Past-paper walk-through

Lewis Diagrams ▪ 2.5

eXercise

Questions in this set

- 2025 Q3
- 2024 Q6
- 2022 Q2
- 2021 Q1
- 2018 Q2
- 2017 Q1
- 2016 Q2
- 2015 Q2
- 2014 Q5

Reading the mark scheme

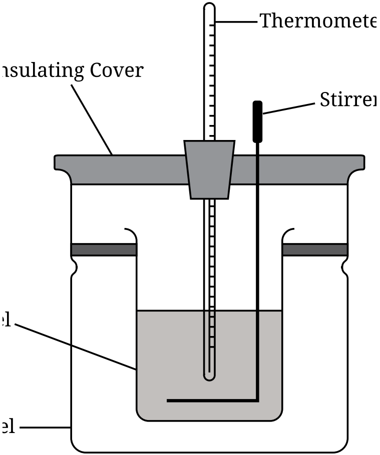
- **B1** a mark that stands on its own – the point is either made or not.
- **M1** a *method* mark: the right approach, even if the number is wrong.
- **A1** an *answer* mark, and it usually needs its M mark first.
- **C1** a working mark on the way to the answer.
- // separates answers the examiner accepts equally.
- **ecf** = error carried forward: a later part is marked on your own earlier answer.
- **owtte** = "or words to that effect" – the wording need not match.

Question 3

2025 ▪ Q3

White phosphorus is composed of P_4 molecules with a tetrahedral structure, as shown in the diagram on the left. Each P atom is bonded to the other three P atoms by single bonds, as shown in the incomplete Lewis diagram on the right.
[Left: a ball-and-stick tetrahedral structure of P_4, showing four P atoms (spheres) at the vertices of a tetrahedron connected by bonds (sticks).]
[Right: an incomplete Lewis diagram showing four P atoms arranged in a tetrahedral projection (one P at top, one P in the middle/front, two P at the bottom left and right), connected by single bonds forming the P4 skeleton, with no lone pairs drawn yet.]
(a) In the box in part A, complete the Lewis diagram for P_4 by drawing the nonbonding electrons.

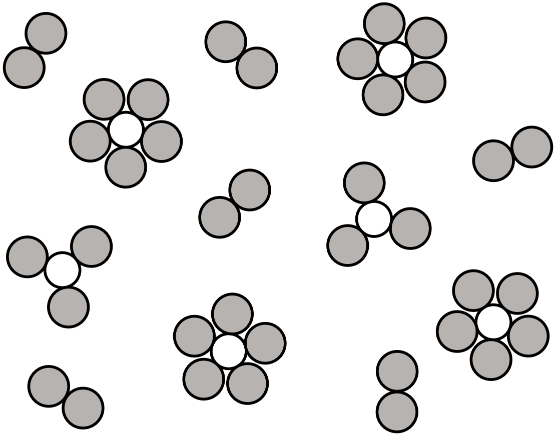
Question 3



Question 3

Mass of P_4O_{10}	0.100 g
Mass of H_2O	100.0 g
Initial temperature	22.00° C
Final temperature	22.38° C
Molar mass of P_4O_{10}	283.9 g/mol
Specific heat of H_2O	4.18 J/(g·°C)

Question 3



Question 3

2025 ▪ Q3

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[Right: an incomplete Lewis diagram showing four P atoms arranged in a tetrahedral projection (one P at top, one P in the middle/front, two P at the bottom left and right), connected by single bonds forming the P4 skeleton, with no lone pairs drawn yet.]

(b) The reaction of white phosphorus with oxygen to form $P_4O_{10}(s)$ is thermodynamically favorable at 298 K. The reaction is represented by equation 1.

Equation 1: $P_4(s) + 5\,O_2(g) \rightarrow P_4O_{10}(s)$

Question 3

(b)(i) The entropy change of the reaction, ΔS°, is negative. Using particle-level reasoning, explain why the entropy decreases as the reaction progresses.
(b)(ii) The enthalpy change of the reaction, ΔH°, is also negative. A student claims that the favorability of the reaction is driven by enthalpy and **not** by entropy. Is the student's claim correct? Justify your answer by using the relationship between ΔG°, ΔH°, and ΔS°.

Question 3

2025 ▪ Q3

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(c) $P_4O_{10}(s)$ reacts exothermically with water to form phosphoric acid, as represented by equation 2.

Equation 2: $P_4O_{10}(s) + 6\,H_2O(l) \rightarrow 4\,H_3PO_4(aq)$

Question 3

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

[Calorimeter diagram: a coffee-cup-style calorimeter labeled "Thermometer" (inserted through the insulating cover), "Stirrer" (inserted alongside the thermometer), "Insulating Cover" (the lid), "Inner Vessel" (the cup holding the solution, shaded), and "Outer Vessel" (the outer supporting cup).]

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

Quantity	Value
Mass of P_4O_{10}	0.100 g
Mass of H_2O	100.0 g
Initial temperature	$22.00°$C
Final temperature	$22.38°$C
Molar mass of P_4O_{10}	283.9 g/mol
Specific heat of H_2O	4.18 J/(g $\cdot°$ C)

(c)(i) Calculate the amount of heat, q, released during the experiment, in kJ. Assume that the specific heat of the solution is the same as that of water.

Question 3

(c)(ii) Calculate the value of ΔH°_{rxn} for equation 2 in $\mathrm{kJ/mol}_{rxn}$. Include the sign in your answer.

Question 3

2025 ▪ Q3

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[Right: an incomplete Lewis diagram showing four P atoms arranged in a tetrahedral projection (one P at top, one P in the middle/front, two P at the bottom left and right), connected by single bonds forming the P4 skeleton, with no lone pairs drawn yet.]

(d) The chemist weighed out 0.100 g P_4O_{10} of and 100.0 g of H_2O to perform a second trial. In the second trial, some of the solid P_4O_{10} stuck to the weighing paper and was not transferred to the calorimeter. Given that P_4O_{10} is the limiting reactant,

Question 3

would ΔT for the second trial be greater than, less than, or equal to the value in the first trial? Justify your answer.

$P_4(s)$ also reacts readily with $Cl_2(g)$ to produce phosphorus trichloride, $PCl_3(g)$, which in turn reacts with $Cl_2(g)$ in an equilibrium process to produce $PCl_5(g)$. The reactions are represented by equations 3 and 4.

Equation 3: $P_4(s) + 6\,Cl_2(g) \rightarrow 4\,PCl_3(g)$ $\qquad \Delta H_1^\circ = -1148$ kJ/mol$_{rxn}$

Equation 4: $PCl_3(g) + Cl_2(g) \rightleftharpoons PCl_5(g)$ $\qquad \Delta H_2^\circ = -88$ kJ/mol$_{rxn}$

Question 3

2025 ▪ Q3

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[Right: an incomplete Lewis diagram showing four P atoms arranged in a tetrahedral projection (one P at top, one P in the middle/front, two P at the bottom left and right), connected by single bonds forming the P4 skeleton, with no lone pairs drawn yet.]

(e) Calculate the standard enthalpy of formation of $PCl_5(g)$ represented by equation 5.

Equation 5: $\frac{1}{4}P_4(s) + \frac{5}{2}Cl_2(g) \rightarrow PCl_5(g) \qquad \Delta H_f^\circ = ?$

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

Question 3

[Particle diagram: a box containing multiple particles at random positions representing an equilibrium mixture; a key indicates two-atom particles (grey-grey) = Cl_2, four-atom tetrahedral-looking particles (grey with three white) = PCl_3, and six-atom particles (grey with five white) = PCl_5. The box shows several Cl_2 particles (pairs of grey circles), several PCl_3 particles (grey center with three white circles), and several PCl_5 particles (grey center with five white circles) scattered throughout.]

Question 3

2025 ▪ Q3

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[Right: an incomplete Lewis diagram showing four P atoms arranged in a tetrahedral projection (one P at top, one P in the middle/front, two P at the bottom left and right), connected by single bonds forming the P4 skeleton, with no lone pairs drawn yet.]

(f) Equation 4 for the reaction that occurs is shown.

Equation 4: $PCl_3(g) + Cl_2(g) \rightleftharpoons PCl_5(g) \qquad \Delta H_2^\circ = -88$ kJ/mol$_{rxn}$

(f)(i) If each particle in the diagram represents a partial pressure of 1.00 atm, what is the value of K_p for the equilibrium mixture at 546 K?

Question 3

(f)(ii) Does the value of K_p increase, decrease, or remain the same when the temperature is increased to 596 K? Justify your answer based on ΔH_2°.

Solution 3

(a)

Mark scheme

- Complete Lewis diagram for P_4: the four P atoms form a tetrahedron, each bonded to the other three P atoms by single bonds, and each P atom bears one lone (nonbonding) pair of electrons — giving each P three bonding pairs plus one lone pair, satisfying the octet rule.

Solution 3

(b)

Mark scheme

- No separate response required — this is the context/stem presenting equation 1 ($P_4(s) + 5\,O_2(g) \rightarrow P_4O_{10}(s)$), thermodynamically favorable at 298 K, that parts (i) and (ii) below refer to.

(b)(i)

Mark scheme

- Because gas particles are more dispersed (have more accessible microstates) than solids, the entropy decreases as the reactants (which include a gas, O_2) convert into the solid product (P_4O_{10}).

Solution 3

(b)(ii)

Mark scheme

- Yes, the student's claim is correct. Given $\Delta G^\circ_{rxn} = \Delta H^\circ_{rxn} - T\Delta S^\circ_{rxn}$, the reaction must have $\Delta G^\circ_{rxn} < 0$ to be favorable. Because the reaction is exothermic, $\Delta H^\circ_{rxn} < 0$ and enthalpy contributes to favorability. $\Delta S^\circ_{rxn} < 0$, so entropy does NOT contribute to favorability — i.e., enthalpy alone drives it.

Solution 3

(c)

Mark scheme

- No separate response required — this is the context/stem describing the calorimetry experiment for the exothermic reaction of $P_4O_{10}(s)$ with water (equation 2: $P_4O_{10}(s) + 6\,H_2O(l) \rightarrow 4\,H_3PO_4(aq)$) that parts (i) and (ii) below use.

Solution 3

(c)(i)

Mark scheme

- $q = mc\Delta T = (100.1\text{ g})(4.18\text{ J}/(\text{g}\cdot{}^\circ\text{C}))(22.38^\circ\text{C} - 22.00^\circ\text{C}) = 160\text{ J} = 0.16\text{ kJ}$ (reported to the correct number of significant figures).

