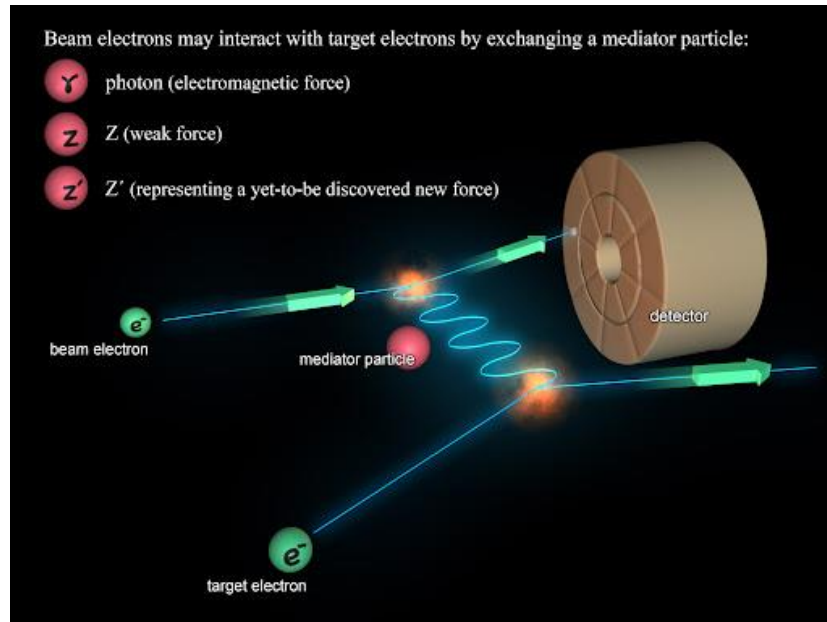


Quantum Electrodynamics

QED

The Strange Theory of Light and Matter

Refined and fully developed in the late 1940s by Richard P. Feynman, Julian S. Schwinger, and Tomonaga Shin'ichiro, independently of one another.



By: Thomas Adams

11/25/2021

What is the Theory of Quantum Electrodynamics?

The theory of Quantum electrodynamics (QED) is an explanation and a description to the phenomena we tend to witness constantly but tend to overlook without thought of explanation as to why they behave in such a way. Such phenomena related to the properties of light are as follows: light goes in a straight line; bends when it goes into water; reflection from a surface (i.e., a mirror or a hot road at times); the separation of light into multiple colors; a lens focusing light; etc. This theory is not limited to not only such phenomena and similar phenomena, but all phenomena of physical world other than those resulting from gravitational effects and radioactive phenomena. In addition, from the words of the renown physicist Richard Feynman,

¹ <http://web.cos.gmu.edu/~vkunkel/feynman1.html>

“The Theory of quantum electrodynamics is also the prototype for new theories that attempt to explain nuclear phenomena, the things that go on inside the nuclei of atoms”.

How can we explain the Theory of Quantum Electrodynamics?

This paper will attempt to inform and help one take a step towards understanding the theory of quantum electrodynamics. Again, from the words of Feynman in his presentation on QED, “will you understand what I’m going to tell you? ...No, you’re not going to understand it... You see, my physics students don’t understand it either. That is because I don’t understand it. Nobody does.” So, you may be wondering why are we interested in learning about something that even a developer of QED cannot understand himself. That is because QED is what allows physicists to make calculations regarding the emission and absorption of light by atoms. Also consider the interactions that occur between charged particles (i.e., electrons) and photons (particles of light). QED allows physicists to obtain very accurate predictions regarding such interactions.

In both Feynman’s book, *QED: The Strange Theory of Light and Matter*², and recorded lectures, *The Douglass Robb Memorial Lectures*³, on the Theory of Quantum electrodynamics, he breaks into four portions. Introduction (phenomena), Photons, Electrons and their Interactions, and Loose ends. This method has aided many in obtaining comprehension of QED, therefore, this research paper will use the same method to do so as well.

