Past-paper walk-through

Representations of Reactions ▪ 4.3

eXercise

Questions in this set

- 2022 Q3
- 2021 Q2
- 2018 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

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) → 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

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

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 $\Delta G°$ ($\Delta G° = -nFE°$).

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

2021 ▪ Q2

Answer the following questions about the element Si and some of its compounds.

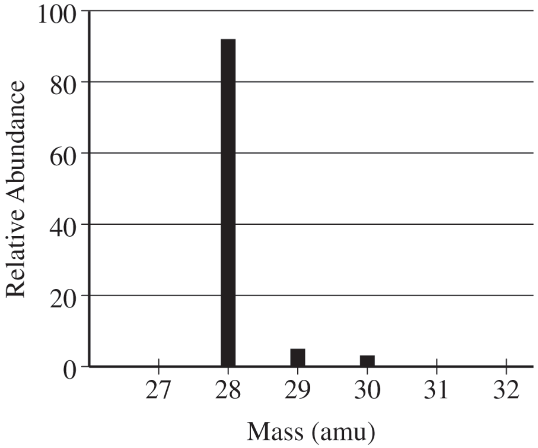
(a)(i) The mass spectrum of a pure sample of Si is shown below.

[Bar graph: Relative Abundance (y-axis, 0 to 100) vs. Mass (amu) (x-axis, 27 to 32). A tall bar of relative abundance ~92 at mass 28; a very small bar at mass 29 (~3); a very small bar at mass 30 (~4); negligible/no bars at 27, 31, 32.]

How many protons and how many neutrons are in the nucleus of an atom of the most abundant isotope of Si?

(a)(ii) Write the ground-state electron configuration of Si.

Question 2



Question 2

2021 ▪ Q2

Answer the following questions about the element Si and some of its compounds.

(b) Two compounds that contain Si are SiO_2 and SiH_4.

At 161 K, SiH_4 boils but SiO_2 remains as a solid. Using principles of interparticle forces, explain the difference in boiling points.

Question 2

2021 ▪ Q2

Answer the following questions about the element Si and some of its compounds.

(c) At high temperatures, SiH_4 decomposes to form solid silicon and hydrogen gas. Write a balanced equation for the reaction.

Question 2

2021 ▪ Q2

Answer the following questions about the element Si and some of its compounds.

(d) A table of absolute entropies of some substances is given below.

Substance	$S°$ (J/(mol · K))
$H_2(g)$	131
$Si(s)$	18
$SiH_4(g)$	205

Explain why the absolute molar entropy of $Si(s)$ is less than that of $H_2(g)$.

Question 2

2021 ▪ Q2

Answer the following questions about the element Si and some of its compounds.

(e) Calculate the value, in $J/(mol \cdot K)$, of ΔS° for the reaction.

Question 2

2021 ▪ Q2

Answer the following questions about the element Si and some of its compounds.

(f) The reaction is thermodynamically favorable at all temperatures. Explain why the reaction occurs only at high temperatures.

Question 2

2021 ▪ Q2

Answer the following questions about the element Si and some of its compounds.

(g) A partial photoelectron spectrum of pure Si is shown below. On the spectrum, draw the missing peak that corresponds to the electrons in the $3p$ sublevel.
[Photoelectron spectrum: Relative Number of Electrons (y-axis) vs. Binding Energy (MJ/mol) (x-axis, logarithmic scale decreasing left to right: 1,000, 100, 10, 1, 0.1). Peaks shown (from left to right, i.e. highest to lowest binding energy): a small peak near ~180 (between 1,000 and 100), a small peak near ~20 (between 100 and 10), a tall peak near ~10, and a small peak near ~1.5 (between 1 and 0.1). No peak is shown corresponding to the $3p$ sublevel — the student must draw it in at the appropriate position and relative height.]

Question 2

2021 ▪ Q2

Answer the following questions about the element Si and some of its compounds.

(h) Using principles of atomic structure, explain why the first ionization energy of Ge is lower than that of Si.

Question 2

2021 ▪ Q2

Answer the following questions about the element Si and some of its compounds.

(i) A single photon with a wavelength of 4.00×10^{-7} m is absorbed by the Si sample. Calculate the energy of the photon in joules.

Solution 2

(a)(i)

Mark scheme

- The mass spectrum's tallest peak (highest relative abundance, ~92%) is at mass 28, so Si-28 is the most abundant isotope. Silicon's atomic number is 14, so this isotope has 14 protons and $(28 - 14 =)$ 14 neutrons.

(a)(ii)

Mark scheme

- Accept either equivalent form of the ground-state electron configuration of Si: $1s^2 2s^2 2p^6 3s^2 3p^2$, or the noble-gas-core notation $[\mathrm{Ne}]3s^2 3p^2$.

Solution 2

(b)

Mark scheme

- SiH4 is composed of discrete molecules, so the only intermolecular forces between SiH4 molecules are (relatively weak) London dispersion forces. SiO2, by contrast, is a network covalent solid with strong covalent Si–O bonds extending throughout the entire structure. Because London dispersion forces are much weaker than covalent bonds, SiH4 boils at a much lower temperature (it is already a gas at 161 K) while SiO2 remains solid.

