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Topic 5.11: Catalysis

Worksheet · AP Chemistry

UNIT 5 · KINETICS

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How to Use This Worksheet

Work in order. Section A checks the definitions. Section B practises the skills on described profiles and mechanisms: barriers in both directions, species identification, and a rate law containing a catalyst. Section C is exam style: judging claims and a full problem.

Reference facts. A catalyst provides an alternative pathway with a lower activation energy and is regenerated, so it cancels out of the overall equation. Catalysed and uncatalysed profiles share the same reactant and product levels, so ΔH is identical on both; only the peaks differ. E_a(reverse) = E_a(forward) − ΔH for any single step. A catalyst speeds the forward and reverse reactions together, so the equilibrium constant, the position of equilibrium and the yield are unchanged; only the time to reach equilibrium falls. A catalyst in the rate-determining step, or in a step before it, appears in the rate law.

Two profiles of the same reaction recur, every level in kJ/mol. Profile U (uncatalysed, one step): reactants 70, peak 190, products 30. Profile C (catalysed, two steps): reactants 70, first peak 135, valley 95, second peak 125, products 30.

Three habits protect every answer. Read every barrier from the level the step starts from, and check each ΔH against the endpoints. Never let a catalyst move an endpoint, an equilibrium or a yield.

Do not look at the answer key until you have attempted every question.

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Section A: Recall and Concepts

A1. (a) Define a catalyst. (b) State how a catalyst increases the rate, in terms of activation energy and collisions. (c) State what happens to the total amount of a catalyst during a reaction. (d) State whether a catalyst appears in the overall equation, and explain why.

A2. (a) State three quantities that a catalyst does not change. (b) State two things that a catalyst does change. (c) A reaction mixture reaches equilibrium sooner when a catalyst is added. State the effect on the equilibrium constant and on the position of equilibrium. (d) State the effect of a catalyst on the yield of product, and explain it in one sentence.

A3. (a) State the difference between a catalyst and an intermediate in a mechanism, in terms of where each first appears. (b) A species is consumed in step 1 of a mechanism and regenerated in step 3. State its label. (c) A species is formed in step 1 and consumed in step 2. State its label. (d) State whether either species appears in the overall equation, and where the catalyst is found at the end.

A4. (a) State two things that stay the same when a catalysed curve is drawn on the same axes as an uncatalysed curve. (b) State what changes. (c) State what a valley between two peaks on the catalysed curve represents.

A5. (a) Define homogeneous catalysis and give one example. (b) Define heterogeneous catalysis and give one example. (c) State what an enzyme is. (d) For a solid catalyst, state the effect of increasing its surface area on the rate, and give the reason.

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Section B: Core Practice

B1. Use Profile U. (a) Calculate E_a(forward). (b) Calculate ΔH and classify the reaction. (c) Calculate E_a(reverse) from the levels. (d) Check your answer to (c) against the identity E_a(reverse) = E_a(forward) − ΔH.

B2. Use Profile C. (a) State how many steps the catalysed mechanism has and state the energy of the species in the valley. (b) Calculate the activation energy of each step. (c) Identify the rate-determining step. (d) Calculate ΔH for each step and show that the values sum to the overall ΔH. (e) State the largest barrier on Profile U and on Profile C, and by how much the largest barrier fell. (f) Calculate E_a(reverse) for step 2 of Profile C from the levels, and check it against the identity.

B3. Iron(III) ions catalyse the reaction between iodide ions and peroxodisulfate ions in aqueous solution. Step 1: $2Fe^{3+} + 2I^- \rightarrow 2Fe^{2+} + I_2$. Step 2: $2Fe^{2+} + S_2O_8^{2-} \rightarrow 2Fe^{3+} + 2SO_4^{2-}$. (a) Add the two steps and cancel species that appear on both sides, to write the overall equation. (b) Identify the catalyst, giving the reason. (c) Identify the intermediate, giving the reason. (d) State whether this catalysis is homogeneous or heterogeneous, and give the reason. (e) Explain why Fe^{3+} does not appear in the overall equation even though it is consumed in step 1.

