Past-paper walk-through

Free Energy and Equilibrium ▪ 9.5

eXercise

Questions in this set

- 2025 Q3
- 2022 Q3
- 2017 Q2
- 2015 Q2

Reading the mark scheme

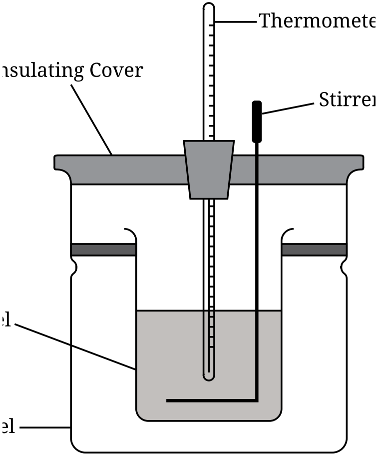
- **B1** a mark that stands on its own – the point is either made or not.
- **M1** a *method* mark: the right approach, even if the number is wrong.
- **A1** an *answer* mark, and it usually needs its M mark first.
- **C1** a working mark on the way to the answer.
- // separates answers the examiner 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.

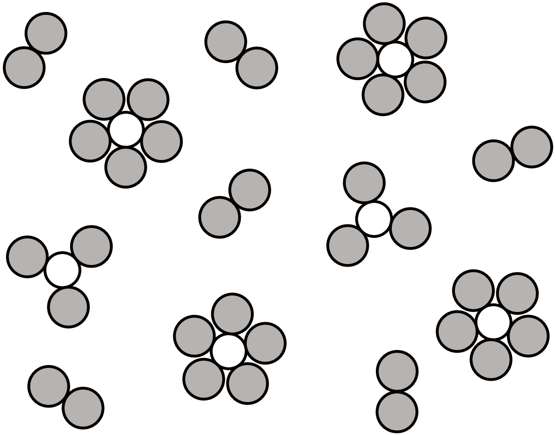
Question 3



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	$4.18\ \mathrm{J/(g{\cdot}°C)}$

Question 3



Question 3

2025 ▪ Q3

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(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 kJ/mol$_{rxn}$. Include the sign in your answer.

Question 3

2025 ▪ Q3

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(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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(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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(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

- $q_{rxn} = -q_{surr} = -0.16$ kJ.
  $$\Delta H^\circ_{rxn} = \frac{-0.16 \text{ kJ}}{0.100 \text{ g } P_4O_{10}} \times \frac{283.9 \text{ g } P_4O_{10}}{1 \text{ mol } P_4O_{10}} \times \frac{1 \text{ mol } P_4O_{10}}{1 \text{ mol}_{rxn}} = -450 \text{ kJ/mol}_{rxn}.$$
  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 ($PCl_3(g) + Cl_2(g) \rightleftharpoons PCl_5(g)$, $\Delta H^\circ_2 = -88$ 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 3

2022 ▪ Q3

Answer the following questions relating to the element aluminum, Al.

(a) Write the complete ground-state electron configuration of an Al atom.

Question 3

2022 ▪ Q3

Answer the following questions relating to the element aluminum, Al.

(b) Based on principles of atomic structure, explain why the radius of the Al atom is larger than the radius of the Al^{3+} ion.

A student plans to combine solid aluminum with an aqueous solution of silver ions.

The student determines the mass of solid $AgNO_3$ needed to prepare the solution with a specific concentration.

Question 3

2022 ▪ Q3

Answer the following questions relating to the element aluminum, Al.

(c) In the following table, briefly list the steps necessary to prepare 200.0 mL of an aqueous solution of $AgNO_3$ using only equipment selected from the choices given. Assume that all appropriate safety measures are already in place. Not all equipment or lines in the table may be needed.

Available equipment: Solid $AgNO_3$ · Weighing paper and scoop · 250 mL beakers · Distilled water · 200.00 mL volumetric flask · Pipet · Balance · 50.0 mL graduated cylinder

| Step | Step Description | |—|—| | 1. | Use weighing paper to measure the determined mass of solid $AgNO_3$ on a balance. | | 2. | | | | | | | | | | | | | | |

Question 3

2022 ▪ Q3

Answer the following questions relating to the element aluminum, Al.

