CNS Institute for Physics Teachers

Title:	**The Phantastic Photon**
Version:	February 1, 2006
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Appropriate Level:	Regents Physics
Abstract:	According to Einstein's theory, light is composed of particles called photons. The color of light determines the wavelength and energy of the photons. Students investigate these relationships by shining colored light from super-bright LEDs onto phosphorescent and fluorescent materials. They determine which LEDs activate glow-in-the dark tape, measure their wavelengths and calculate the photon energies. Students are then asked to apply their knowledge of photons to explain the behavior of fluorescent paints.
Time Required:	Two 40-minute periods
NY Standards Met:	4.1a All energy transfers are governed by the law of conservation of energy. 5.3c On the atomic level, energy is emitted or absorbed in discrete packets called photons. 5.3d The energy of a photon is proportional to its frequency.
Special Notes:	**The Phantastic Photon** is a kit available from the CIPT Equipment Lending Library, www.cns.cornell.edu/cipt/. It is also available commercially from West Hill Biological Resources, Inc., www.westhillbio.com.

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Objectives:

- Students will learn that light exists in discrete packets called photons.
- Students will understand how energy, frequency and wavelength of photons are related.
- Students will gain a working knowledge of phosphorescent and fluorescent materials.

Class Time Required:
Two 40-minute periods.

Teacher Preparation Time:
Prep time is 5-10 minutes. Set out materials needed.

Materials Needed:
The Phantastic Photon kits are available through the CIPT lending library and can be requested on-line at our website www.cns.cornell.edu/cipt after receiving training. Kits are also available for purchase from West Hill Biological Resources at www.westhillbio.com. In addition, each student group needs a meter stick.

Assumed Prior Knowledge of Students:

- Relationship between frequency and wavelength ($f = c/\lambda$)
- Conservation of energy

Background Information for Teacher:
Fluorescent and phosphorescent materials are all around us. These materials contain molecules that can absorb photons. The molecule gains the energy of the photon it absorbs, which puts the molecule in an excited state. At a later time, the molecule loses some of its energy by emitting a visible photon of lower energy. These emitted photons are what make glow-in-the-dark objects glow and fluorescent materials look very bright.

The primary difference between fluorescent and phosphorescent materials is that phosphorescent materials typically take much longer to emit photons from the excited state. For example, glow-in-the-dark objects will continue to give off photons for minutes or even hours after exposure to light. In contrast, fluorescent molecules emit photons very quickly, within nanoseconds of absorbing a photon.

The reason phosphorescent molecules take a long time to return to the ground state is that the excited electron has the wrong spin. Recall that the Pauli Exclusion Principle forbids two electrons of the same spin to occupy the same state. If the excited electron has the same spin as the other electron in the lower energy level, it must flip its spin before it is allowed to occupy that energy level. Since interactions in which an electron flips its spin are very rare, the electron in the higher energy level has to wait a long time to lose its energy and give off a photon.

Students may wonder why fluorescent and phosphorescent materials emit photons of lower energy than what they absorb instead of emitting a photon at the same energy. In other words, some energy is lost; how is it lost and where does it go? The answer is that it isn't really lost. It just shows up in a different form. The molecules have many ways to transfer energy to the environment that do not involve emitting visible photons. The excited molecule might transfer some energy to a photon and some energy to its neighbors through atomic collisions. Another possibility is that the molecule might emit an infrared photon (not visible) and lose a small amount of energy, leaving it in an intermediate state.

Answers to Questions:

A. Glow-in-the-right color

Note: the LED's are not monochromatic; the listed wavelengths are the peaks of the intensity spectrums provided by the manufacturer.

