FIRE

By Kathy De Antonis

Fireworks are one of the most spectacular outdoor shows. They produce amazing bursts of colors that take a variety of shapes. But how do they work? How do they burn into so many colors and patterns? And why, if not handled properly, can they cause serious injuries or even death?

What's inside a firework?

The source of most fireworks is a small tube called an aerial shell that contains explosive chemicals. All the lights, colors, and sounds of a firework come from these chemicals.

An aerial shell is made of gunpowder, which is a well-known explosive, and small globs of explosive materials called stars (Fig. 1). The stars give fireworks their color when they explode. When we watch fireworks, we actually see the explosion of the stars. They are formed into spheres, cubes, or cylinders that are usually 3–4 centimeters (1–1½ inch) in diameter.

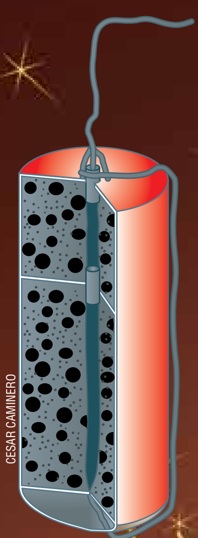

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Figure 1. Structure of an aerial shell. The black balls are the stars, and the gray area is gunpowder. The stars and the powder are surrounding a bursting charge, which also contains black powder.

Each star contains four chemical ingredients: an oxidizing agent, a fuel, a metal-containing colorant, and a binder. In the presence of a flame or a spark, the oxidizing agent and the fuel are involved in chemical reactions that create intense heat and gas. The metal-containing colorant produces the color, and the binder holds together the oxidizing agent, fuel, and colorants.

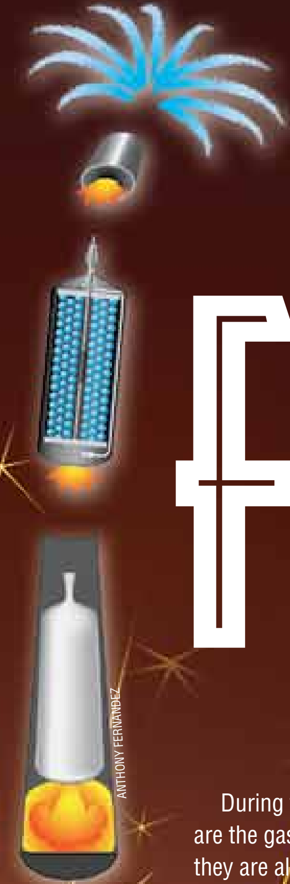
At the center of the shell is a bursting charge with a fuse on top. Igniting the fuse with a flame or a spark triggers the explosion of the bursting charge and of the entire aerial shell.

How fireworks explode

The explosion of a firework happens in two steps: The aerial shell is shot into the air, and then it explodes in the air, many feet above the ground.

To propel the aerial shell into the air, the shell is placed inside a tube, called a mortar, which is often partially buried in sand or dirt. A lifting charge of gunpowder is present below the shell with a fuse attached to it. When this fuse, called a fast-acting fuse, is ignited with a flame or a spark, the gunpowder explodes, creating lots of heat and gas that cause a buildup of pressure beneath the shell. Then, when the pressure is great enough, the shell shoots up into the sky.

After a few seconds, when the aerial shell is high above the ground, another fuse inside the aerial shell, called a time-delay fuse, ignites, causing the bursting charge to explode. This, in turn, ignites the black powder and the stars, which rapidly produce lots of gas and heat, causing the shell to burst open, propelling the stars in every direction.



ANTHONY FERNANDEZ

During the explosion, not only are the gases produced quickly, but they are also hot, and they expand rapidly, according to Charles' Law, which states that as the temperature of enclosed gas increases, the volume increases, if the pressure is constant (Fig. 1). The loud boom that accompanies fireworks is actually a sonic boom produced by the expansion of the gases at a rate faster than the speed of sound!

If the stars are arranged randomly in the aerial shell, they will spread evenly in the sky after the shell explodes. But if the stars are packed carefully in predetermined patterns, then the firework has a specific shape—such as a willow, a peony, or a spinner—because the stars are sent in specific directions during the explosion.

The timing of the two fuses is important. The fast-acting fuse ignites first, propelling the shell into the air, and then the time-delay fuse ignites to cause the aerial shell to explode when it is high in the sky. If the timing of the fuses is not just right, the shell can explode too close to the ground, injuring people nearby.

