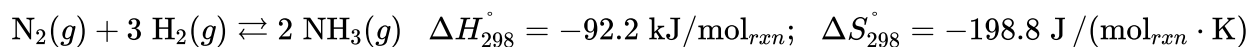


2021 FRQ

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 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 $\text{NH}_3(g)$.

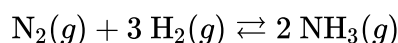
- (i) Calculate the value of ΔG° , in kJ/mol_{rxn} , at 298 K.
- (ii) Calculate the value of the equilibrium constant, K_p , at 298 K.

| 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 ΔH_{298}° , 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 ΔH° , ΔS° , and their effect on ΔG° .



(e) Although the forward reaction represented above is thermodynamically unfavorable at very high temperatures, it can be used to produce NH_3 if the 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 H_2 and NH_3 are given in the table below.

| Substance | Boiling Point |
|---------------|---------------|
| H_2 | 20 K |
| NH_3 | 240 K |

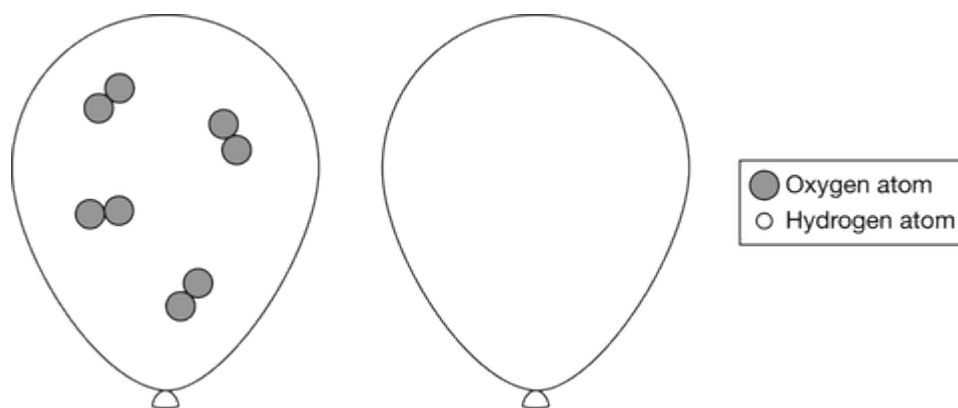
(f) A student claims that $\text{H}_2(g)$ condenses at a much lower temperature than $\text{NH}_3(g)$ because H_2 has stronger intermolecular forces than NH_3 does. There are two errors in the student's reasoning. Identify the student's errors and explain your answer in terms of the specific types of forces involved.

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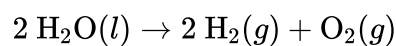
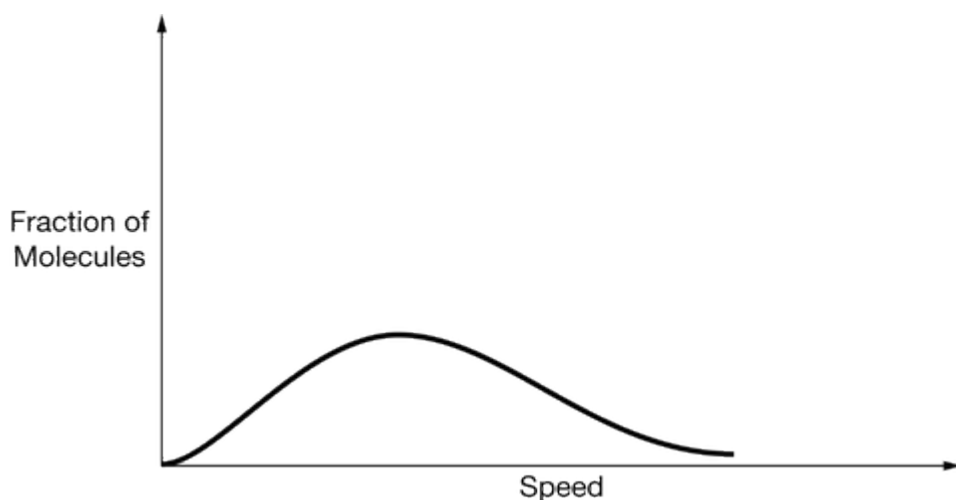
2. For parts of the free response question that require calculations, clearly show the method used and the steps involved in arriving at your answers. You must show your work to receive credit for your answer. Examples and equations may be included in your answers where appropriate.

Answer the following questions 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.

