2021 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.

A student wishes to determine the concentration of $\mathrm{Ag}^{+}(aq)$ in a solution of $\mathrm{AgNO_3}(aq)$. The student combines $10.00\ \mathrm{mL}$ of $\mathrm{AgNO_3}(aq)$ with excess $\mathrm{Na_2SO_4}(aq)$ and observes the formation of a white precipitate. The formation of the precipitate is represented by the following equation.

$$2\ \mathrm{AgNO_3}(aq) + \mathrm{Na_2SO_4}(aq) \rightarrow \mathrm{Ag_2SO_4}(s) + 2\ \mathrm{NaNO_3}(aq)$$

(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	$0.88\ \mathrm{g}$
Mass of filter paper and precipitate immediately after filtration	$4.82\ \mathrm{g}$
Mass of filter paper and precipitate after 10 minutes	$4.37\ \mathrm{g}$
Mass of filter paper and precipitate after 20 minutes	$4.01\ \mathrm{g}$
Mass of filter paper and precipitate after 30 minutes	$3.79\ \mathrm{g}$

(b) Use the data above to calculate the number of moles of $\mathrm{Ag_2SO_4}(s)$ (molar mass $311.8\ \mathrm{g/mol}$) that precipitated.

(c) Calculate the concentration of $\mathrm{Ag}^{+}(aq)$ in the original $10.00\ \mathrm{mL}$ solution of $\mathrm{AgNO_3}(aq)$.

(d) The concentration of $\mathrm{Ag}^{+}(aq)$ determined by the student is significantly higher than the actual concentration of $\mathrm{Ag}^{+}(aq)$. 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.

0	1 ✓

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

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2021 FRQ

$$2\ \mathrm{Ag^+}(aq) + \mathrm{SO_4}^{2-}(aq) \rightarrow \mathrm{Ag_2SO_4}(s)$$

Part B

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

0	1 ✓

The response provides the correct calculated value.

.

$$3.79\ \mathrm{g} - 0.88\ \mathrm{g} = 2.91\ \mathrm{g}$$
$$2.91\ \mathrm{g} \times \frac{1\ \mathrm{mol\ Ag_2SO_4}}{311.8\ \mathrm{g}} = 0.00933\ \mathrm{mol\ Ag_2SO_4}$$

Part C

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

0	1 ✓

The response provides the correct calculated value.

.

$$0.00933\ \mathrm{mol\ Ag_2SO_4} \times \frac{2\ \mathrm{mol\ Ag^+}}{1\ \mathrm{mol\ Ag_2SO_4}} = 0.0187\ \mathrm{mol\ Ag^+}$$
$$\frac{0.0187\ \mathrm{mol\ Ag^+}}{0.0100\ \mathrm{L}} = 1.87M$$

Part D

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

0	1 ✓

The response provides a correct source of error.

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

2021 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 $\mathrm{NH_3}$.

$\mathrm{N_2}(g) + 3\ \mathrm{H_2}(g) \rightleftarrows 2\ \mathrm{NH_3}(g) \quad \Delta H^\circ_{298} = -92.2\ \mathrm{kJ/mol}_{rxn}; \quad \Delta S^\circ_{298} = -198.8\ \mathrm{J}\ /(\mathrm{mol}_{rxn} \cdot \mathrm{K})$

(a) The reaction of $\mathrm{N_2}(g)$ and $\mathrm{H_2}(g)$ to form $\mathrm{NH_3}(g)$ is represented above. The reaction has been studied in order to maximize the yield of $\mathrm{NH_3}(g)$.

(i) Calculate the value of ΔG°, in $\mathrm{kJ/mol}_{rxn}$, at $298\ \mathrm{K}$.

(ii) Calculate the value of the equilibrium constant, K_p, at $298\ \mathrm{K}$.

Bond	**Average Bond Enthalpy** $(\mathrm{kJ/mol})$
$\mathrm{N-H}$	391
$\mathrm{H-H}$	436
$\mathrm{N \equiv N}$	?

(b) Based on the average bond enthalpies in the table above and the value of ΔH°_{298}, calculate the value of the $\mathrm{N \equiv N}$ bond enthalpy.

