Let There Be Quantized Electromagnetic Radiative Energy

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1 Unanswered Questions

1. The basic building blocks of matter, called elementary particles, must all have zero volume. What, then, prevents them from piling in so closely together that the matter they form does *not* have zero volume?
2. How do we know the Heisenberg Uncertainty Principle applies to particle existence, and not merely measurement?
3. How can particles with zero volume interact through virtual particle exchange at all?

2 Some Words About Electric Current

The atomic model used in these lessons so far is akin to a little solar system. Electrons orbit the nucleus like planets at some variety of orbits. If we arrange these atoms near each other and apply a voltage across, it is not hard to imagine the electrons moving like little meteors from solar system to solar system. The electrons closest to the positively charged voltage source leave their solar systems to move towards the attractive charge. This leaves a vacancy in that can be filled by an electron from the next atom, and so forth down the line, until you reach the electrons closest to the negative end of the voltage source trying to escape from that repulsive force.

3 Some Words About Waves and Light

“Light” is a word used in the common vernacular to describe illumination we can see. In the science world, it is understood that the visible spectrum is a relatively small portion of the electromagnetic spectrum. Radio waves, microwaves, infrared (heat) waves, ultraviolet waves, X-rays and more are the same essential phenomenon occurring at different frequencies. Waves have a few important aspects that will come into play.

3.1 Shape

There are two kinds of waves in nature. Sound travels as a longitudinal waves[1]: a series of compressed and uncompressed bits of air are perceived as sound because the changes in pressure cause our eardrums to move, driving the bones behind them to respond. Light, and most of the other waves we’ll discuss, is composed of transverse waves.[2] These are the kinds of waves you see on the surface of water: they have high points (crests) and low points (troughs). When two waves overlap, they combine accordingly. If two crests overlap, they form an even larger crest. Two troughs make a deeper trough. A crest and a trough will cancel each other out, reducing the overall strength of the wave. This is called interference; a sufficiently precise setup can produce some extreme examples.

3.2 Speed

A given wave will travel at a defined speed. This depends primarily[3] on two things: the type of wave, and the material it is waving through. In other words, all sound waves in air travel at the same speed, regardless of pitch.[4] If those same sound waves hit water, they’ll travel through the water at different speeds than in air, but all sound waves in the water will travel at the same speed.[5] The same is true of light in all its forms: radio waves, visible light and X-rays all travel at the same speed through the same medium.[6]

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[1] Etymology of “longitude”: along the distance or direction of motion

[2] Etymology of “transverse”: lying across: waves travel across the direction of motion.

[3] Frequency and other variables have a slight effect on it, but very slight.

[4] Those of us who can only afford concert tickets at large distances from the stage really appreciate this. Concerts would be much less enjoyable if vocals, bass, lead guitar and drums were out of sync by the time the sound reached us.

[5] The speed does depend on the temperature of the medium, meaning the speed of sound in warm air differs from the speed of sound in cold air, but that’s still a property of the medium, not the wave.

[6] Note that Einstein’s relativity specifically sets the universal speed limit as the speed of light in a vacuum, where light travels most quickly. When light is traveling through another material, it slows down. As a result, it *is* possible to travel faster than light, if that light is

3.3 Wavelength

The wavelength is the distance between identical parts of a wave. With transverse waves, it is most easily measured as the distance between two crests or two troughs. (The distances will match.) With longitudinal waves, it is the distance between two consecutive compressed or uncompressed portions of the wave. This property depends on both the medium and the wave itself: all light that is a particular shade of blue will have the same wavelength in air, but when that light moves into water, all light that shade of blue will take on a different, but equally specific wavelength.

3.4 Frequency

Frequency is another word that has common and scientific meanings. In this case, the meanings are more similar than they are with the word light.

Frequency commonly means how often something happens. That's what it means in science, too: we just have specific definitions of the "something." The frequency of a wave is how often a complete wavelength of the wave passes a specific point.

