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Energy in Photons Kit

Chemical Demonstration Kit

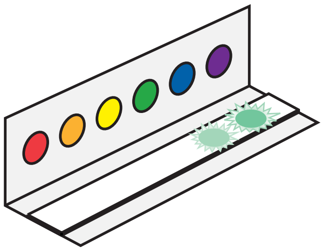
Introduction

Students often confuse the concepts of intensity of light and energy of light. This demonstration provides a clear way to demonstrate that the intensity, or brightness, of light is NOT the same as the amount of energy a particular color of light possesses.

Chemical Concepts

- Phosphorescence
- Transmittance
- Absorbance
- Emission

Materials



Energy in Photons Demonstrator Card—assembled and ready to use*

Light source—classroom lights work well

**Materials included in kit.*

Safety Precautions

Always follow standard laboratory safety rules when performing demonstrations.

Procedure

1. Open the Demonstrator Card and show the class the phosphorescent strip. Explain to them that the common term for phosphorescence is "glow-in-the-dark" and that this strip will glow in the dark.
2. Directly expose the entire phosphorescent strip to the classroom lights for about 15 seconds. Now turn off all the classroom lights and completely darken the room. The entire strip will glow brightly for several minutes and then begin to fade. Once students are satisfied with the glow, turn the classroom lights back on.
3. Show the six colored filters on the Demonstrator Card to the class. Hold the Demonstrator Card up to the light so that the color of light transmitted through each filter is clearly visible. Observe that the color of light transmitted through each filter is the same color as the filter.
4. Have the class predict what will happen if the Demonstrator Card is closed so that only "filtered" light is allowed to shine upon the phosphorescent strip.
5. Close the Demonstrator Card tightly making sure that no light can reach the phosphorescent strip from the sides. Paper clip the sides closed. Expose the closed Demonstrator Card to the classroom lights for at least 30 seconds.
6. Now turn off all the classroom lights and completely darken the room again. Open the Demonstrator Card and show the phosphorescent strip to the class. The strip will only glow under the blue and violet filters!
7. Compare the class' predictions with the actual results. Many students will be surprised that the "lighter" colors, like yellow and orange, did not let "enough light" through to cause the strip to glow. Explain that even though these colors may look brighter, or more intense, only the blue and violet filters let through light with enough energy to make the phosphorescent strip glow (see Discussion for a detailed explanation).

8. Have the class estimate the maximum wavelength needed to excite the phosphorescent strip (and cause it to glow) by using an approximate wavelength for each filter color or by reading the transmission curves for the filters. They should find the wavelength to be about 480 nanometers (nm) (see *Discussion* for a detailed explanation).
9. From the following equation, students can then calculate the minimum energy a photon must have to cause the strip to phosphoresce, or glow.

   $E = hc/\lambda$

   where E = energy in J

   h = Planck's constant = 6.626×10^{-34} J•sec

   c = speed of light = 2.998×10^{8} m/sec

   λ = wavelength in m

   According to the following calculation, they should find that the minimum photon energy is 4.1×10^{-19} J.

$$E = \frac{(6.626 \times 10^{-34}\ \text{J}\cdot\text{sec})(2.998 \times 10^{8}\ \text{m/sec})}{(480\ \text{nm})(1 \times 10^{-9}\ \text{m/nm})} = 4.1 \times 10^{-19}\ \text{J}$$

Tips

- The spots under the blue and violet filters should always glow brightly, but sometimes a small glow can be seen under some of the other filters. This is partly due to stray light creeping in around the filters. Try to keep the Demonstrator Card as tightly closed as possible to prevent any extra light from getting to the phosphorescent strip and causing a slight glow. The slight glow can also be explained by looking at the transmission curves of the filters. For example, the yellow filter clearly lets through light of wavelengths down to about 450 nm. The phosphorescent strip needs an exciting wavelength of about 480 nm or lower. Therefore, a tiny bit of light with enough energy is actually being transmitted through the yellow filter onto the phosphorescent strip.
- To store the Demonstrator Card, insert the solid black strip into the Card so that it is covering the phosphorescent strip. Close the Demonstrator Card and store it in the envelope. This will protect the phosphorescent strip from light and thus lengthen its useful life.

