2 4f^{14} 5d^{10}$ **(+1 point)**

+1 point for correct electron configuration; order of orbitals 6s, 4f, and 5d is flexible

- b. Metal atoms are typically bonded by metallic bonds where valence electrons are shared to form a "sea of electrons." From the electron configuration you obtain above, provide an explanation for why mercury is liquid at room temperature. **(3 points)**

Mercury has **filled 6s, 4f, and 5d orbitals (+1 point)**. The stability of these filled orbitals makes it energetically **unfavorable for mercury to delocalize (+1 point)** its valence electrons to form the "electron sea" required for strong metallic bonding. As a result, **metallic bonding in mercury is weaker**, which contributes to its **low melting point and liquid state (+1 point)** at room temperature.

+1 point for mentioning the filled 6s, 4f, and 5d orbitals

+1 point for explaining how the filled orbitals contribute to the weaker metallic bonding in mercury

+1 point for mentioning weaker metallic bonding leads to low m.p. and liquid state

- c. It turns out that mercury is a classic example of a heavy element influenced by relativistic effects, which arises because the electrons in heavy atoms move at speeds approaching the speed of light, increasing their effective mass. These effects are particularly significant for fast-moving electrons, such as those in mercury's 1s orbital. **(4 points)**

- i. The average radial velocity for a 1s electron in an atom heavier than hydrogen can be approximated using this formula: $\frac{Z}{137} \times c$, where Z is the atomic number, and c is the speed of light. Calculate the mass of 1s electron of mercury using the following formula of special relativity:

$$m_{moving} = \frac{m_{rest}}{\sqrt{1-(v/c)^2}}. \text{ (2 points)}$$

$$v = \frac{80}{137} \times c \approx 58.39\% c \text{ (+1 point)}$$

$$m_{moving} \approx 1.23 m_{rest} = 1.23 \times 9.109390 \times 10^{-31} \text{ kg} \approx 1.12 \times 10^{-30} \text{ kg (+1 point)}$$

+1 point for correctly calculating the average radial velocity for Hg

+1 point for correctly calculating the mass of 1s electron of Hg

- ii. Using the Bohr radius formula: $a_0 = \frac{\epsilon_0 h^2}{m_e e^2 \pi}$, explain qualitatively why an increase in the electron mass will reduce the radius of 1s orbital in mercury. **(2 points)**

Since the Bohr radius is **inversely proportional (+1 point)** to the mass of the electron. An increase in the mass of the electron, due to relativistic effects, will cause the radius of the 1s orbital to **decrease (+1 point)**.

+1 point for mentioning how the radius is related to the electron mass (from the formula)

+1 point for stating that as mass increases, radius decreases

- d. How does the contraction of 1s orbital in mercury influence the repulsion between 1s and 6s valence electrons? How does this effect impact the stability of 6s electrons and the strength of metallic bonding in mercury? Please justify your answer in 3-4 sentences. *(4 points)*

The relativistic contraction of the 1s orbital **reduces 1s electrons' core electron repulsion** to 6s valence electrons **(+1 point)**, which **allows the 6s electrons to be held more tightly to the nucleus (+1 point)**, thereby **increasing the stability of 6s electrons (+1 point)**. As a result, **the 6s electrons become less delocalized, weakening metallic bonding in mercury (+1 point)**. This effect contributes to mercury's unusually low melting point and liquid state at room temperature.

+1 point for mentioning decreased repulsion

+1 point for saying that 6s electrons are held more tightly due to the decreased repulsion, justifying the increased stability

+1 point for answering increased stability

+1 point for answering weaker metallic bonding

- e. The conduction band is a range of energy levels in a material where electrons are free to move throughout the structure, allowing the material to conduct electricity. In metals, some electrons like those in the outermost orbital can easily move between atoms, forming the conduction band. Explain why mercury has a much weaker electrical conductivity compared to gold, its neighbor on the Periodic Table. *(3 points)*

Due to the relativistic contraction of 1s orbital, mercury's 6s electrons are **tightly localized (+1 point)** near the nucleus and **do not contribute effectively** to the conduction band (+1 point). In gold, however, the 6s electrons are **more delocalized and can participate in the conduction band**, resulting in higher electrical conductivity for gold (+1 point).

