A Classical Quantum Theory of Light

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Abstract

The *Zitterbewegung* model of an electron offers a classical interpretation for interference and diffraction of electrons. The idea is very intuitive because it incorporates John Wheeler's idea of mass without mass: we have an indivisible naked charge that has no properties but its charge and its size (the classical electron radius) and it is easy to understand that the electromagnetic oscillation that keeps this tiny circular current going – like a perpetual current ring in some superconducting material – cannot be separated from it. In contrast, we keep wondering: what keeps a photon together? Hence, the real challenge for any realist interpretation of quantum mechanics is to explain the quantization of light: what *are* these photons?

In this paper, we offer a classical quantum theory for light. The intuition behind the model is the same as the one we developed for an electron: we think of the photon as a harmonic electromagnetic oscillator, and its elementary cycle determines its properties, including spin and its size (the effective area of interference).

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Introduction

Richard Feynman described the double-slit experiment with electrons – the interference of an electron with itself – as "a phenomenon which is impossible, *absolutely* impossible, to explain in any classical way, and which has in it the heart of quantum mechanics." The italics are Feynman's. He adds:

> "In reality, it contains the *only* mystery. We cannot make the mystery go away by 'explaining' how it works. We will just *tell* you how it works. In telling you how it works we will have told you about the basic peculiarities of all quantum mechanics."

This statement is an authoritative representation of the Copenhagen interpretation of quantum mechanics, which I might summarize as: "Don't think. Just accept the rules and do the calculations."[1] My previous papers[2] show that it is actually quite easy to develop a hybrid model of an electron – combining its wave and particle characteristics – which does the trick. This hybrid model goes back to a very trivial solution which Erwin Schrödinger discovered when exploring Dirac's wave equation for an electron in free space. It is worth quoting Dirac's summary of it:

> "The variables give rise to some rather unexpected phenomena concerning the motion of the electron. These have been fully worked out by Schrödinger. It is found that an electron which seems to us to be moving slowly, must actually have a very high frequency oscillatory motion of small amplitude superposed on the regular motion which appears to us. As a result of this oscillatory motion, the velocity of the electron at any time equals the velocity of light. This is a prediction which cannot be directly verified by experiment, since the frequency of the oscillatory motion is so high and its amplitude is so small. But one must believe in this consequence of the theory, since other consequences of the theory which are inseparably bound up with this one, such as the law of scattering of light by an electron, are confirmed by experiment." (Paul A.M. Dirac, *Theory of Electrons and Positrons*, Nobel Lecture, December 12, 1933)

David Hestenes is to be credited with the revival of what is now referred to as the *Zitterbewegung* model of an electron and we believe it is a strong contender for a *realist* interpretation of quantum mechanics. The description involves the idea of a naked pointlike charge – a charge with zero rest mass – whizzing around some center at the speed of light. The energy in this oscillation gives the electron its rest mass: it is John Wheeler's idea of 'mass without mass'.[3]

[1] I was told so much when doing the introductory online MIT course on quantum mechanics (edX course 8.01.1*x*): sophomore students should not ask too many questions, especially not if these questions cannot be answered and, therefore, start embarrassing the lecturers.
[2] See, for example: *The Electron as a Harmonic Electromagnetic Oscillator*, 31 May 2019 (http://vixra.org/abs/1905.0521).
[3] An easy-to-read reference to Wheeler's concept of mass without mass is: https://cpb-us-e1.wpmucdn.com/sites.uark.edu/dist/b/383/files/2017/02/Mass-without-Mass.pdf.

We have worked out the details in the mentioned papers so we won't repeat ourselves here. The point is: electron interference *can* be explained classically.[4] The difficulty is how to explain the quantization of light: what *are* these photons? We have an indivisible naked charge that has no properties but its charge and – we should add – its size[5], and it is intuitively easy to grasp that the electromagnetic oscillation that keeps this tiny circular current going – like a perpetual current ring in some superconducting material – cannot be separated from it. In contrast, we should wonder: *what keeps the photon together?*

This question is not easy to answer. It is, effectively, not a coincidence that Paul Dirac, in his introduction to his seminal *Principles of Quantum Mechanics*, focuses mainly on the wave-particle duality of *light* – as opposed to the wave-particle duality of matter-particles (fermions).[6] Hence, if we would want to present a viable realist interpretation of quantum mechanics, then *we need to come up with a classical quantum theory for light*.

We will try to do so in this paper. The intuition behind the model is the same as the one we developed for an electron: we will want to think of the photon as a harmonic electromagnetic oscillator.

The photon as a harmonic electromagnetic oscillator

Angular momentum comes in units of $\hbar$. When analyzing the electron orbitals for the simplest of atoms (the one-proton hydrogen atom), this rule amounts to saying the electron orbitals are separated by a amount of *physical action* that is equal to $h = 2\pi \cdot \hbar$. Hence, when an electron jumps from one level to the next – say from the second to the first – then the atom will lose one unit of h. The photon that is emitted or absorbed will have to pack that somehow. It will also have to pack the related energy, which is given by the Rydberg formula:

$$\mathrm{E}_{n_2} - \mathrm{E}_{n_1} = -\frac{1}{{n_2}^2}\mathrm{E}_R + \frac{1}{{n_1}^2}\mathrm{E}_R = \left(\frac{1}{{n_1}^2} - \frac{1}{{n_2}^2}\right) \cdot \mathrm{E}_R = \left(\frac{1}{{n_1}^2} - \frac{1}{{n_2}^2}\right) \cdot \frac{\alpha^2 \mathrm{m}c^2}{2}$$

[4] See, for example, the interesting work of Stefano Frabboni, Reggio Emilia, Gian Carlo Gazzadi, and Giulio Pozzi, as reported on the phys.org site (https://phys.org/news/2011-01-which-way-detector-mystery-doubleslit.html).

[5] While the *Zitterbewegung* charge is considered to be pointlike, it is *not* dimensionless. We infer its radius from elastic photon scattering experiments: it is equal to the classical or *Thomson* electron radius (r_e), which is $\alpha \approx 1/137$ times the *Compton* radius of the electron (a), which we get from inelastic (Compton) scattering experiments. Inelastic scattering occurs when high-energy photons (the light is X- or gamma-rays, with high frequency and very small wavelength) hit the electron. Their energy is briefly absorbed before the electron comes back to its equilibrium situation by emitting another photon, that is less energetic. The difference in the energy of the incoming and the outgoing photon gives the electron some linear momentum: it accelerates or changes direction. It is because of the interference effect that Compton scattering is referred to as inelastic. In contrast, low-energy photons scatter elastically: the photon seems to bounce off some hard *core*: there is no interference. In our interpretation of the *Zitterbewegung* model of an electron, we think of this hard core as the naked pointlike charge itself and, hence, we can now interpret the fine-structure constant as the radius of the pointlike charge expressed in a natural distance unit (a). Our paper on the anomalous magnetic moment – see: *The Anomalous Magnetic Moment: Classical Calculations*, 11 June 2019 (http://vixra.org/abs/1906.0007) – shows this interpretation can explains the anomaly in a classical way: there is no need for quantum field theory.

[6] See: *Dirac's Philosophical Principles*, 11 June 2019 (http://vixra.org/abs/1906.0160).

To focus our thinking, let us consider the transition from the second to the first level, for which the $1/1^2 - 1/2^2$ is equal 0.75. Hence, the photon energy should be equal to $(0.75) \cdot E_R \approx 10.2$ eV. Now, if the total action is equal to *h*, then the cycle time T can be calculated as:

$$\mathrm{E} \cdot \mathrm{T} = h \Leftrightarrow \mathrm{T} = \frac{h}{\mathrm{E}} \approx \frac{4.135 \times 10^{-15} \mathrm{eV} \cdot \mathrm{s}}{10.2 \ \mathrm{eV}} \approx 0.4 \times 10^{-15} \ \mathrm{s}$$

This corresponds to a wave train with a length of $(3 \times 10^8 \ \mathrm{m/s}) \cdot (0.4 \times 10^{-15} \ \mathrm{s}) = 122$ nm. That is the size of a large molecule and it is, therefore, much more reasonable than the length of the wave trains we get when thinking of transients using the supposed Q of an atomic oscillator.[7] In fact, this length is the wavelength of the light ($\lambda = c/f = c \cdot \mathrm{T} = h \cdot c/\mathrm{E}$) that we would associate with this photon energy.[8]

Let us quickly insert another calculation, which you may find interesting—or not. If we think of an electromagnetic oscillation – as a beam or, what we are trying to do here, as some *quantum* – then its energy is going to be proportional to (a) the square of the amplitude of the oscillation – and we are *not* thinking of a quantum-mechanical amplitude here: we are talking the amplitude of a *physical* wave here – and (b) the square of the frequency. Hence, if we write the amplitude as *a* and the frequency as ω, then the energy should be equal to $\mathrm{E} = k \cdot a^2 \cdot \omega^2$. The k is just a proportionality factor.

