Particle Physics Insights

PERSPECTIVE

A Proposal for the Structure and Properties of the Electron

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Abstract: A model of the electron is proposed in which it is composed of a known and detectable particle. This model clearly defines what is mass, what is energy and why $E = mc^2$. It shows that the special relativity corrections of mass, length and time with velocity are automatically a function of the structure of an electron as it moves. It also proposes the origin of electric charge and uses that origin to derive the equation for the Bohr magnetron. It shows that the electron's spin of $\frac{1}{2}\hbar$ is simply angular momentum, further explaining why the electron has only two states of spin. This model gives an expression for the radius of an electron, at the same time pointing out why it has been detected as a point particle, yet still has angular momentum of $\frac{1}{2}\hbar$. It explains why the mass of an electron increases with velocity while its spin and charge remain the same and its magnetic moment decreases, as well as why its charge spirals when it travels through space. This model gives a physical reason for the existence of the de Broglie wavelength and derives the expression for it. As well as matching the known properties of an electron it also makes predictions of previously unknown properties, pointing out that they may have been detected but not recognized as such.

Keywords: electron, photon, spin, relativistic corrections, electric charge, magnetic moment, dimensions, de Broglie wavelength

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1. Introduction

Although the electron was the first of the sub-atomic particles to be detected and it is the most widely manipulated sub-atomic particle,[1,2] there has never been an adequate structure proposed for it. Reasons for this include different properties the electron appears to exhibit under different circumstances. At times it behaves like a particle, at other times like a wave. Sometimes it behaves like a point particle yet it possesses a property once described as angular momentum and has a magnetic moment as if it had a dimension closer to that of the Compton radius $\hbar/mc$.[3]

It has a zitterbewegung (zbw) associated with it.[4–6] It has a charge of exactly the same magnitude yet opposite polarity to that of a proton, even though it is some 1,836.1526 times less massive than the proton. Its charge doesn't increase when the mass of the electron is increased with velocity. Its quantum mechanical behavior has resulted in some physicists asking "*what really is an electron*?".[7] One statement that summarized scientific thought regarding the electron, was made in 1961 by Margeneau, "*An electron is an abstract thing*".[8] It appears to still represent the viewpoint held by many physicists.

Although it is now over 100 years since the discovery of the electron and despite the fact that it has been the most studied of all of the sub-atomic particles, very little is known about its structure, see for example Barut,[7] Hestenes,[9] Jaynes,[10] and MacGregor,[11] among others. In 1990 at Antigonish, Nova Scotia,[12] a workshop was held to try to work out properties of and a model for the electron. Cambridge University hosted a conference on the electron in 1997, marking the one-hundredth anniversary of its discovery by Thomson. Candidate structures include Bohm's "Amoeba" model,[13] in which the electron can change its shape to accommodate different dimensions depending upon its circumstances; the spinning sphere model,[14] and the "point particle" model with intrinsic properties inserted upon it,[7] the quantum mechanical model,[15] among others.

Despite these and many other attempts, a theory for the structure of the electron remains elusive. On the other hand the behavior of electrons is well predicted from many mathematical models, such as quantum electrodynamics (QED) and the Bohr model of the atom.[16–18] Both Schrodinger and Dirac developed equations in which known electron properties were superimposed.[4,5,19,20] Those equations were successfully used to calculate the expected behavior of electrons under different circumstances. Physical reasons for electrons to have their properties were never given. Their equations and subsequent modifications have been extensively used in predicting the behavior of electrons in electromagnetic fields. In view of the success of the predictions from those theories some scientists doubt the need for a structure to explain the electron. There are still many unanswered questions associated with it. What is the origin of electric charge? What are the dimensions of the electron? How does its magnetic moment originate? What gives an electron its mass? What is the spin of an electron? Is the electron a particle always, sometimes or never? Is it a wave always, sometimes or never?[7,21] Equally important among all of those properties is the ability of a model to explain the origins of the relativistic corrections when an electron moves.

This paper suggests that there is one structure that can explain the properties of an electron. It is based upon properties of a known particle, the photon, the existence of which was predicted by mathematics worked out by Maxwell,[22] before its existence was verified. One of the predictions of Maxwell's equations was that a wave of electromagnetic energy would move through space at the speed of light "c". Hertz demonstrated their existence.[23] Marconi demonstrated a practical application of those waves, when he sent radio messages using electromagnetic waves.[24] In 1905 Einstein used the concept of energy quanta developed in 1900 by Planck to show that these electromagnetic waves were discrete particles of electromagnetic energy when he gave an explanation for the photo-electric effect.[25,26]

So well established is the concept of the photon that there are two constants, the electric permittivity, ε_0 and magnetic permeability, μ_0 of free space, that define a fundamental property of the photon through the relationship $\varepsilon_0\mu_0 = 1/c^2$, where c is the speed of light. A photon has a frequency of oscillation f, which gives it a wavelength, λ, with the photon traveling through free space at $c = f\lambda$. The work of Planck and Einstein showed that the photon has an energy $E = hf$, where h is Planck's constant.[25,26] This paper presents a model for an electron based upon the above mentioned properties of a photon. It gives explanations for some of the known properties of electrons. It also makes some predictions currently unknown to science, which predictions can be used to check the accuracy of this model.

2. The Model

This model proposes that a single sub atomic particle, in this case the electron, consists of a photon traveling at the speed of light, c, in a circle of circumference equal to half its wavelength. That is, the photon rotates on itself twice within its wavelength. It travels at c in radius $r = \lambda/4\pi$. For this reason, it is appropriate to call this the "rotating photon" model. That is the first postulate made in this model. If this rotating photon model has any validity, that postulate and known properties of the photon should lead directly to many of the experimentally observed properties of the electron. A brief description of why a photon may travel in a circle and what are some of the implications is given in section 5.

A schematic illustration of what is meant by a photon traveling two revolutions in the same time and distance as it would take for the same photon to travel one wavelength in a straight line, is given in Figure 1. A purely electromagnetic field forms and collapses to generate its opposite purely electromagnetic field in exactly the same position, locking the opposite fields into each other. The whole front travels that radius at the speed of light c.

The starting point of this model is that each individual electron has a property called spin, which was postulated by Uhlenbeck and Goudsmit when they were attempting to explain the observed behavior of radiation from a material in a magnetic field.[27,28] Their postulation was that each electron had an angular momentum of $\frac{1}{2}\hbar$, where $\hbar = h/2\pi$. Their idea of angular momentum was that of $I\omega$, where I is the moment of inertia of the electron and ω is its angular velocity. To explain the behavior of the emission lines in a magnetic field, they proposed that the electron was indeed spinning like a top or a flywheel.

