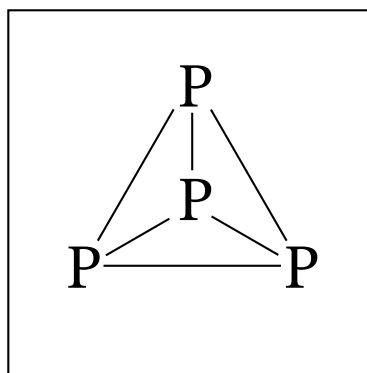
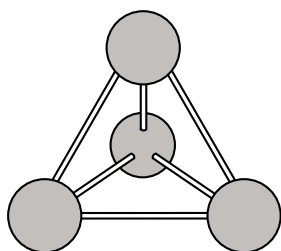
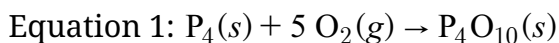


3. White phosphorus is composed of  $P_4$  molecules with a tetrahedral structure, as shown in the diagram on the left. Each P atom is bonded to the other three P atoms by single bonds, as shown in the incomplete Lewis diagram on the right.

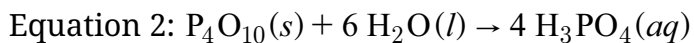


- A. In the box in part A, complete the Lewis diagram for  $P_4$  by drawing the nonbonding electrons.
- B. The reaction of white phosphorus with oxygen to form  $P_4O_{10}(s)$  is thermodynamically favorable at 298 K. The reaction is represented by equation 1.

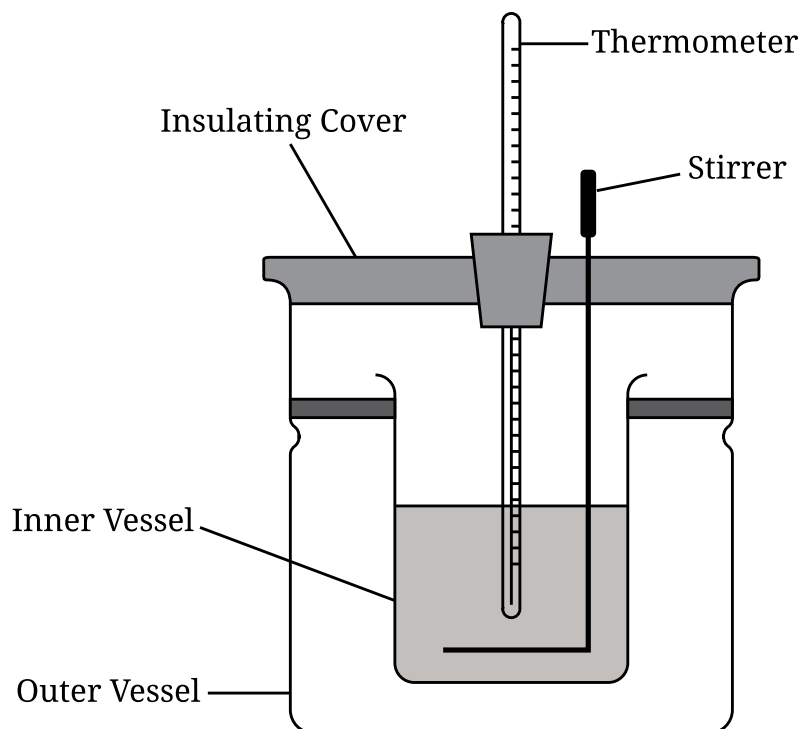


- The entropy change of the reaction,  $\Delta S^\circ$ , is negative. Using particle-level reasoning, explain why the entropy decreases as the reaction progresses.
- The enthalpy change of the reaction,  $\Delta H^\circ$ , is also negative. A student claims that the favorability of the reaction is driven by enthalpy and **not** by entropy. Is the student's claim correct? Justify your answer by using the relationship between  $\Delta G^\circ$ ,  $\Delta H^\circ$ , and  $\Delta S^\circ$ .

$\text{P}_4\text{O}_{10}(s)$  reacts exothermically with water to form phosphoric acid, as represented by equation 2.



A chemist uses a calorimetry experiment to determine the enthalpy change for the reaction, as represented by the following diagram.