Quantum Electrodynamics

Phenomena

One might ask what phenomena does this theory concern. Can the theory of quantum electrodynamics explain the phenomena of why 5 dollars from your bank account went missing this evening? No. The phenomena we are concerned with are that which correlate to things physicists have attempted to explain for centuries over many attempts. One such phenomenon being the motion of electrons going around the nucleus. Attempts at which have been done using mechanical laws, like Newton’s law to describe how the earth orbits the sun, a failure regarding an electron orbiting a nucleus. This phenomenon is one of the bigger pictures we will return to in verifying the theory of quantum electrodynamics.

In addition to said phenomena, we will illustrate another wonderful aspect of quantum electrodynamics that we will not be able to go in depth upon, because that requires a much more extensive amount than what will be covered in this paper. Such phenomena are the sub-grouped phenomena physicists have created in order to aid comprehension of our world, such as the phenomena of motion, heat, sound, light, and of gravity. All such phenomena can be explained by the theory of quantum electrodynamics. All except gravity, a concept that is not yet able to be interpreted by other phenomena.

² Feynman, Richard P. *The Strange Theory of Light and Matter*. Princeton University Press, 1985.

³ <http://www.vega.org.uk/video/subseries/8>

However, to best convey the theory of quantum electrodynamics, we will explore phenomena that we see on an everyday basis with the naked eye, and then use this understanding to dive into the phenomena of how an electron orbits the nucleus in the manner it does so. We begin as Feynman had, with light. One common phenomena of light most have witnessed is one

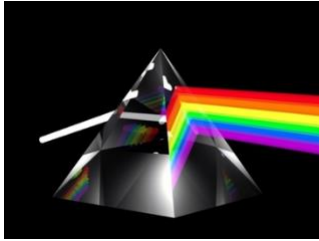


Figure 1. Newtons Light Prism Experiment

in which light enters a prism and exits a range of colors, this is depicted in figure 1⁴. These range of colors of light are light at different frequencies and wavelengths. For our purposes we are going to use red light. In addition, we must convey an important matter before moving forward. Light is composed of these extremely small energy balls, we deem photons. So, for the sake of moving forward, imagine light as a bunch of energy orbs called photons that have nearly no mass and compose light.

Now, we will dive into the phenomena of partial reflection. Partial reflection is a matter of concern we can explain with the of what deem a photomultiplier. A photomultiplier is like a target, every time it is hit it adds a tally to count how many times it's been hit, or something has bounced off it. More specifically, photons. Below figure 2, I have illustrated our photomultiplier with a score board to count how many photons hit from our laser, a dotted ray representing this composition of photons. In such a scenario, we would expect to count 100% of the photons hitting our photomultiplier. Now, let's implementing some glass surface for our laser to play with. We would place a photomultiplier below the glass and on above the glass as shown in figure 3. With this "standard" sized glass, we will find that 4% of the

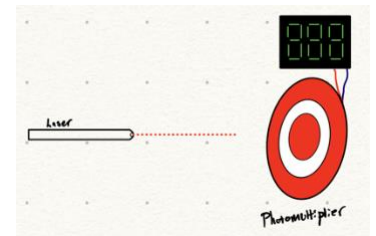


Figure 2. Laser represented as photons, hitting our photomultiplier

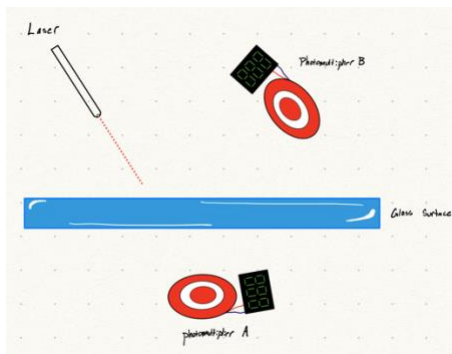


Figure 3. Partial Reflection with glass Surface

photons will be counted above the glass (the reflected photons) and the remaining 96% will be counted at the bottom of the glass (accounting for 100 % of the photons). Now if we were to slightly increase the thickness of the glass surface, we will find that partial reflection will reach 8%, then increasing the thickness even more we get 10% reflection. Now, what do we expect if continuously increase the thickness of the glass, what percent of photons will be reflected? We will come to find by experimentation that as we increase the thickness the percent reflection will peak at 16%. However, as we increase the thickness even

more so, it will decline in percent reflection, to the point where we continuously increase the thickness of the glass but eventually decrease to 0% percent reflected. But once again, with further increase in glass thickness we start to approach move towards 16% reflection and then