The frequency is the characteristic that most scientists use to describe waves, simply because it is the characteristic that depends solely on the wave, and not on the medium. Different colours of light will have different frequencies, but those frequencies are the same whether that light is traveling through air, water, glass, vacuum or transparent aluminum.

Frequency can also be used to tie wavelength and speed together. Imagine we have a wave with a frequency of three wavelengths per second[7] and a wavelength of two meters. Combining these two pieces of information tells us that a single point on the wave will travel a total of six meters in one second. Thus, the speed of a wave can be found by multiplying the frequency and wavelength together.

3.5 Intensity

The intensity of a wave is the amount of that wave coming in. This depends on the energy output of the source: the Sun has a much greater intensity of light

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traveling through a medium. For example, high energy electrons can outrun light in water, and produce something called Čerenkov radiation in the process. This is effectively light's version of a sonic boom.

[7] The most common unit of frequency is the Hertz, named after a major contributor to classical wave theory, where $1Hz$ means one wavelength per second.

than a light bulb that glows the same colour. You can double the energy output by doubling the intensity without changing the frequency, speed, or wavelength of light. Intensity of light is perceived as brightness, while intensity of sound is perceived as volume. Thus armed with the fundamentals of wave theory, we are ready to proceed.

4 The "Neener Neener" Spot

To this point, we have not addressed the nature of light in these lessons. Historically, it was believed that the wave nature of light was well understood by physicists. One of the most compelling arguments that light was a wave, not a particle, came in the form of the Poisson spot, which may be the only phenomenon in the realm of science that was named after the individual who did *not* find it.

Simeon Poisson was a physicist in the early 1800s who was known for having more talent with theory than experiment. In fact, his experiments had an uncanny knack for producing exactly the theoretical result Poisson expected. While physicists were hotly debating whether light was a particle or a wave, Poisson designed an experiment that would seem to settle the debate.

Imagine a calm river. Some object, such as a rock or fallen tree, is protruding from the river's surface. This will create waves and ripples as it disrupts the natural flow of the river. These waves and ripples will wrap around behind the rock, often creating an area of even higher waves than the surrounding area. The same is true for light waves.

If one were to mount a circular object near a light source, then one could set up a similar situation. If light is a wave, and if it falls on this circular object, then the wave could wrap around the obstruction and "add up" on the other side to produce a bright spot in the middle of the shadow. (The observation screen would have to be placed with high precision, but it's possible.) This bright spot would be required if light were a wave, and would be completely inexplicable if light were a particle.

Poisson was a supporter of the particle theory of light, and when he performed the experiment, he found no such bright spot. He promptly declared that light was a particle. However, Dominique Arago knew of Poisson's history of finding exactly the results he expected, so he repeated the experiment and found that the spot was, indeed, right where wave theory predicted it would be. He promptly named the bright spot the "Poisson Spot," simply to rub it in.

Nonetheless, the discovery of the Poisson spot proved beyond a shadow of a doubt that light behaves like a wave.

5 The Blackbody Radiation Problem

By the early 1900s, there were a couple of problems with phenomena involving light. One was the so-called blackbody radiation problem.

A blackbody is an object that is entirely black in colour. A quick experiment with most stoves will reveal that heating a black object to a high enough temperature causes it to glow. The glow is initially red in colour, but as the temperature increases it becomes more yellow, and eventually white. Experiments had verified this pattern is independent of the material involved. Any object heated to a given temperature will glow a particular colour. In other words, it produces light.

Herein lies the problem: in the classical model, light waves were produced by a vibration of the material itself. In that model, a piece of the blackbody would vibrate with heat energy and emit a wave. The wavelength of light would be determined by the heat energy causing the vibration in the original material.

The problem is that shorter wavelengths would be more common than longer wavelengths. Classical theory predicts that most light would be produced in the X-ray and ultraviolet regions, and that the first visible colour as the temperature increased would be violet, not red. Any time theory doesn't match experiment, it's time to review the theory. The blackbody radiation problem was not the only problem with classical theory.

