Physics 100: **Solutions** to Homework Assignment #11

Was Due on Friday, May 4th at the Beginning of Class

Section 1. **Warm-up! Fill-in-the-Blanks (1 pt each)**

1. If an electron is far from the nucleus of the atom it's in, it will have more energy than if it is close to the nucleus.
2. When an electron moves from being far from the nucleus of an atom to being close to it, it loses energy. This energy can into making a photon – a little 'packet' of light.
3. A photon is a particle of light.
4. A blue photon has more energy than a red photon. This is because the energy of a photon is dependent only on its wavelength/frequency. The shorter the wavelength, the higher the energy.
5. The energy of a photon is given by the equation: $E_\gamma = h\,f$. The h is known as *Planck's Constant* and has a value of $6.6 \times 10^{-34}\ Joules/Hz$
6. A photon with a frequency of $3 \times 10^{14}\ Hz$ has an energy of $1.98 \times 10^{-19}\ J$.
7. The acronym L.A.S.E.R. stands for Light Amplification by Stimulated Emission of Radiation.
8. The configuration of electrons around an atom which has the lowest energy for that particular atom is known as the ground state.
9. A configuration of electrons around an atom which has an energy higher than the minimum possible for that particular atom is known as an excited state.
10. A photon is created when an electron decays/de-excites – in other words when it goes from an excited state to either the ground state or a lower-energy excited state.
11. Every element has its own characteristic pattern of electron energy levels which means every element will emit light with its own characteristic pattern of frequencies, also known as its emission spectrum. The individual colors are known as spectral lines.
12. Something with a temperature of $120\ ^\circ C$ has a temperature, in Kelvin of $393.15\ K$. $0\ K$ is also known as absolute zero.
13. The peak frequency of something with a temperature of T (in Kelvin) is given by the equation $f_{max} = T \times 10^{11}\ Hz/Kelvin$, where T represents the temperature, expressed in the unit of Kelvin.
14. Atoms tend to absorb the same frequencies of electromagnetic radiation as they emit.
15. Electrons in atoms can be excited thermally, by absorbing kinetic energy from other electrons (and particles), or absorbing photons.
16. Phosphorescence is similar to fluorescence, but differs in the amount of time it takes for the electrons to de-excite, which is typically very long.
17. When an electron decays from an excited state and gives off a photon it can do so through *spontaneous* emission or stimulated emission. If the latter happens, there must be photons around with the same frequency as the photon to be emitted.
18. A beam of coherent light weakens and spreads very little because each of the photons making it up have the same wavelength/frequency, phase, and direction.

Section 2. **Short Answer Questions (2 pts. each)**

19. Explain why different atoms give off different frequencies of light and other forms of electromagnetic waves.

    Answer: Different atoms have different numbers of protons and electrons that give rise to unique places for the different electrons to exist (i.e. shells). Since the potential energy of an electron depends on how many protons are in the nucleus, how many electrons are between it and the nucleus, and the distance from the nucleus, this means that the electrons for each atom have unique energy levels. For photons emitted from atoms, their frequencies correspond to the spacing between these energy levels and are therefore unique as well.

20. Consider a photon with a wavelength of 540 nm[4]. **(A)** What color is this photon? **(B)** What is its energy? **(C)** If a pulse of a 540 nm laser beam had an energy of 5 mJ,[5] how many photons would it have?

    Answer: **(A)** You could either look up the color of light for a wavelength somewhere on the internet, or you could use your textbook: Figure 27.14, page 521. I'll use the latter. Figure 27.14 gives the color versus the frequency of light, so the first thing we need to do is convert wavelength to frequency using our favorite equation:

$$v = \lambda f \Rightarrow f = \frac{v}{\lambda}$$

Here $v = c = 3 \times 10^8\ m/s$, $\lambda = 540 \times 10^{-9}\ m$, and f is what we're looking for. Putting these numbers in:

$$f = \frac{3 \times 10^8\ m/s}{540 \times 10^{-9}\ m} = 5.55 \times 10^{14}\ Hz$$

According to Figure 27.14, this frequency corresponds to yellowish-green light. In my experience, this wavelength appears to be very green!

(B) The laser pulse is made up of a *lot* of photons. Each photon has an energy given by:

$$E_\gamma = h\, f$$

Where h is Planck's constant: $6.62 \times 10^{-34}\ J/Hz$. Using this, we find the energy of a 540 nm photon is a whopping

$$E_\gamma = \left(6.62 \times 10^{-34}\ J/Hz\right) \times \left(5.55 \times 10^{14}\ Hz\right) = 3.7 \times 10^{-19}\ J$$

This is a small number[6]!