However, relativity theory tells us the energy will have some equivalent mass, which is given by Einstein's mass-equivalence relation: $\mathrm{E} = m \cdot c^2$. Hence, the energy will also be proportional to this equivalent mass. It is, therefore, very tempting to equate k and m. We can only do this, of course, if c^2 is equal to $a^2 \cdot \omega^2$ or – what amounts to the same – if $c = a \cdot \omega$. You will recognize this as a tangential velocity formula, and so you should wonder: the tangential velocity of *what*? The *a* in the $\mathrm{E} = k \cdot a^2 \cdot \omega^2$ formula that we started off with is an amplitude: why would we suddenly think of it as a radius now? I can*not* give you a very convincing answer to that question but – intuitively – we will probably want to think of our photon as having a circular polarization. Why? Because it is a boson and it, therefore, has angular momentum. To be precise, its angular momentum is $+\hbar$ or $-\hbar$. There is no zero-spin state.[9] Hence, if we think of this classically, then we will associate it with circular polarization.

[7] In one of his famous *Lectures* (I-32-3), Feynman thinks about a sodium atom, which emits and absorbs sodium light, of course. Based on various assumptions – assumption that make sense in the context of the blackbody radiation model but *not* in the context of the Bohr model – he gets a Q of about 5×10^7. Now, the frequency of sodium light is about 500 THz (500×10^{12} oscillations per second). Hence, the *decay time* of the radiation is of the order of 10^{-8} seconds. So that means that, after 5×10^7 oscillations, the amplitude will have died by a factor $1/e \approx 0.37$. That seems to be very short, but it still makes for 5 million oscillations and, because the wavelength of sodium light is about 600 nm (600×10^{-9} meter), we get a wave train with a considerable length: $(5 \times 10^6) \cdot (600 \times 10^{-9}$ meter) = 3 meter. *Surely you're joking, Mr. Feynman!* A photon with a length of 3 meter – or longer? While one might argue that relativity theory saves us here (relativistic length contraction should cause this length to reduce to zero as the wave train zips by at the speed of light), this just doesn't feel right – especially when one takes a closer look at the assumptions behind.

[8] This is short-wave ultraviolet light (UV-C). It is the light that is used to purify water, food or even air. It kills or inactivate microorganisms by destroying nucleic acids and disrupting their DNA. It is, therefore, harmful. The ozone layer of our atmosphere blocks most of it.

[9] This is one of the things in mainstream quantum mechanics that bothers me. All courses in quantum mechanics spend like two or three chapters on why bosons and fermions are different (spin-one versus spin-1/2) and, when it comes to the specifics, then the only boson we actually know (the photon) turns out to *not* be a typical boson because it can't have zero spin. Feynman gives some haywire explanation for this is section 4 of *Lecture* III-17. I will let you look it up (Feynman's *Lectures* are online) but, as far as I am concerned, I think it's really one of those things which makes me think of Prof. Dr. Ralston's criticism of his own profession: "*Quantum mechanics is the only subject in physics where teachers traditionally present haywire axioms they don't really believe, and regularly violate in research*." (John P. Ralston, *How To Understand Quantum Mechanics*, 2017, p. 1-10)

We are now ready for some calculations. If the energy E in the Planck-Einstein relation (E = ħ·ω) and the energy E in the energy equation for an oscillator (E = m·a^2·ω^2) are the same – and they should be because we are talking about some thing that has some energy – then we get the following formula for the amplitude or radius a:

$$\mathrm{E} = \hbar \cdot \omega = \mathrm{m} \cdot a^2 \cdot \omega^2 \Leftrightarrow \hbar = \mathrm{m} \cdot a^2 \cdot \omega \Leftrightarrow a = \sqrt{\frac{\hbar}{\mathrm{m} \cdot \omega}} = \sqrt{\frac{\hbar}{\frac{\mathrm{E}}{c^2} \cdot \frac{\mathrm{E}}{\hbar}}} = \sqrt{\frac{\hbar^2}{\mathrm{m}^2 \cdot c^2}} = \frac{\hbar}{\mathrm{m} \cdot c}$$

This is the formula for the Compton radius of an electron ! How can we explain this? What relation could there possibly be between our *Zitterbewegung* model of an electron and the quantum of light? We do not want to confuse the reader too much but things become somewhat more obvious when staring at the illustration below (Figure 1). We think of the *Zitterbewegung* of a free electron as a circular oscillation of a pointlike *charge* (with *zero* rest mass) moving about some center at the speed of light. However, as the electron starts moving along some *linear* trajectory at a relativistic velocity (i.e. a velocity that is a *substantial* fraction of *c*), then the *radius* of the oscillation will have to diminish – because the tangential velocity remains what it is: *c*. The geometry of the situation shows the circumference – so that's the Compton *wavelength* $\lambda_C = 2\pi \cdot a = 2\pi\hbar/\mathrm{m}c$ – becomes a wavelength in this process.

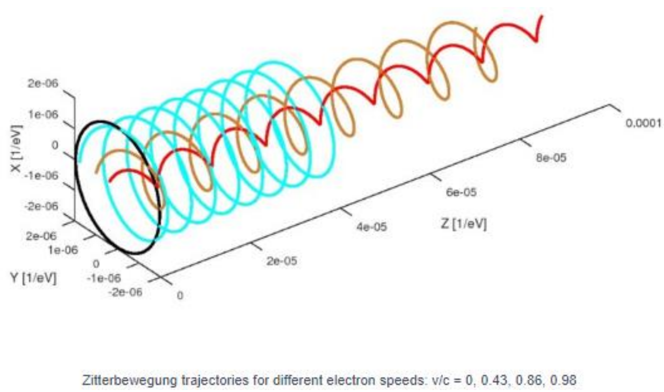


Figure 1: The Compton radius must decrease with increasing velocity

Of course, we should remind ourselves that the m in the $a = \hbar/\mathrm{m}c$ equation here is *not* the mass of the electron but the (equivalent) mass of the photon. The Compton radius of a photon is, therefore, different than the Compton radius of an electron. Let us quickly calculate it for our 10.2 eV photon. We should, of course, express the energy in SI units (10.2 eV ≈ 1.634×10^{-18} *J*) to get what we should get:

$$a = \frac{\hbar}{\mathrm{m} \cdot c} = \frac{\hbar}{\mathrm{E}/c} = \frac{(1.0545718 \times 10^{-18}\, J \cdot s) \cdot (3 \times 10^{8}\, m/s)}{1.634 \times 10^{-18}\, J} \approx 19.4 \times 10^{-9}\ \mathrm{m}$$

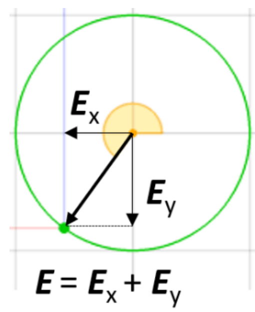
How does this compare to the Compton radius of an electron? The Compton radius of an electron is equal to about 386×10^{-15} m, so that's about 50,000 times *smaller* than the Compton radius of a photon. Unsurprisingly, that's the ratio between the electron's (rest) energy (about 8.187×10^{-14} *J*) and the photon energy (about 1.634×10^{-18} *J*). It is somewhat counterintuitive that the Compton radius is *inversely* proportional to the (rest) mass or energy, but that's how it is.

