Superluminal quantum models of the electron and the photon

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Abstract

The electron is modeled as a charged quantum moving superluminally in a closed helical trajectory, having the Dirac electron's spin, magnetic moment and *Zitterbewegung* properties: speed c, angular frequency $2mc^2/\hbar$ and amplitude $\frac{1}{2}\hbar/mc$. The associated photon model is an uncharged quantum moving superluminally in an open helical trajectory with radius $\lambda/2\pi$.

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Dirac's theory of the relativistic electron [1] did not include a model of the electron itself, and assumed the electron was a point-like particle. Schrödinger [2] analyzed the results of the Dirac equation for a free electron, and described a high-frequency *Zitterbewegung* "trembling motion" which appeared to be due to the interference between positive and negative energy terms in the solution. Barut and Bracken [3] analyzed Schrödinger's *Zitterbewegung* results and proposed a spatial

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description of the electron where the *Zitterbewegung* would produce the electron's spin as the orbital angular momentum of the electron's internal system, while the electron's rest mass would be the electron's internal energy in its rest frame. Barut and Thacker [4] generalized Barut and Bracken's analysis of the internal geometry of the Dirac electron to a proper-time formalism. Hestenes [5-8] reformulated the Dirac equation through a mathematical approach (Clifford algebra) that brings out a geometric approach to understanding *Zitterbewegung* and to modeling the electron, such as identifying the phase of the Dirac spinor with the spatial angular momentum of the electron. The trajectory approach to the Dirac theory has also been utilized by Bohm and Hiley [9] in attempts to understand the spatial structure of the electron. This approach has been elaborated with consideration of the electron's *Zitterbewegung* by Holland [10.]

The photon has also been modeled geometrically, with several results quantitatively similar to those in the present superluminal quantum model of the photon, though obtained through different approaches. Ashworth [11] obtained a superluminal helical photon model whose radius is $\lambda / 2\pi$, the same as in present photon model, from classical mechanics considerations. Kobe [12], in a *Zitterbewegung* approach to the photon, also obtained the same quantitative result for the radius of a classical helical model of the photon based on quantum mechanical considerations, as independently did Sivasubramanian *et al*.[13], whose helical photon model, also based on a *Zitterbewegung* approach to the photon, is explicitly internally superluminal.

The present approach is a unified approach to modeling both the electron and the photon with superluminal helical trajectories. The electron model has several features of the Dirac electron's *Zitterbewegung*.

In this approach, point-like entities are postulated called superluminal quanta (to distinguish them from electrons and photons themselves.) They have an energy *E*, with its associated frequency *f* and angular frequency $\omega = 2\pi f$, a instantaneous momentum $\vec{P}$ with its associated wavelength λ and wave number $k = 2\pi / \lambda$, and an electric charge (in the case of the electron). One superluminal quantum forms a photon or an electron. Superluminal quanta move in helical trajectories, which may be open (for a photon) or closed (for an electron). Movement of the superluminal quantum along its trajectory produces an electron or a photon. The type of helical trajectory determines which particle is produced.

The energy of a superluminal quantum composing either a photon or electron is $E = \hbar\omega$ where ω is the angular frequency of rotation of the superluminal quantum along its helical trajectory, whether the trajectory is open or closed. The momentum vector $\vec{P}$ of a superluminal quantum is directed tangentially along its helical trajectory. The total momentum $\vec{P}$ has a component $p = \hbar k$ that is projected parallel to the helical axis around which the superluminal quantum is moving. $\vec{P}$ changes in direction as the superluminal quantum moves along its helical trajectory. In the photon model, $\vec{P}$ has constant magnitude but changes in direction as the superluminal quantum travels along an open helix having a constant wavelength and curvature. The projected momentum *p* along the helical axis will be constant in magnitude. But in the electron model, $\vec{P}$ changes in magnitude as well as direction with the changing curvature of the closed helical trajectory along which the electron's superluminal quantum travels. Here $\vec{P}$'s projected magnitude *p* along the helical axis, as well as its corresponding wavelength, will also vary in magnitude.

The longitudinal component of the velocity of a superluminal quantum along its helical axis, whether the helix is open in the photon model or closed in the electron model, is postulated to always be exactly the speed of light *c*. In the photon model, the superluminal quantum moves at a constant superluminal speed along an open helical trajectory with a straight axis. In the electron model, the speed of the superluminal quantum varies along the closed helical trajectory and the helical trajectory's axis is circular.