B4. A reaction X + Y → XY is catalysed by a substance Cat. Step 1 (slow): X + Cat → XCat. Step 2 (fast): XCat + Y → XY + Cat. (a) Add the steps and confirm the overall equation. (b) Identify the catalyst and the intermediate. (c) Write the rate law for the reaction, explaining your choice. (d) Calculate the rate when k = 0.80 L mol^{-1} s^{-1}, [X] = 0.30 mol/L and [Cat] = 0.020 mol/L. (e) State the new rate if [Cat] is doubled, and state the value of [Cat] at the end of the run.

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B5. A solid catalyst is used for a gas reaction, first as one solid lump and then ground to a powder of the same mass. (a) State which form gives the faster rate, and explain why in terms of active sites. (b) A poison in the gas stream coats the powder. State the effect on the rate and explain it. (c) State the effect of grinding, and of the poison, on the ΔH of the reaction and on the position of equilibrium. (d) State the pair of observations that would confirm the solid is acting as a catalyst rather than as a reactant.

B6. A reversible reaction reaches an equilibrium mixture containing 70% product. Without a catalyst this takes 40 minutes; with a catalyst it takes 8 minutes. (a) State the percentage of product in the equilibrium mixture with the catalyst present, and explain your answer. (b) After 8 minutes, the catalysed run has more product than the uncatalysed run. Explain why this does not mean the catalyst increased the yield. (c) State what the catalyst does to the rate of the reverse reaction, and explain why that decides the answer to (a).

Section C: Exam Style

C1. Judge each claim about Profiles U and C (levels as stated in Section B), supporting each verdict with a calculation or a level reference. (a) "The catalyst has made the reaction more exothermic, because the catalysed route has lower peaks." (b) "The reverse reaction is also faster on Profile C: its tallest reverse climb is 95 kJ/mol, against 160 kJ/mol on Profile U." (c) "The catalysed route is faster because it has more steps than the uncatalysed route." (d) "The species in the valley of Profile C is the catalyst." (e) "Adding the two catalysed barriers, 65 + 30 = 95 kJ/mol, gives the activation energy of the catalysed reaction."

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C2. Ammonia is made from nitrogen and hydrogen in the Haber process: $N_2 + 3H_2 \rightleftharpoons 2NH_3$, $\Delta H = -92$ kJ/mol, over an iron catalyst. (a) State whether the iron is a homogeneous or heterogeneous catalyst, and give the reason. (b) State the mass of iron present after a long production run, compared with the mass at the start, and explain why. (c) State the effect of the iron on the time taken for the mixture to reach equilibrium. (d) State the effect of the iron on the equilibrium yield of ammonia. (e) Explain, at the level of the gas particles and the iron surface, why the reaction is faster over iron, and why the iron is used in a form with a large surface area. (f) State the effect of the iron on the reverse reaction, the decomposition of ammonia, and explain why both effects must occur together.

C3. Bromide ions catalyse the decomposition of hydrogen peroxide in solution. Step 1 (slow): $H_2O_2 + Br^- \rightarrow H_2O + BrO^-$. Step 2 (fast): $H_2O_2 + BrO^- \rightarrow H_2O + O_2 + Br^-$. (a) Add the two steps and cancel species that appear on both sides, to write the overall equation. (b) Identify the catalyst and the intermediate, giving the reason for each. (c) Write the rate law for the reaction. (d) Calculate the rate when $k = 0.25$ L mol^{-1} s^{-1}, $[H_2O_2] = 0.40$ mol/L and $[Br^-] = 0.10$ mol/L. (e) The energy profile of this catalysed route has two peaks and one valley, while the uncatalysed route has one higher peak. State what the valley holds, and state the two features the catalysed profile must share with the uncatalysed profile.

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Answer Key

A1. (a) A substance that increases the rate of a reaction and is regenerated, so it is present, chemically unchanged, at the end. (b) It provides an alternative pathway with a lower activation energy, so at the same temperature more collisions have enough energy to react and succeed per second. (c) Unchanged: consumed in one step and regenerated in a later step, its total amount at the end equals the amount at the start. (d) No. Used and remade in equal amounts, it cancels when the steps are added, so it never appears in the overall equation.