More often, light from fireworks is produced by luminescence. When fireworks explode in the sky, the gunpowder reactions create a lot of heat, causing the metallic substances present in the stars to absorb energy from the heat and emit light. These metallic substances are actually metal salts, which produce luminescent light of different colors when they are dispersed in the air.

WORKS!

carefully and have an adult in charge," says John Conkling, an adjunct professor of chemistry at Washington College, Chestertown, Md., and former executive director of the American Pyrotechnics Association.

Color	Compound
red	strontium salts, lithium salts lithium carbonate, Li_2CO_3 = red strontium carbonate, $SrCO_3$ = bright red
orange	calcium salts calcium chloride, $CaCl_2$
yellow	sodium salts sodium chloride, NaCl
green	barium compounds + chlorine producer barium chloride, $BaCl_2$
blue	copper compounds + chlorine producer copper(I) chloride, CuCl
purple	mixture of strontium (red) and copper (blue) compounds

HTTP://WWW.SCIFUN.ORG/ ; PROF. BASSAM Z. SHAKHASHIRI, UNIVERSITY OF WISCONSIN-MADISON

Table 1. Colorant compounds used in fireworks and the colors they produce.

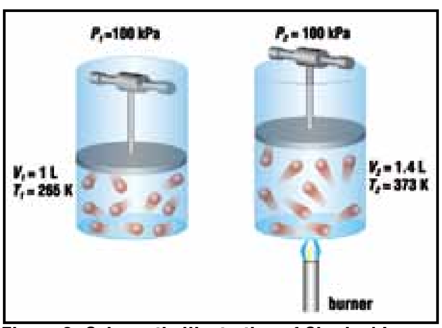


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Figure 2. Schematic illustration of Charles' Law. When the pressure of a volume of gas is constant, an increase in temperature leads to a proportional increase in the volume of the gas. The gas molecules move faster at higher temperatures.

Where do fireworks' colors come from?

What makes fireworks so special is the beautiful colors they produce. These colors are formed in one of two ways: luminescence and incandescence.

Incandescent light is produced when a substance is heated so much that it begins to glow. Heat causes the substance to become hot and glow, initially emitting infrared, then red, orange, yellow, and white light as it becomes increasingly hotter. When the temperature of a firework is controlled, the glow of its metallic substances can be manipulated to be a desired color at the proper time.

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This light is produced by electrons inside the metal atoms (Fig. 3). These electrons absorb energy from the heat, which causes them to move from their original ground-energy state to an excited state. Then, nearly immediately, these electrons go to a lower energy state and emit light with a particular energy and characteristic color.

The color of the light emitted by the electrons varies depending on the type of metal or combination of metals. So, the colors are specific to the metals present in the fireworks. The metal-containing colorants for some common fireworks are listed in Table 1.

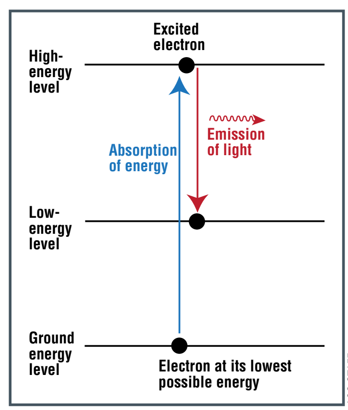

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Figure 3. Principle of luminescence. Heating atoms causes electrons to move from their ground-energy level to a higher energy level (blue arrow). When the excited electrons move to a lower energy level (red arrow), they emit light with a specific energy and characteristic color.

Fireworks' safety

Fireworks are a lot of fun to watch, but they must be handled with great care because they can be dangerous. "When using fireworks, one should follow the label directions very

Knowing the rules and regulations is important, too. According to Conkling, fireworks that are publicly available in stores are legally allowed in 41 of the 50 U.S. states. So, you may not be able to purchase fireworks if your state does not allow it.

Also, regulations require that consumer fireworks should have no more than 50 milligrams (about 1/500th of an ounce) of gunpowder. This may seem like a relatively small amount. But don't be fooled. Even 50 milligrams of gunpowder or less can cause serious injuries. "You would be surprised by how powerful fireworks can be," says Doug Taylor, president of Zambelli Fireworks, one of the largest fireworks companies in the United States.

Some fireworks contain more than the limited amount of 50 milligrams. Although they are illegal, such fireworks—which include the "cherry bombs" and "M-80s"—can be found in some stores or on the black market and cause even more damage.

