Name ____________________________ Topics ID # _____________________

Team Name ____________________________________

2025 WUCT: Wacky Elements Exam

April 5th, 2025
11:00 a.m. – 12:00 p.m.

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

Topics ID

⑨	⑨	⑨	⑨	⑨	⑨
⑧	⑧	⑧	⑧	⑧	⑧
⑦	⑦	⑦	⑦	⑦	⑦
⑥	⑥	⑥	⑥	⑥	⑥
⑤	⑤	⑤	⑤	⑤	⑤
④	④	④	④	④	④
③	③	③	③	③	③
②	②	②	②	②	②
①	①	①	①	①	①
⓪	⓪	⓪	⓪	⓪	⓪

1 HOUR will be allowed for the exam. The examination contains **6** questions on **27** numbered pages, including the last **SCRATCH PAGE**.

TURN IN THE ENTIRE EXAM (<u>INCLUDING THE SCRATCH PAGE</u>) WHEN YOU ARE FINISHED!

Exam Points Breakdown:

1. (17 pts)
2. (19 pts)
3. (18 pts)
4. (19 pts)
5. (14 pts)
6. (13 pts)
Total Points: (100 pts)

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

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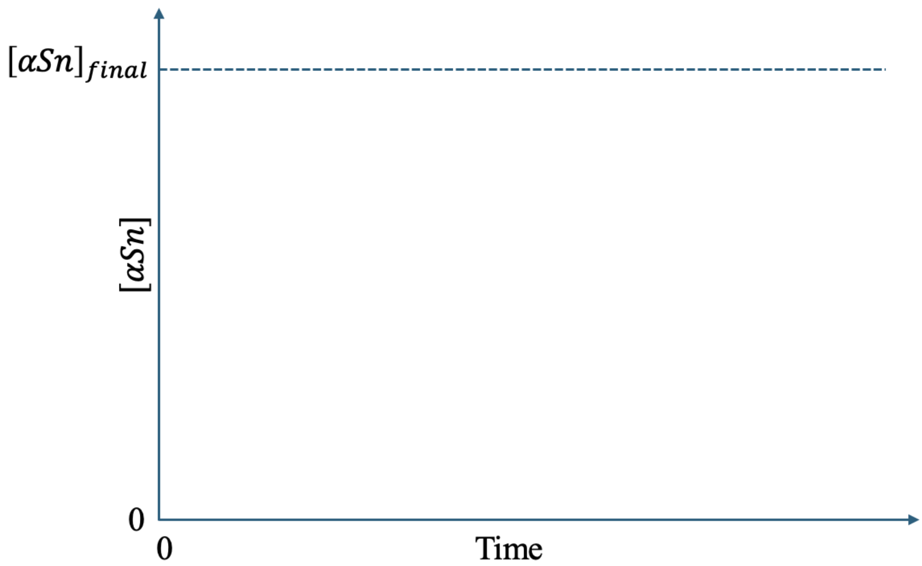
b. Scientists theorized the change in concentration of αSn in this reaction over time can be expressed as $\frac{d[\alpha Sn]}{dt} = k[\alpha Sn][\beta Sn]$. Based on this expression, provide the unit of the rate constant k below. For this question, use molarity (M) as the concentration unit and second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

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)***

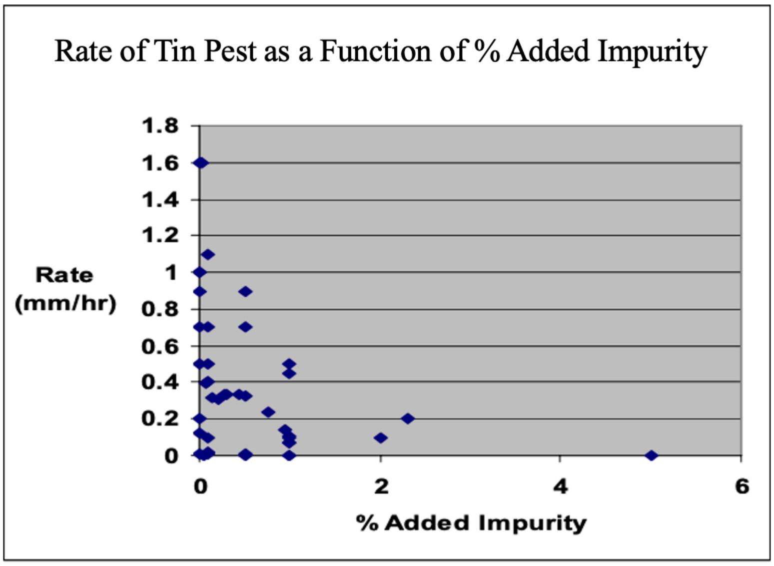
The kinetics of an autocatalytic reaction can change with time. Usually, autocatalytic reactions speed up as final products accumulate. Therefore, the production of the final product will usually start slow and then increase at an accelerating rate. The reaction between αSn and βSn is an example of an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