The following superluminal quantum models of a photon and an electron will illustrate the superluminal quantum's properties more concretely.

The superluminal quantum model of the photon

A photon is modeled as a superluminal quantum traveling along an open helical trajectory of radius R and pitch (wavelength) λ. The trajectory makes an angle θ with the forward direction. In this helical trajectory, these three quantities are related geometrically by $\tan\theta = 2\pi R/\lambda$. The superluminal quantum model for a photon of any wavelength is found to have the following properties:

1) The forward angle θ of the helical trajectory is 45°.

2) The radius of the superluminal quantum's helical trajectory is $R = \lambda / 2\pi$

3) The speed of the superluminal quantum is $\sqrt{2}c = 1.414..c$ along its helical trajectory.

These three results are derived below. An image of the superluminal quantum model of a photon is shown in Figure 1.

Insert Figure 1 about here.

The superluminal quantum, with total momentum $\vec{P}$ directed along its helical trajectory, has a longitudinal component of momentum $P\cos(\theta)$ determined by the wavelength λ of the helix, and a transverse component of momentum $P\sin(\theta)$ that is used to calculate the angular momentum or spin of the photon. The superluminal quantum's longitudinal component of momentum is

$$P\cos(\theta) = h/\lambda \tag{1}$$

the experimental linear momentum of a photon. $\vec{P}$'s transverse component of momentum $P\sin\theta$, acting at the helical radius R from the helical axis, produces an angular momentum or spin S whose longitudinal magnitude in the direction the photon is moving (or in the opposite direction depending on the helicity of the trajectory) is

$$S = RP\sin(\theta) = h/2\pi \tag{2}$$

which is the experimental spin or angular momentum of the photon. Combining equations (1) and (2) gives

$$\sin(\theta)/\cos(\theta) = \tan(\theta) = \lambda/2\pi R \tag{3}$$

Now consider the helical geometry. As the superluminal quantum advances along the helix a distance λ (one wavelength) in the longitudinal direction, the superluminal quantum travels a transverse distance $2\pi R$, i.e. once around the circle of radius R of the helix. From the way the helical trajectory's forward angle θ is defined, we have

$$\tan(\theta) = 2\pi R/\lambda \tag{4}$$

We now have two equations (3) and (4) for $\tan(\theta)$. Setting them equal gives

$$\tan(\theta) = 2\pi R/\lambda = \lambda/2\pi R \tag{5}$$

This will only be true when

$$\lambda = 2\pi R \tag{6}$$

that is, when

$$R = \lambda / 2\pi \tag{7}$$

This result implies that $\tan\theta = 1$ and therefore

$$\theta = 45^{\circ} \tag{8}$$

These results for the superluminal quantum model of the photon are true for any wavelength. Since the longitudinal velocity component of the photon's superluminal quantum along its helical axis is postulated to be *c*, the velocity of the photon's superluminal quantum along its helical trajectory is

$$v = c / \cos(45^{\circ}) = c /(\sqrt{2} / 2) = 1.414..c \tag{9}$$

The superluminal quantum model of the electron

Besides having the electron's experimental spin value and the magnetic moment of the Dirac electron, the superluminal quantum model of the electron, described below, quantitatively embodies the "*Zitterbewegung*", the small and rapid oscillatory motion of the electron that is predicted by the Dirac equation but which has not been experimentally observed.

Zitterbewegung refers to the Dirac equation's predicted rapid oscillatory motion of an electron than adds to its center-of-mass motion. No size or spatial structure of the electron has so far been observed experimentally. High energy electron scattering experiments by Bender *et al*. [14] have put an upper value on the electron's size at about 10^{-18} m. Yet Schrödinger's *Zitterbewegung* results suggest that the electron's rapid oscillatory motion has a magnitude of $R_{zitt} = \frac{1}{2}\hbar / mc$ or 1.9×10^{-13} m and an angular frequency of $\omega_{zitt} = 2mc^2 / \hbar = 1.6\times10^{21} / \sec$, twice the angular frequency $\omega_0 = mc^2 / \hbar$ of a photon whose energy is that contained within the rest mass of an electron. Furthermore, in the Dirac solution the electron's instantaneous speed is c, although experimentally observed electron speeds are always less than c. An acceptable model of the electron would presumably contain these *Zitterbewegung* properties of the Dirac electron.

