A classical explanation of Compton scattering

Jean Louis Van Belle, 12 April 2020

Summary

In this paper, we bring the *Zitterbewegung* electron model and our photon model together to provide a classical explanation of the scattering of photons by electrons. We understand electron-photon interference (which is usually referred to as Compton scattering) as two electromagnetic oscillations interfering (classically) with each other. While developing the model, we offer some reflections on the Uncertainty Principle (Copenhagen interpretation of quantum mechanics). We conclude there is no need for it: God doesn't play dice.

Contents

A classical explanation of Compton scattering

Jean Louis Van Belle, 12 April 2020

Introduction: Feynman's thought experiment

What is uncertainty in quantum mechanics? How does it relate to the philosophical concepts of freedom and determinism? When discussing the philosophical implications of the Uncertainty Principle in quantum mechanics, Richard Feynman notes that, "*from a practical point of view*", we have "indeterminability in classical mechanics as well."[1] He gives the example of water splashing over a dam:

> "If water falls over a dam, it splashes. If we stand nearby, every now and then a drop will land on our nose. This appears to be completely random, yet such a behavior would be predicted by purely classical laws. The exact position of all the drops depends upon the precise wigglings of the water before it goes over the dam. How? The tiniest irregularities are magnified in falling, so that we get complete randomness. Obviously, we cannot really predict the position of the drops unless we know the motion of the water absolutely exactly."

While, from a practical point of view, it may effectively be impossible to know the motion of the water "absolutely exactly", the deeper question is: is it *theoretically* possible? In classical mechanics, we assume it is. In quantum mechanics, we assume it is *not*. Quoting Feynman once again, we may say "the Uncertainty Principle *protects* quantum mechanics." It is probably good to discuss the context in which he uses this phrase. He uses it in the context of a thought experiment. The thought experiment is a variant of the two-slit experiment. The set-up is shown below.[2]

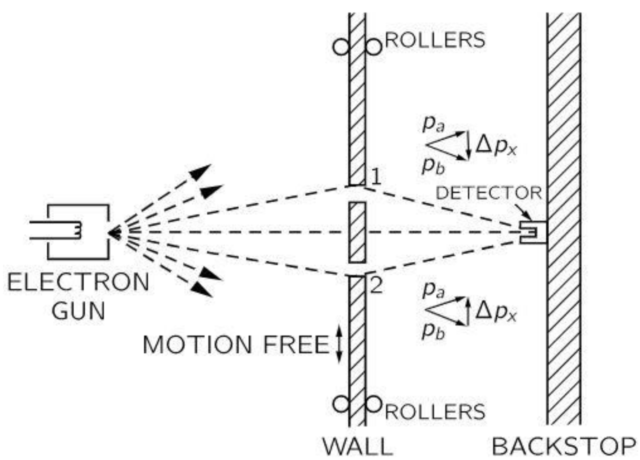


Figure 1: Feynman's thought experiment

Feynman's thought experiment is pretty much the same as the standard two-slit experiment, which you have probably studied *ad nauseam* (Feynman also starts his Lectures on Quantum Mechanics with it), except for the 'wall' with the two slits, which is now "mounted on rollers so that it can move freely up

[1] See: Feynman's Lectures, III-2-6 (https://www.feynmanlectures.caltech.edu/III_02.html#Ch2-S6).

[2] The illustration and much of the text has been borrowed from Feynman's introduction to his Lectures on Quantum Mechanics (https://www.feynmanlectures.caltech.edu/III_01.html#Ch1-S8).

and down." Feynman now develops an argument which may trick us into thinking we might be able to beat the Uncertainty Principle:

> "By watching the motion of the plate carefully we can try to tell which hole an electron goes through. Imagine what happens when the detector is placed at $x = 0$. We would expect that an electron which passes through hole 1 must be deflected downward by the plate to reach the detector. Since the vertical component of the electron momentum is changed, the plate must recoil with an equal momentum in the opposite direction. The plate will get an upward kick. If the electron goes through the lower hole, the plate should feel a downward kick. It is clear that for every position of the detector, the momentum received by the plate will have a different value for a traversal via hole 1 than for a traversal via hole 2. So! Without disturbing the electrons at all, but just by watching the plate, we can tell which path the electron used."

Of course, Feynman only tells us this story to immediately refute it. He thinks we can't beat the Uncertainty Principle:

> "Now in order to do this it is necessary to know what the momentum of the screen is, before the electron goes through. So when we measure the momentum after the electron goes by, we can figure out how much the plate's momentum has changed. But remember, according to the uncertainty principle we cannot at the same time know the position of the plate with an arbitrary accuracy. But if we do not know exactly where the plate is, we cannot say precisely where the two holes are. They will be in a different place for every electron that goes through. This means that the center of our interference pattern will have a different location for each electron. The wiggles of the interference pattern will be smeared out. […]
>
> The uncertainty principle "protects" quantum mechanics. Heisenberg recognized that if it were possible to measure the momentum and the position simultaneously with a greater accuracy, the quantum mechanics would collapse. So he proposed that it must be impossible. Then people sat down and tried to figure out ways of doing it, and nobody could figure out a way to measure the position and the momentum of anything—a screen, an electron, a billiard ball, anything—with any greater accuracy. Quantum mechanics maintains its perilous but still correct existence."

As far as I am concerned, this is *not* Feynman at his best. It's Feynman at his worst. We should, first, note that Feynman implies we cannot position the plate on rollers at $x = 0$ so its momentum is zero as well. Secondly, it is quite non-sensical to describe an electron as some bullet that has some precise momentum in the x- and y-direction and, therefore, as something that would be deflected classically.

These thought experiments are not about the Uncertainty Principle "protecting" quantum physics: it's physicists protecting the Uncertainty Principle. Of course, one wonders: why would they do this? They are searching for the truth as well, don't they?

Maybe. Maybe not. Perhaps they feel quantum-mechanical indeterminism (as opposed to the statistical indeterminism in classical mechanics) is the very last place where God – or the Mystery, or whatever we cannot prove but happen to *believe* in – can hide.

The *Zitterbewegung* model of an electron

You may or may not have heard about this model. Erwin Schrödinger, who coined the term (*Zitterbewegung* refers to a trembling or shaking motion), stumbled upon this idea when he was exploring solutions to Dirac's wave equation for free electrons. It's 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)

We have fully developed the model in other papers, so we will not dwell on it too long here.[3] The *Zitterbewegung* interpretation of quantum mechanics models the electron as a pointlike electric *charge* in a circular orbit. Its tangential velocity is equal to the speed of light and, obviously, equals the product of the radius and the angular velocity: $v = a \cdot \omega = c$, as shown below. Hence, we think of the electron as a current ring.

