Lab 30. Equilibrium Constant and Temperature: How Does a Change in Temperature Affect the Value of the Equilibrium Constant for an Exothermic Reaction?

Introduction

Chemical equilibrium is defined as the point in a reaction where the rate at which reactants transform into products is equal to the rate at which products revert back into reactants. When a reaction is in equilibrium, the concentration of the products and reactants is constant or stable. At this point, there is no further net change in the amounts of reactants or products unless the system is disturbed in some manner. The *equilibrium constant* provides a mathematical description of the equilibrium state for any reversible chemical reaction. To illustrate, consider the following general equation for a reversible reaction:

$$aA + bB \qquad cC + dD$$

The equation for calculating the equilibrium constant, K_{eq}, for this general reaction is provided below. The square brackets refer to the molar concentrations of each substance at equilibrium. The exponents are the stoichiometric coefficients of each substance found in the balanced chemical equation.

$$K_{eq} = \frac{[C]^c[D]^d}{[A]^a[B]^b}$$

The equilibrium constant describes the proportional relationship that exists between the concentration of the reactants and the concentration of the products for a specific chemical reaction when the reaction is in a state of equilibrium. The actual concentrations of the reactants and products that are present in the system at equilibrium will depend on the initial amounts of the reactants that were used at the beginning of the reaction and any extra reactants or products that were added to the system after the reaction started. The concentration ratio of products to reactants described by the equilibrium constant, however, will always be the same as long as the system is in equilibrium and the temperature of the system does not change.

The equilibrium constant is useful because it allows chemists to determine the product- to-reactant concentration ratio that will be present in the reaction mixture at equilibrium before the reaction begins. When $K_{eq} > 1$, the concentration of the products in the system will be greater than the concentration of the reactants. When $K_{eq} < 1$, the concentration of products will be less than the concentration of the reactants. Finally, when $K_{eq} = 1$, the concentration of products and reactants will be equal. A reaction with a large K_{eq} value, as a result, will have a greater product-to-reactant concentration ratio at equilibrium than a reaction with a smaller value.

The equilibrium constant of a reaction will change when the temperature changes. A positive shift in the K_{eq} will cause the product-to-reactant concentration ratio at equilibrium to increase, whereas a negative shift will result in a decrease in the concentration ratio. How the K_{eq} of a reaction will change in response to a change in temperature, however, is not uniform. The change in the K_{eq} of a reaction depends on the direction and magnitude of the temperature change. It will also depend on whether the reaction is exothermic or endothermic.

To control the amount of product or reactant present at the equilibrium point of a reaction in a closed system, chemists need to understand how the equilibrium constant will shift in response to changes in temperature for different types of reactions. You will therefore determine the equilibrium constant for an exothermic reaction and then explore how increases and decreases in temperature change the value of the equilibrium constant for this reaction. You will then develop a rule that you can use to predict how a change in temperature will affect the value of the equilibrium constant for other exothermic reactions.

Your Task

Determine the equilibrium constant for the reaction between iron(III) nitrate and potassium thiocyanate. Then determine how the equilibrium constant for this exothermic reaction is affected by a change in temperature. Once you understand how the equilibrium constant for this reaction changes in response to a change in temperature, you will need to develop a rule that you can use to predict how the equilibrium constant of other exothermic reactions will change in a response to a temperature change.

The guiding question of this investigation is, **How does a change in temperature affect the value of the equilibrium constant for an exothermic reaction?**

Materials

You may use any of the following materials during your investigation:

Consumables	Equipment
• 0.002 M iron(III) nitrate, $Fe(NO_3)_3$ • 0.200 M iron(III) nitrate, $Fe(NO_3)_3$ • 0.002 M potassium thiocyanate, KSCN • Distilled water • Ice	• Colorimeter sensor • Sensor interface • 4 cuvettes • 12 test tubes • Test tube rack • 3 serological pipettes (each 5 or 10 ml) • Pipette bulb • Stirring rod • 6 beakers (each 50 ml) • 2 beakers (each 250 ml, for water baths) • Hot plate • Thermometer

Safety Precautions

Follow all normal lab safety rules. Potassium thiocyanate is toxic by ingestion. Iron(III) nitrate solution contains 1 M nitric acid and is a corrosive liquid; it will also stain clothes and skin. Your teacher will explain relevant and important information about working with the chemicals associated with this investigation. In addition, take the following safety precautions:

- Wear indirectly vented chemical-splash goggles and chemical-resistant gloves and apron while in the laboratory.
- Use caution when working with hot plates because they can burn skin. Hot plates also need to be kept away from water and other liquids.
- Handle all glassware (including thermometers) with care.
- Wash hands with soap and water before leaving the laboratory.