Extensions

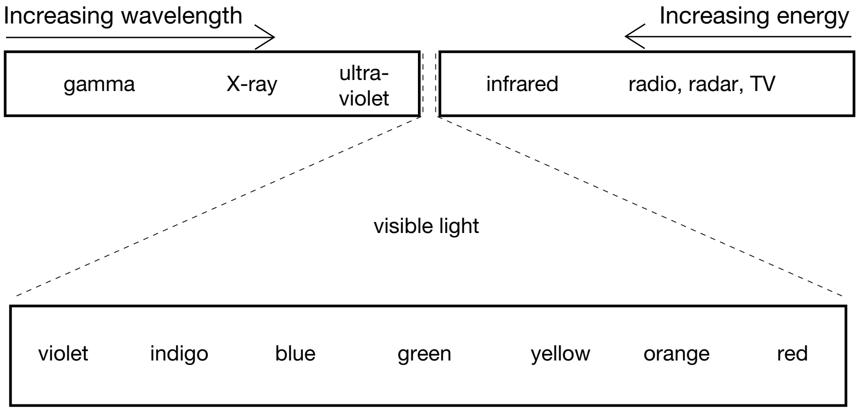
1. To reinforce the concept that it is the energy of the light that matters rather than the intensity, obtain two light sources of different intensity, such as a 40 W bulb and a 100 W bulb. Shine each lightbulb onto the closed Demonstration Card and show your students that in both cases only the violet and blue filters cause the strip to phosphoresce.
2. The maximum wavelength needed to cause the strip to glow can be verified in a spectrophotometer. Cut a narrow strip (so it will just fit in a cuvet) of the phosphorescent strip. First set 0% T with the sample compartment empty. Use an empty cuvet as the blank to set 100% T. Then place the piece of phosphorescent strip in the cuvet, not directly in the spectrophotometer, and measure the absorbance of the strip. Make sure the coated side of the strip is facing the direction from which light comes in the spectrophotometer. For wavelengths of 480 nm and lower, a small glowing spot can be seen on the phosphorescent strip. At higher wavelengths, no glowing is observed. This experiment is best performed in the dark so that the glowing spot is easily seen.
3. The wavelengths of light contained in classroom lights can be compared to those in a UV (black) light using the Demonstrator Card. Perform the demonstration as outlined above using the classroom lights. Then, turn off the lights and shine a black light onto the closed Demonstrator Card for about 30 seconds. When the black light is turned off and the Demonstrator Card is opened, more glowing circles can be observed. Looking at the transmission curves for the filters, explain to the class that many of the filters do not absorb wavelengths between 300 and 400 nm. Therefore, the filters are transmitting these high-energy wavelengths which are sufficient to excite the phosphorescent strip and make it glow.

Discussion

The Electromagnetic Spectrum

In 1865, J. C. Maxwell showed that visible light is a form of *electromagnetic radiation*. All forms of electromagnetic radiation consist of oscillating electric and magnetic fields traveling at a constant speed, the speed of light, 2.998×10^8 m/s. Other familiar forms of electromagnetic radiation include microwave radiation from a microwave oven, X-rays, the infrared radiation in heat from a fire, and radio waves. Together, all forms of electromagnetic radiation make up the electromagnetic spectrum.

Electromagnetic Spectrum



The visible portion of the electromagnetic spectrum is only a small part of the entire spectrum. It spans the wavelength region from about 400 to 700 nm. The human eye sees light of 400 nm as violet and 700 nm as red. Because wavelength is inversely proportional to energy according to the equation $E = hc/\lambda$, violet light is higher energy light than red light. The color of light seen with the human eye varies from red to violet (low to high energy) according to the familiar phrase ROY G BIV: red, orange, yellow, green, blue, indigo, violet. As the color of the light changes, so does the amount of energy it possesses. White light, like that from a fluorescent light, contains all of the colors in the visible spectrum.

Intensity versus Energy of Light: The Photoelectric Effect

Another characteristic of light, in addition to its energy, is its intensity. *Intensity* can be thought of as the brightness of the light. According to the theories of classical physics, energy is proportional to intensity, so that the more intense a light source, the more energy it gives off. Under this assumption, very bright (intense) yellow light should cause the phosphorescent strip in the Demonstrator Card to glow. However, this is not observed. Instead, the phosphorescent strip glows only when blue or violet light is shined on it. This phenomenon is analogous to the photoelectric effect, one of the classical paradoxes that led to the discovery of quantum mechanics.

