Question 6 (8 points)

Answer the following questions related to sulfur and one of its compounds.

(a) Consider the two chemical species S and S\(^{2-}\).

(i) Write the electron configuration (e.g., 1s\(^2\) 2s\(^2\) ...) of each species.

\[
\begin{align*}
S & : 1s^2 2s^2 2p^6 3s^2 3p^4 \\
S^{2-} & : 1s^2 2s^2 2p^6 3s^2 3p^6 \\
\text{Note: Replacement of } 1s^2 2s^2 2p^6 \text{ by } [\text{Ne}] \text{ is acceptable.}
\end{align*}
\]

One point is earned for the correct configuration for S.

One point is earned for the correct configuration for S\(^{2-}\).

(ii) Explain why the radius of the S\(^{2-}\) ion is larger than the radius of the S atom.

The nuclear charge is the same for both species, but the eight valence electrons in the sulfide ion experience a greater amount of electron-electron repulsion than do the six valence electrons in the neutral sulfur atom. This extra repulsion in the sulfide ion increases the average distance between the valence electrons, so the electron cloud around the sulfide ion has the greater radius.

One point is earned for a correct explanation.

(iii) Which of the two species would be attracted into a magnetic field? Explain.

The sulfur atom would be attracted into a magnetic field. Sulfur has two unpaired \(p\) electrons, which results in a net magnetic moment for the atom. This net magnetic moment would interact with an external magnetic field, causing a net attraction into the field. The sulfide ion would not be attracted into a magnetic field because all the electrons in the species are paired, meaning that their individual magnetic moments would cancel each other.

One point is earned for the correct answer with a correct explanation.

(b) The S\(^{2-}\) ion is isoelectronic with the Ar atom. From which species, S\(^{2-}\) or Ar, is it easier to remove an electron? Explain.

It requires less energy to remove an electron from a sulfide ion than from an argon atom. A valence electron in the sulfide ion is less attracted to the nucleus (charge +16) than is a valence electron in the argon atom (charge +18).

One point is earned for the correct answer with a correct explanation.
(c) In the $\text{H}_2\text{S}$ molecule, the $\text{H}–\text{S}–\text{H}$ bond angle is close to 90°. On the basis of this information, which atomic orbitals of the S atom are involved in bonding with the H atoms?

| The atomic orbitals involved in bonding with the H atoms in $\text{H}_2\text{S}$ are $p$ (specifically, $3p$) orbitals. The three $p$ orbitals are mutually perpendicular (i.e., at 90°) to one another. | One point is earned for the correct answer. |

(d) Two types of intermolecular forces present in liquid $\text{H}_2\text{S}$ are London (dispersion) forces and dipole-dipole forces.

1. Compare the strength of the London (dispersion) forces in liquid $\text{H}_2\text{S}$ to the strength of the London (dispersion) forces in liquid $\text{H}_2\text{O}$. Explain.

| The strength of the London forces in liquid $\text{H}_2\text{S}$ is greater than that of the London forces in liquid $\text{H}_2\text{O}$. The electron cloud of $\text{H}_2\text{S}$ has more electrons and is thus more polarizable than the electron cloud of the $\text{H}_2\text{O}$ molecule. | One point is earned for the correct answer with a correct explanation. |

2. Compare the strength of the dipole-dipole forces in liquid $\text{H}_2\text{S}$ to the strength of the dipole-dipole forces in liquid $\text{H}_2\text{O}$. Explain.

| The strength of the dipole-dipole forces in liquid $\text{H}_2\text{S}$ is weaker than that of the dipole-dipole forces in liquid $\text{H}_2\text{O}$. The net dipole moment of the $\text{H}_2\text{S}$ molecule is less than that of the $\text{H}_2\text{O}$ molecule. This results from the lesser polarity of the $\text{H}–\text{S}$ bond compared with that of the $\text{H}–\text{O}$ bond ($\text{S}$ is less electronegative than $\text{O}$). | One point is earned for the correct answer with a correct explanation. |
A student places a mixture of plastic beads consisting of polypropylene (PP) and polyvinyl chloride (PVC) in a 1.0 L beaker containing distilled water. After stirring the contents of the beaker vigorously, the student observes that the beads of one type of plastic sink to the bottom of the beaker and the beads of the other type of plastic float on the water. The chemical structures of PP and PVC are represented by the diagrams below, which show segments of each polymer.

(a) Given that the spacing between polymer chains in PP and PVC is similar, the beads that sink are made of which polymer? Explain.

The PVC beads sink. The spacing between chains is similar, but a Cl atom has a greater mass than CH₃.

1 point is earned for the correct polymer with a correct explanation.

