

# CHEMISTRY

## Section I

Time—1 hour and 30 minutes

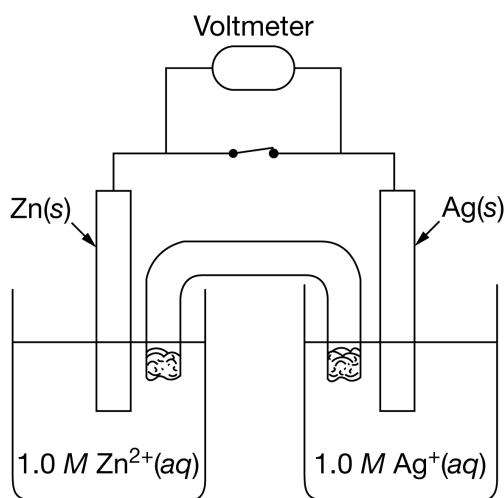
60 Questions

**Note:** For all questions, assume that the temperature is 298 K, the pressure is 1.0 atm, and solutions are aqueous unless otherwise specified.

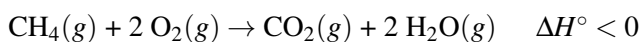
**Directions:** Each of the questions or incomplete statements below is followed by four suggested answers or completions. Select the one that is best in each case and then fill in the corresponding circle on the answer sheet.

1. In his atomic theory, Dalton proposed that all atoms of a given element are identical. Which of the following observations provides the best evidence that the proposal is incorrect?

- (A) The mass spectrum of Cu has a peak at 63 amu and another peak at 65 amu.
- (B) The ionic radius of  $\text{Cl}^-$  is 0.181 nm, and the atomic radius of Cl is 0.079 nm.
- (C) The dipole moment of  $\text{O}_3$  is 0.53 debye, and the dipole moment of  $\text{O}_2$  is 0.00 debye.
- (D) Elemental P can exist in both white and red forms.

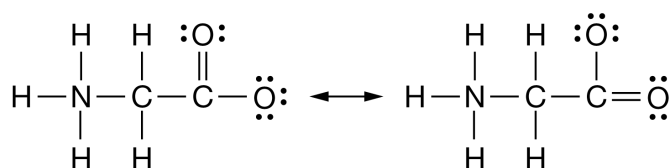


2. Which of the following substances would be the best choice for filling the salt bridge in the galvanic cell shown above, and why?
- (A) Distilled water, because it would avoid contaminating the solutions in the half-cells.
  - (B) 1.0 M  $\text{HCl}(aq)$ , because it would acidify the solutions and catalyze the overall cell reaction.
  - (C) 1.0 M  $\text{CH}_3\text{OH}(aq)$ , because it would increase the pH of the solutions and catalyze the overall cell reaction.
  - (D) 1.0 M  $\text{KNO}_3(aq)$ , because the mobile ions would allow charge to flow between the half-cells.



3. Which of the following statements must be true for the combustion of  $\text{CH}_4(g)$ , represented by the equation above?

- (A) The bond dissociation energy between O atoms in  $\text{O}_2$  is greater than the sum of the bond dissociation energies of the two O–H bonds in  $\text{H}_2\text{O}$ .
- (B) More bonds are formed in the products than are broken in the reactants.
- (C) The sum of the bond dissociation energies of the product molecules is equal to the sum of the bond dissociation energies of the reactant molecules.
- (D) The sum of the bond dissociation energies of the product molecules is greater than the sum of the bond dissociation energies of the reactant molecules.



4. Based on the resonance structures shown above, what are the bond orders of the two carbon-oxygen bonds?

- (A) 1 and 1.5
- (B) 1 and 2
- (C) 1.5 and 1.5
- (D) 2 and 2

| Mass of Solid | Mass of Water | $\Delta T_{\text{water}}$ |
|---------------|---------------|---------------------------|
| 1.0 g         | 2000 g        | +2.1 °C                   |

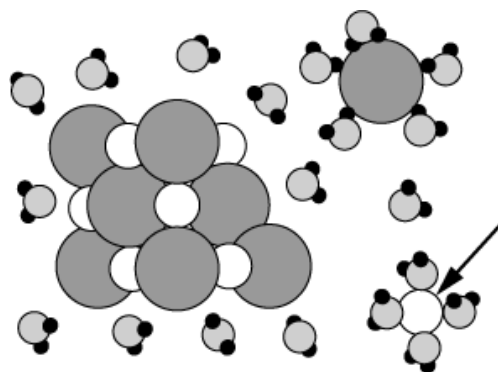
5. A sample of a solid organic compound is completely combusted in a calorimeter. The heat generated by combustion is transferred to the water, causing the temperature of the water to increase. Based on the data in the table above, which of the following is the best estimate of the heat of combustion,  $\Delta H_{\text{comb}}$ , of the organic solid? (The specific heat of water is 4.2 J/(kg·°C).)

- (A) +18 kJ/g
- (B) +8.4 kJ/g
- (C) –8.4 kJ/g
- (D) –18 kJ/g

| Substance | Specific Heat (J/(kg·°C)) | Mass of sample (g) |
|-----------|---------------------------|--------------------|
| Fe(s)     | 0.46                      | 1.0                |
| Al(s)     | 0.91                      | 1.0                |

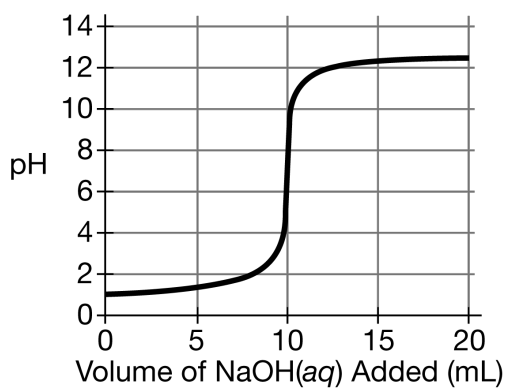
6. Samples of Fe and Al are heated from 25°C to 55°C. Based on the information in the table above, the change in the average kinetic energy of the atoms in the samples is

- (A) higher for the sample Fe, because with its lower specific heat it absorbs more energy
- (B) higher for the sample Al, because with its lower specific heat it absorbs more energy
- (C) the same for both metal samples, because the initial and final temperatures are the same
- (D) the same for both metal samples, because the masses are equal



7. An ionic crystal is added to water and starts to dissolve as shown in the particulate representation above. Based on the orientation of the water molecules, what can be assumed about the charge of the hydrated particle indicated by the arrow?

- (A) The particle is positively charged, because the oxygen atoms in water are attracted to it.
- (B) The particle is negatively charged, because the hydrogen atoms in water are attracted to it.
- (C) The particle is both positively and negatively charged, because the water molecules are attracted to it.
- (D) The particle is neutral, because the dipoles of the water molecules neutralize the charge of the particle.



8. A 20.0 mL sample of a 0.125 M monoprotic acid solution is titrated with a solution of NaOH(aq) unknown concentration. Based on the titration curve above, what is the molar concentration of the NaOH(aq) solution?

(A) 0.063 M  
 (B) 0.125 M  
 (C) 0.250 M  
 (D) 0.500 M



9. The ionization of cyanic acid, HOCN, is represented above. A certain solution of HOCN has a pH of 2.0. What is the approximate concentration of unionized in the HOCN(aq) solution?

(A)  $3 \times 10^{-4} M$   
 (B)  $1 \times 10^{-2} M$   
 (C)  $3 \times 10^{-1} M$   
 (D)  $2 \times 10^0 M$

10. Two solid reactants of varying particle size are combined in a vessel. Assuming that the same mass of each reactant is used in each case, which of the following represents the conditions that will result in the fastest reaction rate?



(A) Temperature = 950° C



(B) Temperature = 500° C

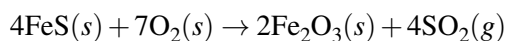


(C) Temperature = 500° C

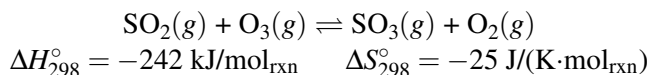


(D) Temperature = 950° C

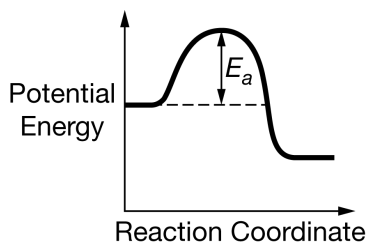
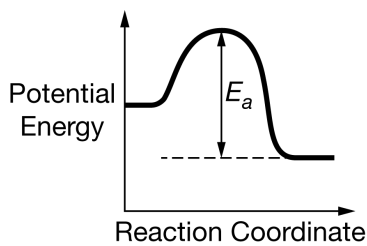
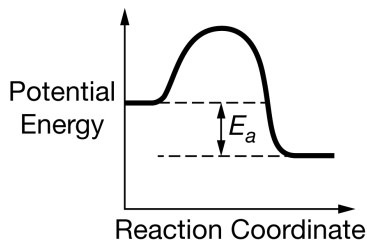
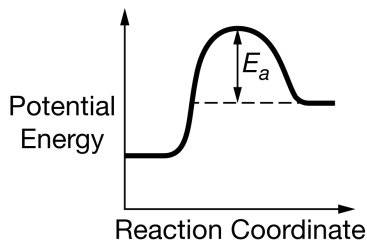
## Questions 11-13



Due to the presence of Fe(s) as an impurity, the combustion of some types of coal results in the formation of  $\text{SO}_2(g)$ , as represented by the equation above. Also,  $\text{SO}_2(g)$  can react with  $\text{O}_3(g)$  to form  $\text{SO}_3(g)$ , as represented by the equation below.



11. Which of the following diagrams shows the correctly labeled activation energy,  $E_a$ , for the reaction between  $\text{SO}_2(g)$  and  $\text{O}_3(g)$ ?



12. Which of the following statements is correct when 2.0 mol of FeS(s) reacts with 4.0 mol of  $\text{O}_2(g)$ ?

- (A)  $\text{O}_2(g)$  is the limiting reactant and 2.0 mol of  $\text{SO}_2(g)$  is formed.
- (B)  $\text{O}_2(g)$  is the limiting reactant and 4.0 mol of  $\text{SO}_2(g)$  is formed.
- (C) FeS(s) is the limiting reactant and 4.0 mol of  $\text{SO}_2(g)$  is formed.
- (D) FeS(s) is the limiting reactant and 0.5 mol of  $\text{O}_2(g)$  remains unreacted.

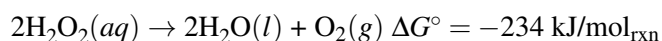
13. Which of the following is most likely to be true about the reaction between  $\text{SO}_2(g)$  and  $\text{O}_3(g)$  at 298 K?

- (A)  $\Delta G^\circ < 0$  and  $T\Delta S^\circ$  is smaller in magnitude than  $\Delta H^\circ$ .
- (B)  $\Delta G^\circ < 0$  and  $T\Delta S^\circ$  is larger in magnitude than  $\Delta H^\circ$ .
- (C)  $\Delta G^\circ > 0$  and  $T\Delta S^\circ$  is smaller in magnitude than  $\Delta H^\circ$ .
- (D)  $\Delta G^\circ > 0$  and  $T\Delta S^\circ$  is larger in magnitude than  $\Delta H^\circ$ .

| Solution                              | $pK_a$ |
|---------------------------------------|--------|
| $\text{HF}(aq)$                       | 3.17   |
| $\text{HC}_2\text{H}_3\text{O}_2(aq)$ | 4.74   |
| $\text{NH}_4^+(aq)$                   | 9.26   |

14. Based on the information in the table above, which of the following pairs of solutions can be used to create a buffer with a pH of 9.3? (Assume all solutions are 1.0 M.)

- (A) 100.0 mL of  $\text{HC}_2\text{H}_3\text{O}_2(aq)$  and 50.0 mL of  $\text{KOH}(aq)$   
 (B) 50.0 mL of  $\text{HF}(aq)$  and 50.0 mL of  $\text{NaF}(aq)$   
 (C) 100.0 mL of  $\text{NH}_3(aq)$  and 100.0 mL of  $\text{HCl}(aq)$   
 (D) 50.0 mL of  $\text{NH}_3(aq)$  and 50.0 mL of  $\text{NH}_4\text{Cl}(aq)$

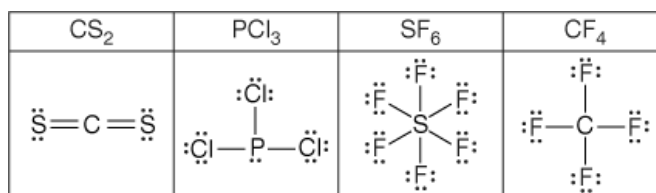


15. The value of  $\Delta G^\circ$  for the reaction represented above implies that the decomposition of  $\text{H}_2\text{O}_2(aq)$  is thermodynamically favorable. However,  $\text{H}_2\text{O}_2(aq)$  is typically stable for up to a year stored in a dark bottle at 298 K. The best explanation for this observation is that the decomposition reaction

- (A) is only thermodynamically favorable in the presence of a catalyst  
 (B) occurs with an increase in entropy because  $\text{O}_2(g)$  is a product  
 (C) is reversible and  $\text{H}_2\text{O}_2(aq)$  is produced almost as fast as it decomposes  
 (D) has a slow rate at 298 K because the activation energy is relatively high

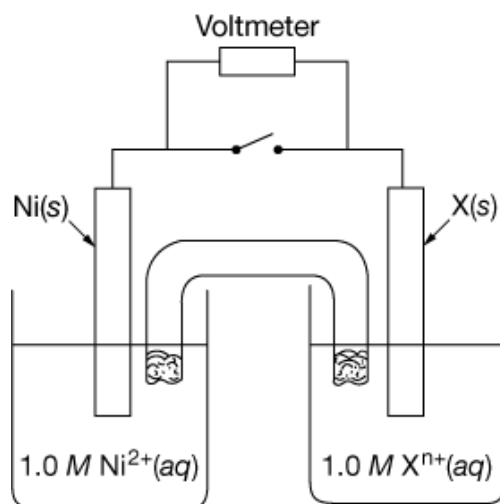
16. The equilibrium constant 1.0 for a reaction is greater than at temperatures above 500 K but less than 1.0 at temperatures below 500 K. What can be concluded about the values of  $\Delta H^\circ$  and  $\Delta S^\circ$  for the reaction? (Assume that  $\Delta H^\circ$  and  $\Delta S^\circ$  are independent of temperature.)

- (A)  $\Delta H^\circ > 0$  and  $\Delta S^\circ > 0$   
 (B)  $\Delta H^\circ > 0$  and  $\Delta S^\circ < 0$   
 (C)  $\Delta H^\circ < 0$  and  $\Delta S^\circ > 0$   
 (D)  $\Delta H^\circ < 0$  and  $\Delta S^\circ < 0$



17. Based on the diagrams shown above, which of the following would have the greatest dipole moment, and why?

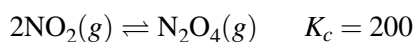
- (A)  $\text{CS}_2$ , because the double bonds create an area of higher electron density around the C atom.  
 (B)  $\text{PCl}_3$ , because the Cl atoms draw electron density away from the P atom and the bond dipoles do not cancel one another.  
 (C)  $\text{SF}_6$ , because it has the greatest number of polar bonds.  
 (D)  $\text{CF}_4$ , because the large electronegativity difference between C and F results in very polar bonds.



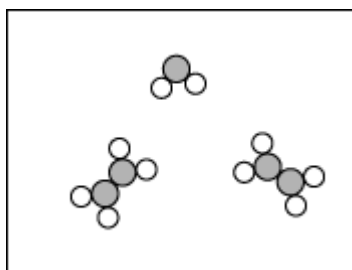
18. In the galvanic cell shown above, the voltmeter connected across the electrodes shows a voltage of 0.52 V. Based on the standard reduction potentials given in the table below, which of the following is most likely the identity of the unknown element, X?

| Half-reaction                                                             | $E^\circ$ (V) |
|---------------------------------------------------------------------------|---------------|
| $\text{Rh}^{3+}(\text{aq}) + 3\text{e}^- \rightarrow \text{Rh}(\text{s})$ | 0.76          |
| $\text{Bi}^{3+}(\text{aq}) + 3\text{e}^- \rightarrow \text{Bi}(\text{s})$ | 0.31          |
| $\text{In}^+(\text{aq}) + \text{e}^- \rightarrow \text{In}(\text{s})$     | -0.14         |
| $\text{Ni}^{2+}(\text{aq}) + 2\text{e}^- \rightarrow \text{Ni}(\text{s})$ | -0.24         |
| $\text{Zn}^{2+}(\text{aq}) + 2\text{e}^- \rightarrow \text{Zn}(\text{s})$ | -0.76         |

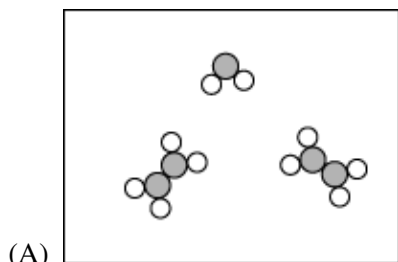
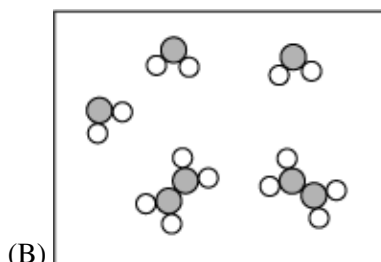
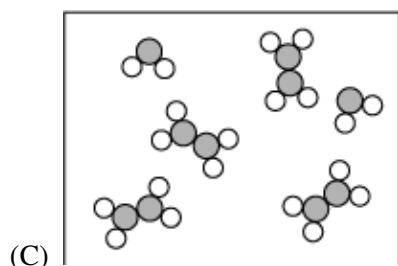
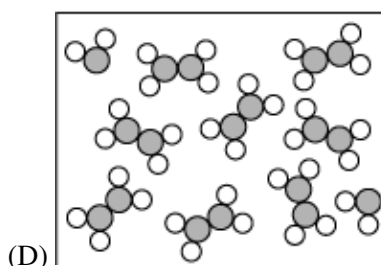
- (A) Rh  
 (B) Bi  
 (C) In  
 (D) Zn
19. A 30 g sample of  $\text{Al}(\text{s})$  is heated to  $50^\circ\text{C}$  and placed in a calorimeter containing of 150 g water at  $20^\circ\text{C}$ . As the system approaches thermal equilibrium, energy is transferred
- (A) from the  $\text{Al}(\text{s})$  to the water and the temperature of the water decreases  
 (B) from the  $\text{Al}(\text{s})$  to the water and the temperature of the  $\text{Al}(\text{s})$  decreases  
 (C) from the water to the  $\text{Al}(\text{s})$  and the temperature of the water increases  
 (D) from the water to the  $\text{Al}(\text{s})$  and the temperature of the  $\text{Al}(\text{s})$  increases



20. The equilibrium system shown above is represented in the diagram below in which each molecule represents one mole of the substance in a 100L container at a constant temperature.



Additional  $\text{N}_2\text{O}_4(g)$  is added to the container and allowed to reestablish equilibrium. Which of the following best represents the system after the equilibrium has been reestablished?



| Compound | Melting Point ( $^{\circ}\text{C}$ ) |
|----------|--------------------------------------|
| MgO      | 2852                                 |
| NaF      | 993                                  |

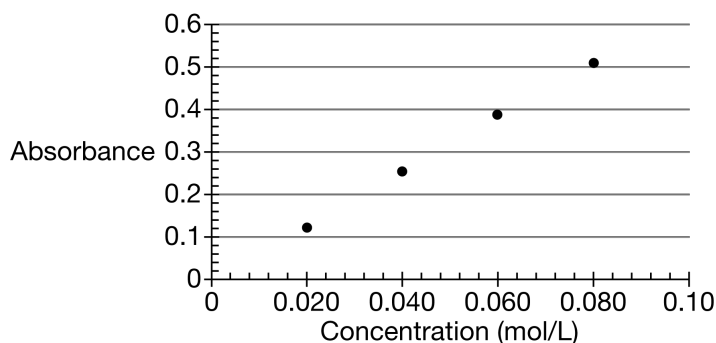
21. The table above shows the melting points of  $\text{MgO}(s)$  and  $\text{NaF}(s)$ . Which of the following best helps explain why the melting point of  $\text{MgO}(s)$  is much higher than that of  $\text{NaF}(s)$ ?

- (A) The mass of  $\text{F}^-$  ions is greater than that of  $\text{O}^{2-}$  ions.  
 (B) The mass of  $\text{Mg}^{2+}$  ions is greater than that of  $\text{Na}^+$  ions.  
 (C) The difference between the electronegativity values of Mg and O is smaller than the difference between the values of Na and F.  
 (D) The charges of  $\text{Mg}^{2+}$  and  $\text{O}^{2-}$  ions are greater than those of  $\text{Na}^+$  and  $\text{F}^-$  ions.

## Questions 22-25

An experiment was performed to investigate the reaction between Zn metal and  $\text{Ni}^{2+}(aq)$  at different concentrations. Because the ion is green, the extent of the reaction was determined using spectrophotometric analysis. Four 20.0 mL standard solutions of  $\text{Ni}^{2+}(aq)$  were prepared by dissolving  $\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$  (molar mass 240 g/mol) in water. The absorbance of each solution was measured; the results are shown both in the table below and in the following plot of the absorbance data.

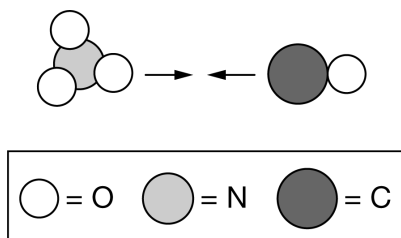
| Solution | $[\text{Ni}]^{2+}$ | Absorbance |
|----------|--------------------|------------|
| 1        | 0.020              | 0.12       |
| 2        | 0.040              | 0.25       |
| 3        | 0.060              | 0.39       |
| 4        | 0.080              | 0.51       |



22. The concentration of  $\text{Cl}^-(aq)$  ions in solution 2 was
- (A) 0.020 M  
(B) 0.040 M  
(C) 0.060 M  
(D) 0.080 M
23. Which of the following equations best represents the reacting species in the reaction between Zn metal and  $\text{NiCl}_2(aq)$
- (A)  $\text{Zn}(s) + \text{NiCl}_2(aq) \rightarrow \text{Zn}^{2+}(aq) + \text{Ni}(s) + 2\text{Cl}^-(aq)$   
(B)  $\text{Zn}(s) + \text{NiCl}_2(aq) \rightarrow \text{ZnCl}_2(aq) + \text{Ni}^{2+}(aq)$   
(C)  $\text{Zn}^{2+}(aq) + \text{Ni}(s) \rightarrow \text{Zn}(s) + \text{Ni}^{2+}(aq)$   
(D)  $\text{Zn}(s) + \text{Ni}^{2+}(aq) \rightarrow \text{Zn}^{2+}(aq) + \text{Ni}(s)$
24. What is the expected absorbance of a standard solution made by dissolving 0.0070 mol of  $\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$  in water to make 100 mL of solution?
- (A) 0.0039  
(B) 0.0080  
(C) 0.045  
(D) 0.45
25. Which species is being oxidized in the reaction between Zn metal and  $\text{NiCl}_2(aq)$ ?
- (A) Zn  
(B)  $\text{Zn}^{2+}$   
(C) Ni  
(D)  $\text{Ni}^{2+}$

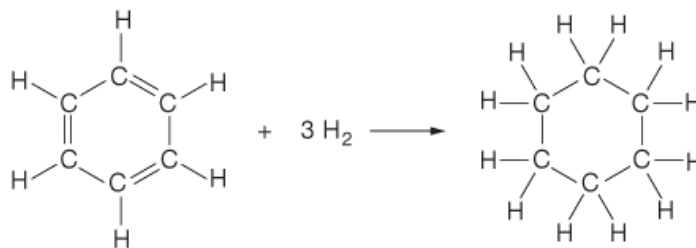
26. A sample of a pure compound is analyzed and found to contain approximately 30 percent N and 70 percent O by mass. The formula for the compound could be

- (A) NO
- (B) NO<sub>2</sub>
- (C) N<sub>2</sub>O
- (D) N<sub>2</sub>O<sub>2</sub>



27. The slowest step in a reaction mechanism requires the collision represented above to occur. Which of the following most likely indicates how the addition of a solid catalyst could increase the rate of the reaction?