Since the light pulse is made up of photons, the total energy in the light pulse is equal to the number of photons in the pulse multiplied by the energy of a single photon:

$$E_{pulse} = (Number\ of\ photons) \times E_{1\ photon} \Rightarrow Number\ of\ photons = \frac{E_{pulse}}{E_{1\ photon}}$$

$$Number\ of\ photons = \frac{5 \times 10^{-3}\ J}{3.7 \times 10^{-19}\ J} = 1.36 \times 10^{14}$$

21. Rank the following in order of decreasing energy: **(A)** An infrared photon, **(B)** A yellow visible light photon, **(C)** A radio photon , **(D)** A UV photon, **(E)** A gamma ray photon, **(F)** A microwave photon, **(G)** A violet visible light photon.

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[4]Remember: *nm* is shorthand for *nanometer*. A *nanometer* is one-billionth of a meter, or 0.000000001 $m = 10^{-9}\ m$.

[5]Remember: *mJ* is shorthand for *milli-Joule*. A *milli-Joule* is one-thousandth of a Joule, or 0.001 $J = 10^{-3}\ J$.

[6]In fact, because it's so small we often use a different unit of energy known as the *electron volt*, which is abbreviated as eV. How it relates to Joules: $1\ eV = 1.602 \times 10^{-19}\ J$. For problems involving the energy of photons, and electrons in atoms, etc. the eV is the natural unit to use. In this case, the energy of a 540 nm photon would be equal to 2.3 eV, a much nicer number to work with!

Answer: The higher the energy of a photon, the higher its frequency and the lower its wavelength[7]. Refer to Figure 26.3 on page 498 of your textbook to rand the photons according to wavelengths. The correct ranking, from highest energy to lowest energy, is:

1. **(E)** A gamma ray photon
2. **(D)** A UV photon
3. **(G)** A violet visible light photon
4. **(B)** A yellow visible light photon
5. **(A)** An infrared photon
6. **(F)** A microwave photon
7. **(C)** A radio photon

22. Match the following types of light production with the best description of how they're done.

(A) Gas Lamp (e.g. Neon Lamp)

(B) Incandescent Lamp

(C) Fluorescent Lamp

(D) Flame

(E) Laser

(1) The light is produced by heating a filament to a very high temperature– usually by passing electricity through it so that electrons bump in to the atoms and heat them. The light produced is different from other types because it contains an infinite number of frequencies due to the atoms being in a solid phase (i.e. not a gas). Generally speaking, the hotter the filament, the bluer the color of the light produced. It is also known as either *thermal radiation* or *black body radiation*.

(2) Various atoms with different characteristic spectra are excited by thermal energy produced by a chemical reaction. When they decay, they generate different frequencies of light that, when taken all together, produce light with many colors.

(3) Coherent light is produced by rigging up a *resonator* which encourages stimulated emission of photons from excited atoms. In this situation, stimulated emission produces a photon with the same phase, direction, and wavelength as the photon that stimulated it.

(4) Inside the bulb, ultraviolet light is created which is absorbed by a coating painted on the glass. The atoms in the coating get excited by the ultraviolet light, but some of the energy of the UV photons is either converted into heat before the excited electrons decay by giving off light or the electrons decay in steps, giving off multiple photons of different frequencies. In this way, the UV light is converted into visible light.

(5) The light emitted is from individual atoms or molecules. The energy comes from electrons 'boiled' off of electrodes which hit the atoms/molecules and cause their electrons to become 'excited' and their return to the 'ground state' is what gives off light. The Northern Lights is another example of this kind of light.

Answer:

(A) $\Leftrightarrow$ **(5)**

(B) $\Leftrightarrow$ **(1)**

(C) $\Leftrightarrow$ **(4)**

(D) $\Leftrightarrow$ **(2)**

(E) $\Leftrightarrow$ **(3)**

[7] $f = c\frac{c}{\lambda}$ $\Rightarrow$ the bigger f is, small λ is since c is a constant (the speed of light).

23. Explain why incandescent light produced by a tungsten filament may have an infinite number of frequencies, but light produced by a tungsten gas only has a few.

    Answer: One main difference is that in a filament, the tungsten atoms are packed closely together, so their electrons interfere with each other. This acts to broaden out their energy lines into large bands so that the number of allowed energy levels increases a lot– so much so, that for all practical purposes almost any energy level transition, and hence generated photon energy, is allowed. This means that a "black" solid can emit and absorb light of any wavelength so its emission spectrum is continuous. For a gas, the different atoms are not packed together so their electrons don't interact too much– the natural energy level spacing of the atom is preserved and so is its emission spectrum.