Solution 3

(c)(ii)

Mark scheme

- $q_{rxn} = -q_{surr} = -0.16\ \text{kJ}.$
  $$\Delta H^{\circ}_{rxn} = \frac{-0.16\ \text{kJ}}{0.100\ \text{g P}_4\text{O}_{10}} \times \frac{283.9\ \text{g P}_4\text{O}_{10}}{1\ \text{mol P}_4\text{O}_{10}} \times \frac{1\ \text{mol P}_4\text{O}_{10}}{1\ \text{mol}_{rxn}} = -450\ \text{kJ/mol}_{rxn}.$$
  The correct (negative) sign must be included.

Solution 3

(d)

Mark scheme

- Less than. If less P_4O_{10} is present (some stuck to the weighing paper), less thermal energy will be transferred to the water during the reaction, causing the temperature increase (ΔT) to be less than it was with the full 0.100 g of P_4O_{10}.

Solution 3

(e)

Mark scheme

- Using Hess's law:
  $$\Delta H^\circ_{f,\mathrm{PCl_5}(g)} = \frac{1}{4}\Delta H^\circ_1 + \Delta H^\circ_2 = \frac{1}{4}(-1148) + (-88) = -375 \text{ kJ/mol.}$$

Solution 3

(f)

Mark scheme

- No separate response required — this is the context/stem presenting equation 4 ($PCl_3(g) + Cl_2(g) \rightleftharpoons PCl_5(g)$, $\Delta H_2^\circ = -88$ kJ/mol$_{rxn}$) that parts (i) and (ii) below refer to.

Solution 3

(f)(i)

Mark scheme

- Reading partial pressures of 1.00 atm per particle from the diagram (4 PCl_5, 2 PCl_3, 6 Cl_2 particles): $K_p = \dfrac{P_{PCl_5}}{(P_{PCl_3})(P_{Cl_2})} = \dfrac{4.00}{(2.00)(6.00)} = \dfrac{1}{3} = 0.333$.

Solution 3

(f)(ii)

Mark scheme

- Decrease. The negative value of ΔH_2° indicates the reaction is exothermic. Because exothermic reactions favor reactant formation at higher temperature (the equilibrium shifts toward reactants as heat is added), the value of K_p decreases.

Question 6

2024 ▪ Q6

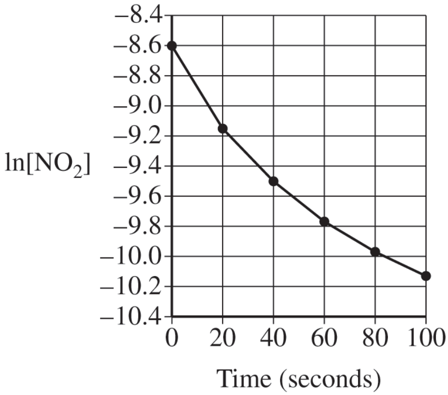
$$2\,\mathrm{NO_2} \rightarrow 2\,\mathrm{NO} + \mathrm{O_2}$$

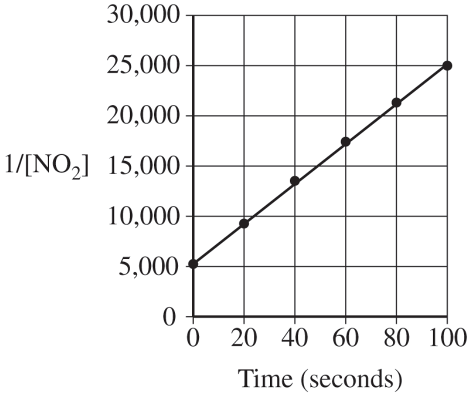
6. At elevated temperatures, NO_2 undergoes decomposition in the gas phase, forming NO and O_2 as represented by the following equation.
A scientist measures the change in $[NO_2]$ over the first 100. s of the reaction at 546°C. The scientist uses the data collected from the experiment to generate the following two graphs.
[Graph 1: $\ln[NO_2]$ vs. Time (seconds); y-axis from -10.4 to -8.4 in increments of 0.2, x-axis 0 to 100 s in increments of 20. Data points (approximately): (0, -8.6), (20, -9.15), (40, -9.55), (60, -9.85), (80, -10.05), (100, -10.15); points connected by a

Question 6

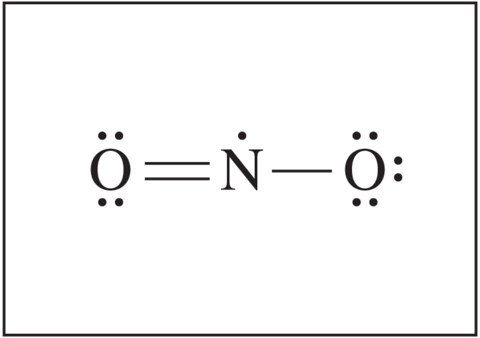
smooth decreasing curve, concave up (linearizing downward but curving), consistent with a non-linear $\ln[NO_2]$ vs. t relationship.]
[Graph 2: $1/[NO_2]$ vs. Time (seconds); y-axis from 0 to 30,000 in increments of 5,000, x-axis 0 to 100 s in increments of 20. Data points (approximately): (0, 5000), (20, 9800), (40, 13800), (60, 18000), (80, 21800), (100, 25200); points lie on a straight line of constant positive slope.]
Based on these data, the scientist makes the claim that the rate law for the reaction is $\mathit{rate} = k[NO_2]^2$.
(a) Explain how the graphs indicate that the reaction is second order with respect to NO_2.

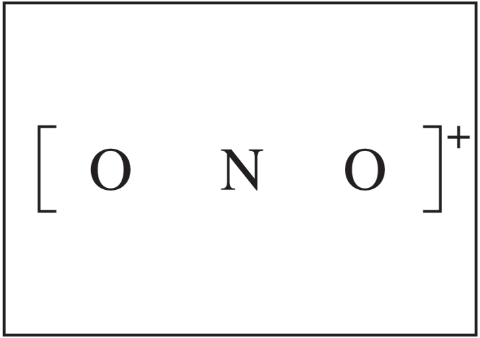
Question 6


ln[NO2]
−8.4
−8.6
−8.8
−9.0
−9.2
−9.4
−9.6
−9.8
−10.0
−10.2
−10.4
0
20
40
60
80
100
Time (seconds)


1/[NO2]
30,000
25,000
20,000
15,000
10,000
5,000
0
0
20
40
60
80
100
Time (seconds)

Question 6





Question 6

2024 ▪ Q6

$$2\,\mathrm{NO_2} \rightarrow 2\,\mathrm{NO} + \mathrm{O_2}$$

6. At elevated temperatures, NO_2 undergoes decomposition in the gas phase, forming NO and O_2 as represented by the following equation.
A scientist measures the change in $[\mathrm{NO_2}]$ over the first 100. s of the reaction at 546°C. The scientist uses the data collected from the experiment to generate the following two graphs.
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Question 6

[Graph 2: $1/[NO_2]$ vs. Time (seconds); y-axis from 0 to 30,000 in increments of 5,000, x-axis 0 to 100 s in increments of 20. Data points (approximately): (0, 5000), (20, 9800), (40, 13800), (60, 18000), (80, 21800), (100, 25200); points lie on a straight line of constant positive slope.]

Based on these data, the scientist makes the claim that the rate law for the reaction is $rate = k[NO_2]^2$.

(b) At a certain point in the reaction, the rate of disappearance of NO_2 is determined to be 6.52×10^{-7} M/s.

Determine the rate of appearance, in M/s, of O_2 at this same point in the reaction.

Question 6

2024 ▪ Q6

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Question 6

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Based on these data, the scientist makes the claim that the rate law for the reaction is $rate = k[NO_2]^2$.

(c) NO_2 is a molecule that contains an odd number of electrons and can be oxidized to form the NO_2^+ ion. In NO_2, the unpaired electron is presumed to be localized on the nitrogen atom, as shown in the Lewis diagram in the box on the left.

[Two boxes side by side. Left box: Lewis structure of NO_2 — O (with two lone pairs) double-bonded on the left to a central N (bearing an unpaired dot, single electron, above it), N single-bonded on the right to another O (bearing three lone pairs, i.e., a negative-type oxygen with full octet): $\ddot{\text{O}} = \dot{\text{N}} - \ddot{\text{O}}:$ with all lone pairs shown as dots. Right box: empty bracket template $[\ \text{O} \quad \text{N} \quad \text{O}\ ]^+$ for the student to complete with

Question 6

the Lewis structure of NO_2^+, showing atoms O, N, O in a row inside square brackets with a superscript plus charge, currently drawn with no bonds or lone pairs (blank template for the student to fill in).]

(c)(i) In the box on the right, complete the Lewis diagram for NO_2^+. Be sure to show all bonding and nonbonding electrons.

(c)(ii) A student makes the claim that the bond angles in NO_2 and NO_2^+ are different from each other. Do you agree or disagree with the student's claim? Justify your answer.

Solution 6

(a)

Mark scheme

- The plot of $1/[\mathrm{NO_2}]$ versus time is the most linear of the tested plots, which indicates that the reaction is second order with respect to NO_2 (a linear $1/[A]$ vs. t plot is the diagnostic signature of second-order kinetics).

Solution 6

(b)

Mark scheme

- Rate of appearance of O_2
  $= 6.52 \times 10^{-7}\ M/\text{s} \times \dfrac{1\ \text{mol } O_2}{2\ \text{mol } NO_2} = 3.26 \times 10^{-7}\ M/\text{s}.$

Solution 6

(c)

Mark scheme

- Context only — shows the given Lewis structure of NO_2 (O with two lone pairs double-bonded to a central N bearing one unpaired/nonbonding electron, N singly bonded to a second O with three lone pairs); sets up parts (c)(i) and (c)(ii). No separate scorable response for this leaf.

Solution 6

(c)(i)

Mark scheme

- Lewis diagram for NO_2^+ (isoelectronic with CO_2): linear $O = N = O$ structure, $[\ddot{O} = N = \ddot{O}]^+$, each O atom has two lone pairs, N has no lone pair and no unpaired electron (all 4 electron domains are used in the two double bonds), overall ion charge $+1$.

Solution 6

(c)(ii)

Mark scheme

- Agree. Accept either justification: (1) NO_2^+ no longer has a nonbonding/unpaired electron on the central N (unlike NO_2), so the two O atoms spread farther apart into a linear 180° geometry, different from NO_2's bent shape. (2) N in NO_2 is *sp*^{2} hybridized (bond angle $\approx 120°$), while N in NO_2^+ is *sp* hybridized (bond angle $= 180°$), so the bond angles differ.

