Household Products Used To Collapse Closed Containers and Demonstrate Avogadro's Law

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Abstract: Three new experiments using cost-effective household products are used to explain the concepts of Avogadro's law, stoichiometry, and thermodynamic properties in introductory and university level chemistry courses. These experiments are designed to grab the students' attention by presenting some surprising effects. The methods of producing carbon dioxide and the effect of crushing containers are very different from those in the literature. These demonstrations have two advantages. First, carbon dioxide is generated in the original containers, and second, the element of surprise stimulates the students' interest to learn more about chemistry.

Introduction

Some home experiments in chemistry have recently been published in journals [1–3], in textbooks [4], and on the Internet [5–6]. Everyday household materials, such as aluminum cans [7–8], plastic beverage bottles [9–10], and balloons [11–12] have been popularly employed for chemical laboratories and demonstrations.

Qualitative and quantitative experiments have been used to demonstrate and explain gas laws such as Boyle's law [8, 13–14], Charles's law [8, 13–14], Gay-Lussac's law [13], and Dalton's law of partial pressure [13]. The demonstration of Avogadro's law, however, has not yet been presented in the literature. Avogadro's hypothesis states that equal numbers of molecules of different gases, when compared at the same temperature and pressure, occupy equal volumes. Accordingly, Avogadro's hypothesis relates an amount (number of molecules) of gas to its volume when temperature and pressure remain constant. The simple gas law implied by this statement is Avogadro's law. Avogadro's law means that the volume of a gas is directly proportional to the amount of gas (that is, to the number of moles, n, of gas, or to the number of molecules of gas) at a constant temperature and pressure [15].

Two effective means of crushing containers attempt to explain the concept of atmospheric pressure. One method involves physical change and another involves chemical reaction. The former method uses an aluminum can or a steel solvent drum crushed by the phase change of water [5, 8, 14, 16–17]. The latter method crushes an aluminum can by using rapidly dissolving ammonia gas in water [18]. These demonstrations, however, exhibit some disadvantages. First, the gas is produced using a gas generator in a fume hood, which is inconvenient in lectures. Second, most containers are not tightly sealed so the crushing effect is weak. This article describes three new experiments to demonstrate Avogadro's law. These experiments use cost-effective household products to illustrate stoichiometry, and they exhibit some surprising effects to attract students' attention. The methods used to produce and collect carbon dioxide and to crush the containers are convenient, exciting, and very different from conventional approaches.

The literature always explains the crushing of the containers with reference to atmospheric pressure. Here, the effects are interpreted not only by referring to atmospheric pressure, but also to Avogadro's law. The carbon dioxide produced and directly collected in the original containers is accounted for by the density of gases and stoichiometry. Moreover, the change in temperature for each process in these experiments is explained by a thermodynamic calculation. The concepts of Avogadro's law and stoichiometry are appropriate for introductory chemistry, and the addition of the thermodynamic calculations is appropriate in university level chemistry.

Experimental

Household Materials and Sources

355-mL empty aluminum can
two 600-mL empty plastic beverage bottles
a sufficiently strong, deflated balloon, more than 8-cm long.
7.0 g baking soda (supermarket)
7.4 g citric acid monohydrate (drugstore)
30 mL liquid drain opener (supermarket)
small plastic spoons
a 3-mL polyethylene dropper with graduations (drugstore)
a 10-cm-by-5-cm piece of adhesive tape
a 50-mL cup with graduations

Handling and Disposal. The liquid drain opener, which contains concentrated sodium hydroxide, is highly caustic and harmful to skin and eyes. Be sure to wear eye protection. Handle the aluminum can and plastic bottle with care to prevent sodium hydroxide solution from leaking from the collapsed container. The demonstration containers should be rinsed in a sink with running water after an appropriate amount of acid is added because unreacted sodium hydroxide solution may remain in them. The rinsed containers may be recycled.

Demonstration Procedures. General Procedures for Demonstrations A through C. Three demonstrations share general procedures: (1) Mix household chemicals in a container to produce carbon dioxide. (2) Wait until the reaction is finished. (3) Use a drain opener to absorb the gas. (4) Seal the container to form a closed system. (5) Observe what happens in next few minutes. Following steps (1) and (4), ask the students to obtain the change in temperature.

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Figure 1. Pictures of the demonstration results.

Occasionally swirl the containers to accelerate the reaction if necessary after steps 1 and 4. Following step 3, quickly wipe up any residue with toilet paper. Use the correct amount of household chemicals as directed. Seal the container as quickly and tightly as possible.