6 The Photoelectric Effect

A second significant problem with classical theory came from the photoelectric effect. This is the phenomenon that drives solar powered calculators and similar technology.

There are some materials in nature that can act as sources of electric current when exposed to light. If you were to put such a material in an electric circuit with no voltage source and shine a light on it, current would flow. At this rudimentary level, the ideas we've established so far are more than enough to explain the phenomenon: light energy is imparted to electrons in orbit, and this energy is enough to cause the electrons to break orbit and travel through the circuit.[8] When we look more closely, the existing theory is proven inadequate. Existing theory would indicate that, once the photoelectric effect is established as a real phenomenon, the relationship between light and current would be simple. Doubling the intensity of light would double the current. Doubling the frequency of light would double the stopping voltage. Neither of these effects were seen.

Problem #1: The light frequency impacts the energy of the electrons in the current. Each electron gains energy from exposure to light, and starts moving in a current. If we add a battery to the circuit which opposes the current, we find that there is a particular voltage level that brings the current to a complete stop. The inexplicable part is that increasing the frequency by 20% also means increasing the voltage, but not by 20%. For example, if the frequency changes from $1000Hz$ to $1200Hz$, the voltage may change from $10V$ to $20V$. Even more strange is that the *absolute* difference is maintained; in the above example, if you increase the frequency by another $200Hz$ to reach $1400Hz$, then the voltage needed to stop the current (called "stopping voltage") increases by the same $10V$ difference we had before, bringing us to $30V$. A frequency of $2000Hz$ would drive this up to $60V$; a 100% gain in frequency caused a 500% gain in stopping voltage.[9]

Problem #2: In order to produce the photoelectric effect, a certain minimum frequency of light is required. No intensity can overcome this: just because photoelectric current flows when the photoelectric material is exposed to a given intensity of light with a frequency of $2000Hz$, there is no guarantee that current will flow with double the intensity of $1000Hz$ light. In fact, there is no guarantee that current will flow at all. Different materials have different minimum frequencies.

Problem #3: Increasing the intensity of light increases the current, but not the stopping voltage. If twice as much light falls on the material, twice as many electrons flow, but each electron carries no more energy it did under the original intensity at the same frequency.

These were extremely perplexing problems, at least until they were studied by a guy named Albert Einstein.

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[8] Electrons were originally discovered as a result of the search for the moving part of electric currents. It was already well known that current was nothing more than electrons in motion.

[9] These are entirely fictitious numbers used for the purposes of explanation only. An increase of $200Hz$ leads to an increase of $8.27 \times 10^{-13}V$ for electrons in all photoelectric materials. This independence of the relationship between materials could be a fourth problem in its own right, but it doesn't seem to be one that greatly concerned the original experimenters, possibly because the solution was found before this was seriously pondered.

7 Quantization of Light

Albert Einstein did not win his Nobel prize for the theory of relativity. Instead, he won it for finding a single explanation for the three problems with the photoelectric effect, and pointing out that the same explanation would also take care of the problems with blackbody radiation.[10] The solution is simple: treat light as a particle.

Ignore the Poisson spot for a moment.[11] Imagine that light is a particle, and that each particle contains a particular quantity of energy. Planck's math had already indicated that this energy would be directly related to the frequency. He refused to believe the quantized light interpretation because of the Poisson spot, but he published anyway because the math worked so well. In his model, energy E and frequency[12] ν of light are related by $E = h\nu$, where h is a constant that exists mainly as a conversion factor between units. A particle of light of a given frequency (or colour) will have a given amount of energy.

Now imagine these particles of light energy falling on a material loaded with orbiting electrons. The electrons are able to absorb this light as energy, but (it seems) they can only absorb one particle at a time. If each particle doesn't have enough energy to get the electron out of orbit around the nucleus, then the electron doesn't go anywhere, and no current is produced. Instead, the energy is either retained as heat, or released as reflected light or blackbody radiation. No intensity of low frequency light will cause an electron to escape atomic orbit and become electric current: this takes care of problem #2.