LED color	Tape glows? (YES or NO)	LED wavelength (nm)
blue	yes	472
red	no	660
green	yes (slightly)	525
orange	no	620
infrared	no	875
violet	yes	430
yellow	no	590
ultraviolet	yes	395

1. What do you notice about the wavelengths of the LEDs that make the tape glow? *The wavelengths that make the tape glow are all relatively short, approximately 530 nm and shorter.*

2. Light is a form of energy. Which wavelengths do you think contain the most energy? Explain. *The shorter wavelengths must contain more energy because they caused the tape to glow brighter.*

3. Notice that the tape always glows the same color no matter what color activates it. Write the color that it glows *green or yellow-green*

4. Estimate the wavelength of light emitted by the tape *~550 nm*

5. How does the *wavelength* of the light emitted by the tape compare to the *wavelengths* of light from LEDs that activated the tape? *The wavelength of the light emitted by the tape is longer than all of the wavelengths that activated the tape.*

6. How do you think the *energy* of the light emitted by the tape compares to the *energy* of light from LEDs that activated the tape? *The energy of the light emitted by the tape is less than the energy of the light that activated the tape.*

7. Why do you think some of the colors of light did not activate the tape? *Some of the wavelengths did not have enough energy to activate the tape.*

B. This is intense!

Distance	Blue LED	Yellow LED	Red LED	Ultraviolet LED
0.01 m	yes	no	no	yes
0.10 m	yes	no	no	yes
1.0 m	yes	no	no	yes

1. Does the intensity of the LED light make a difference in *how brightly* the tape glows? Describe your results. *Yes. For colors that activated the tape, the greater the intensity of the LED light, the brighter the tape glowed.*

2. Does the intensity of the LED light make a difference in *whether* the tape glows or not? Describe your results. *No. Even low intensity light of the right color can make the tape glow.*

3. Do you think the tape would glow if it received only a single particle of light from the ultraviolet LED? *Yes.*

C. Look at What Popped Out!

1. Predict the color of light that will be emitted from the yellow fluorescent paint for each LED. Write your predictions in the table below. Then test your predictions using the LEDs and the spectrometer to analyze the color from the paint. Record your results below.

LED color	Predicted color of light from yellow paint	Observed color of light from yellow paint
Red	--	red
Orange	orange	orange
Yellow	yellow	yellow
Green	yellow	yellow
Blue	yellow	yellow
Violet	yellow	yellow
Ultraviolet	--	yellow

2. Why does the ultraviolet light get converted to yellow light by the yellow fluorescent paint, but the red light remains red? *The ultraviolet light has enough energy to*

activate the fluorescent paint and make it emit yellow light. The red light does not have enough energy and simply gets reflected.

3. White light is composed of all colors of light. Explain why white light makes yellow fluorescent paint look so intensely yellow. *All wavelengths of light shorter than yellow get converted to yellow light. Therefore, the yellow fluorescent paint can emit more intense yellow light than originally present in the incident light.*

4. Predict the color of light that will be emitted from the *different* fluorescent paints for a *green* LED. Write your predictions in the table below. Then test your predictions using the *green* LED and the spectrometer to analyze the color from the paint. Record your results below.

Paint color	**Predicted color of light from paint**	**Observed color of light from paint**
Red	red	red
Orange	orange	orange
Yellow	yellow	yellow
Green	green	green
Blue	green	green

5. Explain your observations from question 4. *Each fluorescent paint emits light of its own color, provided the incident light has great enough energy to activate the paint. Green has enough energy to activate red, orange and yellow paints. It does not have enough energy to activate green or blue paint, so the green light is simply reflected.*

D. Post-lab Questions

1. Complete the chart below by calculating the energy of a single photon of light for each of the LEDs in your set. Remember that the frequency of light *f* is related to its wavelength λ through the formula $f = c/\lambda$ where *c* is 3.0×10^8 m/s.