Solution 2

(c)

Mark scheme

- $SiH_4(g) \rightarrow Si(s) + 2\,H_2(g)$ (state symbols not required; equation is already balanced).

Solution 2

(d)

Mark scheme

- $H_2(g)$ molecules are more highly dispersed (able to move freely and occupy a much larger volume) than Si(s) atoms, and therefore have higher absolute molar entropy. Silicon is a solid, so its atoms are held in fixed positions within the lattice, are far less dispersed, and consequently have lower absolute molar entropy than $H_2(g)$.

Solution 2

(e)

Mark scheme

- $\Delta S^\circ_{rxn} = S^\circ_{\text{products}} - S^\circ_{\text{reactants}} = [18 + 2(131)] - 205 = +75$ J/(mol$_{rxn}$ · K), using S°: Si(s)=18, H2(g)=131 (×2 mol), SiH4(g)=205, all in J/(mol · K).

Solution 2

(f)

Mark scheme

- High temperature is required so the reactant SiH4 molecules have sufficient thermal (kinetic) energy to overcome the activation energy barrier of the reaction. A negative ΔG° (thermodynamic favorability) only indicates the reaction is spontaneous, not that it proceeds at an appreciable rate at low temperature — reaction rate is a kinetic property governed separately by activation energy.

Solution 2

(g)

Mark scheme

- The missing peak (representing the Si 3p electrons) should be drawn as the rightmost peak on the spectrum — i.e., at the lowest binding energy (below the existing 1 MJ/mol region), since 3p electrons are Si's outermost/valence electrons and thus the most weakly bound. Its height should reach the second gridline above the horizontal axis, reflecting that the 3p sublevel holds 2 electrons.

Solution 2

(h)

Mark scheme

- The valence electrons of a Ge atom occupy a higher principal energy level/shell ($n=4$) than those of a Si atom ($n=3$), so the average distance between the nucleus and the valence electrons is greater in Ge than in Si. This greater separation results in weaker Coulombic attraction between the Ge nucleus and its valence electrons, making them less tightly bound and therefore easier to remove — giving Ge a lower first ionization energy than Si.

Solution 2

(i)

Mark scheme

- $E = h\nu = h\dfrac{c}{\lambda} = (6.626 \times 10^{-34}\ \mathsf{J \cdot s})\left(\dfrac{2.998 \times 10^{8}\ \mathsf{m/s}}{4.00 \times 10^{-7}\ \mathsf{m}}\right) = 4.97 \times 10^{-19}\ \mathsf{J}.$

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.

(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.

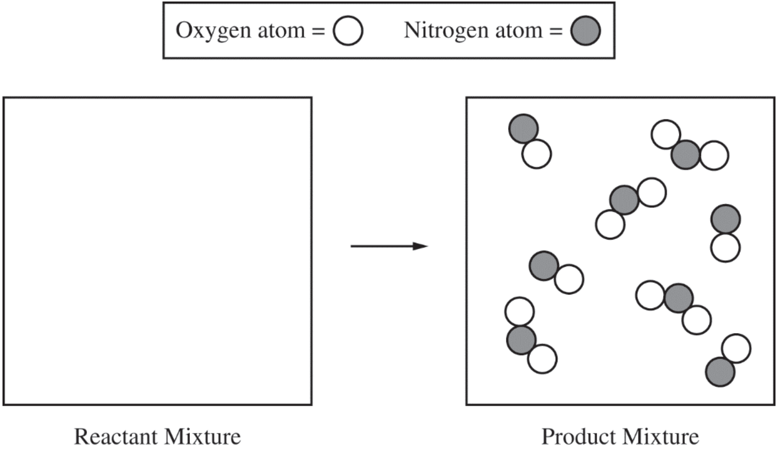
Question 2

[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.

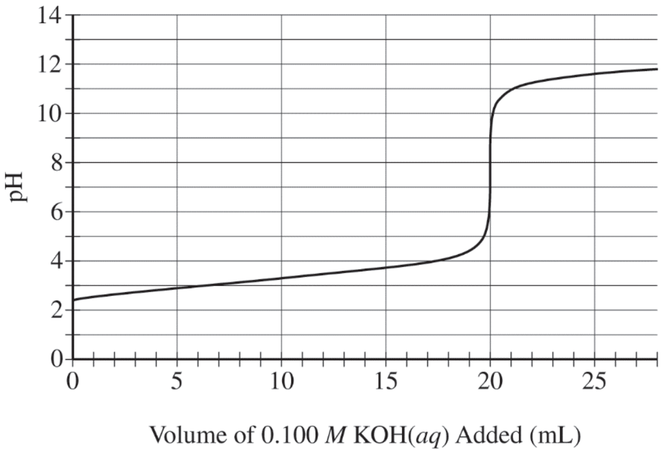
$$\mathrm{NO}(g) + \mathrm{NO_2}(g) \rightleftharpoons \mathrm{N_2O_3}(g)$$

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

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

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.

(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

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

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.

(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

- $NO_2^-(aq)$ 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 (NO_2^-) than the acid (HNO_2) is present. 1 point is earned for the correct choice AND a valid justification.