Once we've hit the threshold frequency, or the frequency of light that is high enough to cause electric current to flow, we can explain the other two problems. If we have photoelectric current and we double the intensity of light, we double the current but don't change the stopping voltage. This also makes sense: with twice as many light particles falling, we can free twice as many electrons to flow, but each individual electron's energy is still limited by the energy of the individual light particles, so the stopping voltage doesn't change. Problem #3 is no longer a problem.

Finally, we have our original problem to deal with. The relationship between stopping voltage and frequency is not strictly linear, though there is a definite and distinct pattern. Planck's formula comes to the rescue on this one, in a

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[10] The mathematics that back it up had already been done by Max Planck to deal with a separate issue.

[11] Einstein did. He had to. If you hold on to the wave model of light the Poisson spot had definitively proven, he could not have explained reality.

[12] In most high school courses, frequency is denoted f. The professionals use the Greek letter "nu," ν, and they use it consistently. This tends to confuse students in their first year of post-secondary with what appears to be a sudden and inexplicable change in notation: the post-secondary institution didn't change the notation, the public school did.

fashion. The solution to this problem will lead to an entirely different pair of problems.

It was well known before the photoelectric effect was fully explored that a charged particle can gain kinetic energy in a circuit if it moves through a voltage difference. If you apply a voltage V to a particle with charge q, then the energy gained (or lost, if the voltage tries to push opposite to the direction of motion) is equal to q times V. Since this is an observable phenomenon, conservation of energy applies.

The total energy used came in through the original particle of light. Some of that energy is used to get the electron out of its orbit, and the rest can be used to make the electron move. This explains things nicely; there is a linear relation with uniform increases because this energy is partitioned into two parts. One part is the energy required to get the electron out of orbit, and the other part is the energy the electron uses to move through the circuit. If we take the energy of the electron moving through the circuit[13] and add the energy needed to get the electron out of orbit, called the *work function*, we get exactly the energy the incoming light particle had by Planck's math.

The blackbody radiation problem is also neatly explained by this solution: to produce the higher frequencies of light that we seem to be missing, we would need to impart a relatively large amount of energy into them. This caps the amount of light particles that can be produced at higher frequencies. Rigorous math proves that this modification is exactly what is needed to produce blackbody radiation in the colours we see at the temperatures at which we see them.

When two distinct problems can be solved by a single, relatively simple idea, that's usually considered definitive proof that the idea is correct. In this case, Einstein proved beyond a shadow of a doubt that light behaves like a particle. We call these particles photons. That term has appeared before; photons are the particles that mediate the electromagnetic force.

7.1 Reconciliation Problem

Now we have seemingly contradictory results. The existence of the Poisson Spot proves, beyond a shadow of a doubt, that light behaves like a wave. Now, Einstein has proven, beyond a shadow of a doubt, that light behaves like a particle. This contradiction will need to be reconciled.

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[13] The energy of the electron moving through the circuit is equal to the charge on the electron multiplied by the voltage required to stop it. That's the amount of energy we had to take away from the electron to make it stop, so that must be the amount of energy it had to begin with.

7.2 Work Function Implications

When we graph most physical phenomena, we usually get smooth curves in the graph. Even rapid changes produce curved graphs, although the curve may be small and tight.

When you graph the frequency of light incident on a photoelectric material against the current that flows out of it, you do not get a curve. When you hit the work function, you get a sudden, sharp change in the current flowing, as though someone hit a switch. This is a different kind of phenomenon than anything we have encountered before.

Beyond that, this also means the work function is extremely well defined. This is not a random number, so electrons are not arranged in the materials as randomly as planets are arranged in a solar system. The atomic model we have been using so far needs to be adjusted, as does our picture of electric current.