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Topic 5.5: Collision Model

Worksheet · AP Chemistry

UNIT 5 · KINETICS

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How to Use This Worksheet

Work in order. Section A checks the definitions and the Maxwell-Boltzmann picture. Section B practises the counting: fractions above E_a, effective collisions per second, and what each change does and does not alter. Section C combines the ideas in exam style.

Reference facts used throughout. An effective collision needs energy at or above the activation energy, E_a, and the correct orientation, in the same collision. Rate is set by collisions per second, times the fraction with enough energy, times the fraction correctly oriented. E_a is fixed by the pathway: temperature and concentration never change it; a catalyst supplies a pathway with a lower E_a.

The distribution table used in several questions counts 1,000 particles in energy bins of 20 kJ/mol. At 300 K the counts from the lowest bin up are 520, 310, 120, 38 and 12. At 400 K they are 280, 300, 220, 120 and 80. Every total is 1,000 particles, because heating a sealed sample cannot create particles.

Three habits protect every answer. Keep the three rate factors separate and state which one a change affects. Check every fraction against the same 1,000 particles. Never let temperature or concentration move E_a in your reasoning: only a catalyst, a new pathway, does that.

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 an effective collision. (b) Define activation energy. (c) State what the steric factor accounts for, and name the other name it is given.

A2. (a) State the two reasons why most collisions do not lead to a reaction. (b) For each, explain in one sentence what goes wrong. (c) Explain why the orientation reason matters far more for large, complex molecules than for single atoms.

A3. A Maxwell-Boltzmann distribution plots the energies of the particles in a sample. (a) State what is plotted on each axis. (b) State what the total area under the curve represents, and whether it changes when the sample is heated. (c) State how E_a is shown on the plot. (d) State what the area to the right of the E_a line represents.

A4. Two reactions run at the same temperature and concentrations, with similar orientation requirements. X is fast, Y is slow. (a) State the difference that best explains this. (b) Explain it in terms of fractions of particles. (c) A student says Y is slow because it releases less energy overall. Explain why that does not explain the rate.

A5. Methane and oxygen sit unreacted until a spark is supplied, even though $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ releases much energy overall. (a) Explain why the spark is needed, in terms of bonds. (b) State what the spark changes for a few particles. (c) Explain why the reaction then keeps going.

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Section B: Core Practice

B1. Use the 300 K distribution from the introduction: counts 520, 310, 120, 38 and 12 across bins of 20 kJ/mol, starting at 0. (a) Show the total is 1,000 particles. (b) Calculate the percentage of particles with energy at or above 60 kJ/mol. (c) Calculate the percentage at or above 40 kJ/mol. (d) Calculate the percentage at or above 80 kJ/mol. (e) Use your answers to explain why a reaction with E_a = 80 kJ/mol is much slower than one with E_a = 40 kJ/mol at this temperature.

B2. A reaction mixture produces 2.50×10^5 collisions per second. At the temperature of the experiment, 4.0% of collisions have enough energy, and 1 collision in 25 has the correct orientation. (a) Calculate how many collisions per second have enough energy. (b) Calculate how many collisions per second are effective. Show the full multiplication. (c) The concentration of one reactant is doubled, at the same temperature, doubling the collision rate. Calculate the new number of effective collisions per second, and state which quantities did not change.

B3. A sample is heated from 300 K to 400 K. Average kinetic energy per mole rises from 3.74 kJ/mol to 4.99 kJ/mol, while the fraction of particles above a given E_a rises from 5.0% to 20.0%. (a) Calculate the factor by which the average kinetic energy increased, and show it equals the ratio of the kelvin temperatures. (b) Calculate the factor by which the fraction above E_a increased. (c) Explain why the fraction grows by a much larger factor than the average energy, mentioning the distribution and its tail. (d) State what happens to the peak and to the total area. (e) Speeds grow by the square root of the temperature ratio: calculate that factor and compare it with (b).