Question 2

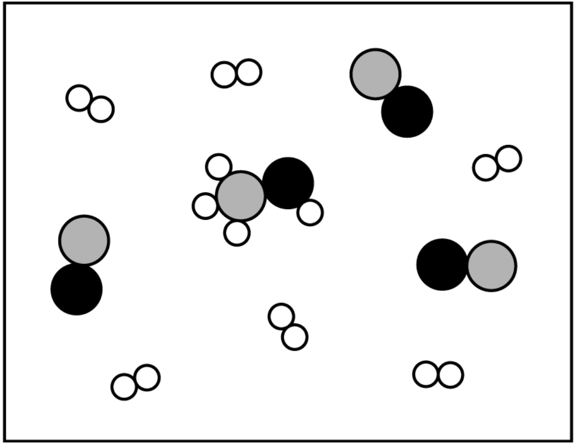
2022 ▪ Q2

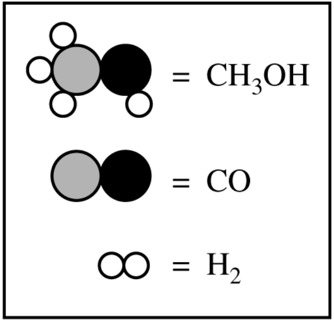
$$CH_3OH(g) \rightleftharpoons CO(g) + 2\,H_2(g) \qquad \Delta H^\circ = 90.0 \text{ kJ/mol}_{rxn}$$

Methanol vapor decomposes to form carbon monoxide gas and hydrogen gas at high temperatures in the presence of a platinum catalyst, as represented by the balanced chemical equation given.

(a) Are the hydrogen atoms oxidized or are they reduced in the forward reaction? Justify your answer in terms of oxidation numbers.

Question 2





Question 2

2022 ▪ Q2

$$CH_3OH(g) \rightleftharpoons CO(g) + 2\,H_2(g) \qquad \Delta H^\circ = 90.0\ \text{kJ/mol}_{rxn}$$

Methanol vapor decomposes to form carbon monoxide gas and hydrogen gas at high temperatures in the presence of a platinum catalyst, as represented by the balanced chemical equation given.

(b) In the following box, draw the complete Lewis electron-dot diagram for the carbon monoxide molecule in which every atom obeys the octet rule. Show all bonding and nonbonding valence electrons.

[A blank box is provided containing the unconnected atomic symbols “C” and “O”, for the student to complete into a full Lewis structure.]

Question 2

2022 ▪ Q2

$$\mathrm{CH_3OH}(g) \rightleftharpoons \mathrm{CO}(g) + 2\,\mathrm{H_2}(g) \qquad \Delta H^\circ = 90.0 \text{ kJ/mol}_{rxn}$$

Methanol vapor decomposes to form carbon monoxide gas and hydrogen gas at high temperatures in the presence of a platinum catalyst, as represented by the balanced chemical equation given.

(c)(i) The values of the standard molar entropies of the compounds involved in the reaction are given in the following table.

Substance	S° (J/(K · mol))
$\mathrm{CH_3OH}(g)$	240.
$\mathrm{CO}(g)$	198
$\mathrm{H_2}(g)$	131

Use the data in the table to calculate the value of the standard entropy change, ΔS°, in J/(K · mol_{rxn}), for the reaction.

Question 2

(c)(ii) Calculate the value of ΔG°, in kJ/mol$_{rxn}$, for the reaction at 375 K. Assume that ΔH° and ΔS° are independent of temperature.

Question 2

2022 ▪ Q2

$$CH_3OH(g) \rightleftharpoons CO(g) + 2\,H_2(g) \qquad \Delta H^\circ = 90.0\ \text{kJ/mol}_{rxn}$$

Methanol vapor decomposes to form carbon monoxide gas and hydrogen gas at high temperatures in the presence of a platinum catalyst, as represented by the balanced chemical equation given.

(d) The following particle-level diagram shows a representative sample of the equilibrium mixture represented by the equation given.
[A rectangular box (the "container") contains a mixture of particles at equilibrium: several two-linked-open-circle pairs (H), and several three-part particles each made of one gray sphere + one black sphere + one small open circle (CO), plus one larger cluster shown as CH OH. A key box beside it identifies: a cluster of one gray sphere +

Question 2

one black sphere + three small open circles = CH_3OH; one gray sphere + one black sphere = CO; two small open circles joined = H_2. Counting the container: there appear to be 1 CH OH particle, 4 CO particles, and 8 H particles.]
Use information from the particle diagram to calculate the partial pressure of CO at equilibrium when the total pressure of the equilibrium mixture is 12.0 atm.

Question 2

2022 ▪ Q2

$$\mathrm{CH_3OH}(g) \rightleftharpoons \mathrm{CO}(g) + 2\,\mathrm{H_2}(g) \qquad \Delta H^\circ = 90.0\ \mathrm{kJ/mol}_{rxn}$$

Methanol vapor decomposes to form carbon monoxide gas and hydrogen gas at high temperatures in the presence of a platinum catalyst, as represented by the balanced chemical equation given.

(e) Write the expression for the equilibrium constant, K_p, for the reaction.

Question 2

2022 ▪ Q2

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Methanol vapor decomposes to form carbon monoxide gas and hydrogen gas at high temperatures in the presence of a platinum catalyst, as represented by the balanced chemical equation given.

(f)

$$\mathrm{CH_3OH}(g) \rightleftharpoons \mathrm{CO}(g) + 2\,\mathrm{H_2}(g)$$

The reaction system represented by the equation is allowed to achieve equilibrium at a different temperature. The following table gives the partial pressure of each species in the equilibrium mixture.

Question 2

Substance	Partial Pressure at Different Temperature
$CH_3OH(g)$	2.7 atm
$CO(g)$	4.2 atm
$H_2(g)$	8.4 atm

Use the information in the table to calculate the value of the equilibrium constant, K_p, at the new temperature.

Question 2

2022 ▪ Q2

$$\mathrm{CH_3OH}(g) \rightleftharpoons \mathrm{CO}(g) + 2\,\mathrm{H_2}(g) \qquad \Delta H^\circ = 90.0\ \mathrm{kJ/mol}_{rxn}$$

Methanol vapor decomposes to form carbon monoxide gas and hydrogen gas at high temperatures in the presence of a platinum catalyst, as represented by the balanced chemical equation given.

(g) The volume of the container is rapidly doubled with no change in temperature. As equilibrium is re-established, does the number of moles of $CH_3OH(g)$ increase, decrease, or remain the same? Justify your answer by comparing the value of the reaction quotient, Q, with the value of the equilibrium constant, K_p.

Solution 2

(a)

Mark scheme

- The H atoms are reduced because they change from an oxidation number of $+1$ (in CH3OH) to 0 (in H2) in the forward reaction.

Solution 2

(b)

Mark scheme

- Complete Lewis electron-dot diagram for CO obeying the octet rule: a carbon–oxygen triple bond (:C$\equiv$O:) with one lone pair on carbon and one lone pair on oxygen, giving each atom an octet (triple bond $= 6$ shared electrons $+ 1$ lone pair $= 8$ electrons around each atom).

Solution 2

(c)(i)

Mark scheme

- $\Delta S°rxn = \Sigma\Delta S°products - \Sigma\Delta S°reactants = (\Delta S°CO(g) + 2\Delta S°H2(g)) - \Delta S°CH3OH(g)$ (1 point for correct stoichiometry, may be implicit). Using the table values (S°: CH3OH(g) = 240. J/(K · mol), CO(g) = 198 J/(K · mol), H2(g) = 131 J/(K · mol)): $\Delta S°rxn = 198 + 2(131) - 240. = 220.$ J/(K · mol_rxn) (1 point for the correct calculated value).

Solution 2

(c)(ii)

Mark scheme

- $\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ = 90.0$ kJ/mol_rxn $- (375$ K$)(0.220$ kJ/(K $\cdot$ mol_rxn$)) = +7.5$ kJ/mol_rxn (assuming ΔH° and ΔS° are independent of temperature).

Solution 2

(d)

Mark scheme

- From the particle-level diagram, CO particles make up 3 of the 10 total gas particles shown in the container. With a total pressure of 12.0 atm: P_CO $=$ (3/10)(12.0 atm) $=$ 3.6 atm.

Solution 2

(e)

Mark scheme

- Kp = (P_CO)(P_H2)² / (P_CH3OH).

Solution 2

(f)

Mark scheme

- Using the partial pressures at the new equilibrium temperature (CH_3OH = 2.7 atm, CO = 4.2 atm, H_2 = 8.4 atm): $K_p = (P_{CO})(P_{H_2})^2 / (P_{CH_3OH}) = (4.2)(8.4)^2 / (2.7) = 110$.

Solution 2

(g) Mark scheme

- Comparison of Q and K (1 point): doubling the container volume causes the partial pressure of each species to decrease by a factor of two; because there are more moles of gaseous products than reactants, the resulting decrease in the numerator of Q is larger (raised to a higher net power) than the decrease in the denominator, making $Qp < Kp$ — explicitly $Qp = [(P\_CO/2)(P\_H2/2)^2] / (P\_CH3OH/2) = Kp/4 \approx 27 < Kp$. Answer and justification (1 point): the number of moles of CH3OH(g) will decrease. Since $Qp < Kp$, the reaction proceeds forward as equilibrium re-establishes, increasing the partial pressures (moles) of the products and decreasing the moles of CH3OH.

Question 1

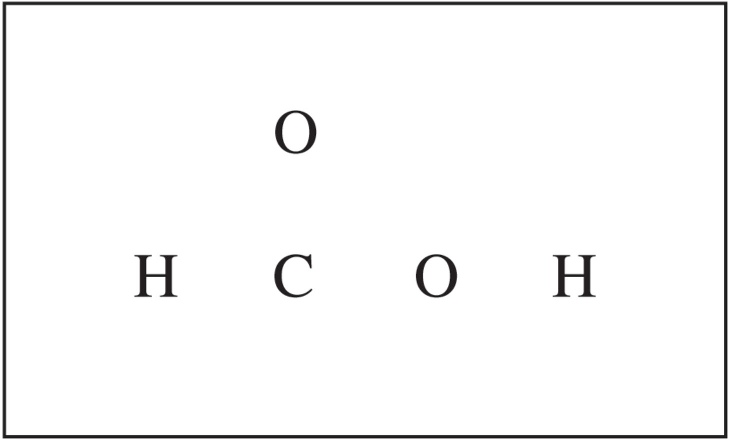
2021 ▪ Q1

$$\mathrm{HCOOH}(aq) + \mathrm{H_2O}(l) \rightleftharpoons \mathrm{H_3O^+}(aq) + \mathrm{HCOO^-}(aq) \qquad K_a = 1.8 \times 10^{-4}$$

Methanoic acid, HCOOH, ionizes according to the equation above.