⁴ "Storyboard Template for Short Film: Storyboard Template, Comic Book Template, Screenplay Writing." Pinterest, <https://www.pinterest.co.uk/pin/461478293044806389/>.

decline back to zero. This oscillation of percent reflection in accordance with the increasing thickness of glass can be shown in figure 4. Newton had made many attempts at why such a phenomenon of partial reflection but was unable to develop a satisfactory theory. Following

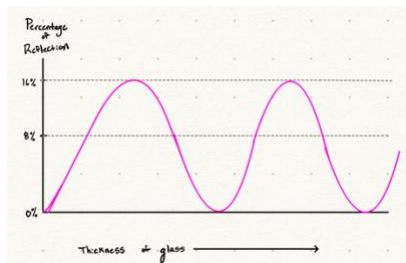


Figure 4. Partial Reflection Phenomena

Newton, many had come to believe this phenomenon could be explained by the theory of waves. But when experiments using very weak light, the wave theory failed regarding this matter. However, with the use of little arrows, QED has proven successful in calculating such phenomena.

Let us demonstrate the use of said arrows. A probability of 16% will have a length of 4% or 0.04. The square of the length is its

probability. Similarly, if the probability is 4% its arrow length is 0.02 and 0% has a length 0.00, and so on. Figure 5 demonstrates this, in an illustrated form. Now what if we have multiple ways an event can occur, and each event has its own arrow. We use the tip to tail method and just attach our arrows together, and the straight path from the first arrow's tail to

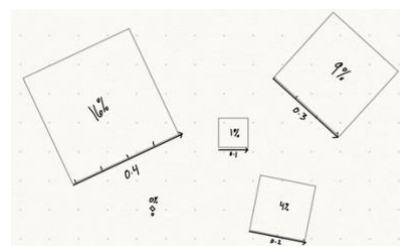


Figure 5. Arrows and Probability Example

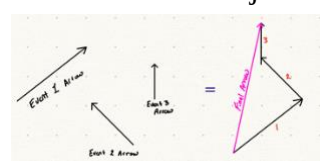


Figure 6. Arrows corresponding to multiple ways an event can occur

the last arrow's tail is deemed our final arrow. An example of this is shown in figure 6. Lastly, we need to use a method to determine our little arrows length and direction. For this we will imagine a stopwatch, imagine analog watch. We stop the clock when a photon arrives at the photomultiplier, and we draw the arrow in the opposite direction of analog watches hand. An example is demonstrated in figure 7. In figure 7, we demonstrate the arrow for

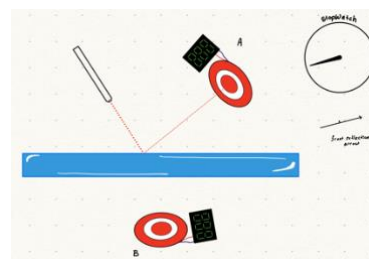


Figure 7. Arrow for front surface reflection

of the front surface of our glass surface of a given thickness, and we provide it a length of 0.2. Now taking this into account what should expect for reflection of the back surface. Since the back surface is a further path, we should expect the stopwatch to move further yielding a new arrow in a different direction. We will take our arrow from the front surface and back surface for a certain glass thickness as shown in figure 8. With our front reflection arrow and back surface and back surface arrow, we can yield our final arrow. The square of final

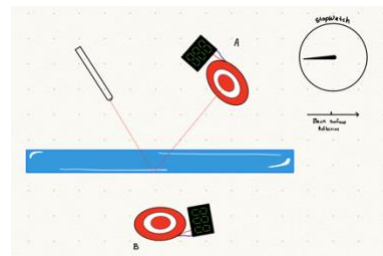


Figure 8. Arrow for back surface reflection

arrow is the probability or number of photons we should expect to be partially reflected to photomultiplier A, an example is demonstrated in figure 9. Now let's demonstrate how this works as we change the thickness of glass surface. If we were to now apply this to our different levels of thickness, we will witness what has been shown in figure 10. As shown from figure 10, we can go from a peak amount of reflection (presumably 16% for red light) down to 0%, then back up from 0% to 16%, repeating once again with no signs of stopping this cycle. This matches the observed behavior of partial reflection as stated previously. This is the

