Past-paper walk-through

Endothermic and Exothermic Processes ▪ 6.1

eXercise

Questions in this set

- 2026 Q3
- 2023 Q3

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

2026 ▪ Q3

Nitrous acid, HNO_2, is a weak acid that ionizes according to Equation 1.

Equation 1: $HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq)$ $\qquad K_a = 5.6 \times 10^{-4}$ at 298 K

(a) Identify a conjugate acid-base pair in the equation. Be sure to clearly label which is the acid and which is the base.

Question 3

Table 1

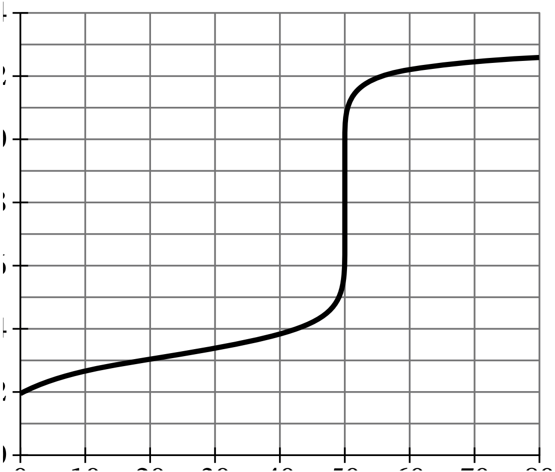
Chemical Equation	Equilibrium Constant
$HNO_2(aq) + H_2O(l) \rightleftarrows NO_2^-(aq) + H_3O^+(aq)$	$K_a = 5.6 \times 10^{-4}$
$H_2O(l) + H_2O(l) \rightleftarrows H_3O^+(aq) + OH^-(aq)$	$K_w = 1.0 \times 10^{-14}$
$HNO_2(aq) + OH^-(aq) \rightarrow NO_2^-(aq) + H_2O(l)$	$K_2 = \ ?$

Question 3

Table 2

Indicator Name	Acid Color	pH Range of Color Change	Base Color
Methyl orange	Red	3.1–4.4	Yellow
Thymol blue	Yellow	8.0–9.6	Blue
Clayton yellow	Yellow	12.2–13.2	Orange

Question 3



Question 3

2026 ▪ Q3

Nitrous acid, HNO_2, is a weak acid that ionizes according to Equation 1.

$$\text{Equation 1: } HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq) \qquad K_a = 5.6 \times 10^{-4} \text{ at } 298 \text{ K}$$

(b)(i) A solution of $HNO_2(aq)$ with an initial concentration of 0.125 *M* has a pH of 2.09.
Calculate the value of $[H_3O^+]$ in the solution. Show the work that leads to your answer.
(b)(ii) **Calculate** $[HNO_2]$ at equilibrium. Show the work that leads to your answer.

Question 3

2026 ▪ Q3

Nitrous acid, HNO_2, is a weak acid that ionizes according to Equation 1.

$$\text{Equation 1: } HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq) \qquad K_a = 5.6 \times 10^{-4} \text{ at } 298 \text{ K}$$

(c)(i) In an experiment, the solution of 0.125 M $HNO_2(aq)$ is heated to 333 K. The new equilibrium concentrations are determined to be $[HNO_2] = 0.114$ M, $[NO_2^-] = 0.0109$ M, and $[H_3O^+] = 0.0109$ M.
Calculate the value of K_a for HNO_2 at 333 K. Show the work that leads to your answer.
(c)(ii) Is the reaction represented by Equation 1 endothermic or exothermic? **Justify** your answer by comparing K_a values at 298 K and 333 K.

