The electron as a harmonic electromagnetic oscillator

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Abstract: This paper complements previous papers and a manuscript offering a full-blown realist interpretation of quantum mechanics based on the *Zitterbewegung* model of an electron. This manuscript would have been published by IOP and WSP if it were not for the casual comments of a critic, who opined our oscillator model is just "casually connecting disparate formulas." This paper explains all the nuances and logical steps in the model in very much detail and we, therefore, hope we succeeded in making the case.

Keywords: *Zitterbewegung*, mass-energy equivalence, wavefunction interpretations, realist interpretation of quantum mechanics.

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Introduction

Our particular flavor of the *zbw* model of an electron takes Einstein's mass-energy equivalence relation ($E = m \cdot c^2$) and equates c to $a \cdot \omega$. We can then use the Planck-Einstein relation ($E = \hbar \cdot \omega$) to find the Compton radius:

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

In the literature, one will usually find references to the Compton *wavelength* λ_C. References to the *reduced* Compton wavelength ($\lambda_C/2\pi$) are not so common, and the *zbw* interpretation of it as an effective radius ($a = \lambda_C/2\pi$) of the electron even less so. However, we find ourselves in good company here. It is not only authors such as David Hestenes or Alexander Burinskii who associate this length with an effective diameter of the electron: even Dirac hinted at it when describing Schrödinger's discovery of the *Zitterbewegung*. Indeed, we may want to remind ourselves that it was Erwin Schrödinger who stumbled upon the idea of the *Zitterbewegung* when he was exploring solutions to Dirac's wave equation for free electrons. It's worth quoting Dirac's summary of it:

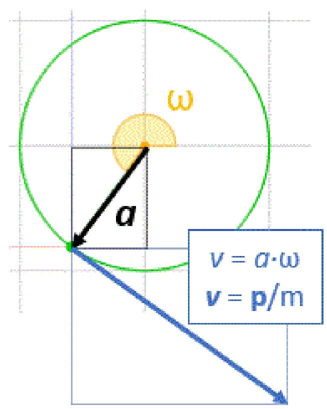
> "The variables give rise to some rather unexpected phenomena concerning the motion of the electron. These have been fully worked out by Schrödinger. It is found that an electron which seems to us to be moving slowly, must actually have a very high frequency oscillatory motion of small amplitude superposed 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)

From the context, it is clear that Dirac's reference to the 'law of scattering of light by an electron' is, effectively, a reference to Compton scattering and, hence, it is good to say a few words about that. 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 Thomson or Lorentz radius, and it is equal to $r_e = \alpha \cdot a \approx a/137 \approx 2.818 \times 10^{-15}$ m. The Thomson scattering radius is referred to as *elastic* because the photon seems to bounce off some hard *core*: there is no interference. This picture is also fully consistent with the *Zitterbewegung* model of an electron: the hard core is just the pointlike charge itself. It is, effectively, pointlike – 10^{-15} m is the *femto*meter scale – but, as we can see, pointlike does not mean dimensionless.

The above directly inspires the $c = a \cdot \omega$ formula we are using: it is just the formula we'd use for the tangential velocity of any object going around in a circle, as illustrated in Figure 1. In our *zbw* model of an electron, we think of the object (the green dot in the illustration) as the pointlike charge. The charge itself has zero rest mass: it is just an electric charge, and the mass of the electron as a whole is the equivalent mass of the two-dimensional motion of the charge—its *Zitterbewegung*. This hybrid description of the electron is Wheeler's idea of mass without mass: the mass of the electron is the equivalent mass of the energy in the oscillation of the pointlike charge.

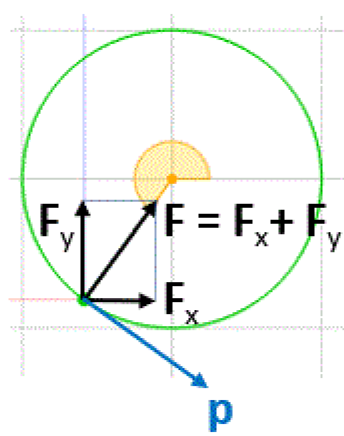
Figure 1: $c = v = a \cdot \omega$



What is the nature of the oscillation?