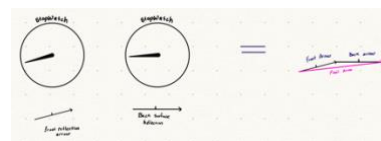


Figure 9. Final Arrow example for front surface and back surface reflection

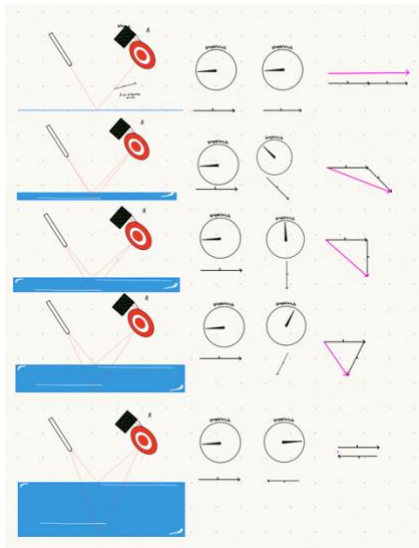


Figure 10. Varying Thickness and Final Arrow cycle

application of the theory of quantum electrodynamics to partial reflection, where the pace at which the stopwatch rotates is biased upon the light's wavelength. For example, with blue light this cycle of going from peak reflection to zero and vice versa is faster, the only differences with different forms (red photon, blue, radio wave, x-rays, etc.) just have changed paced for the speed the stopwatches hand rotates. This unusual approach for creating arrows and placing them together works, and we are going to show how we implement it further. These paces for the stopwatch for different colors is what yields the phenomena of newtons experiment, demonstrated in figure 1. Such is the phenomena of colors produced by partial reflection by white light, iridescence.

Photons: Particles of Light

Now that we have demonstrated the use of the “little arrows” we can now move on to compute correct calculations for other forms of phenomena, such as: light travels in a straight line; light reflects off a mirror at the same angle at which is shined upon the mirror (“the angle of incidence is equal to the angle of reflection”); a lens focuses light; and many others! We will use our new method of understanding to demonstrate the phenomena of which light reflects off a mirror, and the widely established concept amongst physicists, “light travels where time is least”!

To understand what this phenomenon is, we must first elaborate on the matter of photons. When a light emitting source is provided, the photons are within their ability to take paths A, B, C, D, etc. as demonstrated in figure 11. Now that we

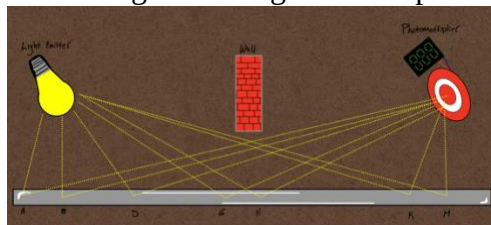


Figure 11. Different Photon paths



Figure 12. Mirror Paths with Final Arrows

have a few examples of ways the light could travel let's break our mirror into several segments as shown in figure 12. As shown in figure 12, we have illustrated the corresponding final arrows at each segment. In this current scenario, we are going to assume has an equally likely of taking path A, B, C, etc.... and as so, there little arrows will all be of the same length no matter the path they have chosen, we used that and the stopwatch method from before to create the resulted arrows in figure 12. Where the direction of the arrows is resultant upon the time it takes the photon to travel from the light source to the mirror, and to the photomultiplier. A result of the time it takes using that indicated path (A, B, C, etc....). Now if we take each of arrows and attempt the tip to tail method as we have demonstrated before. We will begin with the arrow from A and begin from there in

creating our tip to tail result in the resultant illustration in figure 13. Notice that this illustration is symbolic of a sideways 'S'. Where if we were to symbolize these arrows as a single step, we may take walking along this path. Notice for steps A through D, we wouldn't move anywhere, in a sense where are walking in a circle. Similarly, the same can be said for arrows J to L. Regarding the horizontal direction. None the less, are resultant arrow is significantly large, the square of which is the probability or percent of photons that will reflect. Meaning, by this theory, the theory of quantum electrodynamics, light does in fact reflect off a mirror.

