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Topic 5.6: Reaction Energy Profile

Worksheet · AP Chemistry

UNIT 5 · KINETICS

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How to Use This Worksheet

Work in order. Section A checks the vocabulary of the diagram: axes, peaks, valleys, and what each difference between levels means. Section B practises the arithmetic on described profiles: activation energies in both directions, ΔH, a catalysed curve, and a two-peak profile. Section C combines the ideas in exam style.

Reference facts used throughout. E_a(forward) = peak − reactants. ΔH = products − reactants. E_a(reverse) = peak − products, and the three values obey E_a(reverse) = E_a(forward) − ΔH. A peak holds a transition state; a valley between peaks holds an intermediate. On a two-peak profile, the barrier of the second step is measured from the valley, not from the reactants. A catalyst lowers the peak and leaves both flat levels, and so ΔH, unchanged.

Profiles are described in words, with every energy level given in kJ/mol, so each answer can be checked by subtraction alone. Three profiles recur. Profile X: reactants 90, peak 170, products 20. Profile Y: reactants 40, peak 130, products 110. Profile Z: reactants 70, first peak 150, valley 100, second peak 210, products 55.

Three habits protect every answer. Measure every barrier from the level its step starts from, never from zero. Take ΔH from the endpoints only, with its sign. Check each reverse barrier against the identity before moving on.

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

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Section A: Recall and Concepts

A1. (a) State what is plotted on each axis of a reaction energy profile. (b) State what the flat level at the left of the curve represents, and what the flat level at the right represents. (c) State what the highest point of the curve represents.

A2. (a) Define activation energy in terms of two levels on the diagram. (b) Define ΔH in terms of two levels on the diagram. (c) State which of the two quantities involves the peak, and which ignores it completely. (d) State the sign of ΔH for an exothermic reaction and for an endothermic reaction.

A3. (a) State the two names given to the species at the top of the peak. (b) Explain why it cannot be isolated. (c) State how its stability compares with the species on either side of it.

A4. (a) State what a valley between two peaks represents. (b) Give two ways in which an intermediate differs from a transition state. (c) State what the number of peaks on a profile tells you about the mechanism.

A5. (a) State three things a catalyst leaves unchanged on an energy profile. (b) State what it changes, and name the two activation energies that both fall as a result. (c) State what raising the temperature changes among the labelled energies of the diagram. (d) State whether the catalysed curve must show the same number of peaks as the uncatalysed curve, and why.

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Section B: Core Practice

B1. Profile X: reactants 90, peak 170, products 20 kJ/mol. (a) Calculate E_a(forward). (b) Calculate ΔH, with its sign. (c) State whether the reaction is exothermic or endothermic, and name the feature of the levels that decides it.

B2. Stay with Profile X. (a) Calculate E_a(reverse). (b) Show that your answer agrees with the identity $E_a(\text{reverse}) = E_a(\text{forward}) - \Delta H$. (c) State whether the reverse reaction is exothermic or endothermic, and which direction has the larger activation energy.

B3. A catalyst is added to the reaction of Profile X, and the catalysed peak sits at 130 kJ/mol. (a) Calculate the catalysed E_a(forward). (b) Calculate the catalysed E_a(reverse). (c) State the catalysed ΔH and explain why it takes that value. (d) State two features the catalysed and uncatalysed curves share, and one feature they do not share. (e) By how many kJ/mol did the catalyst lower the peak, and by how much did each activation energy fall?

B4. Profile Y: reactants 40, peak 130, products 110 kJ/mol. (a) Calculate E_a(forward). (b) Calculate ΔH, with its sign, and classify the reaction. (c) Calculate E_a(reverse) and check it against the identity. (d) Verify, using your numbers, the rule that for an endothermic reaction E_a(forward) is larger than ΔH.

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B5. Profile Z is a two-peak profile: reactants 70, first peak 150, valley 100, second peak 210, products 55 kJ/mol. (a) State how many elementary steps the mechanism has, and what sits in the valley, at what energy. (b) Calculate the activation energy of step 1. (c) Calculate the activation energy of step 2, stating the level you measured from. (d) Identify the rate-determining step and give the reason. (e) Calculate the overall ΔH and classify the overall reaction. (f) State which peak is higher in absolute energy, and whether it belongs to the rate-determining step in this profile.

B6. An endothermic reaction has reactants at 25 kJ/mol, E_a(forward) = 95 kJ/mol and ΔH = +45 kJ/mol. (a) Calculate the energy of the peak. (b) Calculate the energy of the products. (c) Calculate E_a(reverse) in two ways: from the levels, and from the identity. (d) Describe the full profile in words: where the curve starts, how high it climbs, and where it finishes relative to the start.