In the present superluminal quantum model of the electron, the electron is composed of a charged superluminal point-like quantum moving along a closed, double-looped helical trajectory in the electron model's rest frame, that is, the frame where the superluminal quantum's trajectory closes on itself. (In an moving inertial reference frame, the superluminal quantum's double-looped helical trajectory will not exactly close on itself.) The superluminal quantum's trajectory's closed helical axis' radius is set to be $R_0 = \frac{1}{2}\hbar / mc = 1.9 \times 10^{-13}\,\text{m}$ and the helical radius is set to be $R_{helix} = \sqrt{2} R_0$. The superluminal quantum electron model structurally resembles a superluminal quantum photon model of angular frequency $\omega_0 = mc^2 / \hbar$, wavelength $\lambda_C = h / mc$ (the Compton wavelength) and wave number $k = 2\pi / \lambda_C$ that, instead of having a straight axis, moves in a circular pattern to form a double-looped helical trajectory having a circular axis of circumference $\lambda_C / 2$. After following its helical trajectory around this circular axis once, the electron's superluminal quantum's trajectory is 180^{o} out of phase with itself and doesn't close on itself. But after the superluminal quantum traverses its helical trajectory around the circular axis a second time, the superluminal quantum's trajectory is back in phase with itself and closes upon itself. The total longitudinal distance along its circular axis that the circulating superluminal quantum has traveled before its trajectory closes is λ_C.

In its rest frame, the electron's superluminal quantum carries energy $E = \hbar\omega_0 = mc^2$. Unlike the photon's superluminal quantum which is uncharged, the electron's superluminal quantum carries the electron's negative charge *–e*.

The above closed, double-looping helical spatial trajectory for the superluminal quantum in the electron model is given in rectangular coordinates by

$$\begin{aligned} x(d) &= R_0(1+\sqrt{2}\cos(2\pi d/\lambda_C))\cos(4\pi d/\lambda_C) \\ y(d) &= R_0(1+\sqrt{2}\cos(2\pi d/\lambda_C))\sin(4\pi d/\lambda_C) \\ z(d) &= R_0\sqrt{2}\sin(2\pi d/\lambda_C) \end{aligned} \tag{10}$$

where $R_0 = \frac{1}{2}\hbar/mc$ is the radius of the circle which is the axis of the double-looped helical trajectory, $\lambda_C = h/mc$, and *d* is the distance forward along the circular axis that the superluminal quantum has moved while following its helical trajectory. This forward speed is postulated to be *c*, consistent with the Dirac electron's *Zitterbewegung* results, so in the superluminal quantum's trajectory above, $d = ct$.

Note that when $d = \frac{1}{2}\lambda_C$ (at one traversal of the circular axis of the closed helical trajectory), the term $2\pi d/\lambda_C$ in (10) above has value π. So $\cos(2\pi d/\lambda_C)$ and $\sin(2\pi d/\lambda_C)$ are only 180° into their cycles, which only reaches 2π or 360° when $d = \lambda_C$ (at two traversals of the circular axis of the closed helical trajectory). The second term $4\pi d/\lambda_C$ in (10) above is in phase at both $d = \frac{1}{2}\lambda_C$, which gives the phase 2π (in phase), and $d = \lambda_C$, which gives the phase 4π (in phase), but all of the sine and cosine terms in the equations in (10) have to be in phase for the helical trajectory to close on itself.

Since $d = ct$, the term $\cos(2\pi d/\lambda_C)$ in (10) becomes

$$\cos(2\pi d / \lambda_C) = \cos(2\pi ct / \lambda_C) = \cos(2\pi f_0 t) = \cos(\omega_0 t) \qquad (11)$$

and similarly for the other terms in (10). So the position with time of the superluminal quantum in the electron model becomes

$$\begin{aligned} x(t) &= R_0(1+\sqrt{2}\cos(\omega_0 t))\cos(2\omega_0 t) \\ y(t) &= R_0(1+\sqrt{2}\cos(\omega_0 t))\sin(2\omega_0 t) \\ z(t) &= R_0\sqrt{2}\sin(\omega_0 t) \end{aligned} \qquad (12)$$

where $R_0 = \frac{1}{2}\hbar / mc$ and $\omega_0 = mc^2 / \hbar$. Two images from different perspectives of the superluminal quantum model of an electron are shown in Figure 2.