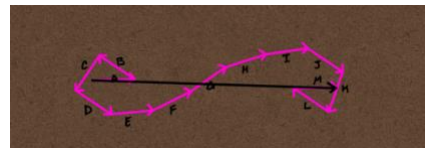


Figure 13. Final Vector

Now one may be thinking, yes, a light does reflect a mirror, most believe this to be an obvious fact. However, to continue further with applying the theory of quantum electrodynamics to the concept that light travels down the path where the time traveling is least. We cannot have assumed that light reflects of a mirror and then apply such a concept to the QED theory to prove the idea that "light travels where time is least"! Like any good proof, one must demonstrate with the same method that one process can occur before implementing it into the next approach using the same method. The method of little arrows.

Previously, we spoke on the matter that the end paths essentially go in a circle, leaving no significant contribution to our final arrow. Thus, we will simply "chop off" the ends of mirror, leaving only the middle portion that has any significant contribution to our final arrow, hardly causing any change or affect to the length of the final arrow. However, where specifically does the greatest contribution to our final arrow occur? This would be where our final arrows point in the same direction. Remember with our arrows, the direction of the arrow is equivalent to the time it takes for the photon to travel the indicated path. Therefore, those arrows that point in nearly the same direction, nearly have the same time in traveling to the photomultiplier (our indication of reflection). This demonstration of same travel time is also demonstrated on our time curve in figure 12. Notice where the time is nearly the same in this curve, is towards the bottom of the curve, the middle of our mirror. This crude process demonstrates the known statement amongst physicists, "light only goes where time is least". To summarize so one doesn't simply think we jump from one thought to another and 'ta-da' we have established a known idea. We established that the middle portion of the mirror, where the time to travel is least, where the greatest contributors to our resultant arrow if not nearly all our final arrow. The final arrow squared is the probability that the photon will take said path. Meaning the greatest probability occurs in the middle portion of our mirror, where once again time is least. Establishing, that light is mostly likely to travel where the time is least!

These phenomena are amongst the very few regarding photons and light, and further observation into Feynman's recorded lectures or book on QED will demonstrate the application of QED into more complex phenomena that require more calculation and application of our "little arrows". I highly recommend those of you who have begun to feel entranced by the theory of QED, investigate Feynman's book on QED. In Chapter 2 of his book, where he implores calculations to demonstrate phenomena such as "the angle of incidence equals the angle of reflection"; mirages; how light appears to go in a straight line, and many other fascinating phenomena regarding photons.

Electrons and Their Interactions

Now has come to pursue the application of QED with electrons and the interactions, key emphasis, and their interactions. Now let's take a step back, in the beginning we stated how QED can describe many phenomena and sub phenomena, such as heat, light, etc.... Now, given sub-phenomena, what is the smallest possible event that we can use to describe compounded to form all phenomena, other than gravitational? The answer comes out to this statement, all phenomena can be described by three basic actions:

Action 1: A photon goes from place,

Action 2: An electron goes from place to place,

Action 3: An electron emits or absorbs a photon.

Regarding our method of arrows, each of these actions has an arrow (an amplitude), and these arrows can be calculated using certain rules. We will use these actions and arrows to establish the interaction of an electron with the nuclei and the way it behaves.