(d) After preparing the solution, the student places some of the solution into a beaker and adds a sample of aluminum. The reaction represented by the following equation occurs.

$$\mathrm{Al}(s) + 3\,\mathrm{Ag}^{+}(aq) \rightarrow \mathrm{Al}^{3+}(aq) + 3\,\mathrm{Ag}(s)$$

The following diagram gives an incomplete particulate representation of the reaction. The beaker on the left represents the system before the mixture reacts. Complete the drawing on the right to represent the system after the reaction has occurred. Be sure to include 1) the correct type and number of particles based on the number shown on the left and 2) the relative spacing to depict the appropriate phases.

Question 3

[Two beaker diagrams side by side connected by a rightward arrow. Left beaker ("before reaction"): shown containing 4 "Al" (shaded circles, representing solid Al atoms clustered at the bottom) and 6 "Ag^{+}" (open circles, representing dissolved silver ions distributed throughout the liquid). Right beaker ("after reaction," to be completed by the student): shown only with 2 "Al" solid particles remaining at the bottom, with the rest of the beaker left blank for the student to draw in the products. A key box below states: "Al" (shaded circle) = Al atom; "Ag" (open circle) = Ag atom; "Al^{3+}" (circle) = Al^{3+} ion; "Ag^{+}" (open circle) = Ag^{+} ion.]

The student finds the standard reduction potentials given in the table, which are related to the reaction that occurs.

Half-Reaction	E°
$Ag^{+}(aq) + e^{-} \rightarrow Ag(s)$	0.80 V
$Al^{3+}(aq) + 3\,e^{-} \rightarrow Al(s)$	-1.66 V

Question 3

2022 ▪ Q3

Answer the following questions relating to the element aluminum, Al.

(e) Using the standard reduction potentials, calculate the value of E° for the reaction.

Question 3

2022 ▪ Q3

Answer the following questions relating to the element aluminum, Al.

(f) Based on the value of E°, would the standard free energy change of the reaction under standard conditions, ΔG°, be positive, negative, or zero? Justify your answer.

Question 3

2022 ▪ Q3

Answer the following questions relating to the element aluminum, Al.

(g) Once the reaction appears to stop progressing, would the change in free energy, ΔG, be positive, negative, or zero? Justify your answer.

Solution 3

(a)

Mark scheme

- Ground-state electron configuration of Al: $1s^2 2s^2 2p\ 3s^2 3p^1$ (equivalently $[Ne]3s^2 3p^1$).

Solution 3

(b)

Mark scheme

- The highest occupied electron shell (n = 3) of the Al atom is at a greater average distance from the nucleus than the highest occupied electron shell (n = 2) of the Al^{3} ion, so the Al atom has the larger radius.

Solution 3

(c)

Mark scheme

- Steps to prepare 200.0 mL of AgNO3(aq) solution (may be consolidated): (1 point) partially fill the 200.00 mL volumetric flask with some distilled water; add the weighed solid AgNO3(s) to the volumetric flask; swirl to dissolve the solid. (1 point, correct step for quantitative dilution) after the solid is dissolved, fill the flask to the calibration (200.00 mL) mark and mix.

Solution 3

(d)

Mark scheme

- Particulate drawing of the beaker after Al(s) + 3Ag (aq) $\rightarrow$ Al^{3} (aq) + 3Ag(s) reacts (1 point each criterion): conservation of matter — draw 4 Al and 8 Ag particles total (matching the atoms present before reaction, some as product, some as leftover ions); conservation of charge — draw 2 Ag ions and 2 Al^{3} ions remaining (i.e., 2 of the 4 Al atoms became Al^{3}, consuming 6 of the 8 Ag to form 6 Ag atoms, leaving 2 Ag unreacted); correct phases of matter — show 6 Ag atoms as solid (clustered together) and 2 Al^{3} ions as aqueous (dispersed in solution).

Solution 3

(e)

Mark scheme

- $E^\circ = E^\circ\text{red} - E^\circ\text{ox} = 0.80\ \text{V} - (-1.66\ \text{V}) = 2.46\ \text{V}$ (equivalently $E^\circ = 0.80\ \text{V} + 1.66\ \text{V} = 2.46\ \text{V}$).

