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Demonstration

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# A Colorful Demonstration to Visualize and Inquire into Essential Elements of Chemical Equilibrium

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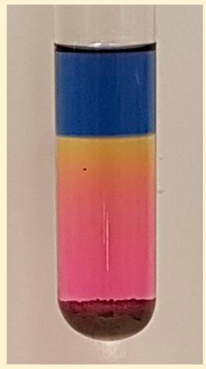
**ABSTRACT:** One of the topics that chemistry teachers have a great challenge introducing is chemical equilibrium. When being introduced to chemical equilibrium, many students have difficulties in understanding that some reactions do not go to completion, as this contrasts most of their supposed prior experiences in chemistry lessons. Students may also struggle with the existence of dynamic equilibrium in which reactants and products constantly transform into each other in a nonvisible manner. The goal of this general chemistry demonstration is to provide teachers with an effective method to help introduce the difficult idea of chemical equilibrium as well as connect chemical equilibrium to acid−base chemistry more successfully. This demonstration will allow students to develop a better understanding of the dynamic nature of chemical equilibrium and Le Chatelier's Principle by letting them interpret measured pH values and observe correlated color changes before and after the addition of different reagents that shift the chemical equilibrium.



**KEYWORDS:** *Demonstrations, Acid/Bases, Equilibrium, Ion Exchange, First Year Undergraduate/General, High School/Introductory Chemistry, Solutions/Solvents*

## ■ INTRODUCTION

The challenge of helping students develop a conceptual understanding of the dynamic nature of chemical equilibrium can make teaching equilibrium a daunting task.[1] It has been shown that students have difficulty relating mathematical representations of chemical equilibria, e.g., the law of mass action, to visual representations of a solved problem[2] and that chemical equilibrium is one of the most difficult concepts for students to comprehend.[3] Depending on the amount of time available, there are hands-on activities that can be utilized to demonstrate equilibrium, such as the use of poker chips to maintain a balance between red and white,[4] or the use of an equilibrium machine which uses air pressure to force different size styrofoam balls back and forth over a divider inside of a box.[5] Such demonstrations, however, come with inherent limitations. The physical nature of these lessons precludes the ability to imagine the changes taking place while the system is at equilibrium. To this end, educators use analogies to teach their students. One such analogy equates shoppers on two different floors to molecules or ions in a solution when describing the process of equilibrium.[6] However, such analogies can be detrimental if not properly constructed.[7] These analogies can lead students to common misconceptions such as the belief that the forward reaction must come to completion before the reverse reaction can begin.[8]

There is a need for new materials, tools, and activities that decrease misconceptions while still enabling students to visualize and conceptualize the dynamic nature of chemical equilibrium.[3] For this reason, this demonstration, which utilizes cation exchange resins, was developed to help students make deductions about chemical equilibrium by observing a continuing change of colors with the addition of reagents. In addition, students will explore the idea that equilibrium is changeable for a brief time when disturbed, and that the speed at which the reaction occurs depends on the amount of reagents added. This demonstration is a precursor to titrations and should be tied to the concept of pH and acid−base equilibria. For this demonstration to be effective, students should be familiar with a basic understanding of chemical kinetics, basic acid−base-reactions, and the behavior of indicators. Understanding of rate expression and reaction mechanisms can help for a deeper understanding with the observed phenomena.

## ■ BACKGROUND

Cation exchange resins are organic polymers containing substituted carboxylic or sulfonic acid groups. Cations are bound to a negatively charged matrix for charge compensation. The cations bound in the matrix are typically metal ions or hydrogen ions (protons). Ion exchange resins (e.g., Amberlyst 15, Dowex, and others) are used in applications such as environmental chemistry, analytical chemistry, catalysis, and chemical technology.[9] Analogous behavior can be observed with other ion exchangers such as zeolites or clays.[10] Ion exchangers are also great tools for learning about chemical equilibria in an illustrative way.