A final intuition may be confirmed by calculating the Compton radius for highly energetic photons. For example, the X-ray photons in the original Compton scattering experiment had an energy of about 17 keV = 17,000 eV and modern-day experiments will use gamma rays with even higher energies. One experiment, for example, uses a cesium-137 source emitting photons with an energy that is equal to 0.662 MeV = 662,000 eV. We can see these high photon energies can easily bridge the gap with the rest energy of the electron they are targeting.

[…] While we can see these calculations makes sense – the Compton radius is, obviously, some kind of effective radius of interference – it does not quite answer the question we started out with: the Compton wavelength becomes the wavelength of the photon but the question remains: what *is* that amplitude?

We will try to give a more detailed answer but, before we do so, let us further explore this *one-cycle photon model* of ours. We can use the elementary wavefunction to represent the rotating field vector or, remembering the F = q_eE equation, the force field (see Figure 2).

Figure 2: The one-cycle photon



It is a delightfully simple model: the photon is just one single cycle traveling through space and time, which packs one unit of angular momentum ($\hbar$) or – which amounts to the same, one unit of physical action (h). This gives us an equally delightful interpretation of the Planck-Einstein relation (f = 1/T = E/h) and we can, of course, do what we did for the electron, which is to express h in two alternative ways: (1) the product of some momentum over a distance and (2) the product of energy over some time. We find, of course, that the distance and time correspond to the wavelength and the cycle time:

$$h = \mathrm{p} \cdot \lambda = \frac{\mathrm{E}}{c} \cdot \lambda \Leftrightarrow \lambda = \frac{hc}{\mathrm{E}}$$

$$h = \mathrm{E} \cdot \mathrm{T} \Leftrightarrow \mathrm{T} = \frac{h}{\mathrm{E}} = \frac{1}{f}$$

Needless to say, the E = mc^2 mass-energy equivalence relation can be written as p = mc = E/c for the photon. The two equations are, therefore, wonderfully consistent:

$$h = \mathrm{p} \cdot \lambda = \frac{\mathrm{E}}{c} \cdot \lambda = \frac{\mathrm{E}}{f} = \mathrm{E} \cdot \mathrm{T}$$

Let us now try something more adventurous: let us try to calculate the strength of the electric field. How can we do that? Energy is some force over a distance and, hence, the force must equal the ratio of the energy and the distance. What distance should we use? The force will vary over the cycle and, hence, this distance is a distance that we must be able to relate to this fundamental cycle. Is it the Compton *radius* (a) or the wavelength (λ)? They differ by a factor 2π only, so let us just try the radius and see if we get some kind of sensible result:

$$\mathrm{F} = \frac{\mathrm{E}}{a} = \frac{2\pi \cdot \mathrm{E}}{\lambda} = \frac{2\pi \cdot h \cdot f}{\lambda} = \frac{2\pi \cdot h \cdot c}{\lambda^2}$$

Does this look weird? Not really. We get the E·λ = h·c equation from *de Broglie*'s h = p·λ = m·c·λ = E·λ/c equation and the equation above respects that equation:

$$\frac{\mathrm{E}}{a} = \frac{2\pi \cdot h \cdot c}{\lambda^2} \Leftrightarrow \mathrm{E} \cdot \lambda = \frac{2\pi \cdot a \cdot h \cdot c}{\lambda} = h \cdot c$$

Let's try the next logical step. The electric field – which we will write as E[10] – is the force per unit charge which, we should remind the reader, is the *coulomb* – *not* the electron charge. Why? Because we use SI units. We, therefore, get a delightfully simple formula for the strength of the electric field vector for a photon[11]:

$$E = \frac{\frac{2\pi hc}{\lambda^2}}{1} = \frac{2\pi hc}{\lambda^2} = \frac{2\pi \mathrm{E}}{\lambda} = \frac{\mathrm{E}}{a}$$

The electric field is the ratio of the energy and the Compton radius. Does this make sense? What about units? We divided by 1 *coulomb* and the physical dimension is, therefore, equal to [E] = [E/a] *per coulomb*. A *joule* is a newton·meter and [E/a] is, therefore, equal to N·m/m = N. We're fine. Let us calculate its value for our 10.2 eV photon (using SI units once again, of course):

$$E \approx \frac{1.634 \times 10^{-18}\, J}{19.4 \times 10^{-9}\, m \cdot C} \approx 84 \times 10^{-12}\, \frac{\mathrm{N}}{\mathrm{C}}$$

Let us return to our original question: what *is* that amplitude? It turns out to be a natural distance unit: if we use it as a divisor, then we get the field strength! Is this significant? We think it is. Significant enough for a small digression we would think.

The meaning of the fine-structure constant

The Compton radius – for a *photon* and, importantly, for an electron – appears as a natural distance unit. Is this significant? What's the deeper meaning here? We find it very interesting because we can now relate this discussion to the meaning of the fine-structure constant. Indeed, I have written a lot about the fine-structure constant—God's Number as it is often referred to, as a result of a quote that Ralph Leighton attributes to Richard Feynman in his transcription of the *Alix Mautner* lectures.[12] We'll

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[10] The E and E symbols should not be confused. E is the magnitude of the electric field vector and E is the energy of the photon. We hope the italics (E) – and the context of the formula, of course! – will be sufficient to help the reader distinguish the electric field vector (E) from the energy (E). We do not needlessly want to multiply the number of symbols we are using here.

[11] The E and E symbols should not be confused. E is the magnitude of the electric field vector and E is the energy of the photon. We hope the italics (E) – and the context of the formula, of course! – will be sufficient to distinguish the electric field vector (E) from the energy (E).

[12] These lectures were recorded and transcribed a few years before Feynman died and, hence, Feynman may not have re-read the transcription. For a discussion, see my blog article on it: https://readingfeynman.org/2015/01/22/the-strange-theory-of-light-and-matter-iii/.

give the full quote, which is made in the context of a discussion on one of the many meanings of the fine-structure constant—which is that of it being a quantum-mechanical coupling constant:

> "There is a most profound and beautiful question associated with the observed coupling constant, i.e. the amplitude for a real electron to emit or absorb a real photon. It is a simple number that has been experimentally determined to be close to 0.08542455. My physicist friends won't recognize this number, because they like to remember it as the inverse of its square: about 137.03597 with about an uncertainty of about 2 in the last decimal place.
>
> It has been a mystery ever since it was discovered more than fifty years ago, and all good theoretical physicists put this number up on their wall and worry about it. Immediately you would like to know where this number for a coupling comes from: is it related to π or perhaps to the base of natural logarithms? Nobody knows. It's one of the greatest damn mysteries of physics: a magic number that comes to us with no understanding by man. You might say the "hand of God" wrote that number, and "we don't know how He pushed his pencil." We know what kind of a dance to do experimentally to measure this number very accurately, but we don't know what kind of dance to do on the computer to make this number come out, without putting it in secretly!"

In my writings on it[13], I have always to demystify this number by showing *how and why exactly* it pops us in this or that formula (e.g. Rydberg's energy formula, the ratio of the various radii of an electron (Thomson, Compton and Bohr radius), the coupling constant, the anomalous magnetic moment, etcetera), as opposed to what most seem to try to do, and that is to further confuse the amateur physicist. However, I must admit that – till now – I wasn't quite able to answer this very simple question: what *is* that fine-structure constant? Why *exactly* does it appear as a scaling constant or a coupling constant in almost any equation you can think of but *not* in, say, Einstein's mass-energy equivalence relation, or the *de Broglie* relations?

I finally have a final answer (pun intended) to the question, and it's surprisingly easy: it is the radius of the naked charge in the electron expressed in terms of the natural distance unit that comes out of our *Zitterbewegung* interpretation of what an electron actually is. That's it. That's all. All the other calculations follow from it.