Solution 3

(f)

Mark scheme

- Negative. The reaction has a positive value of E°, indicating that it is thermodynamically favorable and would therefore have a negative value of ΔG° ($\Delta G^\circ = -nFE^\circ$).

Solution 3

(g)

Mark scheme

- Zero. Once the reaction stops progressing, the system has reached equilibrium: this implies Ecell $= 0$ (no more driving force for the reaction), and since $\Delta G = -nFEcell$, $\Delta G = 0$ at equilibrium.

Question 2

2017 ▪ Q2

Answer the following questions about the isomers fulminic acid and isocyanic acid.

Two possible Lewis electron-dot diagrams for fulminic acid, HCNO, are shown below.

[Two Lewis structures side by side: Left: H–C≡N–Ö: (H bonded to C by a single bond, C triple-bonded to N, N bonded to O by a single bond, O has two lone pairs) Right: H–C̈=N=Ö: (H bonded to C by a single bond, C double-bonded to N, N double-bonded to O, C has one lone pair, O has two lone pairs)]

Fulminic acid can convert to isocyanic acid according to the equation below.

$$HCNO(g) \rightleftharpoons HNCO(g)$$

fulminic acid *isocyanic acid*

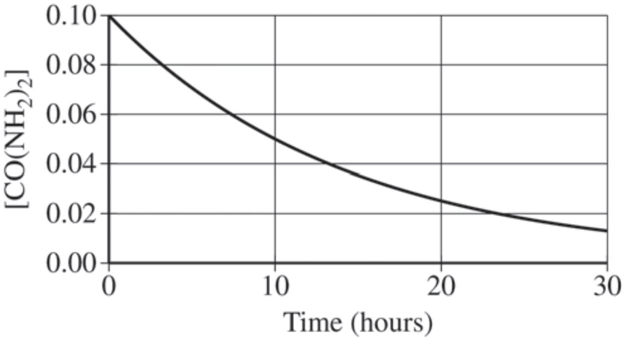
Question 2

| Fulminic Acid | Isocyanic Acid | |—|—| | H–C≡N–Ö: (O has two lone pairs) | H–N̈=C=Ö: (N has one lone pair, O has two lone pairs) |

(a) Explain why the diagram on the left is the better representation for the bonding in fulminic acid. Justify your choice based on formal charges.

Question 2

Time (hours)	$[CO(NH_2)_2]$
0	0.1000
5	0.0707
10	0.0500
15	0.0354
20	0.0250
25	0.0177
30	0.0125



Question 2

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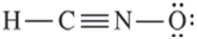	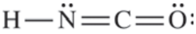

Question 2

Bond	Enthalpy (kJ/mol)		Bond	Enthalpy (kJ/mol)		Bond	Enthalpy (kJ/mol)
N−O	201		C=N	615		H−C	413
C=O	745		C≡N	891		H−N	391

Question 2

2017 ▪ Q2

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Question 2

(b) Using the Lewis electron-dot diagrams of fulminic acid and isocyanic acid shown in the boxes above and the table of average bond enthalpies below, determine the value of ΔH° for the reaction of $HCNO(g)$ to form $HNCO(g)$.

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fulminic acid   *isocyanic acid*

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Question 2

(c) A student claims that ΔS° for the reaction is close to zero. Explain why the student's claim is accurate.

Question 2

2017 ▪ Q2

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fulminic acid *isocyanic acid*

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Question 2

(d) Which species, fulminic acid (HCNO) or isocyanic acid (HNCO), is present in higher concentration at equilibrium at 298 K? Justify your answer in terms of thermodynamic favorability and the equilibrium constant.

Question 2

2017 ▪ Q2

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Question 2

(e)(i) The ammonium salt of isocyanic acid is a product of the decomposition of urea, $CO(NH_2)_2$, represented below.

$$CO(NH_2)_2(aq) \rightleftharpoons NH_4^+(aq) + OCN^-(aq)$$

A student studying the decomposition reaction runs the reaction at $90°C$. The student collects data on the concentration of urea as a function of time, as shown by the data table and the graph below.

Time (hours)	$[CO(NH_2)_2]$
0	0.1000
5	0.0707
10	0.0500
15	0.0354
20	0.0250
25	0.0177
30	0.0125

[Graph: y-axis $[CO(NH_2)_2]$ from 0.00 to 0.10 in increments of 0.02; x-axis "Time (hours)" from 0 to 30; a smooth exponential-decay curve starting at $(0, 0.10)$ and decreasing to approximately $(30, 0.0125)$, consistent with the data table above.]

