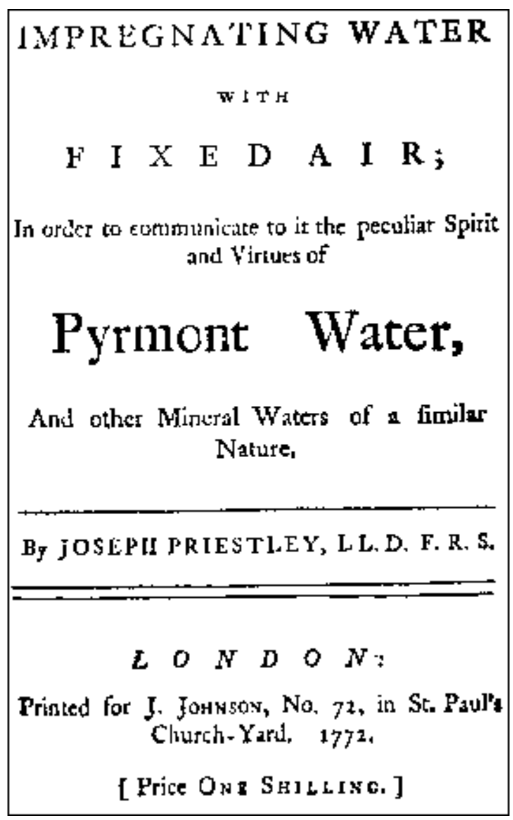
CHAPTER 8 | CARBONATED BEVERAGES — PRIESTLEY'S SODA-WATER

IN 1767 JOSEPH PRIESTLEY MOVED NEXT DOOR TO A BREWERY in Leeds, England. Soon after, he began a series of experiments with the brewery gas that was called *mephitic air* or *fixed air*, the name given by Joseph Black. He had brewery workers perform experiments with candles, burning pieces of wood and the like. In one experiment, Priestley placed a bowl of water above the surface of the fermenting liquor and it quickly developed a pleasant sweet acidic taste not unlike that of Seltzer mineral water. By the end of 1767, Priestley was sharing the treated water with friends.

In 1772, Priestley announced his invention of soda-water in his publication ***Impregnating Water with Fixed Air***. His instructions are clear and easy to follow:

> *"If water be only in contact with fixed air, it will begin to imbibe it, but the mixture is greatly accelerated by agitation, which is continually bringing fresh particles of air and water into contact. All that is necessary, therefore, to make this process expeditious and effectual, is first to procure a sufficient quantity of this fixed air, and then to contrive a method by which the air and water may be strongly agitated in the same vessel, without any danger of admitting the common air to them; and this is easily done by first filling any vessel with water, and introducing the fixed air to it, while it stands inverted in another vessel of water."*


IMPREGNATING WATER

WITH

FIXED AIR;

In order to communicate to it the peculiar Spirit and Virtues of

Pyrmont Water,

And other Mineral Waters of a fimilar Nature.

By JOSEPH PRIESTLEY, LL.D. F.R.S.

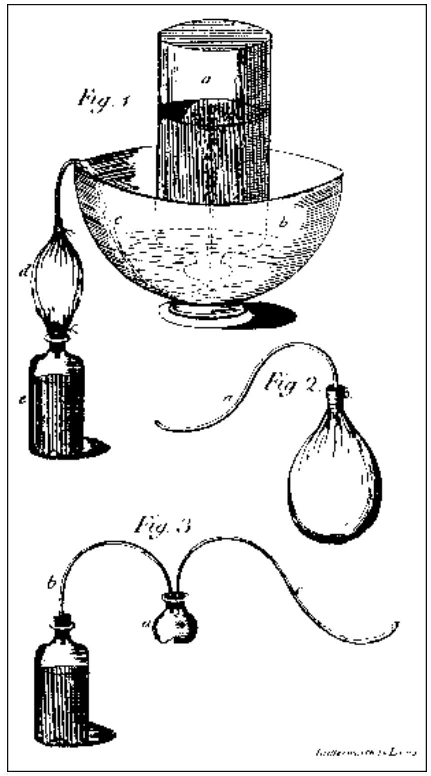
LONDON:

Printed for J. JOHNSON, No. 72, in St. Paul's Church-Yard, 1772.