Why? I have to refer to my classical calculations of the anomalous magnetic moment here[14] because re-explaining would take up too much space. However, we do want to show why it pops up in the context of electron-photon coupling. As a coupling constant, the fine-structure constant will be written as the ratio between (1) $k \cdot q_e^2$ and (2) E·λ. We can interpret this as follows:

1. The $k \cdot q_e^2$ in this ratio is just the product of the electric potential between two elementary charges (we should think of the proton and the electron in our hydrogen atom here) and the distance between them:

$$\mathrm{U}(r) = \frac{k \cdot \mathrm{q_e}^2}{r} = \frac{\mathrm{q_e}^2}{4\pi\varepsilon_0 r} \Leftrightarrow k \cdot \mathrm{q_e}^2 = \mathrm{U}(r) \cdot r$$

[13] See: *Layered Motions: The Meaning of the Fine-Structure Constant*, 23 December 2018 (http://vixra.org/abs/1812.0273).
[14] See: *The Anomalous Magnetic Moment: Classical Calculations*, 11 June 2019 (http://vixra.org/abs/1906.0007).

2. The fine-structure constant can then effectively be written as:

$$\alpha = \frac{k \cdot \mathrm{q_e}^2}{\hbar \cdot c} = \frac{k \cdot \mathrm{q_e}^2}{\hbar \cdot c} = \frac{\mathrm{U}(r) \cdot r}{\mathrm{E}_{photon} \cdot r_{photon}}$$

We can also write this in terms of forces times the *squared* distance:

$$\alpha = \frac{k \cdot \mathrm{q_e}^2}{\hbar \cdot c} = \frac{\mathrm{F_B} \cdot r_\mathrm{B}^2}{\mathrm{F}_\gamma \cdot r_\gamma \cdot r_\gamma} = \frac{\mathrm{F_B} \cdot r_\mathrm{B}^2}{\mathrm{F}_\gamma \cdot r_\gamma^2} = \frac{\mathrm{E_B} \cdot r_\mathrm{B}}{\mathrm{E}_\gamma \cdot r_\gamma}$$

This doesn't look too bad. We use B (from *B*ohr) and γ (gamma) as a subscript in the numerator and denominator respectively to remind ourselves we are talking about the energies and radii of the Bohr orbitals and the photon respectively. Let us write it all out to demonstrate the consistency of this formula, using the generalized formulas (n = 1, 2,…) for these energies ($\mathrm{E_B}$) and radii (r_B)[15]:

$$\alpha = \frac{\mathrm{E_B} \cdot r_\mathrm{B}}{\mathrm{E}_\gamma \cdot r_\gamma} = \frac{\frac{1}{n^2}\alpha^2 \mathrm{m}c^2 \cdot \frac{n^2}{\alpha}\frac{\hbar}{\mathrm{m}c}}{\mathrm{E}_\gamma \cdot \frac{\hbar \cdot c}{\mathrm{E}_\gamma}} = \alpha$$

Sometimes physics can just be *nice*: our simple photon model does a lot of tricks!

Let us make a final check on the logical consistency of this model. We are in a good position to re-visit that $\mathrm{E} = \mathrm{k} \cdot a^2 \cdot \omega^2$ formula here, so let us quickly do that. We said it would be wonderful if we could interpret the proportionality coefficient k as the mass m. Why? Because we have used the $\mathrm{E} = \mathrm{m} \cdot a^2 \cdot \omega^2$ equation before: it gave us this wonderful interpretation of the *Zitterbewegung* as what we referred to as the *rest matter oscillation*. Hence, it is really nice we can repeat that trick here using a Compton radius for the *photon*:

$$\mathrm{E} = \mathrm{k}a^2\omega^2 = \mathrm{k}\frac{\hbar^2 c^2}{\mathrm{E}^2}\frac{\mathrm{E}^2}{\hbar^2} = \mathrm{k}c^2 \Leftrightarrow \mathrm{k} = \mathrm{m}$$

Before we move on, we need to answer an obvious question: what happens when an electron jumps several Bohr orbitals? The angular momentum between the orbitals will then differ by *several* units of $\hbar$. What happens to the photon picture in that case? It will pack the energy difference, but should it also pack several units of $\hbar$? In other words, should we still think of the photon as a one-cycle oscillation, or will the energy be spread over several cycles?

We will let the reader think about this, but our intuitive answer is: the photon is a spin-one particle and, hence, its energy should, therefore, be packed in one cycle only. This is also necessary for the consistency of the interpretation here: when everything is said and done, we do interpret the wavelength as a *physical* distance. To put it differently, the equation below needs to make sense:

$$h = \mathrm{p} \cdot \lambda = \frac{\mathrm{E}}{c} \cdot \lambda = \frac{\mathrm{E}}{f} = \mathrm{E} \cdot \mathrm{T}$$

All of the above were merely some starters. We are now going to start the main course.

[15] These formulas can be found in many classical texts but, if in doubt and if you'd want to see how we get these, see Chapter VII of my manuscript http://vixra.org/abs/1901.0105.

The interference of a photon with itself

Circular and linear polarization states

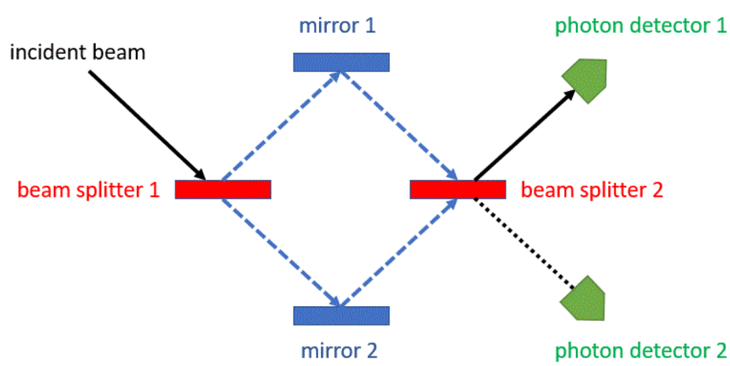
We mentioned that we think of our photon being circularly polarized—*always*. Why? Because it is a boson and it, therefore, has angular momentum. To be precise, its angular momentum is $+\hbar$ or $-\hbar$. There is no zero-spin state. Hence, if we think of this classically, then we will associate it with circular polarization. In a footnote, I mentioned this is one of the many things that bothers me. All courses in quantum mechanics spend like two or three chapters on why bosons and fermions are different (spin-one versus spin-1/2) and, when it comes to the specifics, then the only boson we actually know (the photon) turns out to *not* be a typical boson because it can't have zero spin.

Of course, it is what it is, and we can work with it. In fact, we think it's the key to solving the mystery of Mach-Zehnder interference: how could a photon possibly follow two paths simultaneous, somehow, and then interfere with itself?

The Mach-Zehnder experiment

The Mach-Zehnder interferometer consists of two beam splitters (BS1 and BS2) and two perfect mirrors (M1 and M2). An incident beam coming from the left is split at BS1 and recombines at BS2, which sends two outgoing beams to the photon detectors D0 and D1. More importantly, the interferometer can be set up to produce a precise interference effect which ensures all the light goes into D0, as shown below. Alternatively, the setup may be altered to ensure all the light goes into D1.

Figure 3: The Mach-Zehnder interferometer



If we have a proper *beam* of light, then we have an easy explanation, which goes like this:

- The first beam splitter (BS1) splits the beam into *two* beams.
- These two beams arrive in phase or, alternatively, out of phase and we, therefore, have constructive or destructive interference that recombines the original beam and makes it go towards D0 or, alternatively, towards D1.

However, when we analyze this in terms of a *single* photon – we now think of the photons going one-by-one through the apparatus – then this classical picture becomes quite complicated. Complicated but – as we argue – not impossible. An alternative theory of what happens in the Mach-Zehnder interferometer might be the following one:

1. The incoming photon is circularly polarized (left- or right-handed).

2. The first beam splitter splits our photon into two linearly polarized waves.
3. The mirrors reflect those waves and the second beam splitter recombines the two linear waves back into a circularly polarized wave.
4. The positive or negative interference then explains the binary outcome of the Mach-Zehnder experiment – at the level of a photon – *in classical terms*.

We will detail this in the next section, because what happens in a Mach-Zehnder interferometer is not all that straightforward. We should note, for example, that there are phase shifts along both paths: classical physics tells us that, on transmission, a wave does not pick up any phase shift, but it does so on reflection. To be precise, it will pick up a phase shift of π on reflection. We will refer to the standard textbook explanations of these subtleties and just integrate them in our more detailed explanation in the next section.[16] Before we do so, we will show the assumption that the two linear waves are orthogonal to each other is quite crucial. If they weren't, we would be in trouble with the energy conservation law. Let us show that before we proceed. Why? Because Dirac also mentions it as an argument *against* any classical explanation of the interference phenomenon.