+1 point for mentioning mercury's 6s electrons are more localized due to relativistic effects

+1 point for mentioning mercury's 6s electrons do not contribute effectively to the conduction band

+1 point for mentioning that more localized electrons don't contribute well to conduction bands

- f. Thallium (Tl) and Indium (In) exhibit interesting ionization behaviors. For instance, the energy needed to ionize Tl^+ to Tl^{3+} is higher than that for In^+ to In^{3+} , even though Tl^+ has a larger radius. Compare the electron configuration of Tl^+ and In^+ with that of mercury and explain this phenomenon using what you know about the relativistic effects of mercury's 6s electrons. (3 points)
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Tl^+ is **isoelectronic** with mercury (+1 point), so its 6s electrons experience **similar relativistic effects** (+1 point). These effects stabilize the 6s electrons, **making them hard to ionize** (+1 point). Thus, the energy required to ionize Tl^+ to Tl^{3+} is higher than that for In^+ to In^{3+} .

+1 point for saying that Tl^+ is isoelectronic with mercury

+1 point for saying that Tl^+ experience similar relativistic effects

+1 point for mentioning that 6s electrons are stabilized and therefore hard to ionize

Problem #4: (19 points)

Radioactivity is a topic that is widely explored in college physics and chemistry lab courses. Here we explore a simple, inexpensive implementation of a radioactive isotope generator, which cleverly exploits the different properties between barium (*Ba*) and cesium (*Cs*).

- a. The radioactive isotope used in this question is ^{137}Cs , which spontaneously decays to ^{137}Ba . Which of the following correctly characterizes this decay process? Circle your final answer. (2 points)
- A. This includes a β^- decay, where a proton is converted to a neutron and an electron is released by ^{137}Cs .
- B. This includes a β^- decay, where a neutron is converted to a proton and an electron is released by ^{137}Cs . (+2 points)
- C. This includes a β^+ decay, where a neutron is converted to a proton and a positron is released by ^{137}Cs .
- D. This includes a β^+ decay, where a proton is converted to a neutron and a positron is released by ^{137}Cs .
- b. Using the tabulated data for atomic mass and abundance below, Calculate the relative atomic mass of *Ba*. (2 points)

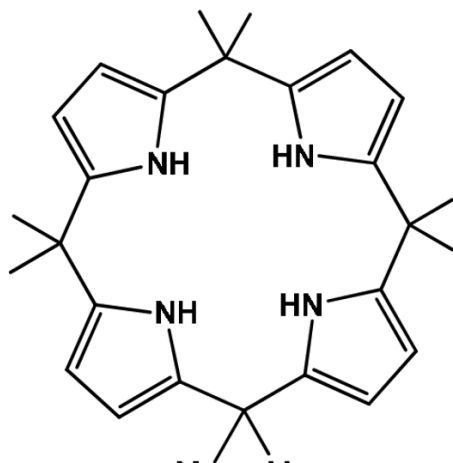
Atomic Mass Number	Atomic Mass (Dalton)	Abundance
130	129.9063260	0.11%
132	131.9050612	0.1%
134	133.90450825	2.45%
135	134.90568845	6.59%
136	135.90457580	7.85%
137	136.90582721	11.2%
138	137.90524706	71.7%

$\Sigma(\text{Atomic mass} \times \text{Abundance})$ (+1 point) = 137.3258 Dalton (+1 point within 0.01 margin)

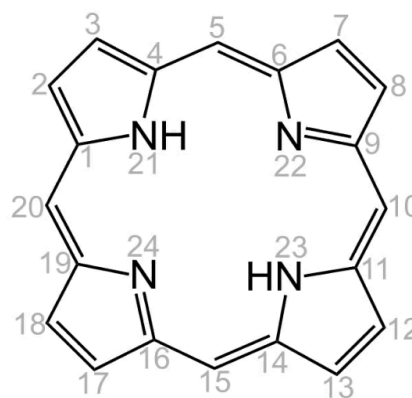
+1 point for using the correct equation

+1 point for obtaining the correct relative atomic mass of barium

- c. The radioactive ^{137}Cs can be separated from fission waste waters using calix[4]pyrroles (left below). Calix[4]pyrroles are similar to Heme groups (right below), which are essential coenzymes of hemoglobin. Unlike Heme, which must be deprotonated in order to coordinate iron, calix[4]pyrroles directly bind ^{137}Cs with the electron-rich pyrrole rings. (5 points)