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B4. For each change, state what happens to collisions per second, the fraction of collisions with enough energy, and E_a. (a) A reactant concentration in solution is doubled, at constant temperature. (b) A gas mixture is compressed into half its volume, at constant temperature. (c) A lump of zinc is replaced by the same mass of zinc powder in $Zn + 2HCl \rightarrow ZnCl_2 + H_2$, same temperature and acid concentration. (d) A cube of side 2 cm is cut into 8 cubes of side 1 cm: calculate the total surface area before and after, and the factor by which surface collisions rise.

B5. A catalyst is added at 300 K. The fraction with enough energy rises from 5.0% on the uncatalysed pathway (E_a = 60 kJ/mol) to 17.0% on the catalysed pathway (E_a = 40 kJ/mol). The mixture has 5.0×10^5 collisions per second, 1 in 10 correctly oriented. (a) Calculate the effective collisions per second without the catalyst. (b) Calculate them with the catalyst, and the factor by which the rate rises. (c) State what the catalyst changed, and two things about the particles it did not change. (d) Explain how its action differs from heating, using the words curve and line.

B6. The reaction $Cl + NOCl \rightarrow NO + Cl_2$ only forms products when the incoming Cl atom strikes the Cl atom of NOCl. (a) A collision in which Cl strikes the nitrogen end has more than enough energy. State its outcome and the reason. (b) A collision in which Cl strikes the chlorine end has only half the activation energy. State its outcome and the reason. (c) State the two conditions this pair of outcomes illustrates, and the name given to the second condition's factor. (d) Explain why a reaction between two single atoms has no orientation problem, while this reaction does.

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Section C: Exam Style

C1. A sealed gas sample is counted in energy bins of 20 kJ/mol: at 300 K the counts are 520, 310, 120, 38 and 12; at 400 K they are 280, 300, 220, 120 and 80. The reaction has E_a = 60 kJ/mol, the gas produces 1.0 × 10^6 collisions per second at both temperatures (treat as given), and 1 collision in 20 is correctly oriented. (a) Verify both distributions count the same total, and state the principle this illustrates. (b) Calculate the percentage of particles above E_a at each temperature. (c) Calculate the effective collisions per second at each temperature and the overall rate factor on heating. (d) A student claims the hotter sample reacts faster because its activation energy has fallen. Correct the claim, referring to the line and the curve. (e) A catalyst at 300 K opens a pathway with E_a = 40 kJ/mol: calculate the effective collisions per second, and state whether heating or catalysing gives the larger rate in this model.

C2. For each experiment, identify which of the three rate factors changes (collision frequency, fraction with enough energy, fraction correctly oriented), which stay the same, and explain in one sentence. (a) Magnesium ribbon with hydrochloric acid is warmed from 20 °C to 40 °C. (b) The reaction is repeated with acid at twice the concentration, at the original temperature. (c) Magnesium powder of the same mass replaces the ribbon, at the original temperature and concentration. (d) Manganese(IV) oxide is added to hydrogen peroxide, $2H_2O_2 \rightarrow 2H_2O + O_2$, at the original temperature. (e) For (d), state whether the oxide changes E_a itself or the fraction above an unchanged E_a.

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C3. Reactions X and Y run at 300 K in this worksheet's distribution. X has E_a = 40 kJ/mol, Y has E_a = 80 kJ/mol. Both mixtures produce 8.0×10^5 collisions per second, 1 in 20 correctly oriented. (a) From the 300 K counts, state the percentage of particles above each E_a. (b) Calculate the effective collisions per second for X and for Y. (c) Calculate the ratio of the rates, X divided by Y. (d) At 400 K, particles above 80 kJ/mol make up 8.0% and those above 40 kJ/mol make up 42%. Calculate the factor by which each reactive fraction grows on heating, state which reaction is more temperature sensitive, and explain the pattern using the tail of the distribution.

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Answer Key

A1. (a) An effective collision has energy at or above the activation energy and the correct orientation in the same collision, so products form. (b) Activation energy, E_a, is the minimum energy colliding particles need to react; it is fixed by the reaction and its pathway. (c) The steric factor accounts for particles needing a specific geometric alignment, so the atoms forming new bonds are the ones that meet. It is also called the orientation factor.