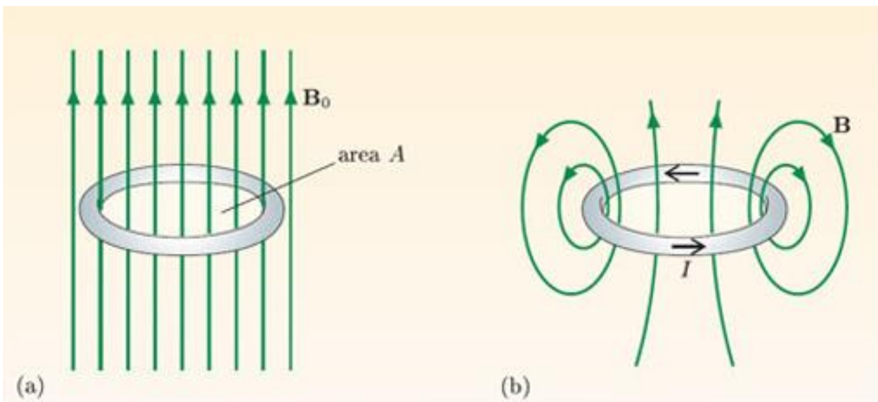
To keep an object with some momentum in a circular orbit, a centripetal force is needed, as shown in Figure 2.

Figure 2: The *Zitterbewegung* model of an electron



What is the nature of this force? Because the force can only grab onto the charge, it must be electromagnetic. Hestenes, who revived the *Zitterbewegung* theory in the 1980s and 1990s, thinks that the nature of the *zbw* current is the same as that of a superconducting current, as illustrated in Figure 3. If we have some magnetic field – let us denote it by $\mathbf{B}_0$, as in the left-hand side (a) of the illustration below – going through a ring made of superconducting material, we can then cool the ring below the critical temperature and switch off the field. Lenz's law – which is nothing but a consequence of Faradays' law of induction – then tells us the *change* (because of the switch-off) in the magnetic field will induce an electromotive force. Hence, we get an *induced* electric current, and its direction and magnitude will be such that the magnetic flux it generates will compensate for the flux change: the induced current in the superconducting circuit will just maintain the flux through the ring at the same value.

Figure 3: A perpetual current in a superconducting ring[1]



This may sound very complicated but it's just yet another application of Maxwell's equations. The hypothesis gives rise to Hestenes' interpretation of the *zbw* model of an electron, which he summarizes as follows:

> "The electron is nature's most fundamental superconducting current loop. Electron spin designates the orientation of the loop in space. The electron loop is a superconducting LC circuit. The mass of the electron is the energy in the electron's electromagnetic field."[2]

The only problem with this interpretation is that, in free space, we do not have any ring to hold and guide our charge. We, therefore, need one or more additional hypotheses. Before we think about what we could possibly use, let us look at that force again.

There is no positive charge at the center, so the situation can surely *not* be compared to an electron orbiting a positively charge nucleus. In fact, the force is perpendicular to the direction of motion of the charge so, yes, this force must be magnetic only. This hypothesis makes sense in light of the force formula for the magnetic force:

$$\mathbf{F}_{magnetic} = q\cdot\boldsymbol{v}\times\mathbf{B} \text{ force formula}$$

[1] Source: Open University, Superconductivity, https://www.open.edu/openlearn/science-maths-technology/engineering-and-technology/engineering/superconductivity/content-section-2.2#. The reader who's interested in the detailed equations proving this fact will find them there.

[2] Email from Dr. David Hestenes to the author dated 17 March 2019.

Note that the formula above follows the usual convention, which is that q is some *positive* charge. Figure 3(b) follows the same convention. Our *zbw* charge will be negative, so we should write F = $-q_e \cdot \boldsymbol{v} \times \mathbf{B}$. We may also want to think about the field density here. A constant flux through the ring does not mean that the magnetic field remained unchanged. In Figure 3(a), we had a uniform magnetic field within the ring, while in Figure 3(b) we have a field that's produced by the current flowing in the ring and, hence, the field density is much larger close to the ring than at its center, even if the total flux has the same value. Why is this important? It is important because we will probably want to know, at some point in the analysis, where the (field) energy is actually located.