Question 3

2026 ▪ Q3

Nitrous acid, HNO_2, is a weak acid that ionizes according to Equation 1.

$$\text{Equation 1: } HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq) \qquad K_a = 5.6 \times 10^{-4} \text{ at } 298 \text{ K}$$

(d) The following information applies to parts D, E, and F.
In a second experiment, a student is given a bottle containing HNO_2 with an unknown molarity. To determine the concentration of the $HNO_2(aq)$ in the bottle, the student titrates 35.0 mL of the $HNO_2(aq)$ with 0.16 M $NaOH(aq)$ at 298 K, which reacts according to Equation 2.

$$\text{Equation 2: } HNO_2(aq) + OH^-(aq) \rightarrow NO_2^-(aq) + H_2O(l)$$

Question 3

The results of the titration are summarized in Figure 1.
[Figure 1: Titration curve, pH vs. Volume of 0.16 M NaOH Added (mL); y-axis pH 0 to 14 in increments of 2, x-axis 0 to 80 mL in increments of 10; curve starts near $(0, 2)$, rises gradually to about $(40, 4)$, then rises steeply (equivalence point) between about 45-55 mL up to about pH 12, then levels off gradually to approximately $(80, 12.7)$.]
Using Figure 1, **identify** the pH at the equivalence point.

Question 3

2026 ▪ Q3

Nitrous acid, HNO_2, is a weak acid that ionizes according to Equation 1.

$$\text{Equation 1: } HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq) \qquad K_a = 5.6 \times 10^{-4} \text{ at } 298 \text{ K}$$

(e) Using Figure 1, **calculate** the molarity $HNO_2(aq)$ of in the bottle. Show the work that leads to your answer.

Question 3

2026 ▪ Q3

Nitrous acid, HNO_2, is a weak acid that ionizes according to Equation 1.

$$\text{Equation 1: } HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq) \qquad K_a = 5.6 \times 10^{-4} \text{ at } 298\text{ K}$$

(f) **Draw** an X on Figure 1 to represent a point in the titration where $[HNO_2] > [NO_2^-]$ in the reaction mixture.

Question 3

2026 ▪ Q3

Nitrous acid, HNO_2, is a weak acid that ionizes according to Equation 1.

$$\text{Equation 1: } HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq) \qquad K_a = 5.6 \times 10^{-4} \text{ at 298 K}$$

(g) Equilibrium constants at 298 K are shown in Table 1 for the acid ionization reaction represented by Equation 1, K_a; the autoionization of water, K_w; and the neutralization reaction represented by Equation 2, K_2.

Chemical Equation	Equilibrium Constant
$HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq)$	$K_a = 5.6 \times 10^{-4}$
$H_2O(l) + H_2O(l) \rightleftharpoons H_3O^+(aq) + OH^-(aq)$	$K_w = 1.0 \times 10^{-14}$
$HNO_2(aq) + OH^-(aq) \rightarrow NO_2^-(aq) + H_2O(l)$	$K_2 = ?$

Question 3

Calculate the value of K_2 for Equation 2 at 298 K. Show the work that leads to your answer.

Question 3

2026 ▪ Q3

Nitrous acid, HNO_2, is a weak acid that ionizes according to Equation 1.

$$\text{Equation 1: } HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq) \qquad K_a = 5.6 \times 10^{-4} \text{ at } 298 \text{ K}$$

(h) The student decides to repeat the experiment, this time using an indicator, and has access to the indicators in Table 2.

Indicator Name	Acid Color	pH Range of Color Change	Base Color
Methyl orange	Red	3.1–4.4	Yellow
Thymol blue	Yellow	8.0–9.6	Blue
Clayton yellow	Yellow	12.2–13.2	Orange

Question 3

The student conducts a second titration by adding two drops of methyl orange indicator to 35.0 mL of the $HNO_2(aq)$ solution and titrating the solution with 0.16 M $NaOH(aq)$ until a color change from red to yellow occurs.
The student claims that methyl orange was the best choice for the indicator. Do you agree or disagree? **Justify** your answer.

Question 3

2023 ▪ Q3

Answer the following questions about an experiment in which $CaCO_3(s)$ is combined with $HCl(aq)$, represented by the following balanced equation.

$$CaCO_3(s) + 2\,HCl(aq) \rightarrow CaCl_2(aq) + CO_2(g) + H_2O(l)$$

(a) Write the balanced net ionic equation for the reaction.