LED color	**Wavelength (nm)**	**Wavelength (m)**	**Frequency (Hz)**	**Photon energy (J)**
infrared	875	8.8×10^{-7}	3.4×10^{14}	2.2×10^{-19}
red	660	6.6×10^{-7}	4.5×10^{14}	3.0×10^{-19}
orange	620	6.2×10^{-7}	4.8×10^{14}	3.2×10^{-19}
yellow	590	5.9×10^{-7}	5.1×10^{14}	3.4×10^{-19}
green	525	5.3×10^{-7}	5.7×10^{14}	3.8×10^{-19}
blue	472	4.7×10^{-7}	6.4×10^{14}	4.2×10^{-19}
violet	430	4.3×10^{-7}	7.0×10^{14}	4.6×10^{-19}
ultraviolet	395	4.0×10^{-7}	7.4×10^{14}	4.9×10^{-19}

2. As wavelength increases, what happens to the energy of a photon? *The energy of a photon decreases as wavelength increases.*

3. An the number of photons increases, what happens to the total energy of the light? *The total energy of the light increases with the number of photons.*

4. The red LED uses about 0.03W (1 W = 1 J/s) and converts most of this power into light. Estimate the number of photons per second produced by the red LED.

$$0.03\frac{\text{J}}{\text{s}}*\frac{1\,\text{photon}}{3.0\times10^{-19}\ \text{J}}=1\times10^{17}\ \frac{\text{photons}}{\text{s}}$$

5. Using the concept of photons, explain why red light, even if it is intense, cannot make the glow-in-the-dark tape glow (emit light). *Intense red light is composed of many red photons, each with energy* 3.0×10^{-19} *J. Photons can only get absorbed one at a time, and each red photon does not have enough energy to activate the tape, which requires* $\sim3.5\times10^{-19}$ *J, the color of yellow-green light.*

6. When the glow-in-the-dark tape absorbs blue photons, it emits lower energy yellow-green photons. If energy is always conserved, explain how the energy emitted can be less than the energy absorbed. *The extra energy is deposited in the glow-in-the-dark tape as heat, or increased kinetic energy of atoms and molecules.*

7. Using the concept of photons, explain why a yellow fluorescent highlighter appears much brighter than a regular yellow marker in normal lighting conditions.

8. In clubs, a black light (ultraviolet light) is sometimes used for special effect to make white clothing glow. Explain how this works.

9. Photoresist, a chemical used in making computer chips, changes its solubility when exposed to ultraviolet light. Why are cleanrooms where photoresist is used illuminated with yellow light? *The yellow light does not have as much energy as ultraviolet light and will not expose the photoresist unintentionally. Also the human eye is most sensitive to yellow light, so it allows workers to see well.*

10. A silicon photodiode used as a light detector can only absorb photons of energy greater than 1.1 eV. Will it absorb photons from the infrared LED? *Converting the threshold energy to Joules gives* $1.1\,\text{eV}*\frac{1.6\times10^{-19}\ \text{Joule}}{1\,\text{eV}}=1.8\times10^{-19}\ \text{J}$

    As calculated in question 1, the energy of a photon from the infrared LED is 2.2×10^{-19} *J, which is above the threshold. Therefore, the silicon photodiode will absorb the photon from the infrared LED.*

Tips for Teachers:

- One possibility to engage students and introduce this lab is to shine a black light on glow-in-the-dark objects and ask students what makes them glow. Another possibility is to shine the room lights and then a blacklight on a paper with fluorescent yellow ink and standard yellow ink from markers, and ask students to explain what they see.

- During this activity it is helpful to have the room lights off because the spectrum from the fluorescent lights can make it difficult to read the spectrometer. Instead, turn on the overhead projector, which has an incandescent bulb, and aim it at a nearby wall. It will provide enough light for student to read the lab.

- If the glow tape has received a lot of exposure to the ultraviolet light, shining a low energy LED such as the red LED may make the tape temporarily glow brighter, surprisingly appearing to activate the tape. In fact, the photons from the red LED are acting on molecules that are *already* in an excited state, helping them to lose energy more quickly and give off photons. If the red LED is held for a short time over the same part of the tape, that region quickly becomes dimmer than the rest of the tape as the excited molecules become depleted.

- In the second activity entitled "This is intense!" it is helpful to cover half of the glow-in-the-dark strip at the greater distances so that a comparison of exposed and unexposed parts is possible.