3. Angular Momentum Considerations

The starting point of this theory is that the angular momentum of an electron is given by

$$I\omega = \tfrac{1}{2}\hbar \qquad (1)$$

The front of such an electromagnetic oscillation traveling at the speed of light c, has an angular velocity ω (= v/r where $r = \lambda/4\pi$), that is given by

$$\omega = 4\pi c/\lambda \qquad (2)$$

Multiplying equation 1 by equation 2 and substituting gives

$$I\omega^2 = \frac{h}{4\pi} \times \frac{4\pi c}{\lambda} \qquad (3)$$

The moment of inertia I of a hoop of mass m and radius r is given by $I = mr^2$. Substituting this into equation 3 and simplifying gives

$$mr^2 \cdot c^2/r^2 = hc/\lambda$$

or

$$mc^2 = hf = E \qquad (4)$$

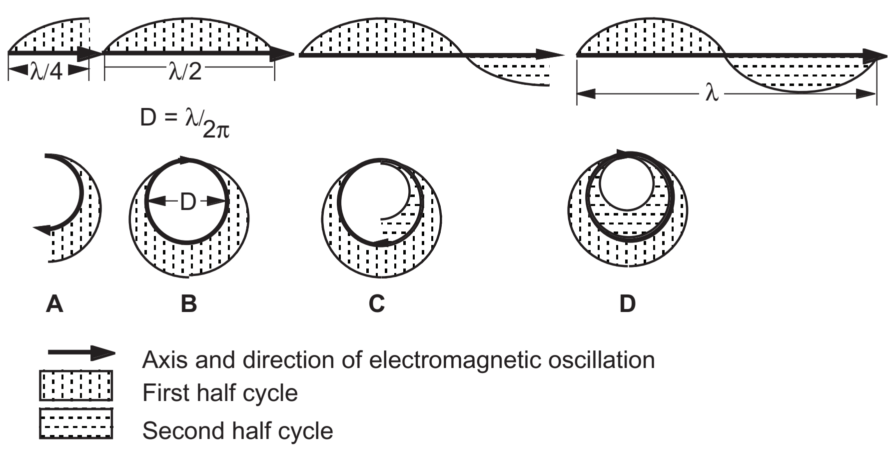

Figure 1. Schematic illustration of the relationship between a linear photon and a rotating photon, shown with the half cycles plotted in the vertical scale and distance in the horizontal. The top set shows the linear trajectory, while the bottom set shows the equivalent in a circular trajectory. For ease of interpretation, the cycles are drawn with different scales. **A**) shows the photon when they have completed 25% of the cycle; **B**) shows 50%; **C**) 75% and **D**) 100% of the cycle. The circular trajectory makes two cycles to complete one wavelength.

Equation 4 is easily recognized as Einstein's relativistic equation that marks the equivalence between mass and energy.[29] In this rotating photon model, the equivalence between mass and energy, given by $E = mc^2$, is that energy E is a photon of frequency f, given by E/h and wavelength $\lambda = c/f$, traveling at c in a straight line, while matter is the same photon traveling at c in a circle such that it makes two complete revolutions within its wavelength, to become the electron. By making two revolutions per wavelength, it is able to remain stationary while still traveling at c, giving it properties of mass and spin normally associated with matter particles. In this regard, this presentation agrees with one of Einstein's statements,[30] "*If the theory corresponds to the facts, radiation conveys inertia between the emitting and absorbing bodies*". That interpretation of photons is held in what is called the Einstein-de Broglie model. Einstein's above mentioned statement shows he believed photons had mass. An alternative interpretation of photons, based upon the Copenhagen Convention, suggests photons do not have mass. Some of the points of the Einstein-de Broglie model and the Copenhagen Convention interpretation are discussed further in Appendix 1. This presentation accepts Einstein's postulate that radiation conveys inertia between emitting and absorbing bodies and hence possesses mass.

This rotating photon model does give a clear definition of mass m in terms of electromagnetic energy, namely

$$m = hf/c^2 \quad \text{and} \quad f = mc^2/h \tag{5}$$

Because $c = f\lambda$, equation 5 yields

$$\lambda = h/mc$$

where λ is the Compton wavelength.[3] From this it is possible to derive an expression for the radius of a particle of mass m,

$$r = \lambda/4\pi = h/4\pi mc = \hbar/2mc \tag{6}$$

4. The Relativistic Corrections

Consider what happens to an electron under this model as it moves. Figure 2A illustrates a hoop moving along its plane of rotation, while Figure 2B illustrates the same hoop moving along its axis of rotation, perpendicular to that plane. All other possible motions should be considered as a combination of those two. In this study, only the path shown in Figure 2B, in which the rotating photon spirals helically through space, shall be considered. This requires each particle of this type to instantaneously orient itself such that the direction of rotation of the photon would always be perpendicular to the direction of travel of the particle.

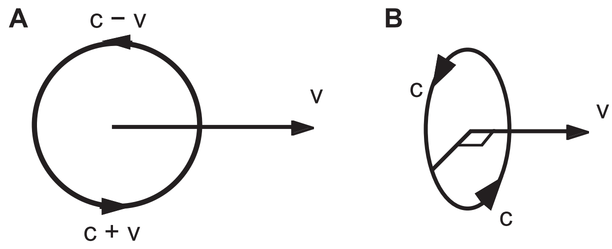

Figure 2. Schematic illustration of the motion of an oscillation in the directions **A**) parallel and **B**) perpendicular to the plane of the rotation of the electromagnetic oscillation. Only the motion illustrated in (**B**), shown in isometric view for easier interpretation, is considered in this study.

Such a particle with radius r_0 at rest with respect to an observer has a perimeter of $2\pi r_0$, which is traveled by the oscillating front in time t (= 0.5 f^{-1} sec), such that $2\pi r_0 = ct$. When it travels at velocity v, with respect to an observer, the oscillation will no longer be represented by a flat hoop when viewed from the side, but by a helix, as illustrated in Figure 3. The front will still travel a distance ct in time t, but from Pythagoras' Theorem, this will be given by

$$(2\pi r_v)^2 + (vt)^2 = (ct)^2$$

where r_v is the radius at velocity v, and can be rewritten as

$$\frac{[(2\pi r_v)^2 + (vt)^2]}{(2\pi r_0)^2} = \frac{(ct)^2}{(2\pi r_0)^2}$$

Since $2\pi r_0 = ct$, this simplifies to

$$\frac{(2\pi r_v)^2}{(2\pi r_0)^2} + \frac{(vt)^2}{(ct)^2} = 1$$

which can be rewritten as

$$\frac{r_v^2}{r_0^2} + \frac{v^2}{c^2} = 1$$

for which one solution is

$$r_v = r_0[1 - (v^2/c^2)]^{0.5} \tag{7}$$

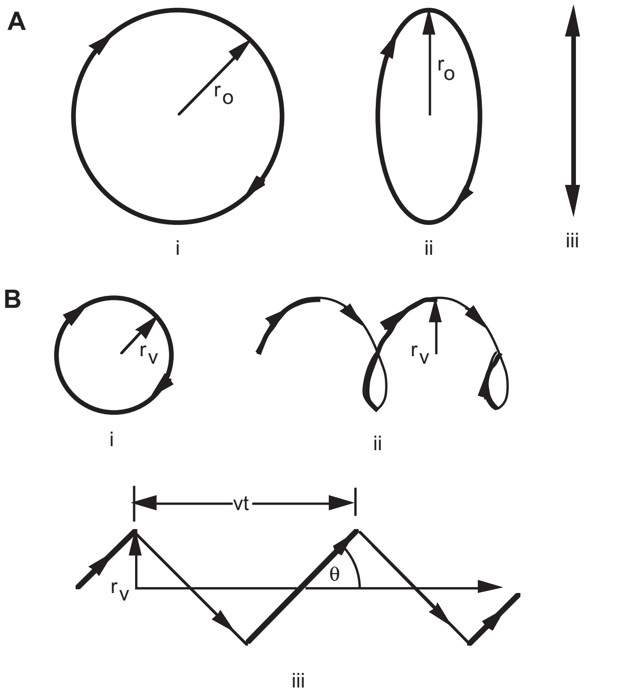

Figure 3. Schematic illustration of the movement of the oscillation front for a particle at rest, **A**) and moving at velocity v, **B**) illustrated from end on, i, at an angle, ii , and side on iii. Note that **B**) ii and **B**) iii illustrate a helix.