- (A) The catalyst could change the reaction from second order to third order.
- (B) The catalyst could increase the particles' speed, thereby increasing the value of the rate constant,  $k$ .
- (C) The catalyst could decrease the particles' speed, making it less likely that the particles will rebound without reacting when they collide.
- (D) The catalyst could adsorb one of the particles, making a successful (reaction-producing) collision with the other particle more likely.



28. In the reaction represented above, which of the following sets correctly identifies the hybridization of the C atoms before and after the reaction occurs?

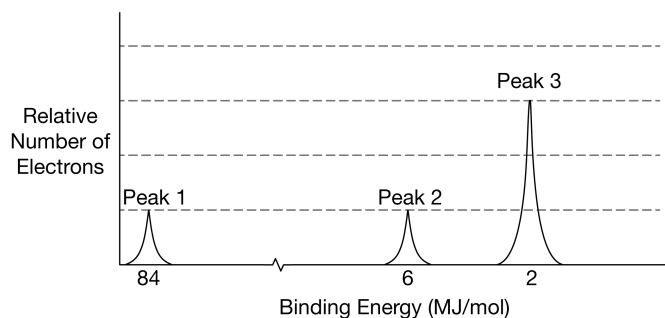
| Set | Before | After  |
|-----|--------|--------|
| A   | $sp^2$ | $sp^2$ |
| B   | $sp^2$ | $sp^3$ |
| C   | $sp^3$ | $sp^2$ |
| D   | $sp^3$ | $sp^3$ |

- (A) Set A
- (B) Set B
- (C) Set C
- (D) Set D

29. A student finds the mass of a pure sample of a metal chloride hydrate. The student heats the sample several times, reaching a constant mass that contains 0.100 mole of anhydrous metal chloride. Which of the following questions about the hydrated metal chloride substance is most likely to be answered by the results of the experiment?

- (A) How many moles of water are in one mole of the substance?
- (B) How many moles of the metal cation are in one mole of the substance?
- (C) What is the identity of the metal cation in the formula of the substance?
- (D) What is the melting point of the substance?

### Questions 30-31



The complete photoelectron spectrum of a pure element is shown in the diagram above.

30. According to the complete photoelectron spectrum, which of the following is the identity of the element?

(A) Be  
(B) C  
(C) O  
(D) Ne

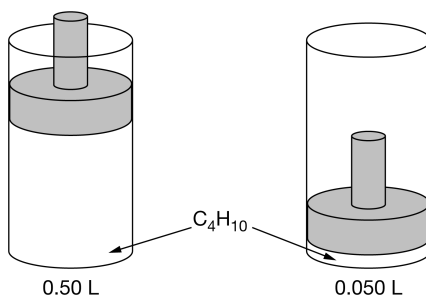
31. If peaks 1 and 2 represent *s* sublevels, which of the following sublevels is represented by peak 3?

(A) *s*  
(B) *p*  
(C) *d*  
(D) *f*

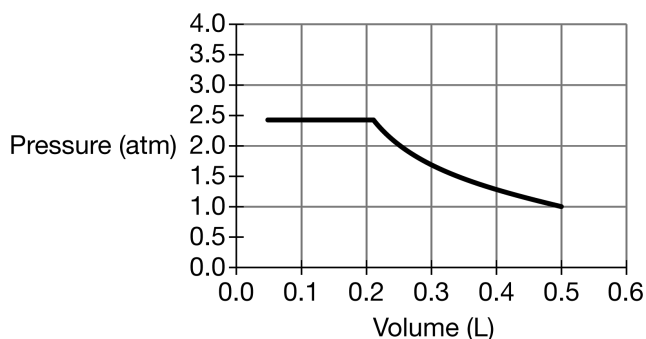
32. In an experiment to estimate the enthalpy change of a reaction, a student makes two aqueous solutions, each containing one of the reactants. The student combines the solutions, both originally at the same temperature, in a calorimeter and records the final temperature of the mixture. In addition to the masses of the solutions and the temperature change of the mixture, which of the following pieces of information does the student need to calculate the enthalpy change of the reaction?

(A) The density of the reaction mixture  
(B) The specific heat capacity of the reaction mixture  
(C) The boiling point of the reaction mixture  
(D) The heat of fusion of the reaction mixture

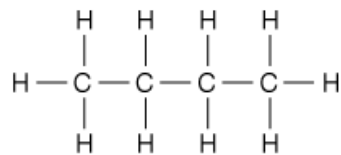
### Questions 33-35



A sample of  $\text{C}_4\text{H}_{10}(g)$  is placed in a rigid vessel with a movable piston. The volume of the gas is reduced by moving the piston downward while the temperature is maintained at  $25^\circ\text{C}$ , as shown above. The pressure of the gas versus its volume is plotted in the graph below.



33. Which of the following best explains the increase in pressure of the  $\text{C}_4\text{H}_{10}(g)$  when its volume is decreased from 0.50 L to 0.21 L?



- (A) The molecules strike the walls of the vessel more frequently.
- (B) The molecules strike the walls of the vessel with different orientations.
- (C) The molecules strike the walls of the vessel with greater force.
- (D) The molecules decompose to produce a greater number of particles.

34. The Lewis electron-dot diagram for  $\text{C}_4\text{H}_{10}$  is shown above. Which of the following is the predominant type of intermolecular force among  $\text{C}_4\text{H}_{10}$  molecules?

- (A) Hydrogen bonding
- (B) London dispersion forces
- (C) Dipole-dipole attractions
- (D) Dipole-induced dipole attractions

35. Which of the following best accounts for the pressure in the vessel remaining constant as the volume decreases below 0.21 L?

- (A) The density of the  $\text{C}_4\text{H}_{10}(g)$  increases.
- (B) The surface area of the interior of the vessel decreases.
- (C) The temperature of the  $\text{C}_4\text{H}_{10}(g)$  decreases.
- (D) Some  $\text{C}_4\text{H}_{10}(g)$  condenses to form  $\text{C}_4\text{H}_{10}(l)$ .

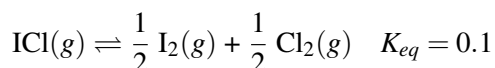
36. Which of the following substances has bonds with the greatest ionic character?

- (A)  $\text{CCl}_4$
- (B)  $\text{CuCl}_2$
- (C)  $\text{CaCl}_2$
- (D)  $\text{NCl}_3$

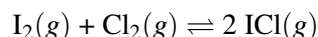
|                                       |                             |
|---------------------------------------|-----------------------------|
| $\text{HOCl}(aq)$                     | $K_a = 3.0 \times 10^{-8}$  |
| $\text{HC}_2\text{H}_3\text{O}_2(aq)$ | $K_a = 1.8 \times 10^{-5}$  |
| $\text{NH}_3(aq)$                     | $K_b = 1.8 \times 10^{-5}$  |
| $\text{C}_6\text{H}_5\text{NH}_2(aq)$ | $K_b = 3.0 \times 10^{-10}$ |

37. The  $K_a$  or  $K_b$  values of some weak acids and bases are listed in the table above. Which of the following solutions has the highest pH?

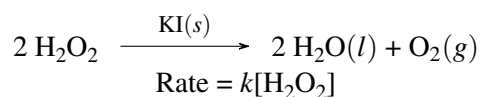
- (A) 0.1 M  $\text{HOCl}(aq)$
- (B) 0.1 M  $\text{HC}_2\text{H}_3\text{O}_2(aq)$
- (C) 0.1 M  $\text{NH}_3(aq)$
- (D) 0.1 M  $\text{C}_6\text{H}_5\text{NH}_2(aq)$



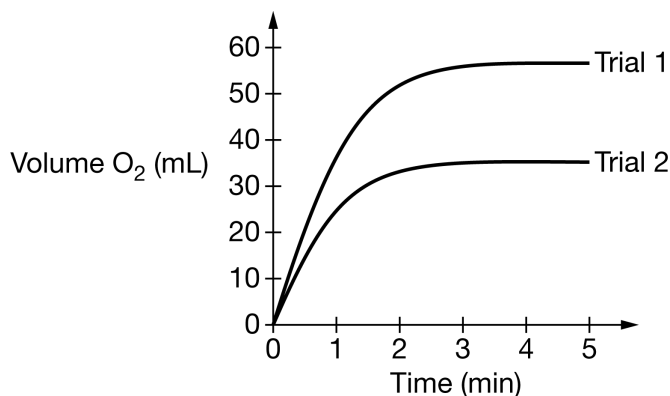
38. Based on the information above, what is the value of for the reaction represented  $k_{eq}$  below?



- (A) 0.01
- (B) 10
- (C) 20
- (D) 100



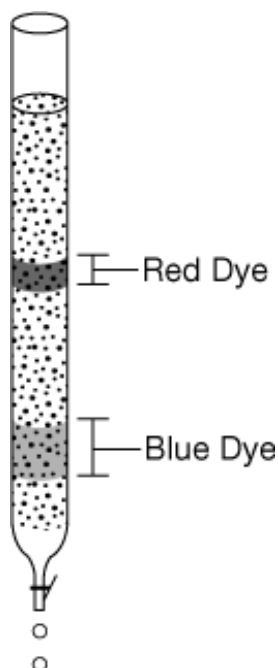
39. A student performed an experiment to study the factors that affect the rate of the first-order catalytic decomposition of  $\text{H}_2\text{O}_2(aq)$ , represented above.



The student monitored the volume of  $\text{O}_2(g)$  produced over time as the reaction proceeded. The data from two trials are plotted in the graph above. Which of the following best explains the results of trial 2 compared with those of trial 1?

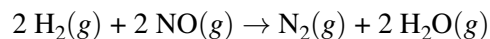
- (A) The reaction temperature in trial 2 was higher than it was in trial 1.
- (B) The volume of the reaction vessel was larger in trial 2 than it was in trial 1.
- (C) The student used a smaller amount of  $\text{KI}(s)$  in trial 2 compared with that used in trial 1.
- (D) The concentration of  $\text{H}_2\text{O}_2(aq)$  was lower in trial 2 than it was in trial 1.

### Questions 40-42



A student placed a sample of a food coloring that contains a mixture of a blue dye and a red dye at the top of a chromatography column filled with a nonpolar stationary phase. When water is poured through the column, two bands of colors are seen in the column, as shown in the diagram above.

40. Which of the following techniques would be best to investigate molecular vibrations in molecules of the red dye?
- (A) Infrared spectroscopy
  - (B) UV/vis spectroscopy
  - (C) Mass spectrometry
  - (D) Gravimetric analysis
41. A student collects a sample of the blue dye from the column in a cuvette. Which of the following is least useful to determine the concentration of the sample using a spectrophotometer set at 640 nm?
- (A) The volume of the sample
  - (B) The path length of the cuvette
  - (C) The absorbance of the dye at 640 nm
  - (D) The molar absorptivity of the dye at 640 nm
42. Which of the following will most likely be observed if  $\text{CH}_3\text{OH}(l)$  is used in the column instead of water? (Assume that both solvents flow through the column at the same rate.)
- (A) The dyes will not pass through the column because  $\text{CH}_3\text{OH}(l)$  is a nonpolar solvent.
  - (B) The dyes will pass through the column at a slower rate because  $\text{CH}_3\text{OH}(l)$  is a less polar solvent than water.
  - (C) The dyes will pass through the column at a faster rate because  $\text{CH}_3\text{OH}(l)$  has a greater molar mass than water.
  - (D) No differences will be observed because the polarity of the solvent does not affect the separation of the dyes.



43. The dissolution of  $\text{BaCO}_3(s)$  in water is represented above. A 20.0 mL sample of  $1.0 \times 10^{-4} M \text{Ba}(\text{NO}_3)_2(aq)$  is mixed with an 80.0 mL sample of  $1.0 \times 10^{-4} M \text{Na}_2\text{CO}_3(aq)$ . Which of the following correctly predicts and explains the outcome?

- (A) A precipitate will form, because  $Q = 1.0 \times 10^{-8}$ .  
 (B) A precipitate will form, because  $Q = 1.6 \times 10^{-9}$ .  
 (C) A precipitate will not form, because  $Q = 1.0 \times 10^{-8}$ .  
 (D) A precipitate will not form, because  $Q = 1.6 \times 10^{-9}$ .

| Compound           | $[\text{Pb}^{2+}]$ in Saturated Solution |
|--------------------|------------------------------------------|
| PbS                | $1.7 \times 10^{-14} M$                  |
| PbCO <sub>3</sub>  | $2.7 \times 10^{-7} M$                   |
| PbCrO <sub>4</sub> | $5.5 \times 10^{-7} M$                   |
| PbSO <sub>4</sub>  | $1.6 \times 10^{-4} M$                   |

44. Based on  $[\text{Pb}^{2+}]$  in saturated solutions of the compounds listed in the table above, which of the compounds has the smallest  $K_{sp}$  value?

- (A) PbS  
 (B) PbCO<sub>3</sub>  
 (C) PbCrO<sub>4</sub>  
 (D) PbSO<sub>4</sub>

|                 |    |                |                  |
|-----------------|----|----------------|------------------|
| Cl <sup>-</sup> | Ar | K <sup>+</sup> | Ca <sup>2+</sup> |
|-----------------|----|----------------|------------------|

45. The four species above have the same electron configuration,  $1s^2 2s^2 2p^6 3s^2 3p^6$ . Which of the following statements correctly identifies the species with the largest radius and provides an explanation based on Coulomb's law?

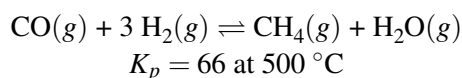
- (A) Cl<sup>-</sup>, because its nuclear charge exerts the least attractive force on the electrons in the 3p sublevel.  
 (B) Ar, because it is a neutral atom and the net force on the electrons in the 3p sublevel is zero.  
 (C) K<sup>+</sup>, because the loss of an electron results in a smaller attractive force between the nucleus and the electrons in the 3p sublevel.  
 (D) Ca<sup>2+</sup>, because the large positive charge on a cation causes increased repulsion among the electrons in the 3p sublevel.

46. The experimental rate law for the reaction represented above is  $\text{rate} = k[\text{H}_2][\text{NO}]^2$ . Which of the following proposed mechanisms is consistent with the rate law?

- (A) Step 1:  $2 \text{NO} \rightarrow \text{N}_2\text{O}_2$  fast  
 Step 2:  $\text{H}_2 + \text{N}_2\text{O}_2 \rightleftharpoons \text{N}_2\text{O} + \text{H}_2\text{O}$  fast  
 Step 3:  $\text{H}_2 + \text{N}_2\text{O} \rightarrow \text{N}_2 + \text{H}_2\text{O}$  slow  
 (B) Step 1:  $2 \text{NO} \rightleftharpoons \text{N}_2\text{O}_2$  fast  
 Step 2:  $\text{H}_2 + \text{N}_2\text{O}_2 \rightarrow \text{N}_2\text{O} + \text{H}_2\text{O}$  slow  
 Step 3:  $\text{H}_2 + \text{N}_2\text{O} \rightarrow \text{N}_2 + \text{H}_2\text{O}$  fast  
 (C) Step 1:  $2 \text{NO} \rightarrow \text{N}_2 + \text{O}_2$  slow  
 Step 2:  $\text{H}_2 + \text{O}_2 \rightarrow \text{H}_2\text{O}_2$  fast  
 Step 3:  $\text{H}_2 + \text{H}_2\text{O}_2 \rightarrow 2 \text{H}_2\text{O}$  fast  
 (D) Step 1:  $2 \text{NO} \rightarrow \text{N}_2 + \text{O}_2$  fast  
 Step 2:  $\text{H}_2 + \text{O}_2 \rightleftharpoons \text{H}_2\text{O}_2$  fast  
 Step 3:  $\text{H}_2 + \text{H}_2\text{O}_2 \rightarrow 2 \text{H}_2\text{O}$  slow

47. Which of the following equations represents a reaction with a negative  $\Delta S^\circ$ ?

- (A)  $2 \text{NO}(g) + \text{O}_2(g) \rightarrow 2 \text{NO}_2(g)$   
 (B)  $2 \text{KClO}_3(g) + 2 \text{KCl}(s) \rightarrow 3 \text{O}_2(g)$   
 (C)  $\text{PCl}_5(g) \rightarrow \text{PCl}_3(g) + \text{Cl}_2(g)$   
 (D)  $\text{C}_3\text{H}_8(g) + 5 \text{O}_2(g) \rightarrow 3 \text{CO}_2(g) + 4 \text{H}_2\text{O}(g)$



48. At a certain time, the partial pressure of the gases in the reaction mixture represented above had the values shown in the table below.

| $P_{\text{CO}}$ | $P_{\text{H}_2}$ | $P_{\text{CH}_4}$ | $P_{\text{H}_2\text{O}}$ |
|-----------------|------------------|-------------------|--------------------------|
| 0.02 atm        | 1.0 atm          | 0.4 atm           | 0.4 atm                  |

Based on the information above, which of the following occurred as the reaction mixture moved toward equilibrium?

- (A) More  $\text{CH}_4(g)$  was produced because the rate of the forward reaction was higher than the rate of the reverse reaction.
- (B) More  $\text{H}_2(g)$  was produced because the rate of the reverse reaction was higher than the rate of the forward reaction.
- (C) More  $\text{CH}_4(g)$  was produced because the total pressure of the  $\text{H}_2(g)$  and  $\text{CO}(g)$  combined was higher than that of the products; thus the reaction shifted to the side with the fewest number of moles of gas.
- (D) More  $\text{H}_2(g)$  was produced because the pressure of  $\text{CO}(g)$  was the least and the reaction shifted to the side with the smaller number of moles of gas.

49.  $\text{CCl}_4(g)$  deviates more from ideal gas behavior than  $\text{CH}_4(g)$  does. Which of the following statements best explains this observation?

- (A) The mass of the  $\text{CCl}_4$  molecule is greater than that of the  $\text{CH}_4$  molecule.
- (B) The bond energy of the C–Cl bond is greater than that of the C–H bond.
- (C) The dipole-dipole forces between  $\text{CCl}_4$  molecules are greater than those between  $\text{CH}_4$  molecules.
- (D) The London dispersion forces between  $\text{CCl}_4$  molecules are stronger than those between  $\text{CH}_4$  molecules.

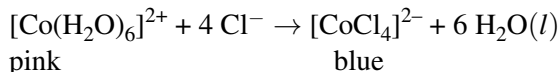
Questions 50-52 refer to the table below.

| Compound | Structure                                                                                                                                                                                                                                                                                                      | Boiling Point (°C) |
|----------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|
| Methanol | $  \begin{array}{c}  \text{H} \\    \\  \text{H}-\text{C}-\ddot{\text{O}}-\text{H} \\    \\  \text{H}  \end{array}  $                                                                                                                                                                                          | 65                 |
| Ethanol  | $  \begin{array}{c}  \text{H} \quad \text{H} \\    \quad   \\  \text{H}-\text{C}-\text{C}-\ddot{\text{O}}-\text{H} \\    \quad   \\  \text{H} \quad \text{H}  \end{array}  $                                                                                                                                   | 78                 |
| Propanal | $  \begin{array}{c}  \text{H} \quad \text{H} \quad \text{:O:} \\    \quad   \quad // \\  \text{H}-\text{C}-\text{C}-\text{C} \\    \quad   \quad \backslash \\  \text{H} \quad \text{H} \quad \text{H}  \end{array}  $                                                                                         | 49                 |
| Hexane   | $  \begin{array}{ccccccc}  \text{H} & \text{H} & \text{H} & \text{H} & \text{H} & \text{H} \\    &   &   &   &   &   \\  \text{H}-\text{C}-\text{C}-\text{C}-\text{C}-\text{C}-\text{C}-\text{H} \\    &   &   &   &   &   \\  \text{H} & \text{H} & \text{H} & \text{H} & \text{H} & \text{H}  \end{array}  $ | 69                 |

50. A 50 mL sample of  $\text{C}_6\text{H}_{14}(l)$  is mixed with a 50 mL sample of  $\text{H}_2\text{O}(l)$ , and the mixture is shaken vigorously. The two liquids do not stay mixed but instead form two separate layers. The density of hexane is 0.66 g/mL, and the density of water is 1.00 g/mL. A 1.0 g sample of  $\text{I}_2(s)$  is added to the mixture, which is shaken again. Which of the following best predicts what happens to the  $\text{I}_2(s)$ ?
- (A)  $\text{I}_2$  will be found mainly in the top layer because it will dissolve more in the  $\text{H}_2\text{O}(l)$ .
- (B)  $\text{I}_2$  will be found mainly in the bottom layer because it will dissolve more in the  $\text{H}_2\text{O}(l)$ .
- (C)  $\text{I}_2$  will be found mainly in the top layer because it will dissolve more in the  $\text{C}_6\text{H}_{14}(l)$ .
- (D)  $\text{I}_2$  will be found mainly in the bottom layer because it will dissolve more in the  $\text{C}_6\text{H}_{14}(l)$ .
51. When a 50 mL sample of  $\text{C}_2\text{H}_5\text{OH}$  is mixed with a 50 mL sample of  $\text{H}_2\text{O}$ , the resulting mixture has a volume of 95 mL, and the container is warm to the touch. Which of the following best describes these observations?
- (A) A chemical reaction occurs, as evidenced by the volume of the resultant mixture being less than the total volume of the initial components.
- (B) A chemical change occurs, as evidenced by the formation of new covalent bonds releasing more energy than is absorbed by the breaking of the existing covalent bonds.
- (C) A physical change occurs, and the solvation process is exothermic.
- (D) A physical change occurs, and the solvation process is endothermic.
52. Which of the following best helps to explain why hexane has a higher boiling point than methanol has?
- (A) Methanol molecules can form hydrogen bonds with other methanol molecules.
- (B) Hexane cannot form hydrogen bonds with other hexane molecules.
- (C) Methanol molecules have attractions to one another due to London dispersion forces.
- (D) Hexane molecules have electron clouds that are larger than those of methanol molecules.