(a) Write the expression for the equilibrium constant, K_a, for the reaction.

Question 1



Question 1

2021 ▪ Q1

$$\mathrm{HCOOH}(aq) + \mathrm{H_2O}(l) \rightleftharpoons \mathrm{H_3O^+}(aq) + \mathrm{HCOO^-}(aq) \qquad K_a = 1.8 \times 10^{-4}$$

Methanoic acid, HCOOH, ionizes according to the equation above.

(b) Calculate the pH of a 0.25 *M* solution of HCOOH.

Question 1

2021 ▪ Q1

$$\text{HCOOH}(aq) + \text{H}_2\text{O}(l) \rightleftharpoons \text{H}_3\text{O}^+(aq) + \text{HCOO}^-(aq) \qquad K_a = 1.8 \times 10^{-4}$$

Methanoic acid, HCOOH, ionizes according to the equation above.

(c) In the box below, complete the Lewis electron-dot diagram for HCOOH. Show all bonding and nonbonding valence electrons.

[Box containing the skeletal atom arrangement of HCOOH (no bonds or lone pairs drawn), laid out as:

```
        O
        |
H - C - O - H
```

Question 1

i.e. a central C bonded to: an O atom above it (drawn separated, no bond line shown), an H atom to its left, and an O atom to its right which is in turn bonded to a further H atom on the far right. The student must add all bonding and nonbonding valence electrons to complete the Lewis structure.]

Question 1

2021 ▪ Q1

$$HCOOH(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + HCOO^-(aq) \qquad K_a = 1.8 \times 10^{-4}$$

Methanoic acid, HCOOH, ionizes according to the equation above.

(d)(i)

$$H_2NNH_2(aq) + H_2O(l) \rightleftharpoons H_2NNH_3^+(aq) + OH^-(aq) \qquad K_b = 1.3 \times 10^{-6}$$

In aqueous solution, the compound H_2NNH_2 reacts according to the equation above. A 50.0 mL sample of 0.25 M $H_2NNH_2(aq)$ is combined with a 50.0 mL sample of 0.25 M $HCOOH(aq)$.

Write the balanced net ionic equation for the reaction that occurs when H_2NNH_2 is combined with HCOOH.

(d)(ii) Is the resulting solution acidic, basic, or neutral? Justify your answer.

Question 1

2021 ▪ Q1

$$HCOOH(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + HCOO^-(aq) \qquad K_a = 1.8 \times 10^{-4}$$

Methanoic acid, HCOOH, ionizes according to the equation above.

(e) When a catalyst is added to a solution of $HCOOH(aq)$, the reaction represented by the following equation occurs.

$$HCOOH(aq) \rightarrow H_2(g) + CO_2(g)$$

Is the reaction a redox reaction? Justify your answer.

Question 1

2021 ▪ Q1

$$\mathrm{HCOOH}(aq) + \mathrm{H_2O}(l) \rightleftharpoons \mathrm{H_3O^+}(aq) + \mathrm{HCOO^-}(aq) \qquad K_a = 1.8 \times 10^{-4}$$

Methanoic acid, HCOOH, ionizes according to the equation above.

(f) [Graph: Total Pressure (atm) on the y-axis (from 0 to above 24, with a dashed horizontal line at 24) vs. Time (hours) on the x-axis. The curve rises steeply from the origin, curving and leveling off asymptotically to a plateau at a total pressure of 24 atm.]

The reaction occurs in a rigid 4.3 L vessel at 25°C, and the total pressure is monitored, as shown in the graph above. The vessel originally did not contain any gas. Calculate the number of moles of $CO_2(g)$ produced in the reaction. (Assume that the amount of $CO_2(g)$ dissolved in the solution is negligible.)

Question 1

2021 ▪ Q1

$$\text{HCOOH}(aq) + \text{H}_2\text{O}(l) \rightleftharpoons \text{H}_3\text{O}^+(aq) + \text{HCOO}^-(aq) \qquad K_a = 1.8 \times 10^{-4}$$

Methanoic acid, HCOOH, ionizes according to the equation above.

(g) After the reaction has proceeded for several minutes, does the amount of catalyst increase, decrease, or remain the same? Justify your answer.

Solution 1

(a)

Mark scheme

- $K_a = \dfrac{[H_3O^+][HCOO^-]}{[HCOOH]}$ — the correct equilibrium-constant expression for the dissociation of HCOOH (products over reactant; water omitted as pure liquid).

Solution 1

(b)

Mark scheme

- ICE table for HCOOH + H2O   H3O+ + HCOO-, initial [HCOOH]=0.25 M: $K_a = 1.8 \times 10^{-4} = \dfrac{x^2}{0.25 - x}$. Assuming $x \ll 0.25$: $x^2 = (1.8 \times 10^{-4})(0.25) \Rightarrow x = [\mathrm{H_3O^+}] = 0.0067\ M$ (1 pt). Then $\mathrm{pH} = -\log[\mathrm{H_3O^+}] = -\log(0.0067) = 2.17$ (1 pt, consistent with the calculated concentration).

Solution 1

(c)

Mark scheme

- Correct complete Lewis structure of HCOOH (formic acid): H–C(=O)–O–H. The central C is bonded to: an H atom (single bond), a terminal O by a double bond (that terminal O carries 2 lone pairs), and a second O by a single bond (that O carries 2 lone pairs and is also single-bonded to the second H). All bonding pairs and all nonbonding (lone) pairs of valence electrons must be shown explicitly.

Solution 1

(d)(i)

Mark scheme

- $H_2NNH_2(aq) + HCOOH(aq) \rightarrow H_2NNH_3^+(aq) + HCOO^-(aq)$ — the weak base H2NNH2 accepts a proton from the weak acid HCOOH; already balanced as written (state symbols not required).

Solution 1

(d)(ii)

Mark scheme

- Acidic. The resulting solution is a mixture of the conjugate acid H2NNH3+ and the conjugate base HCOO-. Because the K_a of $H_2NNH_3^+$ is greater than the K_b of $HCOO^-$, production of $H_3O^+(aq)$ occurs to a greater extent than production of $OH^-(aq)$, so the solution is acidic.

Solution 1

(e)

Mark scheme

- Yes, it is a redox reaction. Accept either valid justification: the oxidation number of hydrogen changes from +1 in HCOOH to 0 in H2 (reduction); or the oxidation number of carbon changes from +2 in HCOOH to +4 in CO2 (oxidation).

Solution 1

(f) Mark scheme

- Reaction HCOOH(aq) $\rightarrow$ H2(g) $+$ CO2(g) produces H2 and CO2 in a 1:1 mole ratio, so each contributes half the total pressure:
  $P_{CO_2} = 24 \text{ atm} \times \dfrac{1 \text{ atm } CO_2}{2 \text{ atm product}} = 12 \text{ atm}$ (1 pt, may be implicit). Then using the ideal gas law $PV = nRT$ with V=4.3 L, T=298 K:
  $n = \dfrac{PV}{RT} = \dfrac{(12 \text{ atm})(4.3 \text{ L})}{(0.08206 \text{ L} \cdot \text{atm} \cdot \text{mol}^{-1}\text{K}^{-1})(298 \text{ K})} = 2.1 \text{ mol } CO_2$ (1 pt).

Solution 1

(g)

Mark scheme

- It would remain the same. In a catalyzed reaction the catalyst is not consumed — it participates in the mechanism but is regenerated — so the net amount of catalyst present stays constant over time.

Question 2

2018 ▪ Q2

$$2\,\mathrm{NO}(g) + \mathrm{O_2}(g) \rightarrow 2\,\mathrm{NO_2}(g)$$

A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $NO(g)$ and $NO_2(g)$, which the student produces by using the reaction represented above.

(a) The particle-level representation of the equimolar mixture of $NO(g)$ and $NO_2(g)$ in the flask at the completion of the reaction between $NO(g)$ and $O_2(g)$ is shown below in the box on the right. In the box below on the left, draw the particle-level representation of the reactant mixture of $NO(g)$ and $O_2(g)$ that would yield the product mixture shown in the box on the right. In your drawing, represent oxygen atoms and nitrogen atoms as indicated below.

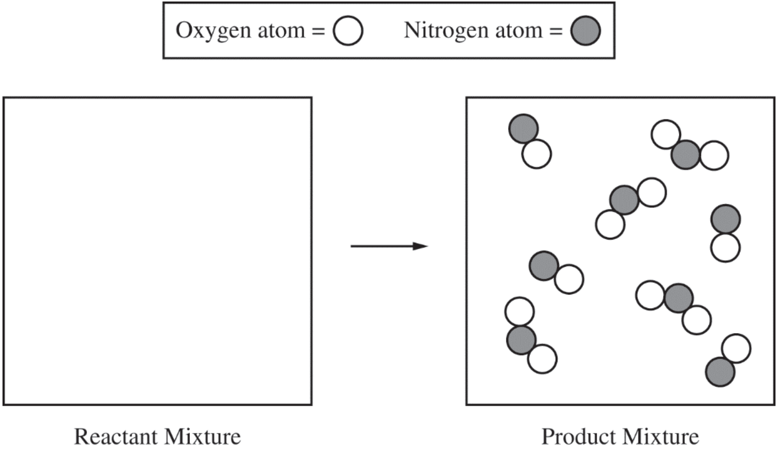
Question 2

[Key: Oxygen atom = open (white) circle; Nitrogen atom = filled (gray) circle.]
[Two boxes side by side connected by an arrow. Left box labeled "Reactant Mixture" is empty (for the student to draw in). Right box labeled "Product Mixture" shows a particle-level representation containing 6 NO molecules (each one open circle bonded to one filled circle) and 6 NO_2 molecules (each one filled circle bonded to two open circles), scattered randomly in the box.]
The student reads in a reference text that NO(g) and $NO_2(g)$ will react as represented by the equation below. Thermodynamic data for the reaction are given in the table below the equation.