In this rotating photon model, a particle will contract laterally as it moves, with the degree of lateral contraction being given by the relativistic correction factor.

When this type of particle moves at increasing velocity, its radius contracts as given in equation 7. However, its angular momentum, Iω, remains constant, because none has been either added or subtracted. Thus angular momentum Iω remains constant at

$$\tfrac{1}{2}\hbar = mr^2 \times c(\sin\theta)/r$$

for all velocities, where θ is the angle between the direction of travel of the particle and the angle traversed by the rotating (spiraling) photon, as shown in Figure 3B iii. The sinθ term comes about because the motion of the photon is now no longer completely circular, some of the velocity c is in the direction of the propagation of the particle and some in the direction of rotation. It is only the component sinθ, in the direction of rotation, which contributes to the angular momentum. This gives

$$m_0 r_0 = m_v r_v \sin\theta,$$

where m_0 and r_0 are the rest mass and rest radius of the electron and m_v and r_v are its mass and radius at velocity v. In this rotating photon model of an electron, the photon cannot spin faster, so to match angular momentum, its mass must increase. As such,

$$m_v = m_0 r_0 / r_v \sin\theta$$

But since sinθ is given by r_v/r_0, this gives

$$m_v = m_0 r_0^2 / r_v^2$$

which, from equation 7, gives

$$m_v = \frac{m_0}{(1 - v^2/c^2)} \qquad (8)$$

Equation 8 means that, as the velocity of a particle of this type increases, its mass would increase at a rate faster than allowed under the relativistic and previously derived relationship $E = mc^2$. This is at odds with the principle of conservation of mass-energy. Thus, either this rotating photon model is not applicable to the structure of an electron, or the rate of rotation must slow down. Considering the latter case, equation 8 can be re-written as

$$m_v = [1 - (v^2/c^2)]^{-0.5} \times m_0[1 - (v^2/c^2)]^{-0.5}$$

indicating that the correction required is $[1 - (v^2/c^2)]^{-0.5}$.

In the above description of the rotating photon, classical concepts of length and time have been used. If time on the moving particle were to slow down according to that relationship, then mass would increase at the slower rate given by

$$m_v = \frac{m_0}{(1 - v^2/c^2)^{0.5}} \qquad (9)$$

which agrees with predictions from Einstein's special theory of relativity.[29] Thus, this rotating photon model requires time interval t_v at velocity v to slow down according to the relationship

$$t_v = \frac{t_0}{(1 - v^2/c^2)^{0.5}} \qquad (10)$$

which again agrees with the special theory of relativity and experimental observation.

With the speed of rotation slowed down, yet the photon still required to travel at c, it must now have a linear forward travel component in its motion, as shown in Figure 4. If the electron were to helically spiral its way through space, it would travel the total distance as seen by a stationary observer. When it has a forward linear motion, it does not have to make the same number of spiral revolutions to go from one position to another. Making fewer revolutions means that it spirals through a shorter distance to reach its destination. As can be seen from equation 10, the correction factor for this forward slip motion is $(1 - v^2/c^2)^{0.5}$. This results in the distance l_v traveled by the rotating photon moving at velocity v, being apparently shortened according to the well-known relativistic correction for distance, namely:

$$l_v = l_0[1 - (v^2/c^2)]^{0.5} \qquad (11)$$

From the above, it can be seen that this rotating photon model of the structure of an electron automatically derives some of the major features of the special theory of relativity, namely

$$E = mc^2 \qquad (4)$$

$$m_v = m_0[1 - (v^2/c^2)]^{-0.5} \qquad (9)$$

$$t_v = t_0[1 - (v^2/c^2)]^{-0.5} \qquad (10)$$

$$l_v = l_0[1 - (v^2/c^2)]^{0.5} \qquad (11)$$

giving a physical reason for the existence of those factors based purely upon the structure of the electron. The reason is that the circumferential speed of a photon spiraling through space remains constant at the speed of light c, and therefore the radius must be altered to suit the velocity. This automatically results in time slowing down, mass increasing and distance decreasing. However, unlike the Einstein/Lorentz contractions, this rotating photon model also predicts a contraction in the width of an individual sub-atomic particle such as an electron, as given in equation 7.

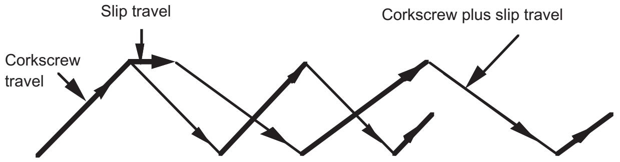

Figure 4. Schematic side view illustration of helical spiral or "corkscrew" travel and helical spiral plus slip travel. The slip component of the travel is forward motion, meaning the spiraling photon does not have to make the same number of spirals required for it to travel the distance between its start point and its end point.

It should be pointed out that it is only the width of individual sub-atomic particles that contract. This contraction does not apply to space as a whole. Lateral dimensions are maintained by electric charge. A hydrogen atom, which has a radius of 0.53 Å at rest with respect to an observer, will still have the same radius when traveling at relativistic velocities with respect to the same observer. Space is foreshortened in the direction of travel of the particle, but not in the other directions. As shall be shown later, electric charge is unaffected by velocity under this rotating photon model. However, the radius of an individual electron will decrease under this model. This is an important difference in modeling the structure of a particle such as an electron, because it enables its size to be reduced at increasing energy. There is one set of experimental data that indicates this may be observed experimentally, namely the experimentally measured dimensions of an electron. High energy electrons have a collision cross section of less than 10^{-17} m at energies above 15 GeV.[31] This in itself does not indicate that the collision dimension of electrons diminishes as their energy increases because there is no established dimension for the electron at rest. However from equation 6, the electron's angular momentum of $\frac{1}{2}\hbar$ suggests that at rest, it has dimensions consistent with a radius of the Compton wavelength divided by 4π, or 1.930796×10^{-13} m. It is proposed here that the observed dimension of less than 10^{-17} m at energies of many GeV is therefore consistent with the radial contraction the electron experienced at high accelerating voltages. This concept describes the dimensions of an electron, having properties equivalent to a radius of some $1.93.. \times 10^{-13}$ m at rest, yet also having a dimension of less than 10^{-17} m at high energies. Its relativistic mass increase enables the electron to maintain its angular momentum of $\frac{1}{2}\hbar$ and still be measured as a "point" particle.

Under this model, the electron's helical motion enables its shape to be described as:

$$x = \frac{\hbar(1 - v^2/c^2)^{0.5}\cos\theta}{2m_0c} \qquad (12a)$$

$$y = \frac{\hbar(1 - v^2/c^2)^{0.5}\sin\theta}{2m_0c} \qquad (12b)$$

$$z = \frac{v}{(1 - v^2/c^2)^{0.5}} t \qquad (12c)$$

with the condition that θ extends from 0 to 4π and t extends from 0 to $h(1 - v^2/c^2)^{0.5}/m_0c^2$. Increasing the values of θ and t describes the motion of the electron as it slip/helically spirals through space. The instantaneous position of the electron is spread out over the co-ordinates determined from equations 12, giving it a finite non zero location, further limiting its ability to be detected with great accuracy. At rest, v = 0 and it is a hoop of radius $\hbar/2m_0c$. At velocity v its radius diminishes and its helical structure is stretched in its direction of motion. The influence of its electromagnetic field extends beyond these dimensions.