The energy conservation law

Suppose the beams would be polarized along the same direction. If *x* is the direction of propagation of the wave, then it may be the *y*- or *z*-direction of anything in-between. The magnitude of the electric field vector will then be given by a sinusoid. Now, we assume we have *two* linearly polarized beams, of course, which we will refer to as beam *a* and *b* respectively. These waves are likely to arrive with a phase difference – unless the apparatus has been set up to ensure the distances along both paths are exactly the same. Hence, the general case is that we would describe *a* by $cos(\omega \cdot t - k \cdot x) = cos(\theta)$ and *b* by $cos(\theta + \Delta)$ respectively. In the classical analysis, the difference in phase (Δ) will be there because of a difference of the path lengths[17] and the recombined wavefunction will be equal to the same cosine function, but with argument $\theta + \Delta/2$, multiplied by an *envelope* equal to $2 \cdot \cos(\Delta/2)$. We write[18]:

$$\cos(\theta) + \cos(\theta + \Delta) = 2 \cdot \cos(\theta + \Delta/2) \cdot \cos(\Delta/2)$$

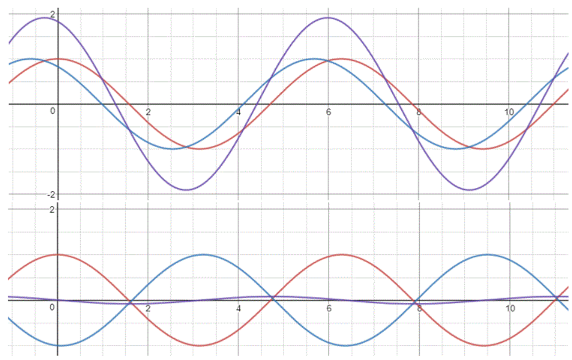
We always get a recombined beam with the same frequency, but when the phase difference between the two incoming beams is small, its amplitude is going to be much larger. To be precise, it is going to be twice the amplitude of the incoming beams for $\Delta = 0$. In contrast, if the two beams are out of phase, the amplitude is going to be much smaller, and it's going to be zero if the two waves are 180 degrees out of phase ($\Delta = \pi$), as shown below. That does not make sense because twice the amplitude means *four* times the energy, and zero amplitude means zero energy. The energy conservation law is being violated: photons are being multiplied or, conversely, are being destroyed.

[16] For a good *classical* explanation of the Mach-Zehnder interferometer, see: K.P. Zetie, S.F. Adams and R.M. Tocknell, January 2000, *How does a Mach–Zehnder interferometer work?* (https://www.cs.princeton.edu/courses/archive/fall06/cos576/papers/zetie_et_al_mach_zehnder00.pdf, accessed on 5 November 2018).
For a good quantum-mechanical explanation (interference of single photons), see – for example – the Mach-Zehnder tutorial from the PhysPort website (https://www.physport.org/curricula/QuILTs/, accessed on 5 November 2018).

[17] Feynman's path integral approach to quantum mechanics allows photons (or probability amplitudes, we should say) to travel somewhat slower or faster than *c*, but that should not bother us here.

[18] We are just applying the formula for the sum of two cosines here. If we would add sines, we would get $\sin(\theta) + \sin(\theta + \Delta) = 2 \cdot \sin(\theta + \Delta/2) \cdot \cos(\Delta/2)$. Hence, we get the same envelope: $2 \cdot \cos(\Delta/2)$.

Figure 4: Constructive and destructive interference for linearly polarized beams



Let us be explicit about the energy calculation. We assumed that, when the incoming beam splits up at BS1, that the energy of the *a* and *b* beam will be split in half too. We know the energy is given by (or, to be precise, proportional to) the square of the amplitude (let us denote this amplitude by *A*).[19] Hence, if we want the energy of the two individual beams to add up to $A^2 = 1^2 = 1$, then the (maximum) amplitude of the *a* and *b* beams must be 1/√2 of the amplitude of the original beam, and our formula becomes:

$$(1/\sqrt{2})\cdot\cos(\theta) + (1/\sqrt{2})\cdot\cos(\theta + \Delta) = (2/\sqrt{2})\cdot\cos(\theta + \Delta/2)\cdot\cos(\Delta/2)$$

This reduces to $(2/\sqrt{2})\cdot\cos(\theta)$ for $\Delta = 0$. Hence, we still get *twice* the energy – $(2/\sqrt{2})^2$ equals 2 – when the beams are in phase and zero energy when the two beams are 180 degrees out of phase. This doesn't make sense.

Of course, the mistake in the argument is obvious. This is why our assumption that the two linear waves are orthogonal to each other comes in: we cannot just add the amplitudes of the *a* and *b* beams because they have different directions. If the *a* and *b* beams – after being split from the original beam – are linearly polarized, then the angle between the axes of polarization should be equal to 90 degrees to ensure that the two oscillations are independent. We can then add them like we would add the two parts of a complex number. Remembering the geometric interpretation of the imaginary unit as a counterclockwise rotation, we can then write the sum of our a and b beams as:

$$(1/\sqrt{2})\cdot\cos(\theta) + i\cdot(1/\sqrt{2})\cdot\cos(\theta + \Delta) = (1/\sqrt{2})\cdot[\cos(\theta) + i\cdot\cos(\theta + \Delta)]$$

What can we do with this? Not all that much, except noting that we can write the $cos(\theta + \Delta)$ as a sine for $\Delta = \pm\,\pi/2$. To be precise, we get:

$$(1/\sqrt{2})\cdot\cos(\theta) + i\cdot(1/\sqrt{2})\cdot\cos(\theta + \pi/2) = (1/\sqrt{2})\cdot(\cos\theta - i\cdot\sin\theta) = (1/\sqrt{2})\cdot e^{-i\cdot\theta}$$

$$(1/\sqrt{2})\cdot\cos(\theta) + i\cdot(1/\sqrt{2})\cdot\cos(\theta - \pi/2) = (1/\sqrt{2})\cdot(\cos\theta + i\cdot\cos\theta) = (1/\sqrt{2})\cdot e^{i\cdot\theta}$$

This gives us the classical explanation we were looking for:

1. The incoming photon is circularly polarized (left- or right-handed).
2. The first beam splitter splits our photon into two linearly polarized waves.

[19] If we would reason in terms of average energies, we would have to apply a 1/2 factor because the average of the $\sin^2\theta$ and $\cos^2\theta$ over a cycle is equal to 1/2.

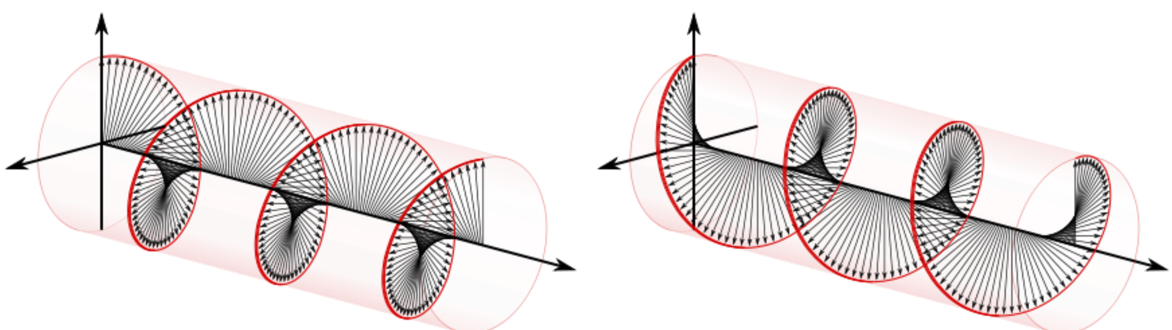
3. The mirrors reflect those waves and the second beam splitter recombines the two linear waves back into a circularly polarized wave.
4. The positive or negative interference then explains the binary outcome of the Mach-Zehnder experiment – at the level of a photon – *in classical terms*.