Insert Figure 2 about here.

In equation (12), at $t = 0$, the superluminal quantum is at $x = R_0(1+\sqrt{2})$, $y = 0$, and $z = 0$. According to the double-looping photon comparison to the electron model, the above equations correspond to a left-circularly polarized photon model of wavelength λ_C, traveling counterclockwise (as seen above from the +z axis) in a closed double loop.

Similarities between the Dirac equation's free electron solution and the superluminal quantum electron model

The superluminal quantum model of the electron share a number of quantitative and qualitative properties with the Dirac equation's electron with *Zitterbewegung*:

1) **The *Zitterbewegung* internal frequency of** $\omega_{zitt} = 2mc^2 / \hbar = 2\omega_0$**.** The superluminal quantum's trajectory in equation (12) is defined by both the frequencies ω_0 and $2\omega_0$. ω_0 is the angular frequency of a photon whose energy is mc^2.

2) **The superluminal quantum model contains the *Zitterbewegung* has an internal radius** $R_0 = \frac{1}{2}\hbar / mc = R_{zitt}$**.** R_0 in equation (12) is the radius of the circular axis of the closed double-looped helical trajectory of the superluminal quantum model.

3) **The *Zitterbewegung* speed-of-light result for the electron.** The Dirac equation has eigenvalue solutions of $\pm c$ for the velocity of the electron (and the positron). The longitudinal component along the circular axis of the superluminal quantum's closed helical trajectory was postulated to be *c*, just as in the superluminal quantum model of the photon. This internal speed *c* is incorporated into the superluminal quantum trajectory equation (10) for the electron model as $d = ct$, where *d* is the forward distance along the helical axis traveled by the superluminal quantum as it follows its helical trajectory. The maximum speed of the electron's superluminal quantum itself is found from the trajectory equations (12) to be 2.515*c*.

4) **Prediction of the electron's antiparticle.** The two possible helicities of the superluminal quantum's closed helical path correspond to an electron and a positron. (The existence of the positron is implied by the results of Dirac's equation.). By reversing the helicity for the superluminal quantum described by the above closed double-looped helix in equation (12), whose left circulating superluminal quantum corresponds to a left-circularly-polarized photon, the corresponding anti-particle's superluminal quantum would be formed, which would correspond to a circulating right circularly polarized photon. A charge of +e would have to be supplied to the positron's superluminal quantum for symmetry. The superluminal quantum electron model does not however predict whether the circulating left-circularly polarized superluminal quantum trajectory

described by equation (12) is actually associated with an electron or a positron. This could be tested by an experiment.

The relationship between charge and helicity in the superluminal quantum electron and photon models is suggestive of a deeper relationship between helicity, spin and charge. The superluminal quantum photon model has an open helical trajectory, spin $\hbar$ and no charge. The superluminal quantum electron model has a closed double-looped helical trajectory, spin $\frac{1}{2}\hbar$ and a negative charge.

5) **The calculated spin of the electron.** The value of R_0 in the electron model's superluminal quantum trajectory in equation (10) is chosen to give the electron's experimental value of spin $\hbar/2$, the spin value also found from the Dirac equation.

The calculation of the electron's angular momentum or spin in the superluminal quantum model of the electron is complicated by the varying radial distance and the correspondingly varying wavelength and therefore momentum of the circulating superluminal quantum along its closed helical trajectory. The instantaneous angular momentum of a circulating object with momentum $\vec{P}$ at a distance $\vec{R}$ from a rotational axis is

$$\vec{S} = \vec{R} \times \vec{P} \tag{13}$$

In the superluminal quantum model for the electron, the superluminal quantum's instantaneous position and momentum can be described by a radial vector $\vec{R}$ and a momentum vector $\vec{\mathrm{P}}(\vec{\mathrm{R}})$. The magnitude of $\vec{R}$, which can be obtained from the electron's superluminal quantum trajectory equation (12), varies with the superluminal quantum's position along its trajectory. The magnitude and direction of $\vec{\mathrm{P}}(\vec{\mathrm{R}})$, the superluminal quantum's instantaneous momentum along its trajectory, are related to the instantaneous wavelength λ of its trajectory.