OK. Back to hypotheses. We used the Planck-Einstein relation ($E = \hbar \cdot \omega$) to calculate the radius $a = \hbar/mc$. The Planck-Einstein relation can be re-written as $E/T = h$. $T = 1/f$ is the cycle time in this equation. From the same equation, it is obvious that it is equal to $T = h/E$ Its value is 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 very small. 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. It is interesting to note that we can write Planck's quantum of action as the product of the electron's energy and the cycle time:

$$h = \mathrm{E} \cdot \mathrm{T} = \mathrm{h} \cdot f \cdot \mathrm{T}$$

Hence, we may think of one cycle packing not only the electron's energy but also as packing one unit of *h*. We can do some more calculations. We can calculate the current:

$$\mathrm{I} = \mathrm{q_e} f = \mathrm{q_e}\frac{\mathrm{E}}{h} \approx (1.6 \times 10^{-19}\ \mathrm{C})\frac{8.187 \times 10^{-14}\ \mathrm{J}}{6.626 \times 10^{-34}\ \mathrm{Js}} \approx 1.98\ \mathrm{A}\ (ampere)$$

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:

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

It is also consistent with the presumed angular momentum of an electron, which is that of a spin-1/2 particle. Here we must make some assumption as to how the effective mass of the electron will be spread over the disk. If we assume it is spread uniformly over the whole disk[3], then we can use the 1/2 form factor for the moment of inertia (*I*). We write:

$$\mathrm{L} = I \cdot \omega = \frac{ma^2}{2}\frac{c}{a} = \frac{mc}{2}\frac{\hbar}{mc} = \frac{\hbar}{2}$$

We now get the correct g-factor for the pure spin moment of an electron:

$$\boldsymbol{\mu} = -\mathrm{g}\left(\frac{\mathrm{q_e}}{2\mathrm{m}}\right)\mathbf{L} \Leftrightarrow \frac{\mathrm{q_e}}{2\mathrm{m}}\hbar = \mathrm{g}\frac{\mathrm{q_e}}{2\mathrm{m}}\frac{\hbar}{2} \Leftrightarrow \mathrm{g} = 2$$

[3] This is a very essential point. It is also very deep and philosophical. We say the energy is in the motion, but it's also in the oscillation. It is difficult to capture this in a mathematical formula. In fact, we think this is the key paradox in the model.

But why would the mass be spread uniformly over the area of our circle with radius *a*? In fact, why would be think of our electron as some disk? We need some more advanced theory to answer such questions.

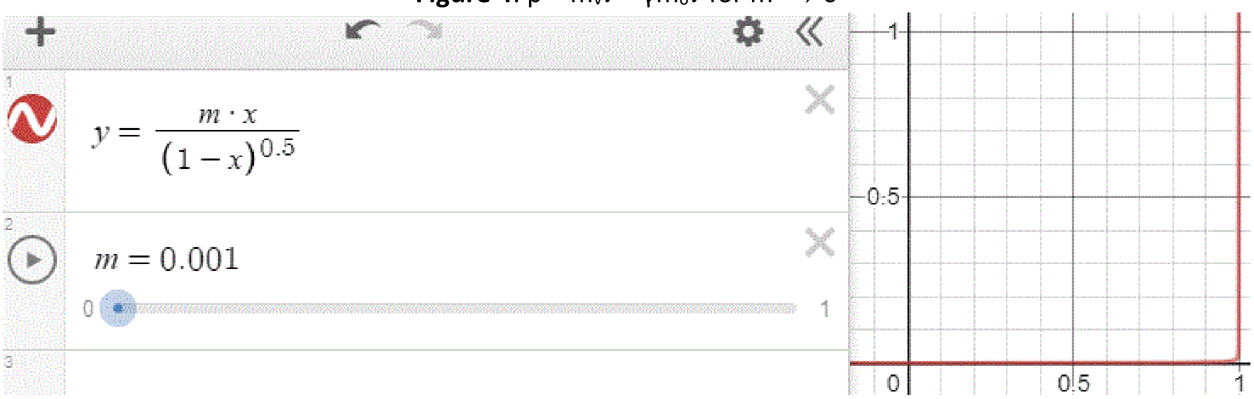
What's the momentum of the pointlike charge?