(c) Although the reaction is thermodynamically favorable at $298\ \mathrm{K}$, it does not occur to an observable extent at this temperature. Explain how the $\mathrm{N \equiv N}$ 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 ΔH°, ΔS°, and their effect on ΔG°.

$\mathrm{N_2}(g) + 3\ \mathrm{H_2}(g) \rightleftarrows 2\ \mathrm{NH_3}(g)$

(e) Although the forward reaction represented above is thermodynamically unfavorable at very high temperatures, it can be used to produce $\mathrm{NH_3}$ if the $\mathrm{NH_3}$ is continually removed from the reaction vessel. Explain in terms of Q and K_p why this method works.

The boiling points of $\mathrm{H_2}$ and $\mathrm{NH_3}$ are given in the table below.

Substance	**Boiling Point**
$\mathrm{H_2}$	$20\ \mathrm{K}$
$\mathrm{NH_3}$	$240\ \mathrm{K}$

2021 FRQ

(f) A student claims that $\mathrm{H_2}(g)$ condenses at a much lower temperature than $\mathrm{NH_3}(g)$ because $\mathrm{H_2}$ has stronger intermolecular forces than $\mathrm{NH_3}$ 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:
  $\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ$
  $\Delta G^\circ = -82.2\,\mathrm{kJ/mol}_{rxn} - (298\,\mathrm{K})(-0.1988\,\mathrm{kJ/(K \cdot mol}_{rxn}))$
  $\Delta G^\circ = -33.0\,\mathrm{kJ/mol}_{rxn}$
- ☐ The response provides the correct calculated value consistent with the calculated value for ΔG°:

$$\Delta G^\circ = -RT \ln K_p$$
$$\ln K_p = \frac{-\Delta G^\circ}{RT} = \frac{-(-33{,}000\,\mathrm{J/mol}_{rxn})}{\left(8.314\,\frac{\mathrm{J}}{\mathrm{K \cdot mol}_{rxn}}\right)(298\,\mathrm{K})} = 13.3$$
$$K_p = e^{13.3} = 6.09 \times 10^5$$

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 FRQ

Bonds Broken		Bonds Formed	
$\mathrm{N} \equiv \mathrm{N}$	x	$6\ \mathrm{N}-\mathrm{H}$	$6(-391)$
$3\ \mathrm{H}-H$	$3(436)$		

$$x + 1308\ \mathrm{kJ/mol} \quad + \quad (-2346\ \mathrm{kJ/\ mol}) = -92.2\ \mathrm{kJ/mol}_{rxn}$$

$$x = 946\ \mathrm{kJ/mol}$$

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 $\mathrm{N} \equiv \mathrm{N}$ 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 ΔH° and ΔS°.
  · 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

$$\Delta G^\circ$$

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.

$$Q = \frac{(P_{NH_3})^2}{(P_{N_2})(P_{H_2})^3}$$

· Removing NH_3 from the reaction vessel reduces the value of Q. The reaction consumes more reactants to generate more 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.

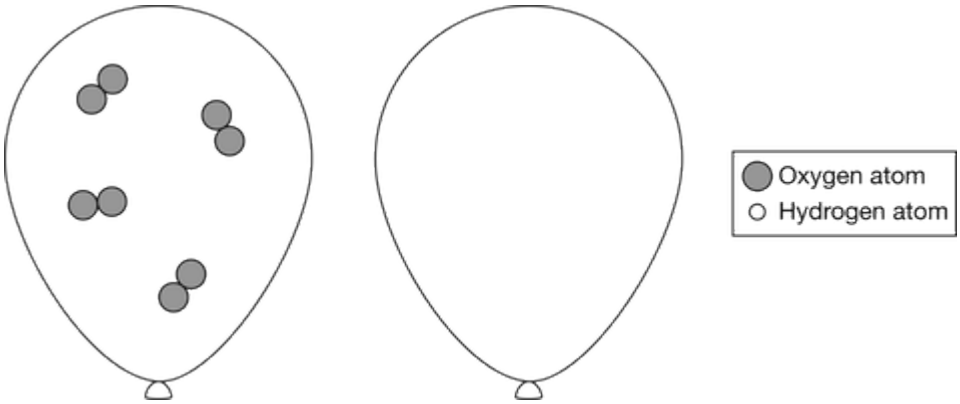
- ☐ The response provides a correct explanation of the boiling point and strength of intermolecular forces.
  · The student has reversed the relationship between a substance's boiling point (condensation temperature) and the strength of its intermolecular forces. A lower boiling point indicates that 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 H_2 experience only London dispersion forces, while molecules of NH_3 experience dipole-dipole forces and hydrogen bonding in addition to London dispersion forces. Therefore, H_2 has weaker intermolecular forces than NH_3 does.

