The difference between a theory and an explanation

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Summary

In this paper, we try to show where quantum mechanics went wrong, and why and when the job of both the academic physicist as well as of the would-be student of quantum mechanics turned into *calculating* rather than *explaining* what might or might not be *happening*. Modern quantum physicists are, effectively, like economists modeling input-output relations: if they are lucky, they get some kind of *mathematical description* of what goes in and what goes out of a process or an interaction, but the math doesn't tell them how stuff actually *happens*.

We bring the *Zitterbewegung* electron model and our photon model together to provide a classical explanation of Compton scattering of photons by electrons so as to show what electron-photon interference might actually *be*: two electromagnetic oscillations interfering (classically) with each other. While developing the model, we also offer some reflections on the *nature* of the Uncertainty Principle.

Contents

The difference between a theory and an explanation

Introduction

The science of physics probes reality both *physically* as well as *logically*. Physical exploration involves experiments, measurements and discoveries. Logical progress occurs when a new theory or explanation emerges. Such theory or explanation should be logically and mathematically consistent and, preferably, be applicable to a great(er) variety of facts. Newton's force law[1] and theory of gravitation, Maxwell's equations, and Einstein's theory of relativity are obvious examples of such theories or explanations.

We are not so sure about quantum mechanics: it is a *theory* that, obviously, *works*. However, it is hard to see what it actually *explains*. In fact, we may want to think of it as a *calculation* rather than as a theory. We may illustrate this by referring to Heisenberg's pioneering of the scattering matrix, which is now more generally referred to as the *S*-matrix in quantum mechanics.[2] Scattering is actually a somewhat misleading term because it may refer to *any* interaction process. As usual, we can rely on Richard Feynman for a more vivid description of what an *S*-matrix actually is:

> "The high-class theoretical physicist working in high-energy physics considers problems of the following general nature (because it's the way experiments are usually done). He starts with a couple of particles, like a proton and a proton, coming together from infinity. (In the lab, usually one particle is standing still, and the other comes from an accelerator that is practically at infinity on atomic level.) The things go crash and out come, say, two K-mesons, six π-mesons, and two neutrons in certain directions with certain momenta. What's the amplitude for this to happen? The mathematics looks like this: The φ-state specifies the spins and momenta of the incoming particles. The χ would be the question about what comes out. For instance, with what amplitude do you get the six mesons going in such-and-such directions, and the two neutrons going off in these directions, with their spins so-and-so. In other words, χ would be specified by giving all the momenta, and spins, and so on of the final products. Then the job of the theorist is to calculate the amplitude $\langle \chi \mid S \mid \varphi \rangle$."[3]

The reader may or may not recognize the latter admonishment. The job of the theorist – or of the student in quantum mechanics – is to *calculate* rather than to *think* about what might or might not be *happening*.

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[1] Newton's force law is often referred to as the law of motion: a force is that what changes the state of motion of an object. The idea of a force acting on a (positive or negative) *charge* came later: it is usually associated with Benjamin Franklin's experiments around 1750 and – more systematically, perhaps – the work of Charles-Augustin de Coulomb, who published three *memoirs* on electromagnetism in 1785. Newton's *Philosophiæ Naturalis Principia Mathematica* (Mathematical Principles of Natural Philosophy) were first published in 1687: scientific revolutions take time.

[2] The *S* in *S*-matrix refers to scattering, not to the German *Spur* (the *trace* of a matrix) or some other term. According to the Wikipedia article on it, a proper *S*-matrix was first introduced by John Archibald Wheeler in a 1937 article on the composite wavefunction for multi-particle nuclei.

[3] See: *How states change with time*, Feynman's *Lectures*, Vol. III, Chapter 8, section 4.

To be precise, ⟨ χ | *S* | φ ⟩ is a *specific* probability *amplitude* associated with the *in*-state φ and the *out*-state χ. These states are referred to as state *vectors*[4] and they are described in terms of *base states* which are written as ⟨ *i* | and | *j* ⟩ for an *out*- and an *in*-state respectively. Hence, the *S*-matrix is actually written as ⟨ *i* | *S* | *j* ⟩ and, assuming we know what it is, we will be able to *resolve* and calculate the ⟨ χ | *S* | φ ⟩ amplitude as Σ_{ij} ⟨ χ | *i* ⟩⟨ *i* | *S* | *j* ⟩⟨ *j* | φ ⟩.

This may all look a bit mind-boggling, and it probably is. Just *google*, for example the *S*-matrix for Compton scattering[5] and let me know how *inspiring* you think this so-called explanation of a *physical process* actually is. For me, it is not an explanation at all. It is like an economist modeling input-output relations: we get a *mathematical description* of what goes in and what goes out but it doesn't tell us how stuff actually *happens*. Furthermore, when the process involves the creation or annihilation of elementary or non-elementary particles (think of short-lived mesons here), even the math becomes ugly. Paraphrasing Dirac, one is then tempted to think that it may be "more important to have beauty in one's equations than to have them fit experiment."[6]

The question, of course, runs deeper than that: we can and should *not* doubt that the likes of Bohr, Pauli, Heisenberg, Schrödinger, Dirac did what we are all doing, and that is to, somehow, try to make sense of it all. Hence, I am sure that even Heisenberg did not initially think of his *interpretation* of these relations as some kind of surrender of reason—which is, effectively, what we think it actually amounts to: stating that it is a law of Nature that even experts cannot possibly understand Nature "the way they would like to", as Richard Feynman put it[7], relegates science to the realm of religious belief.