The Concentration of αSn versus Time



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)***



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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)***

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

<u>Problem #2</u>: *(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:

$$[Ig(NH_3)_4]Cl_2$$

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

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

$$[Ig(OH_2)_6]S_2$$

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

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

$$[Ig(NH_3)_4]Cl_2$$

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)***

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

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

$$[Ig(OH_2)_6]S_2$$

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)***

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)***

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:

$$Ig\,(s) + H_2SO_4\,(aq) + NH_4Cl\,(aq) + KNO_3\,(aq)$$
$$\rightarrow$$
$$IgCl\,(aq) + NH_3\,(g) + NO_2\,(g) + K_2SO_4\,(aq) + H_2O\,(l)$$

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)***

$$\_\_\_\_Ig\,(s) + \_\_\_\_H_2SO_4\,(aq) + \_\_\_\_NH_4Cl\,(aq) + \_\_\_\_KNO_3\,(aq)$$
$$\rightarrow$$
$$\_\_\_\_IgCl\,(aq) + \_\_\_\_NH_3\,(g) + \_\_\_\_NO_2\,(g) + \_\_\_\_K_2SO_4\,(aq) + \_\_\_\_H_2O\,(l)$$

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: ____

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)***

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)***

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

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)***

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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)***

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)***

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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<u>Problem #4</u>: *(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.

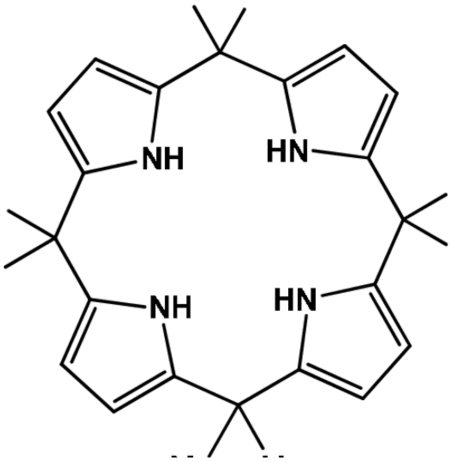
   C. This includes a β^+ decay, where a neutron is converted to a proton and a positron is released by ^{137}Cs.

   D. This includes a β^+ decay, where a proton is converted to a neutron and a positron is released by ^{137}Cs.

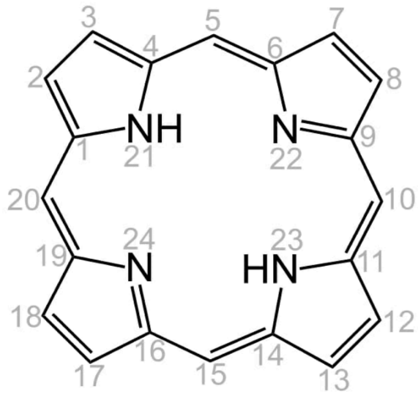
b. Using the tabulated data for atomic mass and abundance below, Calculate the relative atomic mass of Ba. ***(2 points)***

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%

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)***

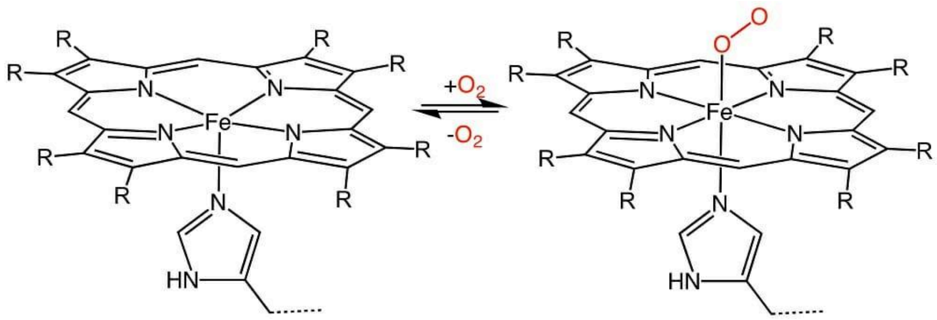


Calix[4]pyrroles



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 $Cs(I)$ cation? ***(1 point)***