Before we try to answer that question, we should think about the momentum vector **p** in Figure 2. It should be relativistic momentum of course, so its magnitude is equal to:

$$p = mc = \gamma m_0 c$$

How should we calculate this? The Lorentz factor goes to infinity as the velocity goes to *c*, and m_0 is equal to zero. So we are multiplying zero by infinity. What do we get? An online graphing tool shows the behavior of the $p = \gamma m_0 v$ function is quite weird. We used desmos.com to produce the graph in Figure 4, which shows what happens with the $p = m_v v = \gamma m_0 v$ for $m = 0.001$ and v/c ranging between 0 and 1.

Figure 4: $p = m_v v = \gamma m_0 v$ for $m \to 0$



It is quite enlightening: p is (very close to) zero for *v*/*c* going from 0 to 1 but then becomes infinity at *v*/*c* = 1 itself. What can we say about this? Perhaps we should say that the momentum of an object with zero rest mass is a nonsensical concept. Let us avoid this for the time being and get back to our analysis of the force. Before we do so, we should distinguish between p, p_x and p_y. The p is the magnitude of p, so that's $p = m \cdot c$, while p_x and p_y are the horizontal and vertical *components* of p, and so they are equal to $p_x = m v_x = \gamma m_0 v_x$ and $p_y = m v_y = \gamma m_0 v_y$ respectively.

The force components and the wavefunction

The force must be electromagnetic and, from its geometry, it is easy to see that the two force components can be written as the following functions of the *magnitude* of the centripetal (F) and the *x* and *y* coordinates:

- $F_x = F \cdot \cos(\theta - \pi) = -F \cdot \cos(\theta) = -F \cdot x/a$
- $F_y = F \cdot \sin(\theta - \pi) = -F \cdot \sin(\theta) = -F \cdot y/a$

We thus get the following formula for the force:

$$\mathbf{F} = \mathbf{F_x} + \mathbf{F_y} = -F \cdot \mathbf{cos}(\theta) - \boldsymbol{i} \cdot F \cdot \sin(\theta)$$

We use boldface for **cos**(θ) and for the imaginary unit ***i*** here so as to ensure we think of them as vector quantities: they have a magnitude, but they also have a direction and – importantly – some origin.

We know that we can represent the position vector ***r*** using the elementary wavefunction:

$$\boldsymbol{r} = a\cdot e^{i\theta} = x + i\cdot y = a\cdot\cos(\theta) + i\cdot a\cdot\sin(\theta) = a\cdot\cos(\omega t) + i\cdot a\cdot\sin(\omega t) = (x, y)$$

Hence, we might be tempted to write the force vector as = $-\mathrm{F}\cdot e^{-i\theta}$. However, the origin of the force vectors is not the same: the origin moves with the position vector. To be precise, origin is a term that is usually reserved to denote the origin of the reference frame. Vectors have an *initial* and a *terminal* point, and what we are saying here is that the initial point of our velocity, force and acceleration vector is *not* the origin.

Does this invalidate our earlier interpretation of the real and imaginary part of the wavefunction as the horizontal and vertical component of the force? To some extent, it does but, perhaps, not *fundamentally* so: the real and imaginary part of our wavefunction still show us how the horizontal and vertical component *vary* as a function of the position of the pointlike charge. We probably just need to think in terms of the force grabbing onto some linear space—not just one single point. We will come back to this. As for now, let us just *try* to calculate F and relate it to the radius a as best as we can.