To be sure, the *accounting rules* and the *properties* of the *S*-matrix (as well as those of operator and Hamiltonian matrices) do incorporate some basic physical principles. One of them is the principle of *reversibility*, which is related to CPT-symmetry. We will say more about this later. As for now, the reader should note that the property of reversibility in *Nature* is logical but somewhat less straightforward than it appears to be at first. If we reverse *all* signs – the direction of time, the directions in space[8], and the sign of the charges – then, yes, *Nature* seems to respect the principle of reversibility.[9] However, we may see what physicists gravely refer to as symmetry-breaking if we only reverse signs of, say, the directions in space and the sign of the charge: some processes violate what is referred to as CP-symmetry, which involves swapping spatial directions and charges only. We are not worried about that: if anything, it shows *physical* time has one direction only. However, because we wrote at length about these things elsewhere, we do not want to bore the reader with unnecessary philosophical reflections here.[10]

[4] Of course, these vectors are a bit different than the usual Cartesian coordinate vectors that you are used to but the idea of base vectors (base states) and combining or adding them remains the same. Physicists will solemnly talk of a Hilbert space but that is just *jargon* meant to impress you.

[5] I did this randomly just now and these two recent articles came out on top: https://arxiv.org/abs/1512.06681 and https://arxiv.org/abs/1810.11455. You may get others. This *input-output calculus* approach allows for endless refinements and, hence, endless research—which is always nice from an academic point of view, of course.

[6] The quote is, apparently, from a May 1963 paper or article in *Scientific American*. We didn't analyze the context in which Dirac is supposed to have said this.

[7] See: Feynman's *Lectures*, III-1-1.

[8] We are talking parity-symmetry here: think of the mirror image of things, or of turning space inside out.

[9] As mentioned, we will make a critical note here later.

[10] See, for example, our paper on the physical meaning of the quantum-mechanical wavefunction (*Euler's wavefunction: the double life of −1*) and our blog post(s) on CPT-symmetry.

We do want to highlight a few points here though, so as to give the reader a bit of an impression of what quantum-mechanical descriptions of physical processes may actually *represent*.

The meaning of spin in quantum mechanics

We must start here by what I now think of as a deep conceptual flaw in the mainstream interpretation of quantum mechanics: the mainstream interpretation does *not* integrate the concept of particle *spin* from the outset because it thinks of the + or − sign in front of the imaginary unit (*i*) in the elementary wavefunction ($a \cdot e^{-i \cdot \theta}$ or $a \cdot e^{+i \cdot \theta}$) as a mathematical convention only. Indeed, most introductory courses in quantum mechanics will show that both $a \cdot e^{-i \cdot \theta} = a \cdot e^{-i \cdot (\omega t - kx)}$ and $a \cdot e^{+i \cdot \theta} = a \cdot e^{+i \cdot (\omega t - kx)}$ are acceptable waveforms for a particle that is propagating in a given direction (as opposed to, say, some real-valued sinusoid). One would expect that the professors would then proceed to provide some argument showing why one would be better than the other, or some discussion on why they might be different but, *no*! That is not the case. The professors usually conclude that "the choice is a matter of convention" and, that "happily, most physicists use the same convention."[11]

We are totally dumbfounded by this. All of the great physicists knew all particles – elementary or not – have spin.[12] All of them also knew it is spin that generates the magnetic moment and that we should, therefore, consider the idea of thinking of elementary particles as a ring current. Indeed, the ring current model is not applicable to electrons (and positrons only). Dirac starts his derivation of his famous wave equation for free electrons in his 1933 Nobel Prize speech with the following remark[13]:

> "This procedure is successful in the case of electrons and positrons. *It is to be hoped that in the future some such procedure will be found for the case of the other particles*. I should like here to outline the method for electrons and positrons, *showing how one can deduce the spin properties* of the electron, and then how one can infer the existence of positrons *with similar spin properties*."

This should suffice to remove any doubt in regard to the importance of the concept of spin in quantum mechanics: it is the lynchpin of everything. As mentioned, the introduction above serves as an introduction to Dirac's derivation of his wave equation for an electron in free space[14] – which we will *not*

[11] In case you wonder, this is a quote from the MIT's edX course on quantum mechanics (8.01.1*x*). We quote this example for the same reason as why we use Feynman's *Lectures* as a standard reference: it is an authoritative course, and it's available online so the reader can check and explore for himself.

[12] Even photons – despite their spin-one property – cannot not come in a zero-spin state. When studying Feynman's *Lectures*, I found that to be one of the weirdest things: Feynman first spends several chapters on explaining spin-one particles to, then, in some obscure footnote suddenly write this: "The photon is a spin-one particle which has, however, no "zero" state." The issue is related to another glaring inconsistency: in the first three chapters of his *Lectures* on physics, he talks about adding wavefunctions and the basic rules of quantum mechanics, and it all happens with a plus sign. However, in his chapter on the theoretical distinction between bosons and fermions, he suddenly says we should be adding the amplitudes of fermions combine with a minus sign. In any case, we cracked our own jokes on the boson-fermion theory and so we should leave it at that.

[13] Needless to say, all *italics* in the quote are ours.