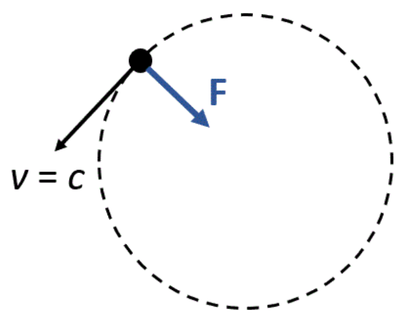


Figure 2: The electron as a current ring

If the tangential velocity is equal to the speed of light, then the *rest* mass of the pointlike charge (think of it as the hard core of the electron) must be zero. However, there is *energy* in this oscillation, and we think of the rest mass of the electron as the equivalent mass of the energy in the oscillation. This hybrid description of the electron embodies Wheeler's idea of mass without mass. We should note that pointlike doesn't mean the charge itself has no dimension whatsoever: we think its size is equal to the *classical* electron radius. Why? Because it would explain the anomalous magnetic moment of an electron. However, we talked about this elsewhere, so we do not want to repeat ourselves here.[4] Equally (if not more) importantly, we also get that radius out of electron-photon scattering experiments (we will say more about that later). Just take a mental note here: if we say pointlike, it means we cannot

[3] See, for example, our *Mass without Mass* paper (http://vixra.org/abs/1908.0225).

[4] See our *Classical Calculations of the Anomalous Magnetic Moment* (http://vixra.org/abs/1906.0007).

analyze the pointlike charge any further: it has, therefore, no structure. It does *not* imply this charge has no dimension whatsoever. In fact, we think objects that have no dimension whatsoever do not *exist*.

Let us get back to the electron itself. The electron as a whole is, obviously, *not* pointlike: its structure is that high-frequency oscillatory motion of small amplitude that comes out of Dirac's equation. That's why the electron has two radii: the Thomson radius (or classical electron radius) and the Compton radius. We can easily calculate the Compton radius. The tangential velocity tells us the radius is equal to $a = c/\omega$. The Planck-Einstein relation ($E = ħ\cdot\omega$) then allows us to substitute ω ($\omega = E/\hbar$). Finally, we can then use Einstein's mass-energy equivalence relation ($E = m\cdot c^2$) to calculate the radius as the ratio of Planck's (reduced) quantum of action and the product of the electron mass and the speed of light:

$$a = \frac{c}{\omega} = \frac{c \cdot \hbar}{\mathrm{E}} = \frac{c \cdot \hbar}{\mathrm{m} \cdot c^2} = \frac{\hbar}{\mathrm{m} \cdot c} = r_{\mathrm{C}} = \frac{\lambda_{\mathrm{C}}}{2\pi} \approx 0.386 \times 10^{-12}\ \mathrm{m}$$

This value has been confirmed *experimentally*. Moreover, it's probably one of the most precise measurement in physics. The calculation is, therefore, astonishingly beautiful. Why? Because it is so simple. Having said that, its *physical* interpretation is, obviously, *not* so simple. We offer following remarks on this:

1. Each *cycle* of the *Zitterbewegung* packs (i) one unit of physical *action* (h) and (ii) the electron's energy ($E = mc^2$). Now, the concept of physical action (*Wirkung*) might not be very familiar nor intuitive to the average student of physics and that, surely, its association with a fundamental *cycle* in Nature must be even less so. We will let the reader think about this, but it is quite significant that, since the revision of SI units (2018-2019), the American National Institute of Standards and Technology prefers to express the CODATA value of Planck's constant (h) in J/Hz rather than N·m·s, even if both are equivalent.[5]

While we let this sink in, we can quickly calculate the cycle *time* from the Planck-Einstein relation, which we like to write as $E/T = h$. The $T = 1/f$ in this equation is, effectively, the cycle time, which we can thus calculate as equal to:

$$\mathrm{T} = \frac{h}{\mathrm{E}} \approx \frac{6.626 \times 10^{-34}\ \mathrm{J \cdot s}}{8.187 \times 10^{-14}\ \mathrm{J}} \approx 0.8 \times 10^{-20}\ \mathrm{s}$$

That's a *very* small amount of time: as Dirac notes, we can*not* directly verify this by experiment.[6] We hope the reader will now intuitively understand why we can write Planck's quantum of action as the product of the electron's energy and the cycle time, and why NIST's preference for the J/Hz dimension for h makes a lot of sense:

$$h = E\cdot T = h\cdot f\cdot T = h\cdot f/f = h$$

We hope the remarks above have not dazzled the reader. If so, the following remarks may be easier to digest.

2. What is the *nature* of this fundamental oscillation? Indeed, to keep an object with some momentum in a circular orbit, a centripetal force is needed – as shown in Figure 2. What is the nature of this force?

---

[5] See https://physics.nist.gov/cgi-bin/cuu/Value?h.

[6] The cycle time of short-wave ultraviolet light (UV-C), with photon energies equal to 10.2 eV is 0.4×10^{-15} s, so that gives an idea of what we're talking about. You may want to compare with frequencies of X- or gamma-ray photons.

Because the force can only grab onto the charge, it must be electromagnetic. In Hestenes' interpretation of the *Zitterbewegung* model[7], the circular current creates a magnetic flux through the ring which keeps the current going – just like in a superconducting ring. This interpretation has one problem: there is no real material ring to hold and guide our charge in free space, so what keeps this thing *tuned*? We must be honest and admit we have no answer to this question. However, that should not prevent us from further exploring what might or might not be going on. To do so, we will present some more calculations. Let us start by calculating the centripetal acceleration: it's equal to:

$$a_c = v_t^2/a = a\cdot\omega^2$$

The reader should note this formula is relativistically correct. Indeed, it might be useful to remind ourselves where this formula comes from. The radius vector $\boldsymbol{a}$ has a horizontal and a vertical component: $x = a\cdot\cos(\omega t)$ and $y = a\cdot\sin(\omega t)$. We can now calculate the two components of the (tangential) velocity vector $\boldsymbol{v} = d\boldsymbol{r}/dt$ as $v_x = -a\cdot\omega\cdot\sin(\omega t)$ and $v_x\, y = -a\cdot\, \omega\cdot\cos(\omega t)$. We can now calculate the components of the (centripetal) acceleration vector $\boldsymbol{a_c}$: $a_x = -a\cdot\omega^2\cdot\cos(\omega t)$ and $a_y = -a\cdot\omega^2\cdot\sin(\omega t)$. The *magnitude* of the centripetal acceleration vector can then be calculated as:

$$a_c^2 = a_x^2 + a_y^2 = a^2\cdot\omega^4\cdot\cos^2(\omega t) + a^2\cdot\omega^4\cdot\sin^2(\omega t) = a^2\cdot\omega^4 \Leftrightarrow a_c = a\cdot\omega^2 = v_t^2/a$$