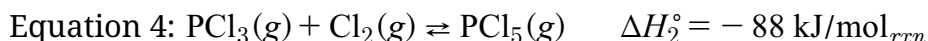
C. The chemist carries out the calorimetry experiment and records the following information.

|                                         |               |
|-----------------------------------------|---------------|
| Mass of $\text{P}_4\text{O}_{10}$       | 0.100 g       |
| Mass of $\text{H}_2\text{O}$            | 100.0 g       |
| Initial temperature                     | 22.00° C      |
| Final temperature                       | 22.38° C      |
| Molar mass of $\text{P}_4\text{O}_{10}$ | 283.9 g/mol   |
| Specific heat of $\text{H}_2\text{O}$   | 4.18 J/(g·°C) |

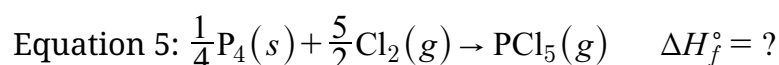
- Calculate the amount of heat,  $q$ , released during the experiment, in kJ. Assume that the specific heat of the solution is the same as that of water.
- Calculate the value of  $\Delta H^\circ_{\text{rxn}}$  for equation 2 in kJ/mol<sub>rxn</sub>. Include the sign in your answer.

- D. The chemist weighed out 0.100 g  $\text{P}_4\text{O}_{10}$  of and 100.0 g of  $\text{H}_2\text{O}$  to perform a second trial. In the second trial, some of the solid  $\text{P}_4\text{O}_{10}$  stuck to the weighing paper and was not transferred to the calorimeter. Given that  $\text{P}_4\text{O}_{10}$  is the limiting reactant, would  $\Delta T$  for the second trial be greater than, less than, or equal to the value in the first trial? Justify your answer.

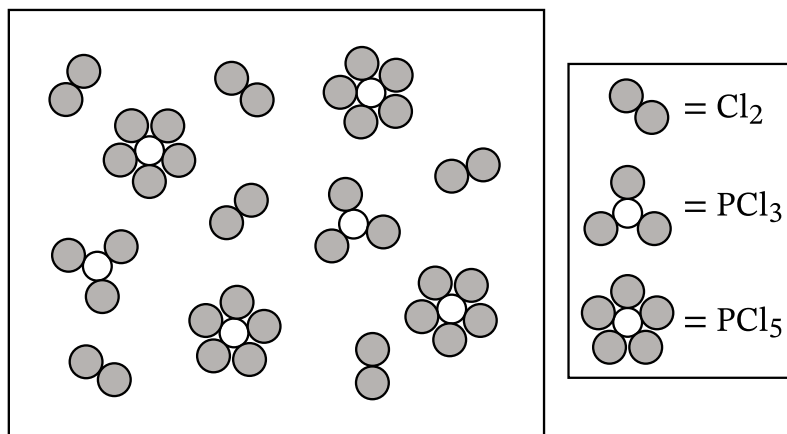
$\text{P}_4(\text{s})$  also reacts readily with  $\text{Cl}_2(\text{g})$  to produce phosphorus trichloride,  $\text{PCl}_3(\text{g})$ , which in turn reacts with  $\text{Cl}_2(\text{g})$  in an equilibrium process to produce  $\text{PCl}_5(\text{g})$ . The reactions are represented by equations 3 and 4.



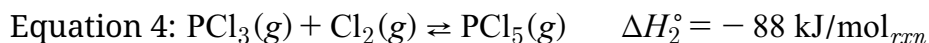
- E. Calculate the standard enthalpy of formation of  $\text{PCl}_5(\text{g})$  represented by equation 5.



The following particle-level diagram represents the contents of the vessel in an equilibrium mixture at 546 K involving equation 4.



- F. Equation 4 for the reaction that occurs is shown.



- If each particle in the diagram represents a partial pressure of 1.00 atm, what is the value of  $K_p$  for the equilibrium mixture at 546 K?
- Does the value of  $K_p$  increase, decrease, or remain the same when the temperature is increased to 596 K? Justify your answer based on  $\Delta H_2^\circ$ .

2. A chemical reaction between maleic acid ( $\text{H}_2\text{C}_4\text{H}_2\text{O}_4$ ) and sodium bicarbonate ( $\text{NaHCO}_3$ ) occurs in the presence of water to produce carbon dioxide and sodium maleate ( $\text{Na}_2\text{C}_4\text{H}_2\text{O}_4$ ), as represented by the following equation.