Calix[4]pyrroles

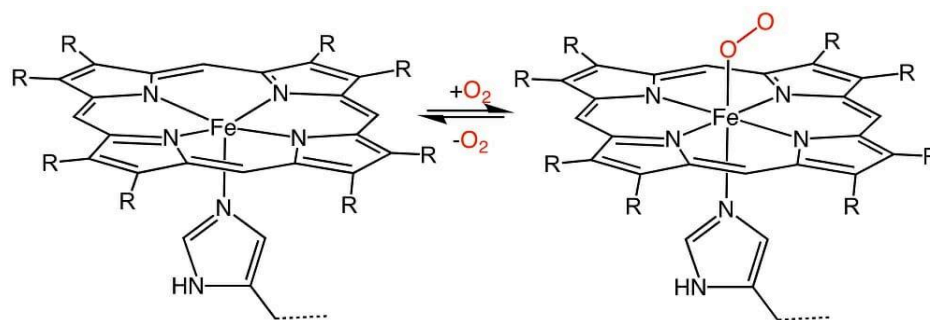


Heme Groups

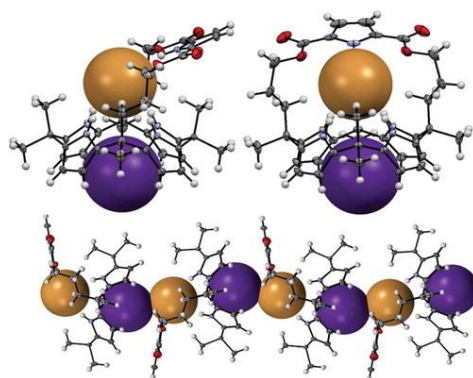
- i. What is **the most important** property of the pyrrole ring **electrons** that make the interaction between the calix[4]pyrroles and the ^{137}Cs strong, where ^{137}Cs exists as $\text{Cs}(I)$ cation? (1 point)

High density OR High polarizability. (This is cation-pi interaction) (+1 point)

+1 point for stating either high density or high polarizability



- ii. As the coenzyme of hemoglobin, heme binds oxygen molecules. Shown above is a scheme for this process. Yet, calix[4]pyrroles use its ring structure to bind metal ions. What is the key **structural difference** between the two compounds, and how does this difference help them serve their respective purposes? *Note: For this question, refer to the oxygen-binding scheme above, and please compare the structures given under the main prompt of question 4 part c. (4 points)*



- The double bonds connecting the pyrroles in Heme are substituted by single bonds in calix[4]pyrroles, (alternatively: Heme has all sp^2 carbons, while calix[4]pyrroles has sp^3 carbons, (+1 points)
 - which disrupts the rigid conjugation that forces the rings coplanar (+1 point).
 - Heme needs to be planar so that oxygen/other residues have space to bind (+1 point).
 - Calix[4]pyrrole needs to be flexible to aim the pyrrole rings toward cesium (+1 point).
- 4 pyrrole rings wrapped around the metal cation (purple sphere). (The figure above ONLY serves an illustrating purpose in the key. It WILL NOT appear on the actual exam!)

+1 point for stating the double bonds connecting pyrroles are substituted by single bond in calix[4]pyrroles OR stating the hybridization of carbons change

+1 point for relating the change in bond structure (or hybridization) will disrupt the conjugation in the rings

+1 point for stating that it is required for heme group to be planar

+1 point for stating calix[4]pyrroles to be able to direct their pyrrole rings toward cesium (detailed point breakdown written above.)

- d. When doing a demo in an experiment course, the instructor extracted the radioactive $^{137\text{m}}\text{Ba}$ (Note: $^{137\text{m}}\text{Ba}$ is the radioactive isotope of non-radioactive ^{137}Ba , and it forms Ba^{2+} ion when dissolved in solution) from ^{137}Cs by column chromatography. The column is loaded with Bio-Rad ZP-1, which consists of 150 mesh zirconium phosphate (ZrP) beads, and equilibrated with 1 M HCl . The solution containing ^{137}Cs and $^{137\text{m}}\text{Ba}$ is charged onto the column, and the eluent is collected directly without the addition of other reagents. 99.9% of the ^{137}Cs is retained on the column. (4 points)
- i. This column chromatography approach functions based on its selectivity for Cs^+ ions over Ba^{2+} ions to absorb Cs^+ to its ion-exchanging sites. This selectivity cannot be explained on the basis of ion charge or size in this case. Explain why these properties cannot account for the selectivity. (2 points)