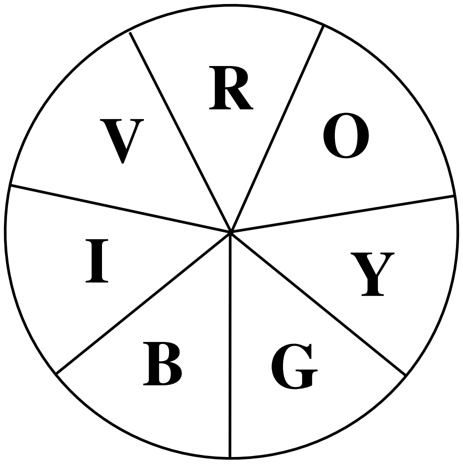
The *photoelectric effect* involves the ejection of electrons from a metal surface when light is shined on it; the energy of the electrons ejected depends upon the wavelength of the light, not the intensity. Einstein explained the photoelectric effect by suggesting that light consists of photons, each with energy $E = h\nu$. If a photon of light strikes a metal surface with more energy than the energy binding an electron to the surface, the photon will cause an electron to be ejected. The more intense a light source (greater number of photons), the greater the number of electrons ejected. If a photon striking the surface of a metal does not have more energy than the energy binding an electron to the surface, an electron cannot be ejected, no matter how many photons (with this amount of energy) strike the surface.

The glowing of the phosphorescent strip in the Demonstrator Card is due to the emission of photons, analogous to the ejection of electrons from the surface of a metal. The phosphorescent material has a critical wavelength (or energy) of light. If a light source is shined on the phosphorescent strip and it contains photons whose energy is greater than the energy needed to cause the strip to glow, it will glow. If the intensity of this source is increased, the glowing of the strip will increase. If, however, a light source is shined on the phosphorescent strip that contains photons whose energy is less than the critical energy for the phosphorescent strip, no glowing will occur, no matter how bright the light source.

Absorption and Transmission of Light

Why do the filters appear violet, blue, green, yellow, orange, and red? They are each composed of different molecules—molecules that absorb different wavelengths of light. For example, the red filter appears red to the human eye because it is transmitting red light. When white light is shined upon the red filter, the molecules in the filter absorb some of the wavelengths of the light and transmit others. All non-red wavelengths of light will be absorbed by the red filter to some extent, although green light will be absorbed the most. The green photons hit the filter and are absorbed by the molecules in the filter. They do not make it through the filter, and hence, a green color is not seen from this filter. In contrast, red photons are not absorbed by the molecules in the red filter, so they pass right through the filter, and a red color is observed.

How is it known that the red filter absorbs the green wavelengths of light? Red and green are *complementary colors*—they are across from each other on the color wheel.



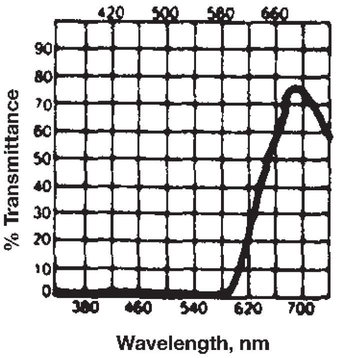
In general, colors opposite each other on the color wheel are complementary colors. For example, by looking at the wheel, the fact that violet and yellow are complementary colors can be seen. Therefore, in analogy to the red filter, it can be assumed that the violet filter absorbs yellow light and transmits violet light. The color wheel and the idea of complementary colors can be used as a first estimation of the wavelengths that are absorbed by a substance based on its color.

The following table lists the wavelengths associated with each of the colors in the visible spectrum and their complements. The representative wavelength can be used as a benchmark for each color. For example, instead of referring to green as light in the wavelength range 500–600 nm, one could simply say that green light is 520 nm.

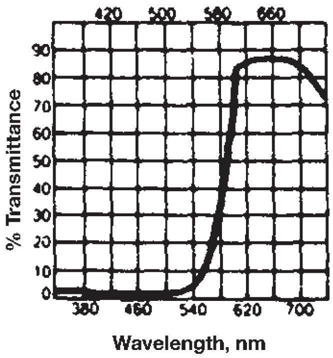
Representative Wavelength, nm	**Wavelength Region, nm**	**Color**	**Complementary Color**
410	400–425	Violet	Yellow-green
470	425–480	Blue	Orange
490	480–500	Blue-green	Red
520	500–560	Green	Red-Violet
565	560–580	Yellow-green	Violet
580	580–585	Yellow	Violet
600	585–650	Orange	Blue
650	650–700	Red	Blue-green

Transmission curves are available for each of the filters in the Demonstrator Card. These curves show which wavelengths of light are actually transmitted by each filter—the highest peak on each curve points to the wavelength that is transmitted the most.