Now, the force law tells us that F is equal to $F = m\cdot a_c = m\cdot a\cdot\omega^2$. However, here we run into problems: what is the mass of our pointlike charge? We said its (rest) mass was zero: it only acquires mass because it moves at the velocity of light. If m_0 is equal to zero, then what should we do with the relativistic $m = \gamma m_0$ formula? A multiplication with zero yields zero—*always*, doesn't it? [...] Well... No. We forget something: the velocity v is equal to c. The Lorentz factor is, therefore, equal to infinity, *always*. So we are multiplying zero with infinity, which gives us... What?

At this point, we need to talk about the concept of the *effective* mass of the pointlike charge. Again, we have done that elsewhere[8] and so we won't repeat ourselves here. We will just insert a summary of our approach, calculations and the key results.

The electron as a two-dimensional electromagnetic oscillation

Let us denote it the effective mass of our pointlike charge as $m_\gamma = \gamma m_0$. The subscript (γ) in m_γ refers to the Lorentz factor, of course. What is its value? of m_γ? It should not be zero, and it should also not be infinity. In addition, it would also be quite sensible to think that m_γ must be smaller than the rest mass of the electron m_e. Indeed, it cannot be larger because the energy of the oscillation would then be larger than $E = mc^2$. So what could it be? Rather than guessing, we may want to remind ourselves that we know the angular momentum of the electron: $L = \hbar/2$. We have calculated it using the $L = I\cdot\omega$ formula and using an educated guess for the moment of inertia ($I = m\cdot a^2/2$)[9], but we also have the $\mathbf{L} = \boldsymbol{r} \times \mathbf{p}$

[7] See, for example: D. Hestenes, Found. Physics., Vol. 20, No. 10, (1990) 1213–1232, *The Zitterbewegung Interpretation of Quantum Mechanics*, http://geocalc.clas.asu.edu/pdf/ZBW_I_QM.pdf, and D. Hestenes, 19 February 2008, *Zitterbewegung in Quantum Mechanics – a research program*, https://arxiv.org/pdf/0802.2728.pdf.
[8] See the above-mentioned *Mass without Mass* paper (http://vixra.org/abs/1908.0225) as well our *Electron as a Harmonic Electromagnetic Oscillator* paper (http://vixra.org/abs/1905.0521).
[9] See the references above.

formula, of course! If $\boldsymbol{r} = \boldsymbol{a}$, then we can write the magnitudes as $L = a \cdot p$. We can now calculate m_γ as follows:

1. $L = \hbar/2 \Rightarrow p = L/a = (\hbar/2)/a = (\hbar/2) \cdot m_e \cdot c/\hbar = mc/2$
2. $p = m_\gamma c$

$$\Rightarrow m_\gamma c = m_e c/2 \Leftrightarrow m_\gamma = m_e/2$$

This is a nice result, because it explains the previously mysterious concept of the effective mass of an electron using common-sense calculations. Let us summarize the result in plain text: the *effective* mass of the pointlike charge – as it whizzes around the center of the two-dimensional oscillation that makes up our electron – is *half* the (rest) mass of the electron. Hence, we can now write the centripetal force F as $F = m \cdot a_c = m \cdot a \cdot \omega^2$ as:

$$F = m_\gamma \cdot a_c = m_\gamma \cdot a \cdot \omega^2 = m_e \cdot a \cdot \omega^2/2$$

All that remains to be done now is to deconstruct and analyze the centripetal force **F** as the sum of two force components. In other words, we think of the circular motion of our pointlike charge as the sum of two perpendicular oscillations. Because the two oscillations are perpendicular and, therefore, independent, we can add the energy of both oscillations and combine the result with the $F = m_\gamma \cdot a_c = m_\gamma \cdot a \cdot \omega^2 = m_e \cdot a \cdot \omega^2/2$ above to get Einstein's mass-energy equivalence relation[10]:

$$E = 2 \cdot F \cdot a = 2 \cdot m_\gamma \cdot a \cdot \omega^2 a = m_e \cdot a^2 \cdot \omega^2 = m_e \cdot c^2$$

The reader who skipped through the rather dense text and calculations should not worry that he will not be able to understand what follows. We only request the reader to try to imagine the electron as a two-dimensional electromagnetic oscillation driving a pointlike electric charge. The whirling around of the pointlike charge, in turn, is what keeps this electromagnetic oscillation going.

Electron-photon interference: Thomson and Compton scattering

So how does it work, *exactly*? At this point, we should probably say a few words about Dirac's reference to the "law of scattering of light by an electron", and how the *Zitterbewegung* model might explain it.

The reader will, without any doubt, know that photons may be scattered elastically or inelastically when interfering with an electron: Compton versus Thomson scattering. Compton scattering involves electron-photon interference: a high-energy photon (the light is X- or gamma-rays) will hit an electron and its energy is briefly absorbed before the electron comes back to its equilibrium situation by emitting another photon. The wavelength of the emitted photon will be longer. The photon has, therefore, less energy, and the difference in the energy of the incoming and the outgoing photon gives the electron some linear momentum. Because of the interference effect, Compton scattering is referred to as inelastic.

In contrast, low-energy photons scatter elastically. Elastic scattering experiments yield a much smaller effective radius of the electron. It is the so-called classical electron radius, which is also known as the

[10] Energy is a force over a distance and the calculations, therefore, involve integrals which, although simple, we will not write down here. We refer the interested reader, once again, to our *Mass without Mass* paper for more detail. (http://vixra.org/abs/1908.0225).