The instantaneous wavelength λ at a point on the double-looped helical trajectory in equation (12) can be defined consistently as twice the circumference of the circle that is parallel to the *x*-*y* plane and centered on the *z*-axis, having radius *R* and passing through that point on the trajectory. The radial distance *R* from the *z*-axis to that point is then directly proportional to the instantaneous wavelength λ at that point:

$$R = K\lambda \tag{14}$$

where *K* is the proportionality constant. From equation (10) and the above definition of the instantaneous value of λ,

$$K = R_0 / \lambda_C = 1/4\pi \tag{15}$$

Substituting equation (15) into equation (14), the relation of *R* to the instantaneous wavelength λ at a point on the trajectory is

$$R = \lambda / 4\pi \tag{16}$$

Now *p*, the magnitude of the longitudinal component of $\vec{\mathrm{P}}(\vec{\mathrm{R}})$ along the above-defined circle of radius *R*, is postulated to be inversely proportional to the instantaneous wavelength λ at that point, that is,

$$p = h / \lambda \tag{17}$$

the same as a photon's momentum relationship with its wavelength. This is consistent with the photon model because the superluminal quantum model of the electron is basically a charged circulating superluminal quantum model of a photon.

It is this component *p* of the superluminal quantum's total momentum $\vec{\mathrm{P}}(\vec{\mathrm{R}})$ that contributes to S_z, the free electron's spin or angular momentum. By combining equations

(13), (16) and (17), the instantaneous value of the angular momentum S_z at any point along the closed helical trajectory is given by

$$\begin{aligned} S_z &= Rp = (\lambda / 4\pi)(h/\lambda) \\ &= h/4\pi \\ &= \tfrac{1}{2}\hbar \end{aligned} \tag{18}$$

which is the value of spin of the electron found from the Dirac equation, and which is also experimentally correct. So despite the variation in $\vec{R}$ and $\vec{\mathrm{P}}(\vec{\mathrm{R}})$ of the superluminal quantum along its closed helical trajectory, the instantaneous spin S_z of the electron remains constant.

6) **The calculated magnetic moment of the electron.** For the closed, double-looped helical trajectory of the charged superluminal quantum given in equation (12) the electron's magnetic moment M_z is found from

$$M_z = \frac{-e}{4\pi} \int_{\theta=0}^{2\pi} (R_x(\theta)V_y(\theta) - R_y(\theta)V_x(\theta))d\theta \tag{19}$$

The superluminal quantum electron's magnetic moment's value in equation (19) was set to be $M_z = -e\hbar/2m$, the value of the Bohr magneton (corresponding to the magnetic moment of the Dirac electron). Using the closed double-looped helical trajectory structure of equation (12) and solving equation (19) for the unknown value R for the radius of the superluminal quantum's closed helical trajectory that would yield $M_z = -e\hbar/2m$, gave $R = \sqrt{2}R_0$ where $R_0 = \tfrac{1}{2}\hbar/mc$. It is this radius $R = \sqrt{2}R_0$ that was then included in equations (10) and (12) to obtain the trajectory of the superluminal quantum model of the electron.

7) **The electron's motion is the sum of its center-of-mass motion and its *Zitterbewegung*, with the motion of the electron's charge distinct from the motion of its mass.** For the Dirac electron this is described in [3] where the *Zitterbewegung* is obtained by solving the Heisenberg equations of motion for the position operator $\vec{\mathrm{x}}(t)$ using the Dirac Hamiltonian $H = m\gamma^0 + \vec{\mathrm{p}}\cdot\vec{\alpha}$ $(\hbar = c = 1)$. The coordinate operator $\vec{\mathrm{x}}(t)$ contains a "center-of-mass" part $\vec{\mathrm{X}}(t) = H^{-1}\vec{\mathrm{p}}t + \vec{a}$ $(\vec{a} = \text{constant vector})$ that moves with a uniform velocity on momentum eigenstates, and an oscillatory part $\vec{\xi}(t) = \frac{i}{2}[\vec{\alpha}(0) - H^{-1}\vec{p}]H^{-1}e^{-2iHt}$ which is the *Zitterbewegung*. So in the Dirac free electron solution, $\vec{\mathrm{x}}(t) = \vec{\mathrm{X}}(t) + \vec{\xi}(t)$, where $\vec{\mathrm{x}}(t)$ is interpreted as the position of the electron's center of charge, which oscillates rapidly according to $\vec{\xi}(t)$ about the center of mass $\vec{\mathrm{X}}(t)$. The center-of-mass motion $\vec{\mathrm{X}}(t)$ is the subluminal linear motion of the Dirac free electron, while the *Zitterbewegung* $\vec{\xi}(t)$ is the electron's speed-of-light oscillatory motion. In the superluminal quantum model of the electron, equation (12) , corresponding to $\vec{\xi}(t)$, describes the trajectory of the electron's superluminal charged quantum, whose longitudinal component of velocity around its closed helical trajectory's circular axis is *c*. Equation (12), representing the motion of the superluminal charge in the electron's in the rest frame, can have an added linear position component *vt* (corresponding to the electron's center-of-mass velocity *v*) in the *z* direction which would correspond to $\vec{\mathrm{X}}(t)$ above. The double-looping helical trajectory, which closes on itself exactly in the rest frame, would therefore not close exactly in a moving frame due to the small average displacement of the charged quantum in the z direction during each cycle of the superluminal quantum along its helical trajectory. The position of the electric charge in