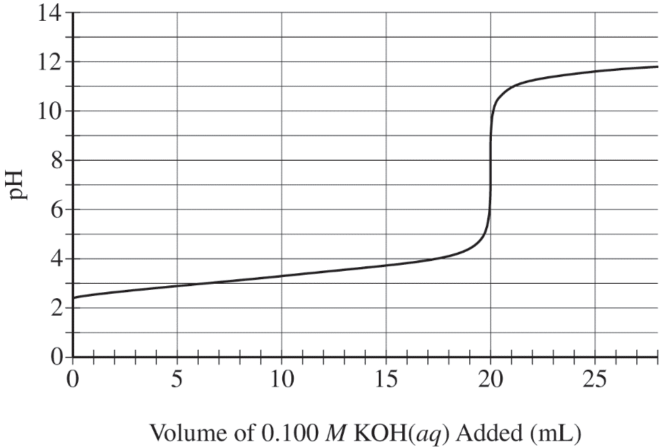
$$\mathrm{NO}(g) + \mathrm{NO_2}(g) \rightleftharpoons \mathrm{N_2O_3}(g)$$

ΔH°_{298}	ΔS°_{298}	ΔG°_{298}
-40.4 kJ/mol$_{rxn}$	-138.5 J/(K · mol$_{rxn}$)	0.87 kJ/mol$_{rxn}$

Question 2


Oxygen atom =
Nitrogen atom =
Reactant Mixture
Product Mixture

Question 2



Question 2

$$NO(g) + NO_2(g) \rightleftarrows N_2O_3(g)$$

ΔH°_{298}	ΔS°_{298}	ΔG°_{298}
$-40.4\ kJ/mol_{rxn}$	$-138.5\ J/(K \cdot mol_{rxn})$	$0.87\ kJ/mol_{rxn}$

Question 2

2018 ▪ Q2

$$2\,\mathrm{NO}(g) + \mathrm{O_2}(g) \rightarrow 2\,\mathrm{NO_2}(g)$$

A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $NO(g)$ and $NO_2(g)$, which the student produces by using the reaction represented above.

(b)(i) The student begins with an equimolar mixture of $NO(g)$ and $NO_2(g)$ in a rigid reaction vessel and the mixture reaches equilibrium at 298 K.

Calculate the value of the equilibrium constant, K, for the reaction at 298 K.

(b)(ii) If both P_{NO} and $P_{\mathrm{NO_2}}$ in the vessel are initially 1.0 atm, will $P_{\mathrm{N_2O_3}}$ at equilibrium be equal to 1.0 atm? Justify your answer.

Question 2

2018 ▪ Q2

$$2\,\mathrm{NO}(g) + \mathrm{O_2}(g) \rightarrow 2\,\mathrm{NO_2}(g)$$

A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $NO(g)$ and $NO_2(g)$, which the student produces by using the reaction represented above.

(c) The student hypothesizes that increasing the temperature will increase the amount of $N_2O_3(g)$ in the equilibrium mixture. Indicate whether you agree or disagree with the hypothesis. Justify your answer.

$N_2O_3(g)$ reacts with water to form nitrous acid, $HNO_2(aq)$, a compound involved in the production of acid rain. The reaction is represented below.

Question 2

$$N_2O_3(g) + H_2O(l) \rightarrow 2\,HNO_2(aq)$$

Question 2

2018 ▪ Q2

$$2\,\mathrm{NO}(g) + \mathrm{O_2}(g) \rightarrow 2\,\mathrm{NO_2}(g)$$

A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $NO(g)$ and $NO_2(g)$, which the student produces by using the reaction represented above.

(d)(i) The skeletal structure of the HNO_2 molecule is shown in the box below.
[Box showing the skeletal structure: H O N O, written left to right in a line.]
Complete the Lewis electron-dot diagram of the HNO_2 molecule in the box below, including any lone pairs of electrons.

(d)(ii) Based on your completed diagram above, identify the hybridization of the nitrogen atom in the HNO_2 molecule.

Question 2

To produce an aqueous solution of HNO_2, the student bubbles $N_2O_3(g)$ into distilled water. Assume that the reaction goes to completion and that HNO_2 is the only species produced. To determine the concentration of $HNO_2(aq)$ in the resulting solution, the student titrates a 100. mL sample of the solution with 0.100 M $KOH(aq)$. The neutralization reaction is represented below.

$$HNO_2(aq) + OH^-(aq) \rightarrow NO_2^-(aq) + H_2O(l)$$

The following titration curve shows the change in pH of the solution during the titration.
[Titration curve graph: Y-axis pH from 0 to 14 in increments of 2. X-axis "Volume of 0.100 M KOH(aq) Added (mL)" from 0 to 25+ in increments of 5. The curve starts around pH 2.3 at 0 mL, rises very gradually and slightly through a small buffer region

Question 2

to about pH 4 near 15-18 mL, then rises steeply (equivalence point) around 20 mL up to about pH 12, then levels off gradually toward pH 12-13 by 25 mL.]

Question 2

2018 ▪ Q2

$$2\,\mathrm{NO}(g) + \mathrm{O_2}(g) \rightarrow 2\,\mathrm{NO_2}(g)$$

A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $NO(g)$ and $NO_2(g)$, which the student produces by using the reaction represented above.

(e)(i) Use the titration curve and the information above to determine the initial concentration of the $HNO_2(aq)$ solution.

(e)(ii) Use the titration curve and the information above to estimate the value of pK_a for $HNO_2(aq)$.

Question 2

2018 ▪ Q2

$$2\,NO(g) + O_2(g) \rightarrow 2\,NO_2(g)$$

A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $NO(g)$ and $NO_2(g)$, which the student produces by using the reaction represented above.

(f) During the titration, after a volume of 15 mL of 0.100 M $KOH(aq)$ has been added, which species, $HNO_2(aq)$ or $NO_2^-(aq)$, is present at a higher concentration in the solution? Justify your answer.

Solution 2

(a)

Mark scheme

- The reactant mixture must contain 8 NO(g) molecules and 2 O2(g) molecules. As 2 NO(g) + O2(g) -> 2 NO2(g) proceeds (O2 limiting), 4 NO react with the 2 O2 to form 4 NO2, leaving 4 NO unreacted, giving the equimolar 4 NO : 4 NO2 product mixture shown. 1 point is earned for correctly representing the molecules of NO and O2 (8 NO + 2 O2, drawn as separate diatomic particles using the given atom key); 1 point is earned for correctly representing atom conservation between the reactant and product boxes (same total number of N atoms and O atoms in both boxes).

Solution 2

(b)(i)

Mark scheme

- DeltaG = -RT ln K, so K = e^(-DeltaG/RT) = e^[-870 J/mol / ((8.314 J/(mol K))(298 K))] = e^(-0.351) = 0.70. 1 point is earned for the correct calculation of K.

Solution 2

(b)(ii)

Mark scheme

- No, P(N2O3) will not equal 1.0 atm at equilibrium. P(N2O3) would only equal 1.0 atm if the reaction went to completion; the value of K (0.70, not much greater than 1) indicates that a substantial amount of reactants (NO and NO2) will remain at equilibrium, so P(N2O3) will be less than 1.0 atm. 1 point is earned for the correct choice ('no') and a valid justification based on the value of K.

Solution 2

(c)

Mark scheme

- Disagree. Because the reaction NO(g) + NO2(g) $<=>$ N2O3(g) is exothermic (DeltaH_298 = -40.4 kJ/mol_rxn), increasing the temperature will favor the formation of the reactants (shift left), according to Le Chatelier's principle, so the amount of N2O3(g) will decrease, not increase. 1 point is earned for the correct choice (disagree) AND a correct justification.

Solution 2

(d)(i)

Mark scheme

- Completed Lewis structure of HNO2 (skeleton H-O-N-O): H is single-bonded to O; that O is single-bonded to N and carries 2 lone pairs; N is double-bonded to the terminal O and carries 1 lone pair; the terminal O carries 2 lone pairs. Formal charges are all zero and every atom (except H) has a complete octet. 1 point is earned for a valid diagram showing all lone pairs and correct bonding (H-O-N=O with 2 lone pairs on each O and 1 lone pair on N).

Solution 2

(d)(ii)

Mark scheme

- The nitrogen atom is sp2 hybridized (it is bonded to 2 O atoms and has 1 lone pair, i.e., 3 electron domains, giving trigonal planar / sp2 geometry). 1 point is earned for the correct answer, sp2.

Solution 2

(e)(i)

Mark scheme

- At the equivalence point (from the titration curve), 20. mL of 0.100 M KOH has been added: 20. mL x 0.100 mol KOH/1000 mL = 0.0020 mol KOH added, which equals 0.0020 mol HNO2 originally present (1:1 stoichiometry of HNO2 + OH- -> NO2- + H2O). Initial concentration = 0.0020 mol HNO2 / 0.100 L = 0.020 M HNO2. 1 point is earned for the correct calculation of the initial concentration.

Solution 2

(e)(ii)

Mark scheme

- pKa is approximately 3.4, read from the pH at the half-equivalence volume (10 mL) on the titration curve, where pH $=$ pKa. 1 point is earned for an acceptable estimate of pKa (values near 3.4 accepted).

Solution 2

(f)

Mark scheme

- NO2-(aq) is present at the higher concentration. The equivalence point is at 20 mL, so the half-equivalence point is at 10 mL; after 15 mL of KOH has been added, the titration is past the half-equivalence point, so more of the conjugate base (NO2-) than the acid (HNO2) is present. 1 point is earned for the correct choice AND a valid justification.

Question 1

2017 ▪ Q1

$$CS_2(g) + 3\,Cl_2(g) \rightarrow CCl_4(g) + S_2Cl_2(g)$$

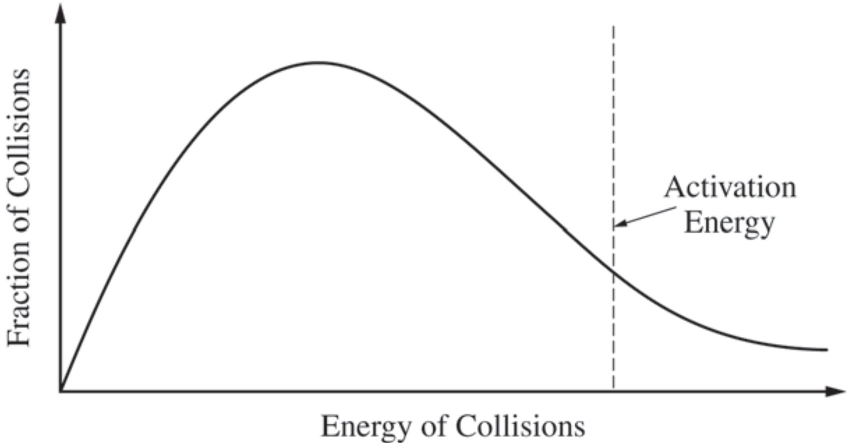
Carbon tetrachloride, $CCl_4(g)$, can be synthesized according to the reaction represented above. A chemist runs the reaction at a constant temperature of $120°C$ in a rigid 25.0 L container.