53. A 0.08 M solution of  $\text{CH}_3\text{COOH}$  ( $\text{p}K_a = 4.74$ ) is titrated with 0.10 M  $\text{NaOH}(aq)$ . What is the pH at the equivalence point of the titration and why?

- (A)  $\text{pH} < 7$ , because  $\text{NaOH}(aq)$  is a strong base.
- (B)  $\text{pH} = 7$ , because the titration reaction is a neutralization reaction.
- (C)  $\text{pH} > 7$ , because  $\text{CH}_3\text{COO}^-(aq)$  is a weak base.
- (D)  $\text{pH} > 7$ , because the concentration of  $\text{NaOH}(aq)$  is greater than that of  $\text{CH}_3\text{COOH}(aq)$ .



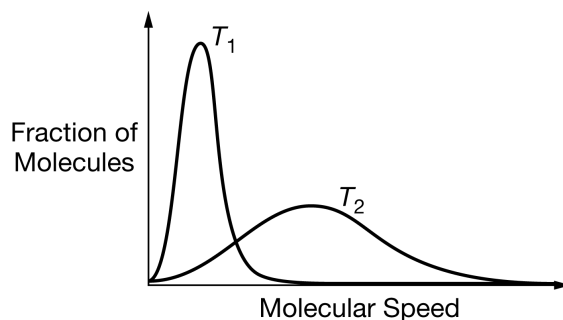
54. The solvent in the nonaqueous system represented above is 2-propanol. If a small amount of water is added to the system, how will the color of the solution be affected, and why?

- (A) The solution will become more pink because more  $[\text{Co}(\text{H}_2\text{O})_6]^{2+}$  will be produced.
- (B) The solution will become more pink because the pH of the solution will increase.
- (C) The solution will become more blue because more  $[\text{CoCl}_4]^{2-}$  will be produced.
- (D) The solution will become more blue because the pH of the solution will decrease.

| Element | Second Ionization Energy (kJ/mol) |
|---------|-----------------------------------|
| Li      | 7300                              |
| Na      | 4560                              |
| K       | 3050                              |
| Rb      | 2630                              |

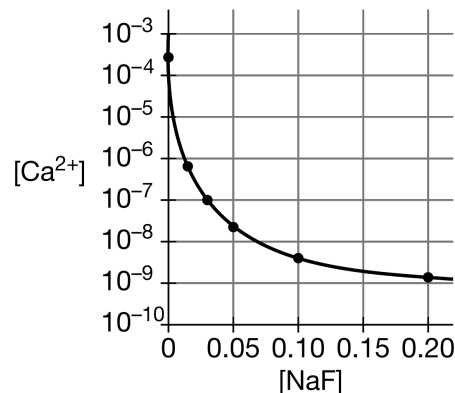
55. The decrease in the second ionization energy of alkali metals going down the group, as shown in the table above, can be best attributed to a decrease in the coulombic force of attraction due to

- (A) the removal of core electrons
- (B) an increase in effective nuclear charge
- (C) an increase in the average distance of the outermost electron from the nucleus
- (D) a decrease in electron-electron repulsion within the outermost shell



56. The diagram above shows the distribution of molecular speed in a sample of gas at two different temperatures,  $T_1$  and  $T_2$ . Which of the following is a correct interpretation of the information provided by the diagram?

- (A) The average speed of the molecules is greater at  $T_1$  than at  $T_2$ .
- (B) The taller peak corresponds to the higher temperature,  $T_1$ .
- (C) There are fewer molecules of gas at  $T_2$  than at  $T_1$ .
- (D) The average kinetic energy of the molecules is greater at  $T_2$  than at  $T_1$ .



57. Which of the following statements best explains the trend in the molar solubility of  $\text{CaF}_2(s)$  in various concentrations of  $\text{NaF}(aq)$  shown in the graph above?

- (A) Higher concentrations of  $\text{F}^-(aq)$  allow less  $\text{CaF}_2(s)$  to dissolve before the solution becomes saturated.
- (B) Higher concentrations of  $\text{Na}^+(aq)$  lead to more favorable attractions between  $\text{Na}^+(aq)$  ions and  $\text{F}^-(aq)$  ions, thus less  $\text{CaF}_2(s)$  dissolves.
- (C) Higher concentrations of  $\text{F}^-(aq)$  produce more  $\text{OH}^-(aq)$  through hydrolysis, causing  $\text{Ca}(\text{OH})_2(s)$  to precipitate, thus more  $\text{CaF}_2(s)$  dissolves.
- (D) Higher concentrations of  $\text{F}^-(aq)$  cause the formation of the  $\text{CaF}_4^{2-}(aq)$  complex ion, which allows more  $\text{CaF}_2(s)$  to dissolve.

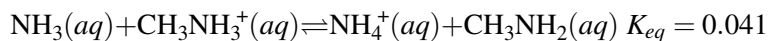
| Acid | Structure                                    |
|------|----------------------------------------------|
| HClO | $\text{H}-\ddot{\text{O}}-\ddot{\text{Cl}}:$ |
| HBrO | $\text{H}-\ddot{\text{O}}-\ddot{\text{Br}}:$ |
| HIO  | $\text{H}-\ddot{\text{O}}-\ddot{\text{I}}:$  |

58. A 0.1 *M* aqueous solution of which of the acids shown in the table above would have a pH closest to 7.0, and why?

- (A) HClO, because Cl has the highest electronegativity.
- (B) HBrO, because Br has the lowest electronegativity.
- (C) HIO, because I has the lowest electronegativity.
- (D) All three solutions will have the same pH because they are all monoprotic acids.

59. The value of  $K_w$  at 37°C is  $2.4 \times 10^{-14}$ . Which of the following statements about the pH and pOH of pure water at 37°C is correct?

- (A)  $\text{pH} < 7$  and  $\text{pOH} > 7$  because water dissociates to a lesser extent at 37°C than at 25°C.
- (B)  $\text{pH} > 7$  and  $\text{pOH} < 7$  because the dissociation of water is endothermic, and  $\text{pH} + \text{pOH} = 14$ .
- (C)  $\text{pH} = \text{pOH} < 7$  because because water dissociates to a greater extent at 37°C than at 25°C.
- (D)  $\text{pH} = \text{pOH} = 7$  because  $[\text{H}_3\text{O}^+] = [\text{OH}^-]$  for pure water.



60. Which of the following species is the strongest base in the reaction represented above?

- (A)  $\text{NH}_3(aq)$
- (B)  $\text{CH}_3\text{NH}_3^+(aq)$
- (C)  $\text{CH}_4^+(aq)$
- (D)  $\text{CH}_3\text{NH}_2(aq)$

**STOP**  
**END OF SECTION I**

# CHEMISTRY

## Section II

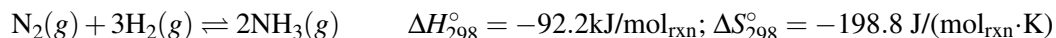
Time—1 hour and 45 minutes

### 7 Questions

**Note:** 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.

**Directions:** 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.

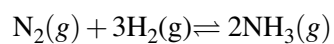
1. Answer the following questions related to  $\text{NH}_3$ .



- (a) The reaction of  $\text{N}_2(g)$  and  $\text{H}_2(g)$  to form  $\text{NH}_3(g)$  is represented above. The reaction has been studied in order to maximize the yield of  $\text{NH}_3(g)$ .
- Calculate the value of  $\Delta G^\circ$ , in  $\text{kJ/mol}_{\text{rxn}}$ , at 298K.
  - Calculate the value of the equilibrium constant,  $K_p$ , at 298K.

| Bond | Average Bond Enthalpy (kJ/mol) |
|------|--------------------------------|
| N–H  | 391                            |
| H–H  | 436                            |
| N≡N  | ?                              |

- (b) Based on the average bond enthalpies in the table above and the value of  $\Delta H_{298}^\circ$ , calculate the value of the  $\text{N}\equiv\text{N}$  bond enthalpy.
- (c) Although the reaction is thermodynamically favorable at 298 K, it does not occur to an observable extent at this temperature. Explain how the  $\text{N}\equiv\text{N}$  bond enthalpy affects the rate of the reaction.
- (d) The reaction is usually carried out at a very high temperature in the presence of a catalyst. Explain why the reaction is thermodynamically unfavorable at very high temperatures. Justify your answer in terms of  $\Delta H^\circ$ ,  $\Delta S^\circ$ , and their effect on  $\Delta G^\circ$ .



- (e) Although the forward reaction represented above is thermodynamically unfavorable at very high temperatures, it can be used to produce  $\text{NH}_3$  if the  $\text{NH}_3$  is continually removed from the reaction vessel. Explain in terms of  $Q$  and  $K_p$  why this method works.

The boiling points of  $\text{H}_2$  and  $\text{NH}_3$  are given in the table below.

| Substance     | Boiling Point |
|---------------|---------------|
| $\text{H}_2$  | 20 K          |
| $\text{NH}_3$ | 240 K         |

- (f) A student claims that  $\text{H}_2(g)$  condenses at a much lower temperature than  $\text{NH}_3(g)$  because  $\text{H}_2$  has stronger intermolecular forces than  $\text{NH}_3$  does. There are two errors in the student's reasoning. Identify the student's errors and explain your answer in terms of the specific types of forces involved.

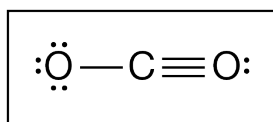


Diagram X

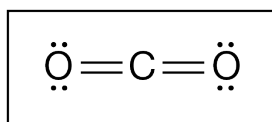


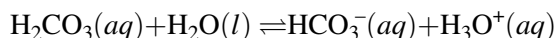
Diagram Z

2. Answer the following questions related to  $\text{CO}_2$ .

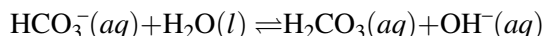
- Two possible Lewis electron-dot diagrams for  $\text{CO}_2$  are shown above. Explain in terms of formal charges why diagram Z is the better diagram.
- Identify the hybridization of the valence orbitals of the C atom in the  $\text{CO}_2$  molecule represented in diagram Z.
- A 0.1931 mol sample of dry ice,  $\text{CO}_2(s)$ , is added to an empty balloon. After the balloon is sealed, the  $\text{CO}_2(s)$  sublimates and the  $\text{CO}_2(g)$  in the balloon eventually reaches a temperature of  $21.0^\circ\text{C}$  and pressure of 0.998 atm. The physical change is represented by the following equation.



- What is the sign (positive or negative) of the enthalpy change for the process of sublimation? Justify your answer.
  - List all the numerical values of the quantities, with appropriate units, that are needed to calculate the volume of the balloon.
  - Calculate the final volume, in liters, of the balloon.
- (d)  $\text{CO}_2(g)$  reacts with water to form  $\text{H}_2\text{CO}_3(aq)$ , which quickly ionizes in water to form  $\text{HCO}_3^-(aq)$  and  $\text{H}_3\text{O}^+(aq)$ , as shown in the following equation.



- Identify one of the conjugate acid-base pairs in the equation above.
  - When the concentration of  $\text{CO}_2$  in water increases, more  $\text{H}_2\text{CO}_3$  forms. Does the increase in the formation of  $\text{H}_2\text{CO}_3$  cause the value of the reaction quotient,  $Q$ , for the system to increase, decrease, or remain the same? Justify your answer.
- (e) A student investigates the acid-base properties of  $\text{HCO}_3^-(aq)$ . The reaction of  $\text{HCO}_3^-(aq)$  with  $\text{H}_2\text{O}(l)$  is represented below.



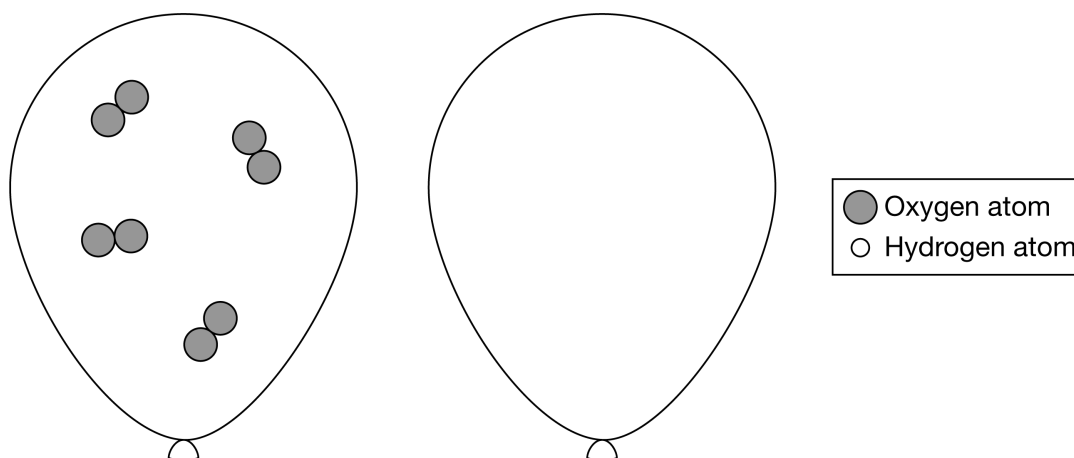
- The student measured the pH of a 0.100 M solution of  $\text{HCO}_3^-(aq)$  as 9.68. Calculate the concentration of  $\text{OH}^-(aq)$  in the solution.

$$K_b = \frac{[\text{H}_2\text{CO}_3][\text{OH}^-]}{[\text{HCO}_3^-]}$$

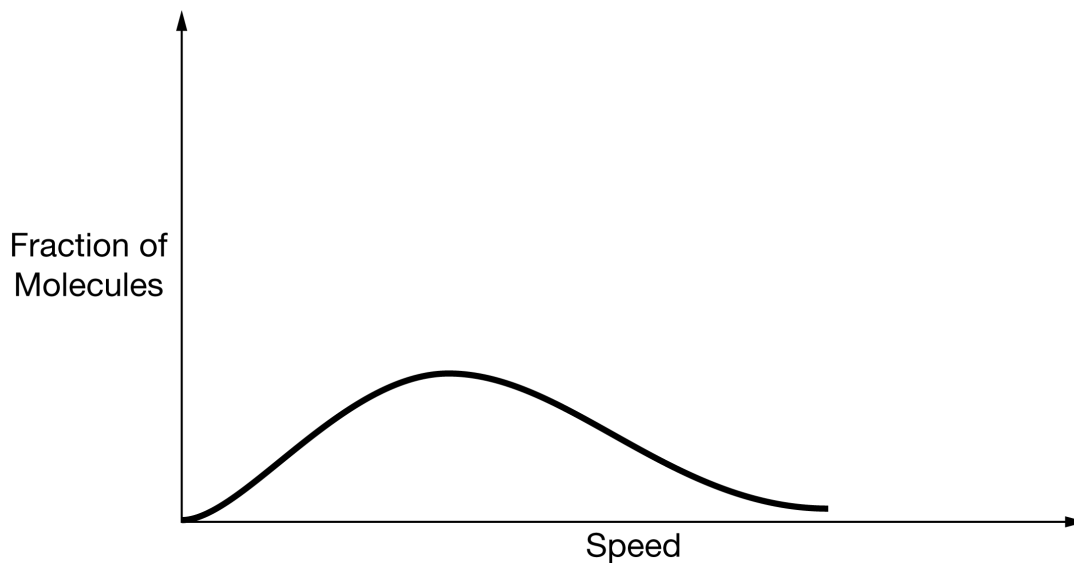
- The  $K_b$  expression for the reaction of  $\text{HCO}_3^-(aq)$  with  $\text{H}_2\text{O}(l)$  is given above. Calculate the value of  $K_b$  for the reaction.
- The student then carried out a second experiment at the same temperature to determine  $K_b$ . In the experiment, the student measured the pH of 0.300 M  $\text{HCO}_3^-(aq)$ . Would the value of  $K_b$  calculated in the second experiment be greater than, less than, or equal to the value of  $K_b$  calculated in part (e)(ii)? Justify your answer.

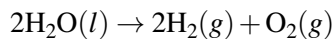
3. Answer the following questions about hydrogen and oxygen gases.

- (a) A particle-level representation of  $\text{O}_2(g)$  is shown in the balloon below on the left. The balloon on the right contains the same volume of  $\text{H}_2(g)$  at the same temperature and pressure. In the balloon on the right, draw a representation of  $\text{H}_2(g)$  with the appropriate number and distribution of particles.

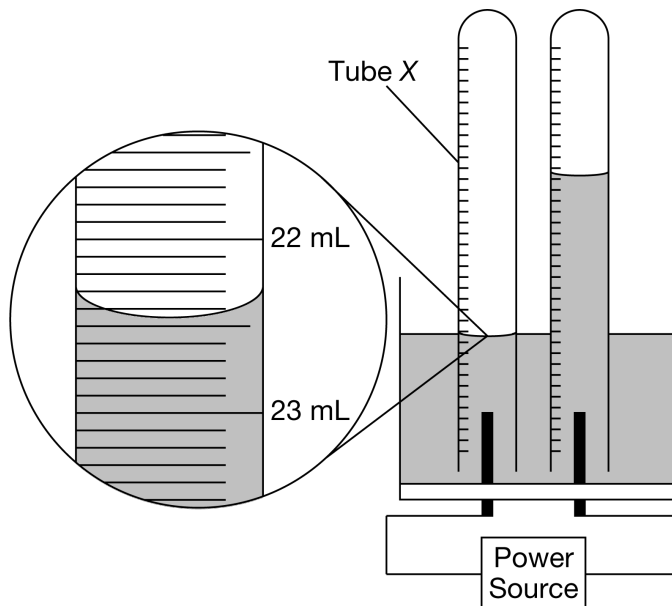


- (b) The graph below shows the Maxwell-Boltzmann distribution for  $\text{H}_2(g)$ . On the same graph, draw the distribution curve for  $\text{O}_2(g)$  at the same temperature.

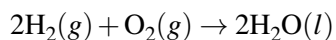




To generate the  $\text{H}_2(g)$  and the  $\text{O}_2(g)$ , a student performs electrolysis of water, represented by the equation above. The student collects the gases in tubes and then adjusts the position of one of them so that the water levels inside and outside of the tube are the same, as shown in the following diagram.

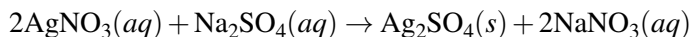


- Is the gas collected in tube X  $\text{H}_2(g)$  or  $\text{O}_2(g)$ ? Justify your answer.
- What volume should the student report for the gas in tube X?
- Is  $\text{H}_2(g)$  produced at the anode or cathode? Justify your answer in terms of oxidation numbers.
- The atmospheric pressure in the lab was 0.989 atm at  $22.0^\circ\text{C}$ . The vapor pressure of water at  $22.0^\circ\text{C}$  is 0.026 atm. Calculate the pressure of dry gas in tube X.
- The value of  $E^\circ$  for the electrolysis of water is  $-1.23\text{V}$ . In a second trial of the experiment, the power source was replaced with a voltmeter. Would the volume of hydrogen gas produced be greater than, less than, or equal to the volume produced in the original experiment? Justify your answer.
- The student considers the reverse reaction and proposes a mechanism with a single, elementary step as shown below.



Explain, in terms of particle collisions, why this mechanism is unlikely to be correct.

4. A student wishes to determine the concentration of  $\text{Ag}^+(aq)$  in a solution of  $\text{AgNO}_3(aq)$ . The student combines 10.00 mL of  $\text{AgNO}_3(aq)$  with excess  $\text{Na}_2\text{SO}_4(aq)$  and observes the formation of a white precipitate. The formation of the precipitate is represented by the following equation.



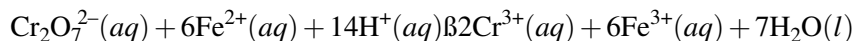
- (a) Write the balanced net ionic equation for the precipitation reaction.

The student collects the precipitate by filtration and measures the mass of the filter paper and precipitate every 10 minutes as it dries. The student records the data in the following table.

|                                                                   |        |
|-------------------------------------------------------------------|--------|
| Mass of dry filter paper                                          | 0.88 g |
| Mass of filter paper and precipitate immediately after filtration | 4.82 g |
| Mass of filter paper and precipitate after 10 minutes             | 4.37 g |
| Mass of filter paper and precipitate after 20 minutes             | 4.01 g |
| Mass of filter paper and precipitate after 30 minutes             | 3.79 g |

- (b) Use the data above to calculate the number of moles of  $\text{Ag}_2\text{SO}_4(s)$  (molar mass 311.8 g/mol) that precipitated.
- (c) Calculate the concentration of  $\text{Ag}^+(aq)$  in the original 10.00 mL solution of  $\text{AgNO}_3(aq)$ .
- (d) The concentration of  $\text{Ag}^+(aq)$  determined by the student is significantly higher than the actual concentration of  $\text{Ag}^+(aq)$ . Based on the student's data table, identify an error in the experimental procedure that led to this result.

5. A student determines the mass percent of iron in a sample of iron ore by doing a redox titration. The student finds the mass of the sample and then dissolves it in acid to a total volume of 25.00 mL. Using a buret, the student titrates the 25.00 mL solution with 0.017 M  $\text{K}_2\text{Cr}_2\text{O}_7$ . The following reaction occurs during the titration.

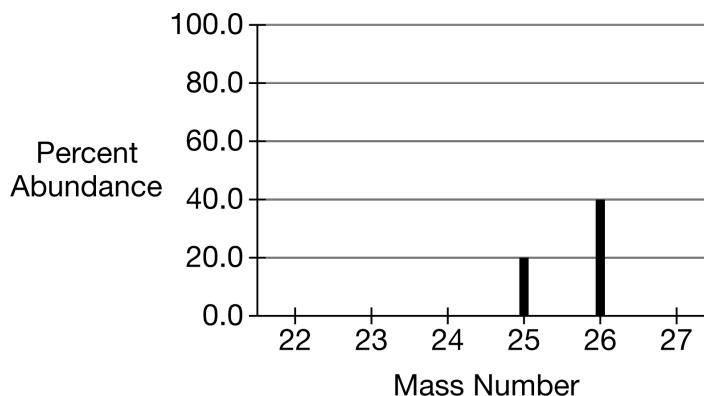


The student collects the following data.

|                                     |         |
|-------------------------------------|---------|
| Mass of iron ore in original sample | 0.36 g  |
| Buret reading at end point          | 45.52mL |
| Initial buret reading               | 15.05mL |

- (a) How many moles of  $\text{Fe}^{2+}(\text{aq})$  reacted with the  $\text{Cr}_2\text{O}_7^{2-}(\text{aq})$ ?
- (b) Assuming that all the iron in the ore was  $\text{Fe}^{2+}$ , calculate the mass percent of iron in the ore sample.
- (c) The student learns that the actual mass percent of iron in the ore sample is greater than the experimental value calculated in part (b). The student claims that the difference between the actual and experimental values could have been caused by rinsing the buret with distilled water just prior to filling it with 0.017 M  $\text{K}_2\text{Cr}_2\text{O}_7(\text{aq})$ . Do you agree with the student's claim? Explain your reasoning.

