PhysicsQuest 2025: Photon Frenzy

| **Title:** Photon Frenzy  **Subtitle:** Exploring the Quantum Side of Light  Developed by - Reggie Wilcox - MIT; Austin Bartuek, Phong Dang, Joseph Henning, Valerie Milton - Louisiana State University | | |
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| **Total Time:** 15-20 minutes  **Audience:** Middle School Science Teachers  **Education Level:** Grades 5 - 10 | | |
| **Content Area:** Quantum Mechanics  **Educational topic:** Quantization of Light, Photoelectric Effect  **Objectives:** Understand that light is quantized, its energy depends on the color, and that color can affect how light interacts with matter.  **Key Question:**  What is a photon? How does the quantization of light affect the way light interacts with matter? | | |
| [**Next Generation Science Standards**](https://www.nextgenscience.org/sites/default/files/MSDCI.pdf)**:**  **MS-PS4-1.** Use mathematical representations to describe a simple model for waves that includes how the amplitude of a wave is related to the energy in a wave.  **MS-PS4-2.** Develop and use a model to describe that waves are reflected, absorbed, or transmitted through various materials.  [**QIS Key Concepts:**](https://q12education.org/wp-content/uploads/2023/12/MS-QIS-Key-Concepts-FINAL-12-7-2023.pdf)  **MS Science 8.2 Quantum Communication -** Students will identify that photons in certain regions of the electromagnetic spectrum are useful for both classical and quantum communication.  **MS Science 4.3 Quibits -** At the quantum level, light is made up of indivisible units called photons. | | |
| **Materials** | * LED Sensor Board * CR2032 Battery * LED * 2x Jumper Wires * 2 Flashlights (if your budget allows, buy more for each group) * 1 Blue filter (if your budget allows, buy more for each group) * 1 Yellow filter(if your budget allows, buy more for each group) * Binder clips | |
| **Overview:** Students will learn about quantization of light into photons and how light, color and energy are related. Students will apply different colors of light to the supplied sensor boards board. They will explore how the color of the light changes the way that light interacts with the LED sensor and therefore matter. Finally, students will interpret and develop an explanation for their experimental results. | | |
| **Teacher Background:**  Electromagnetic waves are waves which result from oscillations between electric and magnetic fields. These waves can propagate through a vacuum and travel at the speed of light. Radio waves, microwaves, x-rays, and light are all forms of electromagnetic waves. The type of wave depends on its wavelength, with visible light having wavelengths 400 - 700 nm. This is less than 1/100 of the width of an average human hair.  Quantum mechanics is used to describe systems which are very small. In this theory, physical systems are quantized, forcing them to exist in discrete states. This contrasts with classical physics where states are continuous. For example, quantities such as momentum and energy, which we think of as continuous variables, can only take on a set of discrete values in quantum mechanics. The quantized states in large, macro-scale systems are very close to each other, which makes them look like continuous systems. For smaller, quantum-scale systems, this discrete spacing becomes much more important resulting in important, observable effects. The quantized nature of light emitted from Cdots was explored in Activity 2 of this set.  Another consequence of quantum mechanics is that waves, which carry energy, are also quantized as discrete particles. For electromagnetic waves, these quantized particles are called photons. Like the classical wave description of light, photons also have a wavelength, which determines their color. Red light has a longer wavelength, while blue light has a shorter wavelength. Each photon carries a discrete set of energy, which is determined by its wavelength: shorter wavelengths have a higher energy. A fixed color light source’s brightness is adjusted by varying the number of photons emitted.  When photons hit matter, they can knock electrons loose and cause a current to flow. This effect is known as the photoelectric effect. (Fun Fact: Einstein received the Nobel Prize for theorizing the photoelectric effect). Because electron energies are quantized in matter, a photon must have enough energy to raise the electron to the next energy level, otherwise it does not interact with the electron. It was this observation, that lower energy photons were unable to create a current, that led to the discovery that light is quantized. The experiment that we are performing today is meant to mimic this discovery.  