2021 FRQ

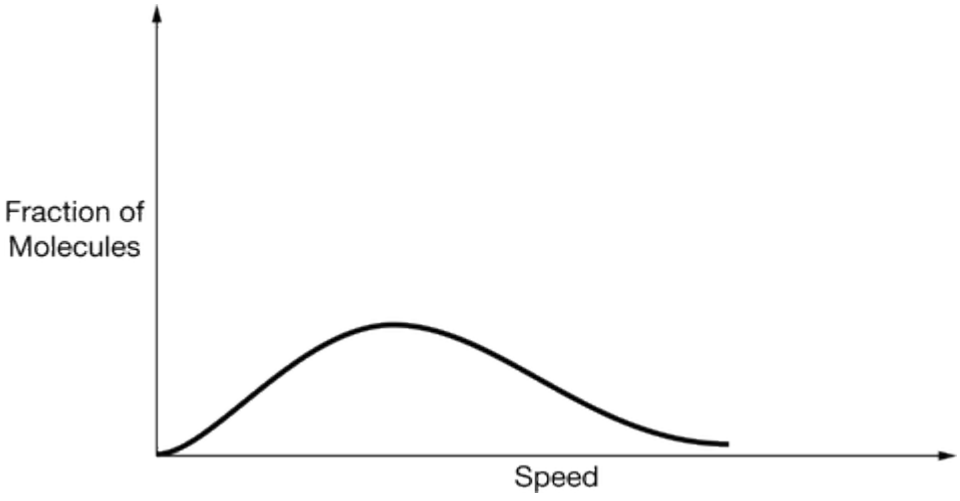
3. For parts of the free response question that require calculations, clearly show the method used and the steps involved in arriving at your answers. You must show your work to receive credit for your answer. Examples and equations may be included in your answers where appropriate.

Answer the following questions about hydrogen and oxygen gases.

(a) A particle-level representation of $O_2(g)$ is shown in the balloon below on the left. The balloon on the right contains the same volume of $H_2(g)$ at the same temperature and pressure. In the balloon on the right, draw a representation of $H_2(g)$ with the appropriate number and distribution of particles.



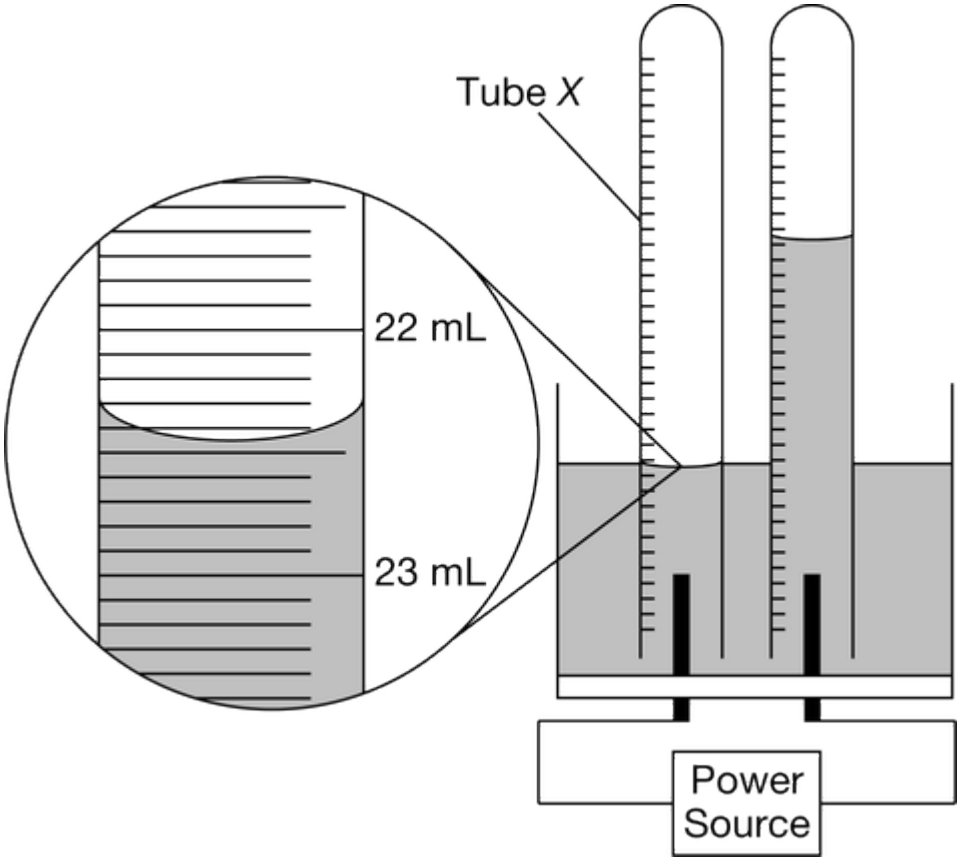
(b) The graph below shows the Maxwell-Boltzmann distribution for $H_2(g)$. On the same graph, draw the distribution curve for $O_2(g)$ at the same temperature.