Investigation Proposal Required? ☐ Yes ☐ No

Getting Started

The first step in this investigation is to determine the equilibrium constant for the reaction between iron(III) nitrate and potassium thiocyanate at room temperature. Iron(III) ions react with thiocyanate ions to form $FeSCN^{2+}$ complex ions according to the following reaction:

$$\underset{\text{Yellow}}{Fe^{3+}(aq)} + \underset{\text{Colorless}}{SCN^{-}(aq)} \leftrightarrows \underset{\text{Orange-Red}}{FeSCN^{2+}(aq)}$$

The equilibrium constant expression for this reaction is

$$K_{eq} = \frac{[FeSCN^{2+}]}{[Fe^{3+}][SCN^{-}]}$$

You can determine the value of K_{eq} by mixing solutions with known concentrations of Fe^{3+} and SCN^{-} and then measuring the concentration of the $FeSCN^{2+}$ ions in the mixture once the reaction is at equilibrium. The equilibrium concentration of the $FeSCN^{2+}$ ions in the solution can be determined by measuring the absorbance of the solution using a colorimeter. This is possible because the $FeSCN^{2+}$ ions produce a red color and the amount of light absorbed by the solution is directly proportional to the concentration of the $FeSCN^{2+}$ ions in it. You can, as a result, determine the $FeSCN^{2+}$ concentration of any solution by simply comparing the absorbance of that solution with the absorbance of a solution with a known $FeSCN^{2+}$ concentration (called a standard solution).

You will need to make a standard solution and five different test solutions to determine the equilibrium constant for the reaction between iron(III) nitrate and potassium thiocyanate at room temperature. Prepare the standard solution and five test solutions as described in Table L30.1.

TABLE L30.1

Components of the standard and test solutions

Sample	Reactants (ml)			
	0.200 M $Fe(NO_3)_3$	0.002 M $Fe(NO_3)_3$	0.002 M KSCN	Distilled water
Standard solution	9.00	0.00	1.00	0.00
Test solution 1	0.00	5.00	1.00	4.00
Test solution 2	0.00	5.00	2.00	3.00
Test solution 3	0.00	5.00	3.00	2.00
Test solution 4	0.00	5.00	4.00	1.00
Test solution 5	0.00	5.00	5.00	0.00

Once you have your solutions prepared, you can measure the absorbance of each one. Your teacher will show you how to use the calorimeter to measure the absorbance of the solutions. You will need to determine the concentration of $FeSCN^{2+}$ in each test solution and then use this information to calculate an average equilibrium constant for the reaction. To accomplish this task, follow the procedure below:

1. Calculate the concentration of the Fe^{3+} and SCN^- ions in the standard solution and the five test solutions using the dilution equation ($M_1V_1 = M_2V_2$).
2. Calculate the concentration of the $FeSCN^{2+}$ ions in the standard solution and each test solution at equilibrium using the following equation:

$$[FeSCN^{2+}]_{Equilibrium} = \frac{A_{TestSolution}}{A_{StandardSolution}} \times [FeSCN^{2+}]_{Standard}$$

   Assume the concentration of the $FeSCN^{2+}$ in the standard solution at equilibrium is equal to the concentration of the SCN^- ions in the standard solution at the start of the reaction. You can make this assumption because all of the SCN^- ions should have been converted to $FeSCN^{2+}$ ions due to the large amount of Fe^{3+} that was added to the standard solution.

3. Calculate the equilibrium concentration of Fe^{3+} ions in each test solution by subtracting the equilibrium concentration of $FeSCN^{2+}$ from the initial concentration of Fe^{3+} ions using the equation

$$[Fe^{3+}]_{TestSolutionEquilibrium} = [Fe^{3+}]_{TestSolutionInitial} - [FeSCN^{2+}]_{TestSolution}$$

4. Calculate the equilibrium concentration of SCN^- ions in each test solution by subtracting the equilibrium concentration of $FeSCN^{2+}$ from the initial concentration of SCN^- ions using the equation

$$[SCN^-]_{TestSolutionEquilibrium} = [SCN^-]_{TestSolutionInitial} - [FeSCN^{2+}]_{TestSolution}$$

5. Calculate the value of the equilibrium constant for the five test solutions using the equation

$$K_{eq} = \frac{[FeSCN^{2+}]}{[Fe^{3+}][SCN^-]}$$

6. Calculate the average equilibrium constant for the reaction.

The second step in your investigation is to conduct an experiment to determine how a change in temperature affects the equilibrium constant for the reaction between iron(III) nitrate and potassium thiocyanate. To conduct this experiment, you must determine what type of data you need to collect, how you will collect the data, and how you will analyze the data.