PP is synthesized from propene, C₃H₆, and PVC is synthesized from vinyl chloride, C₂H₃Cl. The structures of the molecules are shown below.

H \[\equiv\ C\equiv\ C\equiv\ CH₃\]
Propene

H \[\equiv\ C\equiv\ Cl\]
Vinyl Chloride (chloroethene)

(b) The boiling point of liquid propene (226 K) is lower than the boiling point of liquid vinyl chloride (260 K). Account for this difference in terms of the types and strengths of intermolecular forces present in each liquid.

Both substances have dipole-dipole interactions and London dispersion forces (or propene is essentially nonpolar with only LDFs while vinyl chloride has both LDFs and dipole-dipole forces). Propene contains a CH₃ group, but vinyl chloride contains a Cl atom. Vinyl chloride thus has a larger electron cloud, is more polarizable, and has a larger dipole moment. Thus intermolecular attractions are stronger in vinyl chloride, which results in it having the higher boiling point.

1 point is earned for a discussion of intermolecular forces and for a comparison of their relative strengths.
6. Answer each of the following in terms of principles of molecular behavior and chemical concepts.

(a) The structures for glucose, \( C_6H_{12}O_6 \), and cyclohexane, \( C_6H_{12} \), are shown below.

![Glucose and Cyclohexane Structures](image)

Identify the type(s) of intermolecular attractive forces in

(i) pure glucose

<table>
<thead>
<tr>
<th>Hydrogen bonding OR dipole-dipole interactions OR van der Waals interactions (London dispersion forces may also be mentioned.)</th>
<th>One point is earned for a correct answer.</th>
</tr>
</thead>
</table>

(ii) pure cyclohexane

<table>
<thead>
<tr>
<th>London dispersion forces</th>
<th>One point is earned for London dispersion forces.</th>
</tr>
</thead>
</table>

(b) Glucose is soluble in water but cyclohexane is not soluble in water. Explain.

<table>
<thead>
<tr>
<th>The hydroxyl groups in glucose molecules can form strong hydrogen bonds with the solvent (water) molecules, so glucose is soluble in water. In contrast, cyclohexane is not capable of forming strong intermolecular attractions with water (no hydrogen bonding), so the water-cyclohexane interactions are not as energetically favorable as the interactions that already exist among polar water molecules.</th>
<th>One point is earned for explaining the solubility of glucose in terms of hydrogen bonding or dipole-dipole interactions with water.</th>
</tr>
</thead>
<tbody>
<tr>
<td>OR</td>
<td>One point is earned for explaining the difference in the polarity of cyclohexane and water.</td>
</tr>
<tr>
<td>• Glucose is polar and cyclohexane is nonpolar.</td>
<td>OR</td>
</tr>
<tr>
<td>• Polar solutes (such as glucose) are generally soluble in polar solvents such as water.</td>
<td>One point is earned for any one of the three concepts; two points are earned for any two of the three concepts.</td>
</tr>
<tr>
<td>• Nonpolar solutes (such as cyclohexane) are not soluble in the polar solvent.</td>
<td>---</td>
</tr>
</tbody>
</table>
(c) Consider the two processes represented below.

Process 1: \( \text{H}_2\text{O}(l) \rightarrow \text{H}_2\text{O}(g) \) \( \Delta H^\circ = +44.0 \text{ kJ mol}^{-1} \)

Process 2: \( \text{H}_2\text{O}(l) \rightarrow \text{H}_2(g) + \frac{1}{2} \text{O}_2(g) \) \( \Delta H^\circ = +286 \text{ kJ mol}^{-1} \)

(i) For each of the two processes, identify the type(s) of intermolecular or intramolecular attractive forces that must be overcome for the process to occur.

<table>
<thead>
<tr>
<th>In process 1, hydrogen bonds (or dipole-dipole interactions) in liquid water are overcome to produce distinct water molecules in the vapor phase.</th>
<th>One point is earned for identifying the type of intermolecular force involved in process 1.</th>
</tr>
</thead>
<tbody>
<tr>
<td>In process 2, covalent bonds (or sigma bonds, or electron-pair bonds) within water molecules must be broken to allow the atoms to recombine into molecular hydrogen and oxygen.</td>
<td>One point is earned for identifying the type of intramolecular bonding involved in process 2.</td>
</tr>
</tbody>
</table>

(ii) Indicate whether you agree or disagree with the statement in the box below. Support your answer with a short explanation.

When water boils, \( \text{H}_2\text{O} \) molecules break apart to form hydrogen molecules and oxygen molecules.

| I disagree with the statement. Boiling is simply Process 1, in which only intermolecular forces are broken and the water molecules stay intact. No intramolecular or covalent bonds break in this process. | One point is earned for disagreeing with the statement and providing a correct explanation. |
A student learns that ionic compounds have significant covalent character when a cation has a polarizing effect on a large anion. As a result, the student hypothesizes that salts composed of small cations and large anions should have relatively low melting points.