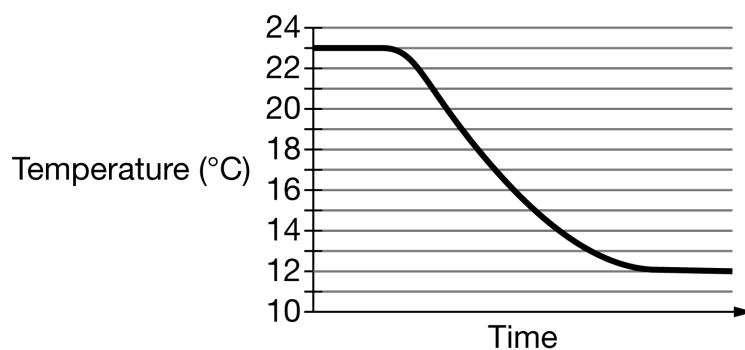
6. The three stable isotopes of Mg are Mg-24, Mg-25, and Mg-26. A rock sample from another planet has a different distribution of the three stable isotopes than what is found on Earth. A partial mass spectrum for Mg in the rock sample is shown below.



- (a) Draw a line on the graph to show the mass of the missing isotope and its percent abundance.
- (b) Use the completed mass spectrum to calculate the average atomic mass of Mg on the other planet.
- (c) The first ionization energy of magnesium samples found on Earth is experimentally determined to be 736 kJ/mol. If a similar experiment is conducted to determine the first ionization energy of magnesium in the rock sample from another planet, will it be greater than, less than, or equal to the first ionization energy of magnesium found on Earth? Explain your reasoning.

|                 | Successive Ionization Energies (kJ/mol) |        |       |
|-----------------|-----------------------------------------|--------|-------|
|                 | First                                   | Second | Third |
| Mg              | 736                                     | 1450   | 7740  |
| Unknown element | 496                                     | 4560   | 6910  |

- (d) A table of successive ionization energies for Mg and an unknown element is shown above. Predict the identity of the unknown element.



7. A student conducts an experiment to determine the value of  $\Delta H_{\text{soln}}^{\circ}$  for the dissolution of  $\text{NaC}_2\text{H}_3\text{O}_2(s)$ . The student dissolves 10.0 g of  $\text{NaC}_2\text{H}_3\text{O}_2(s)$  in room-temperature water in a beaker and measures the temperature over time. The data are given in the graph above.
- The student touches the side of the beaker after the dissolution has occurred and observes that it is cold. What experimental evidence is consistent with the student's observation?
  - Is the dissolution of  $\text{NaC}_2\text{H}_3\text{O}_2(s)$  endothermic or exothermic? Justify your answer in terms of the flow of energy between the system and surroundings.
  - The student calculated the energy change for the dissolution to be 4600 J. Based on this value, calculate  $\Delta H_{\text{soln}}^{\circ}$  in kJ/mol.

# APPENDIX - ANSWERS

## AP CHEMISTRY 2021

Multiple-choice key transcribed from the matching supplied source.

| Question | Answer | Question | Answer | Question | Answer |
|----------|--------|----------|--------|----------|--------|
| 1        | A      | 21       | D      | 41       | A      |
| 2        | D      | 22       | D      | 42       | B      |
| 3        | D      | 23       | D      | 43       | D      |
| 4        | C      | 24       | D      | 44       | A      |
| 5        | D      | 25       | A      | 45       | A      |
| 6        | C      | 26       | B      | 46       | B      |
| 7        | A      | 27       | D      | 47       | A      |
| 8        | C      | 28       | B      | 48       | A      |
| 9        | C      | 29       | A      | 49       | D      |
| 10       | D      | 30       | D      | 50       | C      |
| 11       | A      | 31       | B      | 51       | C      |
| 12       | D      | 32       | B      | 52       | D      |
| 13       | A      | 33       | A      | 53       | C      |
| 14       | D      | 34       | B      | 54       | A      |
| 15       | D      | 35       | D      | 55       | C      |
| 16       | A      | 36       | C      | 56       | D      |
| 17       | B      | 37       | C      | 57       | A      |
| 18       | D      | 38       | D      | 58       | C      |
| 19       | B      | 39       | D      | 59       | C      |
| 20       | D      | 40       | A      | 60       | D      |

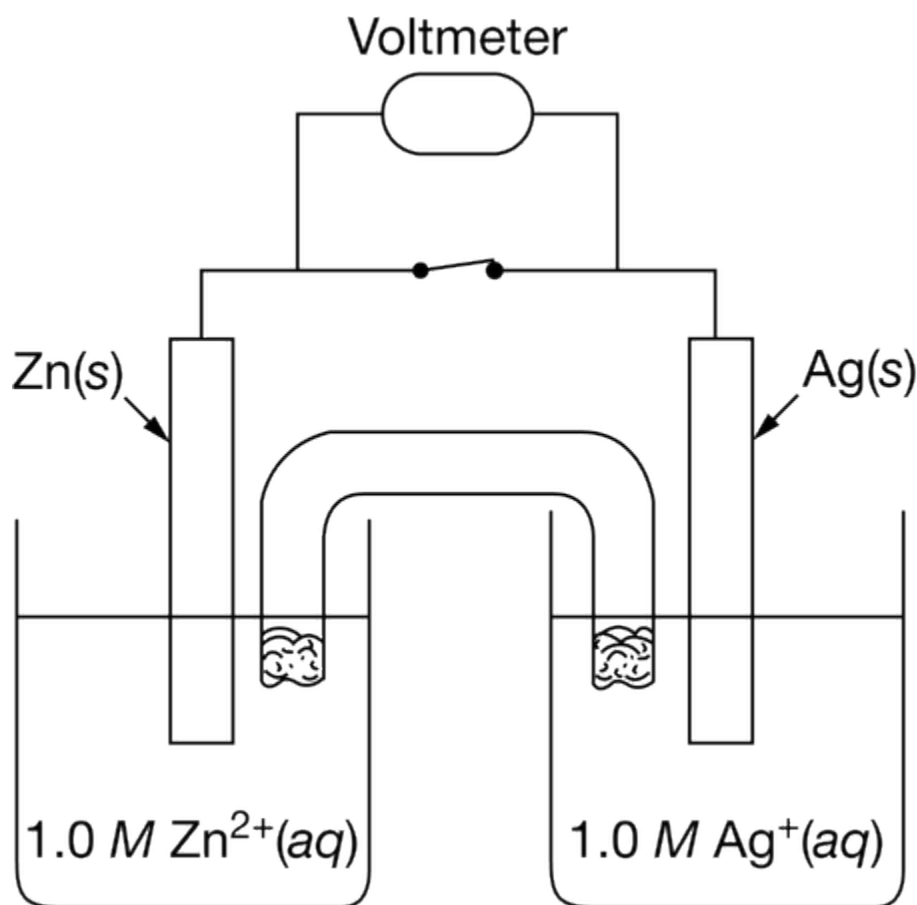
Scoring-extract items 61-67 correspond to FRQs 1-7.

## 2021 Form I: MCQ

1. In his atomic theory, Dalton proposed that all atoms of a given element are identical. Which of the following observations provides the best evidence that the proposal is incorrect?

- (A) The mass spectrum of Cu has a peak at 63 amu and another peak at 65 amu. ✓
- (B) The ionic radius of  $\text{Cl}^-$  is 0.181 nm, and the atomic radius of Cl is 0.079 nm.
- (C) The dipole moment of  $\text{O}_3$  is 0.53 debye, and the dipole moment of  $\text{O}_2$  is 0.00 debye.
- (D) Elemental P can exist in both white and red forms.

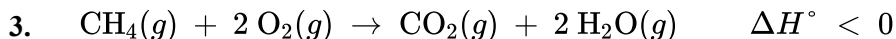
2.



Which of the following substances would be the best choice for filling the salt bridge in the galvanic cell shown above, and why?

- (A) Distilled water, because it would avoid contaminating the solutions in the half-cells.
- (B) 1.0 M  $\text{HCl}(aq)$ , because it would acidify the solutions and catalyze the overall cell reaction.
- (C) 1.0 M  $\text{CH}_3\text{OH}(aq)$ , because it would increase the pH of the solutions and catalyze the overall cell reaction.
- (D) 1.0 M  $\text{KNO}_3(aq)$ , because the mobile ions would allow charge to flow between the half-cells. ✓

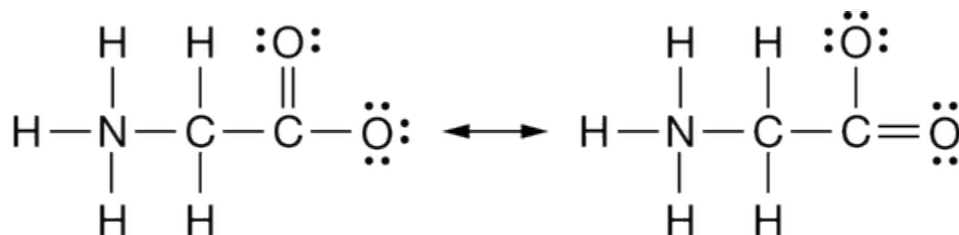
## 2021 Form I: MCQ



Which of the following statements must be true for the combustion of  $\text{CH}_4(g)$ , represented by the equation above?

- (A) The bond dissociation energy between O atoms in  $\text{O}_2$  is greater than the sum of the bond dissociation energies of the two O – H bonds in  $\text{H}_2\text{O}$ .
- (B) More bonds are formed in the products than are broken in the reactants.
- (C) The sum of the bond dissociation energies of the product molecules is equal to the sum of the bond dissociation energies of the reactant molecules.
- (D) The sum of the bond dissociation energies of the product molecules is greater than the sum of the bond dissociation energies of the reactant molecules. ✓

4.



Based on the resonance structures shown above, what are the bond orders of the two carbon-oxygen bonds?

- (A) 1 and 1.5
- (B) 1 and 2
- (C) 1.5 and 1.5 ✓
- (D) 2 and 2

5.

| Mass of<br><br>Solid | Mass of<br>Water | $\Delta T_{\text{water}}$ |
|----------------------|------------------|---------------------------|
| 1.0 g                | 2000.0 g         | + 2.1 °C                  |

A sample of a solid organic compound is completely combusted in a calorimeter. The heat generated by combustion is transferred to the water, causing the temperature of the water to increase. Based on the data in the table above, which of the following is the best estimate of the heat of combustion,  $\Delta H_{\text{comb}}$ , of the organic solid? (The specific heat of water is  $4.18 \text{ J/g}^\circ\text{C}$ .)

## 2021 Form I: MCQ

- (A)  $+18 \text{ kJ/g}$   
(B)  $+8.4 \text{ kJ/g}$   
(C)  $-8.4 \text{ kJ/g}$   
(D)  $-18 \text{ kJ/g}$



6.

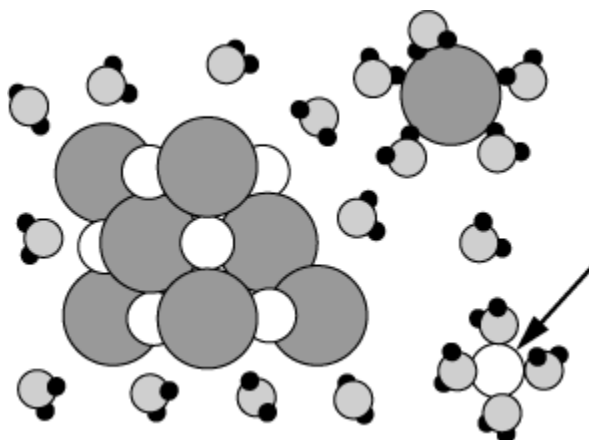
| Substance      | Specific Heat<br>( $\text{J}/(\text{g} \cdot ^\circ\text{C})$ ) | Mass of Sample<br>(g) |
|----------------|-----------------------------------------------------------------|-----------------------|
| $\text{Fe}(s)$ | 0.46                                                            | 1.0                   |
| $\text{Al}(s)$ | 0.91                                                            | 1.0                   |

Samples of Fe and Al are heated from  $25^\circ\text{C}$  to  $75^\circ\text{C}$ . Based on the information in the table above, the change in the average kinetic energy of the atoms in the samples is

- (A) higher for the Fe sample, because with its lower specific heat it absorbs more energy  
(B) higher for the Al sample, because with its higher specific heat it absorbs more energy  
(C) the same for both metal samples, because the initial and final temperatures are the same  
(D) the same for both metal samples, because the masses are equal



7.



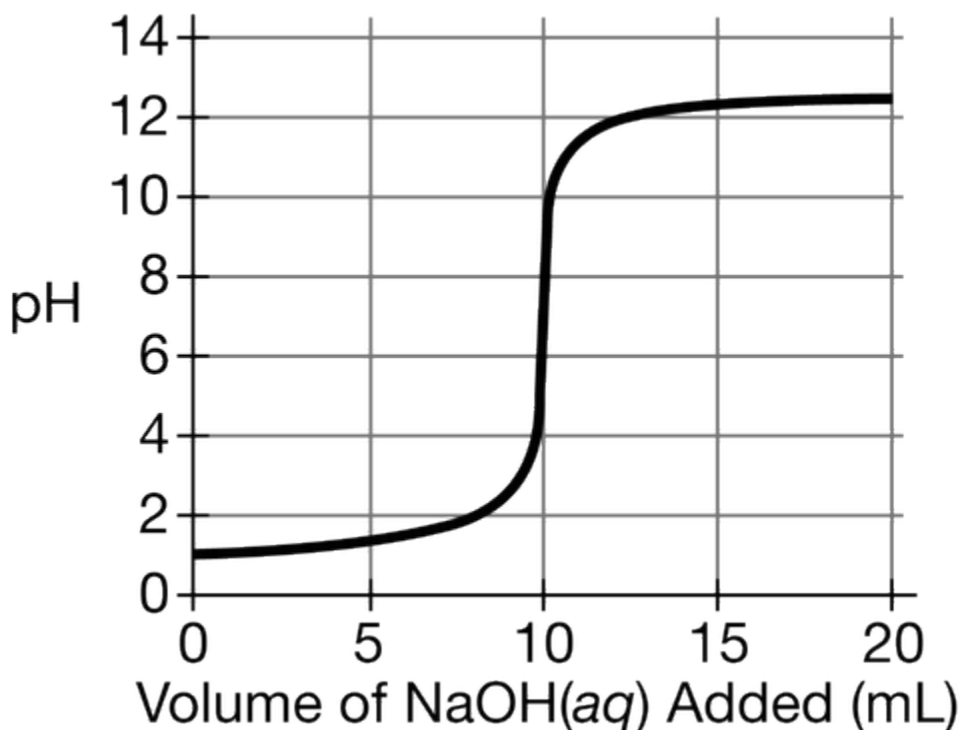
An ionic crystal is added to water and starts to dissolve as shown in the particulate representation above. Based on the orientation of the water molecules, what can be assumed about the charge of the hydrated particle indicated by the arrow?

- (A) The particle is positively charged, because the oxygen atoms in water are attracted to it.  
(B) The particle is negatively charged, because hydrogen atoms in water are attracted to it.  
(C) The particle is both positively and negatively charged, because the water molecules are attracted to it.  
(D) The particle is neutral, because the dipoles of the water molecules neutralize the charge of the particle.



## 2021 Form I: MCQ

8.



A 20.0 mL sample of a 0.125  $M$  monoprotic acid solution is titrated with a  $\text{NaOH}(aq)$  solution of unknown concentration. Based on the titration curve above, what is the molar concentration of the  $\text{NaOH}(aq)$  solution?

- (A) 0.063  $M$   
(B) 0.125  $M$   
(C) 0.250  $M$   
(D) 0.500  $M$



The ionization of cyanic acid,  $\text{HOCN}$ , is represented above. A certain solution of  $\text{HOCN}$  has a pH of 2.0. What is the approximate concentration of unionized  $\text{HOCN}(aq)$  in the solution?

- (A)  $3 \times 10^{-4} M$   
(B)  $1 \times 10^{-2} M$   
(C)  $3 \times 10^{-1} M$   
(D)  $2 \times 10^0 M$



10. Two solid reactants of varying particle size are combined in a vessel. Assuming that the same mass of each reactant is used in each case, which of the following represents the conditions that will result in the fastest reaction rate?

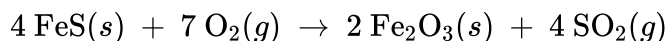
## 2021 Form I: MCQ

(A)   
Temperature = 950° C

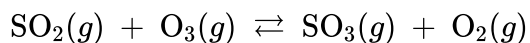
(B)   
Temperature = 500° C

(C)   
Temperature = 500° C

(D)   
Temperature = 950° C



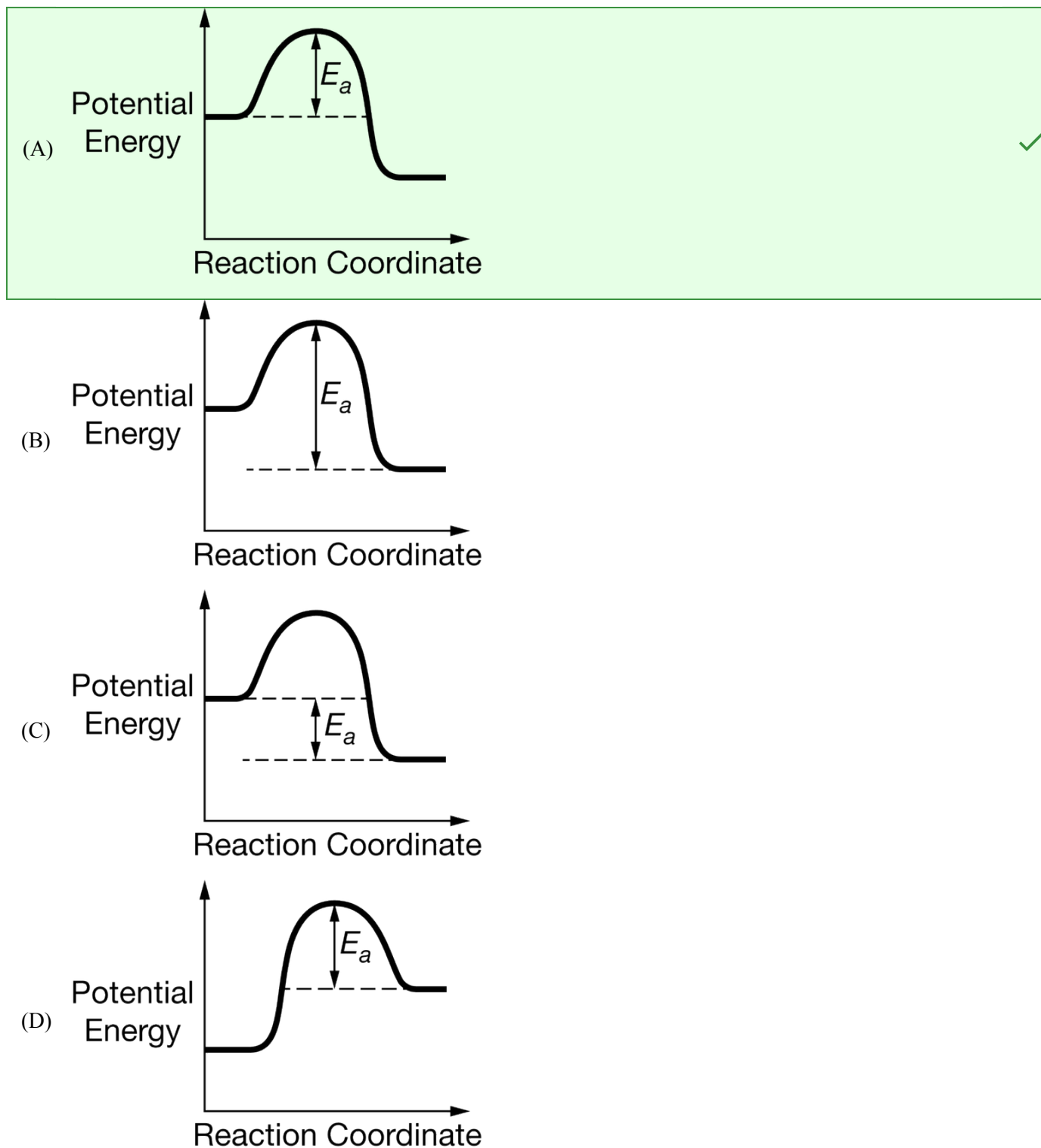
Due to the presence of  $\text{FeS}(s)$  as an impurity, the combustion of some types of coal results in the formation of  $\text{SO}_2(g)$ , as represented by the equation above. Also,  $\text{SO}_2(g)$  can react with  $\text{O}_3(g)$  to form  $\text{SO}_3(g)$ , as represented by the equation below.



$$\Delta H_{298}^\circ = -242 \text{ kJ/mol}_{rxn} ; \Delta S_{298}^\circ = -25 \text{ J/(K} \cdot \text{mol}_{rxn})$$

11. Which of the following diagrams shows the correctly labeled activation energy,  $E_a$ , for the reaction between  $\text{SO}_2(g)$  and  $\text{O}_3(g)$ ?

## 2021 Form I: MCQ



12. Which of the following statements is correct when 2.0 mol of  $\text{FeS}(s)$  reacts with 4.0 mol of  $\text{O}_2(g)$  ?

## 2021 Form I: MCQ

- (A)  $\text{O}_2(g)$  is the limiting reactant and 2.0 mol of  $\text{SO}_2(g)$  is formed.
- (B)  $\text{O}_2(g)$  is the limiting reactant and 4.0 mol of  $\text{SO}_2(g)$  is formed.
- (C)  $\text{FeS}(s)$  is the limiting reactant and 4.0 mol of  $\text{SO}_2(g)$  is formed.
- (D)  $\text{FeS}(s)$  is the limiting reactant and 0.5 mol of  $\text{O}_2(g)$  remains unreacted. ✓

13. Which of the following is most likely to be true about the reaction between  $\text{SO}_2(g)$  and  $\text{O}_3(g)$  at 298 K?

- (A)  $\Delta G^\circ < 0$  and  $T\Delta S^\circ$  is smaller in magnitude than  $\Delta H^\circ$ . ✓
- (B)  $\Delta G^\circ < 0$  and  $T\Delta S^\circ$  is larger in magnitude than  $\Delta H^\circ$ .
- (C)  $\Delta G^\circ > 0$  and  $T\Delta S^\circ$  is smaller in magnitude than  $\Delta H^\circ$ .
- (D)  $\Delta G^\circ > 0$  and  $T\Delta S^\circ$  is larger in magnitude than  $\Delta H^\circ$ .

14.

| Solution                              | $\text{p}K_a$ |
|---------------------------------------|---------------|
| $\text{HF}(aq)$                       | 3.17          |
| $\text{HC}_2\text{H}_3\text{O}_2(aq)$ | 4.74          |
| $\text{NH}_4^+(aq)$                   | 9.26          |

Based on the information in the table above, which of the following pairs of solutions can be used to create a buffer with a pH of 9.3? (Assume all solutions are 1.0 M.)