A2. (a) Any three of: ΔH; the equilibrium constant; the position of equilibrium; the yield; the reactant and product energies. (b) The rate, and the pathway (mechanism), including its activation energy. (c) Neither changes: the catalyst speeds both directions equally, so the constant and the position are the same; only the time taken to reach equilibrium is shorter. (d) None. Yield is fixed by the equilibrium position and the reactant amounts, and the catalyst changes neither, so the same amount of product forms, only sooner.

A3. (a) A catalyst first appears as a reactant: present from the start, consumed early, regenerated later. An intermediate first appears as a product: formed in one step, consumed in a later step, existing only during the reaction. (b) A catalyst. (c) An intermediate. (d) Neither: both cancel when the steps are added. The catalyst remains in the mixture, unchanged and in the same total amount.

A4. (a) The reactant level and the product level, and therefore ΔH. (b) The peaks: they are lower, and their number may differ. (c) An intermediate of the catalysed mechanism: a species formed in the first catalysed step and consumed in the second.

A5. (a) The catalyst shares the reactants' phase: for example, an acid dissolved in the same aqueous solution as the reactants. (b) The catalyst is in a different phase from the reactants: for example, solid platinum acting on exhaust gases in a catalytic converter. (c) A biological catalyst: a protein that provides a low-barrier pathway for a reaction in a living cell. (d) The rate increases: reaction on a solid happens at surface active sites, and a larger area exposes more sites, so more particles react per second.

B1. (a) E_a(forward) = 190 − 70 = 120 kJ/mol. (b) ΔH = 30 − 70 = −40 kJ/mol: products below reactants, so exothermic. (c) E_a(reverse) = 190 − 30 = 160 kJ/mol. (d) Identity: E_a(forward) − ΔH = 120 − (−40) = 160 kJ/mol, matching (c).

B2. (a) Two steps: there are two peaks. The valley species sits at 95 kJ/mol. (b) Step 1: 135 − 70 = 65 kJ/mol. Step 2: 125 − 95 = 30 kJ/mol, measured from the valley, the level step 2 starts from. (c) Step 1 is rate-determining: its barrier of 65 kJ/mol is the largest. (d) Step 1: 95 − 70 = +25 kJ/mol. Step 2: 30 − 95 = −65 kJ/mol. Sum: +25 + (−65) = −40 kJ/mol. Overall ΔH from the endpoints: 30 − 70 = −40 kJ/mol, matching. (e) Largest barrier on Profile U: 120 kJ/mol. Largest barrier on Profile C: 65

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kJ/mol. The largest barrier fell by 55 kJ/mol (120 − 65), which is why the catalysed route is faster. (f) From the levels, step 2 in reverse climbs from the products to the second peak: 125 − 30 = 95 kJ/mol. Identity: E_a(forward) − ΔH for step 2 = 30 − (−65) = 95 kJ/mol, matching.

B3. (a) Adding the steps: $2Fe^{3+} + 2I^- + 2Fe^{2+} + S_2O_8^{2-}$ on the left, and $2Fe^{2+} + I_2 + 2Fe^{3+} + 2SO_4^{2-}$ on the right. Cancelling $2Fe^{3+}$ and $2Fe^{2+}$ from both sides leaves the overall equation $2I^- + S_2O_8^{2-} \rightarrow I_2 + 2SO_4^{2-}$. (b) Fe^{3+}: present at the start, consumed in step 1 and regenerated in step 2, so it cancels. (c) Fe^{2+}: formed in step 1 and consumed in step 2, so it also cancels, but it was not present at the start. (d) Homogeneous: catalyst and reactants are all ions in the same aqueous solution, one phase. (e) Every Fe^{3+} ion used in step 1 is remade in step 2, so over the full mechanism none is used up. A species that is neither a net reactant nor a net product cannot appear in the overall equation.

B4. (a) Adding the steps: X + Cat + XCat + Y on the left, XCat + XY + Cat on the right. Cancelling Cat and XCat leaves X + Y → XY, as required. (b) Cat is the catalyst: consumed in step 1 and regenerated in step 2. XCat is the intermediate: formed in step 1 and consumed in step 2. (c) Step 1 is the slow step and is elementary, so the rate law takes its form from step 1: rate = k[X][Cat]. The catalyst appears because it is in that step. (d) Rate = 0.80 × 0.30 × 0.020 = 0.0048 mol L^{-1} s^{-1}. (e) Doubling [Cat] doubles the rate to 0.0096 mol L^{-1} s^{-1} (first order in Cat). [Cat] is still 0.040 mol/L at the end: regenerated as fast as it is used, its concentration never falls.