5. Electric Charge and Magnetic Moment—why Photons can Travel in a Circle

Why should a photon travel in a circle when there is no known circular solution to Maxwell's equations? Known examples of photons traveling in a curved path include reflection, refraction at interfaces of different refractive index and a mirage. A photon can travel in a curved path, provided there is something to cause that curvature.

Consider the propagation of photons under both the wave and the particle theories, as illustrated in Figure 5. Under those theories, a photon is considered to generate a new wave front at every point on its path. That wave front spreads out in all directions, as schematically illustrated in Figure 5A. In diffraction theory, each point on the photon's path can be regarded as a new source of virtual photons. If something should interfere with the photon's original trajectory, a new source of photons will start at another point and the photon will continue on in the new direction (calculable from QED, or its simplified form of diffraction theory). Without an interfering effect, the conservation of linear momentum applies at the end of the uncertainty principle, causing the photon to continue to travel in a straight line. This same phenomenon can also be regarded as illustrated in Figure 5B. A photon traveling in a particular direction can emit a virtual photon in one direction, as illustrated. The photon itself will, by virtue of the conservation of momentum, travel in the other direction that is required to conserve linear momentum, as indicated. The original photon and the new virtual photon are indistinguishable from each other, within the limits of the uncertainty principle. The two will not separate a distance of greater than the wavelength of the photon, before the original photon will re-absorb the emitted virtual photon and continue on. As such, the two illustrations, figures 5A and 5B, are merely different representations of the same phenomenon. If an interaction should cause the emitted photon to exceed the uncertainty principle, the two will separate and the original photon will continue in a new direction.

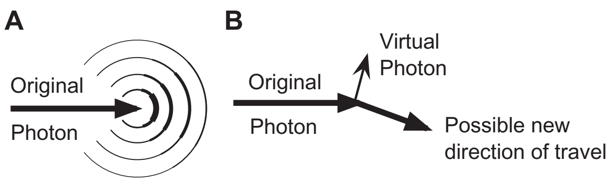

Figure 5. Schematic illustration of the generation of a new wave front at one particular point on the photon. A wave front spreading out from a particular point, the end of the arrow, is illustrated in (**A**) while (**B**) gives possible new directions for the photon after the emission of a virtual photon. Both illustrate the same feature, with (**A**) being the wave representation and (**B**) being one particular particle representation. If no interference occurs, conservation of linear momentum determines that the photon will continue to travel in its original direction. In the event of some interaction, the photon can change its direction.

The ability of a photon to loose part of its energy has been established through Compton scattering.[3] An X-ray can interact with an electron and loose part of its energy. The reverse, where photon energy can increase, has also been detected.[32] The ability of electrons to emit photons has long been known because most photons are emitted by electrons giving up energy. Similarly the ability of electrons to absorb photons has long been known from radiation absorption by materials and by electrons increasing their energy in an electromagnetic field.

Suppose that the original photon has emitted a virtual photon and thus changed its direction. It can now emit a further virtual photon, again in the same general direction as the first, changing its direction once again further in the direction of its original curvature, as shown in Figure 6A. Alternatively absorbing a photon coming from the same direction will also change the direction of the rotating photon in the same manner. Theoretically, this process can continue, with the original photon emitting and absorbing more virtual photons in the same general direction and continually changing its trajectory in the same direction of curvature. By this technique it is possible for a photon to travel in a closed

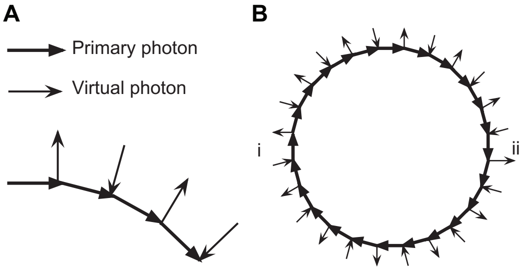

Figure 6. Schematic illustration of how the emission and absorption of photons by a primary photon can result in it traveling a curved path. **A**) illustrates that both emitting and absorbing a photon can result in a change in the direction of the rotating photon, while **B**) illustrates that the continual emission and absorption of photons can result in the primary photon making a closed loop trajectory. In this hypothesis, it is suggested that the emission/absorption of a photon at i is equivalent to the absorption/emission of a photon at ii. Note that the emission or absorption of photons in other than the plane of rotation would have no effect upon the closed loop trajectory.

loop, of which a circle is the most efficient, as illustrated in Figure 6B. In Figure 6B, the emission/absorption of virtual photons at i is regarded being equivalent to the absorption/emission of virtual photons at ii.

The second postulate of this model is that the continual emission and absorption of virtual photons so necessary for the original photon to travel in a closed loop trajectory is the source of electric charge associated with an individual subatomic particle such as an electron. The virtual photons become real when they are exchanged between charged particles.

It is suggested that this hypothesis is supported by at least three different observations. First, in QED theory photons are the force carrying particle for electromagnetism. Their emission and absorption by a particle is the property that imparts electric charge to that particle. Second, the quantity of virtual photons emitted and absorbed will depend upon the angular momentum of the rotating photon. Since this is the same for both the proton and electron, whether at rest or in motion, namely $\frac{1}{2}\hbar$, the quantity of virtual photons will always be the same. If this is the origin of electric charge, the charge should remain the same, irrespective of the particles mass, relativistic or otherwise. This has been observed experimentally.

Third, a charge moving in a circle generates a magnetic field μ, the strength of which is given by

$$\mu = i \cdot n \cdot r \tag{13}$$

where i is the electric current, n is the number of turns and r is its radius. In the case of this rotating photon, i = e/2, where e is the electric charge. As it takes two turns to produce the whole charge e, n = 2. From equation 6 we have $r = \hbar/2mc$. Substituting those into equation 13 yields

$$\mu = e\hbar/2mc \tag{14}$$

Equation 14 corresponds to the Bohr magnetron, μ_B, the fundamental unit of magnetism of an individual sub-atomic particle such as an electron. The origin of electric charge in this rotating photon model is that it is caused by the emission and absorption of virtual photons from the circumference of the rotating photon that is the electron. That it predicts the correct value for the electron's magnetic moment, the Bohr magnetron $e\hbar/2mc$, indicates it is the origin of electric charge of value e. Its origin by this mechanism also predicts that the charge remains constant when its mass is increased with velocity. An illustration of the "classical appearance" of an electron under this model is given in Figure 7. The rotating primary photon generates an electric field in its plane of rotation and a magnetic field perpendicular to that plane.