Thomson or Lorentz radius, and it is equal to a fraction (α) of the Compton radius. To be precise, $r_e = \alpha \cdot r_C \approx 0.0073 \cdot r_C \approx 2.818 \times 10^{-15}$ m. The Thomson scattering radius is referred to as *elastic* because the photon seems to bounce off some hard *core*: there is no interference. Of course, we are talking a limiting case here, which is valid as long as the photon energy is much smaller than the mass energy of the particle.[11]

The terms elastic and inelastic suggest a duality which is not really there. We think of the photon itself as an electromagnetic oscillation that *interferes* with the two-dimensional oscillation. At this point, we should introduce the photon model.

Electron-photon interference: the photon model

In order to understand our (classical) explanation of electron-photon interference as the interference of two electromagnetic oscillations, we should explain the photon model. In order to do so, we should remind ourselves that photons are emitted (and absorbed) by atoms. We described this process elsewhere[12] and, hence, we will limit ourselves to an overview of the basics of the model.

The Bohr orbitals are separated by a amount of *action* that is equal to h. 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. Our photon will have to pack that, somehow. It will also have to pack the related energy, which is given by the Rydberg formula (see above). 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.[13] Now, if the total action is equal to h, then the cycle time T can be calculated as:

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

This corresponds to a wave train with a length of $(3 \times 10^8 \text{ m/s}) \cdot (0.4 \times 10^{-15} \text{ s}) = 122$ 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.[14] In fact, this length is *exactly* equal to the wavelength $\lambda = c/f = c \cdot \mathrm{T} = hc/\mathrm{E}$.

---

[11] The Wikipedia article on Thomson scattering correctly describes Thomson scattering as "the low-energy limit of Compton scattering:" (see: https://en.wikipedia.org/wiki/Thomson_scattering, accessed on 13 December 2019).

[12] See our *Classical Quantum Theory of Light* (http://vixra.org/abs/1906.0200).

[13] 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.

[14] 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: $(5 \times 10^6) \cdot (600 \times 10^{-9} \text{ meter}) = 3$ 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.

What picture of the photon are we getting here? Because of the angular momentum, we will probably want to think of it as a circularly polarized wave, which we may represent by the elementary wavefunction, as shown below.[15] We call this interpretation of the wavefunction the *one-cycle photon*: the wavefunction represents the rotating electric field vector itself or, remembering the $F = q_e E$ equation, the force field.

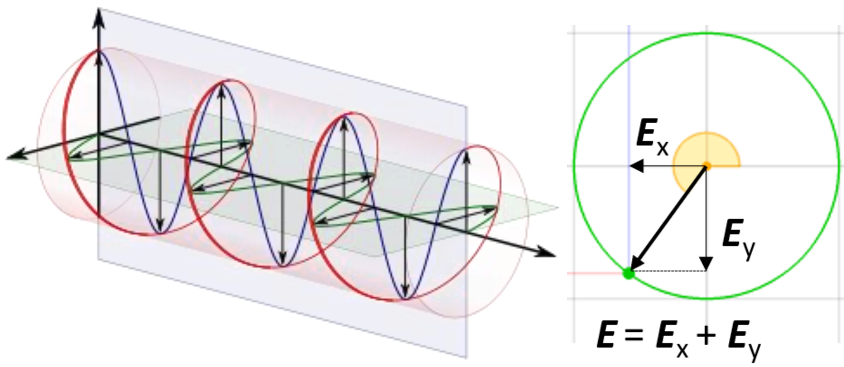


Figure 3: The one-cycle photon

It is a delightfully simple model: the photon is a circularly polarized electromagnetic oscillation 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:

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

In previous papers[16], we show how to calculate the strength of the electric field (E) as a function of the photon's energy (E_γ). The field strength is the force per unit charge which, we should remind the reader,

[15] Note that the wave could be either left- or right-handed.

[16] See, for example, our *Classical Quantum Theory of Light* (http://vixra.org/abs/1906.0200).

is the *coulomb* – *not* the electron charge. Dropping the subscript (γ), we get a delightfully simple formula for the strength of the electric field vector for a photon[17]:

$$E = \frac{\frac{2\pi hc}{\lambda^2}}{1} = \frac{2\pi hc}{\lambda^2} = \frac{2\pi \mathrm{E}}{\lambda} (\frac{N}{C})$$

Let us calculate its value for our 10.2 eV photon. We should, of course, express the photon energy in SI units here:

$$E \approx \frac{2\pi \cdot 1.634 \times 10^{-18}\, J}{122 \times 10^{-9}\, m \cdot C} \approx 84 \times 10^{-12} \mathrm{N/C}$$

This seems pretty reasonable – especially in light of our calculations of the electromagnetic field strength inside the electron, for which we got a humongous value[18]:

$$E = \frac{F}{\mathrm{q_e}} \approx \frac{10.6 \times 10^{-2}\ \mathrm{N}}{1.6\ \times 10^{-19}\ \mathrm{C}} \approx 0.6625 \times 10^{18}\ \mathrm{N/C}$$

This huge value should not surprise us. We get the following value for the internal current of the electron:

$$\mathrm{I} = \mathrm{q_e} f = \mathrm{q_e}\frac{\mathrm{E}}{h} \approx (1.6 \times 10^{-19}\ \mathrm{C})\frac{8.187 \times 10^{-14}\ \mathrm{J}}{6.626 \times 10^{-34}\ \mathrm{Js}} \approx 19.8\ \mathrm{A}\ (ampere)$$

This is huge: a household-level current at the sub-atomic scale. However, this result is consistent with the calculation of the magnetic moment, which is equal to the current times the area of the loop and which is, therefore, equal to:

$$\mu = \mathrm{I} \cdot \pi a^2 = \mathrm{q_e}\frac{\mathrm{m}c^2}{h} \cdot \pi a^2 = \mathrm{q_e} c \frac{\pi a^2}{2\pi a} = \frac{\mathrm{q_e} c}{2}\frac{\hbar}{\mathrm{m}c} = \frac{\mathrm{q_e}}{2\mathrm{m}}\hbar$$

We could do some more calculations, but we will let the matter rest for the time being. The point is: the *Zitterbewegung* electron and our one-cycle photon model are intuitive and make sense, because we can now understand electron-photon interference (the scattering of photons by electrons) as two electromagnetic oscillations interfering with each other.

