Topic 7.3: Reaction Quotient and Equilibrium Constant

Revision Notes · AP Chemistry

UNIT 7 · EQUILIBRIUM

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Writing the Kc Expression

The equilibrium constant Kc is a ratio built from concentrations: product concentrations on top, reactant concentrations underneath, and every concentration raised to the power of its own coefficient in the balanced equation. For aA + bB ⇌ cC + dD:

$K_c = [C]^c[D]^d / [A]^a[B]^b$

For $2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$:

$K_c = [SO_3]^2 / ([SO_2]^2[O_2])$

The 2 in front of SO_3 becomes a square, never a multiplier: $[SO_3]^2$ and $2[SO_3]$ are different expressions, and only the square is correct.

Only species whose concentration can vary appear: gases and dissolved (aqueous) species, with concentrations in mol L^{-1}. K is reported as a pure number, without units.

Solids and Pure Liquids Are Left Out

A pure solid or pure liquid has a concentration fixed by its density and molar mass. As the reaction runs, the amount of solid changes but the concentration of what remains does not, so that constant value is folded into K and the species is simply omitted from the expression.

For $CaCO_3(s) \rightleftharpoons CaO(s) + CO_2(g)$, both solids are omitted:

$K_c = [CO_2]$

The whole expression is one gas concentration.

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Omitted does not mean irrelevant. Enough solid must be present for the equilibrium to exist at all, and adding more of a solid changes nothing in the expression, because its concentration has not changed.

Q: The Same Expression at Any Moment

The reaction quotient Q is calculated from the concentrations in the flask right now, at any moment, equilibrium or not. It has exactly the same algebraic form as K; the only difference is which concentrations go in. K is the value of that same expression when the mixture is at equilibrium, at the stated temperature.

Q changes as the reaction proceeds. K does not: at a fixed temperature K is a constant, and temperature is the only thing that changes its value for a given reaction.

Calculate Q by substitution: write the expression from the equation, put the current concentrations in, then work out the number. The substitution line is where the marks are, because it shows the powers and the omitted species were handled correctly.

Comparing Q With K Predicts the Direction

If Q < K, the mixture holds too little product relative to equilibrium: the net reaction is forward, products rise and reactants fall, and Q climbs until it equals K.

If Q > K, the mixture holds too much product: the net reaction is reverse, products are consumed, and Q falls until it equals K. If Q = K, the mixture is already at equilibrium and there is no net change.

This is Topic 7.2's rate comparison made quantitative: Q < K is the same situation as a forward rate larger than the reverse rate, stated with concentrations instead of rates.

Kp for Gas Mixtures

For gases, partial pressures can stand in for concentrations. Kp is built the same way, products over reactants with coefficients as powers, and solids and pure liquids are omitted just as before. For $2C(s) + O_2(g) \rightleftharpoons 2CO(g)$:

$Kp = (P_CO)^2 / P_O_2$

The two constants are related by:

Kp = Kc(RT)^Δn

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Here Δn is the moles of gas on the product side minus the moles of gas on the reactant side of the balanced equation, R = 0.08206 L atm mol^{-1} K^{-1}, and T is in kelvin. Only gas moles count toward Δn. When Δn = 0, Kp = Kc exactly.

Qp works like Qc: build the pressure expression from the pressures at the moment in question and compare it with Kp to get the direction.

Rewriting the Equation Rewrites K

K belongs to the equation exactly as written, so changing the writing changes the constant in predictable ways. Reverse the equation and products and reactants trade places in the expression: the new constant is the reciprocal, 1/K.

Multiply every coefficient by a factor n and every power in the expression multiplies by n: the new constant is K^n. Halving the equation is the n = ½ case, giving the square root of K.

Add two reactions so that an intermediate cancels, and their expressions multiply: the constant for the overall reaction is $K_1 \times K_2$.

Worked Examples

Example 1: Computing Q and predicting the direction. For $N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$, Kc = 0.50 at the temperature used. A mixture has $[N_2] = 0.50$, $[H_2] = 0.20$ and $[NH_3] = 0.10$ mol L^{-1}. $Q = [NH_3]^2 / ([N_2][H_2]^3) = (0.10)^2 / (0.50 \times (0.20)^3) = 0.01 / (0.50 \times 0.008) = 0.01 / 0.004 = 2.5$. Since Q = 2.5 > K = 0.50, the net reaction is reverse: $[NH_3]$ falls while $[N_2]$ and $[H_2]$ rise, until Q has fallen to 0.50.