- (a) A student combines equal masses of  $\text{H}_2\text{C}_4\text{H}_2\text{O}_4(s)$  chunks and  $\text{NaHCO}_3(s)$  chunks with sufficient water at  $20.0^\circ\text{C}$ . The student determines that  $0.0114\text{ mol}$  of  $\text{CO}_2(g)$  is produced after the reaction goes to completion.

(i) Calculate the number of grams of  $\text{CO}_2(g)$  produced.

- (ii) The  $\text{CO}_2(g)$  produced from the reaction at  $20.0^\circ\text{C}$  was collected and found to have a pressure of  $1.25\text{ atm}$ . Calculate the volume of  $\text{CO}_2(g)$ , in liters.

- (b) The student performs a second experiment that is identical to the first except that the student grinds the chunks of  $\text{H}_2\text{C}_4\text{H}_2\text{O}_4(s)$  and  $\text{NaHCO}_3(s)$  into powder before combining the powder with water.

(i) What happens to the surface area of the reactants when the student grinds the chunks into powder?

- (ii) The rate-determining step for the overall reaction is the dissolving of the solids. Would the time required for the dissolving of the solids in the second experiment be longer than, shorter than, or the same as the time required in the first experiment? Justify your answer based on the collisions between particles.

**GO ON TO THE NEXT PAGE.**

Continue your response to **QUESTION 2** on this page.

- (iii) When the reaction is complete, will the volume of  $\text{CO}_2(g)$  at the end of the second experiment be greater than, less than, or equal to the volume at the end of the first experiment? Justify your answer.

The student conducts additional trials of the experiment and produces the following data table.

| Trial | Mass of $\text{H}_2\text{C}_4\text{H}_2\text{O}_4$<br>(grams) | Mass of $\text{NaHCO}_3$<br>(grams) | Moles of $\text{CO}_2$ Produced<br>(mol) |
|-------|---------------------------------------------------------------|-------------------------------------|------------------------------------------|
| 3     | 1.543                                                         | 1.251                               | 0.01489                                  |
| 4     | 1.543                                                         | 1.686                               | 0.02007                                  |

- (c) Based on the student's data, identify the limiting reactant in trial 3. Justify your answer.

- (d) The reaction has a value of  $\Delta S^\circ$  greater than zero. Using particle-level reasoning, explain why the entropy increases as the reaction progresses.

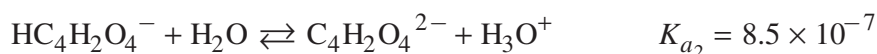
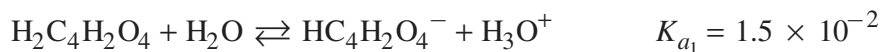
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Continue your response to **QUESTION 2** on this page.

The student notices that the temperature of the reaction mixture decreases as the reaction takes place and correctly determines that the reaction is endothermic.

- (e) The student claims that the reaction is thermodynamically favorable at all temperatures because  $\Delta S_{rxn}^{\circ} > 0$  and the reaction is endothermic. Do you agree or disagree with the student's claim? Justify your answer.

Next, the student investigates the acid-base behavior of maleic acid. The student notes that maleic acid is a diprotic acid. The two acid dissociation processes that occur are represented by the following equations.



- (f) Calculate the  $\text{p}K_{a_2}$  value for the  $\text{HC}_4\text{H}_2\text{O}_4^-$  ion.

- (g) A buffer solution with a pH of 7.00 is prepared using  $\text{C}_4\text{H}_2\text{O}_4^{2-}$  and  $\text{HC}_4\text{H}_2\text{O}_4^-$ . Calculate the ratio

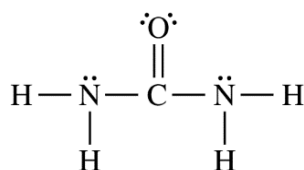
$$\frac{[\text{C}_4\text{H}_2\text{O}_4^{2-}]}{[\text{HC}_4\text{H}_2\text{O}_4^-]} \text{ in this solution.}$$

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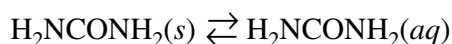
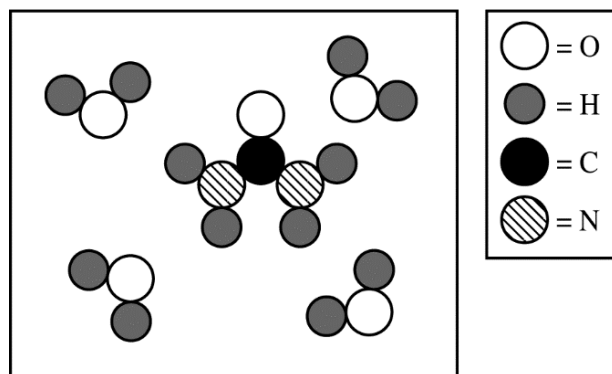
**CHEMISTRY****Section II****Time—1 hour and 45 minutes****7 Questions****YOU MAY USE YOUR CALCULATOR FOR THIS SECTION.**