Question 2

The student proposes that the rate law is $\mathit{rate} = k[\mathrm{CO(NH_2)_2}]$.
Explain how the data support the student's proposed rate law.
(e)(ii) Using the proposed rate law and the student's results, determine the value of the rate constant, k. Include units with your answer.

Question 2

2017 ▪ Q2

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Two possible Lewis electron-dot diagrams for fulminic acid, HCNO, are shown below.
[Two Lewis structures side by side: Left: H–C≡N–Ö: (H bonded to C by a single bond, C triple-bonded to N, N bonded to O by a single bond, O has two lone pairs) Right: H–C̈=N=Ö: (H bonded to C by a single bond, C double-bonded to N, N double-bonded to O, C has one lone pair, O has two lone pairs)]
Fulminic acid can convert to isocyanic acid according to the equation below.

$$\mathrm{HCNO}(g) \rightleftharpoons \mathrm{HNCO}(g)$$

fulminic acid *isocyanic acid*

| Fulminic Acid | Isocyanic Acid | |—|—| | H–C≡N–Ö: (O has two lone pairs) | H–N̈=C=Ö: (N has one lone pair, O has two lone pairs) |

Question 2

(f) The student learns that the decomposition reaction was run in a solution with a pH of 13. Briefly describe an experiment, including the initial conditions that you would change and the data you would gather, to determine whether the rate of the reaction depends on the concentration of $OH^-(aq)$.

Solution 2

(a)

Mark scheme

- In the left diagram (H-C triple-bond N-O: with O having 3 lone pairs... i.e. H-C#N-O:), the C atom has a formal charge of 0 and the O atom has a formal charge of -1. In the right diagram (H-C(double bond)N(double bond)O:), the C atom has a formal charge of -1 and the O atom has a formal charge of 0. The diagram on the left is the better representation because it puts the negative formal charge on oxygen, which is more electronegative than carbon. 1 point earned for a correct assignment of formal charges in the two diagrams; 1 point earned for a correct explanation.

Solution 2

(b)

Mark scheme

- Sum bond enthalpies from each Lewis structure. HCNO (bonds broken): H-C (413) + C#N triple bond (891) + N-O (201) = 1505 kJ/mol. HNCO (bonds formed): H-N (391) + C=N (615) + C=O (745) = 1751 kJ/mol. delta H (standard) = sum(enthalpies of bonds broken) - sum(enthalpies of bonds formed) = 1505 kJ/mol - 1751 kJ/mol = -246 kJ/mol_rxn. 1 point earned for subtracting the enthalpies of bonds formed from the enthalpies of bonds broken; 1 point earned for the correct determination of delta H (standard).

Solution 2

(c)

Mark scheme

- The change from fulminic acid to isocyanic acid is a rearrangement of atoms (isomerization) with no change in phase and no change in the number of molecules, so there is essentially no change in the number of accessible microstates and delta S (standard) is close to zero. 1 point earned for a correct explanation.

Solution 2

(d) Mark scheme

- Isocyanic acid (HNCO) is present in higher concentration at equilibrium. Delta G (standard) is essentially equal to delta H (standard) because delta S (standard) is essentially zero, so delta G (standard) is approximately -246 kJ/mol_rxn, indicating the forward reaction (HCNO -> HNCO) is thermodynamically favorable. Since delta G (standard) is negative, K > 1 (delta G standard = -RT ln K), resulting in a higher equilibrium concentration of product (HNCO) than reactant (HCNO). 1 point earned for the correct choice WITH a valid justification (calculation of delta G standard is sufficient justification); 1 point earned for correctly connecting thermodynamic favorability to the equilibrium constant K.

Solution 2

(e)(i)

Mark scheme

- From inspecting the data table or the graph, the decomposition reaction has a constant half-life (the urea concentration approximately halves every 10 hours: 0.1000 to 0.0500 over the first 10 h, 0.0500 to 0.0250 over the next 10 h, etc.), which indicates the reaction is first order. 1 point earned for a correct explanation.