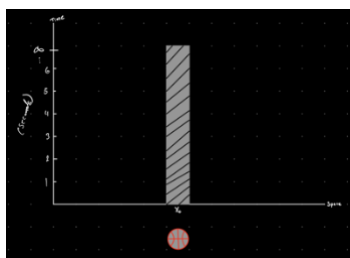


Figure 14. Time vs Space diagram

We will begin with a free-floating spherical object – a ball, this can be a baseball, basketball, soccer ball, etc...., we will leave this decision up to the readers imagination. This ball is space, and simply floating. A space time diagram has been illustrated in figure 14 to help demonstrate this. Now let's have a ball drifting in space at a right angle and then input a wall in its path. The space time diagram for this has been illustrated in figure 15. Note that

when our drifting ball hits our wall it will bounce off at the angle at which it initially collided with the wall with. Now, let's shift perspectives, the ball is a particle, time takes place in much smaller increments, and the particle is moving (drifting) at speeds close to the speed of light! Similar to before, we will now draw a new space time diagram to show two particles moving at the speed of light, traveling from points X1 to X2 and the other particle from X2 to X1. This diagram is shown in figure 16. We will regard this particle specifically as an electron.

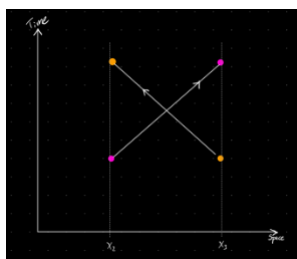


Figure 16. Time Space for two particles

Now let us refer to a photon. Rather than using a straight line for the path traveled for a particle we will use a wiggly line for a photon traveling from point A to point B, within time T1 to T2, as shown in figure 17. This photon has an amplitude to go from A to B, which we will represent as P (A to B). Taking this same idea, we have the amplitude of an electron to go

from A to B symbolized as E (A to B) assuming the electron in question has no polarization, spin- zero. Electrons have polarizations but incorporate such matters would not affect the main concept we are trying to convey and would only complicate said concepts. Thus, for action 1, a photon goes from place to place, we have P (A to B). For action 2, an electron goes from place to

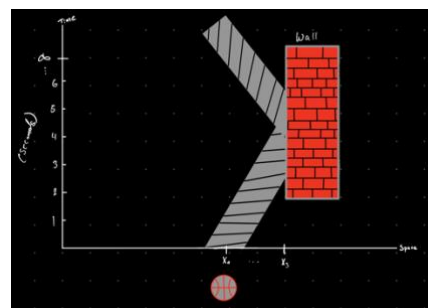


Figure 15. Drifting ball interacts with wall

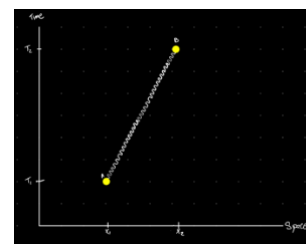


Figure 17. Photon Space time Diagram

place, we have $E(A \text{ to } B)$, a sum of the many arrows we have grown so fond of. Now, how can we convey action 3, an electron emits or absorbs a photon. To aid in simplification we will refer to this action as a “junction” – ‘j’. Our junction, j, the amplitude for an electron to emit or absorb a photon is not a complicated formula like $P(A \text{ to } B)$ or $E(A \text{ to } B)$, it is simply a number. More specifically it is important to inform the reader that an electron traveling in a straight line has an amplitude to emit or absorb a photon, j, and said amplitude is approximated to 0.10. We have represented space time diagrams for actions 1 and 2, so let’s represent the space time diagram for action in figure 18.

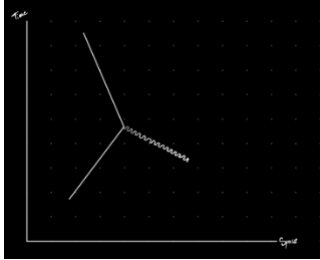


Figure 18. Time vs Space diagram for an electron emitting or absorbing a photon

Now that we have represented our three actions, we can put it together to represent somewhat complicated circumstances. We will use the example provided:

What is the probability of two electrons at point 1 and 2 in space-time ending up at points 3 and 4? However, to further complicate the circumstance, what if a photon is emitted at point 5 and emitted 6?