What about the 1/√2 factor? If the $e^{-i\cdot\theta}$ and $e^{i\cdot\theta}$ wavefunctions can, effectively, be interpreted geometrically as a *physical* oscillation in *two* dimensions – which is, effectively, our interpretation of the wavefunction[20] – then then each of the two (independent) oscillations will pack one half of the energy of the wave. Hence, if such *circularly* polarized wave splits into two *linearly* polarized waves, then the two linearly polarized waves will effectively, pack half of the energy without any need for us to think their (maximum) amplitude should be adjusted. If we now think of the ***x***-direction as the direction of the incident beam in the Mach-Zehnder experiment, and we would want to also think of rotations in the ***xz***-plane, then we need to need to introduce some new convention here. Let us introduce *another* imaginary unit, which we'll denote by *j*, and which will represent a 90-degree counterclockwise rotation in the ***xz***-plane.[21]

The circularly polarized photon and the reality of the linear polarization states

Our photon model is consistent with the assumption they will – altogether – make for a beam that is circularly polarized. The spin direction may, of course, be left-handed or right-handed, as shown below (Figure 5).

Figure 5: Left- and right-handed polarization[22]



We are now coming to the crux of the matter: **we will think of these photons as the sum of two linearly polarized oscillations**. We write:

$$cos\theta + i\cdot sin\theta = e^{i\cdot\theta} \text{ (RHC)}$$

$$cos(-\theta) + i\cdot sin(-\theta) = cos\theta - i\cdot sin\theta = e^{-i\cdot\theta} \text{ (LHC)}$$

What is the geometry here? It is quite simple but let us spell it out so we have no issues of interpretation. If ***x*** is the direction of propagation of the wave, then the ***z***-direction will be pointing

[20] We can assign the physical dimension of the electric field (force per unit charge, N/C) to the two perpendicular oscillations.
[21] This convention may make the reader think of the quaternion theory but we are thinking more of simple Euler angles here: *i* is a (counterclockwise) rotation around the *x*-axis, and *j* is a rotation around the *y*-axis.
[22] Credit: https://commons.wikimedia.org/wiki/User:Dave3457.

upwards, and we get the ***y***-direction from the righthand rule for a Cartesian reference frame.[23] We may now think of the oscillation along the ***y***-axis as the cosine, and the oscillation along the ***z***-axis as the sine. If we then think of the imaginary unit *i* as a 90-degree counterclockwise rotation in the ***yz***-plane (and remembering the convention that angles (including the phase angle θ) are measured counterclockwise), then the right- and left-handed waves can effectively be represented by the wavefunctions above.

It was, in fact, easy visualizations like this that encouraged us to think of a geometric representation of the wavefunction. For example, we may adopt the convention that the imaginary unit should be interpreted as a unit vector pointing in a direction that is perpendicular to the direction of propagation of the wave and one may then write the magnetic field vector as $\mathbf{B} = -i\cdot\mathbf{E}/c$.[24] The minus sign in the $\mathbf{B} = -i\cdot\mathbf{E}/c$. It is there because of consistency: we must combine a classical *physical* right-hand rule for **E** and **B** here as well as the *mathematical* convention that multiplication with the imaginary unit amounts to a *counter*clockwise rotation by 90 degrees. This allows us to re-write Maxwell's equations using complex numbers. We have done that in other papers, so if the reader is interested he can check there.[25] The point to note is that, while we will often sort of forget to show the magnetic field vector, the reader should always think of it – because it is an integral part of the electromagnetic wave: when we think of **E**, we should also think of **B**. Both oscillations carry energy.

The mention of energy brings me to another important point. As mentioned above, we think of a circularly polarized beam – and a photon – as a superposition of two linear waves. Now, these two linearly polarized waves will each pack *half* of the energy of the combined wave. It is a very important point to make because any classical explanation of interference – like the one we will offer in the next section – will need to respect the energy conservation law. Note that, while each wave packs *half* of the energy of the combined wave, their (maximum) amplitude is the same: there is no change there. We can now offer the following classical explanation of the Mach-Zehnder experiment *for one photon only*.[26]

[23] Note the reference frame in the illustrations of the LHC and RHC wave – which we took from Wikipedia – is left-handed. Our argument will use a regular right-handed reference frame.

[24] As usual, we use **boldface** letters to represent geometric vectors – the electric (**E**) and magnetic field vectors (**B**), in this case. There is a risk of confusion between the energy E and the electric field E because we use the same symbols, but the context should make clear what is what.

[25] See, for example, Jean Louis Van Belle, *A geometric interpretation of Schrödinger's equation*, http://vixra.org/pdf/1812.0202v1.pdf.

[26] We have written about this topic before (see: Jean Louis Van Belle, *Linear and circular polarization states in the Mach-Zehnder interference experiment*, 5 November 2018, http://vixra.org/pdf/1811.0056v1.pdf). Hence, we will only offer a summary of what we wrote there.

A classical explanation for the interference of a photon with itself

We may now advance the following *classical* explanation for the results of the one-photon Mach-Zehnder experiment:

Photon polarization	At BS1	At mirror	At BS2	Final result
RHC	Photon ($e^{i\cdot\theta} = cos\theta + i\cdot sin\theta$) is split into two linearly polarized beams: Upper beam (vertical oscillation) = $j\cdot\sin\theta$ Lower beam (horizontal oscillation) = $\cos\theta$	The vertical oscillation gets rotated clockwise and becomes $-j\cdot j\cdot\sin\theta = -j^2\cdot\sin\theta = \sin\theta$ The horizontal oscillation is not affected and is still represented by $\cos\theta$	Photon is recombined. The upper beam gets rotated counter-clockwise and becomes $j\cdot\sin\theta$. The lower beam is still represented by $\cos\theta$	The photon wavefunction is given by $\cos\theta + j\cdot\sin\theta = e^{+j\cdot\theta}$. This is an RHC photon travelling in the *xz*-plane but rotated over 90 degrees.
LHC	Photon ($e^{-i\cdot\theta} = cos\theta - i\cdot sin\theta$) is split into two linearly polarized beams: Upper beam (vertical oscillation) = $-j\cdot\sin\theta$ Lower beam (horizontal oscillation) = $\cos\theta$	The vertical oscillation gets rotated clockwise and becomes $(-j)\cdot(-j)\cdot\sin\theta = = j^2\cdot\sin\theta = -\sin\theta$ The horizontal oscillation is not affected and is still represented by $\cos\theta$	Photon is recombined. The upper beam gets rotated counter-clockwise and becomes $-j\cdot\sin\theta$. The lower beam is still represented by $\cos\theta$	The photon wavefunction is given by $\cos\theta - j\cdot\sin\theta = e^{-j\cdot\theta}$. This is an LHC photon travelling in the *xz*-plane but rotated over 90 degrees.

Of course, we may also set up the apparatus with different path lengths, in which case the two linearly polarized beams will be out of phase when arriving at BS1. Let us assume the phase shift is equal to $\Delta = 180° = \pi$. This amounts to putting a minus sign in front of *either* the sine *or* the cosine function. Why? Because of the $cos(\theta \pm \pi) = -cos\theta$ and $sin(\theta \pm \pi) = -sin\theta$ identities. Let us assume the distance along the upper path is longer and, hence, that the phase shift affects the sine function.[27] In that case, the sequence of events might be like this:

Photon polarization	At BS1	At mirror	At BS2	Final result
RHC	Photon ($e^{i\cdot\theta} = cos\theta + i\cdot sin\theta$) is split into two linearly polarized beams: Upper beam (vertical oscillation) = $j\cdot\sin\theta$ Lower beam (horizontal oscillation) = $\cos\theta$	The vertical oscillation gets rotated clockwise and becomes $-j\cdot j\cdot\sin\theta = -j^2\cdot\sin\theta = \sin\theta$ The horizontal oscillation is not affected and is still represented by $\cos\theta$	Photon is recombined. The upper beam gets rotated counter-clockwise and – because of the longer distance – becomes $j\cdot\sin(\theta + \pi) = -j\cdot\sin\theta$. The lower beam is still represented by $\cos\theta$	The photon wavefunction is given by $\cos\theta - j\cdot\sin\theta = e^{-j\cdot\theta}$. This is an LHC photon travelling in the *xz*-plane but rotated over 90 degrees.