We can calculate the centripetal acceleration: it's equal to $a_c = v_t^2/a = a\cdot\omega^2$. This formula is relativistically correct. It might be useful to remind ourselves how we get this result. The radius vector ***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 $\boldsymbol{v} = \mathrm{d}\boldsymbol{r}/\mathrm{dt}$ as $v_x = -a\cdot\omega\cdot\sin(\omega t)$ and $v_x\ y = -a\cdot\ \omega\cdot\cos(\omega t)$ and, in the next step, 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 this vector is calculated as follows:

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

Now, the force law tells us that F is equal to $\mathrm{F} = \mathrm{m}\cdot a_c = \mathrm{m}\cdot a\cdot\omega^2$ but, again, we have this problem of determining what the mass of our pointlike charge actually is. The $\mathrm{m_0}$ in our $\mathrm{m} = \gamma\mathrm{m_0}$ is zero !

We should find another way. We may note the horizontal and vertical force component behave like the restoring force causing linear harmonic oscillation. This restoring force depends linearly on the (horizontal or vertical) displacement from the center, and the (linear) proportionality constant is usually written as k. In case of a mechanical spring, this constant will be the *stiffness* of the spring. We don't have a spring here so it is tempting to think it models some elasticity of space itself. However, we should probably not engage in such philosophical thought. Let us write down what we have:

$$\mathrm{F_x} = \mathrm{dp_x/dt} = -\mathrm{k}\cdot x = -\mathrm{k}\cdot a\cdot\cos(\omega t) = -\mathrm{F}\cdot\cos(\omega t)$$

$$\mathrm{F_y} = \mathrm{dp_y/dt} = -\mathrm{k}\cdot y = -\mathrm{k}\cdot a\cdot\sin(\omega t) = -\mathrm{F}\cdot\sin(\omega t)$$

Now, it is quite straightforward to show that this constant can always be written as:

$$\mathrm{k} = \mathrm{m}\cdot\omega^2$$

We get that from the *solution* we find for ω when solving the differential equations $\mathrm{F_x} = \mathrm{dp_x/dt} = -\mathrm{k}\cdot x$ and $\mathrm{F_y} = \mathrm{dp_y/dt} = \mathrm{F_y} = \mathrm{dp_y/dt} = -\mathrm{k}\cdot y$ and assuming there is nothing particular about p and m. In other words, we assume there is nothing wrong with $\mathrm{p} = \mathrm{m}\cdot v = \gamma\mathrm{m_0}v$ relation. So we just don't think about the weird behavior of that function. It's a bit like what Dirac did when he *defined* his rather (in)famous Dirac function: the function doesn't make sense mathematically but it works – i.e. we get the right answers – when we use it.

OK. Let's move on here. We have the $k = m \cdot \omega^2$ equation, but we know m is *not* the rest mass of our electron here. We need to find some innovative way of referring to it. Let's call it the *effective* mass of our pointlike charge as it's whizzing around at the speed of light. We need to remember it's a measure of inertia – and we measure that inertia along the horizontal and vertical axis respectively and, hence, we should, perhaps, write something like this: $m = m_\gamma = m_x = m_y$, in line with the distinction we made between p, p_x and p_y. Why m_γ? The notation is just a placeholder: we need to remind ourselves it is a relativistic mass concept and so I used γ (the symbol for the Lorentz factor) to remind ourselves of that. So let us write this:

$$k = m_\gamma \cdot \omega^2$$

From the equations for F_x and F_x, we also know that $k \cdot a = F$, so $k = F/a$. Hence, the following equality must hold:

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

We know the sum of the potential and kinetic energy in a linear oscillator adds up to $E = m \cdot a \cdot \omega^2/2$. We have *two* independent linear oscillations here so we can just add their energies and the ½ factor vanishes. We also know that the total energy in this oscillation must be equal to $E = m \cdot c^2$. The mass factor here is the *rest mass of our electron*, so it's *not* that weird relativistic m_γ concept. *However*, we did equate *c* to $a \cdot \omega^2$. Hence, we can now write the following:

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

The force is, therefore, equal to:

$$F = (m_\gamma/m) \cdot (E/a)$$

Now what can we say about the m_γ/m ratio? We know m_γ is sort of undefined—but it shouldn't be zero and it shouldn't be infinity. It is also quite sensible to think m_γ should be smaller than m. It cannot be larger because than the energy of the oscillation would be larger than $E = mc^2$. What could it be? 1/2, 1/2π? Rather than guessing, we may want to remind ourselves that we know the angular momentum: $L = \hbar/2$. We calculated it using the $L = I \cdot \omega$ formula and using an educated guess for the moment of inertia ($I = m \cdot a^2/2$), but we also have the $\mathbf{L} = \boldsymbol{r} \times \mathbf{p}$ formula, of course! The lever arm is the radius here, so we can write:

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

   $\Rightarrow m_\gamma c = mc/2 \Leftrightarrow m_\gamma = m/2$

We found the grand result we expected to find: 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 of the (rest) mass of the electron.

We can now calculate the force:

$$\mathrm{F} = \frac{1}{2}\frac{\mathrm{E}}{a} \approx \frac{8.187 \times 10^{-14}\ \mathrm{J}}{\frac{2}{2\pi} \cdot 2.246\ \times 10^{-12}\ \mathrm{m}} \approx 0.115\ \mathrm{N}$$

This force is equivalent to a force that gives a mass of about 115 *gram* (1 g = 10^{-3} kg) an acceleration of 1 m/s per second. This is *huge* at the sub-atomic scale. Because this is so enormous, we need to think about energy densities and, perhaps, wonder if general relativity comes into play.

Introducing gravity

We calculated the force, and we found that it was huge. We can also calculate the *numerical* value of the field strength, and we should not be surprised that we get an equally humongous field strength:

$$E = \frac{F}{\mathrm{q_e}} \approx \frac{11.5 \times 10^{-2}\ \mathrm{N}}{1.6\ \times 10^{-19}\ \mathrm{C}} \approx 0.7 \times 10^{18}\ \mathrm{N/C}$$

Just as a yardstick to compare, we may note that the most powerful man-made accelerators reach field strengths of the order of 10^9 N/C (1 GV/m) only. This is a billion times more. Hence, we may wonder if this value makes any sense at all. To answer that question, we can, perhaps, try to calculate some energy *density*. Using the classical formula, we get:

$$u = \epsilon_0 E^2 \approx 8.854 \times 10^{-12} \cdot (0.21 \times 10^{18})^2 \frac{\mathrm{J}}{\mathrm{m}^3} = 0.36 \times 10^{24}\ \frac{\mathrm{J}}{\mathrm{m}^3} = 0.63 \times 10^{24}\ \frac{\mathrm{J}}{\mathrm{m}^3}$$

This amounts to about 7 kg per mm^3 (cubic *milli*meter). Is this a sensible value? Maybe. Maybe not. The rest mass of the electron is tiny, but then the *zbw* radius of an electron is also exceedingly small. It is very interesting to think about what might happen to the curvature of spacetime with such mass densities: perhaps our pointlike charge just goes round and round on a geodesic in its own (curved) space. We are not well-versed in general relativity and we can, therefore, only offer some general remarks here:

1. If we would pack all of the mass of an electron into a black hole, then the Schwarzschild formula gives us a radius that is equal to:

$$r_s = \frac{2\mathrm{Gm}}{c^2} \approx 1.35 \times 10^{-57}\mathrm{m}\ (meter)$$

This exceedingly small number has no relation whatsoever with the Compton radius. In fact, its scale has no relation with whatever distance one encounters in physics: it is *much* beyond the Planck scale, which is of the order of 10^{-35} meter and which, for reasons deep down in relativistic quantum mechanics, physicists consider to be the smallest possibly sensible distance scale.