Example 2: A heterogeneous equilibrium. For $CaCO_3(s) \rightleftharpoons CaO(s) + CO_2(g)$, $Kc = [CO_2] = 0.050$ at the temperature used. A vessel containing both solids has $[CO_2] = 0.020$ mol L^{-1}, so Q = 0.020 < 0.050: the net reaction is forward, $CaCO_3$ decomposes, and $[CO_2]$ rises toward 0.050 mol L^{-1}. Tipping in more $CaCO_3(s)$ leaves Q at 0.020, because the solid appears nowhere in the expression.

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Example 3: Converting Kc to Kp and using Qp. For $2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$ at 1000 K, $K_c = 2.5 \times 10^2$. $\Delta n = 2 - 3 = -1$, so $K_p = K_c(RT)^{\Delta n} = 250 \times (0.08206 \times 1000)^{-1} = 250 / 82.06 = 3.0$. A mixture at the same temperature has $P_{SO_3} = 0.90$ atm, $P_{SO_2} = 0.60$ atm and $P_{O_2} = 0.45$ atm: $Q_p = (0.90)^2 / ((0.60)^2 \times 0.45) = 0.81 / 0.162 = 5.0$. $Q_p > K_p$, so the net reaction is reverse.

Example 4: Rewriting K. For $H_2(g) + I_2(g) \rightleftharpoons 2HI(g)$, $K_c = 64$. Written backwards, $2HI(g) \rightleftharpoons H_2(g) + I_2(g)$, the constant is $1/64 = 0.0156$. Written halved, $\frac{1}{2}H_2(g) + \frac{1}{2}I_2(g) \rightleftharpoons HI(g)$, it is $\sqrt{64} = 8$. And if $A \rightleftharpoons B$ has $K_1 = 2.0$ and $B \rightleftharpoons C$ has $K_2 = 3.0$, adding the reactions cancels B and gives $A \rightleftharpoons C$ with $K = 2.0 \times 3.0 = 6.0$, because the two expressions multiply and the [B] terms cancel.

Traps That Cost Marks in Topic 7.3

"The coefficient multiplies the concentration." Coefficients become powers. Writing $2[SO_3]$ where $[SO_3]^2$ belongs changes every number that follows.

"Every species in the equation goes into the expression." Pure solids and pure liquids never appear. An expression containing $[CaCO_3]$ or $[CaO]$ is wrong before any numbers are touched.

"Q and K are the same thing." Q is built from the concentrations now; K is that expression's value at equilibrium at the stated temperature. A value of Q on its own predicts nothing until it is compared with K.

"Q > K means the reaction runs forward to reach K." Q > K means too much product is present, so the net reaction is reverse and Q falls. The system always moves so that Q approaches K, from whichever side it starts.

"Adding an inert gas raises the total pressure, so Q changes and the mixture shifts." At constant volume the added gas changes no concentration and no partial pressure of any reacting species, so Q and K are both unchanged and nothing shifts.

"Reversing the reaction doubles K, or makes it negative." Reversing inverts the expression, giving 1/K. Equilibrium constants are never negative.

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Key Relationships to Remember

- Kc = product concentrations over reactant concentrations, each raised to its coefficient in the balanced equation
- Pure solids and pure liquids are omitted from K and Q expressions; their constant concentrations are folded into K
- Q uses the concentrations at the moment in question; K is the same expression evaluated at equilibrium, at the stated temperature
- Q < K: net forward; Q > K: net reverse; Q = K: at equilibrium, no net change
- Kp = Kc(RT)^Δn, with Δn = gas moles of products minus gas moles of reactants; Δn = 0 makes Kp = Kc
- Reversing the equation gives 1/K; multiplying the coefficients by n gives K^n; adding reactions multiplies their constants
- Temperature is the only change that alters the value of K for a given reaction
- Finding K from measured equilibrium data is Topic 7.4, and solving for unknown equilibrium concentrations is Topic 7.7

Continue Revising

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Topic 7.3 Worksheet

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