Question 3 (8 points)

$$CH_4(g) + 2\ Cl_2(g) \rightarrow CH_2Cl_2(g) + 2\ HCl(g)$$

Methane gas reacts with chlorine gas to form dichloromethane and hydrogen chloride, as represented by the equation above.

(a) A 25.0 g sample of methane gas is placed in a reaction vessel containing 2.58 mol of $Cl_2(g)$.

(i) Identify the limiting reactant when the methane and chlorine gases are combined. Justify your answer with a calculation.

Cl_2 is the limiting reactant because, in order to react with the given amount of CH_4, more moles of Cl_2 are required than the 2.58 moles of Cl_2 that are present. $25.0\text{ g }CH_4 \times \frac{1\text{ mol }CH_4}{16.04\text{ g }CH_4} \times \frac{2\text{ mol }Cl_2}{1\text{ mol }CH_4} = 3.12\text{ mol }Cl_2$	One point is earned for the correct answer with supporting calculation. (Alternative methods are acceptable.)

(ii) Calculate the total number of moles of $CH_2Cl_2(g)$ in the container after the limiting reactant has been totally consumed.

$2.58\text{ mol }Cl_2 \times \frac{1\text{ mol }CH_2Cl_2}{2\text{ mol }Cl_2} = \mathbf{1.29\text{ mol}}\ CH_2Cl_2$	One point is earned for the correct answer.

Initiating most reactions involving chlorine gas involves breaking the Cl–Cl bond, which has a bond energy of 242 kJ mol^{-1}.

(b) Calculate the amount of energy, in joules, needed to break a single Cl–Cl bond.

$242\ \frac{\text{kJ}}{\text{mol}} \times \frac{1{,}000\text{ J}}{1\text{ kJ}} \times \frac{1\text{ mol}}{6.02 \times 10^{23}} = \mathbf{4.02 \times 10^{-19}\ J}$	One point is earned for the correct answer with appropriate setup.

(c) Calculate the longest wavelength of light, in meters, that can supply the energy per photon necessary to break the Cl–Cl bond.

For electromagnetic radiation, $c = \lambda \nu$ and $E = h\nu$. $\nu = \frac{E}{h} = \frac{4.02 \times 10^{-19}\text{ J}}{6.63 \times 10^{-34}\text{ J s}} = 6.06 \times 10^{14}\text{ s}^{-1}$	One point is earned for a correct setup that is consistent with part (b). (Both appropriate equations or the combined equation $E = hc/\lambda$ are required.)
$\lambda = \frac{c}{\nu} = \frac{3.0 \times 10^{8}\text{ m s}^{-1}}{6.06 \times 10^{14}\text{ s}^{-1}} = \mathbf{4.9 \times 10^{-7}\ m}$	One point is earned for the correct answer.

Question 3 (continued)

The following mechanism has been proposed for the reaction of methane gas with chlorine gas. All species are in the gas phase.

Step 1	$Cl_2 \rightleftarrows 2\,Cl$	*fast equilibrium*
Step 2	$CH_4 + Cl \rightarrow CH_3 + HCl$	*slow*
Step 3	$CH_3 + Cl_2 \rightarrow CH_3Cl + Cl$	*fast*
Step 4	$CH_3Cl + Cl \rightarrow CH_2Cl_2 + H$	*fast*
Step 5	$H + Cl \rightarrow HCl$	*fast*

(d) In the mechanism, is CH_3Cl a catalyst, or is it an intermediate? Justify your answer.

CH_3Cl is an intermediate because it is produced in step 3 and consumed in step 4 of the reaction mechanism.	One point is earned for identification of CH_3Cl with appropriate justification.

(e) Identify the order of the reaction with respect to each of the following according to the mechanism. In each case, justify your answer.

(i) $CH_4(g)$

The order of the reaction with respect to CH_4 is 1. The rate law for the slowest step in the reaction, step 2, is rate = $k\,[CH_4]\,[Cl]$. Because the exponent of CH_4 in the rate law is 1, the order of the reaction with respect to CH_4 is 1.	One point is earned for the correct answer with appropriate justification.

(ii) $Cl_2(g)$

The order of the reaction with respect to Cl_2 is $\frac{1}{2}$. For step 1, $K = \frac{[Cl]^2}{[Cl_2]} \Rightarrow [Cl] = K^{1/2}\,[Cl_2]^{1/2}$ Substituting into the rate law for step 2 (the slowest step in the mechanism): rate = $k\,[CH_4]\,[Cl] = k\,[CH_4](K^{1/2}\,[Cl_2]^{1/2})$ $= (k)(K^{1/2})\,[CH_4]\,[Cl_2]^{1/2}$ Because the exponent of Cl_2 in the rate law is 1/2, the order of the reaction with respect to Cl_2 is 1/2.	One point is earned for the correct answer with appropriate justification.

$$CH_4(g) + 2\,Cl_2(g) \rightarrow CH_2Cl_2(g) + 2\,HCl(g)$$

3. Methane gas reacts with chlorine gas to form dichloromethane and hydrogen chloride, as represented by the equation above.