- (A) 100.0 mL of  $\text{HC}_2\text{H}_3\text{O}_2(aq)$  and 50.0 mL of  $\text{KOH}(aq)$
- (B) 50.0 mL of  $\text{HF}(aq)$  and 50.0 mL of  $\text{NaF}(aq)$
- (C) 100.0 mL of  $\text{NH}_3(aq)$  and 100.0 mL of  $\text{HCl}(aq)$
- (D) 50.0 mL of  $\text{NH}_3(aq)$  and 50.0 mL of  $\text{NH}_4\text{Cl}(aq)$  ✓

15.  $2 \text{H}_2\text{O}_2(aq) \rightarrow 2 \text{H}_2\text{O}(l) + \text{O}_2(g)$        $\Delta G^\circ = -234 \text{ kJ/mol}_{rxn}$

The value of  $\Delta G^\circ$  for the reaction represented above implies that the decomposition of  $\text{H}_2\text{O}_2(aq)$  is thermodynamically favorable. However,  $\text{H}_2\text{O}_2(aq)$  is typically stable for up to a year stored in a dark bottle at 298 K. The best explanation for this observation is that the decomposition reaction

- (A) is only thermodynamically favorable in the presence of a catalyst
- (B) occurs with an increase in entropy because  $\text{O}_2(g)$  is a product
- (C) is reversible and  $\text{H}_2\text{O}_2(aq)$  is produced almost as fast as it decomposes
- (D) has a slow rate at 298 K because the activation energy is relatively high ✓

16. The equilibrium constant for a reaction is greater than 1.0 at temperatures above 500 K but less than 1.0 at temperatures below 500 K. What can be concluded about the values of  $\Delta H^\circ$  and  $\Delta S^\circ$  for the reaction? (Assume that  $\Delta H^\circ$  and  $\Delta S^\circ$  are independent of temperature.)

## 2021 Form I: MCQ

(A)  $\Delta H^\circ > 0$  and  $\Delta S^\circ > 0$

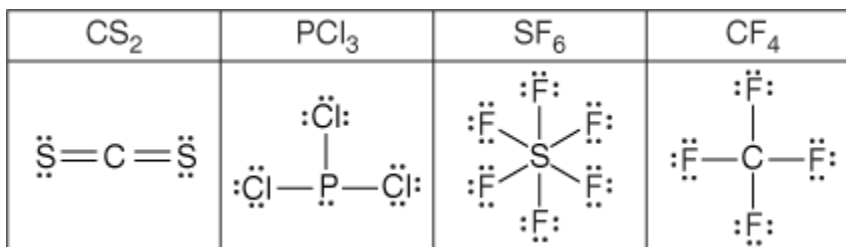


(B)  $\Delta H^\circ > 0$  and  $\Delta S^\circ < 0$

(C)  $\Delta H^\circ < 0$  and  $\Delta S^\circ > 0$

(D)  $\Delta H^\circ < 0$  and  $\Delta S^\circ < 0$

17.



Based on the diagrams shown above, which of the following would have the greatest dipole moment, and why?

(A) CS<sub>2</sub>, because the double bonds create an area of higher electron density around the C atom.

(B) PCl<sub>3</sub>, because the Cl atoms draw electron density away from the P atom and the bond dipoles do not cancel one another.

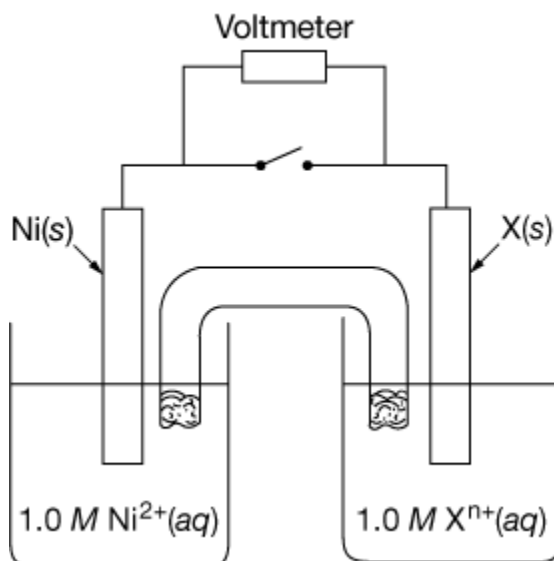


(C) SF<sub>6</sub>, because it has the greatest number of polar bonds.

(D) CF<sub>4</sub>, because the large electronegativity difference between C and F results in very polar bonds.

## 2021 Form I: MCQ

18.



In the galvanic cell shown above, the voltmeter connected across the electrodes shows a voltage of 0.52 V. Based on the standard reduction potentials given in the table below, which of the following is most likely the identity of the unknown element, X?

| Half-Reaction                                                       | $E^\circ$ (V) |
|---------------------------------------------------------------------|---------------|
| $\text{Rh}^{3+}(\text{aq}) + 3 e^- \rightarrow \text{Rh}(\text{s})$ | 0.76          |
| $\text{Bi}^{3+}(\text{aq}) + 3 e^- \rightarrow \text{Bi}(\text{s})$ | 0.31          |
| $\text{In}^+(\text{aq}) + e^- \rightarrow \text{In}(\text{s})$      | -0.14         |
| $\text{Ni}^{2+}(\text{aq}) + 2 e^- \rightarrow \text{Ni}(\text{s})$ | -0.24         |
| $\text{Zn}^{2+}(\text{aq}) + 2 e^- \rightarrow \text{Zn}(\text{s})$ | -0.76         |

- (A) Rh
- (B) Bi
- (C) In
- (D) Zn

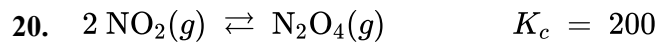


19. A 30. g sample of  $\text{Al}(\text{s})$  is heated to  $50^\circ\text{C}$  and placed in a calorimeter containing 150 g of water at  $20^\circ\text{C}$ . As the system approaches thermal equilibrium, energy is transferred

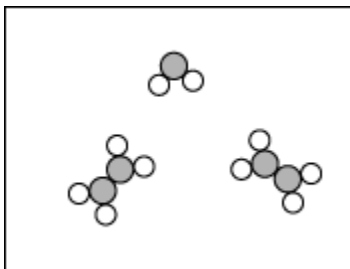
- (A) from the  $\text{Al}(\text{s})$  to the water and the temperature of the water decreases
- (B) from the  $\text{Al}(\text{s})$  to the water and the temperature of the  $\text{Al}(\text{s})$  decreases
- (C) from the water to the  $\text{Al}(\text{s})$  and the temperature of the water increases
- (D) from the water to the  $\text{Al}(\text{s})$  and the temperature of the  $\text{Al}(\text{s})$  increases



## 2021 Form I: MCQ



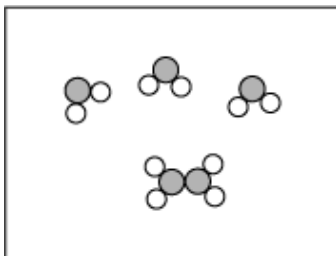
The equilibrium system shown above is represented in the diagram below in which each molecule represents one mole of the substance in a 100. L container at a constant temperature.



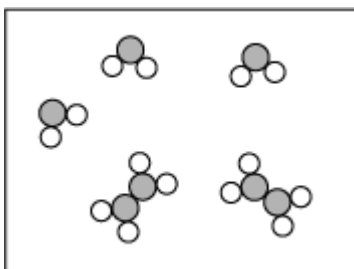
Additional  $\text{N}_2\text{O}_4(g)$  is added to the container and allowed to reestablish equilibrium. Which of the following best represents the system after the equilibrium has been reestablished?

## 2021 Form I: MCQ

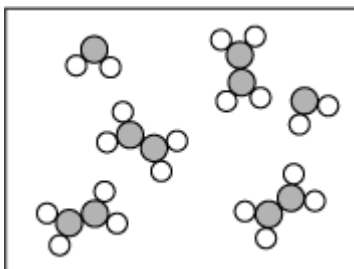
(A)



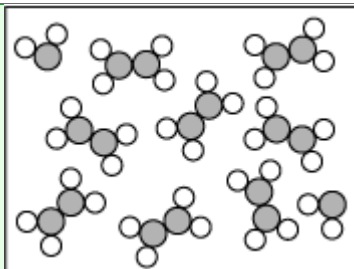
(B)



(C)



(D)



21.

| Compound | Melting Point |
|----------|---------------|
|          | (°C)          |
| MgO      | 2852          |
| NaF      | 993           |

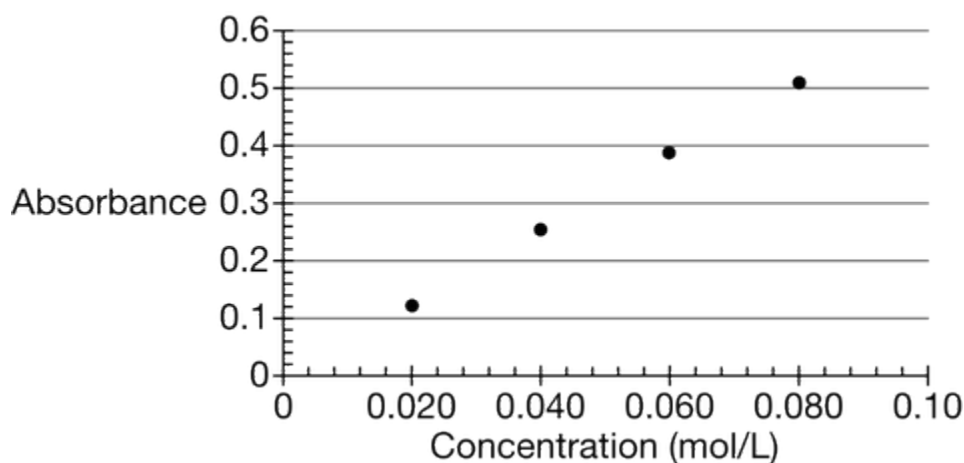
The table above shows the melting points of  $\text{MgO}(s)$  and  $\text{NaF}(s)$ . Which of the following best helps explain why the melting point of  $\text{MgO}(s)$  is much higher than that of  $\text{NaF}(s)$ ?

## 2021 Form I: MCQ

- (A) The mass of  $\text{F}^-$  ions is greater than that of  $\text{O}^{2-}$  ions.
- (B) The mass of  $\text{Mg}^{2+}$  ions is greater than that of  $\text{Na}^+$  ions.
- (C) The difference between the electronegativity values of Mg and O is smaller than the difference between the values of Na and F.
- (D) The charges of  $\text{Mg}^{2+}$  and  $\text{O}^{2-}$  ions are greater than those of  $\text{Na}^+$  and  $\text{F}^-$  ions. ✓

An experiment was performed to investigate the reaction between Zn metal and  $\text{Ni}^{2+}(\text{aq})$  at different concentrations. Because the  $\text{Ni}^{2+}(\text{aq})$  ion is green, the extent of the reaction was determined using spectrophotometric analysis. Four 20.0 mL standard solutions of  $\text{Ni}^{2+}(\text{aq})$  were prepared by dissolving  $\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$  (molar mass 240 g/mol) in water. The absorbance of each solution was measured; the results are shown both in the table below and in the following plot of the absorbance data.

| Solution | $[\text{Ni}^{2+}]$ | Absorbance |
|----------|--------------------|------------|
| 1        | 0.020              | 0.12       |
| 2        | 0.040              | 0.25       |
| 3        | 0.060              | 0.39       |
| 4        | 0.080              | 0.51       |



22. The concentration of  $\text{Cl}^- (\text{aq})$  ions in solution 2 was

- (A) 0.020 M
- (B) 0.040 M
- (C) 0.060 M
- (D) 0.080 M ✓

24. What is the expected absorbance of a standard solution made by dissolving 0.0070 mol of  $\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$  in water to make 100. mL of solution?

## 2021 Form I: MCQ

- (A) 0.0039  
(B) 0.0080  
(C) 0.045

(D) 0.45



25. Which species is being oxidized in the reaction between Zn metal and  $\text{NiCl}_2(aq)$  ?

(A) Zn

(B)  $\text{Zn}^{2+}$

(C) Ni

(D)  $\text{Ni}^{2+}$



23. Which of the following equations best represents the reacting species in the reaction between Zn metal and  $\text{NiCl}_2(aq)$  ?

(A)  $\text{Zn}(s) + \text{NiCl}_2(aq) \rightarrow \text{Zn}^{2+}(aq) + \text{Ni}(s) + 2 \text{Cl}^-(aq)$

(B)  $\text{Zn}(s) + \text{NiCl}_2(aq) \rightarrow \text{ZnCl}_2(aq) + \text{Ni}^{2+}(aq)$

(C)  $\text{Zn}^{2+}(aq) + \text{Ni}(s) \rightarrow \text{Zn}(s) + \text{Ni}^{2+}(aq)$

(D)  $\text{Zn}(s) + \text{Ni}^{2+}(aq) \rightarrow \text{Zn}^{2+}(aq) + \text{Ni}(s)$



26. A sample of a pure compound is analyzed and found to contain approximately 30 percent N and 70 percent O by mass. The formula for the compound could be

(A) NO

(B)  $\text{NO}_2$

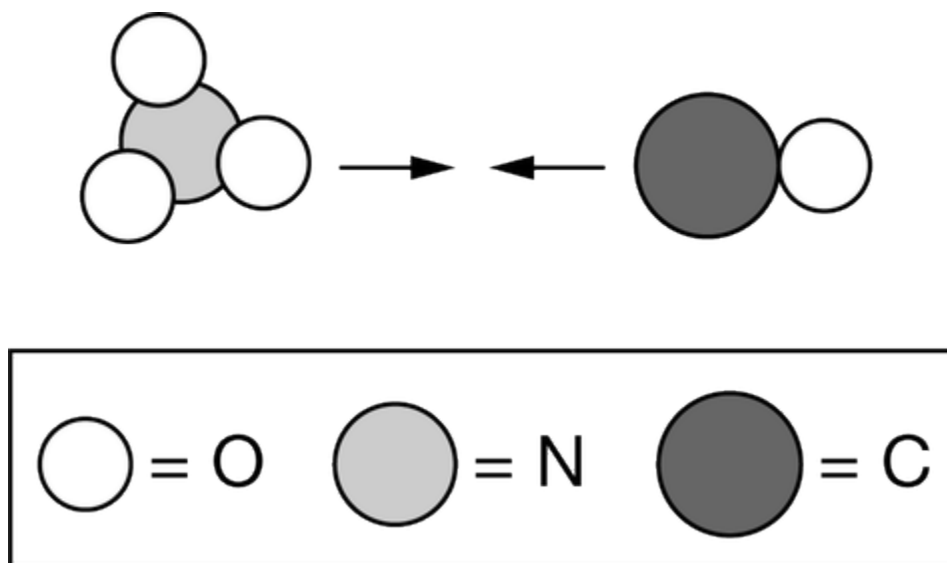
(C)  $\text{N}_2\text{O}$

(D)  $\text{N}_2\text{O}_2$



## 2021 Form I: MCQ

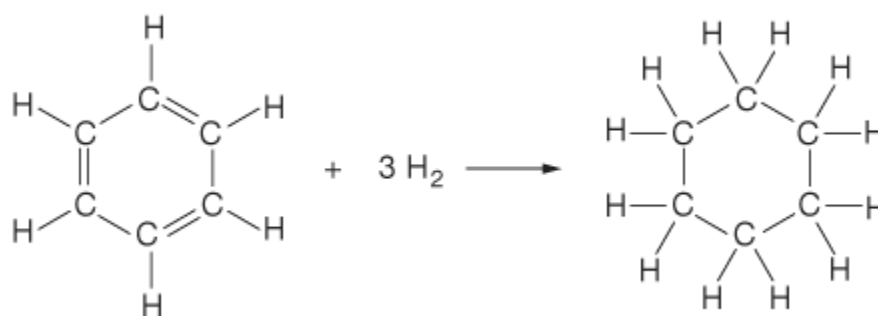
27.



The slowest step in a reaction mechanism requires the collision represented above to occur. Which of the following most likely indicates how the addition of a solid catalyst could increase the rate of the reaction?

- (A) The catalyst could change the reaction from second order to third order.
- (B) The catalyst could increase the particles' speed, thereby increasing the value of the rate constant,  $k$ .
- (C) The catalyst could decrease the particles' speed, making it less likely that the particles will rebound without reacting when they collide.
- (D) The catalyst could adsorb one of the particles, making a successful (reaction-producing) collision with the other particle more likely. ✓

28.



In the reaction represented above, which of the following sets correctly identifies the hybridization of the C atoms before and after the reaction occurs?

Set

Before

After

## 2021 Form I: MCQ

 $sp^2\ sp^2$ 

A

 $sp^2\ sp^3$ 

B

 $sp^3\ sp^2$ 

C

 $sp^3\ sp^3$ 

D

(A) Set A

(B) Set B

(C) Set C

(D) Set D

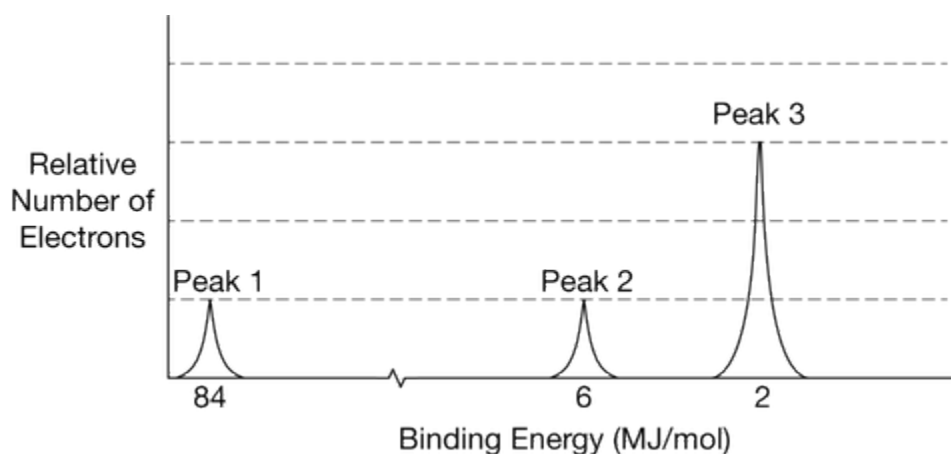
29. A student finds the mass of a pure sample of a metal chloride hydrate. The student heats the sample several times, reaching a constant mass that contains 0.100 mole of anhydrous metal chloride. Which of the following questions about the hydrated metal chloride substance is most likely to be answered by the results of the experiment?

(A) How many moles of water are in one mole of the substance?

(B) How many moles of the metal cation are in one mole of the substance?

(C) What is the identity of the metal cation in the formula of the substance?

(D) What is the melting point of the substance?



The complete photoelectron spectrum of a pure element is shown in the diagram above.

30. According to the complete photoelectron spectrum, which of the following is the identity of the element?

## 2021 Form I: MCQ

- (A) Be
- (B) C
- (C) O

(D) Ne



31. If peaks 1 and 2 represent  $s$  sublevels, which of the following sublevels is represented by peak 3?

(A)  $s$

(B)  $p$

(C)  $d$

(D)  $f$



32. In an experiment to estimate the enthalpy change of a reaction, a student makes two aqueous solutions, each containing one of the reactants. The student combines the solutions, both originally at the same temperature, in a calorimeter and records the final temperature of the mixture. In addition to the masses of the solutions and the temperature change of the mixture, which of the following pieces of information does the student need to calculate the enthalpy change of the reaction?

(A) The density of the reaction mixture

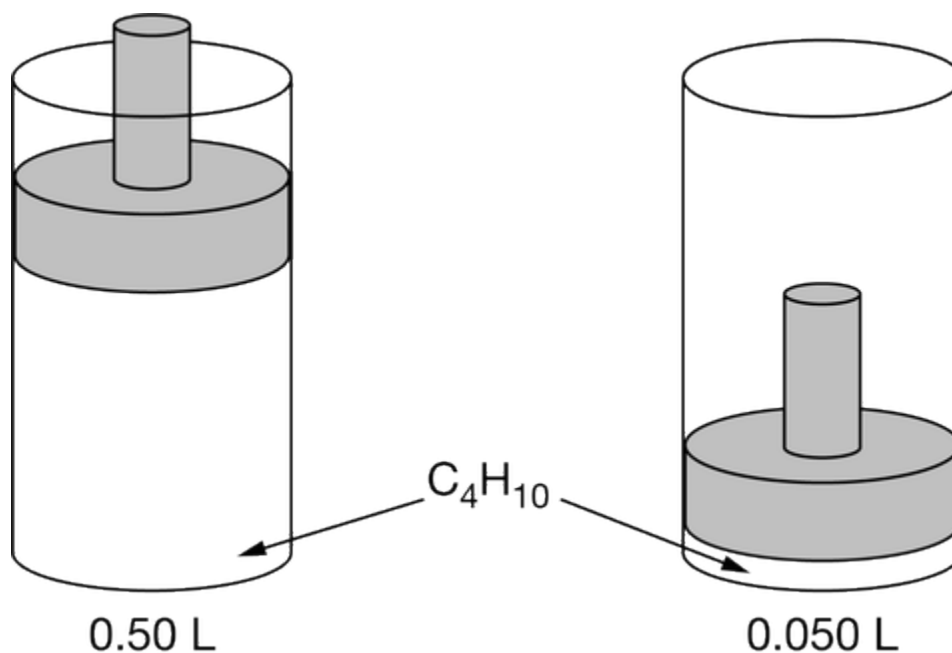
(B) The specific heat capacity of the reaction mixture

(C) The boiling point of the reaction mixture

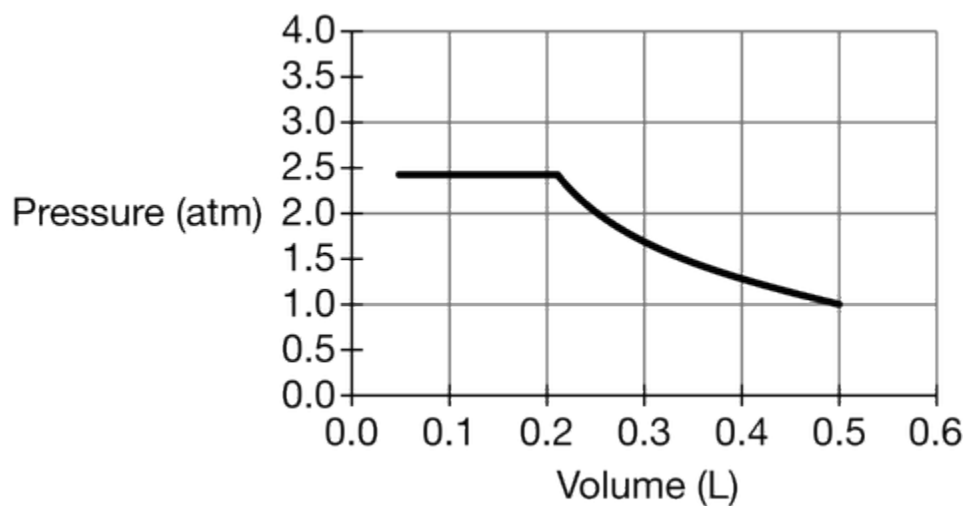
(D) The heat of fusion of the reaction mixture



## 2021 Form I: MCQ



A sample of  $\text{C}_4\text{H}_{10}(g)$  is placed in a rigid vessel with a movable piston. The volume of the gas is reduced by moving the piston downward while the temperature is maintained at  $25^\circ\text{C}$ , as shown above. The pressure of the gas versus its volume is plotted in the graph below.