[14] The concept of free space should not confuse the reader: it makes abstraction of any external fields or forces, such as the force between a positively charged nucleus and the electron in some orbital.

write down but which involves four operators, denoted as α_r p_r (r = 1, 2, 3) and $\alpha_0 mc$ respectively[15] – and says the following about it:

> "The new variables α_r which we have to introduce to get a relativistic wave equation linear in W[16], give rise to the spin of the electron. From the general principles of quantum mechanics one can easily deduce that these variables a give the electron a spin angular momentum of half a quantum and a magnetic moment of one Bohr magneton in the reverse direction to the angular momentum. These results are in agreement with experiment. They were, in fact, first obtained from the experimental evidence provided-by spectroscopy and afterwards confirmed by the theory."

He then continues by leaving us an excellent historical summary of the ring current or *Zitterbewegung* model of the electron[17]:

> "The variables α also 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."

We wrote about this elsewhere[18] and so we will not dwell on it much longer. The question here is: why did such great intellects fail to *fully* exploit the power of Euler's ubiquitous $\psi = a \cdot e^{i\theta}$ function?. Why not? Because the Schrödinger and Dirac may have been *too* obsessed by their wave equation – as opposed to the wavefunction that is its solution. They didn't integrate spin—not from the outset, at least. The mistake is illustrated below.

[15] Dirac's wave equation can be written in various equivalent ways. We refer to Dirac's *Principles of Quantum Mechanics* or, for the reader who can follow Dirac's *very* succinct summary of it, the above-mentioned Nobel Prize speech.

[16] As mentioned, we don't want to get into the detail of (the derivation of) Dirac's equation but the reader should note Dirac only considers the *kinetic* energy of the electron which is, therefore, denoted as W rather than as E = mc^2.

[17] The term *Zitterbewegung* was, effectively, coined by Erwin Schrödinger in a 1930 paper which analyzed the solutions to Dirac's equation (Dirac had derived his equation in 1928 but the whole theoretical framework that accompanied it – his *Principles to Quantum Mechanics* – was also published in 1930 as well.

[18] See our *Explanation of the Electron and Its Wavefunction*.

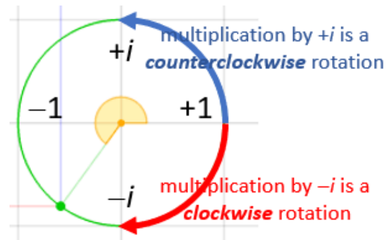

Figure 1: The meaning of +*i* and –*i*

It is a very subtle but fundamental blunder. Spin-zero particles do not exist.[19] All *real* particles – electrons, photons, anything – have spin, and spin (a shorthand for angular momentum) is always in one direction or the other: it is just the *magnitude* of the spin that differs. It is, therefore, completely odd that the plus (+) or the minus (–) sign of the imaginary unit (i) in the $a \cdot e^{\pm i\theta}$ function is *not* being used to include the spin *direction* in the mathematical description.

In fact, we call it a blunder because it is more than just odd: it's plain *wrong* because this non-used *degree of freedom* in the mathematical description leads to the *false* argument that the wavefunction of spin-½ particles have a 720-degree symmetry. Indeed, physicists treat –1 as a *common phase factor* in the argument of the wavefunction: they think we can just multiply a set of amplitudes – let's say *two* amplitudes, to focus our mind (think of a beam splitter or alternative paths here) – with –1 and get the same *states*. We find it rather obvious that that is not necessarily the case: –1 is *not* necessarily a common phase factor. We should think of –1 as a complex number itself: the phase factor may be +π or, alternatively, –π. To put it simply, when going from +1 to –1, it matters how you get there – and vice versa – as illustrated below.[20]

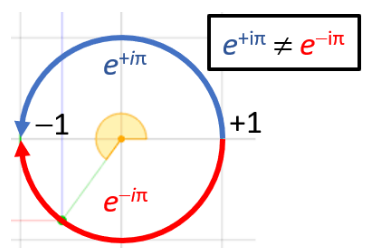

Figure 2: $e^{+i\pi} \neq e^{-i\pi}$

What's the point? It is this: if we exploit the full descriptive power of Euler's function, then all weird symmetries disappear – and we just talk standard 360-degree symmetries in space. Also, weird mathematical conditions – such as the *Hermiticity* of quantum-mechanical operators – can easily be

[19] We are obviously not talking about the zero-spin state of, say, a spin-one atom here. We talk about *elementary* particles only here.

[20] The quantum-mechanical argument is technical, and I did *not* reproduce it in this book. I encourage the reader to glance through it, though. See: *Euler's Wavefunction: The Double Life of – 1*. Note that the $e^{+i\pi} \neq e^{-i\pi}$ expression is *horror* to any mathematician! Hence, if you're a mathematician, you should switch off. If you're an amateur physicist, you should be excited, because it actually *is* the secret key to unlocking the so-called mystery of quantum mechanics. Remember Aquinas' warning: *quia parvus error in principio magnus est in fine*. A small error in the beginning can lead to great errors in the conclusions, and we sure think of this as an error in the beginning!

explained as embodying some common-sense *physical* law: energy and momentum conservation, for example, or *physical* reversibility: we need to be able to play the movie backwards.