The Compton scattering formula

Let us remind ourselves of what we know about Compton scattering. A photon *interacts* with an electron, so we have an incoming photon and an outgoing photon. To be specific, we think of the photon as being briefly absorbed, before the electron emits another photon of *lower* energy. The energy difference between the incoming and outgoing photon then gets added to the *kinetic* energy of the electron according to the law you may or may not remember from your physics classes:

[17] 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).

[18] See our *Mass without Mass* paper for more details (http://vixra.org/abs/1908.0225).

$$\lambda' - \lambda = \Delta f = \frac{h}{\mathrm{m}c}(1 - \cos\theta)$$

We think of the interference as a process during which – temporarily – an unstable wavicle is created. This unstable wavicle does *not* respect the integrity of Planck's quantum of action (E = h·*f*). The equilibrium situation is then re-established as the electron emits a new photon and moves away. Both the electron and the photon respect the integrity of Planck's quantum of action again and they are, therefore, *stable*.

The geometry of the whole thing is simple and difficult at the same time. There is also a formula to calculate the angle of the *outgoing* photon, which uses the angle for the *incoming* photon, but that's all stuff which the reader can look up. The question is: how does this happen, *exactly*?

None of the standard textbooks will try to answer that question, because they don't think of electrons and photons as having some *internal structure* which may explain all of the formulas they get out of their arguments, which are based on the conservation of (1) energy and (2) linear and angular momentum. In contrast, we believe our geometrical models may not only show *why* but also *how* all of this happens.

The Compton wavelength as a circumference

According to our ring current model of an electron, the wavefunction ψ(***x***, *t*) = ψ(*x*, *y*, *z*, *t*) describes the actual position of the pointlike *Zitterbewegung* charge in its oscillatory motion around some center.[19] The challenge, of course, is to relate this to what Feynman refers to as the 'great equation of quantum mechanics', which is the following wave equation for an electron in free space[20]:

---

[19] We are often tempted to use a semicolon to separate the time variable from the space coordinates. Hence, we would prefer to write ψ(***x***, *t*) = ψ(*x*, *y*, *z*; *t*) instead of ψ(***x***, *t*) = ψ(*x*, *y*, *z*; *t*). The semicolon then functions as a *serial* comma. Of course, we are well aware of Minkowski's view on the relativity of space and time: "*Space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality.*" However, we feel space and time are related but also very *separate* categories of our mind: perhaps some very advanced minds may claim they can effectively understand the Universe in terms of four-vector algebra, but we surely do *not*. We understand things in terms of motion, and any equation of motion implies the idea of a motion in space *and* in time—not in some 'kind of union of the two'. What I am saying is that the oft-used concept of spacetime is not something we can easily *imagine*: space and time are fundamentally different categories of the mind. We cannot go backward in time, for example. Not in *our* reality, at least. Why not? Because the ***x*** = (*x*, *y*, *z*) = ($f_x(t)$, $f_y(t)$, $f_z(t)$ = *f*(*t*) – the fundamental equation of motion – would no longer be a proper function: a *physical* object can*not* be at two different places at the same point in time. It can *return to* a place where it was (or it can simply stay where it is), but it will then be there at a *different* point of time. That's why time goes by in one direction only. Why do we highlight this point? Because some physicists – including Feynman – seem to suggest we should think of antimatter as particles traveling back in time. We think that is plain nonsensical. We may define antimatter particles as particles traveling back in space, but not as particles traveling back in time. Using (or abusing) Minkowski's notation, we may say the *metric signature* of an electron (or an antiproton) would be + – – – while that of a positron (or proton) would be + +++.

[20] See: Feynman's *Lectures*, section I-48-6 (https://www.feynmanlectures.caltech.edu/I_48.html#Ch48-S6). We may note that, for some reason, Feynman does not substitute m^2c^2/h^2 for $1/\lambda_C^2$. We must assume he did not think of any possible association or relation here. Needless to say, free space means we don't think of any electromagnetic field or any other force field here. Schrödinger adapted this equation to include a central force field: a hydrogen nucleus (a proton) attracting the electrons around it. It is good to note that Dirac refers to such wave equations as the *equations of motion* of an electron, because that's what they are.

$$\frac{\partial^2\phi}{\partial x^2}+\frac{\partial^2\phi}{\partial y^2}+\frac{\partial^2\phi}{\partial z^2}-\frac{1}{c^2}\frac{\partial^2\phi}{\partial t^2}=\frac{\mathrm{m}^2c^2}{h^2}\phi=\frac{1}{\lambda_C^2}\phi$$

We are not quite there yet. However, we did replace the m^2c^2/h^2 by the Compton wavelength $\lambda_C = h/\mathrm{m}c$ in the formula above because, paraphrasing Prof. Dr. Patrick LeClair, we effectively think of the Compton wavelength as a "*distance scale above which the particle can be localized in a particle-like sense*."[21] We think that's the key to understanding the wave equation above, although we won't discuss it as part of this paper.[22] Here, we only want to talk about how we may want to think of the Compton wavelength.

In order to do so, we should first discuss the 2π factor. Indeed, we have h, not $\hbar$, in this equation. Hence, should we think of the Compton *wavelength* or the Compton *radius* of an electron? 2π is a sizable factor – a factor equal to about 6.28 – so that is large enough to matter when discussing *size*.[23] Of course, we know it is the factor which relates the *circumference* of a circle with its radius but a wavelength is something linear, isn't it? If we should think of the wavelength of an electron, then what should we *imagine* it to be anyway? We all know that *Louis de Broglie* associated a wavelength with the *classical* momentum p = mv of a particle but, again, how should we *imagine* this wavelength? The *de Broglie* relation says $\lambda = h/\mathrm{p} = h/\mathrm{m}v$ goes to infinity (∞) for v going to 0 and m going to m_0 (the rest mass of the electron). Hence, the *de Broglie* and the *Compton* wavelength of an electron are very different concepts:

$$\lambda_C = h/\mathrm{m}c \neq \lambda = h/\mathrm{p} = h/\mathrm{m}v$$

The illustration below (for which credit goes to an Italian group of *zbw* theorists[24]) helps to make an interesting point. Think of the black circle (in the illustration on the left-hand side below) as circumscribing the *Zitterbewegung* of the pointlike charge. Think of it as the electron at rest: its *radius* is the radius of the oscillation of the oscillation of the *zbw* charge $a = \hbar/\mathrm{m}c$. Note that we actually do ask you to make abstraction of the two-dimensional *plane* of the oscillation of the *Zitterbewegung* (*zbw*) charge, which need not be perpendicular to the direction of motion of the electron as a whole: it can be in the same plane or, most likely, it may be *zittering* around itself. The point is this: we can introduce yet

---

[21] We effectively find the *exposé* of Prof. Dr. Patrick R. LeClair on Compton scattering particularly enlightening and we, therefore, refer to his notes here. See: http://pleclair.ua.edu/PH253/Notes/compton.pdf.