2. We are intrigued, however, by suggestions that the Schwarzschild formula should not be used as it because an electron has angular momentum, a magnetic moment and other properties, perhaps, that do not apply when calculating, say, the Schwarzschild radius of the mass of a baseball. To be precise, we are particularly intrigued by models that suggest that, when incorporating the above-mentioned properties of an electron, the Compton radius might actually be the radius of an electron-sized black hole (Burinskii, 2008, 2016).[4]

The integration of gravity into this oscillator model will be our prime focus of research over the coming years. We totally concur with Burinskii's instinct here: the integration of gravity into the model may well provide "*the true path to unification of gravity with particle physics.*"[5]

Conclusions

The most intriguing and interesting aspect of the model is that it yields a realist common-sense interpretation of quantum physics. All pieces fall into place: we can understand the real and the imaginary part of the wavefunction as an oscillating electric and magnetic field. It is, likewise, possible to also analyze Schrödinger's wave equation as a diffusion equation for electromagnetic energy.[6]

The model is simple and nice and should, therefore, be seen as scoring much better on *Occam's Razor* criterion than the current mainstream interpretation of quantum physics. We hope this model will be evaluated somewhat more positively by mainstream academics in the future, especially when complemented by more advanced mathematical techniques (such as Hestenes' geometric calculus) and when integrated with gravity (Burinskii's Kerr-Newman models of an electron, that is).

The basic results are there: this is a pretty complete realist interpretation of QM. Our manuscript[7], for example, also explains what photons actually are, and how they interact with electrons. It also provides an alternative explanation of electron orbitals or, to be precise, a common-sense *physical explanation* of the wave equation and other so-called mysterious quantum-mechanical phenomena (anomalous magnetic moment, Mach-Zehnder interference, etcetera): there is no mystery. It's all plain physics. The Emperor has no clothes.

To conclude this paper, we join the summary results for the spin-only and the orbital electron that result from our zbw electron model (Table 1). We also want to draw the reader's attention to the interesting possibility that the anomalous magnetic moment of an electron might be explained by a very classical coupling between the two moments because of the Larmor precession of the electron in the Penning trap. It may, therefore, not be anomalous at all, and we shouldn't need quantum field theory to explain it.[8]

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[4] See: Alexander Burinskii, *The Dirac–Kerr–Newman electron*, 19 March 2008, https://arxiv.org/abs/hep-th/0507109. A more recent article of Mr. Burinskii (*New Path to Unification of Gravity with Particle Physics*, 2016, https://arxiv.org/abs/1701.01025, relates the model to more recent theories – most notably the "supersymmetric Higgs field" and the "Nielsen-Olesen model of dual string based on the Landau-Ginzburg (LG) field model.".

[5] See: Alexander Burinskii, *The weakness of gravity as an illusion hiding the true path to unification of gravity with particle physics*, Essay written for the Gravity Research Foundation, March 30, 2017

[6] See: Jean Louis Van Belle, *A Geometric Interpretation of Schrödinger's Wave Equation*, 12 December 2018 (http://vixra.org/abs/1812.0202) and Jean Louis Van Belle, *The Wavefunction as an Energy Propagation Mechanism*, 8 June 2018 (http://vixra.org/abs/1806.0106). While we still adhere to the basic intuition and results in these two papers, we would need to update them in light of our more recent updates and corrections to our interpretation.

[7] Jean Louis Van Belle, *The Emperor Has No Clothes: A Realist Interpretation of Quantum Mechanics*, 21 April 2018, pre-published on http://vixra.org/abs/1901.0105.

[8] Jean Louis Van Belle, *The Not-So-Anomalous Magnetic Moment*, 21 December 2018, http://vixra.org/pdf/1812.0233v3.pdf.