$2\ H_2O(l) \rightarrow 2\ H_2(g) + O_2(g)$

To generate the $H_2(g)$ and the $O_2(g)$, 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.



(c) Is the gas collected in tube X $\mathrm{H_2}(g)$ or $\mathrm{O_2}(g)$? Justify your answer.

(d) What volume should the student report for the gas in tube X?

(e) Is $\mathrm{H_2}(g)$ produced at the anode or cathode? Justify your answer in terms of oxidation numbers.

(f) The atmospheric pressure in the lab was $0.989\ \mathrm{atm}$ at $22.0\,^{\circ}\mathrm{C}$. The vapor pressure of water at $22.0\,^{\circ}\mathrm{C}$ is $0.026\ \mathrm{atm}$. Calculate the pressure of dry gas in tube X.

(g) The value of E° for the electrolysis of water is $-1.23\ \mathrm{V}$. 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.

$$2\ \mathrm{H_2}(g) + \mathrm{O_2}(g) \rightarrow 2\ \mathrm{H_2O}(l)$$

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

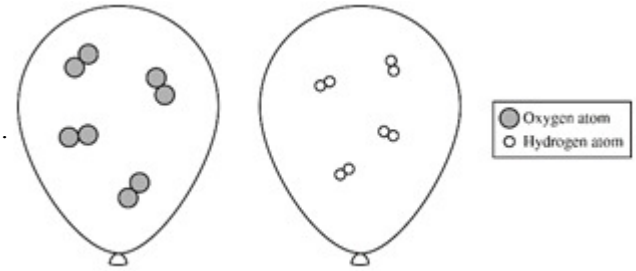
Part A

2021 FRQ

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

0	1	2 ✓

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

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

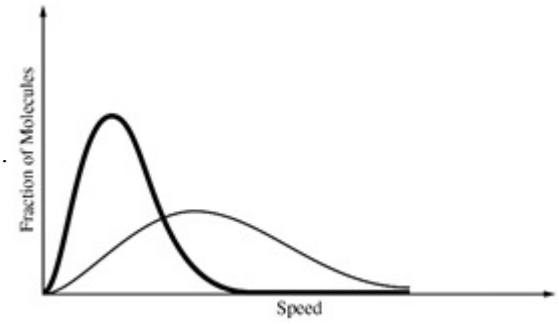
- ☐ The response shows particles that are evenly distributed.
  - See example given.

Part B

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

0	1	2 ✓

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

- ☐ The response shows a curve that has a taller peak than H_2.
  - 

- ☐ The response shows a curve that has a maximum to the left of the peak for H_2 and approaches zero BEFORE the H_2 curve.
  - See example given.

2021 FRQ

Part C

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

0	1 ✓

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.