Here we must note something funny with charges, however. Combining the + and − sign for the imaginary unit with the direction of travel, we get *four possible structures* for the wavefunction for an electron:

Spin and direction of travel	**Spin up ($J = +\hbar/2$)**	**Spin down ($J = -\hbar/2$)**
Positive *x*-direction	$\psi = \exp[i(kx-\omega t)]$	$\psi^* = \exp[-i(kx-\omega t)] = \exp[i(\omega t-kx)]$
Negative *x*-direction	$\chi = \exp[-i(kx+\omega t)] = \exp[i(\omega t-kx)]$	$\chi^* = \exp[i(kx+\omega t)]$

Table 1: Occam's Razor: mathematical possibilities versus physical realities

However, this triggers the obvious question: how do we know it's an electron or a *negative* charge, as opposed to a positron, or a *positive* charge? Indeed, consider a particular direction of the elementary current generating the magnetic moment. It is then very easy to see that the magnetic moment of an electron ($\mu = -q_e\hbar/2m$) and that of a positron ($\mu = +q_e\hbar/2m$) would be opposite. We may, therefore, associate a particular direction of rotation with an angular frequency *vector* **ω** which – depending on the direction of the current – will be up or down with regard to the plane of rotation. We associate this with the spin property, which is also up or down. We, therefore, have another set of four possibilities reflecting one another:

Matter-antimatter	**Spin up ($J = +\hbar/2$)**	**Spin down ($J = -\hbar/2$)**
Electron	$\mu_{e-} = -q_e\hbar/2m$	$\mu_{e-} = +q_e\hbar/2m$
Positron	$\mu_{e+} = +q_e\hbar/2m$	$\mu_{e+} = -q_e\hbar/2m$

Table 2: Electron versus positron spin

So how do we distinguish them? It is a deep philosophical question which we cannot fully answer for the time being. We can only offer a few thoughts here:

1. The idea of time reversal is a wonderful invention of our mind but we think it does *not* correspond to anything real. When charges are involved, you will see two like charges repel each other and, therefore, you will see them move away from each other. However, when playing the movie backward, you will know it the movie cannot be *real* because the same two charges now move *towards* each other. The funny thing is that a reversal of the sign of the charges doesn't help to fix the situation because, say, reversing the charge of two electrons now gives us two positrons moving towards each other, which doesn't make sense physically either!

The reader may think we did, perhaps, not think of P-symmetry: all left-handed things are now right-handed and vice versa, right? Yes, but that doesn't solve the problem here.

2. So what about CPT-symmetry then? Frankly, we think the concept of CPT-symmetry is not all that useful and we, therefore, wonder why physicists are so enthralled about it. We think the concept of motion itself implies that time can have one direction only. If it wouldn't, then we would not be able to describe trajectories in spacetime by a well-behaved function. In other words, the concept of motion itself would become meaningless.

The diagrams below illustrate the point. The spacetime trajectory in the diagram on the right is not *kosher*, because our object travels back in time in not less than three sections of the graph. Spacetime trajectories – or, to put it more simply, *motions* – need to be described by well-defined functions: for every value of *t*, we should have one, and only one, value of *x*. The reverse, of course, is *not* true: a particle can travel back to where it was (or, if there is no motion, just stay where it is). Hence, it is easy to see that the concepts of motion and time are related to us using well-behaved functions to describe reality.[21]

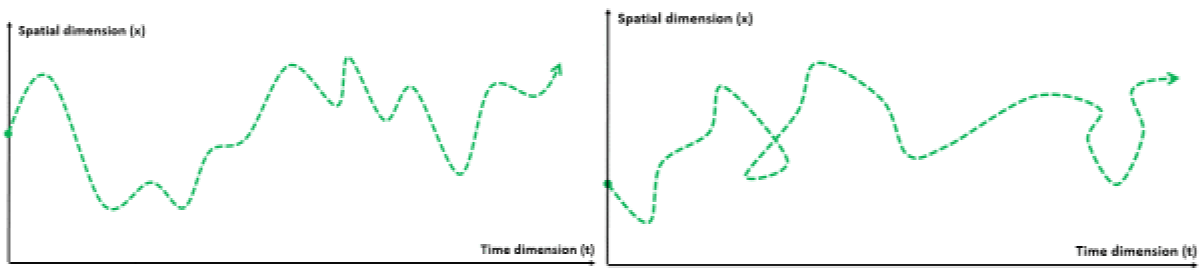

Figure 3: A well- and a not-well behaved trajectory in spacetime[22]

3. The obvious question then is this: what *is* anti-matter then? We have no answer to that. We just feel that the suggestion of some physicists – Richard Feynman, in particular – that anti-particles may be particles travelling back in time is nonsense. Dirac's suggestion that, somehow, antimatter must imply the concept of *negative* energy states is, currently, all we have.[23]

We must now come back to the matter at hand, which is the meaning of conjugates in quantum physics.

The meaning of conjugating amplitudes, wavefunctions and matrices

The ubiquitous concept of a *state* in quantum mechanics is very abstract and general and, therefore, adds to the mystery of the quantum-mechanical description of things. We may start by noting that the concept of an initial and a final state – or an *in*- and an *out*-state – are very intimately linked: they correspond to the *bra* and the *ket* in Dirac's bra-ket notation which – we should not remind the reader – must be read *from right to left*. As such, we like to think the concepts of the initial and final state simply separate the present from the (possible) the future.

In practice, we will use *matrix mechanics* when states are *discrete*, while the wavefunction approach allows us to model how a particle may *evolve* which, in practice, usually means what and where we

[21] We wish the reader who would want to try using other functions to arrive at some kind of description of reality the best of luck.

[22] We actually do not like the concept of spacetime very much: as we hope to have illustrated, time and space are *related*, of course – through special and general relativity theory, to be precise – but they are *not* the same nor are they even similar. We do, therefore, *not* think that some 'kind of union of the two' will replace the separate concepts of space and time any time soon, despite Minkowski's stated expectations in this regard back in 1908.

