Science-1A Lecture: Week-7, Friday, September 24, 2021

We are now headed into some really amazing conclusions of modern physics.

Let's first watch the next Crash Course video:
Special Relativity (CC 42) 8 min 58 s
https://www.youtube.com/watch?v=AInCqm5nCzw&list=PL8dPuuaLjXtN0ge7yDk_UA0ldZJdhwkoV

This is a truly outstanding presentation
except the formula shown at 4:38 is wrong (or misleading) as explained in the comments to the video by Daniel Felsen.
Remember the postulates of Einstein:

1. **The laws of physics are the same in all inertial (not accelerating) reference frames.**
2. **The speed of light in a vacuum is the same for all observers.**

Notice the key parameter $\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$ was calculated in the Calculations Test. Einstein showed that massive objects have $v < c$, so γ is always greater than 1.

Time depends on an observer's speed (Time Dilation):
Bob's clocks on the train are seen by the lady at the platform (call her Ruth) to tick more slowly, so Ruth sees Bob's time slowed down when watching him pass by. As seen by Ruth, Bob's time is stretched out according to the equation: $t_{\text{Ruth}} = \gamma t_{\text{Bob}}$. This is not just for Bob's clock. His heart rate, brain activity, and metabolism are all slowed down as observed by Ruth.

Simultaneity depends on an observer's speed:
As she explains, whether two events happen at the same time (are simultaneous) depends on the speed of the observer. We must be careful to not accidentally assume that everyone sees things happening at the same time!

Length depends on an observer's speed (Length Contraction):
The length of Bob's train is shorter as measured by Ruth according to the equation $l_{\text{Ruth}} = \frac{l_{\text{Bob}}}{\gamma}$.

Bob's train was moving at half the speed of light, so $v/c = 0.5$ and $\gamma = \frac{1}{\sqrt{1-0.5^2}} = 1.1547$.

As Bob's clock records 33.3 ns ticks (10 m divided by c), Ruth measures them at 38.5 ns. From Ruth's point of view, Bob's time is stretched out (dilated).

Bob measures his train length as 100 m, but Ruth measures a shorter (contracted) length for Bob's train as 100 m/1.155 = 86.6 m

The examples and wording used in this video were chosen very carefully. It is terribly easy to make errors when working with relativity; you can easily get tangled up in its logic. For example, it is easy to mix up which reference frame is which or to inappropriately assume simultaneity of two events.

This video is so well done. I urge you to watch it a second time.

In 1971, a set of three extremely accurate atomic clocks were flown around the world, and their times compared with another set that remained on the Earth. The traveling clocks ran slower by exactly the amount predicted using the equations of Einstein's Special and General Theories of Relativity.

Every time the GPS navigation system is used, formulas from both Special and General Relativity (that allows accelerated frames of reference) are utilized. Without them, the GPS locations would be much less accurate.

A big lesson from this video is that Einstein selected some postulates that seemed solid based upon his very strong knowledge of the physics of his time. He then followed through with mathematical logic to see where those postulates took him, no matter how weird the result. As long as his conclusions did not contradict known experimental evidence, he considered them to be valid predictions to be tested by future experiments. That is a beautiful example of how science advances.

When Einstein considered energy and momentum, he decided that they were also dependent on the speed of the observer. He then developed an improved definition of energy that included momentum. That new definition led him to conclude that energy and mass could be inter-converted according to the now famous equation $E=mc^2$.

He also showed that his postulates caused electric and magnetic effects to also depend on an observer's speed, but that their combined effect on the observed behavior of charged particles was unchanged.

Einstein published two other important papers in 1905, one relating the motion of small particles kicked around by much smaller water molecules (Brownian Motion), and another that resolved the puzzling behavior of light when it kicked out electrons from metal (Photoelectric Effect).

Einstein's contemporaries were impressed with his work and felt he deserved a Nobel prize, but were nervous about endorsing his Special Theory of Relativity, so he was given the Nobel prize for his theory of the Photoelectric effect.

It took Einstein another 10 years to produce his General Theory of Relativity that can make predictions for observers in non-inertial (accelerating) reference frames. To do so, he had to master some extremely advanced mathematical techniques dealing with curved space. In the end, he showed how mass distorts the shape of space-time and can produce gravitational waves and black holes, both of which have been confirmed in the past decade.

Here is a video that nicely explains another very weird, but true, consequence of relativity:
Special Relativity and the Twin Paradox
https://www.youtube.com/watch?v=ERgwVm9qWKA

> The first half tells us much of what we saw in the previous video, but the second half is new, amazing, true, and important.

Here is some additional historical background about light. I am becoming convinced that the best introduction to science is using stories of its history.