This rotating photon model uses the concept that a photon makes two revolutions, each with a circumference of half a wavelength, to return to its original starting state. The photon "goes round twice to turn round once". When angular momentum had been established in a rotating photon, its conservation would force the original photon to emit the required

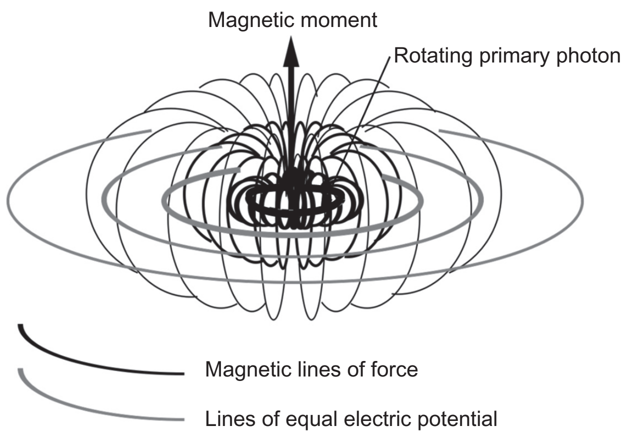

Figure 7. Schematic illustration of the structure of the electron illustrated in terms of its classical electric and magnetic fields. The rotating primary photon has an electric field in its plane of rotation and a magnetic field perpendicular to it, which magnetic field is generated by the charge of the rotating primary photon traveling in its closed loop trajectory to become the electron.

quantity of virtual photons in the appropriate directions to ensure the original photon traveled in the appropriate circular path. In an interaction between an energetic photon, that is one with about the same energy as that of the particle, the two photons would appear similar over short distances and for short time periods. Within the realms of the uncertainty principle, the behavior of a photon and an individual subatomic particle would be expected to be very similar because they are composed of the same electromagnetic oscillations. It is believed that has been observed experimentally.[33]

6. Distribution of Electric Charge

The above presentation has shown how it is possible to visualize an individual particle such as an electron as being a photon traveling in a circle. It has an electric field in its plane of rotation, as illustrated in Figure 6B, and a magnetic moment perpendicular to the plane of rotation. Under QED theory, the emission and absorption of photons is associated with charged particles. As can be seen from Figure 6B, those virtual photons must be emitted in the plane of rotation of the photon if the primary photon is to traverse a curved path. The possibility that photons could be emitted or absorbed in directions perpendicular to that plane has not yet been excluded. However they would not contribute towards the rotation of the photon. In the absence of any other reason for their emission or absorption, there is nothing that can cause virtual photons to be emitted perpendicular to the plane of rotation. With a very strong reason for their emission/absorption in the plane of rotation and no reason for their emission/absorption perpendicular to that plane, it would be expected the electric charge would also be in the plane of that rotation.

It becomes a very important aspect of this model that the electric charge associated with an individual electron will therefore be two dimensional in nature, at least close to it. Referring again to Figure 6B, it means that the charge is concentrated outside the plane of the rotation and may not necessarily exist above or below the circumference of rotation. Therefore it is important to determine if there is any indication of charge being two dimensional in nature. It is suggested that there is supporting evidence for the two dimensional nature of electric charge on electrons.

The first of these is the strength of the electron's magnetic moment. Electrodynamics requires that a magnetic field is generated when an electric charge moves. The electron's magnetic moment $e\hbar/2mc$ requires the charge to be generated over a hoop of radius $\hbar/2mc$ or circumference $h/2mc$. Any other model, such as charge spread uniformly over a sphere, would require either a much larger dimension to obtain the indicated magnetic moment, a much larger charge or some other way of generating a magnetic field that was independent of charge. When the only dimension measured for an electron is below 10^{-17} m, there is no evidence that an electron has a larger dimension. Experimentally the measured charge of an electron is e ($= 1.60217648. \times 10^{-19}$ C). It is constant and never varies. It is e and not some other value. It would require some fundamental change in known properties of electromagnetism to have a magnetic field generated by any method other than by a moving electric charge, be it a closed loop, curved or straight-line path. Such a change would also require some way of attaching the magnetic moment to its mass and electric charge, both known properties, in a manner that included its spin. This would have to be done in such a way that the charge remained constant when the electron's mass increased, its spin would have to remain the same and its magnetic moment would have to decrease. As can be seen from equation 14, the value of the Bohr magnetron is given by the charge of the electron multiplied by its radius, a good indication that the electron's magnetic moment is caused by all its charge being concentrated at its circumference.

The second piece of experimental evidence that supports the concept of charge being two dimensional in nature is the ability of electrons to form groups of two or more electrons in a single structure, as illustrated in Figure 8. Like charges repel each other and therefore if two electrons with charge distributed in three dimensions were to come close to each other, they will repel each other. However, if they have charge in two dimensions only and the axis of the magnetic field is in the third dimension, it is possible for them to approach each other along the magnetic field axis and have the magnetic fields attract each other if their magnetic moments are appropriately aligned. This requires the electrons to have the same spin and could

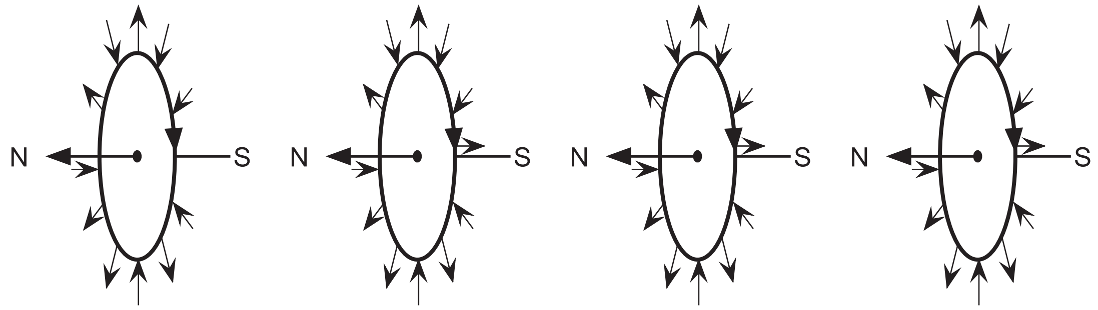

Figure 8. Schematic illustration of a group of electrons being stacked "end on end" as they have the same spin and their magnetic fields attract each other without their like charges repelling each other.

be achieved with a beam of spin polarized electrons. In this situation illustrated in Figure 8, the electric field in the planar dimension will not give rise to mutual electrostatic repulsion.

The third piece of evidence for an electron having its charge distributed in two dimensions comes from what is known as helical Mott scattering.[34,35] This effect predicts that elastically scattered electrons will not follow the true Mott scattering if their charge is either not a point or is spiraling. A number of experimental observations have been made in which one explanation is that the charge distribution of the electron is similar to that determined from the Compton radius, $r = \hbar/mc$. It shows up because a point charge close to a scattering centre will be scattered more than either a diffuse (spread out) charge or a spiraling charge at the same average distance from the scattering centre. At greater distance there will be no difference between the two effects. Therefore a reduction in wide-angle scattering, below that predicted from pure Mott scattering would be expected. An illustration of spiraling electric charge is given in Figure 9. As the rotating photon spirals, its charge distribution spirals with it. The topic was well covered by Mac Gregor.[35] There is considerable scope to explore the possibilities that the charge on individual electrons is two dimensional in nature, being oriented in the plane perpendicular to its direction of travel.

