**How to Make a Laser**

In this worksheet, anything written in black forms the student’s version of the worksheet. The words in blue show the expected answers from the students and the material in red is extra information and suggestions for the teacher.

**Assumed prior student knowledge:** Students should already know that light can be viewed as photons with an energy given by E = hf. They also should know about atomic energy levels, how atoms can emit photons and how atoms can absorb energy from electrons and photons. (This is can be explored using the PhET simulation Neon Lights and other Discharge Lamps.)

1. Light is emitted by a laser pointer and a flashlight. How do the photons differ? The laser photons
2. have more energy
3. are more focussed
4. are going in the same direction
5. all three are correct

Explain how can you demonstrate which answers are correct.

This first question has the students start with concrete objects and observations. They move to the abstract when they apply the photon model of light and try to demonstrate their ideas.

**The answer is not A. The standard laser pointer light is red (one colour, frequency, wavelength) whereas the flashlight has a continuous spectrum. The laser photons all have the same energy, E = hf = hc/. Therefore, the photons are not more energetic and in fact, most of the photons are less energetic than those of the flashlight. A common misconception is that laser light is more powerful or energetic. The wavelengths of the two light sources can be shown by looking at the spots through diffraction gratings.**

**The answer is not B. Students may be thinking of ‘concentration’ if they describe the light as more ‘focussed’. If the light is focussed, this suggests that it has a focal point and will become less focussed at greater distances. This doesn’t happen with the laser pointer. The laser light may or may not be more concentrated. Intensity can be measured with a light detector.**

**C) The most significant difference between the two light sources is that the laser beam does not spread (much). This means that the laser photons must all be going in one direction. This is easily seen by observing spot size at different distances.**

You might want to discuss and demonstrate two other properties which are not likely to be noticed by the students on their own. The laser photons are partially **polarized** and the flashlight is not. This can be shown by placing a polarizing filter in the beam and rotating it.

The laser photons are also **in-phase**. This can be demonstrated with the laser pointer by showing how a single pin in the beam can produce a two-source interference pattern. However, it will be harder to demonstrate clearly why the flashlight cannot do this. The lack of a pattern could also be ascribed to its wide beam which will put the interference fringes too close together to see.

The next part uses the PhET simulation as an interactive lecture. It is important that the students predict and explain before testing each idea. Reset the controls to the default setting and then set the lifetime slider to halfway and shift the colour of the lamp to blue so that the atom does not emit light at the start.

1. Open <https://phet.colorado.edu/en/simulation/lasers>. You are going to figure out how to make a laser. To start with, you want to get a single atom to emit light - any kind of light.
2. **Predict** what the settings on the lamp must be to get the atom to emit light and e**xplain** your reasoning behind these predictions.

This question has the students review what they already know about absorption and emission of photons.

* **The lamp must be turned on. Just turn it on slightly.**
* **The energy of the photons must exactly match the difference in energy between the two levels. This is very different from what happens when you excite atoms with electrons. Electrons must have the exact energy or more. Any excess energy is carried off by the electron, whereas a photon is completely absorbed by the atom. (Photons are also completely absorbed in the photoelectric effect.)**
* **As the intensity of the lamp is increased, there will be more photons absorbed and emitted.**

1. **Observe** what happens and **explain** anything that was different from your predictions or in addition to them.

**As the intensity increases, pairs of photons start to appear. These pairs all travel to the right rather than in random directions.**

Einstein predicted this – but we cannot expect the students to do so. Nor can we expect them to explain it.

3) Sometimes the photons appear in pairs going in the same direction as the original photon. This is the result of **stimulated** **emission** rather than **spontaneous** **emission**.

1. **Predict** and **explain** what will happen if you reduce the lifetime of the excited level.

**There will be less stimulated emission. There will be fewer pairs of photons and the emitted photons will go in all directions, not preferably to the right. Stimulated emission happens if a photon with the matching energy interacts with the atom that is already in the excited state. A reduced lifetime will reduce the chance of this occurring as will a reduced intensity in the lamp.**

1. **Observe** and **explain** any differences or additions to your predictions.

**Students may have mentioned only the lack of pairs of photons or the reduced directionality.**

Stimulated emission is a quantum process. Why it occurs is a bit subtle and will be examined at the end.

4) Select the Multiple Atoms (Lasing) tab at the top. You now have many atoms and each atom has two energy levels. What colours can the atom emit?

A) red and blue B) red, blue and purple C) red, blue and ultraviolet D) red, blue and infrared

This should be a review of what they already know about emission spectra.

**D) It can emit red when the electrons jump from 2 to 1 and blue when they jump from 3 to 1. They can also emit photons when they jump from 3 to 2. This is a smaller jump than the one that makes the red photons, so it must have less energy and is therefore an infrared photon and not ultraviolet.**

Students that choose purple are confusing how our eye perceives light (stimulating two different cones) with the properties of light itself. The default settings do not show the infrared photons. You can make them visible by selecting “display photons emitted from upper energy state”. Afterwards, turn them off because it just makes the image too confusing.

This next part has small groups of students discuss each of the questions below before being allowed to try their ideas on the simulation. To motivate the discussions you can announce that there will be a set of competitions using the simulation. The first contest is to get your laser to explode before everyone else’s laser. The second contest is to reach the maximum output power without exploding. Finally, which group can maintain the highest output power without exploding? If they understand the answers to these questions, they will have a much better chance of winning.