A2. (a) Many collisions lack sufficient energy, and many lack the correct orientation. (b) Energy: below E_a the particles cannot begin breaking bonds, so they separate unchanged. Orientation: even with enough energy, the atoms that must bond do not touch, so no new bonds form. (c) A single atom is the same from every direction, so every approach works. A large molecule presents many atoms, and only the small share of approaches bringing the correct atoms together can work, so most of its collisions fail on orientation alone.

A3. (a) Horizontal axis: particle energy. Vertical axis: number of particles with that energy. (b) The total area is the total number of particles in the sample. It does not change on heating: the sealed sample holds the same particles, only redistributed across energies. (c) E_a is a vertical line at the threshold energy. (d) The fraction of particles with enough energy to react, if they also collide correctly oriented.

A4. (a) Reaction X has the lower activation energy. (b) At the same temperature both face the same distribution. X's lower E_a line sits further left, so a larger fraction of its particles lies above it; Y's higher line leaves only a small tail fraction. (c) Overall energy released sets where products sit relative to reactants, not the height of the barrier particles must cross. A reaction can release much energy yet be slow if E_a is large, or release little yet be fast if E_a is small.

A5. (a) Bonds in CH_4 and O_2 must begin to break before the bonds of CO_2 and H_2O can form, and that needs energy at or above E_a inside a collision. At room temperature almost no collisions carry that much, so the mixture waits unreacted. (b) The spark heats a tiny region, lifting a few particles above E_a so they react. (c) Each reacting particle releases energy that heats its neighbours above E_a, so the reaction supplies its own activation energy and sustains itself.

B1. (a) 520 + 310 + 120 + 38 + 12 = 1,000 particles. (b) Bins at or above 60 kJ/mol: 38 + 12 = 50 particles, so 50 ÷ 1,000 × 100 = 5.0%. (c) At or above 40 kJ/mol: 120 + 38 + 12 = 170, so 17.0%. (d) Above 80 kJ/mol: the top bin alone, 12 ÷ 1,000 × 100 = 1.2%. (e) At E_a = 40 kJ/mol, 17.0% of particles can react; at E_a = 80 kJ/mol only 1.2% can, about one in eighty, so effective collisions are rare and the reaction is far slower.

B2. (a) Collisions with enough energy = $2.50 \times 10^5 \times 0.040 = 1.00 \times 10^4$ per second. (b) Only 1 in 25 of those, a fraction of 0.040, is correctly oriented: effective collisions = $2.50 \times 10^5 \times 0.040 \times 0.040 =$ 400 per second. (c) Doubling the collision rate to 5.00×10^5 gives $5.00 \times 10^5 \times 0.040 \times 0.040 = 800$

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per second. Unchanged: the fraction with enough energy (temperature and distribution unchanged) and E_a; the orientation fraction is unchanged too.

B3. (a) 4.99 ÷ 3.74 = 1.33, the same as 400 ÷ 300 = 1.33, because average kinetic energy is proportional to kelvin temperature. (b) 20.0 ÷ 5.0 = 4: the fraction quadrupled. (c) The average is one point of the distribution; the reactive fraction is the area in the tail beyond E_a. Heating spreads the distribution, and because the tail was thin, a modest shift of the average moves a proportionally much larger share of particles across a fixed threshold far out in the tail. (d) The peak shifts right, lower and broader; the total area stays the same. (e) Speed factor = √(400 ÷ 300) = about 1.15, a rise of only about 15%. Rates respond mainly to the fourfold rise in the reactive fraction, not to the small rise in speeds.

B4. (a) Collisions per second increase (more particles in the same volume meet more often); fraction with enough energy unchanged (temperature unchanged); E_a unchanged. (b) Collisions per second increase (crowding into half the volume, as with concentration); fraction unchanged at constant temperature; E_a unchanged. (c) Collisions per second increase (far more zinc particles sit at the exposed surface); fraction unchanged; E_a unchanged. (d) Before: 6 × (2 × 2) = 24 cm^2. After: each small cube has 6 × (1 × 1) = 6 cm^2, so 8 × 6 = 48 cm^2. Area, and so surface collisions, rise by a factor of 48 ÷ 24 = 2.