[Price ONE SHILLING.]

The cover to Priestley's booklet for impregnating water with fixed air.

One incentive for developing such a method was that it was believed that the drink might prevent scurvy. Priestley improved upon his method for producing soda-water and with the simple equipment shown at right, he was able to cause water to absorb its own volume of fixed air within 30 minutes.



Apparatus used by Priestley's for making soda water. This figure appeared in "Impregnating Water with Fixed Air"

Joseph Priestley is one of the more fascinating figures in the history of chemistry. He was a minister with controversial theories that were not endorsed by his congregations; he was an active member of the *Lunar Society*, a scientific discussion group that met at the time of every full moon; and he supported the French and American revolutions. Until recently, books on the history of chemistry were the only source of information about Priestley and his contemporaries. Nowadays, the internet contains enormous amounts of information about these individuals.

Reading/research assignments featuring historical figures such as Joseph Priestley would enhance students' appreciation for chemistry and science as a humanistic endeavor.

CARBONATED BEVERAGES
INFORMATION FOR THE TEACHER

Suitability

For use by high school and university-level chemistry students. The first two experiments in this chapter are laboratory activities that can be conducted quite early in the first-year high school chemistry course — when classification of matter (homogeneous/heterogeneous solutions), physical and chemical changes are being introduced. The experiments also lend themselves to the following topics: percent composition, chemical formulas, chemical reactions, properties of carbon dioxide, and solutions. Some of the questions address more difficult topics such as mole calculations involving solutions. Experiment 3 is a classroom demonstration for pragmatic reasons. Experiment 4 makes for a sophisticated and interesting demonstration of reaction kinetics vs. solution equilibrium. Experiment 4 is well-suited for a second-year high school chemistry and university-level chemistry.

Background skills required

Students should be able to:

- ❖ generate a gas as learned in Chapter 1
- ❖ measure quantities of liquid reagents
- ❖ accurately read the volume gradations on the syringe (including estimating between two marks)

Time required

Students should be able to perform the first two experiments in a single 45 minute laboratory period.

Website

This chapter is available at our gas website:

http://mattson.creighton.edu/Microscale_Gas_Chemistry.html

Instructions for your students

For classroom use by teachers. Copies of all or part of this document may be made for your students without further permission. Please attribute credit to Professors Bruce Mattson and Mike Anderson of Creighton University and this website.

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PART 1. CARBONATED BEVERAGES
INSTRUCTIONS FOR STUDENTS

General Safety Precautions

Always wear safety glasses. Gases in syringes may be under pressure and could spray liquid chemicals. Follow the instructions and only use the quantities suggested.

Toxicity

Carbon dioxide is relatively non-toxic; however, it is a simple asphyxiant if inhaled in very large quantities. We will not be generating large quantities of carbon dioxide.

EXPERIMENT 1. ESTIMATING THE AMOUNT OF CARBON DIOXIDE IN A CARBONATED BEVERAGE

Equipment

Microscale Gas Chemistry Kit

Chemicals

bottle of sparkling water or sugar-free carbonated beverage

limewater, 1 mL

Suitability

middle school lab, high school lab, university lab, and classroom demonstration

Applications, Topics, Purpose

classification of matter (homogeneous/heterogeneous solutions), physical and chemical changes and properties, chemical formulas, mole calculations involving solutions, percent composition, chemical formulas, chemical reactions, classifying chemical changes, properties of carbon dioxide, solutions, solution equilibrium

Instructions

Remove the plunger from a syringe and place the syringe cap onto the syringe. While holding the syringe at a 45^{o} angle, slowly pour sparkling water (or a carbonated beverage) into the syringe barrel. Try to avoid causing the solution to lose bubbles excessively. After the syringe has been filled to the 20 mL mark, insert the plunger just past the “catch” ridge inside the barrel — listen for the “click”. Rotate the syringe so that the cap is directed upward. Open the cap and discharge all of the air but none of the carbonated beverage. Cap the syringe. Note the volume of the liquid.