Despite people's attention to safety, accidents still happen. Most injuries are caused by the mishandling of firecrackers. When they burn, they can reach temperatures of up to 1,000 °C (1,800 °F). Many people, especially children, are burned by them.

Accidents involving fireworks occur every year. They cause field and house fires and result in injuries and deaths. Many of the accidents involve young people. For instance, in 2009, a 17-year-old boy in Latrobe, Pa., lost his right hand and leg after an M-80 firework exploded in his lap.

Another case involved teenagers who were playing with fountain fireworks—aerial fireworks that shoot up tall fountains of sparks—on the front porch of a duplex home in St. Paul, Minn., when a fire broke out. The flames burned through the second floor and reached the roof, resulting in nine people being displaced from their homes.

Because of the danger associated with consumer fireworks, the American Academy of Pediatrics recommends that children and young adults avoid them altogether and attend local aerial fireworks demonstrations instead. Taylor says watching aerial fireworks can be very moving. "One of the grandchildren of the founder of Zambelli Fireworks was known for saying, 'Grandpa, I like your fireworks because I can feel them in my heart,'" he says. "That's so true! It's really an emotional experience."

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JOHN CONKLING

Interview with Pyrotechnic Chemist John Conkling

During the past 30 years, John Conkling, a fireworks expert at Washington College, Chestertown, Md., has made more than 40 trips to China—the world's major producer of fireworks—to meet with officials from the Chinese fireworks industry. He is the author of *The Chemistry of Pyrotechnics—Basic Principles and Theory*, which many consider the most definitive reference on pyrotechnics, and he holds nine patents dealing with energetic chemical systems. Conkling explains what pyrotechnic chemists do.

What do pyrotechnic chemists do?

They combine compounds to make a mixture that can explode to produce color, light, and audible effects, such as the sizzles, pops, and booms of fireworks. When these compounds are lit by a spark or a flame, explosive chemical reactions occur, creating the light and sound effects seen in fireworks.

The mixtures made by pyrotechnic chemists are used not only for entertainment, but also for emergency signaling–such as pink flares that people put on the road next to car accidents—and military applications, such as mixtures that produce effects visible only with night vision goggles.

How did you become a pyrotechnic chemist?

I was interested in all kinds of science as a child, and eventually, chemistry became my focus. I went to graduate school at Johns Hopkins University, Baltimore, Md., to pursue a Ph.D. in physical organic chemistry. The topic of my thesis (unusual reaction mechanisms involving "nonclassical" pathways) doesn't have much to do with what I do now, but it taught me the discipline of doing research and recording observations.

In 1969, I went on to teach undergraduate chemistry at Washington College, Chestertown, Md., which is where I pursued my undergraduate studies. Soon after that, I was approached by a fireworks company that wanted to hire me for a side project on developing chemical compositions for fireworks that are safe to carry and store. I became really interested in the chemistry of fireworks.

Later, the U.S. Army asked me if I was interested in working on some military pyrotechnic applications involving the production of brightly colored smoke for signaling purposes, and my pyrotechnic chemistry career shot off. Nowadays, I do training seminars for people interested in anything that explodes—from people who design and manufacture fireworks to people who dispose of bombs.

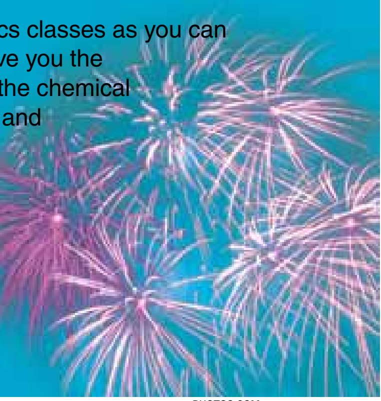
How do you make sure that fireworks are safe?

Mainly, you don't want compounds that explode as they fall on the ground. It's important to develop stable compounds that ignite only in the sky. Fireworks were invented hundreds of years ago, and we have learned through the centuries to avoid certain chemicals and mixtures that are too easy to ignite accidentally. There is also a big push now to make fireworks as environmentally friendly as possible.

Do you have any advice for students who want to become pyrotechnic chemists?

Take as many chemistry and physics classes as you can while in school. These classes will give you the background you need to understand the chemical reactions that take place in fireworks and other pyrotechnic devices. Also, don't experiment on your own with explosive materials! There are many easy ways to make explosives, but that does not mean they are safe.

—Christen Brownlee



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