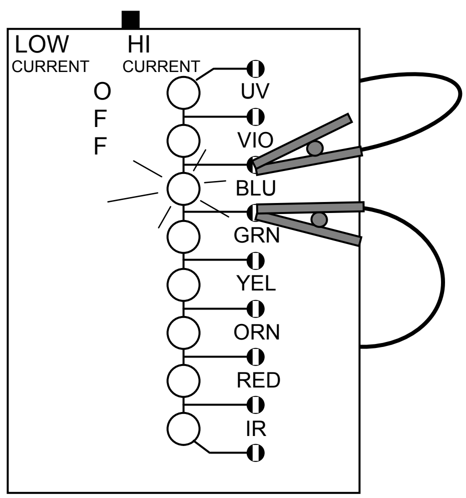
- Note that white paper contains a fluorescent substance that helps it to appear whiter. Therefore, when making your own fluorescent paint cards, it is best to use off-white card stock. Also, when measuring the wavelength of the LEDs, avoid shining the light on white paper or any other fluorescent material, which can lead to an inaccurate measurement.

THE PHANTASTIC PHOTON

Why does ink from a fluorescent highlighter appear so bright? What makes glow-in-the-dark objects glow? How do optical brighteners in laundry detergent make your clothes look whiter? The answer to these questions can be found in the photon theory of light, first proposed by Albert Einstein in 1905. By exposing fluorescent and glow-in-the-dark materials to different colors and intensities of light, you will see photons at work.

Light Emitting Diodes (LEDs)
You have a LED card that looks like the diagram below. There are eight LEDs of different color as labeled on the right side. "UV" stands for ultraviolet and "IR" stands for infrared. These LEDs emit most of their light at colors that your eye cannot see. The other six LEDs have different colors of the rainbow.

Try to light up the blue LED. Attach the red (positive) lead to the terminal at the top of the blue LED and the black (negative) lead to the terminal at the bottom of the blue LED. Switch the small black switch at the top of the card to the "HI CURRENT" setting. This makes a constant current of about 20 mA flow from the red lead to the black lead (and through anything to which the leads are attached).



Experiment with lighting up other LEDs. Can you light more than one at a time? Be sure to turn the switch to "OFF" when you are not using the LED card.

<u>Warning!! Do not stare into the ultraviolet (UV) LED when lit. This can cause eye damage.</u>

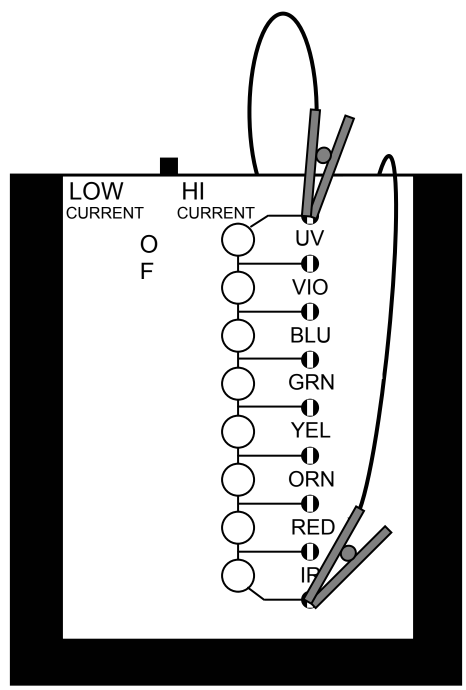
A. Glow-in-the-right color

A glow-in-the-dark object only glows after it is exposed to light. How does the color of light affect the glow-in-the-dark object? You can test this with the LEDs and piece of glow-in-the-dark tape enclosed in black paper.

- Hook up the blue LED and set the switch for "HI" current. Shine the blue LED on the tape for a few seconds. Move the LED away from the tape, and see if the tape is glowing.
- Record your results ("yes" it glows or "no" it does not) in the middle column of the table below. Try this for each LED color on the chart below. If the tape glows, wait at least 30 seconds until it stops glowing to test the next color LED.