Withdraw the plunger and notice the gas coming out of the solution. Tapping the solution will cause more bubbles to leave the solution. After most of the gas has been driven out of the solution, you are ready to measure the relative amounts of carbon dioxide and liquid. If the plunger is free-moving (does not stick), pull the plunger outward to create a negative pressure and then release it. It should return to an equilibrium position where the internal pressure and external pressure are similar. Read the volumes. If the plunger sticks and moves in increments, proceed as follows: 1. Read the volume of liquid present, 2. Hold the plunger outward so that the contents are under reduced pressure and remove the syringe cap under water (this assures that the internal and external pressures are the same); 3. Read the volume of gas in the syringe.

Test the carbon dioxide

The test for CO_2(g) utilizes limewater as in Experiment 1 in Chapter 2. It is also possible to test for CO_2(aq): Add 1 mL limewater to a small test tube. Add 3 drops of sparkling water to form a white precipitate of calcium carbonate.

Teaching tips

1. Pouring slowly helps prevent carbon dioxide loss.
2. Some losses of carbon dioxide are inevitable.
3. Sparkling water works the best. Another option is to use a sugar-free carbonated beverage because the two primary components of the solution are water and carbon dioxide. The artificial sweetener has a very low mass compared to the sugar in a regular carbonated beverage. Avoid carbonated beverages containing sugar.
4. Using small, clean cups and a fresh bottle of sparkling water, allow students to try the "drink of Joseph Priestley".

Questions

1. Describe what occurred when you withdrew the plunger of the syringe containing the carbonated beverage.
2. What volume of carbon dioxide did you collect? What volume of carbonated beverage was initially present? Determine the ratio, volume of carbon dioxide to volume of carbonated beverage.

Advanced Questions

5. Convert the volume of carbonated beverage, assumed to be pure water into moles of water. Convert the volume of carbon dioxide to moles of carbon dioxide using the ideal gas law. Compare moles of carbon dioxide to moles of water.

EXPERIMENT 2. CARBONATING WATER BY PRIESTLEY'S METHOD

Equipment

Microscale Gas Chemistry Kit

Chemicals

$CO_2(g)$, 30 mL

Universal indicator

Limewater, 1 mL

Suitability

middle school lab, high school lab, university lab, and classroom demonstration

Applications, Topics, Purpose

classification of matter (homogeneous/heterogeneous solutions), physical and chemical changes and properties, chemical formulas, percent composition, chemical formulas, chemical reactions, properties of carbon dioxide, solutions, the dissolving process, solution equilibrium, acid anhydrides

Instructions

Draw 30 mL water into a syringe containing 30 mL carbon dioxide. Record the combined volume — which should be 60 mL. Gently rock the syringe back and forth while it is held in a horizontal position (maximizing the surface area between the water and the gas. Within less than a minute the volume of carbon dioxide will decrease. If the plunger does not move freely, push it inward until there is resistance due to positive pressure inside the syringe. Let go of the plunger and it will return to a volume less than its previous value. Carbon dioxide is dissolving in the water. Continue to gently rock the solution, but never shake it. Continue to note the volume of carbon dioxide as a function of time. The reaction that is taking place is:

$$CO_2(g) \rightleftharpoons CO_2(aq)$$

pH test

Test the resulting solution for pH using Universal indicator. Dissolve a few drops of universal indicator solution in a 2 mL water in a test tube. Discharge a 2 - 3 mL of the aqueous solution into the test tube. The solution is acidic because carbon dioxide is an acid anhydride — it forms a small amount of carbonic acid when it dissolves:

$$CO_2(aq) + H_2O(l) \rightleftharpoons H_2CO_3(aq)$$

Limewater test

Test the resulting solution for $CO_2(aq)$. Use the method described in the previous experiment.