Question 3

2023 ▪ Q3

Answer the following questions about an experiment in which $CaCO_3(s)$ is combined with $HCl(aq)$, represented by the following balanced equation.

$$CaCO_3(s) + 2\,HCl(aq) \rightarrow CaCl_2(aq) + CO_2(g) + H_2O(l)$$

(b) A student performs an investigation to study factors that affect the rate of the reaction. In each trial the student combines 50.0 mL of $HCl(aq)$ at $21.2°C$ with 1.00 g of $CaCO_3(s)$ and measures the time required for the reaction to go to completion. The data are given in the following table.
| Trial | Concentration of $HCl(aq)$ (M) | Particle Size of $CaCO_3(s)$ | Time of Reaction (s) | |—|—|—|—| | 1 | 1.00 | Fine powder | 67 | | 2 | 1.00 | Small chunks | 112 | | 3 |

Question 3

1.00 | Large chunk | 342 | | 4 | 3.00 | Fine powder | 22 | | 5 | 3.00 | Small chunks | 227 | | 6 | 3.00 | Large chunk | 114 |

The student correctly identifies that trial 5 is inconsistent with the other trials. Explain why the student's claim is correct using the data in the table.

Question 3

2023 ▪ Q3

Answer the following questions about an experiment in which $CaCO_3(s)$ is combined with $HCl(aq)$, represented by the following balanced equation.

$$CaCO_3(s) + 2\,HCl(aq) \rightarrow CaCl_2(aq) + CO_2(g) + H_2O(l)$$

(c) Based on the reaction conditions and the collisions that occur between particles, explain the reason for the difference in the reaction times for trial 2 and trial 3.

Question 3

2023 ▪ Q3

Answer the following questions about an experiment in which $CaCO_3(s)$ is combined with $HCl(aq)$, represented by the following balanced equation.

$$CaCO_3(s) + 2\,HCl(aq) \rightarrow CaCl_2(aq) + CO_2(g) + H_2O(l)$$

(d) The student claims that the reaction is zero order with respect to $HCl(aq)$. Do you agree or disagree with the student's claim? Justify your answer using the student's data.

Question 3

2023 ▪ Q3

Answer the following questions about an experiment in which $CaCO_3(s)$ is combined with $HCl(aq)$, represented by the following balanced equation.

$$CaCO_3(s) + 2\,HCl(aq) \rightarrow CaCl_2(aq) + CO_2(g) + H_2O(l)$$

(e) The $HCl(aq)$ was present in excess in all trials of the experiment. Determine the molarity of the $HCl(aq)$ in the beaker after the reaction is complete in trial 2. Assume that the volume of the mixture remains constant at 50.0 mL throughout the trial. (The molar mass of $CaCO_3$ is 100.09 g/mol.)

Question 3

2023 ▪ Q3

Answer the following questions about an experiment in which $CaCO_3(s)$ is combined with $HCl(aq)$, represented by the following balanced equation.

$$CaCO_3(s) + 2\,HCl(aq) \rightarrow CaCl_2(aq) + CO_2(g) + H_2O(l)$$

(f)

$$CaCO_3(s) + 2\,HCl(aq) \rightarrow CaCl_2(aq) + CO_2(g) + H_2O(l)$$

In order to measure the enthalpy of the reaction shown, the student repeats trial 1 by mixing 50.0 mL of $HCl(aq)$ with 1.00 g of $CaCO_3(s)$ using a coffee cup calorimeter. The student records the temperature of the system every 20 seconds. The data are given in the following table.

Question 3

Time (s)	Measured Temperature of Solution (°C)
0	21.20
20	21.51
40	21.70
60	21.85
80	21.90
100	21.90

Is the reaction endothermic or exothermic? Justify your answer using the information in the table.

Question 3

2023 ▪ Q3

Answer the following questions about an experiment in which $CaCO_3(s)$ is combined with $HCl(aq)$, represented by the following balanced equation.

$$CaCO_3(s) + 2\,HCl(aq) \rightarrow CaCl_2(aq) + CO_2(g) + H_2O(l)$$

(g)(i) Based on the experimental data, the mass of the system is 51.0 g, and the specific heat of the reaction mixture is 4.0 J/(g · °C).
Calculate the magnitude of heat transfer, q, in joules.
(g)(ii) Calculate the enthalpy of reaction in units of kJ/mol_{rxn}. Include the algebraic sign on your answer.