The sensor board will turn on an indicator LED when there is incident light detected on the sensor LED. When light is shone at the sensor LED, this causes a small current to flow, which is amplified by a pair of transistors, which then lights up the indicator LED. The current generated by the LED is due to the photoelectric effect, where an electron is knocked loose by the energy of a sufficiently high energy photon. The sensor LED used in this experiment was chosen so that it is only sensitive to photons with blue or higher energy.  This forms the basis of the experiment, where students will find that yellow photons cannot light up the LED, but blue ones can. The solution to this finding can only be reconciled with quantum mechanics.  **Advanced Background:**  Light emitting diodes (LEDs) are formed using specially designed crystal structures which force the electron energy levels to be quantized into two main bands: the conduction band and the valence band. There is an energy gap between these bands, known as a band gap. When electrons are forced to cross this gap (for example, using a battery), the electron drops in energy as it crosses the band, emitting the energy difference as a photon. Conversely, when a photon with sufficient energy (higher energy than the color light the LED emits) hits an LED, an electron will be forced up across this band gap in the opposite direction and a current will flow.  The first observation of the photoelectric effect was done by shining ultraviolet light on a metal surface, which physically ejected electrons from the surface. Thus, the energy of the ultraviolet photons was large enough to completely overcome the binding energy of the electrons to the metal and impart kinetic energy to eject them. In the experiment today, we have much lower energy photons which do not completely eject the electrons from the surface. Instead, there is just enough energy to move them across a bandgap into the conduction band, allowing a current to flow.  **Responses to common questions:**   * You cannot knock an electron loose by hitting it with multiple photons because they would need to hit the electron simultaneously, which is extremely unlikely to occur. * Students may be able to get the sensor to turn on with yellow light if they hold the light source very close to the sensor LED. This is because the yellow filters are not perfect and some blue light will still get through. * Light can behave as a wave or as a particle depending on the situation. However, it can only act like one at a single time. In the experiment today, we are observing the particle-like behavior of light.  **Teacher Tips:**  1. Suggested [STEP UP Everyday Actions](https://engage.aps.org/stepup/curriculum/everyday) to incorporate into activity    1. When pairing students, try to have male/female partners and invite female students to share their ideas first    2. As you put students into groups, consider having female or minority students take the leadership role.    3. Take note of female participation. If they seem to be taking direction and following along, elevate their voice by asking them a question about their experiment. 2. Consider using white boards so students have time to work through their ideas and brainstorms before saying them out loud. 3. As students experiment, roam around the room to listen in on discussion and notice experiment techniques. If needed, stop the class and call over to a certain group that has hit on an important concept. 4. Consider [culturally responsive tools and strategies](https://www.nciea.org/blog/a-culturally-responsive-classroom-assessment-framework/) and/or [open ended reflection questions](https://www.cde.state.co.us/standardsandinstruction/es-student-reflections-mc) to help push student thinking, have students track their thinking during the activity, connect to their lives, and create opportunities to develop STEM identity. 5. Allow the work of physicists to come alive by signing up for a virtual visit from a working physicist using [APS’s Physicist To-Go](https://www.aps.org/initiatives/physics-education/k-12/physicists-to-go) program. You can request a plasma scientist to talk about the concepts students learned in this activity! | | |
| **Key Terms (used or presented after the activities - see Foreward for details)**  **Electromagnetic wave -** a wave formed by oscillations between the electric and magnetic field  **Wavelength -** the distance between two adjacent peaks on a wave  **Quantization -** restricting the values to discrete values (eg. 0, 1, 2, 3, 4, etc.)  **Photon** - individual particles of light (quantized light)  **Energy level** - the values of energy which a particle is allowed to have | | |
| **Teacher’s Guide** | | |