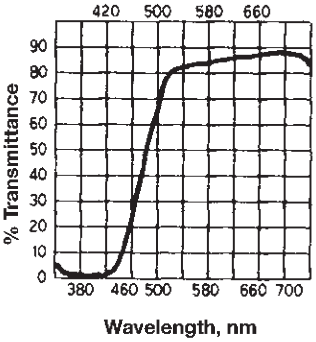
Red



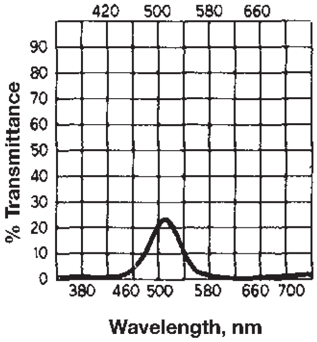
Orange



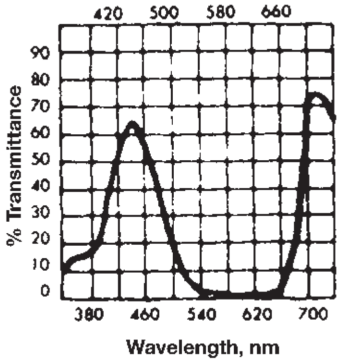
Yellow



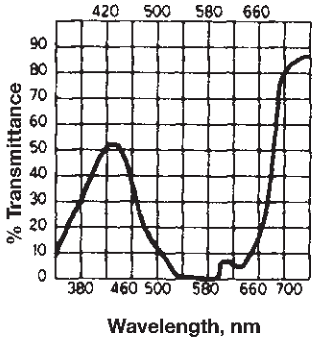
Green



Blue



Violet



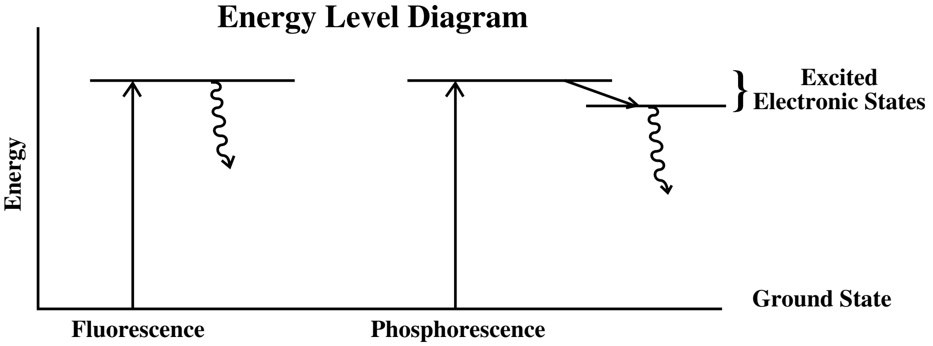
From these curves, the absorbed wavelengths of light can be inferred since absorbance is inversely proportional to transmittance according to the equation $A = -\log T$. Compare the estimation of the absorbed wavelengths for each filter from above with the actual absorption as shown in these transmittance curves. It is evident that these filters are not "pure" filters—they do not transmit a single wavelength, or even a single color in most cases. But, they do filter enough of the other wavelengths so that only a single color appears to be shining through the filter.

The cutoff wavelength for exciting the phosphorescent strip is about 480 nm. Photons with a higher wavelength (less energy) will not cause the strip to glow, while photons with lower wavelengths (more energy) will cause the phosphorescent glow. Looking at the table on page 4, 480 nm is right on the border between blue and green light. Therefore, blue or violet photons (which are not absorbed by the blue and violet filters, but are instead transmitted through these filters) will contain enough energy to excite the strip and cause it to glow. The green, yellow, orange, and red filters absorb the blue and violet photons instead of allowing them to be transmitted. Therefore, the light coming through these filters does not contain enough energy to excite the phosphorescent strip and, as a result, no glow is observed.

Phosphorescence

Luminescence is the emission of radiation (light) by a substance as a result of absorption of energy from photons, charged particles, or chemical change. It is a general term that includes fluorescence, phosphorescence, and chemiluminescence, to name just a few special types. *Phosphorescence* is different from the other types of luminescence in that light continues to be emitted even after the exciting source has been removed. This is sometimes referred to as the "afterglow." In this demonstration, the exciting source is the classroom lights. The strip in the Demonstrator Card glows even after the lights have been turned off (removal of the exciting source), so it can be classified as a phosphorescent material.