(a) A 25.0 g sample of methane gas is placed in a reaction vessel containing 2.58 mol of $Cl_2(g)$.

(i) Identify the limiting reactant when the methane and chlorine gases are combined. Justify your answer with a calculation.

(ii) Calculate the total number of moles of $CH_2Cl_2(g)$ in the container after the limiting reactant has been totally consumed.

Initiating most reactions involving chlorine gas involves breaking the Cl–Cl bond, which has a bond energy of 242 kJ mol^{-1}.

(b) Calculate the amount of energy, in joules, needed to break a single Cl–Cl bond.

(c) Calculate the longest wavelength of light, in meters, that can supply the energy per photon necessary to break the Cl–Cl bond.

The following mechanism has been proposed for the reaction of methane gas with chlorine gas. All species are in the gas phase.

Step 1	$Cl_2 \rightleftarrows 2\,Cl$	*fast equilibrium*
Step 2	$CH_4 + Cl \rightarrow CH_3 + HCl$	*slow*
Step 3	$CH_3 + Cl_2 \rightarrow CH_3Cl + Cl$	*fast*
Step 4	$CH_3Cl + Cl \rightarrow CH_2Cl_2 + H$	*fast*
Step 5	$H + Cl \rightarrow HCl$	*fast*

(d) In the mechanism, is CH_3Cl a catalyst, or is it an intermediate? Justify your answer.

(e) Identify the order of the reaction with respect to each of the following according to the mechanism. In each case, justify your answer.

(i) $CH_4(g)$

(ii) $Cl_2(g)$

Work

uh oh it an intermediate

e) slow step : $CH_4 + Cl \rightarrow CH_3 + HCl$ Rate = $k[CH_4][Cl]$

$k_f[Cl_2] = k_r[Cl]^2$

$\sqrt{\frac{k_f}{k_r}[Cl_2]} = \sqrt{[Cl]^2}$

$[Cl] = \sqrt{\frac{k_f}{k_r}[Cl_2]} = \sqrt{[Cl_2]} = [Cl_2]^{1/2}$

ADDITIONAL PAGE FOR ANSWERING QUESTION 3

a) molar mass of methane = 16.04 g/mol

molar mass Cl_2 = 70.90 g/mol

i) $\frac{25.0 \text{ g } CH_4}{} \left| \frac{1 \text{ mol}}{16.04 \text{ g}} \right. = 1.56 \text{ mol } CH_4$

XS $\frac{1.56 \text{ mol } CH_4}{} \left| \frac{1 \text{ mol } CH_2Cl_2}{1 \text{ mol } CH_4} \right. = 1.56 \text{ mol } CH_2Cl_2$

LR $\frac{2.58 \text{ mol } Cl_2}{} \left| \frac{1 \text{ mol } CH_2Cl_2}{2 \text{ mol } Cl_2} \right. = \boxed{1.29 \text{ mol } CH_2Cl_2} \leftarrow$ L.R

2.58 mol of Cl_2 forms less moles of product (1.29 mol CH_2Cl_2) than 1.56 mol of CH_4 does (1.56 mol CH_2Cl_2), ∴ Cl_2 is the limiting reagent.

ii) L.R is Cl_2 so . . .

$\frac{2.58 \text{ mol } Cl_2}{} \left| \frac{1 \text{ mol } CH_2Cl_2}{2 \text{ mol } Cl_2} \right. = \boxed{1.29 \text{ mol } CH_2Cl_2}$

b) $\frac{242 \text{ kJ}}{1 \text{ mol}} \left| \frac{1 \text{ mol}}{6.02 \times 10^{23} \text{ bonds}} \right| \frac{1000 \text{ J}}{1 \text{ kJ}} = \boxed{4.02 \times 10^{-19} \text{ J}}$

c) $E = h\nu$

$4.02 \times 10^{-19} \text{ J} = (6.63 \times 10^{-34} \text{ J·s})\,\nu$

$\nu = 6.06 \times 10^{14}$

$c = \lambda \nu$

$3.00 \times 10^8 = \lambda (6.06 \times 10^{14})$

$\lambda = \boxed{4.95 \times 10^{-7} \text{ m}}$

d) CH_3Cl is an intermediate because it is formed as a product, and later used as a reactant in the mechanism. It is not factored into the final equation of the mechanism. A catalyst is added as a reactant and formed later as a product.

e) See to the left for work $\quad$ Rate = $k[CH_4][Cl_2]^{1/2}$

← i) CH_4 is first order. ii) Cl_2 is in the ½ order

ADDITIONAL PAGE FOR ANSWERING QUESTION 3

(3) A) i $CH_4(g) + 2Cl_2(g) \rightarrow CH_2Cl_2 + 2HCl(g)$

$25.0g\ CH_4 \times \frac{1mol}{16g} \times \frac{2mol\ HCl}{1mol\ HCl} \times \frac{36.45g}{1mol\ HCl} = 113$ grams HCl