(a)(i) Chlorine gas, $Cl_2(g)$, is initially present in the container at a pressure of 0.40 atm.

How many moles of $Cl_2(g)$ are in the container?

(a)(ii) How many grams of carbon disulfide, $CS_2(g)$, are needed to react completely with the $Cl_2(g)$?

Question 1


Fraction of Collisions
Activation
Energy
Energy of Collisions

Question 1

Cl S S Cl

Question 1

2017 ▪ Q1

$$CS_2(g) + 3\,Cl_2(g) \rightarrow CCl_4(g) + S_2Cl_2(g)$$

Carbon tetrachloride, $CCl_4(g)$, can be synthesized according to the reaction represented above. A chemist runs the reaction at a constant temperature of $120°C$ in a rigid 25.0 L container.

(b)(i) At $30°C$ the reaction is thermodynamically favorable, but no reaction is observed to occur. However, at $120°C$, the reaction occurs at an observable rate. Explain how the higher temperature affects the collisions between the reactant molecules so that the reaction occurs at an observable rate at $120°C$.

(b)(ii) The graph below shows a distribution for the collision energies of reactant molecules at $120°C$. Draw a second curve on the graph that shows the distribution for the collision energies of reactant molecules at $30°C$.

Question 1

[Graph: Maxwell-Boltzmann-type distribution curve; y-axis "Fraction of Collisions" (unlabeled scale), x-axis "Energy of Collisions" (unlabeled scale); a single curve starts at the origin, rises to a peak, then decreases and levels off toward the x-axis; a vertical dashed line partway down the curve's descending portion is labeled "Activation Energy" with an arrow pointing to where it crosses the curve.]

Question 1

2017 ▪ Q1

$$CS_2(g) + 3\,Cl_2(g) \rightarrow CCl_4(g) + S_2Cl_2(g)$$

Carbon tetrachloride, $CCl_4(g)$, can be synthesized according to the reaction represented above. A chemist runs the reaction at a constant temperature of $120°C$ in a rigid 25.0 L container.

(c)(i) S_2Cl_2 is a product of the reaction.

In the box below, complete the Lewis electron-dot diagram for the S_2Cl_2 molecule by drawing in all of the electron pairs.

[Box showing the unfinished skeletal structure: Cl S S Cl (four atoms in a row, single bonds implied between adjacent atoms, no lone pairs or additional dots drawn yet).]

(c)(ii) What is the approximate value of the Cl–S–S bond angle in the S_2Cl_2 molecule that you drew in part (c)(i) ? (If the two Cl–S–S bond angles are not equal, include both angles.)

Question 1

2017 ▪ Q1

$$CS_2(g) + 3\,Cl_2(g) \rightarrow CCl_4(g) + S_2Cl_2(g)$$

Carbon tetrachloride, $CCl_4(g)$, can be synthesized according to the reaction represented above. A chemist runs the reaction at a constant temperature of $120°C$ in a rigid 25.0 L container.

(d)(i) $CCl_4(g)$ can also be produced by reacting $CHCl_3(g)$ with $Cl_2(g)$ at $400°C$, as represented by the equation below.

$$CHCl_3(g) + Cl_2(g) \rightarrow CCl_4(g) + HCl(g)$$

At the completion of the reaction a chemist successfully separates the $CCl_4(g)$ from the $HCl(g)$ by cooling the mixture to $70°C$, at which temperature the $CCl_4(g)$ condenses while the $HCl(g)$ remains in the gaseous state.

Question 1

Identify all types of intermolecular forces present in $\mathrm{HCl}(l)$.
(d)(ii) What can be inferred about the relative strengths of the intermolecular forces in $\mathrm{CCl_4}(l)$ and $\mathrm{HCl}(l)$? Justify your answer in terms of the information above.

Solution 1

(a)(i)

Mark scheme

- n = PV/RT = (0.40 atm x 25.0 L) / (0.08206 L*atm/(mol*K) x 393 K) = 0.31 mol Cl2. 1 point earned for the correct answer with supporting work.

(a)(ii)

Mark scheme

- 0.31 mol Cl2 x (1 mol CS2 / 3 mol Cl2) x (76.13 g CS2 / 1 mol CS2) = 7.9 g CS2. 1 point for using the correct mole ratio (may be implicit); 1 point for the correct mass of CS2.

Solution 1

(b)(i)

Mark scheme

- At the higher temperature the particles have a greater average kinetic energy than at the lower temperature. Thus there are more collisions with sufficient energy to overcome the activation energy. 1 point earned for an appropriate explanation that includes a reference to molecular collisions.

Solution 1

(b)(ii)

Mark scheme

- Draw a second curve on the graph for the 30C collision-energy distribution. 1 point earned for a curve that has a peak above and to the left of the given (120C) curve (lower T -> lower average kinetic energy, so the peak shifts to lower energy and is taller/narrower); 1 point earned for a curve that is below the given curve in the region beyond the activation energy (fewer molecules have collision energy exceeding Ea at the lower temperature).

Solution 1

(c)(i)

Mark scheme

- Completed Lewis structure: :Cl-S-S-Cl: with each Cl bearing 3 lone pairs and each S bearing 2 lone pairs, so every atom (C excluded, none here) satisfies the octet rule across the Cl-S-S-Cl skeleton with single bonds throughout. 1 point earned for a correctly drawn diagram (all electron pairs shown).

Solution 1

(c)(ii)

Mark scheme

- Any value between 104 degrees and 110 degrees is acceptable (bent/angular arrangement about each central S atom, which has 2 bonding pairs and 2 lone pairs, similar to the geometry around O in H2O2). 1 point earned for an acceptable angle that is consistent with the Lewis diagram drawn in part (c)(i).

Solution 1

(d)(i)

Mark scheme

- Dipole-dipole forces and London dispersion forces. 1 point earned for identifying both types of forces (HCl is a polar molecule, so dipole-dipole forces are present in addition to the London dispersion forces present between all molecules).

Solution 1

(d)(ii)

Mark scheme

- The intermolecular forces among CCl4 molecules must be stronger than those among HCl molecules, because the CCl4 condenses at a higher temperature (70C) than HCl, which remains gaseous at that temperature. 1 point earned for the correct answer with a valid justification.

Question 2

2016 ▪ Q2

$$NaHCO_3(s) + HC_2H_3O_2(aq) \rightarrow NaC_2H_3O_2(aq) + H_2O(l) + CO_2(g)$$

A student designs an experiment to study the reaction between $NaHCO_3$ and $HC_2H_3O_2$. The reaction is represented by the equation above. The student places 2.24 g of $NaHCO_3$ in a flask and adds 60.0 mL of 0.875 M $HC_2H_3O_2$. The student observes the formation of bubbles and that the flask gets cooler as the reaction proceeds.

(a) Identify the reaction represented above as an acid-base reaction, precipitation reaction, or redox reaction. Justify your answer.

Question 2

Question 2

2016 ▪ Q2

$$NaHCO_3(s) + HC_2H_3O_2(aq) \rightarrow NaC_2H_3O_2(aq) + H_2O(l) + CO_2(g)$$

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(b) Based on the information above, identify the limiting reactant. Justify your answer with calculations.

Question 2

2016 ▪ Q2

$$NaHCO_3(s) + HC_2H_3O_2(aq) \rightarrow NaC_2H_3O_2(aq) + H_2O(l) + CO_2(g)$$

A student designs an experiment to study the reaction between $NaHCO_3$ and $HC_2H_3O_2$. The reaction is represented by the equation above. The student places 2.24 g of $NaHCO_3$ in a flask and adds 60.0 mL of 0.875 M $HC_2H_3O_2$. The student observes the formation of bubbles and that the flask gets cooler as the reaction proceeds.

(c) The student observes that the bubbling is rapid at the beginning of the reaction and gradually slows as the reaction continues. Explain this change in the reaction rate in terms of the collisions between reactant particles.

Question 2

2016 ▪ Q2

$$NaHCO_3(s) + HC_2H_3O_2(aq) \rightarrow NaC_2H_3O_2(aq) + H_2O(l) + CO_2(g)$$

A student designs an experiment to study the reaction between $NaHCO_3$ and $HC_2H_3O_2$. The reaction is represented by the equation above. The student places 2.24 g of $NaHCO_3$ in a flask and adds 60.0 mL of 0.875 *M* $HC_2H_3O_2$. The student observes the formation of bubbles and that the flask gets cooler as the reaction proceeds.

(d)(i) In thermodynamic terms, a reaction can be driven by enthalpy, entropy, or both. Considering that the flask gets cooler as the reaction proceeds, what drives the chemical reaction between $NaHCO_3(s)$ and $HC_2H_3O_2(aq)$? Answer by drawing a circle around one of the choices below.

Enthalpy only Entropy only Both enthalpy and entropy

(d)(ii) Justify your selection in part (d)(i) in terms of $\Delta G°$.

Question 2

2016 ▪ Q2

$$NaHCO_3(s) + HC_2H_3O_2(aq) \rightarrow NaC_2H_3O_2(aq) + H_2O(l) + CO_2(g)$$

A student designs an experiment to study the reaction between $NaHCO_3$ and $HC_2H_3O_2$. The reaction is represented by the equation above. The student places 2.24 g of $NaHCO_3$ in a flask and adds 60.0 mL of 0.875 M $HC_2H_3O_2$. The student observes the formation of bubbles and that the flask gets cooler as the reaction proceeds.

(e) The HCO_3^- ion has three carbon-to-oxygen bonds. Two of the carbon-to-oxygen bonds have the same length and the third carbon-to-oxygen bond is longer than the other two. The hydrogen atom is bonded to one of the oxygen atoms. In the box below, draw a Lewis electron-dot diagram (or diagrams) for the HCO_3^- ion that is (are) consistent with the given information.
[Empty box provided for the student to draw the Lewis electron-dot diagram(s).]