the Dirac electron is not the same as the position of the electron's center of mass. This is also the case in the superluminal quantum model, where the electron's charge is moving with the superluminal quantum, but the electron as a whole with its total energy content can only move subluminally.

8) **The non-conservation of linear momentum in the *Zitterbewegung* of a free electron.** In the oscillatory *Zitterbewegung* of a free electron, linear momentum is not conserved, a result first pointed out by de Broglie [15]. In the *Zitterbewegung*'s quantum dynamics the expectation value $< dp_k / dt > \neq 0$ even in the absence of an applied force F_k. This lack of conservation of linear momentum in Dirac *Zitterbewegung* is also the case in the superluminal electron model's rest frame due to the rapid changing in magnitude and direction of the superluminal quantum's linear momentum vector $\vec{P}$ as the superluminal quantum moves along its closed helical trajectory. But violations of the conservation of energy can occur in quantum electrodynamics if the time interval in which the violation occurs is shorter than the minimum time permitted for experimental observations by the Heisenberg uncertainty relations. In the same way, violations of conservation of linear momentum in the Dirac electron's *Zitterbewegung* , as well as in the present superluminal model of the electron, may be similarly permitted within the range of the size of the electron's *Zitterbewegung* amplitude $R_0 = \frac{1}{2}\hbar / mc = 1.9 \times 10^{-13}\,\text{m}$.

Testing the superluminal electron and photon models

Testing for the existence of an electron's superluminal quantum with its *Zitterbewegung* angular frequency of 1.6×10^{21} per second would require great ingenuity. Yet this *Zitterbewegung* angular frequency comes directly from solutions to the relativistic Dirac equation. Dirac conceived of the electron as a charged point-like particle whose movement forms the electron's physical characteristics such as its spin and magnetic moment.

It might be objected that in the present models for the electron and the photon, the proposed quanta always travel superluminally, these models violate the relativistic upper limit of *c* on the transport of information. But the elementary particles that superluminal quanta form do not themselves travel faster than *c*, so this is not a valid objection to the possible existence of superluminal quanta.

Since superluminal quanta would form photons that can have angular frequencies much lower than $\omega_{zitt} = 2mc^2 / \hbar = 1.6\times 10^{21} / \mathrm{sec}$, one possible approach to testing the superluminal quantum hypothesis is to detect them in lower frequency photons, possibly in the frequency range of visible light or microwave radiation. Laser or maser radiation is highly coherent and this could facilitate the localization of helically moving superluminal quanta in individual photons that are all moving in phase. Such measurements are discussed in [13] which concerns detecting *Zitterbewegung* in photons.

There is also a possible test of the superluminal quantum hypothesis for the electron. According to this model, an electron and a positron would differ in the direction of their internal helicities. If the electron were structured like a circulating right circularly polarized photon, then a positron would be structured like a circulating left circularly polarized photon, and vice versa. Electrons should therefore differentially absorb or scatter left and right circularly polarized photons having energies corresponding to the rest mass of electrons, because if an electron were composed of a quantum with a righthanded closed helical trajectory, the electron would likely interact differently with incoming left and right circularly polarized photons.

Conclusion

The number of quantitative and qualitative similarities between the Dirac electron with *Zitterbewegung* and the proposed superluminal quantum model of the electron is remarkable, given the relatively simple mathematical model of the electron. This suggests that the superluminal quantum concept may also provide useful physical models for the electron and the photon. Suggestions for testing these models experimentally are presented above.