7. Opposite Charge—Electron and Positron

The requirement of a particle such as an electron to have an anti-particle of equal properties but opposite charge first came from the work of Dirac.[19,20] His prediction was confirmed a few years later.[36] Any model of the electron should also explain the origins of the two different forms of charge, negative and positive. From electrodynamics, it is known that the magnetic field generated by a current flowing in one direction around a circle will produce a magnetic field with the north magnetic pole pointing in the direction given by the "right hand rule". Reverse the direction of rotation of the electric current and the north magnetic pole will point in the other direction. From this it follows that if the photon that is the electron was to rotate in the opposite direction with respect to the north magnetic pole, it would have to generate the opposite electric charge. That is the polarity of the charge emitted by the rotating photon is due to the direction of its rotation with respect to the magnetic field, as illustrated in Figure 10. In Figure 10 the arrow notation is used for the direction of the north magnetic field. A dot represents the head of the arrow traveling towards the observer, showing a north magnetic pole pointing out of the page. A cross

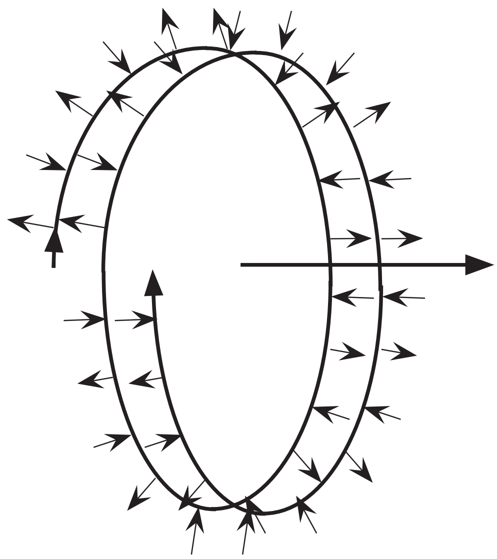

Figure 9. Schematic illustration of a rotating photon spiraling through space, with its virtual photon induced charge also spiraling.

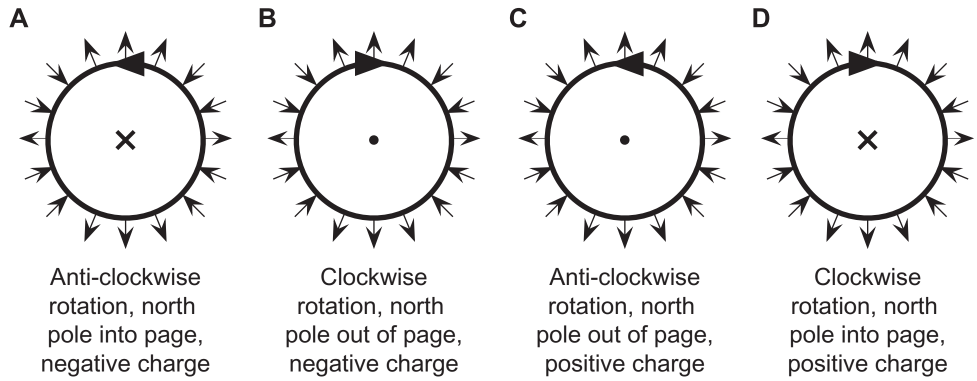

Figure 10. Schematic illustration of the effect of the direction of rotation of the photon with respect to the magnetic field, upon the spin and charge of an electron. The convention used for the direction of the magnetic field, assumed to be north here, is a dot that represents the approaching arrow head of the north pole pointing out of the page, while the cross represents the tail of the arrow of the north pole disappearing into the page and gives the south magnetic pole sticking out of the page. Observing an electron from the opposite side makes both the direction of rotation and the magnetic field change. The electron will still have the same charge, but will have opposite spin. The mirror image of the electron gives the same particle but with opposite charge, ie, a positron.

represents the tail of the arrow traveling away from the observer, showing a north magnetic pole pointing into the page. An anti-clockwise rotation with the north magnetic pole pointing into the page, Figure 10A will generate a negative charge. The same rotation with the north magnetic pole pointing out of the page, Figure 10C, will give a positive charge. A clockwise rotation with the north magnetic pole pointing out of the page, Figure 10B, is a negative charge. An anti-clockwise rotation with the north pole pointing out of the page will be a positive charge.

Although there are four images in Figure 10, they represent four different variations of one situation. Figures 10A and 10B are other side of the page images of each other and represent the two spin states of the electron. Figures 10C and 10D are mirror images of Figures 10B and 10A respectively and represent positrons. The positron is a mirror image of the electron. Figures 10C and 10D represent the two spin states of a positron. For both the electron and positron, the two states of spin are simply the direction from which it is observed.

Just as an electron is a photon rotating in one direction with respect to its magnetic field, a positron is the same photon rotating in the opposite direction with respect to its magnetic field. A positron is a mirror image of an electron. Figure 11 illustrates that an electron moving forward in time will have the same appearance as a positron moving backward in time. A film of an electron moving to the right in real time will, when played backward, display a positron moving to the left, traveling backward in time.

In this rotating photon model, it is easy to understand the conversion from mass to energy when an electron meets a positron. They are attracted to each other because of their opposite charge. When they are close, they align their spins so that their magnetic fields attract each other and they move together. When they meet, they unlock each other's angular momentum and then, instead of two photons, each traveling in a circle, there exists the same two photons each traveling in opposite directions in straight lines. The energy of each photon released by this interaction is determined from equation 4, namely $E = mc^2$. Indeed, when a positron of one energy meets an electron of a slightly different energy, they interact and release photons. Measuring the energy of those photons should show that the two photons produced had the same frequency and energy as the two original particles (although they may exchange energy when they are influencing each other). This conversion of mass to energy when a positron meets an electron

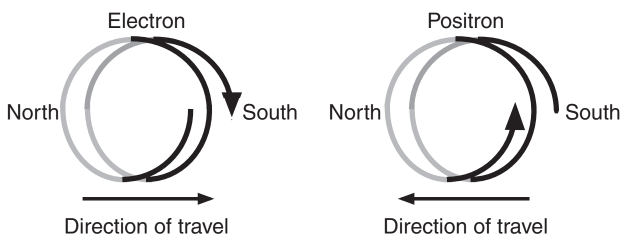

Figure 11. Schematic illustration of an electron spiraling forward (in the direction of the arrow), with its south pole leading. If we now reverse the direction of travel of the electron's spiral, we get the positron traveling backwards in time with its north pole leading.

is simply the conversion of angular momentum of a photon into linear momentum for the same photon.

The conversion of energy to mass occurs when a photon of appropriate energy comes close to the high field region of a nucleus, [eg, when an electron and positron are created by a high energy photon (greater than approximately 1.022. MeV)]. As the photon interacts with the nucleus, it splits into two photons that rotate in opposite directions. No reason for a photon to split into two separate photons is given, although Compton scattering allows photons to split. Then when a closed loop has been established, conservation of angular momentum requires them to be in opposite directions, which automatically gives rise to opposite charge, automatically fulfilling the requirements for conservation of spin, charge (parity, one positive and one negative) and chirality (one turns left, the other right). In this manner, energy is converted to mass.

8. Spin, Chirality and Parity

In this model, the concept of the spin of a particle is that of the angular momentum of the rotating primary photon traveling in a circle and making two revolutions to complete one cycle, namely $I\omega = ½\hbar$. If the photon was traveling such that it made one revolution per cycle, it would have angular momentum, $\hbar$. Angular momentum and hence spin can only have one of two values, either +1 and –1, or up and down, depending upon nomenclature. It cannot possibly have another value because it can only spin one way or another. If any particle has a spin that is different from $½\hbar$, it can only be in units of $½\hbar$, either added or subtracted as a combination of more than one fundamental particle is added. Under this model no other value for spin is possible. No other value of spin has been detected.