[22] We apologize to the reader: we were briefly side-tracked and will keep this as a topic to think about in the future.

[23] The *nature* of a 2π factor is definitely very different from that of a 2 or 1/2 factor, which we often got when analyzing something using non-relativistic equations. A 2π factor is associated with something circular, so we need to explain *what circular feature*, and not in approximate but in *exact* terms—which is not easy in this particular case.

[24] Vassallo, G., Di Tommaso, A. O., and Celani, F, *The Zitterbewegung interpretation of quantum mechanics as theoretical framework for ultra-dense deuterium and low energy nuclear reactions*, in: Journal of Condensed Matter Nuclear Science, 2017, Vol 24, pp. 32-41. Don't worry about the rather weird distance scale (1×10^{-6} eV^{-1}). Time and distance can be expressed in *inverse* energy units when using so-called *natural units* ($c = \hbar = 1$). We are not very fond of using natural units because we think they may *hide* rather than clarify or simplify some of the more fundamental relations. Just note that 1×10^{-9} eV^{-1} = 1 GeV^{-1} ≈ 0.1975×10^{-15} m. As you can see, the *zbw* radius (for v = 0) is of the order of 2×10^{-6} eV^{-1} in the diagram, so that's about 0.4×10^{-12} m, which is more or less in agreement with the Compton radius as calculated ($a_{v=0} \approx 0.386\times10^{-12}$ m).

another definition of a wavelength here—the distance between two crests or two troughs of the wave, as shown in the illustration on the right-hand side.[25]

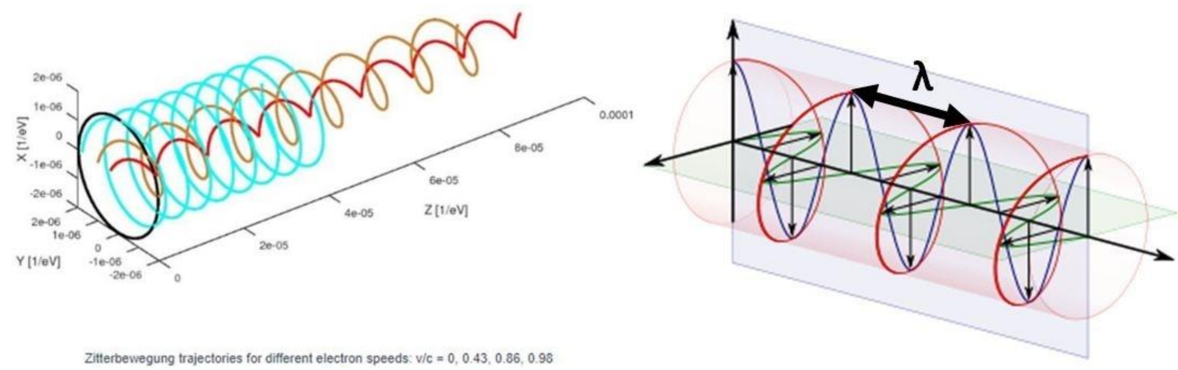


Figure 4: The wavelength(s) of an electron

We should now present a rather particular geometric property of the *Zitterbewegung* (*zbw*) motion: the $a = \hbar/mc$ radius – the Compton radius of our electron – must decrease as the (classical) velocity of our electron increases. That is what is visualized in the illustration on the left-hand side (above). What happens here is quite easy to understand. If the tangential velocity remains equal to *c*, and the pointlike charge has to cover some horizontal distance as well, then the circumference of its rotational motion *must* decrease so it can cover the extra distance. How can we analyze this more precisely? This rather remarkable thing should be consistent with the use of the *relativistic* mass concept in our formula for the *zbw* radius *a*, which we write as:

$$a = \frac{\hbar}{\mathrm{m}c} = \frac{\lambda_C}{2\pi}$$

The λ_C is the *Compton* wavelength, so that's the circumference of the circular motion.[26] How can it decrease? If the electron moves, it will have some kinetic energy, which we must add to the *rest energy*. Hence, the mass m in the denominator (m*c*) increases and, because *ħ* and *c* are physical constants, *a* must decrease.[27] How does that work with the frequency? The frequency is proportional to the energy ($E = \hbar \cdot \omega = h \cdot f = h/T$) so the frequency – in whatever way you want to measure it – must also *increase*. The *cycle* time T, therefore, must *decrease*. What happens, really, is that we are stretching our Archimedes' screw, so to speak. It is quite easy to see that we get the following formula for our new λ wavelength:

[25] Because it is a wave in two or three dimensions, we cannot really say there are crests or troughs, but the terminology might help you with the interpretation of the rather particular geometry here, which is that of an Archimedes screw, but that's only because of the rather particular orientation of the *plane* of the *zbw* oscillation, which we ask you *not* to accept for granted: you should, instead, imagine the plane of oscillation itself is probably *not* stable: the (in)famous uncertainty in quantum mechanics may actually be related to our lack of knowledge in regard to the plane of the *zbw* oscillation: it may itself be *zittering* around.

[26] Needless to say, the *C* subscript stands for the *C* of Compton, not for the speed of light (*c*).

[27] We advise the reader to always think about proportional ($y = kx$) and inversely proportional ($y = x/k$) relations in our *exposé*, because they are not always intuitive.

$$\lambda = v \cdot \mathrm{T} = \frac{v}{f} = v \cdot \frac{h}{\mathrm{E}} = v \cdot \frac{h}{\mathrm{m}c^2} = \frac{v}{c} \cdot \frac{h}{\mathrm{m}c} = \beta \cdot \lambda_C$$

Can the (classical or linear) velocity go to *c*? In theory, yes, but, in practice, *no*. The m in the formula is not the mass of the *zbw* charge but the mass of the electron as a whole. That is *non*-zero for *v* = 0, unlike the rest mass of the *zbw* charge, which only acquires mass because of its motion. We calculated this *relativistic* mass of the *zbw* charge as equal to 1/2 of the electron (rest) mass. The point is this: we are *not* moving a zero-mass thing here. The energy that is, therefore, required to bring *v* up to *c* will be infinitely large: think of the enormous energies that are required to speed electrons up to *near-lightspeed* in accelerators.

