

Flame Tests: Which Ion Causes the Color?

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In this Activity, students perform simple flame tests using eleven commercially available compounds, cotton swabs, and a Bunsen burner. They then determine whether the cations or anions are responsible for the flame test colors.

Background

Many chemistry textbooks describe the chemicals responsible for the colors of commercial fireworks, but few describe flame tests as an experimental method or explain why certain atoms emit colored light in a flame. Atoms placed in a flame absorb thermal energy, causing electrons within the atom to move from lower to higher energy states. When these electrons return to lower energy states, they emit energy in the form of electromagnetic waves (light). For some atoms (such as those of alkali metals, alkaline earth metals, and copper), wavelengths are in the visible spectrum. Flame tests can confirm the presence of specific metal cations in a sample. While the cations in an ionic compound usually cause flame test colors, there are some anions and neutral molecules that generate flame test colors. For example, the borate ion ($B_4O_7^{2-}$) and boric acid (H_3BO_3) both produce green flame tests due to the presence of boron. Color images of the various flame tests can be seen on page 1683 and are also available in this issue of *JCE Online*.^W

Integrating the Activity into Your Curriculum

This Activity introduces flame tests in an inquiry-based manner. Most laboratory manuals state that the metal cation in an ionic compound is usually responsible for flame test colors and students verify this fact. In this Activity, students investigate whether the cation or the anion is responsible. This Activity also illustrates the importance of controlling variables and making meaningful comparisons.

About the Activity

This Activity uses a flame test technique from a recent *Journal* article (1, Method 1). Perform the tests in a fume hood. Students first perform flame tests with a cotton swab dipped in water and a swab dipped in 3 M HCl to show that neither imparts a color to the flame. HCl is used because the addition of chloride ions to the samples can cause the flame test colors to be stronger and more vivid (2). A swab left in the flame for an extended time will start to burn, turning the flame dull orange. Remind students that if testing a compound turns the swab light-brown/black, the dull orange color in the flame is due to the compound or the swab burning. Cream of tartar shows this burning effect the most; check that students see the light purple color within the predominantly orange flame.

Chloride compounds show different flame test colors (HCl = colorless, $CaCl_2$ = red-orange, NaCl = orange-yellow, KCl = light purple), implying Cl^- is not responsible for the colors; otherwise, the flame colors would be the same. Comparing $CaCO_3$ (red-orange) and Na_2CO_3 (orange-yellow) or $MgSO_4$ (colorless) and $CaSO_4$ (red-orange) also shows that the anions are not responsible. Sodium compounds show the same flame test colors (all orange-yellow), suggesting Na^+ is responsible for the colors. Comparing $CaCO_3$ and $CaCl_2$ (both red-orange) or $KC_4H_5O_6$ and KCl (both light purple) also indicates that it is the common cation causing the flame test colors.

All materials are available at grocery stores (cotton swabs, antacid tablets, boric acid [used for an eye wash], cream of tartar, MSG, table salt, salt substitute, washing powder [detergent booster]), hardware stores (muriatic acid, deicer/dehumidifier, Epsom salt, TSP cleaner), and craft stores (plaster of Paris). Muriatic acid is typically 12M HCl. Use 3 parts water to 1 part acid to make 3M HCl, adding the concentrated acid to the water. If you cannot find washing soda, heat baking soda: $2 NaHCO_3(s) \rightarrow Na_2CO_3(s) + H_2O(g) + CO_2(g)$. Phosphate-free "TSP" (typically sodium metasilicate, Na_2SiO_3) works if regular TSP is unavailable. The salt substitute should not contain NaCl.

Answers to Questions

1. It is important to know the flame test colors for the swab and the acid because they are present in every flame test and could affect your results.
2. The cations are responsible. Compounds with matching cations produce the same color flame tests. Compounds with matching anions do not produce the same color flame tests.
3. KCl would make good purple fireworks. $CaCl_2$ would make good red fireworks.
4. Green. Since the cation is generally responsible for the flame test color, copper(II) gluconate should have the same color flame test as copper(II) sulfate.
5. Equal should show no flame test color other than due to the burning of aspartame (dull orange flame), Ace-K should have a purple flame, and Sweet 'N Low should have a red-orange flame.
6. Cations or anions are not necessary in this case. Boric acid produces a green flame test.

References, Additional Related Activities, and Demonstrations

1. Sanger, Michael J.; Phelps, Amy J. Simple Flame Test Techniques Using Cotton Swabs. *J. Chem. Educ.* 2004, 81, 969–970.
2. Zumdahl, S. S.; Zumdahl, S. A. *Chemistry*, 6th ed.; Houghton Mifflin: Boston, 2003; pp 302–303.

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Flame Tests: Which Ion Causes the Color?

For most Americans, a Fourth of July celebration is not complete without spectacular fireworks and the crowd's "oohs" and "ahhs". Have you ever wondered what causes the brilliant array of firework colors? These colors are usually the result of the interaction of an ionic compound (like sodium chloride, NaCl) with the extreme temperatures present in the firework's explosion. But which ion—the cation or the anion—is generally responsible for this color? In this Activity, you will perform flame tests on solid compounds, in which each compound is placed in a Bunsen burner. You will then determine whether the cation or the anion is responsible for these flame test colors.