Specific Procedures for Demonstration A Using an Aluminum Can. Remove the lift ring from an empty 355-mL aluminum can. Place two spoonfuls (two pea-sized amounts, 1.4 g) of baking soda and three spoonfuls (three pea-sized amounts, 1.8 g) of citric acid, and add about 10 mL of water into the can. When the hissing sound slows, confirm the presence of carbon dioxide in the container by extinguishing a glowing splint. Place about 10 mL of liquid drain opener in a small cup having a 10-cm length of adhesive tape at hand. When the can is filled with carbon dioxide, immediately pour the drain opener into the can. Seal the opening with the tape as fast as possible to make a closed system by pressing the tape tightly onto the area close to the opening.

Specific Procedures for Demonstration B Using a Plastic Bottle. Remove the label from the outside of an empty 600-mL plastic bottle. Place four spoonfuls (four pea-sized amounts, 2.8 g) of baking soda, six spoonfuls (six pea-sized amounts, 3.6 g) of citric acid, and about 10-mL of water into the bottle. When the bottle is filled with carbon dioxide, immediately pour about 10 mL of the drain opener into the bottle. Screw the cap tightly onto the bottle.

Specific Procedures for Demonstration C Using a Plastic Bottle and a Balloon. The household chemicals are mixed as in Demonstration B. An 8-cm or longer deflated balloon strong enough for inflation and whose opening is slightly smaller than the mouth of the bottle is used. When the bottle is filled with carbon dioxide, immediately pour about 10 mL of the drain opener into the bottle. Seal the bottle mouth as fast and tightly as possible. An effective way to seal the bottle is to place the balloon inside the bottle by holding the opening upward and stretching it over the mouth.

Results

The containers turn cold as the baking soda, citric acid, and water are mixed to produce carbon dioxide gas; they become hot as the drain opener absorbs the gas.

These experiments also demonstrate some spectacular effects after the closed system is formed. In Demonstration A, the aluminum can wrinkles within a few minutes to become four-sided with some startling sounds. It becomes gradually crushed and finally collapses [19]. In Demonstration B, the crushing of the plastic bottle is more dramatic than that of the can. In Demonstration C, the balloon is gradually inflated inside the bottle until it nearly touches the bottom of the bottle. Figure 1 and the Supplementary Materials show these effects.

Discussion

Carbon dioxide is produced and directly collected by the upward displacement of air in the original containers without using a gas generator because the density of carbon dioxide (1.98 g/L) is greater than that of air (1.29 g/L). The carbon dioxide fills the containers because the quantities of the household products are used according to stoichoimetry.

To demonstrate the filling of the containers by carbon dioxide a glowing splint is placed over the opening of each container. The container is filled with carbon dioxide if the glowing splint is extinguished.

Demonstrations A through C involve two important reactions, shown in eqs 1 and 2 below.

$$3\ NaHCO_3(s) + C_6H_8O_7{\bullet}H_2O(s) + n\ H_2O(l) \rightarrow$$
$$3\ Na^+(aq) + 3CO_2(g) + C_6H_5O_7^{3-}(aq) + (n + 4)\ H_2O(l) \quad (1)$$

$$2\ NaOH(aq) + CO_2(g) \rightarrow 2\ Na^+(aq) + CO_3^{2-}(aq) + H_2O(l) \quad (2)$$

By stoichiometry, two spoonfuls of baking soda (1.4 g) are equivalent to 17 mmol (1.4 g/ 84.00 g mol^{-1}) of sodium bicarbonate. Similarly, three spoonfuls of citric acid monohydrate (1.8 g) contains 8.6 mmol (1.8 g/ 210.14 g mol^{-1}). In eq 1, the amount of the acid greatly exceeds 5.7 mmol (17 mmol / 3), and an excess of 2.9 mmol (8.6 mmol – 5.7 mmol) is used; therefore, 17 mmol, 420 mL (0.017 mol × 82.058 mL atm K^{-1} mol^{-1} × 298 K/1.00 atm) of carbon dioxide is produced at room temperature. This amount (420 mL) of carbon dioxide should be large enough to fill a 355-mL aluminum can. Similarly, the amount of each chemical can be doubled to generate 840 mL of the gas, enough to fill a 600-mL plastic bottle.