What is light? This question puzzled scientists for hundreds of years. It acts like a particle since it seems to always go in straight lines and can bounce off mirrors. It carries energy and can warm up things that absorb it. But about 350 years ago, scientists noticed that light could sometimes act like a wave when passed through small holes or slits as was described in Wednesday's Lab. It could interfere with itself like sound and water waves that can add or subtract when passing through each other. So scientists asked is light a wave or a particle? The answer is that it is both at once, but that answer required another 200 years of scientific investigation.

Water waves need water, sound waves need air, but what carried light waves? It was known that light waves could travel through the void of intergalactic space, but there was such a strong conviction that some mystery resilient medium must carry light that a word was invented for the stuff that light wiggled through. It was called the aether. Light waves were thought to wiggle in this aether the way sound waves wiggle in air or water waves wiggle in water.

Maxwell's Equations provided a theoretical basis for electric and magnetic fields pulling each other through the vacuum of space without the need for any aether, but the idea of an aether remained prevalent in physics discussions.

A famous experiment called the Michelson-Morley Experiment was performed in 1887 to attempt to observe the effect of the aether on speed-of-light measurements as the Earth circled the sun. The idea was that light would move slightly faster or slower depending on the direction a sensitive speed-of-light experiment moves through the aether. Since the Earth moves around the sun, half of the year the Earth would be moving one way through the aether and the other half it would be moving in the opposite direction. Measuring a difference would support the existence of the aether. The experiment was a very difficult experiment, but when it had been completed, no aether was detected. Light traveled at the same speed no matter what direction the experiment was traveling as it encircled the Sun.

This next video tells more about light and initiates our discussion of quantum mechanics.
Quantum Mechanics - Part 1 (CC 43) 8 min 45 s
https://www.youtube.com/watch?v=7kb1VT0J3DE&list=PL8dPuuaLjXtN0ge7yDk_UA0ldZJdhwkoV

This is another outstanding presentation of a difficult subject.

Black-body radiation, the T^4 law, Planck's Equation, and the Photoelectric Effect are all important.

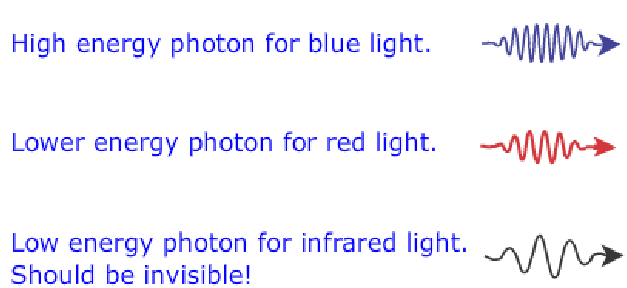
My summary of the photoelectric effect is at
https://yosemitefoothills.com/Science-1A/Handouts/Week-07/NatureOfLight-PhotoelectricEffect.pdf .

Light as chunks of waves called photons
When Planck developed his equation for black-body radiation mentioned in this video, he invented an idea that light came in chunks with energies that were proportional to frequency. That led him to an equation that explained away the ultra-violet catastrophe, but he really did not think that the light chunk idea was true. He considered it just a weird helpful mathematical idea.

Einstein, however, took that idea seriously and called those chunks "light quanta", now called photons. He then used them to explain the Photoelectric Effect.

An illustration of the electric field of photons of different energies is at the right. The higher the photon energy, the higher is the frequency of its wiggles.

In contrast to a pure tone that has the same amplitude for a long time and a very precise frequency, a photon is a pulse of light with a spread of frequencies.



Photon energies are proportional to the center frequency of the pulse ($E=hf$ with $h=6.63\times10^{-34}\,\mathrm{J/Hz}$), and their polarization is in the direction of their electric field.

I have made an animation of a traveling wave like a photon. It was created by adding together many closely spaced waves centered around a central frequency to produce a pulse like that shown in the illustration above. That animation showing how a pulse of light travels is at *https://yosemitefoothills.com/Science-1A/Handouts/Week-07/Photon.gif* .

These images make it clear how a photon is a chunk of a wave with wave and particle properties. Its wave properties are from its internal structure and its particle properties are from its packaged nature and energy content.

Radio waves have extremely weak photons. How can they be detected by a radio receiver?
We are unable to detect individual radio frequency photons. At frequencies 10^5 times lower than light, the formula $E=hf$ tells us that their photons are 10^5 times weaker than light photons. The answer is that a radio transmission antenna launches about 10^{28} photons per second that are all coherent. They are all working in unison to move electrons in the antennas of distant radio receivers.

Lasers are special for the same reason. Their photons are coherent at light frequencies. I'll need to explain how lasers work in a future lecture.