5) You are going to make a laser that emits a beam of red light.

a) You can adjust the lifetimes of the electronic energy levels. What should the setting on each be? Explain.

**The upper level should have a short time, so it will empty fast and fill up the lasing energy level. The lower level should have a long lifetime so the electrons stay here longer and will be more likely to be stimulated to emit. (This is like loading many guns or mousetraps.)**

b) You can adjust the controls on the lamp. What should the intensity and colour be set to? Explain.

**The lamp control should be turned to high. The colour should be left as is because the default sets the energy for the upper electronic energy level.**

c) You can add mirrors (enable mirrors) to the right and left sides of the laser. How will the mirrors help?

**Mirrors give the photons more opportunities to stimulate emission because they keep the photons in the tube. They also ensure that the stimulated emission is amplified in one direction – perpendicular to the mirrors.**

d) The reflectivity of the mirror on the right can be adjusted so that some, all, or none of the light gets through. What should it be set to? Explain.

**If the reflectivity is set at 100% you will get maximum lasing and eventually explode the laser. This is how you win the first contest.**

**If you set the reflectivity to 100% and then reduce it to 0% just before exploding, you will get the greatest output power and win the second contest.**

**If you set the reflectivity to some value in between, you can get a continuous laser and win the third contest. Note: The simulation has only a small number of atoms, so the power level fluctuates quite a bit and it is hard to maintain a high level.**

e) Why is light being sent into the tube at right angles to its length?

**This new lamp arrangement ensures that there is lots of light entering the laser perpendicular to the axis of the tube. This means that there will not be much stimulated emission in this direction. This allows for maximize lasing along the laser tube axis.**

6) Stimulated emission is a quantum process.

a) There is no classical version of stimulated emission, but it has similarities to resonance and to chain reactions. Watch **32 Metronomes Demonstration of Resonance** <https://www.youtube.com/watch?v=_bJ1gNnlsfE> and **Mousetrap Fission** <https://www.youtube.com/watch?v=vjqIJW_Qr3c> what aspects of stimulated emission do these demonstrations match?

The 32 metronomes show how matching frequencies can result in a very ordered system, but there is no amplification. The Mousetrap Fission, shows amplification of an initial energy input by having many systems ready to be triggered to release energy.

b) Watch **Minute Physics: How lasers work (in theory)** and explain how stimulated emission differs from spontaneous emission.

<https://www.youtube.com/watch?v=y3SBSbsdiYg&list=PLED25F943F8D6081C%20>

Photons are **bosons** and tend to be in the same state as opposed to **fermions** that cannot be in the same state. He uses the term ‘want’ to be in the same state – but photons have no feelings. However you word it, this description about fermions and bosons will not be an ‘explanation’ just a description of a fundamental law of nature. It just is. Students will probably have learnt about the Pauli Exclusion Principle in chemistry, where electrons cannot be in the same state as others and so, even at the lowest energies, there are only two in the lowest energy level.)

1. Watch Smarter Every Day 33: How lasers work (in practice) The previous video links this. <http://bit.ly/uBwhU2>

Minute Physics, Smarter Every Day and Veratasium <https://www.youtube.com/user/1veritasium> have hundreds of short videos about physics. They often go really fast and need support from slower activities to promote lasting learning. Students often go to look at more of them than are required.

These next two questions are meant to consolidate the ideas in this lesson and to connect the physics with applications. They will need to do some internet research.

7) The word laser comes from **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation.

1. What is the difference between light and radiation in a laser?

**There is no difference. The radiation refers to electromagnetic radiation which is light. The two different words were used to give it a cool name. The other possibilities – lasel and raser don’t work.**

1. An amplifier in a music system adds more energy to the signal making it louder. How is amplification different in a laser?

**In a laser, the amplification is a result of increasing the organization of the light (matching direction and phase) and not through increasing the energy going out.**

1. The simulation showed a laser whose input power is from light. Most continuous lasers get their power from electricity. How are fluorescent light bulbs similar to and different from lasers?

**A fluorescent bulb and a laser use electrical energy to excite atoms which releases the energy as light. A fluorescent bulb contains mercury gas which also has a line spectrum like a laser. However, it has several lines, not one. (The uv light is absorbed by the phosphor coating on the tube and converted to a continuous spectrum.) The photons emitted in a fluorescent bulb are produced by spontaneous emission – not stimulated emission - and so the light is emitted in random direction, phase and polarization. There is no need for mirrors.**

The difference in the two spectra can be seen with a good diffraction grating.

8) When lasers were first produced they were described as a solution looking for a problem. Describe one use for a low powered laser and one for a high powered laser. Explain how the laser light’s properties are an improvement over the tool that it has replaced.

**Low power: Lasers are used in music players, scanning product barcodes, laser pointers, laser sights, laser printers, levels and surveying, communication through optical fibres. They are used rather than other light sources because the light is so concentrated and directional. In music players, there is no needle wearing down the record. Optical fibres can carry more data than electrical wires.**

**High power: It is used in surgery because the spot is so small and the energy is so concentrated. The heat generated when it is absorbed cauterizes the wounds and prevents bleeding. In manufacturing it is used for precise cutting, welding, drilling and marking. There has been a lot of research into laser weapons but not much has resulted. Lots of scientific applications: inertial confinement fusion, optical tweezers, spectroscopy.**

The PhET website has other lessons using this simulation. The version by Perkins is a great source of many multiple-choice concept questions.