The point is this: an electron does not become photon-like when moving at near-lightspeed velocities. However, we do see that the *circumference* of the circle that circumscribes the two-dimensional *zbw* oscillation of the *zbw* charges does seem to transform into some linear wavelength when *v* goes to *c*!

Of course, we immediately admit this still does not *explain* what's going on, *exactly*. It only shows we should not necessarily think of the Compton wavelength as a purely *linear* feature.

Another remark that we should make here is that, while we emphasize that we should not think of a photon as a *charge* travelling at lightspeed – it is *not*—and I mean *not at all*: photons do *not* carry charge[28] – the analysis above does relate the geometry of our *zbw* electron to the geometry of our photon model. Let us quickly introduce that now as part of a larger reflection of what may or may not be going on in photon-electron interactions.

Probing electrons with photons

The relation between what we think of as the *radius* of the *Zitterbewegung* oscillation of the electric charge ($a = \hbar/\mathrm{m_e}c$), the *Compton* wavelength of an electron ($\lambda_C = h/\mathrm{m_e}c$), and the *wavelength* of a photon ($\lambda = c/f$) is not very obvious. However, we should not be discouraged because we immediately note on thing, at least: the wavelength of a photon is the same as its Compton wavelength *and* its *de Broglie* wavelength. Furthermore, because $v = c$ and, therefore, $\beta = 1$, it is also equal to that *third* wavelength we introduced above: $\lambda = \beta\lambda_C$. In short, the wavelength of a photon is its wavelength, so we write:

$$\lambda = \frac{c}{f} = \frac{ch}{\mathrm{E}} = \frac{ch}{\mathrm{m}c^2} = \frac{h}{\mathrm{m}c} = \frac{h}{\mathrm{p}}$$

But so what *is* that wavelength, *really*? Indeed, we should probably start by recognizing this: when probing the *size* of an electron with photons, we had better have some idea of what a photon actually *is*. Indeed, almost any textbook will tell you that, because of the wave nature of light, there is a limitation on how close two spots can be and still be seen as two separate spots: that distance is *of the order of* the wavelength of the light that we are using.[29] There is a reason for that, of course, and it's got as much to do with the wave as with the particle nature of light. Light comes in lumps too: photons. These

[28] This is, in fact, the quintessential difference between matter-particles and energy carriers such as photons (for the electromagnetic force) and neutrinos (for the strong(er) force).

[29] See, for example, Feynman's discussion of using photons to try to detect electrons as part of the two-slit experiment (https://www.feynmanlectures.caltech.edu/III_01.html#Ch1-S6)

photons *pack* energy but they also pack one (natural) unit of *physical action* (h) or – what amounts to the same – one unit of angular momentum ($\hbar$).

Let us recall the basics of what we actually presented already.[30] 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:

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

To focus our thinking, we considered the transition from the second to the first level, for which the $1/1^2 - 1/2^2$ factor is equal 0.75. Hence, the energy of the photon that is being emitted will be equal to $(0.75)\cdot \mathrm{E}_R \approx 10.2$ 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 wavelength of $(3\times10^8\ \mathrm{m/s})\cdot(0.4\times10^{-15}\ \mathrm{s}) = 122$ nm, which is the wavelength of the light ($\lambda = c/f = c\cdot\mathrm{T} = \mathrm{h}\cdot c/\mathrm{E}$) that we would associate with this photon energy.[31] This rather simple calculation is sufficient to illustrate our photon model: we think of a photon as being *pointlike* but, at the same time, the Planck-Einstein relation tells us it packs *one wavelength*—or *one cycle*. The *integrity* of that cycle is associated with its energy (E) and its cycle time (T) or – alternatively – with its momentum (p) and its wavelength (λ), as evidenced in the $\mathrm{E}\cdot\mathrm{T} = \mathrm{p}\cdot\lambda = h$ relation:

$$\left.\begin{array}{r}\mathrm{p} = \mathrm{m}c = \dfrac{\mathrm{E}}{c^2}c = \dfrac{\mathrm{E}}{c} \Leftrightarrow \mathrm{p}c = \mathrm{E}\\ c = f\lambda = \dfrac{\mathrm{E}}{h}\lambda = \Leftrightarrow \dfrac{hc}{\lambda} = \mathrm{E}\end{array}\right\} \Longrightarrow \mathrm{p}\cdot c = \frac{h\cdot c}{\lambda} \Leftrightarrow \mathrm{p}\cdot\lambda = h = \mathrm{E}\cdot\mathrm{T}$$

So, yes, the equations above sort of vaguely tell us that if we think of measuring some distance or some time – as we do when we probe an electron with photons – that we will have to content ourselves with measuring it in wavelength units (λ) or, equivalently, in cycle time units ($\mathrm{T} = 1/f = \lambda/c$).

However, when probing electrons as part of Compton scattering processes, we are beating the usual game here: we are actually measuring an *effective radius of interference* not in terms of the wavelength of the light that we are using but in terms of the *difference* in the wavelength of the photon that goes in and comes out of the scattering process. That's what the Compton scattering formula tells us:

[30] We apologize to the reader for some repetition with earlier sections: the second version of this paper is actually a merger of the first version and an entirely new but much more condensed text we were preparing – until we realized the two texts were quite complementary, and so we basically let one follow the other.

[31] Just so you can imagine what we are talking about, 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. Fortunately, the ozone layer of our atmosphere blocks most of it.

$$\lambda' - \lambda = \Delta f = \frac{h}{\mathrm{m}c}(1 - \cos\theta)$$

You've probably gone through the analysis here *ad nauseam* already, and so you know the 1 − cosθ factor on the right-hand side of this equation goes from 0 to 2 as θ goes from 0 to π. Hence, the maximum possible change in the wavelength is equal to $2\lambda_C$, which we get from a head-on collision with the photon being scattered backwards at 180 degrees.[32] However, that doesn't answer the question in regard to the 2π factor: the *h*/m*c* factor is still the Compton *wavelength*, so that is 2π times the radius: $\lambda_C = 2\pi \cdot a = 2\pi\hbar/\mathrm{m}c$. In fact, mentioning the $2\lambda_C$ value for the *maximum* difference in wavelength introduces an *additional* factor 2.