Both the photon and the electron are modeled as helically circulating superluminal point-like quanta having both particle-like (E and $\vec{P}$) and wave-like (ω and λ) characteristics. Although they have precise trajectories, superluminal quanta may be associated with the relativistic quantum mechanical functions that characterize photons and electrons, i.e. the wave functions of the equations of Maxwell, Schrödinger and Dirac. The superluminal electron and photon models may therefore show wave interference and diffraction patterns, as in the precisely defined trajectory approach to electrons of Bohm and Hiley [9].

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Figure Captions

Figure 1. Modeling a photon. A superluminal quantum moves along a 45 degree open helical trajectory at speed 1.414 *c*. The radius of the helix is $R = \lambda / 2\pi$. The speed of the superluminal quantum is 1.414c.

Figure 2. Modeling an electron. Two views of the superluminal quantum's closed double-looped helical trajectory. The circle in the x-y plane of radius $R_0 = \frac{1}{2}\hbar / mc$ =1.9 x 10^{-13} m, is the axis of the closed helix. The maximum speed of the superluminal quantum in the electron's rest frame is 2.515*c* .

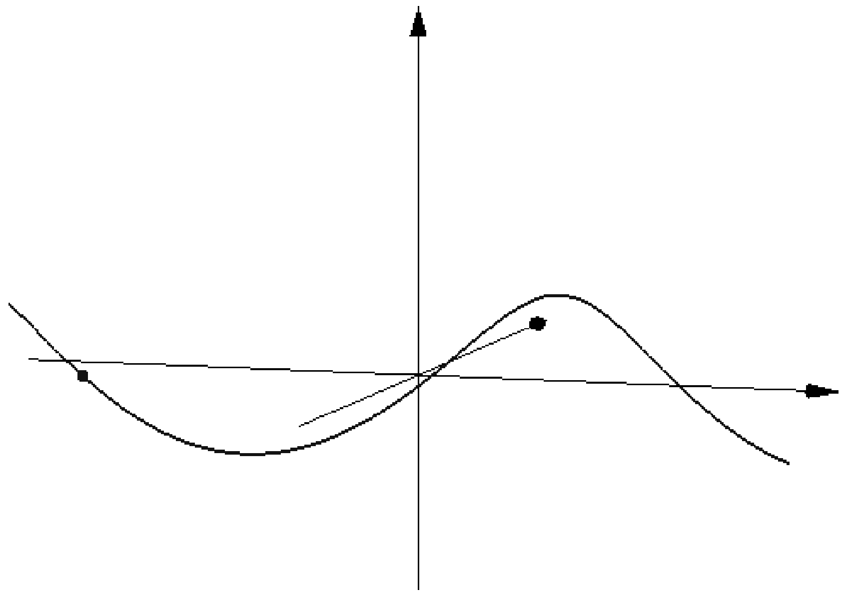

Figure 1. Model of a photon. A superluminal quantum moves along its 45-degree open helical trajectory. The radius of the helix is $R = \lambda / 2\pi$. The speed of the superluminal quantum is 1.414c.

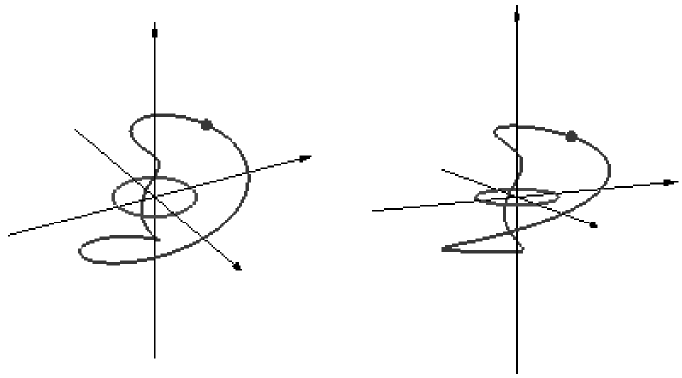

Figure 2. Model of an electron. Two views of a superluminal quantum moving along its closed double-looped helical trajectory. The circle in the x-y plane of radius $R_0 = \frac{1}{2}\hbar / mc = 1.9 \times 10^{-13}$ m is the axis of the closed helix. The maximum speed of the superluminal quantum in the electron's rest frame is 2.515c .

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