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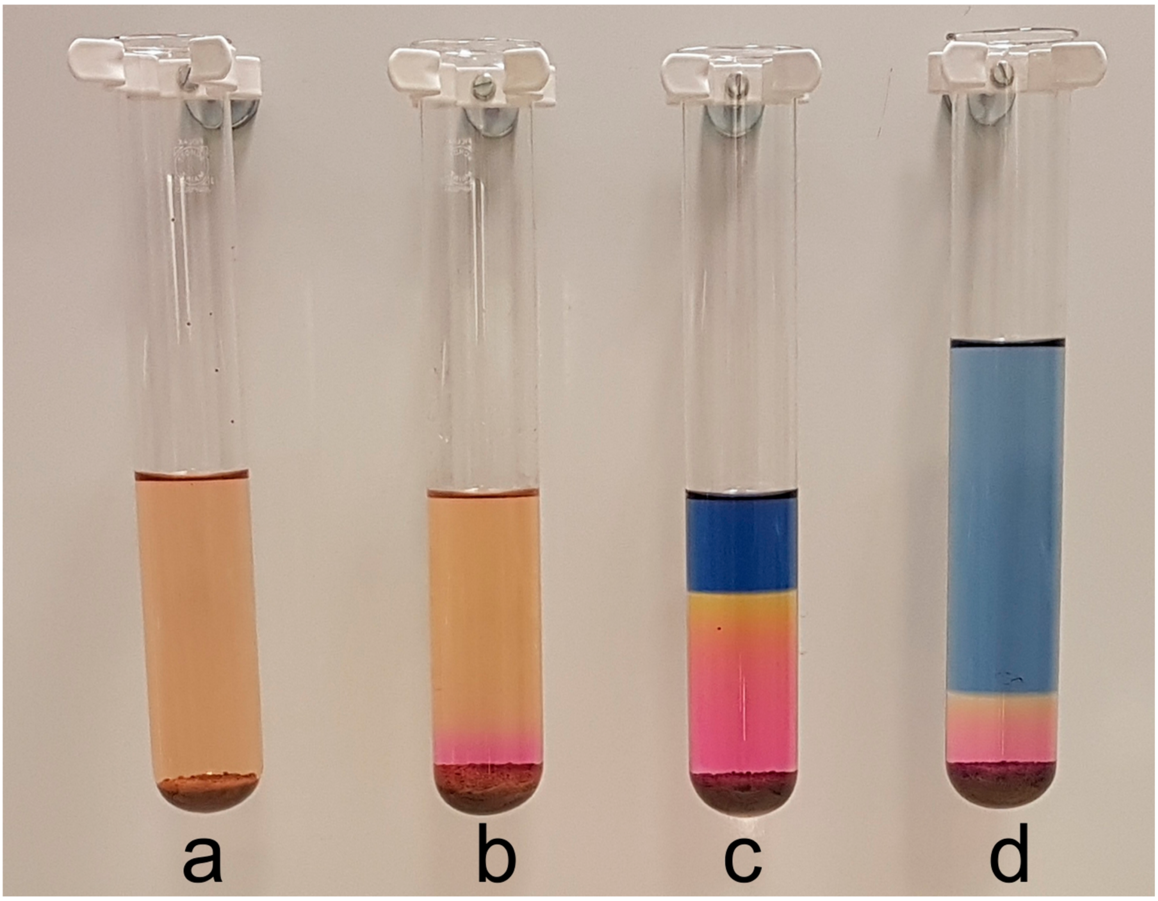


**Figure 1.** Color distribution in different phases of the demonstration: (a) Amberlyst 15 in an aqueous solution of thymol blue, (b) after addition of sodium chloride, (c) after addition of sodium hydroxide solution, settling of the solid and subsequent balancing of the chemical equilibrium, and (d) when the solid state acid is nearly exhausted.

If protons are bound to an ion-exchange resin, the resin acts as a solid-state acid.[11] A solid-state acid is protonated in the solid state and may partially dissociate in solution similar to a typical weak acid. The resin used in this demonstration, Amberlyst 15, contains protonated sulfonate groups similar in structure to sulfurous acid. This solid-state acid only partially dissociates in water due to the buildup of negative charges in its dissociated form. Other cations, if available in the solution, may be exchanged for the bound protons. An example of the reaction governing the exchange of hydrogen ions for cations is shown in the following equilibrium (eq 1) using sodium as the cation:

$$XH + Na^+ + H_2O \rightleftarrows XNa + H_3O^+ \qquad (1)$$

X is the matrix of the resin, zeolite, or clay.

## A Colorful Chemical Demonstration for Illustrating Chemical Equilibrium

**Equipment and Chemicals.** For the demonstration, the following materials are needed: test tube (approximately 25 × 150 mm), stopper, glass rod, pH meter, Amberlyst 15 (acid form), sodium chloride, water, thymol blue (w/v 0.2% in ethanol), water (deionized), and sodium hydroxide (0.2 M).

**Procedure and Observations.** The following protocol describes each step of the demonstration:

1. Add 1 g of the acidic ion-exchange resin Amberlyst 15 to the test tube. Fill the test tube with water up to 6−7 cm (the test tube should be about half full, see Figure 1). Add about 20 drops of the thymol blue solution. A yellow color should appear (Figure 1a). Measure and record the pH of the solution.
2. Add 2 g of sodium chloride to the solution. A color change to red should be observed in the lower part of the solution (Figure 1b). Mix the solution, and the color of the entire solution will turn red. Measure and record the pH.
3. Add sodium hydroxide solution dropwise until the solution in the upper two-thirds remains intensely blue. Next, mix by horizontally slewing around the test tube until the solution is completely blue. After the resin settles, an increasingly intense red color should be observed above the solid, which will change slowly to orange, then yellow, and finally to blue (Figure 1c).
4. Stir the suspension with the glass rod. The blue color should disappear completely. The solution at the surface of the solid resin should still be red; the rest of the solution should be yellow. Measure and record the pH.
5. Now add an additional amount of the sodium hydroxide solution dropwise until the solution in the upper part remains blue. Swirl the test tube again. The same color distribution seen in step 3 should appear. Stir and record the pH again.
6. This process can be repeated several times. The intensity of the red color at the surface of the ion exchange reaction will steadily decrease with each repetition, and the volume of sodium hydroxide needed to neutralize the