To determine *what type of data you need to collect*, think about the following questions:

- What type of measurements or observations will you need to record during each experiment?
- When will you need to make these measurements or observations?

To determine *how you will collect the data*, think about the following questions:

- What will serve as your independent variable?
- What types of comparisons will you need to make?
- How will you change the temperature of the reaction?
- What will you do to reduce measurement error?
- How will you keep track of the data you collect and how will you organize it?

To determine *how you will analyze the data*, think about the following questions:

- What type of calculations will you need to make?
- What type of graph could you create to help make sense of your data?

The last step in this investigation is to develop a rule that you can use to predict how the equilibrium constant of other exothermic reactions will change in a response to a temperature change. This rule will serve as your answer to the guiding question of this investigation.

Connections to Crosscutting Concepts, the Nature of Science, and the Nature of Scientific Inquiry

As you work through your investigation, be sure to think about

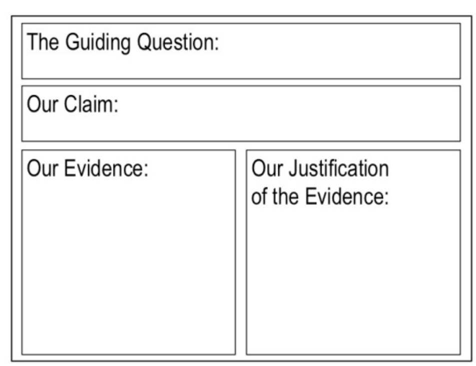
- how scientists must define the system they are studying and then use models to understand it,
- why it is important to understand what makes a system stable or unstable and what controls the rates of change in a system,
- the importance of imagination and creativity in science, and
- the role of experiments in science.

Initial Argument

Once your group has finished collecting and analyzing your data, you will need to develop an initial argument. Your argument must include a *claim*, which is your answer to the guiding question. Your argument must also include *evidence* in support of your claim. The evidence is your analysis of the data and your interpretation of what the analysis means. Finally, you must include a *justification* of the evidence in your argument. You will therefore need to use a scientific concept or principle to explain why the evidence that you decided to use is relevant and important. You will create your initial argument on a whiteboard. Your whiteboard must include all the information shown in Figure L30.1.

FIGURE L30.1

Argument presentation on a whiteboard



Argumentation Session

The argumentation session allows all of the groups to share their arguments. One member of each group stays at the lab station to share that group's argument, while the other members of the group go to the other lab stations one at a time to listen to and critique the arguments developed by their classmates. The goal of the argumentation session is not to convince others that your argument is the best one; rather, the goal is to identify errors or instances of faulty reasoning in the initial arguments so these mistakes can be fixed. You will therefore need to evaluate the content of the claim, the quality of the evidence used to support the claim, and the strength of the justification of the evidence included in each argument that you see. To critique an argument, you might need more information than what is included on the whiteboard. You might, therefore, need to ask the presenter one or more follow-up questions, such as:

- How did your group collect the data? Why did you use that method?
- What did your group do to make sure the data you collected are reliable? What did you do to decrease measurement error?
- What did your group do to analyze the data, and why did you decide to do it that way? Did you check your calculations?
- Is that the only way to interpret the results of your group's analysis? How do you know that your interpretation of the analysis is appropriate?
- Why did your group decide to present your evidence in that manner?
- What other claims did your group discuss before deciding on that one? Why did you abandon those alternative ideas?
- How confident are you that your group's claim is valid? What could you do to increase your confidence?

Once the argumentation session is complete, you will have a chance to meet with your group and revise your original argument. Your group might need to gather more data or design a way to test one or more alternative claims as part of this process. Remember, your goal at this stage of the investigation is to develop the most valid or acceptable answer to the research question!

Report

Once you have completed your research, you will need to prepare an *investigation report* that consists of three sections that provide answers to the following questions:

1. What question were you trying to answer and why?
2. What did you do during your investigation and why did you conduct your investigation in this way?
3. What is your argument?

Your report should answer these questions in two pages or less. The report must be typed and any diagrams, figures, or tables should be embedded into the document. Be sure to write in a persuasive style; you are trying to convince others that your claim is acceptable or valid!