Note: Save the rest of the solution in the syringe for the next experiment.

Teaching tips

1. Share the passage from Priestley's instructions with your students.
2. Provide a chart of indicator color vs. the corresponding pH to your students.

Indicator Colors		
pH	**Universal**	**Red Cabbage**
4.0	Red	Red
5.0	Orange Red	Purple
6.0	Yellow Orange	Purple
7.0	Dark Green	Purple
8.0	Light Green	Blue
9.0	Blue	Blue-Green
10.0	Reddish Violet	Green
11.0	Violet	Green
12.0	Violet	Green
13.0	Violet	Green-Yellow
14.0	Violet	Yellow

Questions

1. What purpose is served by holding the syringe in a horizontal position?
2. Does carbon dioxide dissolve quickly? Sketch a syringe held in a vertical position and filled with 30 mL carbon dioxide and 30 mL water. Suppose that the water contains some universal indicator. How would you predict the solution would appear (color) after a minute? After several minutes? Do you predict layers of colors?

Advanced Questions

3. Aqueous carbon dioxide forms an equilibrium with carbonic acid. Write the equilibrium expression.
4. What is the significance of the long and short arrow in the equilibrium expression?

PART 2. CLASSROOM DEMONSTRATIONS

EXPERIMENT 3. FREEZING CARBONATED BEVERAGES PRODUCES "SNOWY" ICE

Equipment

Microscale Gas Chemistry Kit
4 L (1 gallon) sealable plastic bag
freezer

Chemicals

bottle of sparkling water or sugar-free carbonated beverage or CO_2(aq) solution (in the syringe) from the previous experiment

Suitability

classroom demonstration

Applications, Topics, Purpose

matter, classification of matter (homogeneous/heterogeneous solutions), physical and chemical changes and properties, chemical formulas, properties of carbon dioxide, the dissolving process

Instructions

Joseph Priestley noted that soda water looked more like snow than ice when frozen. Fill one syringe with 30 mL water, but no air. Fill a second syringe with 30 mL sparkling water as was done in Experiment 1: While holding the syringe at a 45^o angle, slowly pour sparkling water (or a carbonated beverage) into the syringe barrel. Try to avoid causing the solution to lose bubbles excessively. After the syringe has been filled to the 30 mL mark, insert the plunger just past the "catch" ridge inside the barrel (listen for the "click"). Rotate the syringe so that the cap is directed upward. Open the cap and discharge all of the air but none of the carbonated beverage. Cap the syringe.

Place both syringes inside the sealable bag and place them in the freezer. Check after 30 minutes, 60 minutes, etc. Water will freeze into a clear plug with little noticeable volume change — still 30 mL. Sparkling water, however, will discharge carbon dioxide as it freezes causing the plunger to move outward and the ice formed to "look like snow". It is white and grainy with numerous holes — pockets of carbon dioxide gas.

After the liquids are completely frozen (overnight), remove them from the freezer. Remove the syringe cap and hold the syringes under hot water in order to remove the plunger. Add a 10 - 20 mL hot water to the syringe in order to melt part of the solid so that the ice plug can be poured out of the syringe for closer inspection. The water ice plug will appear clear, solid and hard. The sparkling water ice plug is crumbly and easily broken. One can also hear the sparkling water ice plug making fizzing noises. When added to a cup of hot water, some carbon dioxide effervesces from the solid as it melts.

Teaching tips

While the solubility of carbon dioxide, like all gases, is greater in cold water than in hot water, gases are generally far less soluble in solid water. As the sparkling water is cooled and freezes, it releases carbon dioxide and causes the water crystals to separate as they are formed — thus forming Priestley's soda water snow.

Questions

1. Describe the appearance of the two ice samples as they are forming.
2. Why does the plunger move outward in the syringe with the sparkling water (or carbonated beverage)?
3. Would the sparkling water (or carbonated beverage) taste flat after it were allowed to melt?
4. Could the carbonation be returned to the liquid? Explain how.