Question 2

2016 ▪ Q2

$$NaHCO_3(s) + HC_2H_3O_2(aq) \rightarrow NaC_2H_3O_2(aq) + H_2O(l) + CO_2(g)$$

A student designs an experiment to study the reaction between $NaHCO_3$ and $HC_2H_3O_2$. The reaction is represented by the equation above. The student places 2.24 g of $NaHCO_3$ in a flask and adds 60.0 mL of 0.875 M $HC_2H_3O_2$. The student observes the formation of bubbles and that the flask gets cooler as the reaction proceeds.

(f) A student prepares a solution containing equimolar amounts of $HC_2H_3O_2$ and $NaC_2H_3O_2$. The pH of the solution is measured to be 4.7. The student adds two drops of 3.0 M $HNO_3(aq)$ and stirs the sample, observing that the pH remains at 4.7. Write a balanced, net-ionic equation for the reaction between $HNO_3(aq)$ and the chemical species in the sample that is responsible for the pH remaining at 4.7.

Solution 2

(a)

Mark scheme

- It is an acid-base reaction: the weak acid HC2H3O2 reacts with the weak base HCO3—, with HC2H3O2 donating a proton. (Equivalently: no solid precipitates, so it is not a precipitation reaction; no oxidation numbers change, so it is not a redox reaction.) 1 point for identifying the reaction as acid-base, 1 point for a valid justification.

Solution 2

(b)

Mark scheme

- 2.24 g $NaHCO_3 \times$ (1 mol / 84.0 g) $=$ 0.0267 mol $NaHCO_3$. 60.0 mL $\times$ (0.875 mol $HC_2H_3O_2$ / 1000 mL) $=$ 0.0525 mol $HC_2H_3O_2$. $NaHCO_3(s)$ and $HC_2H_3O_2(aq)$ react in a 1:1 ratio, so the smaller mole amount, $NaHCO_3(s)$, is the limiting reactant. 1 point for calculating the number of moles of each reactant, 1 point for correctly identifying $NaHCO_3$ as the limiting reactant, consistent with the calculation.

Solution 2

(c)

Mark scheme

- As the reaction proceeds, both reactants are consumed and their concentrations decrease; collisions between reactant particles become less frequent as concentrations decrease, so the reaction rate slows. 1 point for a valid explanation in terms of collision frequency between reactant particles.

Solution 2

(d)(i)

Mark scheme

- 'Entropy only' should be circled. Because the flask gets cooler as the reaction proceeds, the reaction is endothermic and cannot be driven by a favorable enthalpy change — it must be driven by entropy. 1 point for circling 'Entropy only'.

Solution 2

(d)(ii)

Mark scheme

- $\Delta G° = \Delta H° - T\Delta S°$; a reaction is thermodynamically favorable when $\Delta G°$ is negative. Since the reaction is endothermic (flask gets cooler, $\Delta H°$ is positive), enthalpy does not help make $\Delta G°$ negative, so the reaction is not driven by enthalpy. Because the reactants contain no gas while one product (CO2) is a gas, $\Delta S°$ must be positive, which helps make $\Delta G°$ negative — so the reaction is entropy-driven. 1 point for a valid justification referencing the signs of $\Delta H°$, $\Delta S°$, and $\Delta G°$.

Solution 2

(e) Mark scheme

- A correct Lewis structure for HCO3− has a central C bonded to three O atoms: one C=O double bond, one C—O single bond to an O bearing three lone pairs (charge −1 on that O), and one C—O single bond to the O—H oxygen (two lone pairs on that O), with the H attached to that same oxygen. Because two C-to-O bonds are equal length and the third (C—OH) is longer, resonance exists between the two equivalent non-OH oxygens — shown either as two resonance structures or as one structure with a double-headed resonance arrow between those two oxygens. 1 point for a correct Lewis structure of HCO3−, 1 point for indicating resonance between the two equivalent (non-OH) oxygens.

Solution 2

(f)

Mark scheme

- $C2H3O2- + H3O+ \rightarrow HC2H3O2 + H2O$ (equivalently: $C2H3O2- + H+ \rightarrow HC2H3O2$). 1 point for a correct, balanced net-ionic equation showing the acetate ion neutralizing the added $H3O+/H+$, which is why the pH remains at 4.7 (buffer action).

Question 2

2015 ▪ Q2

Ethene, $C_2H_4(g)$ (molar mass 28.1 g/mol), may be prepared by the dehydration of ethanol, $C_2H_5OH(g)$ (molar mass 46.1 g/mol), using a solid catalyst. A setup for the lab synthesis is shown in the diagram above. The equation for the dehydration reaction is given below.
[Diagram of the lab synthesis setup: on the left, a test tube labeled "Test Tube" contains "Glass Wool with Ethanol" and "Solid Catalyst", heated from below by a "Bunsen Burner", both mounted on a stand. A delivery tube leads from the test tube on the right to a second, inverted test tube labeled "Ethene" that is collecting gas over water in a basin, also mounted on a stand.]

$$C_2H_5OH(g) \xrightarrow{\text{catalyst}} C_2H_4(g) + H_2O(g) \qquad \Delta H^\circ_{298} = 45.5\ \text{kJ/mol}_{rxn};\ \Delta S^\circ_{298} = 126\ \text{J/(K} \cdot \text{mol}$$

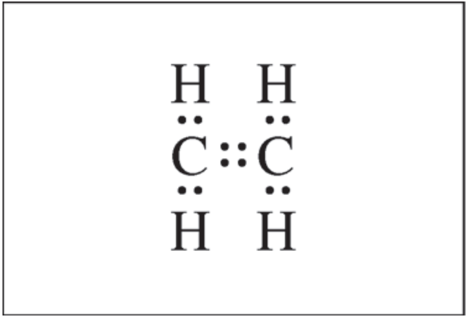
Question 2

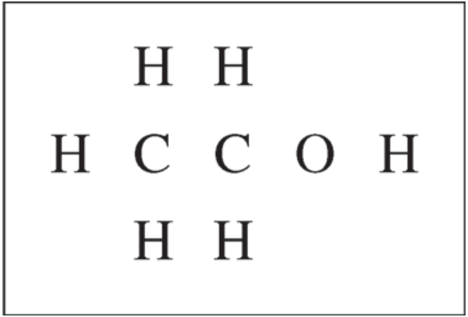
ethanol ethene water

A student added a 0.200 g sample of $C_2H_5OH(l)$ to a test tube using the setup shown above. The student heated the test tube gently with a Bunsen burner until all of the $C_2H_5OH(l)$ evaporated and gas generation stopped. When the reaction stopped, the volume of collected gas was 0.0854 L at 0.822 atm and 305 K. (The vapor pressure of water at 305 K is 35.7 torr.)

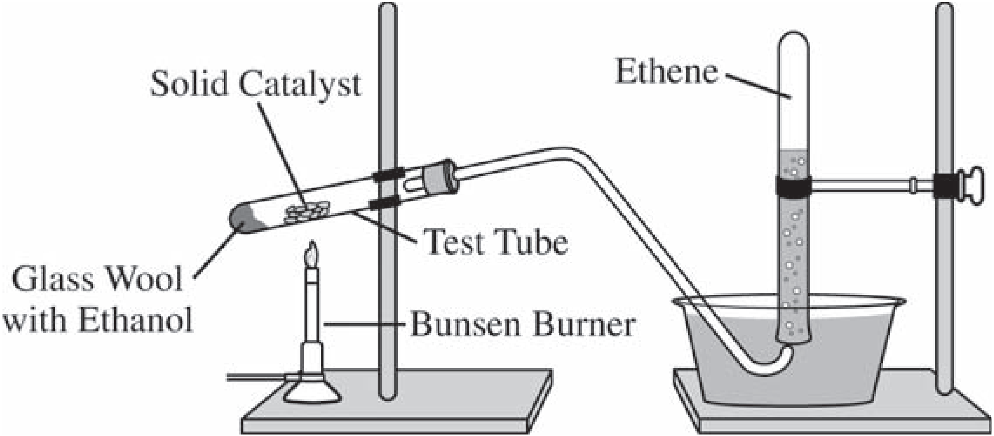
(a)(i) Calculate the number of moles of $C_2H_4(g)$ that are actually produced in the experiment and measured in the gas collection tube.

(a)(ii) Calculate the number of moles of $C_2H_4(g)$ that would be produced if the dehydration reaction went to completion.





Question 2


Solid Catalyst
Ethene
Test Tube
Glass Wool
with Ethanol
Bunsen Burner

Question 2

2015 ▪ Q2

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ethanol ethene water

Question 2

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(b) Calculate the percent yield of $C_2H_4(g)$ in the experiment.

Question 2

2015 ▪ Q2

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ethanol ethene water

Question 2

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(c) Because the dehydration reaction is not observed to occur at 298 K, the student claims that the reaction has an equilibrium constant less than 1.00 at 298 K. Do the thermodynamic data for the reaction support the student's claim? Justify your answer, including a calculation of ΔG°_{298} for the reaction.

Question 2

2015 ▪ Q2

Ethene, $C_2H_4(g)$ (molar mass 28.1 g/mol), may be prepared by the dehydration of ethanol, $C_2H_5OH(g)$ (molar mass 46.1 g/mol), using a solid catalyst. A setup for the lab synthesis is shown in the diagram above. The equation for the dehydration reaction is given below. [Diagram of the lab synthesis setup: on the left, a test tube labeled "Test Tube" contains "Glass Wool with Ethanol" and "Solid Catalyst", heated from below by a "Bunsen Burner", both mounted on a stand. A delivery tube leads from the test tube on the right to a second, inverted test tube labeled "Ethene" that is collecting gas over water in a basin, also mounted on a stand.]

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ethanol ethene water

Question 2

A student added a 0.200 g sample of $C_2H_5OH(l)$ to a test tube using the setup shown above. The student heated the test tube gently with a Bunsen burner until all of the $C_2H_5OH(l)$ evaporated and gas generation stopped. When the reaction stopped, the volume of collected gas was 0.0854 L at 0.822 atm and 305 K. (The vapor pressure of water at 305 K is 35.7 torr.)

(d) The Lewis electron-dot diagram for C_2H_4 is shown below in the box on the left. In the box on the right, complete the Lewis electron-dot diagram for C_2H_5OH by drawing in all of the electron pairs.

[Two boxes side by side. Left box: the completed Lewis structure of C_2H_4 — two carbon atoms double-bonded to each other, each carbon also bonded to two hydrogen atoms (H H above, H H below), with all lone pairs and bonding pairs shown as dots. Right box: the skeletal (bonds-only, no lone pairs drawn) atom arrangement for C_2H_5OH — H H above the two carbons, "H C C O H" in a row, and H H below the first carbon — for the student to complete with electron pairs.]