The two stated values of spin are due to the direction from which the particle is observed. An electron observed on the plane of the page, will be seen as illustrated in Figure 10A, with the photon rotating anti-clockwise and will be defined as a spin −1 or spin down particle. Viewed from the other side of the page, the particle shown in Figure 10B, rotating clockwise will be a spin +1 or spin up particle. No fractional spins will be observed because the rotating photon always travels with its axis of rotation along the direction of travel.

An electron approaching two observers, see Figure 12, will be seen by both observers to be a spin +1 particle at position a. As it passes observer 1, it becomes a spin −1 particle to observer 1 at position b-1, but remains a spin +1 particle to observer 2 at position b-2. When it passes observer 2 at c, it becomes a spin –1 particle for observer 2 as well. In this model the spin of an electron depends upon the direction from which it is observed.

That property known as "chirality" refers to the right handedness or left handedness of the object under consideration. It can be easily appreciated by looking at Figure 10. Use your thumb as the direction of the arrow tip and close your fingers in a clenched fist with thumb up. If you point the thumb of your left hand towards your eyes, you will see the arrangement of your fingers indicating the arrangement in Figure 10B. Now point the thumb of your left hand away from your eye and you will see the arrangement

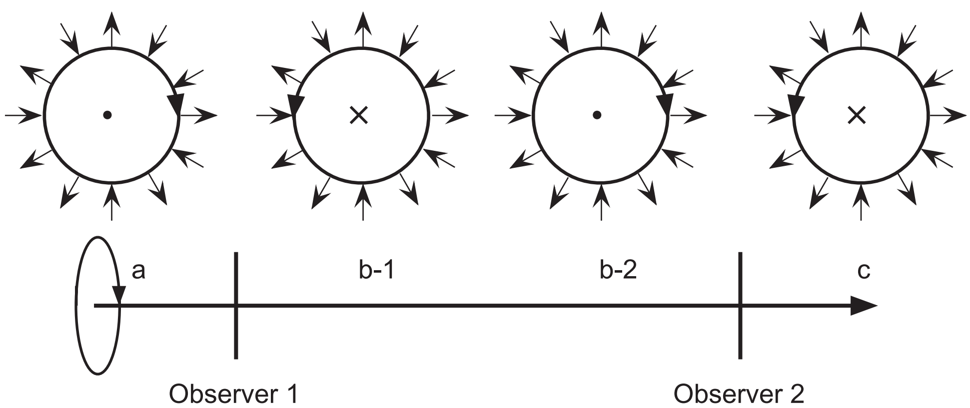

Figure 12. Schematic illustration of the change of spin as a traveling electron passes observers. The spin or an electron changes as it passes an observer. At positions (**A**) and (**C**) both observers see the same spin for the electron. At position B between the two observers 1 and 2, they see the electron as having a different spin.

shown in Figure 10A. As such, both of these have a "left handed" chirality. In the same manner, the particles illustrated in Figures 10C and 10D have a "right handed" chirality. If you now look at the example in Figure 12, you will see that the electron under consideration has a left handed chirality, even though its spin changes as it passes from one side of the observer to the other. It is also apparent from Figure 10 that the positron is a mirror image of the electron. It follows directly from section 7 that parity is always retained, in so much as any change from mass to energy or energy to mass for one particle will always be accompanied by the equivalent change to its opposite counterpart.

9. Particle or Wave?

An electron has a well-defined mass and magnetic moment (for a given velocity), a well-defined charge and spin (for all velocities) and a limited dimension, all attributes that make up a particle. They can be extracted and moved to create all sorts of marvelous properties. Yet at the same time that it behaves like a particle the electron has some very well established properties that make it a wave.

The obvious reason for this is that they have a wavelength, as postulated by de Broglie.[37] His hypothesis was that electromagnetic waves have a momentum $p = h/\lambda$, so he expected a particle to have a wavelength $\lambda = h/p$, which was subsequently verified.[38] So what causes an electron to have a wavelength? Some physicists have looked to that property of an electron known as zitterbewegung, predicted by Schrödinger.[4,5] The zbw of an electron is the frequency f of the photon that it is, which, from equation 5, is given by $f = mc^2/h$. In the case of an electron at rest, its zbw is $\approx 1.235590 \times 10^{20}$ Hz. The zbw establishes a varying electromagnetic field around the electron.

The energy E of a moving electron with momentum p is given by

$$E^2 = p^2c^2 + m_0^2c^4 \qquad (15)$$

In this rotating photon model all the energy of the photon is incorporated into the electron by an increase in its frequency. In this case

$$E^2 = m_v^2c^4 = (hf_v)^2 \qquad (16)$$

Under this rotating photon model, an electron is entirely an electromagnetic entity, consisting of a photon rotating twice in its wavelength. At rest its motion is entirely in its plane of rotation. However as it moves, it has two components to its electromagnetic field, the planar component of its rotation and the linear component of its motion. These are shown in Figure 13, where the arrow represents the direction of motion of the electron. When the electron is moving at velocity v, it has an energy $E = hf_v$, as given in equation 16 and illustrated in Figure 13. From this it can be seen that the photon has two components, its rest energy and the kinetic energy associated with its linear motion.

The rotational component of the electron at rest is unavailable for any interaction, except for exchanging photons in an electromagnetic interaction. That leaves only the translational component of the moving electron's electromagnetic field available for interaction. That is the wavelength of its kinetic energy. However the electron is entirely composed of an electromagnetic wave. Its total energy $E = hf_v$. Its rest energy is hf_0. The kinetic energy component of the electromagnetic field, pc, is given by

$$E \sin\theta = hf_v \sin\theta = pc = hf_{KE}$$

where f_{KE} is the frequency of the moving electron with kinetic energy KE transformed in the direction of travel of the electron. Substituting c/λ_{KE} for f_{KE} and simplifying yields

$$pc = hc/\lambda_{KE}$$

where λ_{KE} is the component wavelength of the electromagnetic oscillation that is the electron, in the direction of its travel, namely

$$\lambda_{KE} = h/p \qquad (17)$$

which is the expression for the de Broglie wavelength.[37] From the above it is seen that the de Broglie wavelength is the forward motion component of the rotating photon's electromagnetic field oscillation, ie, its zbw.

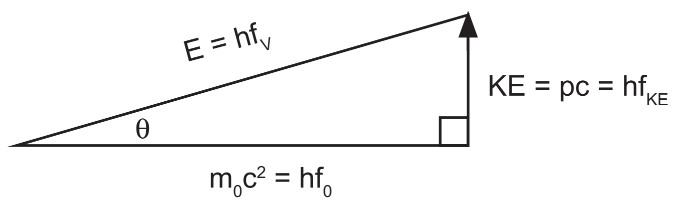

Figure 13. Diagrammatic representation of equations 15 and 16.

It is also the only part of an electron's electromagnetic wave that is available for interaction with the external world, charge interactions excluded. Experimental observations point out that electrons behave as waves according to de Broglie's prediction and the derivation of equation 17. It is perhaps obvious in hindsight that equations 16 and 17 are automatic consequences of this rotating photon model.