Section C: Exam Style

C1. A reaction has reactants at 60 kJ/mol, a peak at 180 kJ/mol and products at 100 kJ/mol. (a) Calculate E_a(forward), ΔH and E_a(reverse), and classify the reaction. (b) A catalyst lowers the peak to 140 kJ/mol. Calculate both catalysed activation energies and state the catalysed ΔH. (c) Explain, using the levels, why the catalyst speeds up the reverse reaction as well as the forward one. (d) The mixture is heated instead, with no catalyst. State what happens to each of the three levels and to the rate, and explain the rate change without moving any level. (e) A student calculates the forward E_a of the uncatalysed reaction as 180 − 100 = 80 kJ/mol. Explain the error, and state what the value 80 kJ/mol actually measures.

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C2. A two-step mechanism has this profile: reactants 30, first peak 160, valley 70, second peak 130, products 90 kJ/mol. (a) Calculate the activation energy of each step. (b) Identify the rate-determining step, with the reason. (c) State the energy of the intermediate and calculate the overall ΔH, classifying the overall reaction. (d) A catalyst lowers only the second peak, to 110 kJ/mol. Calculate the new barrier of step 2 and state whether the rate-determining step changes, with the reason. (e) A student says step 2 must be rate-determining because its peak is the one the reaction reaches last. Correct the claim.

C3. Judge each claim about Profile X (reactants 90, peak 170, products 20 kJ/mol), supporting each verdict with a calculation or a level reference. (a) "Heating the reaction mixture lowers the peak to 150 kJ/mol." (b) "The catalyst made ΔH more negative, from −70 to −110 kJ/mol." (c) "The intermediate in this reaction could in principle be isolated, but the transition state could not." (d) "E_a(reverse) = E_a(forward) − ΔH holds for this profile, giving 150 kJ/mol." (e) "The products of Profile X are more stable than the reactants by 70 kJ/mol."

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Answer Key

A1. (a) Vertical axis: potential energy, in kJ/mol. Horizontal axis: reaction progress, the reaction coordinate, running from reactants to products; it is not a time axis. (b) The left level is the energy of the reactants; the right level is the energy of the products. (c) The transition state, the highest-energy arrangement of atoms along the pathway.

A2. (a) Activation energy is the peak energy minus the reactant energy: the climb from the reactant level to the transition state. (b) ΔH is the product energy minus the reactant energy. (c) Activation energy involves the peak; ΔH ignores it completely and uses only the two flat levels. (d) Exothermic: ΔH is negative, because the products sit lower. Endothermic: ΔH is positive, because the products sit higher.

A3. (a) The transition state and the activated complex. (b) It is an energy maximum, a fleeting arrangement with bonds partly broken and partly formed; it falls at once to reactants or to products, so it cannot be collected or stored. (c) It is less stable than everything around it: it is the least stable arrangement on the whole pathway.

A4. (a) An intermediate: a real species formed in one step and consumed in the next. (b) An intermediate sits at a local energy minimum in a valley, while a transition state sits at a maximum on a peak; an intermediate is a real species that can sometimes be detected or isolated, while a transition state can never be isolated. (c) The number of peaks equals the number of elementary steps in the mechanism.

A5. (a) The reactant level, the product level, and ΔH. (b) It lowers the peak, by providing an alternative pathway; E_a(forward) and E_a(reverse) both fall. (c) None of them: heating changes no labelled energy. It changes how many particles can cross the unchanged barrier. (d) No. The catalysed curve is a different pathway, so it may pass through a different transition state and a different number of steps, and so show a different number of peaks. Only the endpoints are fixed.

B1. (a) E_a(forward) = 170 − 90 = 80 kJ/mol. (b) ΔH = 20 − 90 = −70 kJ/mol. (c) Exothermic: the products sit lower than the reactants, so ΔH is negative and energy is released overall.

B2. (a) E_a(reverse) = 170 − 20 = 150 kJ/mol. (b) E_a(forward) − ΔH = 80 − (−70) = 150 kJ/mol, matching (a). (c) The reverse reaction is endothermic, since its ΔH is +70 kJ/mol. The reverse direction has the larger activation energy: 150 against 80 kJ/mol.

B3. (a) Catalysed E_a(forward) = 130 − 90 = 40 kJ/mol. (b) Catalysed E_a(reverse) = 130 − 20 = 110 kJ/mol. (c) ΔH = 20 − 90 = −70 kJ/mol, unchanged: the catalyst moves only the peak, and ΔH is set by the two flat levels, which never moved. (d) Shared: the reactant level at 90 kJ/mol and the product level at 20 kJ/mol, and so ΔH itself. Not shared: the peak, 130 against 170 kJ/mol, and so both activation energies. (e) The peak fell by 170 − 130 = 40 kJ/mol. E_a(forward) fell from 80 to 40 kJ/mol,

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and E_a(reverse) fell from 150 to 110 kJ/mol: each fell by the same 40 kJ/mol, because both climbs end at the one lowered peak.