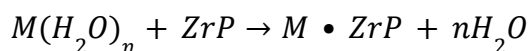
If charge explains this selectivity, barium having 2 positive charges would be absorbed more strongly than cesium. (+1 point)

If size explains this selectivity, barium being smaller than cesium should fit better into the cavities. (+1 point)

+1 point for comparing the number of charges on Cs^+ and Ba^{2+}

+1 point for explaining the selectivity using the perspective from the atomic size of two atoms

- ii. Research has shown that to be incorporated into the crystal lattice, the incoming ions need to lose the highly-ordered solvent molecules (in this case, H_2O) that wrap tightly around them. This binding process can be written as:



Recall: ZrP is the bead for chromatography. M represents metal ions.

Which of the following does not explain the selectivity of ZrP, given that they are all true statements? *Hint: the phosphate group, P, in ZrP is negatively charged. (2 points)*

- A. Ba^{2+} , due to its smaller size, has less water molecules surrounding it.
- B. Ba^{2+} , due to its positive charge, attracts the water molecule strongly and binds to them more tightly.
- C. Ba^{2+} , due to its smaller size, interacts poorer with the beads' binding sites.
- D. Ba^{2+} , due to its positive charge, repels stronger with the Zr^{4+} on the bead. (+2 points)

Explanation:

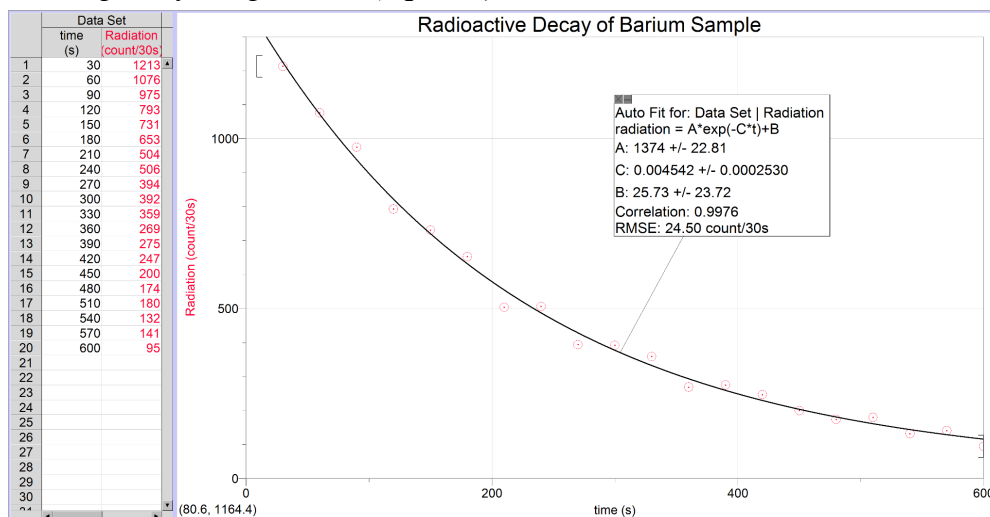
A: Removing solvent molecules gains entropy. Hence, getting rid of fewer water molecules gains less entropy, which is less favorable.

B. A strong metal ion-water interaction means more heat needs to be absorbed to remove the water shell. Hence, ΔH is more positive, which is less favorable.

C. The cavities on the beads fit Cs^+ better. Ionic interactions decrease with the size of the ions, so the smaller Ba^{2+} has a weaker interaction with the ion exchange loci. This means a smaller enthalpy compensation, which is less favorable.

D. It does not explain selectivity since the overall interaction manifests as attraction. It is true that Ba^{2+} repels with Zr^{4+} stronger, but also attracts phosphate group (PO_3^{4-}) stronger.

- e. A Geiger counter is used to quantify radiation. In an experiment conducted in the intro physics lab here at WashU, the following data of radiation from the extracted sample of $^{137\text{m}}\text{Ba}$ was collected by the writer of this problem. Given that radiation count is proportional to the number of $^{137\text{m}}\text{Ba}$ present, answer the following questions. *Note: $\exp(y)$ means e^y , and ignore the value of B when working on the calculation part of this problem. (6 points)*



- i. Calculate the half life of this decay in minutes. (2 points)

$$A = A_0 e^{-kt}, k = C = 0.004542 \text{ s}^{-1}$$

$$t_{1/2} = \frac{\ln 2}{k} = 152.6 \text{ s} = 2.54 \text{ min (+1 point for unit, and +1 point for correct answer)}$$

+1 point for solving the correct half life of the decay shown on the graph within a margin of error of 0.1 s

+1 point for the correct unit of the final answer (converting seconds to minutes.)