Advanced Questions

5. When ice forms, what type of intermolecular forces are involved? What type of intermolecular forces exist between carbon dioxide and water?
6. Sketch a qualitative graph that shows the solubility of a gas such as carbon dioxide (x-axis) vs. temperature (y-axis) for an aqueous solution of carbon dioxide.

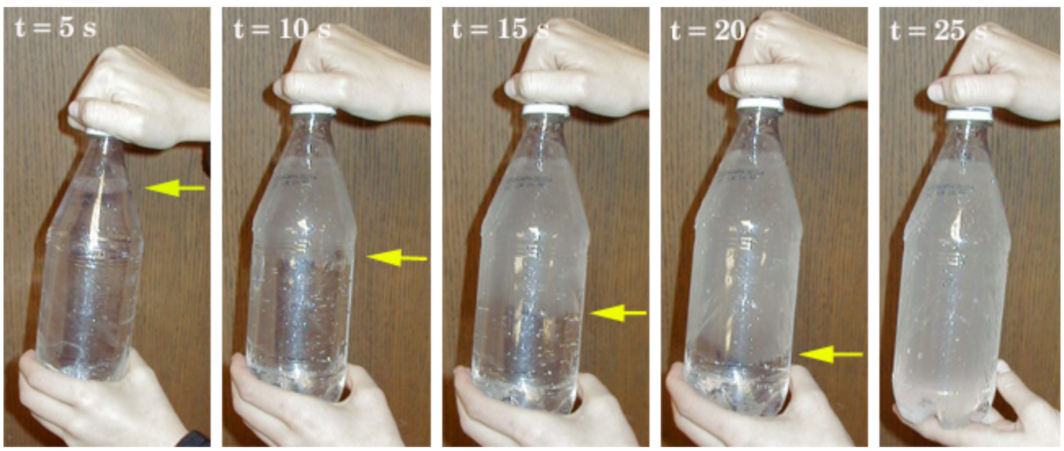
EXPERIMENT 4. SPECTACULAR CRYSTALLIZATION OF SUPER-COOLED CARBONATED BEVERAGES.

Equipment	Chemicals
pail	unopened bottle of sparkling water or sugar-free carbonated beverage, pre-cooled to refrigerator temperature
thermometer	salt
refrigerator	ice (or snow)

Instructions

Prepare a salt ice bath by filling a 4 – 8 L (1 - 2 gallon) pail tub with ice cubes or snow. Add tap water just until the air pockets between the ice cubes are gone. If you use snow, add water to form a thick slush. Adding water increases the surface area in contact with the bottles and hastens cooling. Sprinkle about one cup of table salt evenly over the bath and stir to mix. Stir the contents of the bath and place the bottles of carbonated beverage in the bath. Add more ice or snow as necessary. The temperature of the bath should be between –5 and –10 ^{O}C. Allow the bottles to cool in the ice bath for thirty minutes. (A longer cooling time may be necessary if the bottles have not been pre-cooled in a refrigerator.)

Remove a bottle form the ice bath and open it. The solution will solidify starting at the top moving downward. Within 30 seconds, the contents will have solidified. A movie of this process is available at our website, (http://mattson.creighton.edu/SodaWater/SodaWater.html). By the time the solid has developed to the bottom of the bottle, it appears to be completely solid with little or no liquid. Pour the contents into a plastic cup or beaker. The contents will pour quite easily as a slush and students will be surprised to see that the contents are not as solid as they first appeared.



Teaching tips

1. Our explanation of this experiment is: The super-cooled solution remains liquid in part due to the freezing point lowering exhibited by solutions. When the bottle is opened, carbon dioxide starts to effervesce from the solution which (a) lowers the concentration of solute and diminishes the magnitude of freezing point lowering (b) further lowers the temperature of the solution due to the endothermic outgassing reaction: $CO_2(aq) \longrightarrow CO_2(g)$ DH = 20.3 kJ/mol and (c) provides nucleation sites at the surface for the formation of ice crystals.
2. Place the sparkling water in the refrigerator a day before they are needed.
3. Use a “scope-cam” to project the crystal growth onto a screen. Sometimes large needles will grow and other times a round blob of crystalline solid is formed.
4. A YouTube movie of this crystallization is available at: https://www.youtube.com/watch?v=1spOIbM_CPg&feature=em-upload_owner.