Why does a phosphorescent material continue to glow even after the exciting source has been removed? This can be explained by looking at an energy level diagram for the phosphorescent material. In both phosphorescence and fluorescence, a light source is shined on the material, and a photon is absorbed. The energy from the photon is transferred to an electron which makes a transition to an excited electronic state. From this excited electronic state, the electron naturally wants to relax back down to its ground state. When the electron relaxes back down, it does not necessarily jump down to the ground state in a single step. The relaxation pathway varies, and is different depending on whether the material is fluorescing or phosphorescing.



In fluorescence, the electron relaxes down to a lower energy state and emits a photon in the process. If this photon has a wavelength in the visible portion of the electromagnetic spectrum, we observe a colorful, glowing effect. This process is practically instantaneous so the fluorescence is observed as soon as the exciting source is present and disappears as soon as the exciting source is removed. An example of fluorescence is the way white shirts washed in Tide® glow under a black light.

In phosphorescence, the excited electron first makes a slow transition to another excited state very close in energy to the initial excited state. From this second excited state, the electron then relaxes down to a state lower in energy, emitting a photon in the process. The characteristic afterglow of phosphorescence is due to the delayed emission that occurs because the transition between the first two excited states is slow.

Connecting to the National Standards

This laboratory activity relates to the following National Science Education Standards (1996):

Unifying Concepts and Processes: Grades K–12
Evidence, models, and explanation
Content Standards: Grades 5–8
Content Standard B: Physical Science, properties and changes of properties in matter, transfer of energy.
Content Standards: Grades 9–12
Content Standard B: Physical Science, structure of atoms, structure and properties of matter, interactions of energy and matter

Answers to Worksheet Questions

1. Describe what happened in this demonstration.

   A phosphorescent strip was placed inside a card with six colored filters, violet, blue, green, yellow, orange, and red. The strip was exposed to the classroom light via these filters for about thirty seconds. The lights were then turned off and the strip was removed. Only the areas underneath the violet and blue filters glowed.

2. Explain why the phosphorescent strip only glowed in the blue and violet regions upon being covered with the entire demonstrator card?

   The reason that the blue and violet regions allowed the strip to glow and the other colors did not is because photons with a higher wavelength (less energy) will not cause the strip to glow. Photons with lower wavelengths (more energy) will cause the strip to glow. Blue and violet have a smaller wavelength of 430–480 nm which means they have more energy and enable the strip to glow.

3. What is the difference between intensity and energy of light, and how does it relate to this demonstration?

   The intensity of a light is its “brightness.” The more intense a light is, the more photons are transmitted. A light’s energy, on the other hand, is inversely proportional to a light’s wavelength. Therefore, violet light has a shorter wavelength but more energy than red light. The brighter colors here were yellow and orange, but the colors with the most energy were violet and blue. Thus violet and blue were the only colors with enough energy to cause the phosphorescent strip to glow.

4. In phosphorescence, a photon is absorbed by a substance when a light shines on it. The photon is transferred to an electron, which becomes "excited" and jumps to a higher energy level. It then slowly works its way down to its ground state, first moving to a slightly lower excited state. Another photon is released when the electron moves from the second excited state to its ground state. Explain how this process produces phosphorescence's characteristic "afterglow."

   Because the electron's move back to its ground state is delayed, the release of the photon is delayed. That photon is responsible for glow of the substance, so therefore the glow is delayed as well.

5. Phosphorescence requires an exciting source to occur. What was the exciting source in this demonstration?

   The light in the classroom was the exciting source.

Acknowledgments

Thanks to Rhonda Reist of Olathe High School, Olathe, KS for providing us with the idea for this "brilliant" demonstration.

Additional materials for the *Energy in Photons Kit* are available from Flinn Scientific, Inc.

Catalog No.	Description
AP4576	Energy in Photons Kit
P0272	Phosphorescent Flash Paint
AP4794	Phosphorescent Vinyl Sheet, 12″ × 12″

Consult your *Flinn Scientific Catalog/Reference Manual* for current prices.

Name: ____________________________________

Energy in Photons Demonstration Worksheet

Discussion Questions

1. Describe what happened in this demonstration.

2. Explain why the phosphorescent strip only glowed in the blue and violet regions upon being covered with the entire demonstrator card?

3. What is the difference between intensity and energy of light, and how does it relate to this demonstration?

4. In phosphorescence, a photon is absorbed by a substance when a light shines on it. The photon is transferred to an electron, which becomes "excited" and jumps to a higher energy level. It then slowly works its way down to its ground state, first moving to a slightly lower excited state. Another photon is released when the electron moves from the second excited state to its ground state. Explain how this process produces phosphorescence's characteristic "afterglow."

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