[23] We do offer some *very* speculative thoughts on the nature of antimatter in our paper on [*The Ring Current Model for Antimatter and Other Questions*], but we do not want to mention these here because we feel these ideas do not make all that much sense.

expect its momentum and position to be. One of Feynman's very first examples of a state is the *spin* state of *spin-one* atoms[24], which may be +1, 0 or −1. These are referred to as *base states*. Base states need to be independent, which is captured by the usual *Kronecker delta rule*:

$$\langle\, i \mid j \,\rangle = \delta_{ij}$$

This basically says a base state is a base state: $\langle\, i \mid j \,\rangle = 1$ if, and only if, $i = j$. Otherwise $\langle\, i \mid j \,\rangle = 0$. It obviously also means a particle can be in one state only at any point in time. The *evolution* from one state to another involves a *process* or – another oft-used terms in introductory courses – an *apparatus*, such as a *filter*, which may also be referred to as polarizer.[25] Now, the *amplitude* for a particle to go from state φ to state χ will be $\langle\, \chi \mid \varphi \,\rangle$. An amplitude is, of course, a *probability* amplitude here: it is a complex number or a *complex-valued* wavefunction. There is a most remarkable *law* in quantum mechanics, and it is this: **the amplitude to go from the *out*-state χ to the *in*-state φ is the (complex) conjugate of the amplitude to go from the *in*-state φ to the *out*-state χ** – and vice versa, of course! It is more easily written like this:

$$\langle\, \varphi \mid \chi \,\rangle = \langle\, \chi \mid \varphi \,\rangle^* \text{ and } \langle\, \chi \mid \varphi \,\rangle = \langle\, \varphi \mid \chi \,\rangle^*$$

Feynman *proves* this rule for a three-state system and a simple *filter* apparatus[26] but we find it easier to think of it as a simple consequence of this theoretical possibility of *reversibility*: a sign reversal of the imaginary unit *i*. Instead of +*i* (or, conversely, −*i*), we now use −*i* (or, conversely, +*i*) in our wavefunction. It is probably easiest to also show what this means in terms of actual *probabilities* rather than amplitudes. Indeed, we get the actual *probability* – some real-valued number between 0 and 1 – from taking the absolute square[27] of the complex-valued amplitude.

In our realist interpretation, we understand this quantum-mechanical rule in terms of mass or energy densities: we think of the oscillating or *Zitterbewegung* charge as passing more time here than there and, hence, the associated *energy density* will be higher here than there.[28] However, that interpretation does not matter here. We just want to show you that we can use this quantum-mechanical rule for calculating probabilities to derive the above-mentioned quantum-mechanical reversibility law. Indeed, the absolute square of a complex number is the product of the same number with its complex conjugate. We, therefore, get this[29]:

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[24] While a photon is generally considered to be a spin-one particle, it does not have a zero state. In contrast, spin-one atoms are *composite* particles and, hence, its component particles may effectively line up in a way that produces a spin-zero state.

[25] We find the term somewhat confusing but a polarized beam is a beam of particles with the same spin.

[26] See: Feynman's Lectures, III-5-5 (*Interfering Amplitudes*) and III-5-6 (*The Machinery of Quantum Mechanics*).

[27] The absolute square is, obviously, a shorthand for the absolute value of the square.

[28] You may think of this like follows. The energy in an oscillation – *any* physical oscillation – is always proportional to the *square* of the (maximum) amplitude of the oscillation, so we can write this: $E \propto a^2$. To be precise, the energy of an electron in our ring current model is equal to $E = m \cdot a^2 \cdot \omega^2$. We get this from (1) Einstein's mass-energy equivalence relation ($E = m \cdot c^2$) and (2) our interpretation of *c* (lightspeed) as a tangential velocity ($c = a \cdot \omega$). We think the mass of the electron is just the equivalent mass of the energy of the *Zitterbewegung* charge in its oscillation. We, therefore, think it makes sense to think that the probability of actually *finding* the charge here or there will be proportional to the energy density here and there.

[29] The reader should carefully note what is commutative and what not here!

$$|\langle \varphi \mid \chi \rangle|^2 = \langle \varphi \mid \chi \rangle\langle \varphi \mid \chi \rangle^* = \langle \chi \mid \varphi \rangle^*\langle \chi \mid \varphi \rangle = \langle \chi \mid \varphi \rangle^*\langle \chi \mid \varphi \rangle = |\langle \chi \mid \varphi \rangle|^2$$

At this point, the reader may wonder what we want to say here. We are just saying that the quantum-mechanical $\langle \varphi \mid \chi \rangle = \langle \chi \mid \varphi \rangle^*$ rule only states physical processes should be reversible in space and in time, and that it amounts to stating that **the probability of going from the *out*-state χ to the *in*-state φ is the same as going from the *in*-state φ to the *out*-state χ**.

The question is: does this rule or law make sense? In other words, is it true, ***always*?** In mechanics – think of elastic collisions of particles or particles moving in force fields – it should be the case. However, when disintegration processes are involved, one should not expect this law to apply. Why not? Disintegration involves unstable systems moving to some kind of *stable* state. Energy, angular momentum, and linear momentum will be conserved, but that's about all we can say about it. Inventing new quantities to be conserved – such as strangeness – or invoking other consequences of so-called symmetry-breaking processes does not add much explanatory power in our view.