LED color	Tape glows? (YES or NO)	LED wavelength (nm)
blue		
red		
green		
orange		
infrared		875 nm
violet		
yellow		
ultraviolet		395 nm

- Take the black plastic LED card holder out from the back of the spectrometer and insert the LED card into the slots so that the LEDs face out, the switch faces up and the leads come out the top. Attach the leads to light all the LEDs and put the current switch on "HI." Slide the LED card holder back into the spectrometer.
- Read the wavelength of the six visible LEDs by holding the spectrometer up and looking through the diffraction grating at the scale to the left and right of the LED strip. The scale tells the wavelength of the light in nanometers. Each LED produces a range of colors. Determine the brightest color produced by each LED and write its wavelength in the table. For some LEDs, it may help to get a more accurate reading by switching to the "LOW" current setting.



Answer the following questions:

1. What do you notice about the wavelengths of the LEDs that make the tape glow?

2. Light is a form of energy. Which wavelengths do you think contain the most energy? Explain.

3. Notice that the tape always glows the same color no matter what color activates it. Write the color that it glows ____________________.

4. Estimate the wavelength of light emitted by the tape ________________.

5. How does the *wavelength* of the light emitted by the tape compare to the *wavelengths* of light from LEDs that activated the tape?

6. How do you think the *energy* of the light emitted by the tape compares to the *energy* of light from LEDs that activated the tape?

7. Why do you think some of the colors of light did not activate the tape?

B. This is intense!

The light from an LED gets more intense as you move the LED closer. Is intensity an important factor in whether or not the glow-in-the-dark tape glows?

- With the lights dimmed, place a piece of paper so that it covers half of the tape, blocking it from exposure to the LED light.
- Expose the tape for a few seconds to one distance/color of LED combination at a time, as outlined in the table below.
- After each trial, remove the paper and examine the entire tape to see if the paper left a shadow. If so, then the exposed part of the tape is glowing; write "Yes" in the space provided. If there is no difference, the exposed tape is not glowing; write "No."

Distance	Blue LED	Yellow LED	Red LED	Ultraviolet LED
0.01 m				
0.10 m				
1.0 m				

Answer the following questions:

1. Does the intensity of the LED light make a difference in *how brightly* the tape glows? Describe your results.

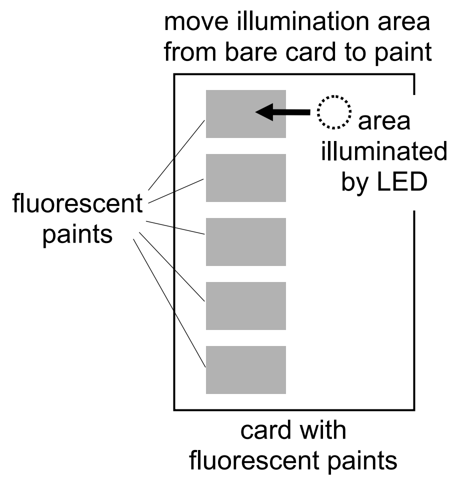
2. Does the intensity of the LED light make a difference in *whether* the tape glows or not? Describe your results.

3. Do you think the tape would glow if it received only a single particle of light from the ultraviolet LED?

C. Look at What Popped Out!

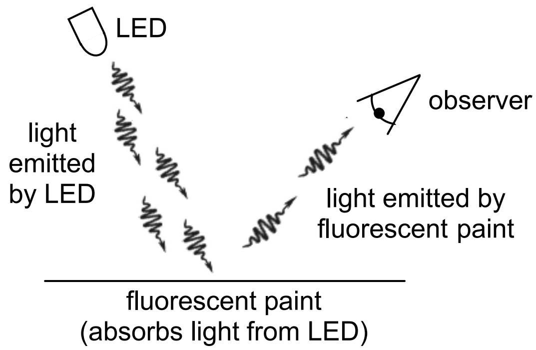
What makes fluorescent colors look so bright? Do fluorescent colors look bright in all kinds of light? You can test this with the LEDs and the manila card with different colors of fluorescent poster paint.