0	1 ✓

The response provides the correct answer.

· $22.45\ \text{mL}$

Part E

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

0	1 ✓

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.

0	1 ✓

2021 FRQ

The response provides the correct calculated value.

.

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

Part G

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

0	1 ✓

The response provides the correct answer and a valid justification.

· Less than. The reaction is thermodynamically unfavorable (negative E°_{cell}), 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.

0	1 ✓

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.

2021 FRQ

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 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 $25.00\ \text{mL}$. Using a buret, the student titrates the $25.00\ \text{mL}$ solution with $0.017\ M\ \text{K}_2\text{Cr}_2\text{O}_7$. The following reaction occurs during the titration.

$$\text{Cr}_2\text{O}_7{}^{2-}(aq) + 6\ \text{Fe}^{2+}(aq) + 14\ \text{H}^+(aq) \rightarrow 2\ \text{Cr}^{3+}(aq) + 6\ \text{Fe}^{3+}(aq) + 7\ \text{H}_2\text{O}(l)$$

The student collects the following data.

Mass of iron ore in original sample	$0.36\ \text{g}$
Buret reading at end point	$45.52\ \text{mL}$
Initial buret reading	$15.05\ \text{mL}$

(a) How many moles of $\text{Fe}^{2+}(aq)$ reacted with the $\text{Cr}_2\text{O}_7{}^{2-}(aq)$?

(b) Assuming that all the iron in the ore was 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 $0.017\ M\ \text{K}_2\text{Cr}_2\text{O}_7(aq)$. 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.

0	1	2 ✓

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

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

.

2021 FRQ

$$45.52\ \text{mL} - 15.05\ \text{mL} = 30.47\ \text{mL}$$
$$0.03047\ \text{L} \times \frac{0.017\ \text{mol}\ \text{Cr}_2\text{O}_7{}^{2-}}{1\ \text{L}} = 5.2 \times 10^{-4}\ \text{mol}\ \text{Cr}_2\text{O}_7{}^{2-}$$

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

.

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

Part B

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

✓

0	1

The response provides the correct calculated value, consistent with the moles of Fe^{2+}.

.

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

(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.

✓

0	1

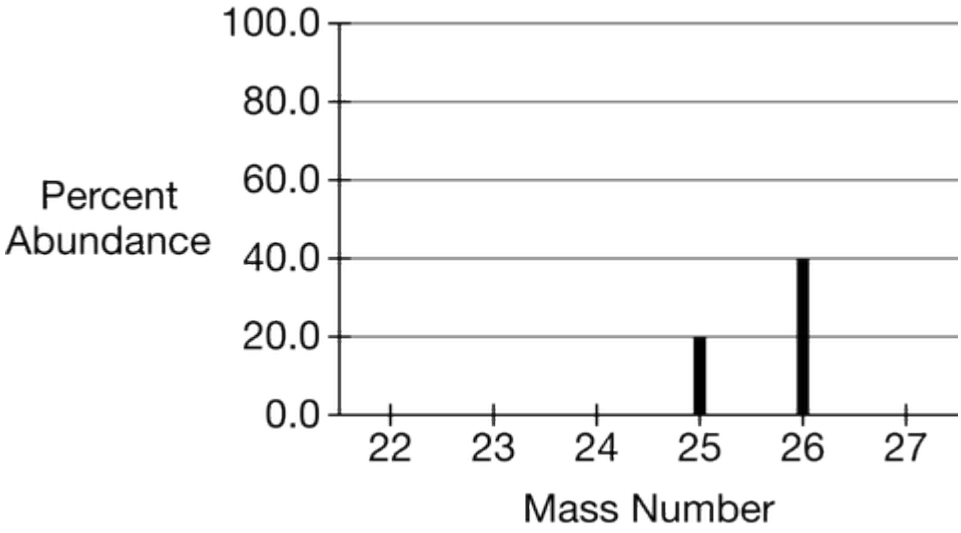
The response provides the correct answer and a valid justification.

· 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 $0.017\ M$ (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).

2021 FRQ

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.