[27] The reader can easily work out the math for the opposite case (longer length of the lower path).

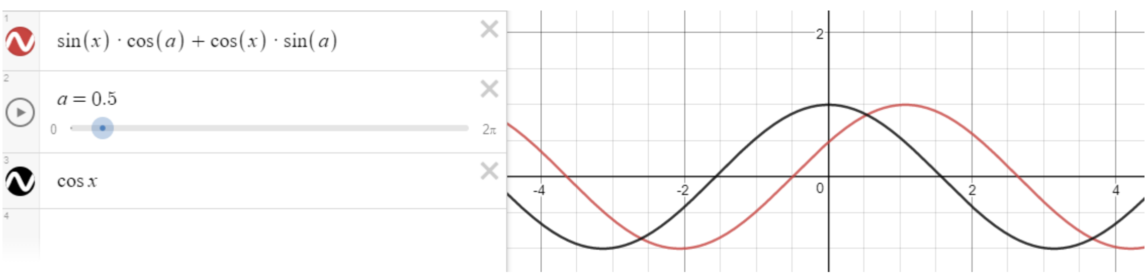
LHC	Photon ($e^{-i\cdot\theta} = cos\theta - i\cdot sin\theta$) is split into two linearly polarized beams: Upper beam (vertical oscillation) = $-j\cdot\sin\theta$ Lower beam (horizontal oscillation) = $\cos\theta$	The vertical oscillation gets rotated clockwise and becomes $(-j)\cdot(-j)\cdot\sin\theta$ = = $j^2\cdot\sin\theta = -\sin\theta$ The horizontal oscillation is not affected and is still represented by $\cos\theta$	Photon is recombined. The upper beam gets rotated counter-clockwise and – because of the longer distance – becomes $-j\cdot\sin(\theta + \pi) = +j\cdot\sin\theta$. The lower beam is still represented by $\cos\theta$	The photon wavefunction is given by $\cos\theta + j\cdot\sin\theta = e^{+j\cdot\theta}$. This is an RHC photon travelling in the *xz*-plane but rotated over 90 degrees.

What happens when the difference between the phases of the two beams is not equal to 0 or 180 degrees? What if it is some random value in-between? Do we get an elliptically polarized wave or some other nice result? Denoting the phase shift as Δ, we can write:

$$cos\theta + j\cdot sin(\theta + \Delta) = cos\theta + j\cdot(sin\theta\cdot cos\Delta + cos\theta\cdot sin\Delta)$$

However, this is also just a circularly polarized wave, but with a random phase shift between the horizontal and vertical component of the wave, as shown below. Of course, for the special values $\Delta = 0$ and $\Delta = \pi$, we get $cos\theta + j\cdot sin\theta$ and $cos\theta - j\cdot sin\theta$ once more.

Figure 6: Random phase shift between two waves

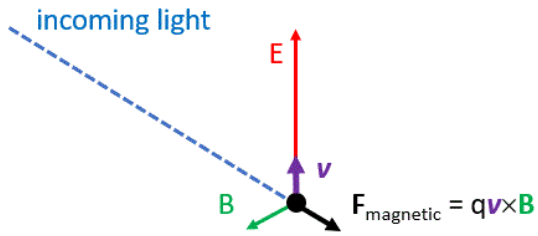


Are we done? For the purposes of this paper, yes. We think we have shown that we can interpret the linear polarization states as something *real*: the linear polarization state carries *half* the energy of the photon – after it leaves the beam splitter. It carries *no* angular momentum and these linearly polarized half-photons can, therefore, not be absorbed by an electron. Why not? Here, we should remind ourselves of the classical picture of how an electromagnetic wave interferes with an electron orbital.

Photon-electron interactions and conservation of angular momentum

The one-cycle photon model we developed presents the photon as an oscillating electromagnetic field and, hence, we will want to think of the classical picture of an interaction. The illustration below (Figure 7) shows what happens if a *linearly* polarized light beam hits a charged particle (think of an electron). The electric field will cause the charge to move upwards and, as it acquires some velocity, the magnetic field comes into play too. The magnetic force on the particle is given by the $\mathbf{F} = q\boldsymbol{v}\times\mathbf{B}$, and it gives us the classical explanation for the momentum of light, which is also referred to as referred to as radiation or *light pressure*.

Figure 7: The pushing momentum of light



The magnetic force – which is just denoted as ***F*** in the diagram above – will be equal to ***F*** = q***v***×***B***, and the right-hand rule for a vector cross-product tells us the direction of that force is going to be in the direction of the beam. Furthermore, because the magnitude of the *magnetic* field (***B***) is 1/*c* times that of the *electric* field ***E***, one can also show that the pushing momentum of light will be equal to the 1/*c* times the *energy* that is being absorbed. That explains the simplest of simple equations for a photon that – without any doubt – you have seen many times already, but for which you might not have a *mental* picture:

$$\mathrm{p} = \mathrm{m} \cdot c = \frac{\mathrm{E}}{c^2} \cdot c = \frac{\mathrm{E}}{c}$$

The 1/*c* factor may feel like the momentum – or the magnetic field itself – are not very important, but we would like to remind the reader we could choose to use equivalent distance and time units, so *c* = 1 and the whole things looks very different.[28] Hence, you should not think the magnetic force is, somehow, less real or not so important. The magnetic force becomes *very* important when velocities become relativistic. Indeed, if we just think magnitudes, then we can write this[29]:

$$F_{\mathrm{magnetic}} = \mathrm{q} \cdot v \cdot B = \mathrm{q} \cdot v \cdot \frac{E}{c} = \mathrm{q} \cdot \beta \cdot E$$

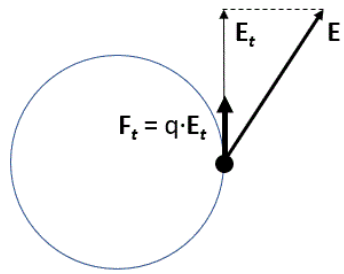
This shows the magnitude of the magnetic force approaches that of the electrostatic force when the velocity approaches that of light. It is, therefore, rather strange most textbooks in physics will only focus on the electric field vector when discussing light. *Big mistake!* We tend to focus on the electric force only and forget the magnetic force is always there, too!

However, in this initial exploration, we will follow the convention and that is to think of the electric vector as the *primary* one. Think, for example, of how an electric field might give a jolt to an electron in an atomic orbital, as shown below (Figure 8).

[28] It is quite interesting to think this through. Using equivalent units will, of course, also change the way we measure acceleration. Hence, Newton's force law will only make sense if we also use natural units for mass (or, what amounts to the same, for force).

[29] As usual, there is a risk of confusing the reader because we use the same symbol (E and *E*) for energy and electric field, but the context should make clear what is what.

Figure 8: How the electric field of a photon might drive an orbital electron



We think the illustration – as simple as it is – bridges classical mechanics with quantum mechanics because it shows we're not only transferring energy: we're also transferring angular momentum. Now, the *quantum* in quantum mechanics tells us that angular momentum comes in discrete units: Planck's unit ($\hbar$). To be precise, we interpret the reality of Planck's quantum of action – which, in its reduced form ($\hbar = h/2\pi$), is, effectively, a unit of angular momentum – as implying that photon absorption and emission by an atom (think of the electron orbitals here) should respect *the integrity of a cycle*. You may criticize and say: what is this rule? Some new random interpretation of quantum mechanics? Our answer is: yes. That's what's on offer here. Something new, but it is not random.