| **Objectives**\***:**   * Students understand that light is quantized into particles called photons * Students understand that blue photons have more energy than yellow photons * Students understand that because light is quantized, some types of light have enough energy to knock an electron loose in the circuit and light up the bulb.   \*It is important to understand that student goals may be different and unique from the lesson goals. We recommend leaving room for students to set their own goals for each activity. | | |
| **Before the Experiment:** | | 1. We invite you to watch a [brief video demonstration](https://www.youtube.com/watch?v=c02x1VJYZX8&list=PLgxD9DiwxLGp_3vj3biSPG88gIyU6Vzpz&index=7) of the developer conducting the experiment you’ll be facilitating with your students. 2. Consider exploring XXX’s narrative using the lessons ideas detailed on the Introduction found in your materials kits. 3. Show the students the introduction [video](https://www.youtube.com/watch?v=-9MCT7eElEQ&list=PLgxD9DiwxLGp_3vj3biSPG88gIyU6Vzpz&index=3). The key points that they should take away is that:    1. Light is made of particles called photons    2. How the sensor board works |
| **Setting Up** | | 1. Hand each group the required materials    1. 1x Sensor Board    2. 1x CR2302 Battery    3. 1x LED    4. 2x Jumper Wires 2. Have the students assemble the sensor board (Note: Assembling the board incorrectly will not damage the board, but it will not work unless all components are put in the correct way) 3. Have the students check that their boards work 4. Help any students having trouble getting their boards working |
| **During the Experiment** | | **Preliminary Data**   1. Students will observe how the sensor board interacts with the LED flashlight. This is to get them familiar with the light turning on when they shine a flashlight on it.   **Make a hypothesis**   1. Based on their observations of the filtered light, they should make a hypothesis about what each color light should do when they shine it on the sensor board.   **Test Your Hypothesis**   1. Set up a flashlight station with the flashlights fixed using a ring stand or tape.    1. Attach a binder clip the yellow filter and blue filter so students can hold it up in front of flashlight    2. Have student groups take turns shining different colors of light on the sensor board.    3. Have students record their results.   Note: if your budget allows, feel free to buy more flashlights and filters so each group can have one.  **Answer Key**: They should observe that the blue filter has no effect on turning on the sensor board LED, while the yellow filter either turns off the LED completely, or reduces the brightness dramatically. |
| **Conclusion** | | 1. The students’ conclusions should detail whether their hypothesis was correct. It is perfectly fine if their hypotheses are wrong (the experiment was designed to be a little bit misleading). It is important that they understand that having a wrong hypothesis is okay. All great scientists have incorrect hypotheses. It is how they learn from being incorrect to discover new and exciting things that makes them great. 2. This part guides the students through thinking about quantization    1. Remind students of the dual nature of light as a wave and a particle. Ask students to describe when in this experiment light behaved as a wave and when it behaved as a particle. Have them use evidence from the activity to support their claims.    2. They should write that the blue photon knocks an electron loose, while the yellow photon does not.    3. This question is to get them thinking about kicking a ball softly and having it come back to them (ie. yellow light failing to knock electron loose because it is too low energy) and having it escape the valley (ie. blue light knocks an electron loose).    4. After thinking about a ball behaving in the same way as the electrons, the students should be able to guess that the energy of the photon is what determines if the LED lights up. 3. The students should be able to explain that because blue photons have more energy, they are able to knock electrons loose from the LED and cause the light to turn on, while yellow photons have less energy and cannot knock electrons loose from the LED. 4. Have students watch the conclusion [video](https://www.youtube.com/watch?v=tksriJGI-JE&list=PLgxD9DiwxLGp_3vj3biSPG88gIyU6Vzpz&index=4). Have them update any previous explanation if this video gives them any new ideas. |
| **Student’s Guide** | | |
| **Intro:**  Today, you’ll dive into an electrifying experiment, exploring the very phenomenon that helped Einstein unlock the secrets of the universe—and win a Nobel Prize! Light is made up of tiny particles called photons, but they are so small that we can’t see them with our eyes. Instead, we study how photons interact with different materials to understand how they work. In this experiment, you'll use the supplied sensor board to explore how the color of light changes the way it interacts with matter and come up with ideas to explain what you observe. | | |