Photons as quantum probability waves
This discussion will strain your credibility just as did relativity theory, but just like relativity, the predictions from the theory of quantum mechanics have been overwhelmingly confirmed by a vast variety of careful experiments.

After watching the interference experiments and hearing about photons, one can ask the question "What happens in an interference experiment when the laser is so dim that it emits only one photon at a time?" How can a single photon interfere with itself?

The answer comes from the strange theory called **quantum mechanics** where photons, electrons, nuclei, and atoms are all described as being probability waves that only take effect when "detected". When photon probability waves are detected, electric and magnetic field effects are felt and energy is transferred to the detector which might be a CCD pixel, an eye retinal cell, or an electron in a metal. Until that moment of detection, the photon is a probability wave that can interfere with itself, but has no effect on matter. Upon detection, its probability waves vanish.

Imagine that an alien scientist named Xzzypt in a far away planet and I are both using telescopes to look at the same star when a particular atom in that star has emitted a single photon with energy E. As explained above, this photon will have an frequency centered around $f=E/h$ with $h=6.63\times10^{-34}\,\mathrm{J/Hz}$.

Just as Einstein explained in the photoelectric effect, where only one electron gets all the energy from a particular photon without any sharing with other electrons. All the energy from the atom watched by Xzzypt and I will only end up at one place. If by amazingly good fortune a retinal cell in my eye gets that photon energy, Xzzypt will not see anything. If Xzzypt gets the photon energy I will not see anything. If the photon energy goes to the rock or anywhere else in the universe, neither Xzzypt nor I will see anything.

The probability wave spreads out from the atom at the speed of light, getting weaker the farther it goes. By the time it gets to Xzzypt or me, it has a terribly small chance of giving one of us its energy. We will both see light from that star, however, because there are something like 10^{50} atoms in the star and that huge number raises our chance that some of those atoms will send out photons that we can see. Xzzypt and I may see light from that star, **but not from the same atoms**.

Now if you will accept that explanation, we can finally consider the interference experiment using a single photon at a time. Each photon is a probability wave that interferes with itself as it leaves the hole in the end of the laser and heads toward the whiteboard. The whiteboard will then receive the probability wave, but where will the energy go? The likelihood of a particular spot getting the photon energy depends on the square of the probability wave amplitude at that spot. Where the probability wave is strongest will be more likely to get the energy, but it still might by chance go to a location with less probability.

So, as each succeeding photon strikes the whiteboard, spots of light will appear. After a great many photons, a pattern will become apparent. It will be the same pattern we see in the lab when we use 10^{15} photons per second from the laser. There will be more photons striking the parts of the pattern where the light constructively interferes (adds) and fewer where it destructively interferes (cancels).

Particles are also probability waves

Even massive particles like electrons are waves, but with wavelengths given by $\lambda_{\text{electron}}=\frac{h}{m_e v}$. For an electron with mass $m_e=9.11\times10^{-31}\,\text{kg}$ moving at one-hundredth the speed of light, this becomes $\lambda_{\text{electron}}=2.426\times10^{-10}\,\text{m}=242.6\,\text{pm}$. This short wavelength helps electron microscopes produce images with more than 1000 times greater resolution than optical microscopes.

When we study atoms, we will learn that it is no accident that the size of atoms is similar to that of electron wavelengths.

Since massive particles are also probability waves, do electrons diffract and interfere? Yes, although their probability waves are governed by different wave equations than Maxwell's equations.

The undulating electric field around us

All the light and radio waves around us produce an exceeding complicated undulating electric field. This is explained by Nobel Prize winning physicist Richard Feynman in the following video. My generation of physicists revered Richard Feynman.

> **Richard Feynman talks about light (5 min 54 s)**
> *https://www.youtube.com/watch?v=FjHJ7FmV0M4*
> Please ignore his comment about the person who dives into the swimming pool, but listen closely to how he describes the electromagnetic field around us.

Holograms

Have you ever wondered why you cannot fix the focus of a picture after the image is recorded?

When an image is taken using light, it is usually preserved as intensity variations on a film or in a CCD. Only the light energy is recorded. But waves also have phase information which controls how they interfere. That phase information is discarded during the normal photographic process.

Holograms are clever ways that very high resolution film and a coherent reference light beam can preserve both amplitude and phase information. Since holograms record all the light information, they can be used to recreate the actual light waves. That allows true 3D images to be seen at different viewing angles.

The following video provides a more complete explanation:
How 3D holograms work (4 min 18 s)
https://www.youtube.com/watch?v=0ics3RVSn9w

That's probably enough food for thought about light. Light once seemed so simple...