We should now re-consider the question we had asked you to explore previously: what happens when an electron jumps several Bohr orbitals? The angular momentum between the orbitals will then differ by several units of $\hbar$. What happens to the photon picture in that case? It will pack the energy difference, but will it also pack several units of $\hbar$? The answer is negative: we should still think of the photon as a one-cycle oscillation. Its energy will not be spread over several cycles. In other words, the two equations below need to make sense for *all* transitions:

$$photon: \mathrm{S} = h = \mathrm{p}_\gamma \cdot \lambda_\gamma = \frac{\mathrm{E}_\gamma}{c}\lambda_\gamma = \frac{\mathrm{E}_\gamma}{f_\gamma} = \mathrm{E}_\gamma \cdot \mathrm{T}_\gamma$$

$$electron\ transition: \mathrm{S} = n \cdot h = \mathrm{p}_n \cdot \lambda_n = \mathrm{m}_e v_n \lambda_n = \mathrm{E}_n \cdot \mathrm{T}_n$$

Hence, the law of conservation of angular momentum needs to be re-interpreted: the idea of an elementary cycle needs to be added, and an elementary cycle is *different* for a *zbw* charge, an electron orbital or – in this case – a photon.

How beam splitters actually work

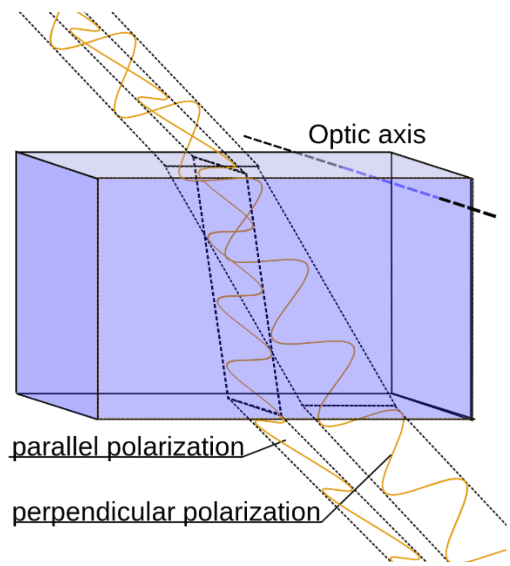
You may say my solution is artificial: why would a beam splitter changes the polarization of the incoming light? As a matter of fact, that is what many beam splitters actually do. We already hinted at the fact that the physics of polaroids or beam splitters can be very complicated. The chemical formula for a tourmaline crystal, for example, is the following one: $XY_3Z_6(T_6O_{18})(BO_3)_3V_3W$.[30] While being crystalline, it is a very complicated structure and it is, therefore, rather remarkable that its optical properties are remarkably simple: tourmaline is a *polaroid* material, which means that it has an *optic axis*: a polaroid will transmit light that is linearly polarized *parallel* to the axis of the polaroid, with very little or no

[30] There are some placeholder symbols in this formula. The formula can be further explained by noting the following: X = Ca, Na, K, ▢ = vacancy; Y = Li, Mg, Fe^{2+}, Mn^{2+}, Zn, Al, Cr^{3+}, V^{3+}, Fe^{3+}, Ti^{4+}, vacancy; Z = Mg, Al, Fe^{3+}, Cr^{3+}, V^{3+}; T = Si, Al, B; B = B, vacancy; V = OH, O; W = OH, F, O.

absorption, but light that is polarized in a direction that is *perpendicular* to the axis of the polaroid will be very strongly absorbed.

Beam splitters are even more remarkable devices. There are many types of beam splitters but classical beam splitters will use birefringent material. Birefringence involves *double refraction*: a beam of light, when incident upon a birefringent material, will be split into two beams taking slightly different paths and – importantly – the polarization of the two outgoing beams will differ from that of the incident beam. The illustration below (**Figure 9**) shows the case for incoming circularly polarized light and outgoing linearly polarized light.[31]

Figure 9: How circularly polarized lights splits into linearly polarized beams



Conclusions

Mystery solved? We think so. The explanation of the interference of a photon with itself in a Mach-Zehnder interferometer experiment may come across as somewhat artificial but it is surely consistent with the way beam splitters actually work – *physically*, that is. However, even if the reader might *feel* our explanation could be *ad hoc* – which we don't think it is – such *sentiment* is not to the point here: what we wanted to do here is to show that an alternative explanation – using classical concepts and hypotheses – is, in fact, *possible*. We are *not* saying our alternative theory is *the* explanation.

What we are saying is that the mainstream view that the 'mystery' in quantum mechanics will, forever, remain a mystery is not based on any reasonable assumption. A common-sense or realist interpretation of quantum mechanics is, therefore, an idea whose time has come. Bell's No-Go Theorem should not prevent us from trying to go *every*where: all that it takes is – as Bell himself pointed out – some kind of 'radical conceptual renewal'.

[31] The illustration is taken from Wikipedia's article on birefringence (https://en.wikipedia.org/wiki/Birefringence) and was made by Mikael Häggström. He is doctor specialized in imaging for medical purposes. Hence, we assume this illustration is basically correct although we could not trace its origin to this or that textbook.

We hope our papers show how that 'radical conceptual renewal' might look like. It is, in fact, not all that radical: one just need to apply the basic conservation laws (energy, linear and angular momentum) *consistently* while, at the same time, accepting angular momentum comes in discrete units: Planck's unit. What we are saying, basically, is that quantum electrodynamics – as a theory, and in its current shape and form – is incomplete: it is all about electrons and photons – and the interactions between the two – but the theory lacks a good description of what electrons and photons actually *are*. All of the weirdness of Nature is, therefore, in this weird description of the fields: perturbation theory, gauge theories, Feynman diagrams, quantum field theory, etcetera. This complexity in the mathematical framework does not match the intuition that, if the theory has a simple circle group structure[32], one should not be calculating a zillion integrals all over space over 891 4-loop Feynman diagrams to explain the magnetic moment of an electron in a Penning trap.[33] This is what motivated our search for a *geometric* model of both the electron as well as the photon, which we think have offered here.

A final note should be made on Uncertainty. All of our formulas look pretty certain, so what about Uncertainty, then? Here, we would refer the interested reader to our remarks on that in our manuscript.[34] We suggest Planck's quantum of action might have to be interpreted as a *vector*—just like the angular momentum vector. The uncertainty – or the probabilistic nature of Nature, so to speak – might, therefore, not be in its *magnitude*, but in its *direction*. Many quantum-mechanical equations – such as Schrödinger's equation, for example – should probably also be written as vector equations.[35]

Jean Louis Van Belle, 13 June 2019

[32] QED is an Abelian gauge theory with the symmetry group U(1). This sounds extremely complicated but you can interpret this rather simply: it means its mathematical structure is basically the same as that of classical electromagnetics.

[33] We refer to the latest theoretical explanation of the anomalous magnetic moment here: Stefano Laporta, *High-precision calculation of the 4-loop contribution to the electron g-2 in QED*, 10 July 2017, https://arxiv.org/abs/1704.06996. As for our classical explanation, see: *The Anomalous Magnetic Moment: Classical Calculations*, 11 June 2019 (http://vixra.org/abs/1906.0007).

[34] *The Emperor Has No Clothes: A Realist Interpretation of Quantum Mechanics*, 21 April 2019 (http://vixra.org/abs/1901.0105).

[35] We made a start with this in a previous paper: Jean Louis Van Belle, *A geometric interpretation of Schrödinger's equation*, http://vixra.org/pdf/1812.0202v1.pdf.

References

Academics will usually add a long list of books and articles here, but I don't want to do that. I would also advice interested readers to not trust too much in the latest update of this or that textbook. I recommend reading originals such as Dirac's *Principles of Quantum Mechanics*, which is the topic of this paper!

There are several advantages of reading original work. The most obvious advantage is that they are often available online. More importantly, however, they are also widely referenced in various discussion fora. Hence, if you have an issue with this or that interpretation, or some formula, in an original book of one of the founding fathers of quantum mechanics, then you will be able to *google* for help very easily.

Feynman's Lectures is and remains a classic for me (http://www.feynmanlectures.caltech.edu/). Some of his *Lectures* on quantum mechanics – such as chapter 4, on identical particles – suffer from excessive and speculative generalization (see my paper on *Philosophy and Physics* in this regard: http://vixra.org/abs/1906.0082), but even this chapter makes you think for yourself. That is very valuable, in my humble view, because I find more modern textbooks often too confident in their approach: they emphasize what we know, as opposed to what we don't know. Feynman's Lectures also have the advantage that you get the math you need with the physics you study.

However, in case you'd want a good mathematical introduction, Mathews and Walker's *Mathematical Methods of Physics*, is a reference that stands out for me.