- ii. Identify the experimental meaning of coefficient B. (1 point)

Background radiation. (+1 point)

- iii. The manufacturer of this radioactive isotope generator states that the sample is safe to throw away when it shows a decay rate 0.5% of its original rate. How long (minutes) should I wait until I can safely dispose of this sample? (3 points)

$$rate = kA$$

When $r = 0.5\% r_0$, $kA = 0.5\% kA_0$, so the problem is actually asking for when

$$A = 0.5\% A_0 \text{ (+1 point)}$$

$$0.005A_0 = A_0 e^{-kt}$$

$$0.005 = e^{-kt}$$

$$t = -\frac{\ln(0.005)}{k} = 1166.5 \text{ s} = 19.44 \text{ min (+1 point for unit and +1 point for correct answer)}$$

+1 point for using the correct concentration of A

+1 point for correct t in seconds

+1 point for the correct unit of the final answer (converting seconds to minutes.)

Problem #5: (14 points)

Neodymium (*Nd*, atomic number 60) is well-known for its use in creating powerful permanent magnets, such as those in electric motors and headphones. The unique magnetic properties of neodymium arise from its unpaired *f*-electrons and its position in the lanthanide series. In this problem, you will explore the electronic structure and magnetism of neodymium.

- a. The magnetic moment (μ) of an atom can be roughly calculated using the formula $\mu = \sqrt{n(n + 2)}$, where n is the number of unpaired electrons. How does the magnetic moment of neodymium atoms compare to gadolinium ions (*Gd*, atomic number 64), Gd^{3+} ? Calculate the magnetic moments of both neodymium atoms and gadolinium ions, and justify your answer in 2-3 sentences. *Note: The unit of magnetic moment is Bohr Magnetons (μ_B).* **(5 points)**

Justification:

Gd^{3+} has an electron configuration of $[Xe]4f^7$, so there are **7 unpaired electrons (+1 points)**. *Nd* has an electron configuration of $[Xe]4f^4 6s^2$, so there are **4 unpaired electrons (+1 point)**. Since gadolinium ions have more unpaired electrons than neodymium atoms, their magnetic moment is greater. **(+1 point)**

$$\mu (Nd) = \sqrt{n(n + 2)} = \sqrt{4 * (4 + 2)} = \sqrt{24} = 4.899 \mu_B \text{ (+1 point)}$$

$$\mu (Gd^{3+}) = \sqrt{n(n + 2)} = \sqrt{7 * (7 + 2)} = \sqrt{63} = 7.937 \mu_B \text{ (+1 point)}$$

+1 points each for correctly stating the number of unpaired electrons for *Nd* and Gd^{3+}

+1 point for stating that *Gd* has a larger magnetic moment

+1 point each for the correctly calculated magnetic moments of a neodymium atom and a gadolinium ion

- b. When neodymium is combined with iron and boron, it forms the alloy $Nd_2Fe_{14}B$, which is used to make some of the strongest permanent magnets. This alloy's strong magnetic properties arise from its high magnetic anisotropy, meaning that the structure of the material determines that there will be a preferred direction to magnetize the material. In crystals, the arrangement of atoms plays a major role in their properties. A crystal with high symmetry has atoms arranged in a repeating, uniform pattern, making it easier for magnetic properties to align evenly in different directions. A crystal with low symmetry, on the other hand, has a less uniform atomic arrangement, which can make the material more resistant to changes in magnetism along certain directions. From the information given, how might you characterize the symmetry of the atomic arrangement in this alloy crystal—high symmetry or low symmetry? Justify your answer in a few sentences. **(3 points)**

The crystal structure (or the atomic arrangement in the alloy crystal of $Nd_2Fe_{14}B$) is likely to have **low symmetry (+1 point)**. In a **less symmetric structure**, the atoms may **interact more strongly in certain directions**, making the material **more resistant to** changes in properties like **magnetism**. **(+2 points)**

+1 point for correctly choosing low symmetry

+2 points for the correct justification of how symmetry related to magnetic anisotropy