B4. (a) E_a(forward) = 130 − 40 = 90 kJ/mol. (b) ΔH = 110 − 40 = +70 kJ/mol, so the reaction is endothermic: the products sit above the reactants. (c) E_a(reverse) = 130 − 110 = 20 kJ/mol. Check by the identity: 90 − 70 = 20 kJ/mol, matching. (d) E_a(forward) = 90 kJ/mol is larger than ΔH = +70 kJ/mol, as the rule requires: the peak at 130 kJ/mol stands above the product level at 110 kJ/mol as well as above the reactants at 40 kJ/mol.

B5. (a) Two elementary steps. The valley holds an intermediate, at 100 kJ/mol. (b) Step 1: 150 − 70 = 80 kJ/mol. (c) Step 2: 210 − 100 = 110 kJ/mol, measured from the valley at 100 kJ/mol, the level step 2 starts from. (d) Step 2 is rate-determining: its barrier of 110 kJ/mol is the tallest, so it is crossed most slowly and limits the overall rate. (e) Overall ΔH = 55 − 70 = −15 kJ/mol, so the overall reaction is exothermic. (f) The second peak, at 210 kJ/mol, is higher than the first peak at 150 kJ/mol, and it does belong to the rate-determining step here, step 2.

B6. (a) Peak = 25 + 95 = 120 kJ/mol. (b) Products = 25 + 45 = 70 kJ/mol. (c) From the levels: 120 − 70 = 50 kJ/mol. From the identity: 95 − 45 = 50 kJ/mol, matching. (d) The curve starts at 25 kJ/mol, climbs 95 kJ/mol to a peak at 120 kJ/mol, then falls only partway, to 70 kJ/mol, finishing 45 kJ/mol above where it started: the shape of an endothermic reaction.

C1. (a) E_a(forward) = 180 − 60 = 120 kJ/mol. ΔH = 100 − 60 = +40 kJ/mol, so the reaction is endothermic. E_a(reverse) = 180 − 100 = 80 kJ/mol, and the identity checks: 120 − 40 = 80 kJ/mol. (b) Catalysed E_a(forward) = 140 − 60 = 80 kJ/mol. Catalysed E_a(reverse) = 140 − 100 = 40 kJ/mol. Catalysed ΔH is still +40 kJ/mol, because neither flat level moved. (c) The reverse climb is measured from the product level up to the same peak. Lowering the peak from 180 to 140 kJ/mol shortens that climb from 80 to 40 kJ/mol, so a larger fraction of product particles can cross back each second: the reverse reaction speeds up too. (d) All three levels stay exactly where they were: reactants 60, peak 180, products 100 kJ/mol, and ΔH stays +40 kJ/mol. The rate still rises, because heating increases the fraction of particles with energy at or above the unchanged E_a of 120 kJ/mol. (e) The student measured from the product level instead of the reactant level. The forward E_a is the climb from the reactants: 180 − 60 = 120 kJ/mol. The value 80 kJ/mol is E_a(reverse), the climb from the products to the same peak.

C2. (a) Step 1: 160 − 30 = 130 kJ/mol. Step 2: 130 − 70 = 60 kJ/mol. (b) Step 1 is rate-determining: its barrier of 130 kJ/mol is the tallest, so it is crossed most slowly. (c) The intermediate sits at 70 kJ/mol. Overall ΔH = 90 − 30 = +60 kJ/mol, so the overall reaction is endothermic. (d) New step 2 barrier = 110 − 70 = 40 kJ/mol. The rate-determining step does not change: step 1's barrier is still 130 kJ/mol and still the tallest, and the catalyst lowered only the peak of step 2. (e) Position along the axis is irrelevant. A step's barrier is the climb from the level that step starts from, and the rate-determining step is the one with the tallest climb. Step 2 climbs only 60 kJ/mol from its valley, against the 130 kJ/mol climb of step 1.

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C3. (a) False. Temperature changes no labelled energy, so the peak stays at 170 kJ/mol. Heating raises the fraction of particles able to cross the unchanged barrier of 80 kJ/mol. (b) False. ΔH = products − reactants = 20 − 90 = −70 kJ/mol on both pathways. A catalyst lowers the peak only and never moves the product level, so ΔH cannot become −110 kJ/mol. (c) False as stated for this profile: Profile X has a single peak and no valley, so it has no intermediate at all. The general contrast behind the claim is right, since intermediates are real species and transition states cannot be isolated, but there is no intermediate in this reaction to isolate. (d) True: 80 − (−70) = 150 kJ/mol, which matches the direct reading, peak − products = 170 − 20 = 150 kJ/mol. (e) True. The products sit at 20 kJ/mol and the reactants at 90 kJ/mol, so the products are lower in energy, and so more stable, by 90 − 20 = 70 kJ/mol. That gap is exactly the energy released, the size of ΔH.

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