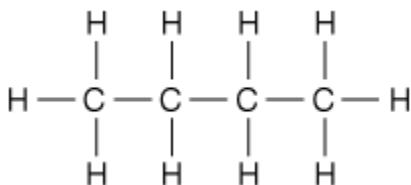


33. Which of the following best explains the increase in pressure of the  $\text{C}_4\text{H}_{10}(g)$  when its volume is decreased from 0.50 L to 0.21 L?

## 2021 Form I: MCQ

- (A) The molecules strike the walls of the vessel more frequently. ✓
- (B) The molecules strike the walls of the vessel with different orientations.
- (C) The molecules strike the walls of the vessel with greater force.
- (D) The molecules decompose to produce a greater number of particles.

34.



The Lewis electron-dot diagram for  $\text{C}_4\text{H}_{10}$  is shown above. Which of the following is the predominant type of intermolecular force among  $\text{C}_4\text{H}_{10}$  molecules?

- (A) Hydrogen bonding
- (B) London dispersion forces ✓
- (C) Dipole-dipole attractions
- (D) Dipole-induced dipole attractions

35. Which of the following best accounts for the pressure in the vessel remaining constant as the volume decreases below 0.21 L?

- (A) The density of the  $\text{C}_4\text{H}_{10}(g)$  increases.
- (B) The surface area of the interior of the vessel decreases.
- (C) The temperature of the  $\text{C}_4\text{H}_{10}(g)$  decreases.

(D) Some  $\text{C}_4\text{H}_{10}(g)$  condenses to form  $\text{C}_4\text{H}_{10}(l)$ . ✓

36. Which of the following substances has bonds with the greatest ionic character?

- (A)  $\text{CCl}_4$
- (B)  $\text{CuCl}_2$
- (C)  $\text{CaCl}_2$  ✓
- (D)  $\text{NCl}_3$

## 2021 Form I: MCQ

37.

|                                       |                             |
|---------------------------------------|-----------------------------|
| $\text{HOCl}(aq)$                     | $K_a = 3.0 \times 10^{-8}$  |
| $\text{HC}_2\text{H}_3\text{O}_2(aq)$ | $K_a = 1.8 \times 10^{-5}$  |
| $\text{NH}_3(aq)$                     | $K_b = 1.8 \times 10^{-5}$  |
| $\text{C}_6\text{H}_5\text{NH}_2(aq)$ | $K_b = 3.8 \times 10^{-10}$ |

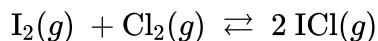
The  $K_a$  or  $K_b$  values of some weak acids and bases are listed in the table above. Which of the following solutions has the highest pH?

- (A) 0.1 M  $\text{HOCl}(aq)$   
(B) 0.1 M  $\text{HC}_2\text{H}_3\text{O}_2(aq)$   
(C) 0.1 M  $\text{NH}_3(aq)$   
(D) 0.1 M  $\text{C}_6\text{H}_5\text{NH}_2(aq)$



38.  $\text{ICl}(g) \rightleftharpoons \frac{1}{2} \text{I}_2(g) + \frac{1}{2} \text{Cl}_2(g) \quad K_{eq} = 0.1$

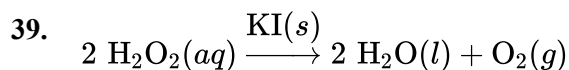
Based on the information above, what is the value of  $K_{eq}$  for the reaction represented below?



- (A) 0.01  
(B) 10  
(C) 20  
(D) 100

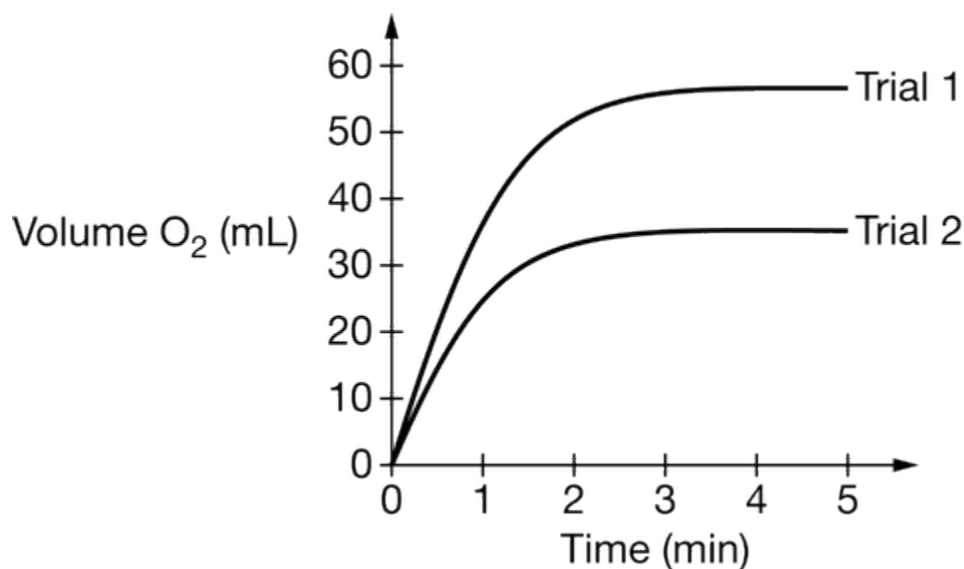


## 2021 Form I: MCQ



$$\text{Rate} = k[\text{H}_2\text{O}_2]$$

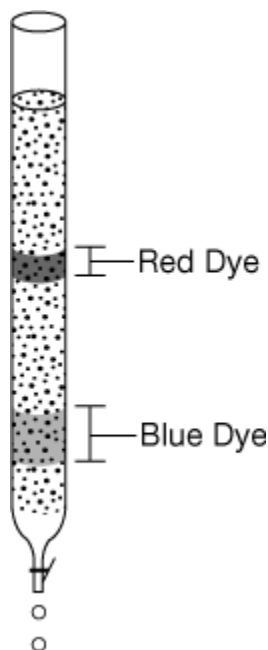
A student performed an experiment to study the factors that affect the rate of the first-order catalytic decomposition of  $\text{H}_2\text{O}_2(aq)$ , represented above.



The student monitored the volume of  $\text{O}_2(g)$  produced over time as the reaction proceeded. The data from two trials are plotted in the graph above. Which of the following best explains the results of trial 2 compared with those of trial 1?

- (A) The reaction temperature in trial 2 was higher than it was in trial 1.
- (B) The volume of the reaction vessel was larger in trial 2 than it was in trial 1.
- (C) The student used a smaller amount of  $\text{KI}(s)$  in trial 2 compared with that used in trial 1.
- (D) The concentration of  $\text{H}_2\text{O}_2(aq)$  was lower in trial 2 than it was in trial 1. ✓

## 2021 Form I: MCQ



A student placed a sample of a food coloring that contains a mixture of a blue dye and a red dye at the top of a chromatography column filled with a nonpolar stationary phase. When water is poured through the column, two bands of colors are seen in the column, as shown in the diagram above.

40. Which of the following techniques would be best to investigate molecular vibrations in molecules of the red dye?

(A) Infrared spectroscopy



(B) UV / vis spectroscopy

(C) Mass spectrometry

(D) Gravimetric analysis

41. A student collects a sample of the blue dye from the column in a cuvette. Which of the following is least useful to determine the concentration of the sample using a spectrophotometer set at 640 nm?

(A) The volume of the sample



(B) The path length of the cuvette

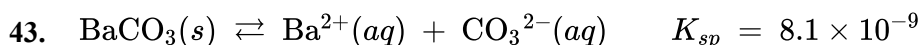
(C) The absorbance of the dye at 640 nm

(D) The molar absorptivity of the dye at 640 nm

42. Which of the following will most likely be observed if  $\text{CH}_3\text{OH}(l)$  is used in the column instead of water? (Assume that both solvents flow through the column at the same rate.)

## 2021 Form I: MCQ

- (A) The dyes will not pass through the column because  $\text{CH}_3\text{OH}(l)$  is a nonpolar solvent.
- (B) The dyes will pass through the column at a slower rate because  $\text{CH}_3\text{OH}(l)$  is a less polar solvent than water. ✓
- (C) The dyes will pass through the column at a faster rate because  $\text{CH}_3\text{OH}(l)$  has a greater molar mass than water.
- (D) No differences will be observed because the polarity of the solvent does not affect the separation of the dyes.



The dissolution of  $\text{BaCO}_3(s)$  in water is represented above. A 20.0 mL sample of  $1.0 \times 10^{-4} M \text{Ba}(\text{NO}_3)_2(aq)$  is mixed with an 80.0 mL sample of  $1.0 \times 10^{-4} M \text{Na}_2\text{CO}_3(aq)$ . Which of the following correctly predicts and explains the outcome?

- (A) A precipitate will form, because  $Q = 1.0 \times 10^{-8}$ .
- (B) A precipitate will form, because  $Q = 1.6 \times 10^{-9}$ .
- (C) A precipitate will not form, because  $Q = 1.0 \times 10^{-8}$ .
- (D) A precipitate will not form, because  $Q = 1.6 \times 10^{-9}$ . ✓

44.

| Compound           | $[\text{Pb}^{2+}]$ in Saturated Solution |
|--------------------|------------------------------------------|
| PbS                | $1.7 \times 10^{-14} M$                  |
| PbCO <sub>3</sub>  | $2.7 \times 10^{-7} M$                   |
| PbCrO <sub>4</sub> | $5.5 \times 10^{-7} M$                   |
| PbSO <sub>4</sub>  | $1.6 \times 10^{-4} M$                   |

Based on  $[\text{Pb}^{2+}]$  in saturated solutions of the compounds listed in the table above, which of the compounds has the smallest  $K_{sp}$  value?

- (A) PbS ✓

- (B) PbCO<sub>3</sub>
- (C) PbCrO<sub>4</sub>
- (D) PbSO<sub>4</sub>

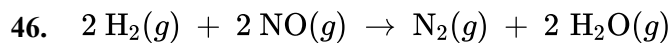
45.

|               |    |              |                  |
|---------------|----|--------------|------------------|
| $\text{Cl}^-$ | Ar | $\text{K}^+$ | $\text{Ca}^{2+}$ |
|---------------|----|--------------|------------------|

The four species above have the same electron configuration,  $1s^2 2s^2 2p^6 3s^2 3p^6$ . Which of the following statements correctly identifies the species with the largest radius and provides an explanation based on Coulomb's law?

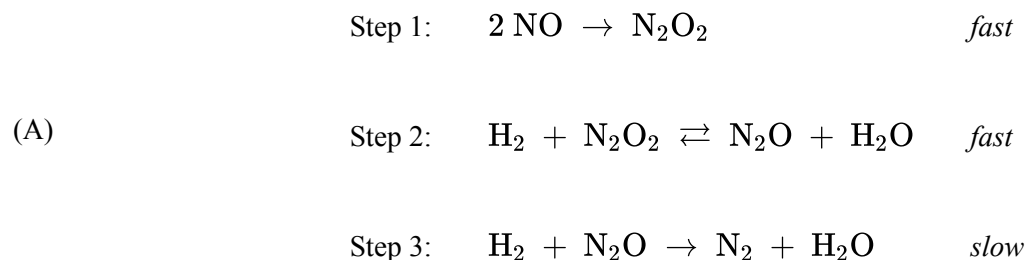
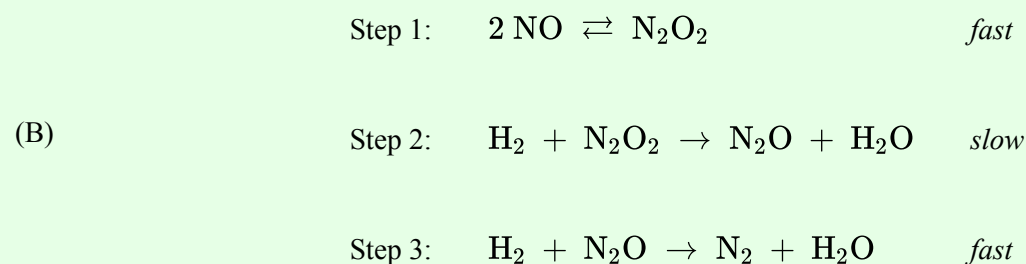
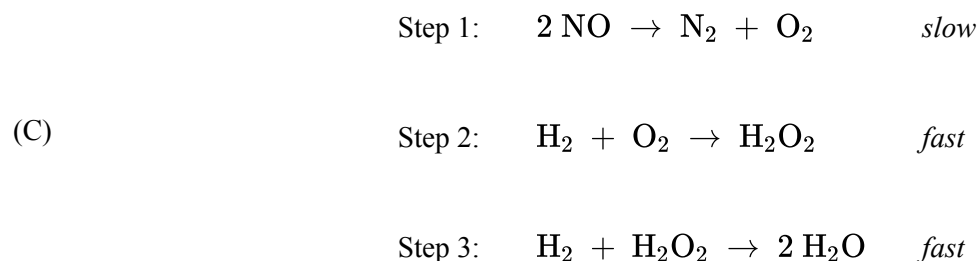
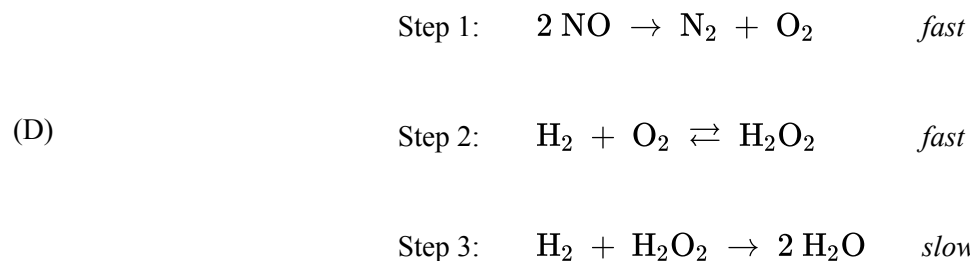
## 2021 Form I: MCQ

- (A)  $\text{Cl}^-$ , because its nuclear charge exerts the least attractive force on the electrons in the  $3p$  sublevel. ✓
- (B)  $\text{Ar}$ , because it is a neutral atom and the net force on the electrons in the  $3p$  sublevel is zero.
- (C)  $\text{K}^+$ , because the loss of an electron results in a smaller attractive force between the nucleus and the electrons in the  $3p$  sublevel.
- (D)  $\text{Ca}^{2+}$ , because the large positive charge on a cation causes increased repulsion among the electrons in the  $3p$  sublevel.

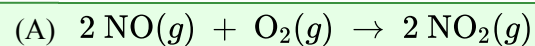
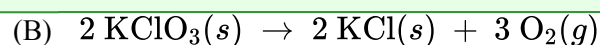
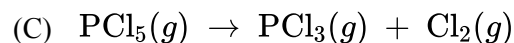
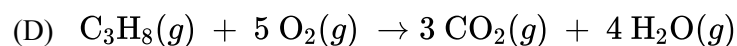


The experimental rate law for the reaction represented above is  $\text{rate} = k[\text{H}_2][\text{NO}]^2$ . Which of the following proposed mechanisms is consistent with the rate law?

## 2021 Form I: MCQ



47. Which of the following equations represents a reaction with a negative  $\Delta S^\circ$  ?



## 2021 Form I: MCQ



At a certain time, the partial pressure of the gases in the reaction mixture represented above had the values shown in the table below.

| $P_{\text{CO}}$ | $P_{\text{H}_2}$ | $P_{\text{CH}_4}$ | $P_{\text{H}_2\text{O}}$ |
|-----------------|------------------|-------------------|--------------------------|
| 0.02 atm        | 1.0 atm          | 0.4 atm           | 0.4 atm                  |

Based on the information above, which of the following occurred as the reaction mixture moved toward equilibrium?

- (A) More  $\text{CH}_4(g)$  was produced because the rate of the forward reaction was higher than the rate of the reverse reaction. ✓
- (B) More  $\text{H}_2(g)$  was produced because the rate of the reverse reaction was higher than the rate of the forward reaction.
- (C) More  $\text{CH}_4(g)$  was produced because the total pressure of the  $\text{H}_2(g)$  and  $\text{CO}(g)$  combined was higher than that of the products; thus the reaction shifted to the side with the fewest number of moles of gas.
- (D) More  $\text{H}_2(g)$  was produced because the pressure of  $\text{CO}(g)$  was the least and the reaction shifted to the side with the smaller number of moles of gas.
49.  $\text{CCl}_4(g)$  deviates more from ideal gas behavior than  $\text{CH}_4(g)$  does. Which of the following statements best explains this observation?
- (A) The mass of the  $\text{CCl}_4$  molecule is greater than that of the  $\text{CH}_4$  molecule.
- (B) The bond energy of the C-Cl bond is greater than that of the C-H bond.
- (C) The dipole-dipole forces between  $\text{CCl}_4$  molecules are greater than those between  $\text{CH}_4$  molecules.
- (D) The London dispersion forces between  $\text{CCl}_4$  molecules are stronger than those between  $\text{CH}_4$  molecules. ✓

## 2021 Form I: MCQ

| Compound | Structure                                                                                                                                                                                                                                                                                           | Boiling Point (°C) |
|----------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|
| Methanol | $\begin{array}{c} \text{H} \\   \\ \text{H}-\text{C}-\ddot{\text{O}}-\text{H} \\   \\ \text{H} \end{array}$                                                                                                                                                                                         | 65                 |
| Ethanol  | $\begin{array}{c} \text{H} \quad \text{H} \\   \quad   \\ \text{H}-\text{C}-\text{C}-\ddot{\text{O}}-\text{H} \\   \quad   \\ \text{H} \quad \text{H} \end{array}$                                                                                                                                  | 78                 |
| Propanal | $\begin{array}{c} \text{H} \quad \text{H} \quad \text{:O:} \\   \quad   \quad // \\ \text{H}-\text{C}-\text{C}-\text{C} \\   \quad   \quad \backslash \\ \text{H} \quad \text{H} \quad \text{H} \end{array}$                                                                                        | 49                 |
| Hexane   | $\begin{array}{cccccc} \text{H} & \text{H} & \text{H} & \text{H} & \text{H} & \text{H} \\   &   &   &   &   &   \\ \text{H}-\text{C}-\text{C}-\text{C}-\text{C}-\text{C}-\text{C}-\text{H} \\   &   &   &   &   &   \\ \text{H} & \text{H} & \text{H} & \text{H} & \text{H} & \text{H} \end{array}$ | 69                 |

50. A 50 mL sample of  $\text{C}_6\text{H}_{14}(l)$  is mixed with a 50 mL sample of  $\text{H}_2\text{O}(l)$ , and the mixture is shaken vigorously. The two liquids do not stay mixed but instead form two separate layers. The density of hexane is 0.66 g/mL, and the density of water is 1.00 g/mL. A 1.0 g sample of  $\text{I}_2(s)$  is added to the mixture, which is shaken again. Which of the following best predicts what happens to the  $\text{I}_2(s)$ ?
- (A)  $\text{I}_2$  will be found mainly in the top layer because it will dissolve more in the  $\text{H}_2\text{O}(l)$ .
- (B)  $\text{I}_2$  will be found mainly in the bottom layer because it will dissolve more in the  $\text{H}_2\text{O}(l)$ .
- (C)  $\text{I}_2$  will be found mainly in the top layer because it will dissolve more in the  $\text{C}_6\text{H}_{14}(l)$ . ✓
- (D)  $\text{I}_2$  will be found mainly in the bottom layer because it will dissolve more in the  $\text{C}_6\text{H}_{14}(l)$ .
51. When a 50. mL sample of  $\text{C}_2\text{H}_5\text{OH}$  is mixed with a 50. mL sample of  $\text{H}_2\text{O}$ , the resulting mixture has a volume of 95 mL, and the container is warm to the touch. Which of the following best describes these observations?
- (A) A chemical reaction occurs, as evidenced by the volume of the resultant mixture being less than the total volume of the initial components.
- (B) A chemical change occurs, as evidenced by the formation of new covalent bonds releasing more energy than is absorbed by the breaking of the existing covalent bonds.
- (C) A physical change occurs, and the solvation process is exothermic. ✓
- (D) A physical change occurs, and the solvation process is endothermic.
52. Which of the following best helps to explain why hexane has a higher boiling point than methanol has?

## 2021 Form I: MCQ

- (A) Methanol molecules can form hydrogen bonds with other methanol molecules.
- (B) Hexane cannot form hydrogen bonds with other hexane molecules.
- (C) Methanol molecules have attractions to one another due to London dispersion forces.

(D) Hexane molecules have electron clouds that are larger than those of methanol molecules. ✓

53. A 0.08 *M* solution of  $\text{CH}_3\text{COOH}$  ( $\text{p}K_a = 4.74$ ) is titrated with 0.10 *M*  $\text{NaOH}(aq)$ . What is the pH at the equivalence point of the titration and why?

- (A)  $\text{pH} < 7$ , because  $\text{NaOH}(aq)$  is a strong base.
- (B)  $\text{pH} = 7$ , because the titration reaction is a neutralization reaction.

(C)  $\text{pH} > 7$ , because  $\text{CH}_3\text{COO}^-(aq)$  is a weak base. ✓

(D)  $\text{pH} > 7$ , because the concentration of  $\text{NaOH}(aq)$  is greater than that of  $\text{CH}_3\text{COOH}(aq)$ .

54. 
$$\underset{\text{pink}}{[\text{Co}(\text{H}_2\text{O})_6]^{2+}} + 4 \text{Cl}^- \rightleftharpoons \underset{\text{blue}}{[\text{CoCl}_4]^{2-}} + 6 \text{H}_2\text{O}(l)$$

The solvent in the nonaqueous system represented above is 2-propanol. If a small amount of water is added to the system, how will the color of the solution be affected, and why?

(A) The solution will become more pink because more  $[\text{Co}(\text{H}_2\text{O})_6]^{2+}$  will be produced. ✓

- (B) The solution will become more pink because the pH of the solution will increase.
- (C) The solution will become more blue because more  $[\text{CoCl}_4]^{2-}$  will be produced.
- (D) The solution will become more blue because the pH of the solution will decrease.

55.