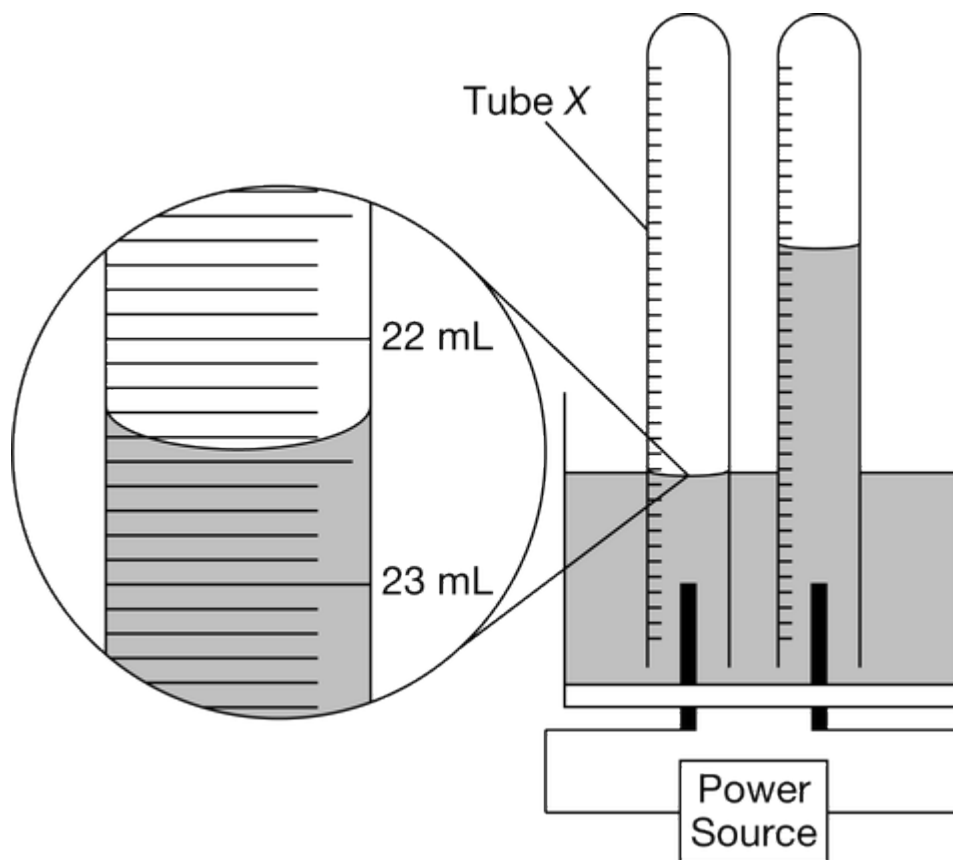


- (b) The graph below shows the Maxwell-Boltzmann distribution for $\text{H}_2(g)$. On the same graph, draw the distribution curve for $\text{O}_2(g)$ at the same temperature.

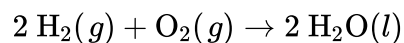


To generate the $\text{H}_2(g)$ and the $\text{O}_2(g)$, a student performs electrolysis of water, represented by the equation above. The student collects the gases in tubes and then adjusts the position of one of them so that the water levels inside and outside of the tube are the same, as shown in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

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- (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°C . The vapor pressure of water at 22.0°C is 0.026 atm . Calculate the pressure of dry gas in tube X .
- (g) The value of E° for the electrolysis of water is -1.23 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.

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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 related to CO_2 .

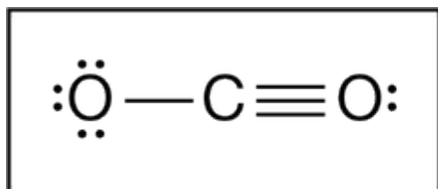


Diagram X

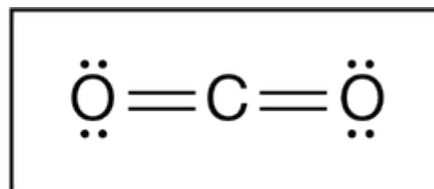
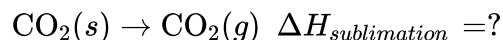
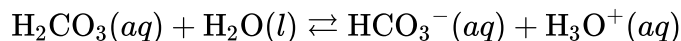


Diagram Z

- (a) Two possible Lewis electron-dot diagrams for 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 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°C and pressure of 0.998 atm. The physical change is represented by the following equation.



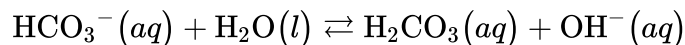
- (i) What is the sign (positive or negative) of the enthalpy change for the process of sublimation? Justify your answer.
- (ii) List all the numerical values of the quantities, with appropriate units, that are needed to calculate the volume of the balloon.
- (iii) Calculate the final volume, in liters, 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 CO_2 in water increases, more H_2CO_3 forms. Does the increase in the formation of H_2CO_3 cause the value of the reaction quotient, Q , for the system to increase, decrease, or remain the same? Justify your answer.