B5. (a) The powder: grinding exposes far more surface, and since reaction happens at surface active sites, the powder offers many more sites for gas particles to adsorb and react per second. (b) The rate falls: the poison coats the surface and blocks the active sites, so fewer gas particles can use the catalysed pathway, and the rate drops back toward the uncatalysed rate. (c) No effect in either case: neither grinding nor poisoning moves an energy level or favours one direction, so ΔH and the equilibrium position stay exactly as they were. (d) The reaction reaches completion sooner with the solid present, and the solid is recovered with its mass unchanged at the end.

B6. (a) 70%: the catalyst speeds both directions equally, so the balance between them and the equilibrium mixture are unchanged; the mixture just arrives at 70% product sooner. (b) At 8 minutes the uncatalysed run is still travelling toward equilibrium, so it has made less product so far. Yield is the amount at equilibrium: 70% in both runs. The catalyst changed the timing, not the amount. (c) It speeds the reverse reaction by the same factor: the lowered barrier is crossed in both directions, so neither side is favoured and the composition cannot move.

C1. (a) False. ΔH comes from the endpoints only: 30 − 70 = −40 kJ/mol on Profile U, and the same on Profile C. The reaction is exactly as exothermic on both routes; peaks play no part in ΔH. (b) True. On Profile U the reverse climb is 190 − 30 = 160 kJ/mol. On Profile C the reverse climbs are 125 − 30 = 95 kJ/mol for step 2 and 135 − 95 = 40 kJ/mol for step 1, so the tallest reverse climb is 95 kJ/mol, well below 160 kJ/mol. (c) False. The number of steps does not set the rate; the largest barrier does. Profile C is faster because its largest barrier, 65 kJ/mol, is far below Profile U's 120 kJ/mol. (d) False. A valley holds an intermediate, formed in step 1 and consumed in step 2. The

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catalyst is present at the start and is consumed and regenerated across the steps, not stored in a valley. (e) False. Step barriers are never added, so 95 kJ/mol means nothing here: the rate is governed by the largest single barrier, 65 kJ/mol.

C2. (a) Heterogeneous: the iron is a solid and the reactants are gases, in different phases, and the reaction takes place on the iron surface. (b) The same mass: the iron is regenerated, never converted into ammonia or anything else, so none is used up however much ammonia forms. (c) Sooner: the lower activation energy means the mixture settles to its equilibrium composition in less time. (d) None: both directions speed up equally, so the position of equilibrium and the equilibrium yield are unchanged; only the wait is shorter. (e) Gas particles adsorb onto active sites on the iron surface, where their pathway has a lower activation energy than the gas phase route. A larger fraction of them therefore has enough energy to react, and the products leave, freeing the sites for more particles. A large surface area exposes more of those sites to the gas at any moment, so more particles per second use the surface pathway. (f) It speeds it up as well: the catalysed route is the same pathway travelled in reverse, its lowered peaks cutting the reverse barrier just as they cut the forward one. The two effects are inseparable, which is why the equilibrium position cannot shift.

C3. (a) Adding the steps: $2H_2O_2 + Br^- + BrO^-$ on the left, and $2H_2O + O_2 + Br^- + BrO^-$ on the right. Cancelling Br^- and BrO^- from both sides leaves the overall equation $2H_2O_2 \rightarrow 2H_2O + O_2$. (b) Br^- is the catalyst: present at the start, consumed in step 1, regenerated in step 2. BrO^- is the intermediate: formed in step 1, consumed in step 2. (c) Step 1 is the slow step and Br^- takes part in it, so the rate law is rate = $k[H_2O_2][Br^-]$. (d) Rate = $0.25 \times 0.40 \times 0.10 = 0.010$ mol L^{-1} s^{-1}. (e) The valley holds the intermediate, BrO^-. The catalysed profile must share the reactant and product levels with the uncatalysed profile, so both routes have the same ΔH; only the peaks may differ.

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