[…]

Let us wrap up here—this *section* of our paper, at least! Let's summarize the basics of our discussion above: if we can go *from* state φ *to* state χ, then we must be able to go *back* to state φ *from* state χ in space and in time. This amounts to playing a movie backwards: an exploding suitcase bomb will, in practice, *not* suddenly un-explode and get back into the suitcase but, theoretically (read: making abstraction of arguments involving entropy and other *macroscopic* considerations), such reversed processes may be *imagined*.[30]

We can now think of an apparatus or a process that will be operating on some state $|\psi\rangle$ to produce some other state $|\varphi\rangle$, which we would write as:

$$\langle\varphi|A|\psi\rangle$$

We can now take the complex conjugate:

$$\langle\varphi|A|\psi\rangle^* = \langle\psi|A^\dagger|\varphi\rangle$$

$A^\dagger$ is, of course, the conjugate transpose of A – we write: $A^\dagger_{ij}=(A_{ji})^*$ – and we will call the operator (and the matrix) Hermitian if the conjugate transpose of this operator (or the matrix) gives us the same operator matrix, so that is if $A^\dagger = A$. Many quantum-mechanical operators are Hermitian, and we will also often *impose* that condition on the *S*-matrix. Why? Because you should think of an operator or an *S*-matrix as a symmetric apparatus or a reversible process. It's as simple as that. Hence, the Hermiticity condition amounts to a simple reversibility condition too!

Needless to say, we may be mistaken, of course! We, therefore, invite the professional reader to challenge this interpretation! The professional reader may also note we forgot to specify the second of the three basic rules of quantum math, and that's the resolution of amplitudes into base states—which is written like this:

[30] This rather extreme example of before and after states is, perhaps, less extreme than it appears to be: the proton-proton collisions in CERN's LHC colliders are quite violent too, albeit at a much smaller scale. However, as mentioned, one should not necessarily expect that the *disintegration* processes involved in the creation of such *disequilibrium* situations would or should be reversible.

$$\langle \chi \mid \varphi \rangle = \Sigma_{\text{all } i} \langle \chi \mid i \rangle\langle i \mid \varphi \rangle$$

This, too, can be shown to be true based on a thought experiment[31] or, else, one can use a much more abstract argument (as Dirac does as part of his formalization of the theoretical framework for working with amplitudes) and simply write:

$$\mid \; = \Sigma_{\text{all } i} \mid i \rangle\langle i \mid$$

This, then allows us to do what we did, and that's to write the $\langle \chi \mid S \mid \varphi \rangle$ amplitude as $\Sigma_{ij} \langle \chi \mid i \rangle\langle i \mid S \mid j \rangle\langle j \mid \varphi \rangle$.

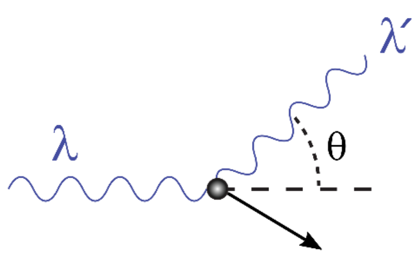
Any case, this is all very abstract and, therefore, very tiring. Furthermore, it does not amount to what we think of as any *real* explanation for real-life physical processes: it merely *describes* them. As mentioned, this is more like economists modeling input-output relations: we get a *mathematical description* of what goes in and what goes out but it doesn't tell us how stuff actually *happens*.

So how would or might a *real* explanation then look like? Let us illustrate this using the example of Compton scattering.

A real explanation of Compton scattering

Energy and momentum conservation

Compton scattering is referred to as inelastic because the frequency of the incoming and outgoing photon are different. The situation is illustrated below.



The reader will be familiar with the formulas and, most probably, also with how these formulas can be derived from two very classical laws only: (1) energy conservation and (2) momentum conservation. Let us quickly do this to remind the reader of the elegance of classical reasoning:

1. The energy conservation law tells us that the total (relativistic) energy of the electron ($E = m_e c^2$) and the incoming photon must be equal to the total energy of the outgoing photon and the electron, which is now moving and, hence, includes the kinetic energy from its (linear) motion. We use a prime (') to designate variables measured after the interaction. Hence, $E_{e'}$ and $E_{\gamma'}$ are the energy of the moving electron (e') and the outgoing photon (γ') in the state after the event. We write:

$$E_e + E_\gamma = E_{e'} + E_{\gamma'}$$

[31] Feynman provides such argument based on placing an open filter (no masks) in-between two other filters. See the above-mentioned reference to Feynman's *Lectures* (III-5-5).

We can now use (i) the mass-energy equivalence relation (E = mc^2), (ii) the Planck-Einstein relation for a photon (E = $h \cdot f$) and (iii) the relativistically correct relation ($E^2 - p^2c^2 = m^2c^4$) between energy and momentum for *any* particle – charged or non-charged, matter-particles or photons or whatever other distinction one would like to make[32] – to re-write this as[33]:

$$\mathrm{m_e}c^2 + hf = \sqrt{\mathrm{p}_{\mathrm{e}'}^2 c^2 + \mathrm{m_e^2}c^4} + hf' \Leftrightarrow \mathrm{p}_{\mathrm{e}'}^2 c^2 = (hf - hf' + \mathrm{m_e^2}c^4)^2 - \mathrm{m_e^2}c^4 \ (1)$$