Questions

1. Describe the appearance of the ice as it was forming.
2. What is the purpose of adding salt in the ice bath? What temperature did you achieve?
3. Have you ever accidentally frozen a container of carbonated beverage? What happened?
4. Would the carbonated beverage eventually freeze without removing the cap?
5. Does the frozen beverage have less dissolved carbon dioxide than the liquid form? Explain using personal observations.

Advanced Questions

6. When ice forms, what type of intermolecular forces are involved? What types of intermolecular forces exist between carbon dioxide and water?
7. What caused the ice to start forming after the cap was removed? Why did the solution remain liquid until the cap was removed?

EXPERIMENT 5. ON THE CARBON DIOXIDE/CARBONIC ACID EQUILIBRIUM

Equipment

Microscale Gas Chemistry Kit

Chemicals

bottle of carbonated beverage
vinegar, 10 mL
phenolphthalein, 1 mL
3 M NaOH(aq), 1 mL

Suitability

high school lab, university lab, and classroom demonstration

Applications, Topics, Purpose

LeChâtelier's principle, rates of chemical reactions (chemical kinetics), solution equilibrium, acids and bases

Instructions

When $CO_2(g)$ dissolves in neutral water, a small portion of it reacts with water to produce carbonic acid, $H_2CO_3(g)$:

$$CO_2(aq) + H_2O(l) \rightleftarrows H_2CO_3(aq) \qquad K^{25^o} = [H_2CO_3]/[CO_2] = 1.7 \times 10^{-3}$$

At 25 ^oC the ratio of CO_2 to carbonic acid, $[CO_2]/[H_2CO_3]$, is approximately 600:1.

The equilibrium is relatively slow to become established. At neutral or acidic pH values, the reaction takes place by a first order rate law with a small rate constant:

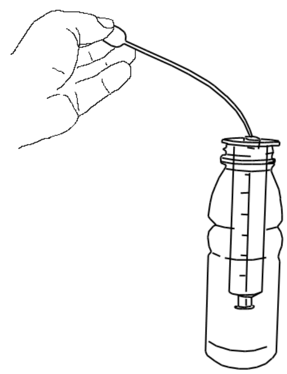
$$\text{Step 1: } CO_2(aq) + H_2O(l) \rightleftarrows H_2CO_3(aq) \text{ (slow)}$$

$$\text{rate} = k[CO_2] \quad k = 0.030\ s^{-1}$$

$$\text{Step 2: } H_2CO_3(aq) + OH^-(aq) \rightleftarrows HCO_3^-(aq) \quad \text{fast}$$

We can demonstrate this kinetic slowness by reacting a solution of CO_2/H_2CO_3 with NaOH(aq). As a control, we will react vinegar, another weak acid, with NaOH(aq).

Cap a syringe barrel with plunger removed. While holding the syringe at a 45° angle, slowly pour sparkling water (or a carbonated beverage) into the syringe barrel. Try to avoid causing the solution to lose bubbles. After the syringe has been filled to the 55 mL mark, add 4 drops of phenolphthalein and then "top off" with additional sparkling water. Place the syringe in a wide-mouth bottle for support as shown in the figure. Float a vial cap on the surface of the sparkling water and carefully add 5 drops of 3 M NaOH(aq) to the vial cap.



Remove the syringe cap and allow all but 20 mL of the sparkling water/phenolphthalein solution to drain from the syringe. Recap the syringe. (The portion that was drained can be saved for a second trial.) Insert the plunger just past the "catch" ridge inside the barrel. Shake the contents to mix the two solutions. The color will immediately turn pink due to excess NaOH(aq), but within 3 seconds will return to colorless as more $CO_2(aq)$ shifts to $H_2CO_3(aq)$ in order to re-establish the equilibrium.