(a) Select two compounds from the table and explain how the data support the student's hypothesis.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Melting Point (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiI</td>
<td>449</td>
</tr>
<tr>
<td>KI</td>
<td>686</td>
</tr>
<tr>
<td>LiF</td>
<td>845</td>
</tr>
<tr>
<td>NaF</td>
<td>993</td>
</tr>
</tbody>
</table>

LiI and KI. LiI has a small cation and a large anion and KI has a large cation and the same large anion. The melting point of LiI (with its smaller cation) is lower than that of KI.

OR

LiI and LiF. LiI has a small cation and a large anion and LiF has the same small cation and a small anion. The melting point of LiI (with its larger anion) is lower than that of LiF.

OR

LiI and NaF. LiI has a small cation and a large anion and NaF has a relatively small cation and a small anion. The melting point of LiI (with its larger anion) is lower than that of NaF.

1 point is earned for choosing an appropriate pair of compounds (LiI/KI, LiI/LiF, or LiI/NaF).

1 point is earned for an explanation that supports the hypothesis.

(b) Identify a compound from the table that can be dissolved in water to produce a basic solution. Write the net ionic equation for the reaction that occurs to cause the solution to be basic.

Either LiF or NaF is acceptable.

\[ F^- + H_2O \leftrightarrow HF + OH^- \]

1 point is earned for choosing one of the correct compounds.

1 point is earned for writing a correct balanced equation.
The boiling points, dipole moments, and polarizabilities of three hydrogen halides are given in the table above.

(a) Based on the data in the table, what type of intermolecular force among the molecules HCl(/), HBr(/), and HI(/) is able to account for the trend in boiling points? Justify your answer.

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Boiling Point of Compound (K)</th>
<th>Dipole Moment (debyes)</th>
<th>Polarizability (10^{-24} \text{ cm}^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCl</td>
<td>188</td>
<td>1.05</td>
<td>2.63</td>
</tr>
<tr>
<td>HBr</td>
<td>207</td>
<td>0.80</td>
<td>3.61</td>
</tr>
<tr>
<td>HI</td>
<td>238</td>
<td>0.38</td>
<td>5.44</td>
</tr>
</tbody>
</table>

London dispersion forces account for the trend in boiling points.
As polarizability of the molecules increases, so does the boiling point of the substance.
London dispersion forces depend upon the polarizability of molecules, thus more polarizable molecules have stronger intermolecular forces.

1 point is earned for identifying London dispersion forces.
1 point is earned for explaining the link between polarizability and boiling point.

(b) Based on the data in the table, a student predicts that the boiling point of HF should be 174 K.
The observed boiling point of HF is 293 K. Explain the failure of the student’s prediction in terms of the types and strengths of the intermolecular forces that exist among HF molecules.

HF molecules have London dispersion forces and hydrogen bonding. The hydrogen bonding is stronger than both regular dipole-dipole forces and London dispersion forces and accounts for HF’s higher boiling point.

1 point is earned for a correct explanation.
(c) A representation of five molecules of HBr in the liquid state is shown in box 1 below. In box 2, draw a representation of the five molecules of HBr after complete vaporization has occurred.

| The drawing in Box 2 should show the undissociated molecules randomly distributed throughout the box. | 1 point is earned for an acceptable diagram. |
The structures of two compounds commonly found in food, lauric acid, \( \text{C}_{12}\text{H}_{24}\text{O}_{2} \), and sucrose, \( \text{C}_{12}\text{H}_{22}\text{O}_{11} \), are shown above.

(a) Which compound, lauric acid or sucrose, is more soluble in water? Justify your answer in terms of the intermolecular forces present between water and each of the compounds.

Sucre is more soluble than lauric acid. Stronger interactions occur between sucrose and water molecules due to a greater capacity for hydrogen bonding as a result of a larger number of \(-\text{OH}\) groups in sucrose. Although lauric acid molecules have one site for hydrogen bonding, the long hydrocarbon chain causes London dispersion forces to be the predominant, yet weaker, interaction with water molecules.

(b) Assume that a 1.5 g sample of lauric acid is combusted and all of the heat energy released is transferred to a 325 g sample of water initially at 25°C. Calculate the final temperature of the water if \( \Delta H_{\text{combustion}} \) of lauric acid is \(-37\) kJ/g and the specific heat of water is \(4.18\) \(\text{J/(g\cdot K)}\).
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Question 4

<table>
<thead>
<tr>
<th>Element</th>
<th>Atomic Radius (pm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au</td>
<td>135</td>
</tr>
<tr>
<td>Pd</td>
<td>140</td>
</tr>
</tbody>
</table>

White gold is a common alloy of gold and palladium that is often used in jewelry. The atomic radii of the metals are given in the table above.