2. This looks rather monstrous but things will fall into place soon enough because we will now derive another equation based on the momentum conservation law. Momentum is a vector, and so we have a vector equation here[34]:

$$\vec{\mathrm{p}}_\gamma = \vec{\mathrm{p}}_{\gamma'} + \vec{\mathrm{p}}_{\mathrm{e}'} \Leftrightarrow \vec{\mathrm{p}}_{\mathrm{e}'} = \vec{\mathrm{p}}_\gamma - \vec{\mathrm{p}}_{\gamma'}$$

For reasons that will be obvious later – it is just the usual thing: ensuring we can combine two equations into one, as we did with our formulas for the radius – we square this equation and multiply with Einstein's constant c^2 to get this[35]:

$$\vec{\mathrm{p}}_{\mathrm{e}'}^2 = \vec{\mathrm{p}}_\gamma^2 + \vec{\mathrm{p}}_{\gamma'}^2 - 2\vec{\mathrm{p}}_\gamma \vec{\mathrm{p}}_{\gamma'} \Leftrightarrow \mathrm{p}_{\mathrm{e}'}^2 c^2 = \mathrm{p}_\gamma^2 c^2 + \mathrm{p}_{\gamma'}^2 c^2 - 2(\mathrm{p}_\gamma c)(\mathrm{p}_{\gamma'} c) \cdot \cos\theta$$

$$\Leftrightarrow \mathrm{p}_{\mathrm{e}'}^2 c^2 = h^2 f^2 + h^2 f'^2 - 2(hf)(hf') \cdot \cos\theta \ (2)$$

3. We can now combine equations (1) and (2):

$$\mathrm{p}_{\mathrm{e}'}^2 c^2 = (Eq.1) = (Eq.1) = (hf - hf' + \mathrm{m_e^2}c^4)^2 - \mathrm{m_e^2}c^4 = h^2 f^2 + h^2 f'^2 - 2(hf)(hf') \cdot \cos\theta$$

The reader will be able to do the horrible stuff of actually squaring the expression between the brackets and verifying only cross-products remain. We get:

$$(hf - hf')\mathrm{m_e}c^2 = h(f - f')\mathrm{m_e}c^2 = h^2 ff'(1 - \cos\theta)$$

---

[32] This is, once again, a standard textbook equation but – if the reader would require a reminder of how this formula comes out of special relativity theory – we may refer him to the online *Lectures* of Richard Feynman. Chapters 15 and 16 offer a concise but comprehensive overview of the basics of relativity theory and section 5 of Chapter 6 gives the reader the formula he needs here. It should be noted that we dropped the 0 subscript for the rest mass or energy: m_0 = m. The *prime* symbol (') takes care of everything here and so you should carefully distinguish between primed and non-primed variables.

[33] We realize we are cutting some corners. We trust the reader will be able to *google* the various steps in-between.

[34] We could have used **boldface** to denote vectors, but the calculations make the arrow notation more convenient here. So as to make sure our reader stays awake, we note that the objective of the step from the first to the second equation is to derive a formula for the (linear) momentum of the electron *after* the interaction. As mentioned, the linear momentum of the electron *before* the interaction is zero, because its (linear) velocity is zero: $\mathbf{p}_e = \mathbf{0}$.

[35] We do not want to sound disrespectful when referring to c^2 as Einstein's constant. It has a deep meaning, in fact. Einstein does not have any fundamental constant or unit named after him. Nor does Dirac. We think c^2 would be an appropriate 'Einstein constant'. Also, in light of Dirac's remarks on the nature of the strong force, we would suggest naming the unit of the strong charge after him. More to the point, note these steps – finally ! – incorporated the directional aspect we needed for the analysis. Note that we also use the rather obvious E = pc relation for photons in the transformation of formulas here.

Multiplying both sides of the equation by the $1/hm_eff'$ constant yields the formula we were looking for:

$$\frac{(f-f')\mathrm{m_e}c}{f\cdot f'} = \frac{f\mathrm{m_e}c - f'^{\mathrm{m_e}}c}{f\cdot f'} = \frac{h}{\mathrm{m_e}c}(1-\cos\theta)$$

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

The formulas allow us also to calculate the angle in which the electron is going to recoil. It is equal to:

$$\cot\left(\frac{\theta}{2}\right) = \left(1+\frac{\mathrm{E_\gamma}}{\mathrm{E_e}}\right)\tan\ \varphi$$

The h/mc factor on the left-hand side of the right-hand side of the formula for the difference between the wavelengths is, effectively, a distance: about 2.426 *pico*meter (10^{-12} m). The $1-\cos\theta$ factor goes from 0 to 2 as θ goes from 0 to π. Hence, the maximum difference between the two wavelengths is about 4.85 pm. This corresponds, unsurprisingly, to *half* the (relativistic) energy of an electron.[36] Hence, a highly energetic photon could lose up to 255 keV.[37] That sounds enormous, but Compton scattering is usually done with highly energetic X- or gamma-rays.

Could we imagine that a photon loses all of its energy to the electron? No. We refer to Prof. Dr. Patrick LeClair's course notes on Compton scattering[38] for a very interesting and more detailed explanation of what actually happens to energies and frequencies, and what depends on what exactly. He shows that the electron's kinetic energy will always be a *fraction* of the incident photon's energy, and that fraction may approach but will never actually reach unity. In his words: "This means that there will always be some energy left over for a scattered photon. Put another way, it means that a stationary, free electron cannot absorb a photon! Scattering must occur. Absorption can only occur if the electron is bound to a nucleus."