24. Estimate the peak color corresponding to a star with a temperature of 6,000 K.

    Answer: If we find f_{max}, then we can find λ_{max} using our favorite wave equation, $\lambda = \frac{v}{f}$. We find f_{max} using the relation $f_{max} = T \times 10^{11}\ Hz/Kelvin$:

$$f_{max} = T \times 10^{11}\ Hz/Kelvin = (6,000\ K) \times 10^{11}\ Hz/K = 6 \times 10^{14}\ Hz$$

    Solving our favorite wave equation: $\lambda_{max} = fraccf_{max} = frac3 \times 10^{8}\ m/s6 \times 10^{14}\ Hz = 0.5 \times 10^{-6}\ m = 500\ nm$ 500 nm corresponds to the color green.

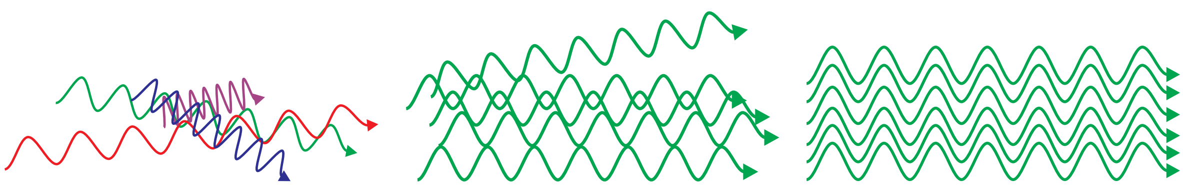
25. Give an example of **(A)** *coherence* and **(B)** *incoherence* that you may experience in everyday life.

    Answer:

    (A) An example of *coherence* could be a marching band: they're all stepping together (same frequency and in phase) and traveling in the same direction.
    (A) An example of *incoherence* may be a herd of cats: they're running all over the place in different directions and frequencies of steps.

26. Draw a representative diagram of each of the following: **(A)** incoherent, multi-chromatic light, **(B)** incoherent, mono-chromatic light, **(C)** coherent light.

    Answer:



(a) Incoherent, multi-chromatic light (b) Incoherent, mono-chromatic light (c) Coherent light

Figure 1: Solutions to Problem 26

27. List five ways in which lasers are commonly used.

    Answer: Answers can vary a lot, because there's a lot uses for lasers. Here are five:

(1) CD/DVD/HDDVD/Blueray players: the laser is focused onto the disk and the reflections off of little pits and such are what encode the data. The monochromatic nature of the light allows for superior detection of the pits (much like the optical mouse *vs* the laser mouse) and allows for a tighter focus point– higher packing of the data.

(2) Survey Equipment and Speeding Traps: lasers can be used to accurately determine how far away something is. A short pulse of laser light can be made. The time it takes the laser light to travel out and bounce back tells you how far away something is. This is how the distance from the Earth to the Moon was determined (Apollo astronauts put reflective mirrors on the moon!). Police LIDAR (**Li**ght **D**etection **A**nd **R**anging) uses the same principle, but determines your speed may making repeated measurements of your distance and figuring out how quickly that's changing, In both cases, the tight, focused beam of the laser allows this to happen– imagine trying to use a light bulb and see its reflection from the Moon! By the time the light got to the Moon, it would be so spread out that you'd never detect it.

(3) Medical applications: lasers are used in surgery to accurately cut and remove tissue. Since laser light can be channeled into optical fiber, a very small, non-invasive scalpel can be made. Lasers can also be used to correct vision[a]. On a more cosmetic level, lasers are also used to remove body hair[b] and tatoos[c].

(4) Cutting Materials: a lot of materials these days are cut using lasers[d]. Because the light is coherent, it can pack a lot of energy into a small space– meaning that quickly and accurately cutting anything from steel to styrofoam is possible.

(5) Microscopy: there are a lot of fancy microscopes out there that use lasers, such as the laser Confocal Microscope[e]. They all rely on the laser's coherent output in some way or another: in laser confocal microscope, this allows the beam to be very tightly focused.