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(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.

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

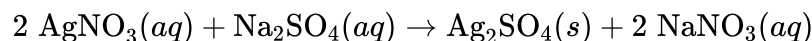
(ii) The K_b expression for the reaction of $\text{HCO}_3^- (aq)$ with $\text{H}_2\text{O} (l)$ is given above. Calculate the value of K_b for the reaction.

(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.

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 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.

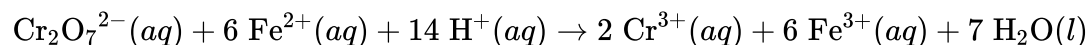
| | |
|---|--------|
| Mass of dry filter paper | 0.88 g |
| Mass of filter paper and precipitate immediately after filtration | 4.82 g |
| Mass of filter paper and precipitate after 10 minutes | 4.37 g |
| Mass of filter paper and precipitate after 20 minutes | 4.01 g |
| Mass of filter paper and precipitate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

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.

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.

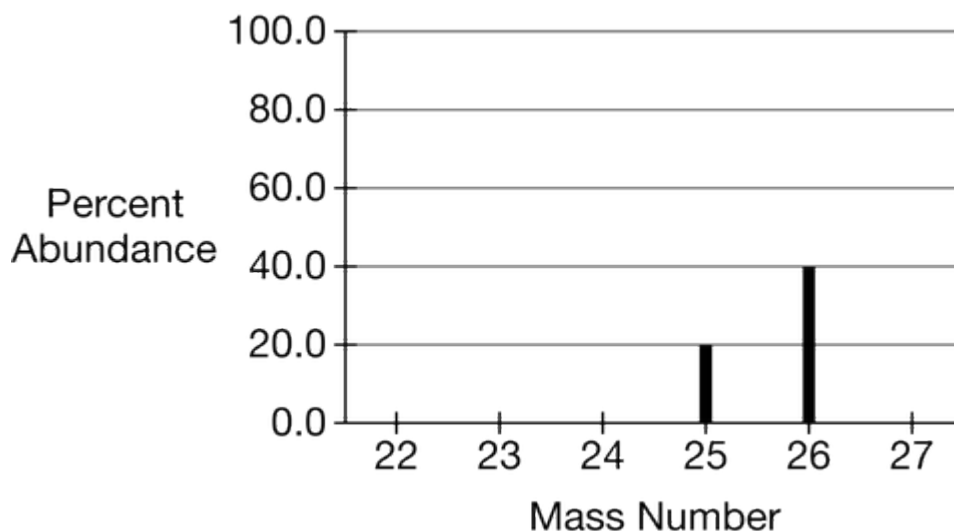
| | |
|-------------------------------------|----------|
| Mass of iron ore in original sample | 0.36 g |
| Buret reading at end point | 45.52 mL |
| Initial buret reading | 15.05 mL |

- (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 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.

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.

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.



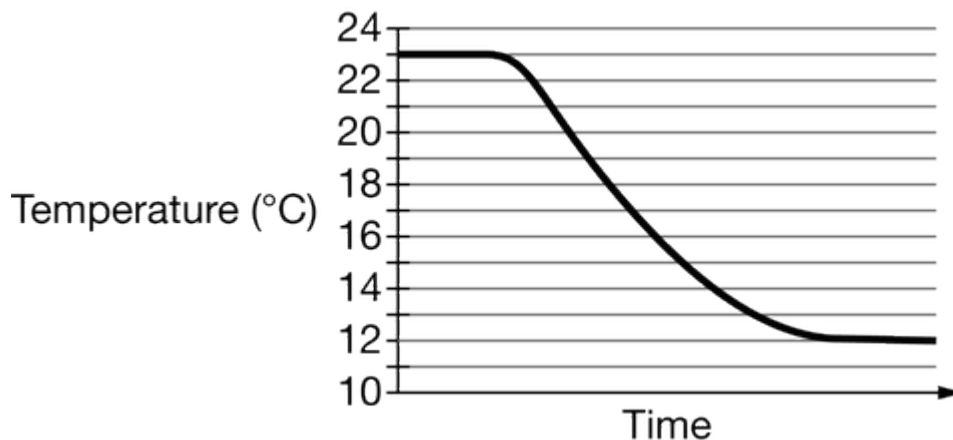
- (a) Draw a line on the graph to show the mass of the missing isotope and its percent abundance.
- (b) Use the completed mass spectrum to calculate the average atomic mass of Mg on the other planet.
- (c) The first ionization energy of magnesium samples found on Earth is experimentally determined to 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.

2021 FRQ

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 ΔH_{soln}° 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 ΔH_{soln}° in kJ/mol.