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)***

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d. When doing a demo in an experiment course, the instructor extracted the radioactive ^{137m}Ba (*Note:* ^{137m}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 ^{137m}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)***

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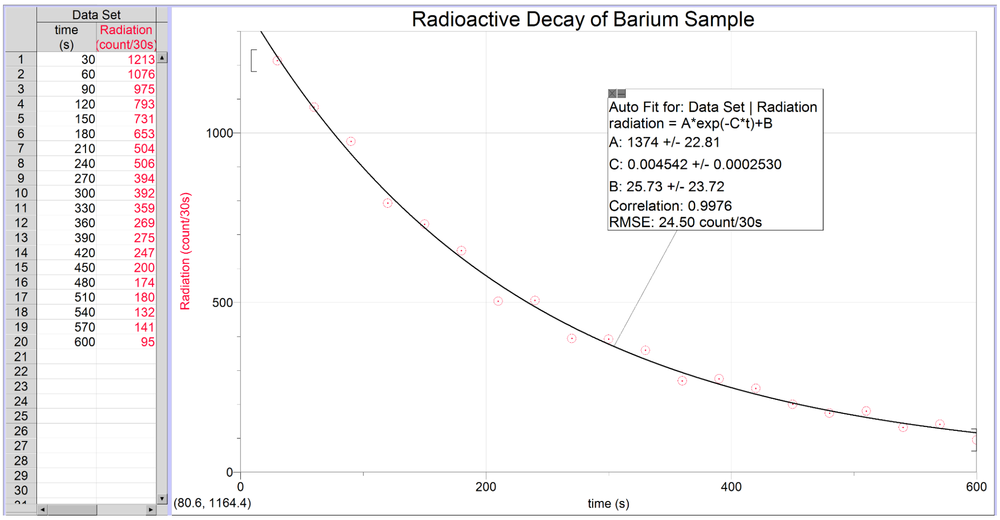
ii. Research has shown that to be incorporated into the crystal lattice, the incoming ions need to lose the highly-ordered solvent molecules (in this case, H_2O) that wrap tightly around them. This binding process can be written as:

$$M(H_2O)_n + ZrP \rightarrow M \bullet ZrP + nH_2O$$

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.

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 ${}^{137m}Ba$ was collected by the writer of this problem. Given that radiation count is proportional to the number of ${}^{137m}Ba$ 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)***



	Data Set time (s)	Radiation (count/30s)
1	30	1213
2	60	1076
3	90	975
4	120	793
5	150	731
6	180	653
7	210	504
8	240	506
9	270	394
10	300	392
11	330	359
12	360	269
13	390	275
14	420	247
15	450	200
16	480	174
17	510	180
18	540	132
19	570	141
20	600	95

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

ii. Identify the experimental meaning of coefficient B. ***(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)***

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

Justification:

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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)***

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)***

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 J/g·°C. ***(3 points)***

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**).

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

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°C; the vapor pressure of pure H_2O at 25°C is 23.76 mmHg; the vapor pressure of pure D_2O at 25°C is 22.82 mmHg, and the density of the liquid mixture is 1.052 g/cm³. ***(9 points)***

   i. Briefly explain what makes the vapor pressure of D_2O lower than H_2O at the same temperature? (***3 points)***

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   ii. Based on the density provided (1.052 g/cm³), 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)***

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iii. Given that the ΔH^{o}_{vap} for H_2O is 40.65 kJ mol^{-1}, and the ΔH^{o}_{vap} for D_2O is 41.61 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:* $P_{H_2O\ at\ 25°C} = 23.76\ mmHg,\ P_{D_2O\ at\ 25°C} = 22.82\ mmHg$. Make sure you quantitatively calculate these two differences. ***(5 points)***

SCRATCH PAGE