Question 2

2015 ▪ Q2

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ethanol ethene water

Question 2

A student added a 0.200 g sample of $C_2H_5OH(l)$ to a test tube using the setup shown above. The student heated the test tube gently with a Bunsen burner until all of the $C_2H_5OH(l)$ evaporated and gas generation stopped. When the reaction stopped, the volume of collected gas was 0.0854 L at 0.822 atm and 305 K. (The vapor pressure of water at 305 K is 35.7 torr.)

(e) What is the approximate value of the C–O–H bond angle in the ethanol molecule?

Question 2

2015 ▪ Q2

Ethene, $C_2H_4(g)$ (molar mass 28.1 g/mol), may be prepared by the dehydration of ethanol, $C_2H_5OH(g)$ (molar mass 46.1 g/mol), using a solid catalyst. A setup for the lab synthesis is shown in the diagram above. The equation for the dehydration reaction is given below. [Diagram of the lab synthesis setup: on the left, a test tube labeled "Test Tube" contains "Glass Wool with Ethanol" and "Solid Catalyst", heated from below by a "Bunsen Burner", both mounted on a stand. A delivery tube leads from the test tube on the right to a second, inverted test tube labeled "Ethene" that is collecting gas over water in a basin, also mounted on a stand.]

$$C_2H_5OH(g) \xrightarrow{\text{catalyst}} C_2H_4(g) + H_2O(g) \qquad \Delta H^\circ_{298} = 45.5\ \text{kJ/mol}_{rxn};\ \Delta S^\circ_{298} = 126\ \text{J/(K} \cdot \text{mol}_{rxn})$$

ethanol ethene water

Question 2

A student added a 0.200 g sample of $C_2H_5OH(l)$ to a test tube using the setup shown above. The student heated the test tube gently with a Bunsen burner until all of the $C_2H_5OH(l)$ evaporated and gas generation stopped. When the reaction stopped, the volume of collected gas was 0.0854 L at 0.822 atm and 305 K. (The vapor pressure of water at 305 K is 35.7 torr.)

(f) During the dehydration experiment, $C_2H_4(g)$ and unreacted $C_2H_5OH(g)$ passed through the tube into the water. The C_2H_4 was quantitatively collected as a gas, but the unreacted C_2H_5OH was not. Explain this observation in terms of the intermolecular forces between water and each of the two gases.

Solution 2

(a)(i)

Mark scheme

- First find the partial pressure of dry ethene by subtracting water's vapor pressure at 305 K from the total pressure: 35.7 torr x (1 atm / 760 torr) = 0.0470 atm; P_ethene = P_total - P_water = 0.822 atm - 0.0470 atm = 0.775 atm (1 point for this pressure calculation). Then apply the ideal gas law: n = PV/RT = (0.775 atm)(0.0854 L) / [(0.08206 L*atm*mol^-1*K^-1)(305 K)] = 0.00264 mol C2H4 actually produced and collected (1 point for the correct number of moles of ethene gas).

Solution 2

(a)(ii)

Mark scheme

- 0.200 g C_2H_5OH x (1 mol C_2H_5OH / 46.1 g C_2H_5OH) x (1 mol C_2H_4 / 1 mol C_2H_5OH) = 0.00434 mol C_2H_4 would be produced if the dehydration reaction went to completion. 1 point for the correct number of moles of ethene produced.

Solution 2

(b)

Mark scheme

- Percent yield = (actual yield / maximum possible yield) x 100 = (0.00264 mol / 0.00434 mol) x 100 = 60.8%. 1 point for the correct percent yield.

Solution 2

(c)

Mark scheme

- Yes, the thermodynamic data support the student's claim. DeltaG_298 = DeltaH - T*DeltaS = 45.5 kJ/mol_rxn - (298 K)(0.126 kJ/(K*mol_rxn)) = 8.0 kJ/mol_rxn (1 point for the correct calculation of DeltaG). Because DeltaG_298 > 0, K_p = e^(-DeltaG/RT) < 1.00, which confirms the equilibrium constant is less than 1.00 at 298 K, supporting the student's claim (1 point for a valid justification linking a positive DeltaG to K < 1).

Solution 2

(d)

Mark scheme

- The completed Lewis structure of C2H5OH (ethanol) must show all bonding pairs (the C-C bond, four C-H bonds, one C-O bond, and the O-H bond) plus the two nonbonding (lone) electron pairs on the oxygen atom; a line may be used in place of a dot pair. 1 point for a correct, complete diagram.

Solution 2

(e)

Mark scheme

- The C-O-H bond angle in ethanol is approximately 109 degrees, since the oxygen atom is roughly sp3-hybridized (bent/tetrahedral electron geometry) with two lone pairs. 1 point is earned for any answer from 100 degrees to 115 degrees.

Solution 2

(f) Mark scheme

- Ethene ($C2H4$) is nonpolar, so it can only interact with polar water molecules through weak dipole/induced-dipole forces, making it only slightly soluble in water (1 point for comparing the solubility of ethene in water with the solubility of ethanol in water in terms of their difference in polarity). Ethanol ($C2H5OH$) is polar and its -OH group can form hydrogen bonds with water molecules as it dissolves, making ethanol much more soluble in water; this is why the $C2H4(g)$ passing through the tube was quantitatively collected as a gas while the unreacted $C2H5OH(g)$ was not (1 point for describing the intermolecular forces between ethene and water as weak dipole/induced-dipole forces AND attributing ethanol's

Solution 2

solubility in water to the hydrogen bonds formed between ethanol and water molecules).

Question 5

2014 ▪ Q5

[Table:]

Nonmetal	C	N	O	Ne	Si	P	S	Ar
Formula of Compound	CF_4	NF_3	OF_2	No compound	SiF_4	PF_3	SF_2	No compound

Some binary compounds that form between fluorine and various nonmetals are listed in the table above. A student examines the data in the table and poses the following hypothesis: the number of F atoms that will bond to a nonmetal is always equal to 8 minus the number of valence electrons in the nonmetal atom.

(a) Based on the student's hypothesis, what should be the formula of the compound that forms between chlorine and fluorine?

Question 5

Question 5

Nonmetal	C	N	O	Ne	Si	P	S	Ar
Formula of Compound	CF_4	NF_3	OF_2	No compound	SiF_4	PF_3	SF_2	No compound

Question 5

Halogen	Formula(s)
F	F_2
Cl	
Br	BrF, BrF_3 , BrF_5
I	IF, IF_3 , IF_5 , IF_7

Question 5

2014 ▪ Q5

[Table:]

Nonmetal	C	N	O	Ne	Si	P	S	Ar
Formula of Compound	CF_4	NF_3	OF_2	No compound	SiF_4	PF_3	SF_2	No compound

Some binary compounds that form between fluorine and various nonmetals are listed in the table above. A student examines the data in the table and poses the following hypothesis: the number of F atoms that will bond to a nonmetal is always equal to 8 minus the number of valence electrons in the nonmetal atom.

(b) In an attempt to verify the hypothesis, the student researches the fluoride compounds of the other halogens and finds the formula ClF_3. In the box below, draw a complete Lewis electron-dot diagram for a molecule of ClF_3.

[A blank rectangular box provided for the student to draw the Lewis structure.]

Question 5

2014 ▪ Q5

[Table:]

Nonmetal	C	N	O	Ne	Si	P	S	Ar
Formula of Compound	CF_4	NF_3	OF_2	No compound	SiF_4	PF_3	SF_2	No compound

Some binary compounds that form between fluorine and various nonmetals are listed in the table above. A student examines the data in the table and poses the following hypothesis: the number of F atoms that will bond to a nonmetal is always equal to 8 minus the number of valence electrons in the nonmetal atom.

(c) Two possible geometric shapes for the ClF_3 molecule are trigonal planar and T-shaped. The student does some research and learns that the molecule has a dipole moment. Which of the two shapes is consistent with the fact that the ClF_3 molecule has a dipole moment? Justify your answer in terms of bond polarity and molecular structure.

Question 5

2014 ▪ Q5

[Table:]

Nonmetal	C	N	O	Ne	Si	P	S	Ar
Formula of Compound	CF_4	NF_3	OF_2	No compound	SiF_4	PF_3	SF_2	No compound

Some binary compounds that form between fluorine and various nonmetals are listed in the table above. A student examines the data in the table and poses the following hypothesis: the number of F atoms that will bond to a nonmetal is always equal to 8 minus the number of valence electrons in the nonmetal atom.

(d) In an attempt to resolve the existence of the ClF_3 molecule with the hypothesis stated above, the student researches the compounds that form between halogens and fluorine, and assembles the following list.

Halogen	Formula(s)
F	F_2
Cl	
Br	BrF, BrF_3, BrF_5
I	IF, IF_3, IF_5, IF_7

Question 5

Based on concepts of atomic structure and periodicity, propose a modification to the student's previous hypothesis to account for the compounds that form between halogens and fluorine.

Solution 5

(a)

Mark scheme

- ClF (chlorine has 7 valence electrons, so by the hypothesis $8 - 7 = 1$ F atom bonds to it).

Solution 5

(b)

Mark scheme

- A complete Lewis structure for ClF3: a central Cl atom single-bonded to three F atoms, with two nonbonding (lone) electron pairs on Cl and three nonbonding pairs on each F atom (T-shaped arrangement: F–Cl(F)(F) with Cl bearing 2 lone pairs and each F bearing 3 lone pairs). Full credit requires a central Cl surrounded by three bonding pairs to F atoms and two nonbonding pairs on Cl, plus three nonbonding pairs on each F (dots or line/dash notation both acceptable).

Solution 5

(c)

Mark scheme

- The molecule is T-shaped. A T-shaped structure is asymmetric, so its bond dipoles do not cancel and the molecule has a net dipole moment (polar). A trigonal planar structure would be symmetric, with the three Cl–F bond dipoles canceling to give a net dipole of zero (nonpolar), which is inconsistent with the observation that ClF3 has a dipole moment.

Solution 5

(d)

Mark scheme

- An acceptable modified hypothesis must address both atomic structure and periodicity, e.g.: the number of F atoms bonded to a halogen is always an odd number (reflecting the odd number of valence/unpaired electrons available for bonding), and as the atomic number (size) of the central halogen atom increases going down the group, the number of F atoms that can bond to it increases (consistent with Cl forming only ClF and ClF3, while the larger Br and I form progressively more fluorides: BrF/BrF3/BrF5 and IF/IF3/IF5/IF7).