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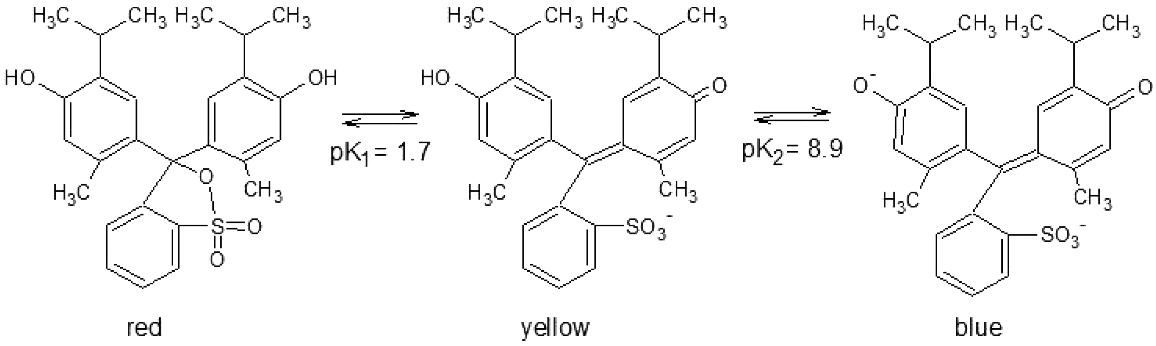


**Figure 2.** Structures and colors of thymol blue at different pH ranges.

acid will become progressively smaller (Figure 1d). Eventually, the entire solution will remain blue. Continue recording the pH after each step.

## ■ HAZARDS

Diluted sodium hydroxide solution is corrosive.

## ■ DISCUSSION

Initially, no red coloration in the solution appears because, prior to the addition of sodium chloride, no cations are available; nearly all of the protons remain bound to the resin. After the addition of sodium chloride, some of the protons in the solid acid are exchanged for sodium ions, and the solution becomes acidic near the solid. This can be understood according to Le Chatelier's principle: the addition of salt causes a readjustment of the equilibrium, resulting in the formation of products according to eq 1. With subsequent stirring, the released hydronium ions are distributed throughout the solution, as evidenced by the yellow/red color of the entire solution at different pH values (Figure 2).

With the addition of sodium hydroxide, free hydronium ions are neutralized. Excess hydroxide ions in the solution cause the indicator to appear blue. However, the addition of NaOH also increases the concentration of $Na^+$ ions, which can displace additional protons in the resin. New hydronium ions are formed at the phase interface, and the chemical equilibrium is subjected to a new stress. The slow diffusion of hydronium ions into the solution creates a gradient of different pH values throughout the solution until the solution is again mixed.

This cycle can be repeated up to seven times. With the use of 1 g of Amberlyst 15, a total of up to 24 mL of a 0.2 M sodium hydroxide solution may be added. However, the intensity of the color at the resin surface decreases as the number of hydronium ions released decreases. Finally, once nearly all of the protons have been exchanged and neutralized, the solution will remain mainly blue after the addition of a small amount of base (Figure 1d).

## ■ EXPERIENCES

This demonstration has been used for many years in high school chemistry classes and teacher education in Germany. Different teachers have used this demonstration to visually introduce the phenomena of chemical equilibrium. Informal feedback on the demonstration provided by the teachers indicates a very motivating effect. Generally, the demonstration leads to many different questions, both on the phenomenon as well as on the uncommon nature of a solid state material that behaves as an acid. This can lead into further inquiry into chemical equilibrium and the nature of solid state acids. When introducing the demonstration to prospective teachers in their undergraduate teacher education program in Germany, similar questions generally arise. While student teachers should minimally know the essential elements of the concept of chemical equilibrium, for many of them, it is quite uncommon to see how the equilibrium slowly balances and how the capacity of the resin decreases. When asked to do the demonstration on their own, most prospective teachers needed to practice it a few times to determine how much sodium hydroxide solution to add and how to mix the solution to obtain the best effects and maximum number of repetitions.

## ■ CONCLUSIONS AND IMPLICATIONS

One of the most difficult tasks when teaching chemistry is encouraging a student to go beyond memorizing facts and begin thinking conceptually about the processes occurring in a chemical system.[12] By giving students a visual representation of equilibrium and the tools to shift the equilibrium, the concept can be connected to a visual impression. This demonstration is a discovery activity targeting equilibrium which would then lead into discussions about the acid−base equilibria. It may act as a bridge between equilibrium and pH and ease future learning. It can also be varied in many ways. It can become an inquiry experiment, e.g., by varying the ion exchanger, the amount of salt, or the additions of sodium hydroxide solution. Having students observe a changing color spectrum along with an increase or decrease in measured pH values will allow the teacher to associate a shift in chemical equilibrium with a variation in concentration of $H^+$ and $OH^-$ ions.

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### Notes

The authors declare no competing financial interest.

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