[a] http://health.howstuffworks.com/lasik4.htm
[b] http://en.wikipedia.org/wiki/Laser_hair_removal
[c] http://people.howstuffworks.com/tattoo-removal4.htm
[d] http://en.wikipedia.org/wiki/Laser_cutting
[e] http://en.wikipedia.org/wiki/Confocal_laser_scanning_microscopy

28. Shown below in Figure 2 is the thermal emission spectrum of a star at rest with respect to the Earth[8]. **(A)** If the peak in the emission spectrum is at 400 nm, what is its surface temperature? **(B)** Explain what the sharp dips in the spectrum are.

[8] Or at least the Doppler Effect has already been taken into account! Unlike Problem 29 :)

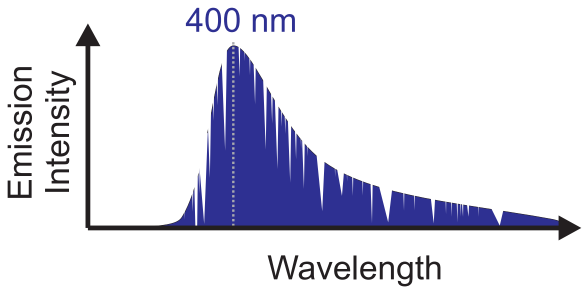


Figure 2: The emission spectrum of a star's surface peaks at 400 nm. How hot is it and what are those sharp dips? See Problem 28

Answer:

(B) This part is just like Problem 24, only we're looking for the temperature instead of the emission wavelength:

$$T = \frac{f_{max}}{\times 10^{11}\ Hz/Kelvin}$$

We find f_{max} using our favorite wave equation:

$$f_{max} = \frac{c}{\lambda_m ax} = \frac{3 \times 10^8\ m/s}{400 \times 10^9\ m} = 7.5 \times 10^1 4\ Hz$$

Putting that into the original equation:

$$T = \frac{7.5 \times 10^1 4\ Hz}{\times 10^{11}\ Hz/Kelvin} = 7,500\ Kelvin$$

(B) These sharp dips are Fraunhofer Lines, due to different gasses between the star and the Earth. The gasses absorb the colors corresponding to their spectral lines so they don't make it to the Earth. These are discussed in the textbook in Chapter 30, page 589.

29. Shown below in Figure 3 are the emission spectra of helium sitting still in a laboratory and three stars, as measured by astronomers. **(A)** Which star(s) are moving away from the Earth? **(B)** Which star(s) are moving toward the Earth? **(C)** Which star has the highest speed, relative to the Earth?

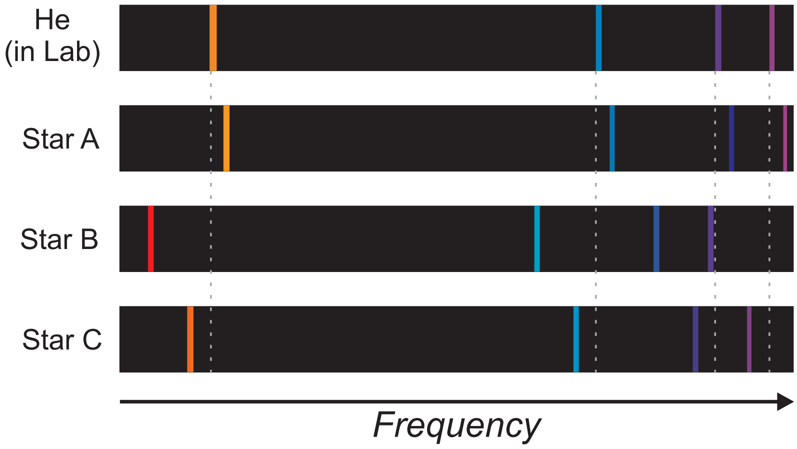


Figure 3: The emission spectrum helium sitting at rest in the lab and three different stars, as observed by astronomers. See Problem 29

Answer: All of these questions revolve around the concept of the Doppler Shift. Remember: if a source of waves is moving towards you, you will see the waves having a higher frequency than if the source was at rest with respect to you. The converse is true for the source moving away from you (i.e. you will see the waves as having a lower frequency). Stars have a lot of He around them, so it's common to see the spectrum of He. Shifts in this spectrum tell us how the stars are moving with respect to the Earth.

(A) The stars that are moving away from the Earth will give off light with lower frequency than He at rest in the lab. This is the case for Star B and Star A.

(B) The stars that are moving towards the Earth give off light that is shifted to a higher frequency. In this case, only Star A is moving towards the Earth.

(C) The Doppler Effect is greater if the relative speed between the source and observer is greater. The greatest Doppler Shift is occurring for Star B, so we expect that one to be moving away the fastest.