**Directions:** Questions 1–3 are long free-response questions that require about 23 minutes each to answer and are worth 10 points each. Questions 4–7 are short free-response questions that require about 9 minutes each to answer and are worth 4 points each.

Write your response in the space provided following each question. Examples and equations may be included in your responses where appropriate. For calculations, clearly show the method used and the steps involved in arriving at your answers. You must show your work to receive credit for your answer. Pay attention to significant figures.

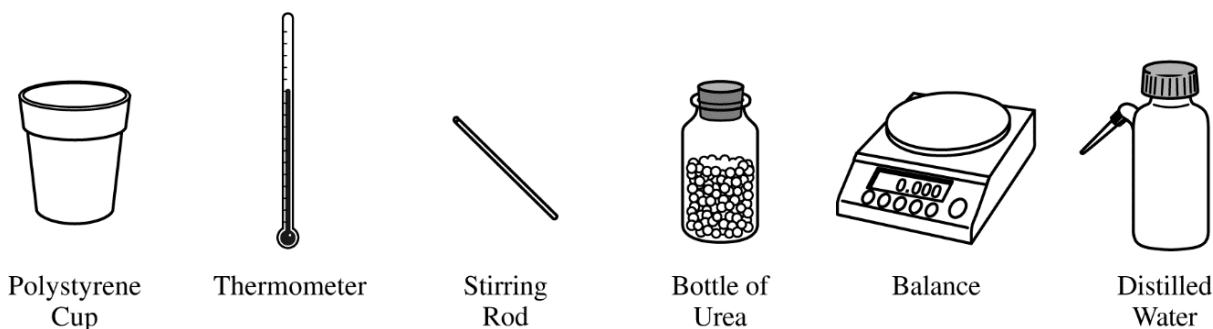


1. The compound urea,  $\text{H}_2\text{NCONH}_2$ , is widely used in chemical fertilizers. The complete Lewis electron-dot diagram for the urea molecule is shown above.
- (a) Identify the hybridization of the valence orbitals of the carbon atom in the urea molecule.
- (b) Urea has a high solubility in water, due in part to its ability to form hydrogen bonds. A urea molecule and four water molecules are represented in the box below. Draw ONE dashed line (----) to indicate a possible location of a hydrogen bond between a water molecule and the urea molecule.



The dissolution of urea is represented by the equation above. A student determines that 5.39 grams of  $\text{H}_2\text{NCONH}_2$  (molar mass 60.06 g/mol) can dissolve in water to make 5.00 mL of a saturated solution at 20.°C.

- (c) Calculate the concentration of urea, in mol/L, in the saturated solution at 20.°C.
- (d) The student also determines that the concentration of urea in a saturated solution at 25°C is 19.8 M. Based on this information, is the dissolution of urea endothermic or exothermic? Justify your answer in terms of Le Chatelier's principle.



- (e) The equipment shown above is provided so that the student can determine the value of the molar heat of solution for urea. Knowing that the specific heat of the solution is 4.18 J/(g·°C), list the specific measurements that are required to be made during the experiment.

|                                | $S^\circ$ (J/(mol·K)) |
|--------------------------------|-----------------------|
| $\text{H}_2\text{NCONH}_2(s)$  | 104.6                 |
| $\text{H}_2\text{NCONH}_2(aq)$ | ?                     |

- (f) The entropy change for the dissolution of urea,  $\Delta S^\circ_{\text{soln}}$ , is 70.1 J/(mol·K) at 25°C. Using the information in the table above, calculate the absolute molar entropy,  $S^\circ$ , of aqueous urea.
- (g) Using particle-level reasoning, explain why  $\Delta S^\circ_{\text{soln}}$  is positive for the dissolution of urea in water.
- (h) The student claims that  $\Delta S^\circ$  for the process contributes to the thermodynamic favorability of the dissolution of urea at 25°C. Use the thermodynamic information above to support the student's claim.