Try This

You will need: Bunsen burner, 14 cotton swabs, mortars and pestles, distilled water, dilute muriatic acid (3M HCl), small containers, and eleven compounds: antacid tablets ($\text{Ca}^{2+}\text{CO}_3^{2-}$), deicer/dehumidifier ($\text{Ca}^{2+}[\text{Cl}^-]_2$), cream of tartar ($\text{K}^+\text{C}_4\text{H}_5\text{O}_6^-$), Epsom salt ($\text{Mg}^{2+}\text{SO}_4^{2-}$), MSG ($\text{Na}^+\text{C}_5\text{H}_8\text{NO}_4^-$), plaster of Paris ($\text{Ca}^{2+}\text{SO}_4^{2-}$), table salt (Na^+Cl^-), salt substitute (K^+Cl^-), TSP cleaner ($[\text{Na}^+]_3\text{PO}_4^{3-}$), washing powder ($[\text{Na}^+]_2\text{CO}_3^{2-}$), and boric acid (H_3BO_3).

Be Safe! Flame tests require adequate ventilation and should be performed in a hood. Muriatic acid is volatile and can cause dangerous fumes. Dip cotton swabs in water to extinguish before placing in a trash can.

1. Prepare a table with four columns: compound tested, cation present, anion present, and flame test color.
2. Light a Bunsen burner and adjust to produce a blue flame. Dip a cotton swab into distilled water. Place the swab in the flame for ≈ 5 seconds. What color is the flame? Does the color change? Record your observations.
3. Dip another cotton swab into distilled water and place it in the flame until the swab begins to smolder and burn, and turns light-brown/black. What color is the flame? Record your observations.
4. Dip a cotton swab into dilute muriatic acid (3M HCl). Place the swab in the flame for ≈ 5 seconds. Record your observations. HCl is used to enhance the flame test colors.
5. There are eleven compounds to test. Some of the compounds are fine powders and some are large crystals or tablets. Crush any crystals or tablets into a fine powder with a mortar and pestle. Use a different mortar and pestle for each compound that needs to be crushed.
6. Test each compound using the following procedure. Use a new swab for each powder. Record your observations. Place a small amount of each powder into a separate small container. Dip a cotton swab in dilute muriatic acid (3M HCl), then dip the wet swab into a powder. Place the swab in the flame for ≈ 5 seconds and observe the color of the flame. If the swab starts to smolder and turn light-brown/black, then part of the flame color is due to the swab or compound burning in the flame, and you should ignore this color (the color from step 3 above).

Data Analysis

Anions: Four compounds contain the Cl^- anion. If the Cl^- anion is responsible for the flame test color, would you expect the flame test colors for these four compounds to be the same or different? Compare the flame test colors for these compounds. Compare the flame test results of another pair of compounds with the same anion (e.g., $\text{CaCO}_3/\text{Na}_2\text{CO}_3$ or $\text{MgSO}_4/\text{CaSO}_4$). Do your data suggest that the anion is responsible for the flame test color?

Cations: Four compounds contain the Na^+ cation. If the Na^+ cation is responsible for the flame test color, would you expect the flame test colors for these four compounds to be the same or different? Compare the flame test colors for these compounds. Compare the flame test results of another pair of compounds with the same cation (e.g., $\text{CaCO}_3/\text{CaCl}_2$ or $\text{KC}_4\text{H}_5\text{O}_6/\text{KCl}$). Do your data suggest that the cation is responsible for the flame test color?

Questions

1. Why is it important to test the flame test colors of the cotton swab and the muriatic acid?
2. Which ion (cation or anion) is responsible for each of the flame test colors of the ionic compounds? Explain.
3. Which of the ionic compounds in this experiment would be good for making purple fireworks? Red fireworks?
4. Potassium gluconate ($\text{K}^+\text{C}_6\text{H}_{11}\text{O}_7^-$) produces a light purple flame. Copper(II) sulfate ($\text{Cu}^{2+}\text{SO}_4^{2-}$) produces a green flame. What flame color would you expect for copper(II) gluconate ($\text{Cu}^{2+}[\text{C}_6\text{H}_{11}\text{O}_7^-]_2$)? Explain.
5. How could you tell the following three white artificial sweetener powders apart using flame tests? You have: Equal ($\text{C}_{14}\text{H}_{18}\text{N}_2\text{O}_5$, a non-ionic compound), Ace-K ($\text{K}^+\text{C}_3\text{H}_4\text{NO}_4\text{S}^-$), and Sweet 'N Low ($\text{Ca}^{2+}[\text{C}_7\text{H}_4\text{NO}_3\text{S}^-]_2$).
6. Boric acid is a molecular, non-ionic compound. Based on its flame test, are cations or anions needed to produce a flame test color?

Information from the World Wide Web (accessed Sep 2004)

Chemistry of Fireworks and Pyrotechnics. <http://chemistry.about.com/od/fireworks/pyrotechnics/>

Flame Test Colors from Minerals. <http://www.webmineral.com/help/FlameTest.shtml>

Flame Test Post-Lab Assignment/Reading Quiz. <http://mrgale.com/labs/flmtes/fltPL.htm>

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