- c. Lanthanide contraction refers to the decreasing atomic and ionic radii across the lanthanide series. How might lanthanide contraction influence the bonding and magnetic properties of the neodymium in the $Nd_2Fe_{14}B$ alloy? *Note: In some cases, a smaller atomic size can allow atoms to pack more tightly, potentially enhancing bonding strength. (3 points)*

Lanthanide contraction reduces the size of neodymium atoms (**+1 point**) (smaller atomic and ionic radii), enhancing the bonding strength between neodymium and other elements like iron and boron due to the tighter packing (**+1 point**). This stronger bonding contributes to the stability of the crystal structure, which contributes to the high magnetic anisotropy of the alloy (**+1 point**)

+1 point for mentioning that Lanthanide contraction reduces the size of neodymium atoms

+1 point for mentioning stronger bonding due to contraction and tighter packing

+1 point for connecting stronger bonding to stability and magnetic properties of the alloy

- d. The magnetic property of a $Nd_2Fe_{14}B$ magnet is influenced by temperature. At higher temperatures, the magnetism of the alloy decreases. This phenomenon is quantified by the Curie temperature (T_c), the temperature above which a material loses its permanent magnetic properties. $Nd_2Fe_{14}B$ has a Curie temperature of approximately 312°C . Suppose a sample of $Nd_2Fe_{14}B$ weighs 5.00 g. Calculate the amount of energy (in Joules) required to heat this sample from room temperature (25°C) to its Curie temperature, assuming the specific heat capacity of the alloy is $0.45 \text{ J/g}\cdot^\circ\text{C}$. (3 points)

Energy required to heat the sample:

$$q = mc\Delta T = 5.00 \text{ g} \times 0.45 \frac{\text{J}}{\text{g}\cdot^\circ\text{C}} \times (312^\circ\text{C} - 25^\circ\text{C}) = 645.75 \text{ J}$$

+1 point for using the correct formula

+1 point for correctly substituting all four values

+1 point for the correct final answer

Problem #6: (13 points)

Hydrogen has three naturally-occurring isotopes: protium (1H), deuterium (2H or D), and tritium (3H or T). Even though these atoms have the same chemical properties, they have different masses and different physical properties.

- a. For the following sentence, circle the option that correctly completes the sentence. (2 points)

Isotopes have the same number of (**protons** / **neutrons**), and a different number of (**protons** / **neutrons**).

+1 point for each correct answer.

- b. Given the table below and the fact that hydrogen has an average atomic mass of 1.008 amu, calculate the experimentally-determined mass of 1H . Show all work and circle the final answer. (2 points)

Isotope	Natural Abundance (%)	Experimentally-Determined Mass (amu)
1H	99.9885	?
2H	0.0115	2.0141
3H	negligible	3.0160

Average atomic mass of $^1H = (\text{abundance of isotope})(\text{isotope mass})$

$$1.008 = (3.0160 \text{ amu})(0) + (2.0141 \text{ amu})(0.000115) + (x)(0.999885) \text{ (+1 point)}$$

$$x \approx 1.00788 \text{ amu (+1 point)}$$

+1 point for correctly using the parameter in the table and correct setup

+1 point for correctly calculating the experimentally-determined mass of 1H

- c. Now, imagine you're conducting research on isotope separation and have collected the following data about a sample of water: the sample contains a mixture of H_2O and D_2O at $25^\circ C$; the vapor pressure of pure H_2O at $25^\circ C$ is 23.76 mmHg; the vapor pressure of pure D_2O at $25^\circ C$ is 22.82 mmHg, and the density of the liquid mixture is 1.052 g/cm^3 . (9 points)
- i. Briefly explain what makes the vapor pressure of D_2O lower than H_2O at the same temperature? (3 points)

D_2O molecules form stronger intermolecular forces because their heavier weight leads to less bond stretching (+1 point), and these stronger interactions require more energy to overcome. (+1 point) This makes D_2O molecules less likely to escape into the vapor phase (+1 point) at any given temperature. Hence, it will have a lower vapor pressure than H_2O .