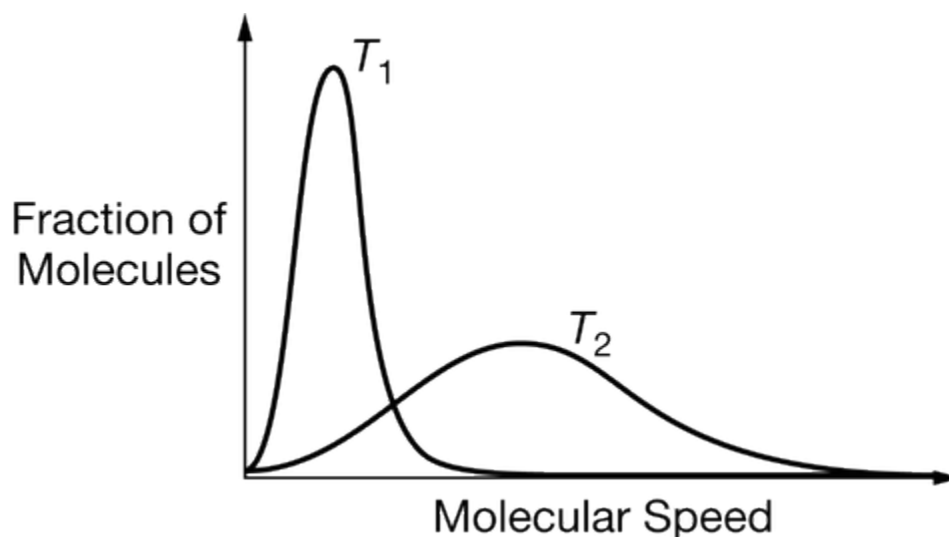
| Element | Second Ionization Energy |
|---------|--------------------------|
|         | (kJ/mol)                 |
| Li      | 7300                     |
| Na      | 4560                     |
| K       | 3050                     |
| Rb      | 2630                     |

The decrease in the second ionization energy of alkali metals going down the group, as shown in the table above, can be best attributed to a decrease in the coulombic force of attraction due to

## 2021 Form I: MCQ

- (A) the removal of core electrons  
(B) an increase in effective nuclear charge  
(C) an increase in the average distance of the outermost electron from the nucleus ✓  
(D) a decrease in electron-electron repulsion within the outermost shell

56.

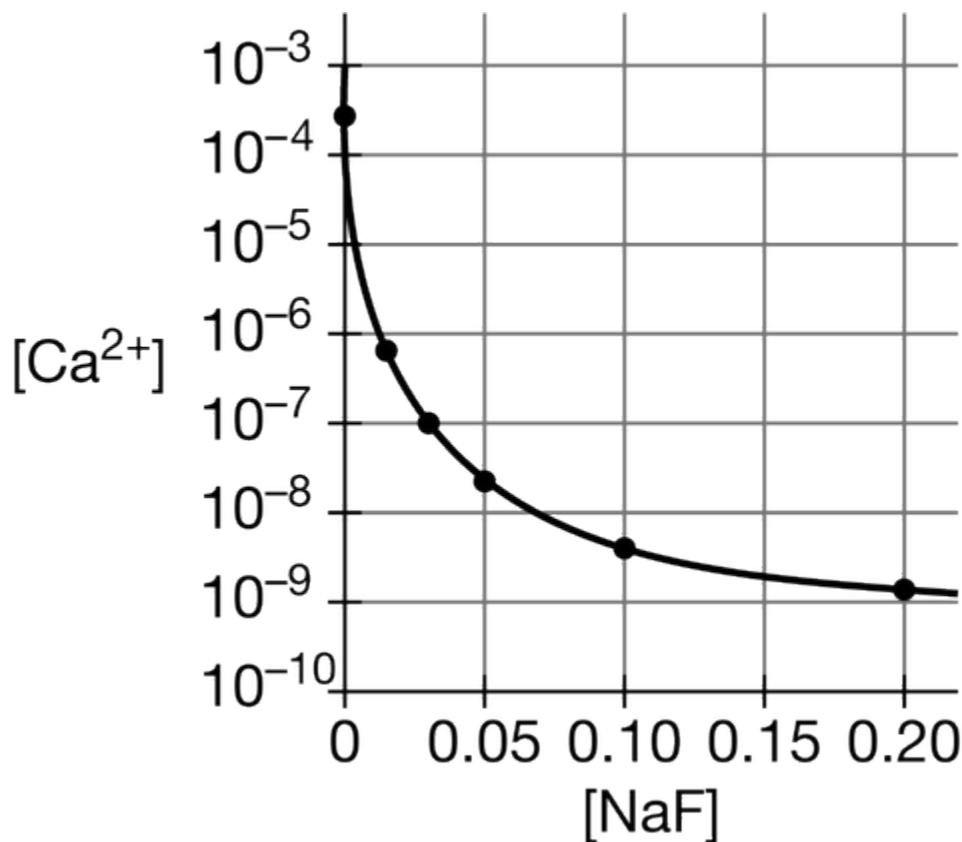


The diagram above shows the distribution of molecular speed in a sample of gas at two different temperatures,  $T_1$  and  $T_2$ . Which of the following is a correct interpretation of the information provided by the diagram?

- (A) The average speed of the molecules is greater at  $T_1$  than at  $T_2$ .  
(B) The taller peak corresponds to the higher temperature,  $T_1$ .  
(C) There are fewer molecules of gas at  $T_2$  than at  $T_1$ .  
(D) The average kinetic energy of the molecules is greater at  $T_2$  than at  $T_1$ . ✓

## 2021 Form I: MCQ

57.



Which of the following statements best explains the trend in the molar solubility of  $\text{CaF}_2(s)$  in various concentrations of  $\text{NaF}(aq)$  shown in the graph above?

- (A) Higher concentrations of  $\text{F}^-(aq)$  allow less  $\text{CaF}_2(s)$  to dissolve before the solution becomes saturated. ✓
- (B) Higher concentrations of  $\text{Na}^+(aq)$  lead to more favorable attractions between  $\text{Na}^+(aq)$  ions and  $\text{F}^-(aq)$  ions, thus less  $\text{CaF}_2(s)$  dissolves.
- (C) Higher concentrations of  $\text{F}^-(aq)$  produce more  $\text{OH}^-(aq)$  through hydrolysis, causing  $\text{Ca}(\text{OH})_2(s)$  to precipitate, thus more  $\text{CaF}_2(s)$  dissolves.
- (D) Higher concentrations of  $\text{F}^-(aq)$  cause the formation of the  $\text{CaF}_4^{2-}(aq)$  complex ion, which allows more  $\text{CaF}_2(s)$  to dissolve.

## 2021 Form I: MCQ

58.

| Acid | Structure                                    |
|------|----------------------------------------------|
| HClO | $\text{H}-\ddot{\text{O}}-\ddot{\text{Cl}}:$ |
| HBrO | $\text{H}-\ddot{\text{O}}-\ddot{\text{Br}}:$ |
| HIO  | $\text{H}-\ddot{\text{O}}-\ddot{\text{I}}:$  |

A 0.1 *M* aqueous solution of which of the acids shown in the table above would have a pH closest to 7.0, and why?

- (A) HClO, because Cl has the highest electronegativity.
- (B) HBrO, because Br has the lowest electronegativity.
- (C) HIO, because I has the lowest electronegativity. ✓
- (D) All three solutions will have the same pH because they are all monoprotic acids.

59. The value of  $K_w$  at 37°C is  $2.4 \times 10^{-14}$ . Which of the following statements about the pH and pOH of pure water at 37°C is correct?

- (A)  $\text{pH} < 7$  and  $\text{pOH} > 7$  because water dissociates to a lesser extent at 37°C than at 25°C.
- (B)  $\text{pH} > 7$  and  $\text{pOH} < 7$  because the dissociation of water is endothermic, and  $\text{pH} + \text{pOH} = 14$ .
- (C)  $\text{pH} = \text{pOH} < 7$  because water dissociates to a greater extent at 37°C than at 25°C. ✓
- (D)  $\text{pH} = \text{pOH} = 7$  because  $[\text{H}_3\text{O}^+] = [\text{OH}^-]$  for pure water.

60.  $\text{NH}_3(aq) + \text{CH}_3\text{NH}_3^+(aq) \rightleftharpoons \text{NH}_4^+(aq) + \text{CH}_3\text{NH}_2(aq) \quad K_{eq} = 0.041$

Which of the following species is the strongest base in the reaction represented above?

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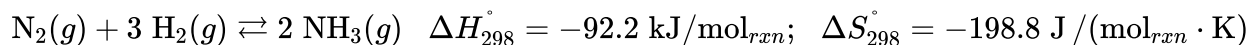
- (A)  $\text{NH}_3(aq)$   
(B)  $\text{CH}_3\text{NH}_3^+(aq)$   
(C)  $\text{NH}_4^+(aq)$   
(D)  $\text{CH}_3\text{NH}_2(aq)$



## 2021 Form I: FRQ

1. For parts of the free response question that require 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. Examples and equations may be included in your answers where appropriate.

Answer the following questions related to  $\text{NH}_3$ .



(a) The reaction of  $\text{N}_2(g)$  and  $\text{H}_2(g)$  to form  $\text{NH}_3(g)$  is represented above. The reaction has been studied in order to maximize the yield of  $\text{NH}_3(g)$ .

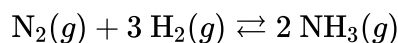
- (i) Calculate the value of  $\Delta G^\circ$ , in  $\text{kJ/mol}_{rxn}$ , at 298 K.
- (ii) Calculate the value of the equilibrium constant,  $K_p$ , at 298 K.

| Bond         | Average Bond Enthalpy (kJ/mol) |
|--------------|--------------------------------|
| N – H        | 391                            |
| H – H        | 436                            |
| N $\equiv$ N | ?                              |

(b) Based on the average bond enthalpies in the table above and the value of  $\Delta H_{298}^\circ$ , calculate the value of the N  $\equiv$  N bond enthalpy.

(c) Although the reaction is thermodynamically favorable at 298 K, it does not occur to an observable extent at this temperature. Explain how the N  $\equiv$  N bond enthalpy affects the rate of the reaction.

(d) The reaction is usually carried out at a very high temperature in the presence of a catalyst. Explain why the reaction is thermodynamically unfavorable at very high temperatures. Justify your answer in terms of  $\Delta H^\circ$ ,  $\Delta S^\circ$ , and their effect on  $\Delta G^\circ$ .



(e) Although the forward reaction represented above is thermodynamically unfavorable at very high temperatures, it can be used to produce  $\text{NH}_3$  if the  $\text{NH}_3$  is continually removed from the reaction vessel. Explain in terms of  $Q$  and  $K_p$  why this method works.

The boiling points of  $\text{H}_2$  and  $\text{NH}_3$  are given in the table below.

| Substance     | Boiling Point |
|---------------|---------------|
| $\text{H}_2$  | 20 K          |
| $\text{NH}_3$ | 240 K         |

## 2021 Form I: FRQ

(f) A student claims that  $\text{H}_2(g)$  condenses at a much lower temperature than  $\text{NH}_3(g)$  because  $\text{H}_2$  has stronger intermolecular forces than  $\text{NH}_3$  does. There are two errors in the student's reasoning. Identify the student's errors and explain your answer in terms of the specific types of forces involved.

## Part A

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



|   |   |   |
|---|---|---|
| 0 | 1 | 2 |
|---|---|---|

The response meets **all** the following criteria.

- ☐ The response provides a correct calculated value:
- $$\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ$$
- $$\Delta G^\circ = -82.2 \text{ kJ/mol}_{rxn} - (298 \text{ K})(-0.1988 \text{ kJ}/(\text{K} \cdot \text{mol}_{rxn}))$$
- $$\Delta G^\circ = -33.0 \text{ kJ/mol}_{rxn}$$
- ☐ The response provides the correct calculated value consistent with the calculated value for  $\Delta G^\circ$ :

$$\Delta G^\circ = -RT \ln K_p$$

$$\ln K_p = \frac{-\Delta G^\circ}{RT} = \frac{-(-33,000 \text{ J/mol}_{rxn})}{(8.314 \frac{\text{J}}{\text{K} \cdot \text{mol}_{rxn}})(298 \text{ K})} = 13.3$$

$$K_p = e^{13.3} = 6.09 \times 10^5$$

## Part B

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



|   |   |   |
|---|---|---|
| 0 | 1 | 2 |
|---|---|---|

The response meets **all** the following criteria.

- ☐ The response identifies endothermic and exothermic bond enthalpies:
- $$\Delta H^\circ_{rxn} = \sum(\Delta H^\circ_{bonds\ broken}) - \sum(\Delta H^\circ_{bonds\ formed})$$
- OR
- Assignment of positive and negative signs to bond enthalpies (see the following sample response)
- ☐ The response provides the correct calculated value:
- .

## 2021 Form I: FRQ

| Bonds Broken                                                                                                    | Bonds Formed                          |
|-----------------------------------------------------------------------------------------------------------------|---------------------------------------|
| $\text{N} \equiv \text{N} \quad x$<br>$3 \text{H} - \text{H} \quad 3(436)$                                      | $6 \text{N} - \text{H} \quad 6(-391)$ |
| $x + 1308 \text{ kJ/mol} + (-2346 \text{ kJ/mol}) = -92.2 \text{ kJ/mol}_{\text{rxn}}$ $x = 946 \text{ kJ/mol}$ |                                       |

## Part C

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



|   |   |
|---|---|
| 0 | 1 |
|---|---|

The response provides a correct explanation equivalent to the following.

· The large bond energy of the  $\text{N} \equiv \text{N}$  bond contributes to a high activation energy for the reaction, which causes the reaction to proceed slowly.

## Part D

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



|   |   |   |
|---|---|---|
| 0 | 1 | 2 |
|---|---|---|

The response meets **all** the following criteria.

- ☐ The response provides a correct explanation of thermodynamic favorability.  
 · For any thermodynamically unfavorable process, the sign of

$$\Delta G^\circ$$

will be positive.

- ☐ The response provides a valid justification based on the relative magnitudes of  $\Delta H^\circ$  and  $\Delta S^\circ$ .  
 · At high temperature, the

$$-T\Delta S^\circ$$

term becomes a larger positive value and eventually becomes larger in magnitude than the

$$\Delta H^\circ$$

term, causing the

## 2021 Form I: FRQ

$$\Delta G^\circ$$

value to become positive

## Part E

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



|   |   |
|---|---|
| 0 | 1 |
|---|---|

The response provides a correct explanation.

$$Q = \frac{(P_{\text{NH}_3})^2}{(P_{\text{N}_2})(P_{\text{H}_2})^3}$$

· Removing  $\text{NH}_3$  from the reaction vessel reduces the value of  $Q$ . The reaction consumes more reactants to generate more  $\text{NH}_3$  because  $Q < K$ .

## Part F

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



|   |   |   |
|---|---|---|
| 0 | 1 | 2 |
|---|---|---|

The response meets **all** the following criteria.

- ☐ The response provides a correct explanation of the boiling point and strength of intermolecular forces.
  - The student has reversed the relationship between a substance's boiling point (condensation temperature) and the strength of its intermolecular forces. A lower boiling point indicates that the intermolecular forces between particles are weaker.
- ☐ The response provides a correct explanation based on the intermolecular forces in each substance.
  - The student has misjudged the relative strength of intermolecular forces of the two substances. Molecules of  $\text{H}_2$  experience only London dispersion forces, while molecules of  $\text{NH}_3$  experience dipole-dipole forces and hydrogen bonding in addition to London dispersion forces. Therefore,  $\text{H}_2$  has weaker intermolecular forces than  $\text{NH}_3$  does.

## 2021 Form I: FRQ

2. For parts of the free response question that require 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. Examples and equations may be included in your answers where appropriate.

Answer the following questions related to  $\text{CO}_2$ .

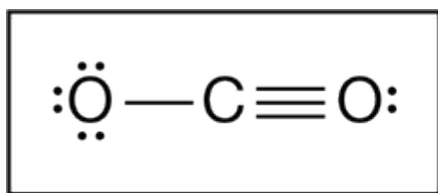


Diagram X

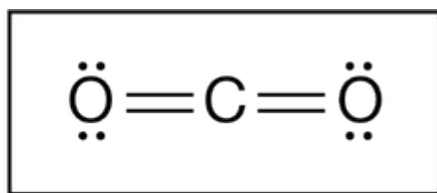
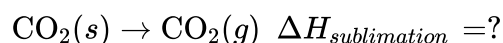
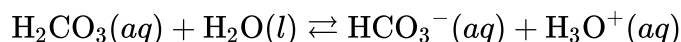


Diagram Z

- (a) Two possible Lewis electron-dot diagrams for  $\text{CO}_2$  are shown above. Explain in terms of formal charges why diagram Z is the better diagram.
- (b) Identify the hybridization of the valence orbitals of the C atom in the  $\text{CO}_2$  molecule represented in diagram Z.
- (c) A 0.1931 mol sample of dry ice,  $\text{CO}_2(s)$ , is added to an empty balloon. After the balloon is sealed, the  $\text{CO}_2(s)$  sublimates and the  $\text{CO}_2(g)$  in the balloon eventually reaches a temperature of  $21.0^\circ\text{C}$  and pressure of 0.998 atm. The physical change is represented by the following equation.



- (i) What is the sign (positive or negative) of the enthalpy change for the process of sublimation? Justify your answer.
- (ii) List all the numerical values of the quantities, with appropriate units, that are needed to calculate the volume of the balloon.
- (iii) Calculate the final volume, in liters, of the balloon.
- (d)  $\text{CO}_2(g)$  reacts with water to form  $\text{H}_2\text{CO}_3(aq)$ , which quickly ionizes in water to form  $\text{HCO}_3^-(aq)$  and  $\text{H}_3\text{O}^+(aq)$ , as shown in the following equation.

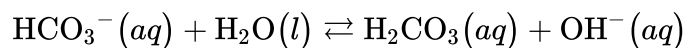


- (i) Identify one of the conjugate acid-base pairs in the equation above.
- (ii) When the concentration of  $\text{CO}_2$  in water increases, more  $\text{H}_2\text{CO}_3$  forms. Does the increase in the formation of  $\text{H}_2\text{CO}_3$  cause the value of the reaction quotient,  $Q$ , for the system to increase, decrease, or

## 2021 Form I: FRQ

remain the same? Justify your answer.

(e) A student investigates the acid-base properties of  $\text{HCO}_3^-(aq)$ . The reaction of  $\text{HCO}_3^-(aq)$  with  $\text{H}_2\text{O}(l)$  is represented below.



(i) The student measured the pH of a 0.100 M solution of  $\text{HCO}_3^-(aq)$  as 9.68. Calculate the concentration of  $\text{OH}^-(aq)$  in the solution.

$$K_b = \frac{[\text{H}_2\text{CO}_3][\text{OH}^-]}{[\text{HCO}_3^-]}$$

(ii) The  $K_b$  expression for the reaction of  $\text{HCO}_3^-(aq)$  with  $\text{H}_2\text{O}(l)$  is given above. Calculate the value of  $K_b$  for the reaction.

(iii) The student then carried out a second experiment at the same temperature to determine  $K_b$ . In the experiment, the student measured the pH of 0.300 M  $\text{HCO}_3^-(aq)$ . Would the value of  $K_b$  calculated in the second experiment be greater than, less than, or equal to the value of  $K_b$  calculated in part (e)(ii)? Justify your answer.

## Part A

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



|   |   |
|---|---|
| 0 | 1 |
|---|---|

The response provides a correct explanation equivalent to the following.

· In Diagram X, the oxygen on the left has a formal charge of  $-1$  while the oxygen on the right has a formal charge of  $+1$ . In Diagram Z, all atoms have a formal charge of 0, therefore Diagram Z is a better structure because it minimizes the formal charge on each atom.

## Part B

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



|   |   |
|---|---|
| 0 | 1 |
|---|---|

The response includes the correct answer.

☐

*sp*

## 2021 Form I: FRQ

## Part C

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



|   |   |   |   |
|---|---|---|---|
| 0 | 1 | 2 | 3 |
|---|---|---|---|

The response meets **all** the following criteria.

- ☐ The response identifies that  $\Delta H$  is positive **and** provides a valid justification:
  - $\Delta H > 0$  (*positive or +*) Energy must be absorbed by the molecules in the solid to overcome the attractive intermolecular forces and convert to a gas.
- ☐ The response lists **all** the following quantities:
  - $n = 0.1931 \text{ mol}$
  - $T = 294.2 \text{ K}$
  - $R = 0.08206 \text{ L}\cdot\text{atm}/(\text{mol}\cdot\text{K})$
  - $P = 0.998 \text{ atm}$
- ☐ The response provides the correct calculated value:
  - $V = \frac{nRT}{P} = \frac{(0.1931 \text{ mol})(0.08206 \text{ L}\cdot\text{atm}/(\text{mol}\cdot\text{K}))(294.2 \text{ K})}{0.998 \text{ atm}} = 4.67 \text{ L}$

## Part D

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



|   |   |   |
|---|---|---|
| 0 | 1 | 2 |
|---|---|---|

The response meets **all** the following criteria.

- ☐ The response includes **one** of the following correct answers:
  - $\text{H}_2\text{CO}_3$  and  $\text{HCO}_3^-$
  - OR
  - $\text{H}_3\text{O}^+$  and  $\text{H}_2\text{O}$
- ☐ The response provides a correct answer and a valid justification.
  - Decrease. Because  $\text{H}_2\text{CO}_3$  is a reactant, it appears in the denominator of the  $Q$  expression. Therefore,  $Q$  decreases when  $\text{H}_2\text{CO}_3$  increases.

$$Q = \frac{[\text{HCO}_3^-][\text{H}_3\text{O}^+]}{[\text{H}_2\text{CO}_3]}$$

## Part E

## 2021 Form I: FRQ

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



|   |   |   |   |
|---|---|---|---|
| 0 | 1 | 2 | 3 |
|---|---|---|---|

The response meets **all** the following criteria.

- ☐ The response provides a correct calculated value:  
 $\text{pOH} = 14.00 - \text{pH} = 14.00 - 9.68 = 4.32$   
 $[\text{OH}^-] = 10^{-\text{pOH}} = 10^{-4.32} = 4.8 \times 10^{-5} M$
- ☐ The response provides a correct calculated value:  

$$K_b = \frac{[\text{H}_2\text{CO}_3][\text{OH}^-]}{[\text{HCO}_3^-]}$$

$$K_b = \frac{(4.8 \times 10^{-5})(4.8 \times 10^{-5})}{0.100 - 4.8 \times 10^{-5}} \approx \frac{(4.8 \times 10^{-5})(4.8 \times 10^{-5})}{0.100} = 2.3 \times 10^{-8}$$
- ☐ The response provides the correct answer and a valid justification equivalent to **one** of the following:  
 · Equal to.  $K_b$  is constant for a species at a given temperature and will be the same regardless of the concentration of the base.  
 OR  
 · Equal to. A solution with higher  $[\text{HCO}_3^-]$  will also have proportionately higher  

$$[\text{H}_2\text{CO}_3]$$
  
 and  

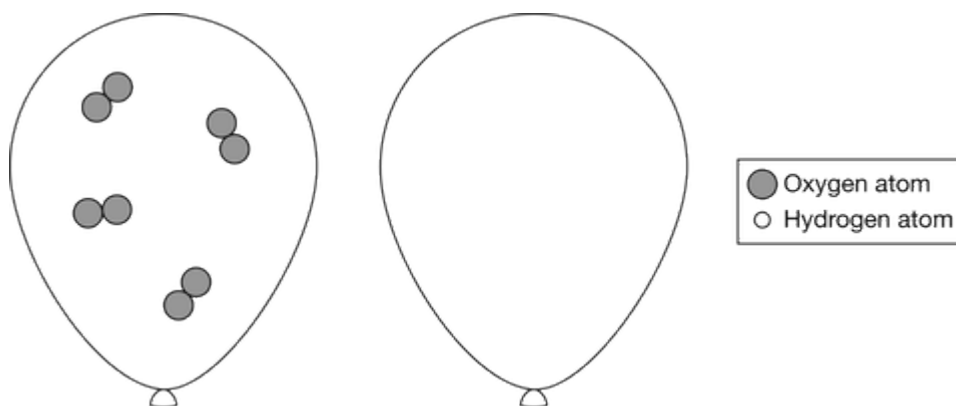
$$[\text{OH}^-]$$
  
 , resulting in the same value of  $K_b$ .