| **Objective:**  Use the quantization of light to explain your experimental results.  After reading the introduction, what is your essential question or objective for this activity? | | |
| **Before the Experiment** | | 1. Watch the introduction [video](https://www.youtube.com/watch?v=-9MCT7eElEQ&list=PLgxD9DiwxLGp_3vj3biSPG88gIyU6Vzpz&index=3) to learn about how the sensor board works and how light is composed of particles. |
| **Setting Up** | | 1. Collect your materials from your teacher. This will include:    1. 1x Sensor Board    2. 1x CR2302 Battery    3. 1x LED    4. 2x Jumper Wires 2. Assemble the sensor board (Pay special attention to make sure you put the parts in the right way!)    1. Put the battery into the holder on the back of the sensor board (the positive (+) side should face away from the board)    2. Connect both wires to the connector on bottom right of the front of the board    3. Connect the LED leads into the wires (the longer LED lead should be inserted into the”LED +” wire, the shorter LED lead should be inserted into the “LED -” wire) 3. Shine the flashlight onto the sensor LED on the sensor board to check that everything works. The LED on the wires should light up! 4. If the LED does not light up, double check all components, correct the reversed components and try again. If it still doesn’t work, ask your teacher for help. |
| **During the Experiment** | | **Preliminary Data**   1. Shine the flashlight onto the sensor LED. Observe and record what happens with the indicator LED.   **Make a hypothesis**   1. What do you think will happen when you shine blue light on the sensor LED? What about yellow light? Write down your hypotheses.   **Test Your Hypothesis**   1. Take turns with other groups using the flashlight station. 2. Hold the binder clip and put the blue filter in front of the flashlight and look at the light. **Do not shine it at the sensor board yet**. Observe and record how the light changes. Note changes in color, brightness, etc. 3. Hold the binder clip and put the yellow filter in front of the flashlight. **Do not shine it at the sensor board yet**. Observe and record how the light changes. Note changes in color, brightness, etc. 4. Test your hypotheses by shining each color light on the sensor LED.    1. Record what happens with each color.    2. Pay attention to how this is different from the white light (no filter) and from each other. |
| **Conclusion** | | 1. Did your experiment prove or disprove your hypothesis? Either is okay, that is why we perform experiments. In fact, we sometimes learn more when our hypotheses are not correct because that means we have encountered something new! 2. Recall from the videos that light can be described as both a wave and a quantized particle.   a. In this exploration, describe a time when light behaved as a wave?  b. In this exploration, describe a time when light behaved as a particle?   1. We want to see if we can use the quantization of light to explain our experimental results. Remember: Quantization is when a system is forced to take on discrete (defined, definite) values, such as light behaving as particles called photons.    1. Based on your experiment, what happens when a blue photon hits an electron in the LED?    2. What about a yellow photon?   4. As an analogy, imagine the electron as a ball sitting in a valley and the photon hitting it as you giving it a kick. How would the strength of your kick affect what happens to the ball?   * 1. Based on this analogy, can you think of a property of the blue and yellow photons which might cause them to interact with electrons differently?  1. Watch the conclusion [video](https://www.youtube.com/watch?v=tksriJGI-JE&list=PLgxD9DiwxLGp_3vj3biSPG88gIyU6Vzpz&index=4). You may update your previous explanation if this video gives you any new ideas.   3. Was your personal essential question answered? If so, what is the answer? If not, what additional information would you need to answer it? |
| **Additional Resources:** | | |
| **Assessment/Extension activities\*\* (optional to extend thinking after the lesson):**   * Real world connections -   + Sign up for [Physicists To-Go](https://www.aps.org/programs/outreach/physiciststogo.cfm) to have a scientist talk to your students. * Suggestions for drawing, illustrating, presenting content in creative ways * Engineering and design challenges connected to the content   + if engineering challenges have a time constraint, students are allowed to keep iterating and developing their ideas outside of class time and continue to participate in the challenge at a later date   \*\*Real world situations/connections can be used as is, or changed to better fit a student’s own community and cultural context. | | |