An illustration to the above circumstance has been provided in figure 19. To obtain our probability, we must consider that we have simultaneous actions occurring with their own amplitudes. To obtain the new amplitude of this entire event we put our amplitudes together by multiplication. We multiply the amplitudes from 1 to 5, where our first electron emits a photon; 5 to 3 where our electron continues; 2 to 6, where our second electron absorbs a photon, and then continues from 6 to 4; and lastly our photon from 5 to 6. The mathematical representation of this circumstance’s amplitude is shown below:

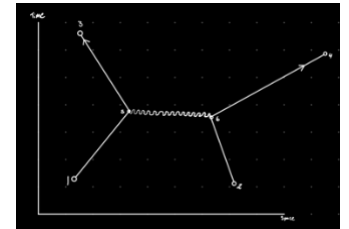


Figure 19. Space time diagram to our more complicated circumstance

$$E(1 \text{ to } 5) \times j \times E(5 \text{ to } 3) \times E(2 \text{ to } 6) \times j \times E(6 \text{ to } 4) \times P(5 \text{ to } 6) = \text{New Amplitude}$$

The square of this *New Amplitude* is the probability of the circumstance stated below will occur. Note however, figure 19 is referred to as a Feynman Diagram, and is one of many ways the Feynman diagram could have been illustrated for the event occurring in our specific circumstance. To demonstrate, another Feynman diagram has been illustrated in figure 20. In this case the first electron ends up at point 4 rather than the second, and similarly the second electron ends up at point 3. As a result, multiplication of the given amplitudes in figure 20 will need to be implemented in a new set of multiplication to yield our *New Amplitude*.

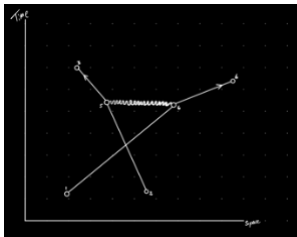


Figure 20. New Feynman Diagram for the same circumstance

Keep in mind that points in 5 and 6 can occur anywhere, and at any time within space time! As such, the calculations for all these different positions must be calculated and added together, a tedious task where the rules are simple but continuously reimplemented. Demonstrating the matter of the fact that the calculations are not difficult but take a significant number of little arrows. In comparison, what we have just demonstrated was in a sense an easy problem!

One such demonstration of this comparison is the case of an electron in an atom. To incorporate such a matter with what we have just reviewed, let it be said that $E(A \text{ to } B)$ has an

additional factor other than using little arrows to obtain E (A to B). This factor being 'n', for the nucleus. In our previous demonstrations, 'n' had simply been equated to zero. The nucleus of an atom is composed of, at the very least, one proton. The amplitude for a proton going from place to place can also be represented as E (A to B) but with a much higher value of n . In addition, since the nucleus containing the proton is so extremely heavy in comparison to an electron, it can be illustrated to essentially remain unmoved as time transpires.

The "easiest" atom for us to illustrate this is the hydrogen atom, with one proton and one electron. The proton can keep the electron "dancing" around, nearby, through the exchange photons. Emitting and absorbing photons back and forth. Where the amplitude of photon to emit and absorb a photon is opposite but equal to that of an electron, signified as $-j$. Figure 21, shows

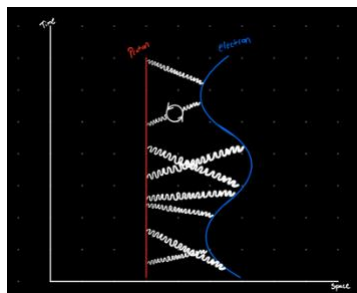


Figure 21. Hydrogen Atom Representation

a Feynman diagram for how the proton keeps the electron within a specified range to the nucleus in a hydrogen atom. Recall that we previously investigated the scattering of light. Atoms with several protons greater than 1, and its associated number of electrons are responsible for the scattering of light. Such phenomena representing this matter is the sky. This also accounts for partial reflection, a matter we explored earlier. The sky is blue because the light from the sun is scattered when it interacts with the atoms in the air, providing us our blue sky. To provide a visualization of what a diagram might look like this, we will use the hydrogen atom

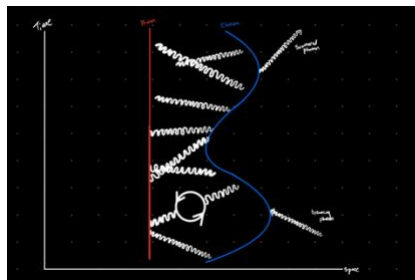


Figure 22. Electron scattering light within an Atom

because using the atoms that are required to do so would incorporate so many wiggly lines and straight lines, it would be incompressible. Figure 22, the phenomena of the scattering of light by an electron in an atom. As shown in the illustration, the proton (in the nucleus) is exchanging photons, and as they do so, from outside the atom, a photon hits the electron and is absorbed, the incoming photon. Then, a new photon is emitted, the scattered photon.