Who ordered *that*? Let us advance a *possible* explanation: we are *not* saying it is *the* explanation, but it may be *an* explanation. It goes like follows.

The electron-photon excitation: a temporary spin-2 particle?

We think the energy of the incident photon – as an electromagnetic oscillation, that is – is temporarily absorbed by the electron and, hence, the electron is, therefore, in an excited state, which is a state of non-equilibrium. As it returns to equilibrium, the electron emits some of the excess energy as a new photon, and the remainder gives the electron as a whole some additional momentum.

How should we model this? One intriguing possibility is that the electron radius becomes larger because it must now incorporate *two* units of *h* or, when talking angular momentum, two units of *ħ*. So we should, perhaps, re-do our calculation of the Compton radius of our electron as follows:[33]

$$\left.\begin{array}{c}\left.\begin{array}{c}\mathrm{E} = \mathrm{m}c^2 \\ \mathrm{E} = 2hf = 2\hbar\omega\end{array}\right\} \Rightarrow \mathrm{m}c^2 = 2\hbar\omega \\ c = a\omega \Leftrightarrow a = \dfrac{c}{\omega} \Leftrightarrow \omega = \dfrac{c}{a}\end{array}\right\} \Rightarrow \mathrm{m}a^2\omega^2 = 2\hbar\omega \Longrightarrow \mathrm{m}\frac{c^2}{\omega^2}\omega^2 = \frac{2\hbar c}{a} \Leftrightarrow a = \frac{2\hbar}{\mathrm{m}c}$$

This may actually work—as long as we remember the energy and mass factors here are the *combined* energies and masses of the electron *and* the photon. Of course, this triggers the next question: what's the typical energy or mass of the incoming photon? To demonstrate the Compton shift, Compton used X-ray photons with an energy of about 17 keV, so that's about 3.3% of the energy of the electron, which is equal to 511 keV. For practical purposes, we may say the photon doesn't change the energy of the electron very much but, of course, it is significant enough to cause a significant *change* in the state of motion of the electron.[34]

Hence, the excited state of an electron may involve a *larger* radius—twice as large, *approximately*. Do we think it explains the above-mentioned factor 2? We will let the reader think for himself here as we

[32] The calculation of the angle of the *outgoing* photon involves a different formula, which the reader can also look up from any standard course. See, for example, Prof. Dr. Patrick R. LeClair's lecture on Compton scattering, which we referenced already. The reader should note that the 1 − cosθ is equal to −1 for ±π, and that there is *no* change in wavelength for θ = 0, which is when the photon goes straight through, in which case there is no scattering.
[33] See: (https://vixra.org/abs/1907.0475).
[34] Arthur Compton actually did *not* fire photons into free electrons but into electron shells bound into atoms: it is only because the *binding* energy between the nucleus and the orbital electron is much lower than the energy of the X-ray photons that one could think of the electrons as being free. In fact, the experiment knocked them out of their orbitals!

haven't made our mind up on it yet.

The details of the interaction

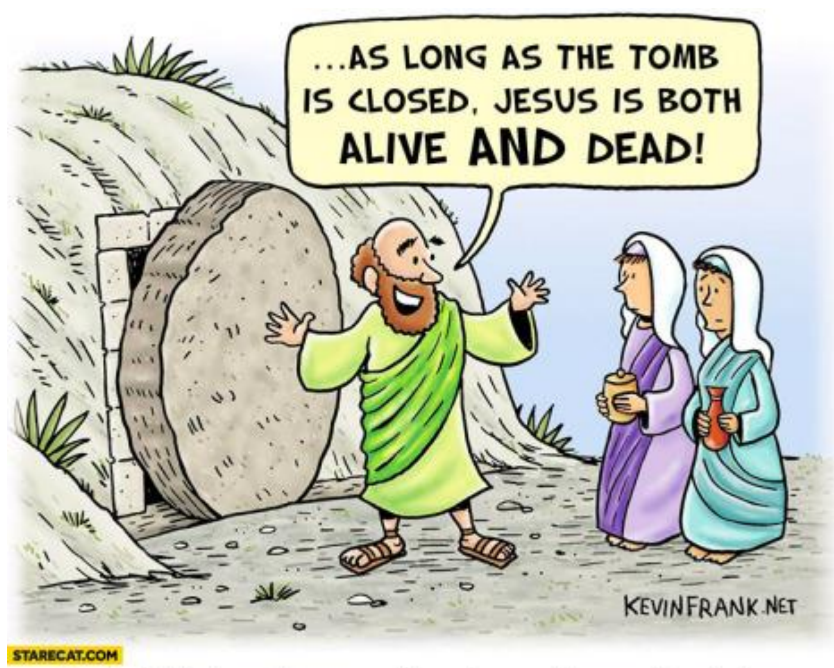
You may or may not be happy with what we wrote so far. We still haven't given you the *details* of the whole process. How does it work, *exactly*? The answer is: we don't know, but we have some clues.

For example, we think the *plane* of the *Zitterbewegung* oscillation must play a crucial role in determining the angles of the incoming as well as the outgoing photon. Also, it is quite obvious that the *circular motion* of the *zbw* charge must explain the π or 2π factor. It is *not* a size factor: the size of the electron is of the order of the Compton *radius* (a) but, because of the circular motion, it is actually the *circumference* of the motion ($\lambda = 2\pi a$) that must enter the Compton scattering formula.

The image of a hand sling throwing a stone comes to mind, of course—but that's probably too simplistic: throwing some mass out by converting circular to linear motion is easy enough to imagine, but here we're not talking mass. At the same time, our models are all 'mass without mass' models and so they show that energy is, ultimately, motion: an oscillating force on a charge in case of the electron – or, in case of the photon, an oscillating electromagnetic field. The motion that's associated with an electron is circular, while the motion of the oscillating electromagnetic field is linear. As such, we may – figuratively speaking – say that 'circular' motion is being converted into 'linear' motion, and vice versa.

In terms of the 'mechanics' of what might actually be going on when a photon is absorbed or emitted by an electron, that's all what we can give you for the time being ! You'll have to admit we can't quite show you what's going on inside of the box, but we did open it at least, didn't we?

Let us, on that note, conclude this paper with a Happy Easter cartoon !



Saint Schrodinger, the forgotten disciple.

Jean Louis Van Belle, 12 April 2020