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 $736\ \text{kJ/mol}$. 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

2021 FRQ

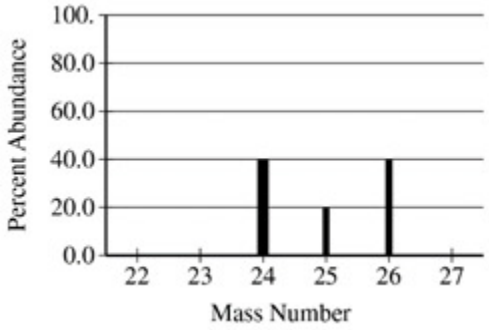
of the unknown element.

Part A

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

0	1 ✓

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



Part B

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

0	1 ✓

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.

2021 FRQ

0	1 ✓

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.

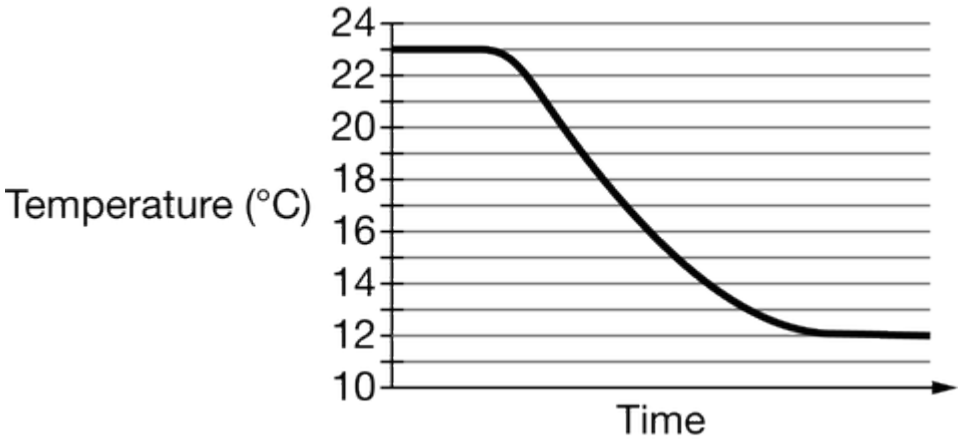
0	1 ✓

The response provides a correct answer.

· Sodium (or any alkali metal)

2021 FRQ

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.



A student conducts an experiment to determine the value of ΔH°_{soln} for the dissolution of $\mathrm{NaC_2H_3O_2}(s)$. The student dissolves 10.0 g of $\mathrm{NaC_2H_3O_2}(s)$ 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 $\mathrm{NaC_2H_3O_2}(s)$ 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 ΔH°_{soln} in $\mathrm{kJ/mol}$.

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 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.

2021 FRQ

0	1 ✓

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.

0	1	2 ✓

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

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

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

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

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

2021 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 $\mathrm{CO_2}$.

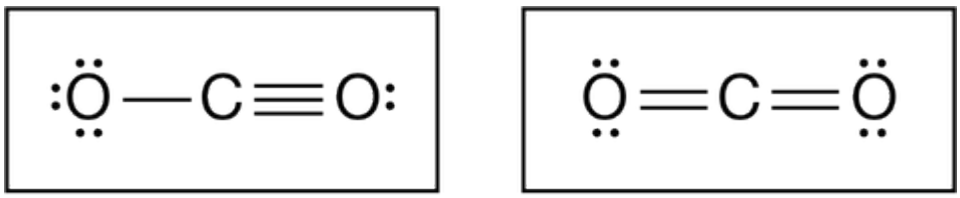


Diagram *X* Diagram *Z*

(a) Two possible Lewis electron-dot diagrams for $\mathrm{CO_2}$ 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 $\mathrm{CO_2}$ molecule represented in diagram Z .

(c) A $0.1931\ \mathrm{mol}$ sample of dry ice, $\mathrm{CO_2}(s)$, is added to an empty balloon. After the balloon is sealed, the $\mathrm{CO_2}(s)$ sublimes and the $\mathrm{CO_2}(g)$ in the balloon eventually reaches a temperature of $21.0^\circ\mathrm{C}$ and pressure of $0.998\ \mathrm{atm}$. The physical change is represented by the following equation.