Once again, the examples used to demonstrate here on the implication of the theory of quantum of electrodynamics on electrons and their interactions are one of many. Further demonstrations on this matter and more in depth understanding and demonstrations of calculations and more complex phenomena can be found and demonstrated in Feynman's book, "QED: The Strange Theory of light and matter". Here goes into matters regarding electrons and their interactions regarding QED, such as: the phenomena of partial reflection and transmittance of light by a layer of glass; optics; index of refraction; and magnetic moment.

Loose Ends

When it comes to the matter of the theory of Quantum electrodynamics, it has held up for over 50 years. One may believe the characteristic of amplitudes in the quantum electrodynamics theory may have eventually led to problems of sorts. However, physicists have incorporated and implemented the use of amplitudes for quite some time now. New phenomena and new particles have arisen since the establishment of QED and the use of amplitudes, and it has continued to fit perfectly with said new phenomena and particles. Amplitudes we square to obtain the probability

of event, or otherwise known as the square of our final arrow. A final arrow resulted from the implementation of tip to tail method of a bunch of little arrows. Amplitude has proven no experimental doubt, where our theoretical values match with our experimental values.

Additionally, this does not denote the fact that the theory of quantum electrodynamics does not have any problems associated within it. This method of little arrows can be complex, and at times can take graduate students three or four years to master. It is a matter of improving the techniques for analyzing theory's true meaning in different and possibly more complex circumstances.

Nonetheless, the theory of quantum electrodynamics has and will serve as a significant base for describing other sorts of phenomena in many other areas of physics. For example, the composition of nuclei. Nuclei are composed of protons and neutrons. What holds the protons and neutrons within the nucleus? This introduced in 1970 the theory of quantum theory of strong interactions, otherwise known as quantum chromodynamics, QCD. A theory strongly related to QED, but rather than the main actors being protons and electrons, we have particles deemed quarks. Where protons and neutrons are composed of quarks, and rather than exchange of gluons. In fact, we can make diagrams for the exchanging of gluons between quarks and are extremely like the diagrams we draw for the protons and electrons exchanging photons. But for the theory of QCD, we incorporate gluon theory – where we have conservation of “color”. As well as conservation of “color” we have particles that are exchanged similarly to a photon, the W particle (a charged particle) and Z particle (neutral charged particle).

Lastly, we will conclude with one final matter. As we progress in the discovery of new particles, we find that elements are shared. That in a sense, we are getting the same things but with heavier. For example, the discovered tau and muon particles are essentially heavier versions of the electron, sharing the same characteristics of an electron but with greater mass. Let's take the muon. It has a mass 200 times higher than the electron. Implementing QED, the “stopwatch hand” simply moves 200 times faster than the electrons, and we can implement our amplitudes and little arrows. As we search for new particles, colliding them at even greater energies, we are left with the mystery of this repetition of particles with the same properties but heavier masses. As Feynman had once said, “Nature seems to keep piling on these particles as if to drug us”. However, we are concerned with the character of these laws brought upon nature, providing us the same particles but heavier masses. We will conclude with a statement by Feynman regarding that matter, “the *character* of those laws – the framework of amplitudes, the diagrams that represent the interactions to be calculated and so on – appears to be the same as for the theory of quantum electrodynamics, our best example of a good theory”.

References

**Please note all images not illustrated by the writer, Thomas Adams, are referenced accordingly on there allocated pages. In addition, all quotes and statements quoted by Feynman are implemented from his book on QED, referenced on page 2. Lastly, all illustrations by Thomas Adams regarding the matter of demonstrating/explain the theory of QED are modifications and or revisions of the those displayed in the previously stated book on QED.*