- Shine light from the UV LED on the fluorescent paints. Then shine light from the red LED on the fluorescent paints. Which light makes the paints "pop out" or look brighter?
- Let's take a closer look. Shine the light from the UV LED on the card where there are no paints. It should look violet. Now shine the light from the UV LED on the yellow fluorescent paint. The light should look yellow.



- Do the same thing with the red LED. Does the red light also change color on the yellow paint?
- Let's analyze this. Shine the light from the UV LED on the card where there are no paints. Take the spectrometer (without the LED holder) and aim it so that you can see pool of violet light on the card when you look through the diffraction grating and the slit. You should see the diffracted light fall on the scale to either side of the slit.
- Now shine the light from the UV LED on the yellow fluorescent paint. Aim the spectrometer at the yellow paint where the LED illuminates it. Did the wavelength of the light change?
- Try the same thing with the red LED, analyzing the light from the card and from the paint with the spectrometer. Does the wavelength shift as it did for the UV LED?

The diagram below shows that the light from the LED gets absorbed by the fluorescent paint. Then the paint emits light, some of which reaches your eye.



Answer the following questions:

1. Predict the color of light that will be emitted from the yellow fluorescent paint for each LED. Write your predictions in the table below. Then test your predictions using the LEDs and the spectrometer to analyze the color from the paint. Record your results below.

LED color	Predicted color of light from yellow paint	Observed color of light from yellow paint
Red	--	red
Orange		
Yellow		
Green		
Blue		
Violet		
Ultraviolet	--	yellow

2. Why does the ultraviolet light get converted to yellow light by the yellow fluorescent paint, but the red light remains red?

3. White light is composed of all colors of light. Explain why white light makes yellow fluorescent paint look so intensely yellow.

4. Predict the color of light that will be emitted from the *different* fluorescent paints for a *green* LED. Write your predictions in the table below. Then test your predictions using the *green* LED and the spectrometer to analyze the color from the paint. Record your results below.

Paint color	**Predicted color of light from paint**	**Observed color of light from paint**
Red		
Orange		
Yellow		
Green		
Blue		

5. Explain your observations from question 4.

D. Post-lab Questions

According to Einstein's theory, light is composed of tiny particles called "photons." A photon is the smallest possible amount of light. You can think of it as a really tiny packet of energy. The energy of a single photon is proportional to the frequency of the light. If E is the energy of a single photon and f is its frequency, then

$$E = hf$$

where h is a named Plank's constant and is equal to **6.6×10^{-34} J·s.**

1. Complete the chart below by calculating the energy of a single photon of light for each of the LEDs in your set. Remember that the frequency of light f is related to its wavelength λ through the formula $f = c/\lambda$ where c is 3.0×10^{8} m/s.

LED color	**Wavelength (nm)**	**Wavelength (m)**	**Frequency (Hz)**	**Photon energy (J)**
infrared				
red				
orange				
yellow				
green				
blue				
violet				
ultraviolet				

2. As wavelength increases, what happens to the energy of a photon?

3. An the number of photons increases, what happens to the total energy of the light?

4. The red LED uses about 0.03W (1 W = 1 J/s) and converts most of this power into light. Estimate the number of photons per second produced by the red LED.

5. Using the concept of photons, explain why red light, even if it is intense, cannot make the glow-in-the-dark tape glow (emit light).

6. When the glow-in-the-dark tape absorbs blue photons, it emits lower energy yellow-green photons. If energy is always conserved, explain how the energy emitted can be less than the energy absorbed.

7. Using the concept of photons, explain why a yellow fluorescent highlighter appears much brighter than a regular yellow marker in normal lighting conditions.

8. In clubs, a black light (ultraviolet light) is sometimes used for special effect to make white clothing glow. Explain how this works.

9. Photoresist, a chemical used in making computer chips, changes its solubility when exposed to ultraviolet light. Why are cleanrooms where photoresist is used illuminated with yellow light?

10. A silicon photodiode used as a light detector can only absorb photons of energy greater than 1.1 eV. Will it absorb photons from the infrared LED?