Solution 3

(a)

Mark scheme

- Balanced net ionic equation:
  $CaCO_3(s) + 2\,H^+(aq) \rightarrow Ca^{2+}(aq) + CO_2(g) + H_2O(l)$ (equivalently with hydronium: $CaCO_3(s) + 2\,H_3O^+(aq) \rightarrow Ca^{2+}(aq) + CO_2(g) + 3\,H_2O(l)$).
  State symbols not required.

Solution 3

(b)

Mark scheme

- Accept either explanation: (1) Even though [HCl] is greater in trial 5 than trial 2, the reaction time is significantly longer; trials 2 and 5 are otherwise identical, and the trend from trials 1 and 4 shows that a higher [HCl] gives a shorter reaction time, so concentration alone cannot explain trial 5 — particle size must be the cause. (2) The reaction time in trial 5 (small chunks) is longer than in trial 6 (large chunks), even though trials 5 and 6 are otherwise identical; the trend from trials 1, 2, and 3 shows that larger chunks of solid give a longer reaction time.

Solution 3

(c)

Mark scheme

- The reaction time in trial 2 is shorter than in trial 3 because the calcium carbonate in trial 2 has a larger surface area, meaning more $CaCO_3$ particles are exposed to H^+ particles in solution (1 point). A larger interface between the two reacting substances means more particle collisions occur per unit time, giving a higher frequency of successful collisions in which particles react to form products, i.e. a higher reaction rate (1 point).

Solution 3

(d)

Mark scheme

- Disagree. Accept either justification: (1) If the reaction were zeroth order with respect to HCl, changing [HCl] would not affect the reaction rate, so reaction time would be the same for trials differing only in [HCl] — but the data for trials 1 and 4 (and likewise 3 and 6) show that changing [HCl] significantly alters the time of reaction. (2) The reaction appears first order, not zeroth order, with respect to [HCl]: tripling [HCl] results in a reaction time that is $1/3$ of that when $[HCl] = 1.00$ M, meaning the rate has also tripled, indicating a first-order process.

Solution 3

(e) Mark scheme

- Moles of HCl reacted: $1.00\text{ g CaCO}_3 \times \dfrac{1\text{ mol}}{100.09\text{ g}} = 0.00999\text{ mol CaCO}_3$; $0.00999\text{ mol CaCO}_3 \times \dfrac{2\text{ mol HCl}}{1\text{ mol CaCO}_3} = 0.0200\text{ mol HCl reacted (1 point)}$. Remaining [HCl]: initial HCl $= 0.0500\text{ L} \times 1.00\text{ mol/L} = 0.0500\text{ mol}$; $0.0500 - 0.0200 = 0.0300\text{ mol remaining}$; $\dfrac{0.0300\text{ mol}}{0.0500\text{ L}} = 0.600\ M\text{ HCl remaining}$ (1 point).

Solution 3

(f)

Mark scheme

- Exothermic. The solution temperature increases as the reaction proceeds (per the calorimeter data), indicating heat is released to the surroundings.

Solution 3

(g)(i)

Mark scheme

- $q_{surr} = mc\Delta T = (51.0\ \text{g})\left(4.0\ \frac{\text{J}}{\text{g}\cdot{}^\circ\text{C}}\right)(21.90^\circ\text{C} - 21.20^\circ\text{C}) = 140\ \text{J}$ (sign not required).

Solution 3

(g)(ii)

Mark scheme

- $q_{sys} = -q_{surr} = -140\ \text{J} = -0.14\ \text{kJ}$; moles reacted $= 1.00\ \text{g CaCO}_3 \times \dfrac{1\ \text{mol CaCO}_3}{100.09\ \text{g CaCO}_3} \times \dfrac{1\ \text{mol}_{rxn}}{1\ \text{mol CaCO}_3} = 0.00999\ \text{mol}_{rxn}$; $\Delta H^\circ_{rxn} = \dfrac{-0.14\ \text{kJ}}{0.00999\ \text{mol}_{rxn}} = -14\ \text{kJ/mol}_{rxn}$ (include the algebraic sign).