$\mathrm{CO_2}(s) \rightarrow \mathrm{CO_2}(g)\ \ \Delta H_{sublimation} = ?$

(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) $\mathrm{CO_2}(g)$ reacts with water to form $\mathrm{H_2CO_3}(aq)$, which quickly ionizes in water to form $\mathrm{HCO_3}^-(aq)$ and $\mathrm{H_3O}^+(aq)$, as shown in the following equation.

$\mathrm{H_2CO_3}(aq) + \mathrm{H_2O}(l) \rightleftarrows \mathrm{HCO_3}^-(aq) + \mathrm{H_3O}^+(aq)$

(i) Identify one of the conjugate acid-base pairs in the equation above.

(ii) When the concentration of $\mathrm{CO_2}$ in water increases, more $\mathrm{H_2CO_3}$ forms. Does the increase in the formation of $\mathrm{H_2CO_3}$ cause the value of the reaction quotient, Q, for the system to increase, decrease, or remain the same? Justify your answer.

2021 FRQ

(e) A student investigates the acid-base properties of $\mathrm{HCO_3}^-(aq)$. The reaction of $\mathrm{HCO_3}^-(aq)$ with $\mathrm{H_2O}(l)$ is represented below.

$$\mathrm{HCO_3}^-(aq) + \mathrm{H_2O}(l) \rightleftarrows \mathrm{H_2CO_3}(aq) + \mathrm{OH}^-(aq)$$

(i) The student measured the pH of a $0.100\ M$ solution of $\mathrm{HCO_3}^-(aq)$ as 9.68. Calculate the concentration of $\mathrm{OH}^-(aq)$ in the solution.

$$K_b = \frac{[\mathrm{H_2CO_3}][\mathrm{OH}^-]}{[\mathrm{HCO_3}^-]}$$

(ii) The K_b expression for the reaction of $\mathrm{HCO_3}^-(aq)$ with $\mathrm{H_2O}(l)$ 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 $0.300\ M\ \mathrm{HCO_3}^-(aq)$. 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 $(\mathrm{e})(\mathrm{ii})$? 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*

Part C

2021 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 identifies that ΔH 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:
  · $n = 0.1931\,\text{mol}$
  · $T = 294.2\,\text{K}$
  · $R = 0.08206\,{}^{\text{L·atm}}/_{\text{(mol·K)}}$
  · $P = 0.998\,\text{atm}$
- ☐ The response provides the correct calculated value:
  · $V = \frac{nRT}{P} = \frac{(0.1931\,\text{mol})(0.08206\,{}^{\text{L·atm}}/_{\text{(mol·K)}})(294.2\,\text{K})}{0.998\,\text{atm}} = 4.67\,\text{L}$

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:
  · H_2CO_3 and $\text{HCO}_3{}^-$
  OR
  · H_3O^+ and H_2O
- ☐ The response provides a correct answer and a valid justification.
  · Decrease. Because H_2CO_3 is a reactant, it appears in the denominator of the Q expression. Therefore, Q decreases when H_2CO_3 increases.

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

Part E

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

2021 FRQ

0	1	2	3 ✓

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

- ☐ The response provides a correct calculated value:
  $\mathrm{pOH} = 14.00 - \mathrm{pH} = 14.00 - 9.68 = 4.32$
  .
  $\left[\mathrm{OH}^-\right] = 10^{-\mathrm{pOH}} = 10^{-4.32} = 4.8 \times 10^{-5}\, M$
- ☐ The response provides a correct calculated value:
  $K_b = \frac{[\mathrm{H_2CO_3}]\left[\mathrm{OH}^-\right]}{[\mathrm{HCO_3}^-]}$
  .
  $K_b = \frac{\left(4.8\times10^{-5}\right)\left(4.8\times10^{-5}\right)}{0.100-4.8\times10^{-5}} \approx \frac{\left(4.8\times10^{-5}\right)\left(4.8\times10^{-5}\right)}{0.100} = 2.3 \times 10^{-8}$
- ☐ 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 $\left[\mathrm{HCO_3}^-\right]$ will also have proportionately higher

  $$[\mathrm{H_2CO_3}]$$

  and

  $$\left[\mathrm{OH}^-\right]$$

  , resulting in the same value of K_b.