+1 point for stating the D_2O forms strong intermolecular interaction than H_2O (students do not need to mention less bond stretching)

+1 point for stating that these strong interactions are harder to overcome

+1 point for explaining how higher energy requirement contributes to the lower vapor pressure of D_2O molecule

- ii. Based on the density provided (1.052 g/cm^3), estimate whether this sample is more enriched in deuterium compared to natural abundance. Explain your reasoning. *Note: natural water has a deuterium concentration of about 0.0115 %.* **(1 point)**

Yes, this sample is significantly enriched compared to natural abundance. This is shown by the fact that **the density (1.052 g/cm^3) is much higher than regular water (1.000 g/cm^3).** **(+1 point)**. This suggests substantial deuterium enrichment above the natural abundance of 0.0115%.

+1 point for comparing the density of the liquid mixture with that of pure H_2O

- iii. Given that the ΔH_{vap}° for H_2O is $40.65 \text{ kJ mol}^{-1}$, and the ΔH_{vap}° for D_2O is $41.61 \text{ kJ mol}^{-1}$. If the temperature is increased to 50°C , compare the absolute difference in vapor pressures between H_2O and D_2O with that in 25°C . Note: $P_{H_2O \text{ at } 25^{\circ}\text{C}} = 23.76 \text{ mmHg}$, $P_{D_2O \text{ at } 25^{\circ}\text{C}} = 22.82 \text{ mmHg}$. Make sure you quantitatively calculate these two differences. **(5 points)**

The difference in 25°C : $\left| P_{H_2O} - P_{D_2O} \right| = |23.76 \text{ mmHg} - 22.82 \text{ mmHg}| = 0.94 \text{ mmHg}$
(+1 point)

For the difference in 50°C :

Using the Clausius-Clapeyron equation: $\ln\left(\frac{P_2}{P_1}\right) = \frac{-\Delta H_{vap}^{\circ}}{R} \left(\frac{1}{T_2} - \frac{1}{T_1}\right)$, where P_2 and T_2 denote the final vapor pressure and temperature, and P_1 and T_1 denote values at 25°C .

Use e as the base to take the exponential of both sides: $\left(\frac{P_2}{P_1}\right) = e^{\frac{-\Delta H_{vap}^{\circ}}{R} \left(\frac{1}{T_2} - \frac{1}{T_1}\right)}$.

Hence, $P_2 = P_1 * e^{\frac{-\Delta H_{vap}^{\circ}}{R} \left(\frac{1}{T_2} - \frac{1}{T_1}\right)}$. **(+1 point)**

Plug in number for H_2O : $P_{H_2O \text{ at } 50^{\circ}\text{C}} = P_{H_2O \text{ at } 25^{\circ}\text{C}} * e^{\left[\frac{-40.65 \text{ kJ/mol}}{8.314 \times 10^{-3} \text{ kJ/mol/K}} \left(\frac{1}{(50+273.15)\text{K}} - \frac{1}{(25+273.15)\text{K}}\right)\right]}$

$P_{H_2O \text{ at } 50^{\circ}\text{C}} = 23.76 \text{ mmHg} * 3.556 = 84.49 \text{ mmHg}$ **(+0.5 points)**

Same for D_2O , $P_{D_2O \text{ at } 50^{\circ}\text{C}} = P_{D_2O \text{ at } 25^{\circ}\text{C}} * e^{\left[\frac{-41.61 \text{ kJ/mol}}{8.314 \times 10^{-3} \text{ kJ/mol/K}} \left(\frac{1}{(50+273.15)\text{K}} - \frac{1}{(25+273.15)\text{K}}\right)\right]}$

$P_{D_2O \text{ at } 50^{\circ}\text{C}} = 22.82 \text{ mmHg} * 3.664 = 83.62 \text{ mmHg}$ **(+0.5 points)**

So, the difference in 50°C :

$\left| P_{H_2O} - P_{D_2O} \right| = |84.49 \text{ mmHg} - 83.62 \text{ mmHg}| = 0.87 \text{ mmHg}$ **(+1 point)**

$\therefore 0.87 \text{ mmHg} < 0.94 \text{ mmHg}$

\therefore The absolute difference in vapor pressures between H_2O and D_2O is **smaller in 50°C** . **(+1 point)**

+1 point for correctly calculating the difference between P_{H_2O} and P_{D_2O} in 25°C

+1 point for correctly evoking and transforming the Clausius-Clapeyron equation.

+0.5 points for correctly calculating each of the P_{H_2O} and P_{D_2O} value in 50°C

+1 point for correctly calculating the difference between P_{H_2O} and P_{D_2O} in 50°C

+1 point for comparing the difference of vapor pressures in 25°C and 50°C

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