In eq 2, about 10 mL of the drain opener that contains 16.7 M sodium hydroxide [20] contains 170 mmol (10 mL × 16.7 M) of NaOH, consuming 85 mmol (170 mmol / 2), 2100 mL (85 mmol × 24.5 L mol^{-1}) of carbon dioxide according to stoichiometry. Thus, 10 mL of the drain opener should suffice to absorb 14 mmol (355 mL / 24.5 L mol^{-1}) of carbon dioxide in a 355-mL aluminum can or 24 mmol in a 600-mL plastic bottle. The drain opener used contains a large excess of sodium hydroxide because the drain opener also needs to neutralize 2.9 mmol of excess of citric acid in eq 1.

The atmospheric pressure that acts on the surface of each container greatly exceeds the pressure inside it because sodium hydroxide absorbs carbon dioxide in eq 2; therefore, these experiments can crush the can and bottle and inflate the balloon.

According to Avogadro's law and considering eq 2, the amount of gas decreases as carbon dioxide is absorbed by sodium hydroxide in a closed container. Consequently, the containers are crushed in Demonstrations A and B, and the balloon is inflated in Demonstration C.

Thermodynamic Calculations

The change in temperature observed in these experiments can be discussed in terms of a calculated enthalpy change [21–24]. Suppose that all species are in their standard states, and the concentration of each solution is 1.0 M. Mixing baking soda, citric acid, and water (process 1) involves four enthalpy changes. These involve (a) the dissolution of solid baking soda, (b) the dissolution of solid citric acid monohydrate, (c) the dissolution of gaseous carbon dioxide in water, and (d) the reaction of aqueous sodium carbonate with aqueous citric acid. Event c may be neglected due to the low solubility of carbon dioxide in water and its low rate of dissolution. Hence, the heat change of process 1 is nearly the sum of that of eq 1 (that is, events a and b and reaction d) and that of the dissolution of excess citric acid monohydrate in water. In eq 1, ΔH°_{f} of this reaction is equivalent to +126 kJ {[3(–240.1) + 3(–393.510) + (– 1519.9) + (*n* + 4)(–285.830)] kJ – [3(–950.8) + (–1838) + *n*(–285.830)] kJ} [23]. By calculation, the enthalpy change of solution of citric acid monohydrate is +32 kJ mol^{-1} [24]. Thus, the heat change of process 1 in Demonstration A is +0.81 kJ [(+126 kJ × 17 mmol/3 mol) + (+32 kJ mol^{-1} × 2.9 mmol)]. The positive heat change (+0.81 kJ) shows that process 1 is endothermic; the thermodynamic calculation is in line with the observation of the coldness of the can.

Putting the drain opener into the containers (process 2) involves two enthalpy changes. These include (a) the drain opener's absorbing carbon dioxide and (b) the neutralization of sodium hydroxide with excess citric acid. In eq 2, ΔH°_{f} of event a is –111 kJ {[2(–240.1) + (–677.1) + (–285.830)] kJ – [2(–469.2) + (–393.510)] kJ}. The heat change of process 2 is at least that of eq 2 because event b is exothermic; therefore, the enthalpy change of the process in Demonstration A should be more negative than –1.6 kJ [–111 kJ × (355 mL × 10^{-3} L/mL)/24.5 L]. The negative heat change (–1.6 kJ) indicates that process 2 is exothermic. Moreover, the loss of heat to the surroundings in process 2 (–1.6 kJ) is much greater than the gain of heat in process 1 (+0.81 kJ) so that the can becomes hot. In this case, the calculation agrees with the observation of the change in temperature.

In eq 2, ΔG°_{f} of the drain opener absorbing carbon dioxide is –56 kJ {[2(–261.9) + (–527.8) + (–237.141)] kJ – [2(–419.2) + (–394.373)] kJ}. ΔG°_{f} of this reaction with a large negative value (–56 kJ), more negative than –10 kJ, indicates that process 2 is spontaneous and that the reactants transform almost entirely into products when equilibrium is reached [25]. Hence, the calculation of free energy change is verifiable for the crushing of the containers and the inflation of the balloon in process 2.

Conclusions

Three new demonstrations using household products can effectively explain the concepts of Avogadro's law, stoichiometry, thermodynamic properties in introductory and university level chemistry courses. These experiments are attractive to students who wish to learn more about chemistry, and they motivate those students to investigate chemical phenomena in their daily life. These demonstrations may also encourage instructors to design other experiments using cost-effective household products.

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Supporting Materials: Photographs of the demonstrations are available in the Supporting Materials s00897020528b.zip.

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