What is actually happening?

A photon *interacts* with an electron, so we actually 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 we just derived:

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

Now, 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 ($E = h\cdot f$). 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, for example, also a

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[36] The energy is inversely proportional to the wavelength: $E = h\cdot f = hc/\lambda$.

[37] The electron's rest energy is about 511 keV.

[38] See the *exposé* of Prof. Dr. Patrick R. LeClair on Compton scattering.

formula for 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*? And what determines the *plane* which is formed by the outgoing photon and the recoiling electron?

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. Let us walk over the basics of that.

The Compton wavelength as a circumference

According to our ring current model of an electron, the wavefunction $\psi(\boldsymbol{x}, t) = \psi(x, y, z, t)$ describes the actual position of the pointlike *Zitterbewegung* charge in its oscillatory motion around some center.[39] We may therefore paraphrase Prof. Dr. Patrick LeClair and identify the Compton wavelength with a "*distance scale within which we can localize the electron in a particle-like sense*."[40] Why are we so sure of that?

We should first discuss the 2π factor. Indeed, we have h, not $\hbar$, in the 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*.[41] 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 $\mathrm{p} = \mathrm{m}v$ 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:

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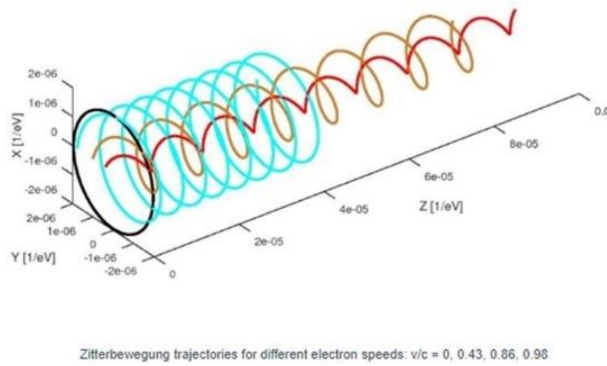
[39] We are often tempted to use a semicolon to separate the time variable from the space coordinates. Hence, we would prefer to write $\psi(\boldsymbol{x}, t) = \psi(x, y, z; t)$ instead of $\psi(\boldsymbol{x}, t) = \psi(x, y, z; t)$. The semicolon then functions as a *serial* comma. Of course, we 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 $\boldsymbol{x} = (x, y, z) = (f_x(t), f_y(t), f_z(t) = f(t)$ – 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.

[40] See the reference above.

[41] 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.

$$\lambda_C = h/mc \neq \lambda = h/p = h/mv$$

The illustration below (for which credit goes to an Italian group of *zbw* theorists[42]) 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 $a = \hbar/mc$. 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 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.[43]



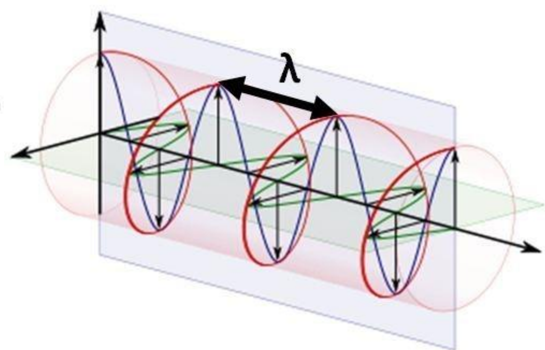


Figure 4: The wavelength(s) of an electron

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:

[42] 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} $\approx 0.1975\times10^{-15}$ 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).

[43] 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.

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

The λ_C is the *Compton* wavelength, so that's the circumference of the circular motion.[44] 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.[45] 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:

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

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[46] – 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*

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

[45] 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.

[46] 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).

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.[47] 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 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 have actually presented a few times in previous papers already.[48] 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 $(3\times10^8$ m/s$)\cdot(0.4\times10^{-15}$ 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.[49] 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:

[47] See, for example, Feynman's discussion of using photons to try to detect electrons as part of the two-slit experiment.

[48] See, for example, our paper on *Relativity, Light, and Photons*.

[49] 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.

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

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 (T = $1/f$ = λ/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:

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

We already mentioned that 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.[50] However, that doesn't answer the question in regard to the 2π factor: the $h/\mathrm{m}c$ 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 $\hbar$. So we should, perhaps, re-do our calculation of the Compton radius of our electron as follows:

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

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

[50] 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.

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.[51]

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 haven't made our mind up on it yet.

Conclusions

The professional reader will point out that – despite our claim we'd give you a *real* explanation of Compton scattering – we failed to produce all of the *details* of the process. How does it work, *exactly*? We effectively did not work out all of the details, but we do have some very strong *clues* here on how a *definitive* explanation – including *all* relevant variables, including the mentioned *plane* formed by the outgoing photon and the recoiling electron – may look like. The *plane* of the *Zitterbewegung* oscillation, for example, must – without any doubt – 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? Just in case you think we didn't, we invite you – once again – to google the papers explaining the *S*-matrix of Compton scattering processes.[52] We are sure you will prefer to re-read our paper and – who knows? – start doing some pretty calculations yourself!

Jean Louis Van Belle, 15 April 2020

[51] 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!

[52] As mentioned in the introduction, we rather randomly googled the following two papers: https://arxiv.org/abs/1512.06681 and https://arxiv.org/abs/1810.11455. You may get others. This *input-output calculus* approach allows for endless refinements and, hence, endless research—which is always nice from an academic point of view, of course.