$2.58mol\ Cl_2 \times \frac{2mol\ HCl}{2mol\ Cl_2} \times \frac{36.45g}{1mol\ HCl} = 94.0$ grams HCl

Cl_2 gas is limiting b/c it produces least amount of product.

ii) $2.58\ mol\ Cl_2 \times \frac{1mol\ CH_2Cl_2}{2\ mol\ Cl_2} = \boxed{1.29\ mol\ CH_2Cl_2}$

B) $242\ kJ/mol \times \frac{1000\ J}{1\ kJ} = \boxed{242,000\ J/mol}$

C) $E = h\nu$ $\quad c = \lambda\nu$

$242,000J = 6.63\times10^{-34}\ Js\ \nu$ $\quad c = \lambda\nu$

$\nu = 3.65\times10^{38}s$ $\quad 3.0\times10^{8}\ m/s = \lambda\ (3.65\times10^{38}s)$

$\boxed{\lambda = 8.22\times10^{-31}m}$

D) It is an intermediate b/c it occurs as a product in one of the reactions and the mechanism and then is canceled out in the following step. Unlike a catalyst it was formed during the mechanism not added to it.

E) i CH_4 is first order because there is only one CH_4 in the slow step (rate determining step).

ii) Cl_2 is zero order because it does not occur in the slow step (rate determining step.)

ADDITIONAL PAGE FOR ANSWERING QUESTION 3

a i) $25g\ CH_4 \cdot \frac{1\ mol}{16g} \cdot \frac{1\ mol\ CH_2Cl_2}{1\ mol\ CH_4} = 1.56\ mol\ CH_2Cl_2$

$2.58\ mol\ Cl_2 \cdot \frac{1\ mol\ CH_2Cl_2}{2\ mol\ Cl_2} = 1.29\ mol\ CH_2Cl_2$

Cl_2 is the limiting reactant

ii) $1.29\ mol\ CH_2Cl_2$

b) $242 \frac{kJ}{mol} \cdot \frac{1000J}{1kJ} = 242{,}000J$

c) $242{,}000J = (6.63 \times 10^{-34}\ Js)v$

$v = 3.6 \times 10^{38}\ s^{-1}$

$(3 \times 10^8\ m/s) = \lambda(3.6 \times 10^{38}\ s^{-1})$

$\lambda = 8.22 \times 10^{-31}\ m$

d) catalyst, it is the product of the slow reaction and is then used in the fast reaction

e) i) 1st order, because there is 1 mol of CH_4 for every Cl_2

ii) 2nd order, because there are 2 mol of Cl for every Cl_2

Question 3

Overview

This question tested students' knowledge and a diverse set of skills relating to the topics of stoichiometry, bond energy, and kinetics. Parts (a)(i) and (a)(ii) assessed their ability to understand the mole relationships in a chemical reaction. When given quantities of two reactants in part (a)(i), one in grams and one in moles, students were required to mathematically justify their selection of the limiting reactant. In part (a)(ii) students were expected to calculate the amount of a product in moles based on their selection of the limiting reactant in part (a)(i). Parts (b) and (c) focused on bond energy; students needed to calculate the energy required to break a bond in part (b) and to calculate the wavelength of electromagnetic radiation required to break the bond in part (c). Parts (d) and (e) required students to answer questions about the kinetics of a reaction. In part (d) they had to recognize the placement and understand the meaning of an intermediate in a reaction mechanism, and in parts (e)(i) and (e)(ii) they were assessed on their ability to determine and justify the order of a reaction with respect to different reactants from the given mechanism.

Sample: 3A
Score: 8

This response earned all 8 points: 1 for part (a)(i), 1 for part (a)(ii), 1 for part (b), 2 for part (c), 1 for part (d), 1 for part (e)(i), and 1 for part (e)(ii).

Sample: 3B
Score: 6

The point was not earned in part (b) because Avogadro's number is not used to convert the energy from per mole to per bond. The point was not earned in part (e)(ii) because the order with respect to Cl_2 that is given is incorrect.

Sample: 3C
Score: 4

The point was not earned in part (b) because Avogadro's number is not used to convert the energy from per mole to per bond. Two points were earned in part (c), however, for calculating a wavelength consistent with the incorrect energy calculated in part (b). The point was not earned in part (d) because CH_3Cl is incorrectly identified as a catalyst. The point was not earned in part (e)(i) because, although the order is correctly identified, the justification is supplied by referring to the mole ratio of CH_4 to Cl in the rate-determining step. The point was not earned in part (e)(ii) because the order with respect to Cl_2 that is given is incorrect.