Table 1: Intrinsic spin versus orbital angular momentum

Spin-only electron (*Zitterbewegung*)	Orbital electron (Bohr orbitals)
$\mathrm{S} = \mathrm{h}$	$\mathrm{S}_n = n\mathrm{h}$ for $n = 1, 2, \ldots$
$\mathrm{E} = \mathrm{m}c^2$	$\mathrm{E}_n = -\frac{1}{2}\frac{\alpha^2}{n^2}\mathrm{m}c^2 = -\frac{1}{n^2}\mathrm{E}_R$
$r = r_\mathrm{C} = \frac{\hbar}{\mathrm{m}c}$	$r_n = n^2 r_\mathrm{B} = \frac{n^2 r_\mathrm{C}}{\alpha} = \frac{n^2}{\alpha}\frac{\hbar}{\mathrm{m}c}$
$v = c$	$v_n = \frac{1}{n}\alpha c$
$\omega = \frac{v}{r} = c \cdot \frac{\mathrm{m}c}{\hbar} = \frac{\mathrm{E}}{\hbar}$	$\omega_n = \frac{v_n}{r_n} = \frac{\alpha^2}{n^3\hbar}\mathrm{m}c^2 = \frac{\frac{1}{n^2}\alpha^2\mathrm{m}c^2}{n\hbar}$
$\mathrm{L} = I \cdot \omega = \frac{1}{2} \cdot \mathrm{m} \cdot a^2 \cdot \omega = \frac{\mathrm{m}}{2} \cdot \frac{\hbar^2}{\mathrm{m}^2 c^2}\frac{\mathrm{E}}{\hbar} = \frac{\hbar}{2}$	$\mathrm{L}_n = I \cdot \omega_n = n\hbar$
$\mu = \mathrm{I} \cdot \pi {r_\mathrm{C}}^2 = \frac{\mathrm{q_e}}{2\mathrm{m}}\hbar$	$\mu_n = \mathrm{I} \cdot \pi {r_n}^2 = \frac{\mathrm{q_e}}{2\mathrm{m}} n\hbar$
$\mathrm{g} = \frac{2\mathrm{m}}{\mathrm{q_e}}\frac{\mu}{\mathrm{L}} = 2$	$\mathrm{g}_n = \frac{2\mathrm{m}}{\mathrm{q_e}}\frac{\mu}{\mathrm{L}} = 1$

References

This paper discusses general principles in physics only. Hence, references were mostly limited to references to general physics textbooks. For ease of reference – and because most readers will be familiar with it – we often opted to refer to:

1. Feynman's *Lectures* on Physics (http://www.feynmanlectures.caltech.edu). References for this source are per volume, per chapter and per section. For example, Feynman III-19-3 refers to Volume III, Chapter 19, Section 3.

One should also mention the rather delightful set of Alix Mautner Lectures, although we are not so impressed with their transcription by Ralph Leighton:

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

Specific references – in particular those to the mainstream literature in regard to Schrödinger's *Zitterbewegung* – were mentioned in the footnotes. We should single out the various publications of David Hestenes and Francesco Celani:

3. David 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.
4. David Hestenes, 19 February 2008, *Zitterbewegung in Quantum Mechanics – a research program*, https://arxiv.org/pdf/0802.2728.pdf.
5. Francesco Celani et al., *The Electron and Occam's Razor*, November 2017, https://www.researchgate.net/publication/320274514_The_Electron_and_Occam's_Razor.

We would like to mention the work of Stefano Frabboni, Reggio Emilia, Gian Carlo Gazzadi, and Giulio Pozzi, as reported on the phys.org site (https://phys.org/news/2011-01-which-way-detector-mystery-double-slit.html). In addition, it is always useful to read an original:

6. Paul A.M. Dirac, 12 December 1933, Nobel Lecture, *Theory of Electrons and Positrons*, https://www.nobelprize.org/uploads/2018/06/dirac-lecture.pdf

We should, perhaps, also mention the following critical appraisal of the quantum-mechanical framework:

7. *How to understand quantum mechanics* (2017) from John P. Ralston, Professor of Physics and Astronomy at the University of Texas.

It is one of a very rare number of exceptional books that address the honest questions of amateur physicists and philosophers upfront. We love the self-criticism: "Quantum mechanics is the only subject in physics where teachers traditionally present haywire axioms they don't really believe, and regularly violate in research." (p. 1-10)

Finally, I would like to thank Prof. Dr. Alex Burinskii for taking me seriously. He is in a different realm – and he has made it clear that my writings are extremely simplistic and probably serve pedagogic purposes only. However, his confirmation that I am not making any *fundamental* mistakes while trying to understand the fundamentals, have kept me going on this. We refer to his publications (Burinskii, 2008, 2016, 2017) in the body of our paper itself.