B5. (a) $5.0 \times 10^5 \times 0.050 \times 0.10$ = 2,500 per second. (b) $5.0 \times 10^5 \times 0.17 \times 0.10$ = 8,500 per second, a factor of 8,500 ÷ 2,500 = 3.4. (c) The catalyst changed the pathway, lowering E_a from 60 to 40 kJ/mol. It did not change the temperature or the particles' energies: the distribution, collision rate and orientation fraction are unchanged in this model. (d) Heating moves the curve: the distribution spreads to higher energies while the E_a line stays put. A catalyst moves the line: the distribution stays put while the threshold shifts lower. Both enlarge the area to the right of the line, by opposite moves.

B6. (a) No reaction: the energy suffices, but Cl meets the wrong end, so the Cl to Cl bond cannot form and the particles separate unchanged. (b) No reaction: the orientation is correct, but at half the activation energy the collision cannot begin breaking bonds, and the particles separate unchanged. (c) The energy condition (energy at or above E_a) and the orientation condition; the second condition's factor is the steric, or orientation, factor. (d) An atom has no ends: every approach brings the same atom into contact, so orientation cannot fail. NOCl has distinct ends, and only its chlorine end can bond to the incoming atom, so a share of collisions is wasted on the wrong end.

C1. (a) 300 K: 520 + 310 + 120 + 38 + 12 = 1,000. 400 K: 280 + 300 + 220 + 120 + 80 = 1,000. Equal totals illustrate that the total area under the curve, the particle count of a sealed sample, is conserved on heating. (b) Above 60 kJ/mol: at 300 K, 38 + 12 = 50, so 5.0%; at 400 K, 120 + 80 = 200, so 20.0%. (c) At 300 K: $1.0 \times 10^6 \times 0.050 \times 0.050$ = 2,500 per second. At 400 K: $1.0 \times 10^6 \times 0.20 \times 0.050$ = 10,000 per second, a factor of 10,000 ÷ 2,500 = 4. (d) E_a has not fallen: it is fixed by the

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pathway and its line stays at 60 kJ/mol. The curve changed, spreading to higher energies and carrying a larger fraction past the unchanged line. (e) With E_a = 40 kJ/mol at 300 K the fraction is 17.0%, so effective collisions = $1.0 \times 10^6 \times 0.17 \times 0.050$ = 8,500 per second. Heating gives 10,000 per second, larger than 8,500, so heating gives the larger rate in this model, though the catalyst achieves most of the gain with no heating.

C2. (a) Fraction with enough energy: warming spreads the distribution so more particles exceed the unchanged E_a. Collision frequency rises slightly (faster particles); orientation fraction and E_a stay the same. (b) Collision frequency: doubling concentration doubles how often particles meet. Fraction with enough energy, orientation fraction and E_a stay the same. (c) Collision frequency: the powder exposes far more surface particles for acid to strike. The other factors stay the same. (d) Fraction with enough energy, by a different route from (a): the catalyst supplies a lower E_a pathway, so more of the existing distribution lies above the threshold. Collision frequency, particle energies and orientation fraction stay the same. (e) It changes E_a itself: the threshold moves lower because the pathway differs, and the fraction grows because the line moved, not because any particle gained energy.

C3. (a) Above 40 kJ/mol at 300 K: 120 + 38 + 12 = 170, so 17.0% for X. Above 80 kJ/mol: the top bin alone, 12, so 1.2% for Y. (b) X: $8.0 \times 10^5 \times 0.17 \times 0.050$ = 6,800 per second. Y: $8.0 \times 10^5 \times 0.012 \times 0.050$ = 480 per second. (c) Ratio = 6,800 ÷ 480 = about 14.2: X is roughly fourteen times faster, purely because its barrier is lower. (d) X: 42 ÷ 17 = about 2.5. Y: 8.0 ÷ 1.2 = about 6.7. Y, the high E_a reaction, is more temperature sensitive: its threshold sits far out in the thin tail, and spreading the curve moves proportionally far more particles across a distant threshold than across one nearer the bulk, so high barriers gain most, relatively, from heating.

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