Solution 2

(e)(ii)

Mark scheme

- Since the reaction is first order: k = 0.693 / t(1/2) = 0.693 / 10. h = 0.069 h^-1 (equivalently k = (ln[A]0 - ln[A]t)/t = (ln 0.1000 - ln 0.0500) / 10. h = 0.069 h^-1). 1 point earned for the correct value of k with correct units.

Solution 2

(f)

Mark scheme

- Perform the experiment again starting at a different initial concentration of OH-(aq) (changing only [OH-], holding other variables such as temperature and initial urea concentration constant), and measure how the concentration of CO(NH2)2 changes over time; compare the resulting rate/rate constant to that obtained at pH 13. 1 point earned for the description of a valid experiment (correct changed initial condition and data to be gathered).

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

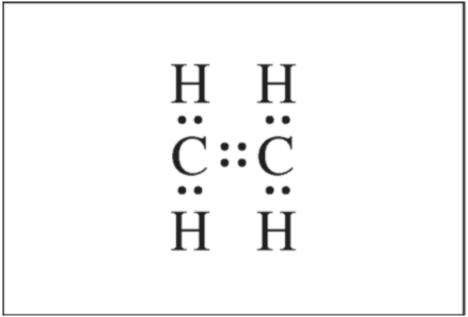
ethanol ethene water

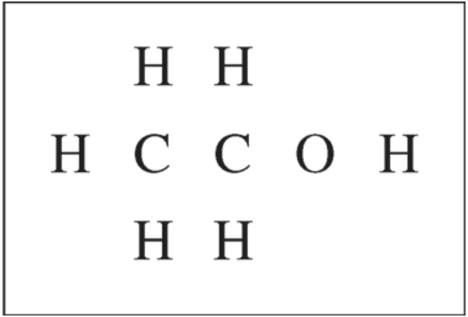
A student added a 0.200 g sample of $C_2H_5OH(l)$ to a test tube using the setup shown above. The student heated the test tube gently with a Bunsen burner until all of the $C_2H_5OH(l)$ evaporated and gas generation stopped. When the reaction stopped, the volume of collected gas was 0.0854 L at 0.822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

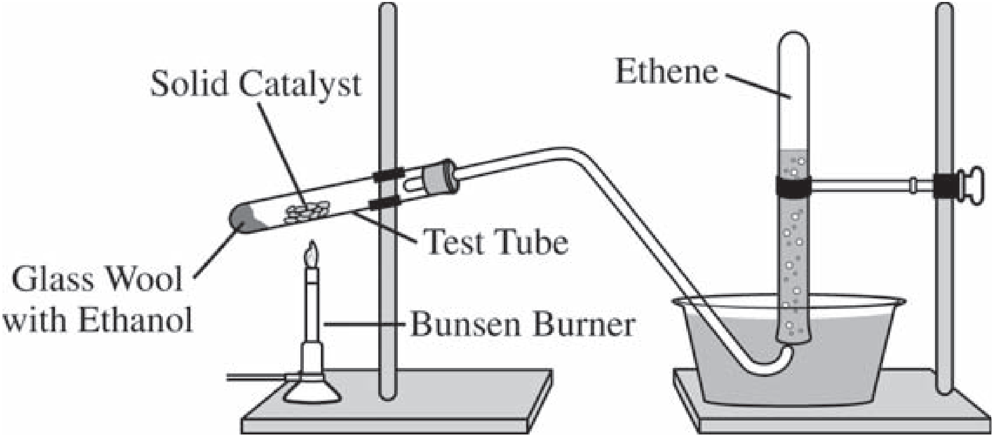
(a)(ii) Calculate the number of moles of $C_2H_4(g)$ that would be produced if the dehydration reaction went to completion.

Question 2





Question 2


Solid Catalyst
Ethene
Test Tube
Glass Wool
with Ethanol
Bunsen Burner

Question 2

2015 ▪ Q2

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ethanol ethene water

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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

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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

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ethanol　　　　ethene　water

Question 2

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(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

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

Question 2

2015 ▪ Q2

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ethanol ethene water

Question 2

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(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 $C2H5OH$ x (1 mol $C2H5OH$ / 46.1 g $C2H5OH$) x (1 mol $C2H4$ / 1 mol $C2H5OH$) = 0.00434 mol $C2H4$ 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).