## 2021 Form I: FRQ

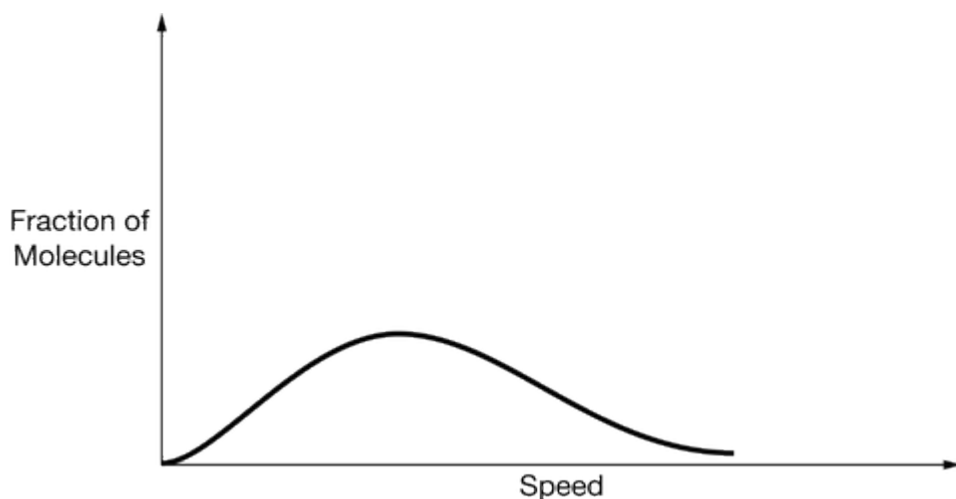
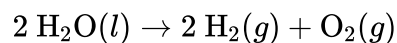
3. For parts of the free response question that require calculations, clearly show the method used and the steps involved in arriving at your answers. You must show your work to receive credit for your answer. Examples and equations may be included in your answers where appropriate.

Answer the following questions about hydrogen and oxygen gases.

- (a) A particle-level representation of  $\text{O}_2(g)$  is shown in the balloon below on the left. The balloon on the right contains the same volume of  $\text{H}_2(g)$  at the same temperature and pressure. In the balloon on the right, draw a representation of  $\text{H}_2(g)$  with the appropriate number and distribution of particles.



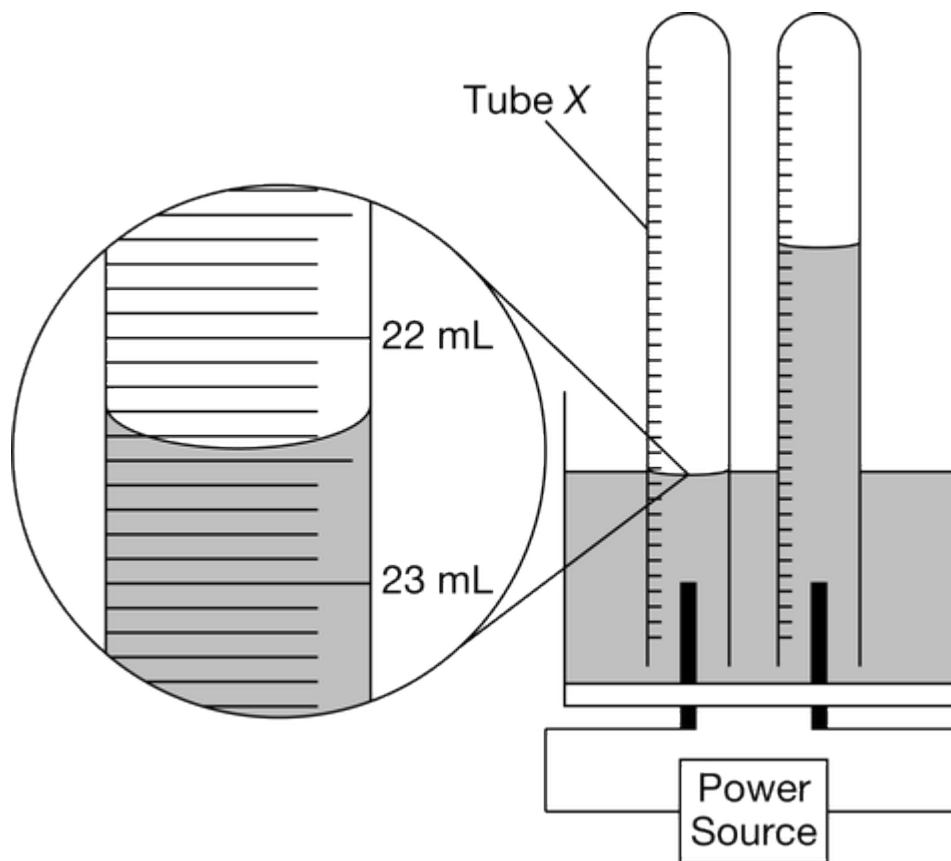
- (b) The graph below shows the Maxwell-Boltzmann distribution for  $\text{H}_2(g)$ . On the same graph, draw the distribution curve for  $\text{O}_2(g)$  at the same temperature.



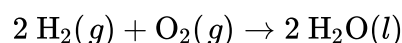
To generate the  $\text{H}_2(g)$  and the  $\text{O}_2(g)$ , a student performs electrolysis of water, represented by the equation

## 2021 Form I: FRQ

above. The student collects the gases in tubes and then adjusts the position of one of them so that the water levels inside and outside of the tube are the same, as shown in the following diagram.



- (c) Is the gas collected in tube  $X$   $\text{H}_2(g)$  or  $\text{O}_2(g)$ ? Justify your answer.
- (d) What volume should the student report for the gas in tube  $X$ ?
- (e) Is  $\text{H}_2(g)$  produced at the anode or cathode? Justify your answer in terms of oxidation numbers.
- (f) The atmospheric pressure in the lab was 0.989 atm at  $22.0^\circ\text{C}$ . The vapor pressure of water at  $22.0^\circ\text{C}$  is 0.026 atm. Calculate the pressure of dry gas in tube  $X$ .
- (g) The value of  $E^\circ$  for the electrolysis of water is  $-1.23\text{ V}$ . In a second trial of the experiment, the power source was replaced with a voltmeter. Would the volume of hydrogen gas produced be greater than, less than, or equal to the volume produced in the original experiment? Justify your answer.
- (h) The student considers the reverse reaction and proposes a mechanism with a single, elementary step as shown below.



Explain, in terms of particle collisions, why this mechanism is unlikely to be correct.

## Part A

## 2021 Form I: FRQ

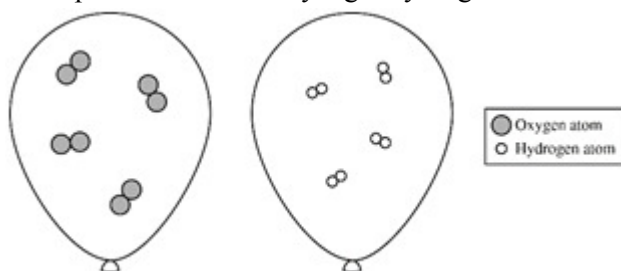
Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



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|---|---|---|
| 0 | 1 | 2 |
|---|---|---|

The response meets **all** of the following criteria.

- ☐ The response shows exactly eight hydrogen atoms as four diatomic molecules.



- ☐ The response shows particles that are evenly distributed.  
· See example given.

## Part B

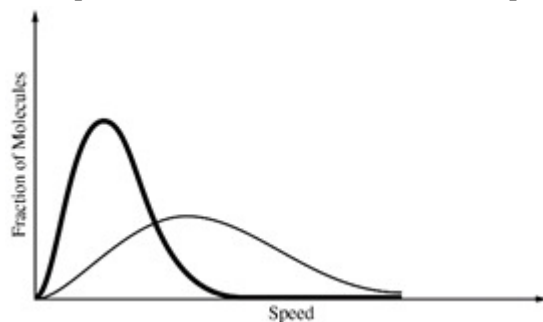
Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



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The response meets **all** the following criteria.

- ☐ The response shows a curve that has a taller peak than  $\text{H}_2$ .



- ☐ The response shows a curve that has a maximum to the left of the peak for  $\text{H}_2$  and approaches zero BEFORE the  $\text{H}_2$  curve.  
· See example given.

## Part C

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Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



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The response provides the correct answer and a valid justification.

· Hydrogen. The stoichiometry of the reaction indicates that there should be twice as many moles of hydrogen produced as oxygen, and the volume of gas is proportional to the number of moles.

**Part D**

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



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The response provides the correct answer.

· 22.45 mL

**Part E**

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



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The response provides the correct answer and a valid justification.

· Cathode. Hydrogen is reduced from +1 to 0 in the electrolysis process, and reduction occurs at the cathode.

**Part F**

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



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The response provides the correct calculated value.

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$$P_{gas} = 0.989 \text{ atm} - 0.026 \text{ atm} = 0.963 \text{ atm}$$

## Part G

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



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The response provides the correct answer and a valid justification.

· Less than. The reaction is thermodynamically unfavorable (negative  $E_{cell}^{\circ}$ ), so the battery is needed to drive the reaction. Therefore, no hydrogen would be produced without the battery.

OR

· Less than. A voltmeter only measures electrical potential and does not supply it.

## Part H

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



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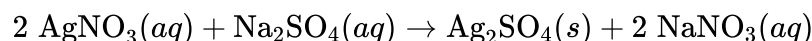
The response provides the correct answer and a valid justification.

· Three-body (termolecular) elementary reactions are unlikely because of the low probability of three molecules colliding simultaneously.

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4. For parts of the free response question that require 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. Examples and equations may be included in your answers where appropriate.

A student wishes to determine the concentration of  $\text{Ag}^+(aq)$  in a solution of  $\text{AgNO}_3(aq)$ . The student combines 10.00 mL of  $\text{AgNO}_3(aq)$  with excess  $\text{Na}_2\text{SO}_4(aq)$  and observes the formation of a white precipitate. The formation of the precipitate is represented by the following equation.



- (a) Write the balanced net ionic equation for the precipitation reaction.

The student collects the precipitate by filtration and measures the mass of the filter paper and precipitate every 10 minutes as it dries. The student records the data in the following table.

|                                                                   |        |
|-------------------------------------------------------------------|--------|
| Mass of dry filter paper                                          | 0.88 g |
| Mass of filter paper and precipitate immediately after filtration | 4.82 g |
| Mass of filter paper and precipitate after 10 minutes             | 4.37 g |
| Mass of filter paper and precipitate after 20 minutes             | 4.01 g |
| Mass of filter paper and precipitate after 30 minutes             | 3.79 g |

- (b) Use the data above to calculate the number of moles of  $\text{Ag}_2\text{SO}_4(s)$  (molar mass 311.8 g/mol) that precipitated.

- (c) Calculate the concentration of  $\text{Ag}^+(aq)$  in the original 10.00 mL solution of  $\text{AgNO}_3(aq)$ .

- (d) The concentration of  $\text{Ag}^+(aq)$  determined by the student is significantly higher than the actual concentration of  $\text{Ag}^+(aq)$ . Based on the student's data table, identify an error in the experimental procedure that led to this result.

## Part A

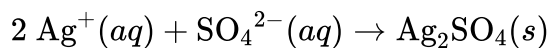
Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



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The response provides a correct balanced equation (state symbols not required).

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## Part B

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



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The response provides the correct calculated value.

$$3.79 \text{ g} - 0.88 \text{ g} = 2.91 \text{ g}$$
$$2.91 \text{ g} \times \frac{1 \text{ mol Ag}_2\text{SO}_4}{311.8 \text{ g}} = 0.00933 \text{ mol Ag}_2\text{SO}_4$$

## Part C

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



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The response provides the correct calculated value.

$$0.00933 \text{ mol Ag}_2\text{SO}_4 \times \frac{2 \text{ mol Ag}^+}{1 \text{ mol Ag}_2\text{SO}_4} = 0.0187 \text{ mol Ag}^+$$
$$\frac{0.0187 \text{ mol Ag}^+}{0.0100 \text{ L}} = 1.87M$$

## Part D

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



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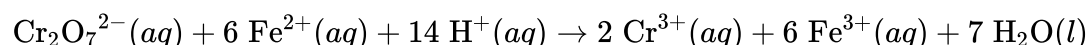
The response provides a correct source of error.

· The student did not wait for the precipitate to dry completely (reach a constant mass)

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5. For parts of the free response question that require 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. Examples and equations may be included in your answers where appropriate.

A student determines the mass percent of iron in a sample of iron ore by doing a redox titration. The student finds the mass of the sample and then dissolves it in acid to a total volume of 25.00 mL. Using a buret, the student titrates the 25.00 mL solution with 0.017 M  $\text{K}_2\text{Cr}_2\text{O}_7$ . The following reaction occurs during the titration.



The student collects the following data.

|                                     |          |
|-------------------------------------|----------|
| Mass of iron ore in original sample | 0.36 g   |
| Buret reading at end point          | 45.52 mL |
| Initial buret reading               | 15.05 mL |

- (a) How many moles of  $\text{Fe}^{2+}(\text{aq})$  reacted with the  $\text{Cr}_2\text{O}_7^{2-}(\text{aq})$  ?
- (b) Assuming that all the iron in the ore was  $\text{Fe}^{2+}$ , calculate the mass percent of iron in the ore sample.
- (c) The student learns that the actual mass percent of iron in the ore sample is greater than the experimental value calculated in part (b). The student claims that the difference between the actual and experimental values could have been caused by rinsing the buret with distilled water just prior to filling it with 0.017 M  $\text{K}_2\text{Cr}_2\text{O}_7(\text{aq})$ . Do you agree with the student's claim? Explain your reasoning.

## Part A

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



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The response meets **all** the following criteria.

- ☐ The response provides the correct calculated number of moles of  $\text{Cr}_2\text{O}_7^{2-}$ .

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$$45.52 \text{ mL} - 15.05 \text{ mL} = 30.47 \text{ mL}$$

$$0.03047 \text{ L} \times \frac{0.017 \text{ mol Cr}_2\text{O}_7^{2-}}{1 \text{ L}} = 5.2 \times 10^{-4} \text{ mol Cr}_2\text{O}_7^{2-}$$

- ☐ The response provides the correct calculated number of moles of  $\text{Fe}^{2+}$ , consistent with the moles of  $\text{Cr}_2\text{O}_7^{2-}$ .

$$5.2 \times 10^{-4} \text{ mol Cr}_2\text{O}_7^{2-} \times \frac{6 \text{ mol Fe}^{2+}}{1 \text{ mol Cr}_2\text{O}_7^{2-}} = 0.0031 \text{ mol Fe}^{2+}$$

## Part B

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



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| 0 | 1 |
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The response provides the correct calculated value, consistent with the moles of  $\text{Fe}^{2+}$ .

$$0.0031 \text{ mol Fe}^{2+} \times \frac{55.85 \text{ g}}{1 \text{ mol}} = 0.17 \text{ g Fe}$$
$$\frac{0.17 \text{ g Fe}}{0.36 \text{ g sample}} \times 100 = 47\%$$

(48% without rounding in earlier steps)

## Part C

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



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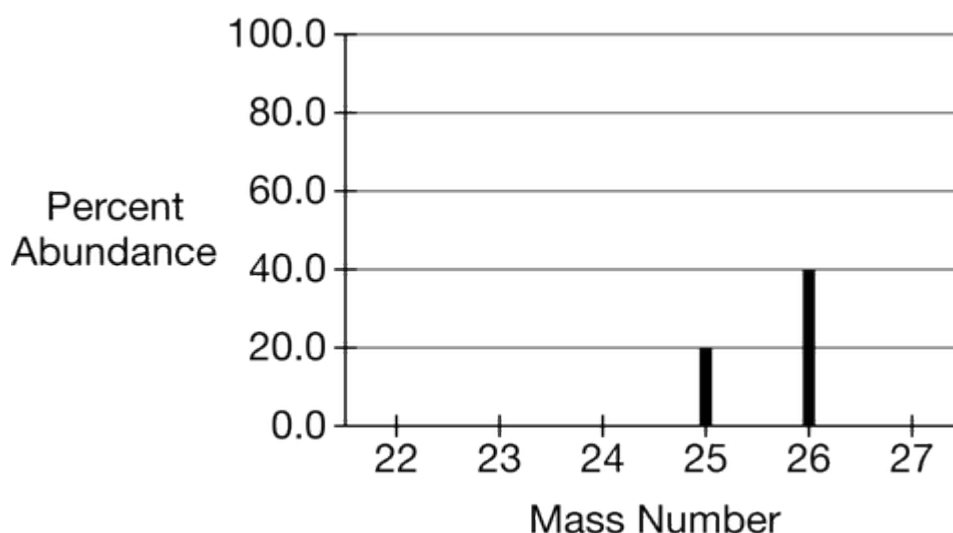
The response provides the correct answer and a valid justification.

Disagree. The distilled water dilutes the  $\text{K}_2\text{Cr}_2\text{O}_7(aq)$  solution, requiring a greater volume to reach the endpoint of the titration. This increased volume, when multiplied by  $0.017 \text{ M}$  (the concentration of  $\text{K}_2\text{Cr}_2\text{O}_7(aq)$ ), would result in a greater calculated number of moles of iron (and thus a higher experimental % of iron).

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6. For parts of the free response question that require 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. Examples and equations may be included in your answers where appropriate.

The three stable isotopes of Mg are Mg-24, Mg-25, and Mg-26. A rock sample from another planet has a different distribution of the three stable isotopes than what is found on Earth. A partial mass spectrum for Mg in the rock sample is shown below.



- (a) Draw a line on the graph to show the mass of the missing isotope and its percent abundance.
- (b) Use the completed mass spectrum to calculate the average atomic mass of Mg on the other planet.
- (c) The first ionization energy of magnesium samples found on Earth is experimentally determined to be 736 kJ/mol. If a similar experiment is conducted to determine the first ionization energy of magnesium in the rock sample from another planet, will it be greater than, less than, or equal to the first ionization energy of magnesium found on Earth? Explain your reasoning.

|                 | Successive Ionization Energies (kJ/mol) |        |       |
|-----------------|-----------------------------------------|--------|-------|
|                 | First                                   | Second | Third |
| Mg              | 736                                     | 1450   | 7740  |
| Unknown element | 496                                     | 4560   | 6910  |

- (d) A table of successive ionization energies for Mg and an unknown element is shown above. Predict the identity

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of the unknown element.

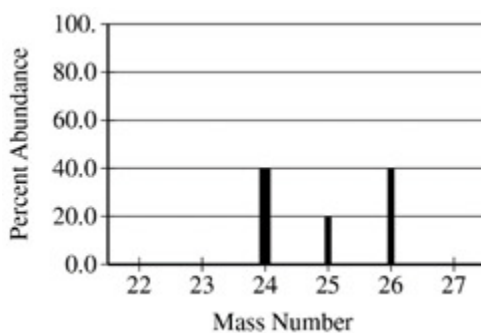
## Part A

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



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The response provides the correct a correct answer showing a line with a height of 40 and an atomic mass of 24 amu .



## Part B

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



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The response provides the correct calculated value.

$$\frac{24(40) + 25(20) + 26(40)}{100} = 25 \text{ amu}$$

## Part C

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



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The response provides a correct answer and a valid explanation equivalent to one of the following.

· Equal to. All atoms of magnesium have the same number of protons and electrons and therefore the same first ionization energy.

OR

· Equal to. Ionization energy is not affected by the number of neutrons (neutral particles) present and is therefore identical for all isotopes.

**Part D**

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



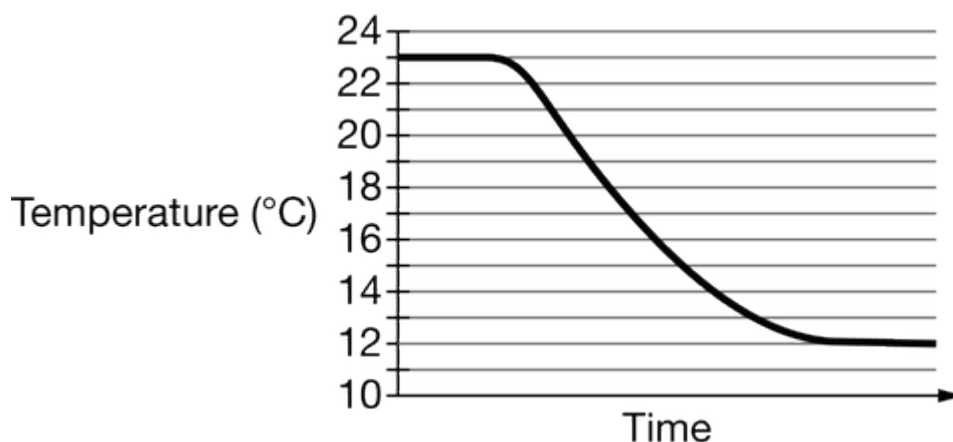
|   |   |
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The response provides a correct answer.

· Sodium (or any alkali metal)

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7. For parts of the free response question that require 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. Examples and equations may be included in your answers where appropriate.



A student conducts an experiment to determine the value of  $\Delta H_{soln}^\circ$  for the dissolution of  $\text{NaC}_2\text{H}_3\text{O}_2(s)$ . The student dissolves 10.0 g of  $\text{NaC}_2\text{H}_3\text{O}_2(s)$  in room-temperature water in a beaker and measures the temperature over time. The data are given in the graph above.

- (a) The student touches the side of the beaker after the dissolution has occurred and observes that it is cold. What experimental evidence is consistent with the student's observation?
- (b) Is the dissolution of  $\text{NaC}_2\text{H}_3\text{O}_2(s)$  endothermic or exothermic? Justify your answer in terms of the flow of energy between the system and surroundings.
- (c) The student calculated the energy change for the dissolution to be 4600 J. Based on this value, calculate  $\Delta H_{soln}^\circ$  in kJ/mol.

## Part A

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



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The response provides a correct answer.

· According to the graph, the temperature of the mixture after dissolution is lower, which is consistent with the observation that the beaker feels cold after the dissolution.

## Part B

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.

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The response provides the correct answer and a valid justification.

· Endothermic. The decrease in temperature indicates that energy flows from the beaker and water (surroundings) to the dissolving solid (system).

**Part C**

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



|   |   |   |
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| 0 | 1 | 2 |
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The response meets **all** the following criteria.

- ☐ The response provides the correct calculated number of moles (may be implicit):

$$10.0 \text{ g NaC}_2\text{H}_3\text{O}_2 \times \frac{1 \text{ mol}}{82.03 \text{ g}} = 0.122 \text{ mol NaC}_2\text{H}_3\text{O}_2$$

- ☐ The response provides the correct calculated enthalpy change (with units) consistent with the number of moles.

$$\Delta H_{\text{soln}}^{\circ} = \frac{4600 \text{ J}}{0.122 \text{ mol}} = 38,000 \text{ J/mol} = 38 \text{ kJ/mol}$$