(a) A particular ring is made from an alloy that is 75 mole percent gold and 25 mole percent palladium. Using the box below, draw a particle-level diagram of the solid alloy consisting of 12 atoms with a representative proportion of atom types. Your diagram should clearly indicate whether the alloy is interstitial or substitutional. Use empty circles for gold and shaded circles for palladium.

![Diagram](image)

Diagram should show 12 circles in a regular array, 9 empty and 3 shaded. 1 point is earned for the correct number of each type of circle. 1 point is earned for showing an acceptable arrangement (i.e., regular array of circles of about the same size).

White-gold jewelry is often coated with rhodium to modify the color and durability.

(b) A student hypothesizes that placing the ring in a 1.0 M solution of Rh(NO₃)₃(aq) will result in a reaction in which Rh metal is deposited on the white-gold ring. Based on the information in the table below, calculate $E^\circ$ for the reactions that may occur between ions in the solution and atoms in the ring, and indicate whether or not the student’s hypothesis is correct.

<table>
<thead>
<tr>
<th>Half-Reaction</th>
<th>$E^\circ$ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au³⁺(aq) + 3 e⁻ → Au(s)</td>
<td>1.50</td>
</tr>
<tr>
<td>Pd²⁺(aq) + 2 e⁻ → Pd(s)</td>
<td>0.92</td>
</tr>
<tr>
<td>Rh³⁺(aq) + 3 e⁻ → Rh(s)</td>
<td>0.76</td>
</tr>
</tbody>
</table>

Au + Rh³⁺ → Au³⁺ + Rh
0.76 V − 1.50 V = −0.74 V
3 Pd + 2 Rh³⁺ → 3 Pd²⁺ + 2 Rh
0.76 V − 0.92 V = −0.16 V

The student’s hypothesis is incorrect. (Both voltages are negative, so the reactions are not thermodynamically favorable under these conditions.) 1 point is earned for the $E^\circ$ calculations.

1 point is earned for the claim.
Scoring Guidelines for Question 6

Question 6
(4 Points)

H₂O molecule

LiCl crystal

The structures of a water molecule and a crystal of LiCl(s) are represented above. A student prepares a 1.0 M solution by dissolving 4.2 g of LiCl(s) in enough water to make 100 mL of solution.

(a) In the space provided below, show the interactions of the components of LiCl(aq) by making a drawing that represents the different particles present in the solution. Base the particles in your drawing on the particles shown in the representations above. Include only one formula unit of LiCl and no more than ten molecules of water. Your drawing must include the following details.

- identity of ions (symbol and charge)
- the arrangement and proper orientation of the particles in the solution

LiCl (aq)
The sketch should clearly show:

1. A clear representation of at least one Li⁺ ion and one Cl⁻ ion separated from each other, labeled, and charged;
2. Each ion surrounded by at least two H₂O molecules; and
3. H₂O molecules with the proper orientation around each ion (i.e., the oxygen end of the water molecules closer to the lithium ion and the hydrogen end of the water molecules closer to the chloride ion).

1 point is earned for a correctly drawn and labeled particulate representation of the ions. (Representation must indicate that the smaller ion is Li⁺. Representations that include more than one formula unit of LiCl (dissolved or undissolved) are acceptable as long as at least one of the formula units is separated into its ions and the ions are correctly labeled with their respective identities and charges.)

1 point is earned for a correctly drawn particulate representation of water molecules of hydration surrounding the ions.

1 point is earned for correctly representing the orientation of the water molecules of hydration with the proper polarity.

(b) The student passes a direct current through the solution and observes that chlorine gas is produced at the anode. Identify the chemical species produced at the cathode and justify your answer using the information given in the table below.

<table>
<thead>
<tr>
<th>Half-reaction</th>
<th>Standard Reduction Potential at 25°C (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li⁺(aq) + e⁻ → Li(s)</td>
<td>−3.05</td>
</tr>
<tr>
<td>2 H₂O(l) + 2 e⁻ → H₂(g) + 2 OH⁻(aq)</td>
<td>−0.83</td>
</tr>
</tbody>
</table>

H₂(g) and OH⁻(aq)
The hydrogen atoms in H₂O are reduced to H₂ at the cathode because this reaction has a higher (more favorable or less negative) standard reduction potential than the reduction of lithium ions to Li(s).

1 point is earned for correctly identifying either of the chemical species produced at the cathode with the proper justification.

Note: the justification must clearly indicate that "higher" means "less negative." A "lower magnitude" negative value also earns the point.