For comparison purposes, we will compare how acetic acid with a concentration similar to that of the $CO_2(aq)/H_2CO_3(aq)$ solution. Dilute 10 mL of vinegar (assumed to be 5% by mass acetic acid) with 90 mL of water. Add five drops of phenolphthalein to the solution. Perform the experiment as was done with sparkling water: Cap a syringe barrel (without plunger) with a syringe cap. Pour the diluted vinegar solution into the syringe barrel. Fill to the very top. Place the syringe in a wide-mouth bottle for support as shown in the figure. Float the vial cap on the surface of the sparkling water and carefully add 5 drops of 3 M NaOH(aq) to the vial cap. Remove the syringe cap and allow all but 20 mL of the diluted vinegar solution to drain from the syringe. Recap the syringe. (The portion that was drained can be saved for a second trial.) Insert the plunger just past the "catch" ridge inside the barrel. Shake the contents to mix the two solutions. The color will turn pink, but only for a split second, and then will return to colorless. The pink color persists only due the time it takes for diffusion of the two chemicals to take place.

Teaching tips

1. The number of moles of hydroxide added is less than the amount of acid present in either of these two solutions.
2. Explain to your students the observed color changes and timeframes for both parts of this experiment.

Questions

1. Approximately 0.35 g of CO_2 dissolve per 100 mL cold water at 1 atm pressure. Given the volume used, convert this to units of moles.
2. Calculate the molar concentration of acetic acid present. Given the volume used, convert this to units of moles.
3. Given the volume and molar concentration of NaOH(aq) used, convert this to units of moles. Assume that 20 drops = 1 mL. Was NaOH(aq) used in excess or was it the limiting reagent?
4. Given the following equilibrium and kinetic rate constant, explain why the pink color persists in the reaction between NaOH(aq) as the limiting reagent and excess carbon dioxide/carbonic acid.

$$\text{Step 1: } CO_2(aq) + H_2O(l) \rightleftarrows H_2CO_3(aq) \text{ (slow)}$$

$$\text{rate} = k[CO_2] \qquad k = 0.030\ s^{-1}$$

Disposal of carbon dioxide samples

Unwanted carbon dioxide samples can be safely discharged into the room.

Clean-up and storage

At the end of the experiments, clean all syringe parts, caps and tubing with soap and water. Rinse all parts with water. Be careful with the small parts because they can easily be lost down the drain. Store plunger out of barrel.

SUMMARY OF MATERIALS AND CHEMICALS NEEDED FOR CHAPTER 8. CARBONATED BEVERAGES — PRIESTLEY'S SODA-WATER.

Equipment and materials required for Part 1: Student Experiments (Experiments 1 – 2)

Item	For Demo	For 5 pairs	For 10 pairs
Microscale Gas Chemistry Kit (Chapter 1)	1	5	10
sparkling water (or sugar free carbonated beverage)	1 bottle	2 bottles	4 bottles

Chemicals required for Part 1: Student Experiments (Experiments 1 – 2)

Item	For Demo	For 5 pairs	For 10 pairs
limewater	3 mL	20 mL	40 mL
universal indicator	10 mL	50 mL	100 mL
sodium bicarbonate, $NaHCO_3$	2 g	10 g	20 g
vinegar	10 mL	50 mL	100 mL

Equipment and materials required for Part 2: Advanced Experiments and Demonstrations (Experiments 3 - 5)

Item	For Demo
Microscale Gas Kit (See Chapter 1)	1
freezer	1
4 L (1 gallon) sealable plastic bag	1
carbonated beverage (or sugar free carbonated beverage)	1 bottle

Chemicals required for Part 2: Advanced Experiments and Demonstrations (Experiments 3 - 4)

Item	For Demo
sodium bicarbonate, $NaHCO_3$	2 g
vinegar	10 mL
phenolphthalein	1 mL
NaOH(aq), 3 M	1 mL