The earlier question, "Is an electron a particle or wave?" can now be answered. It is always a particle and it is always a wave. Whether it behaves as a particle or a wave depends entirely upon the situation in which it is placed. A low energy electron has a wavelength of the order of atomic dimensions and will be diffracted and otherwise interact as if it were a wave. High-energy electrons have such a short wavelength that there are no structures with which their wave component can interact and they will behave as particles.

10. The Structure of an Electron

The rotating photon model presented herein has been used to describe the structure and properties of an electron. Its dimensions are given in equations 12. They depend upon its mass and velocity. Experimental observations show that its rest mass m_0 is $9.109382. \times 10^{-31}$ kg, its electric charge e is $1.60217648. \times 10^{-19}$ C and its spin is $\frac{1}{2}\hbar$. Those values, this model and the physical constants h and c define its structure and properties. Visualizations of its rest appearance are given in Figures 6B and 7. It is a photon of energy $E = m_0c^2 = 0.5109989.$ MeV traveling at the speed of light in a circle such that it makes two revolutions within its wavelength. It goes around twice to turn around once. Its structure at rest is that of a hoop of electromagnetic energy. From equation 5, the photon's frequency $f = 1.235598.. \times 10^{20}$ Hz and its wavelength $\lambda = 24.263102. \times 10^{-13}$ m. From equation 6, this gives the hoop a radius $r = 1.9307963. \times 10^{-13}$ m. Its electric charge is generated at its circumference by its necessity to continually emit and absorb virtual photons to enable the primary photon to rotate in its curved trajectory. Its magnetic moment is caused by the rotating photon generating its electric charge e at its circumference of radius $\hbar/2mc$ and is the Bohr magnetron $\mu_B = e\hbar/2mc$. The photon rotates in one direction with respect to its magnetic field, making it negatively charged. Its spin is angular momentum $I\omega$ caused by the photon being a rotating hoop, which has a moment of inertia $I = mr^2$ and angular velocity $\omega = c/r$. The different values of spin are merely the different directions from which it can be viewed. If the photon rotates in the opposite direction with respect to the magnetic field it generates, it has identical properties to the electron, but opposite charge, making it a positron. The positron is a mirror image of the electron. When an electron and positron meet, they unlock each other's angular momentum and travel in straight lines away from each other, conserving momentum, both linear and angular, as well as charge, chirality and parity.

When an electron moves, it moves in the direction perpendicular to its plane of rotation, as illustrated in Figures 2B and 9. This means that it is automatically subjected to the special relativity corrections of mass, length and time as it moves. Additionally its radius diminishes according to equation 7 and its length increases according to equation 12C. Its electric charge spirals through space. It also means that the mass, charge, magnetic moment and spin are combined together in the one structure such that when the electron moves, its mass increases, its spin and electric charge remain the same and its magnetic moment decreases. As its mass increases, its zbw also increases. Its de Broglie wavelength is the component of its zbw in its direction of motion.

11. Summary and Conclusions

The model is based upon the concept that an individual electron is a photon of the appropriate energy rotating twice within its circumference, giving it a radius of $\lambda/4\pi$. This model used known properties of the photon and made two postulates: i) that a particle is composed of a photon making two revolutions per wavelength; ii) that the reason it can do this is because it is continually emitting and absorbing virtual photons which give it the property of electric charge. The electron's properties follow automatically from the Einstein/de Broglie model of a photon, in which it is considered to have mass $m = E/c^2$ when traveling at c. With that as the foundation, this model offered explanations for the following known properties of the electron:

1. The origin of spin = $\frac{1}{2}\hbar$. It is simply angular momentum $I\omega$.

2. Why an electron can only have two states of spin and why they are always the same quantity but opposite sign. The photon can only rotate one way or the other. The different spin states are simply the "other side of the page" image of the same state.
3. The reason for the equivalence of mass and energy through $E = mc^2$. E is the photon traveling in a straight line, m is the same photon traveling in a circle of circumference equal to half its wavelength.
4. The origin of the special relativistic variations in mass, length and time as the electron moves.
5. Why the electron, which has a measured diameter of less than 10^{-17} m can also have an angular momentum of $\frac{1}{2}\hbar$.
6. The origin of its electric charge—it is caused by the continual emission and absorption of virtual photons required to enable the primary photon to travel in a circle.
7. The origin of its magnetic moment, showing that the Bohr magnetron is the electron's charge multiplied by its radius.
8. Why the mass of an electron increases, its electric charge and spin remain constant and its magnetic moment decreases with an increase in its velocity, yet all are bound together in the structure that is the electron without the need for any additional process to keep them together.
9. How the electron and positron annihilate each other when they meet. They simply unlock each other's angular momentum and the two linear photons move apart in opposite directions so that momentum is conserved.
10. If the electron and positron have different energies, the photons emitted will have different energies, with each photon having the energy of its original particle given by $E = (p^2c^2 + m_0{}^2c^4)^{1/2}$.
11. A physical description of chirality, parity and duality for an electron.
12. Why an electron has a de Broglie wavelength associated with it. It is the forward component of the electron's zitterbewegung, determined by adding the kinetic energy of its motion to the rest energy of the electron. Its wavelength $\lambda = h/p$, is as de Broglie postulated.
13. Why the electron's charge spirals as it travels through space.
14. The structure that requires the electron to go round twice so that it can turn round once.
15. A positron is a mirror image of an electron.
16. Why a positron traveling backwards in time is indistinguishable from an electron traveling forward in time.

It is believed that the ability of this rotating photon model to predict so many known properties of the electron gives a solid basis for the correctness of the two postulates made. In addition to giving an explanation for those phenomena, this model also makes the following predictions:

17. The electron is totally electromagnetic in nature.
18. At rest the electron is a hoop of radius $r = \hbar/2m_0c$.
19. The electron's charge is generated at its circumference, not at a point.
20. When an electron moves, it orients itself such that its axis of rotation is in its direction of motion.
21. In motion, the electron is described by a helix that is subjected to the relativistic correction factor $(1 - v^2/c^2)^{0.5}$, with its radius diminishing by that amount and its spiral separation increasing by the same factor, as given in equations 12.
22. The charge on an individual electron is in the two dimensions of the photon's plane of rotation (at least when measured close to it).
23. The axis of an electron's magnetic moment is perpendicular to its plane of rotation.

The above has presented a pictorial insight into some of the complex properties of electrons and briefly indicated how this rotating photon model has explained some of the different and sometimes apparently conflicting phenomena associated with electrons. All of those properties of the electron are a direct result of the rotating primary photon. Its properties of spin, electric charge and magnetic moment are all generated by the rotating primary photon emitting and absorbing virtual photons. Its dimensions are defined by its mass and velocity. Under this model, electrons come with all the correct properties of chirality and duality as well as the special relativity corrections of mass, length, time and magnetic moment with velocity.

This model gives an explanation to a question raised by Barut when discussing the Classical Relativistic

Spinning Electron.[7] "If a spinning particle is not quite a point particle, not a solid three dimensional top, what can it be? What is a structure that can appear under probing with electromagnetic fields as a point particle, yet as far as spin and wave properties are concerned exhibits a size of the order of the Compton wavelength?" This model answers that question very effectively. The electron is a spinning photon! Being totally electromagnetic in nature, it has an electromagnetic wave length as postulated by de Broglie. It should be pointed out that this is not the first "entirely electromagnetic model of the electron" to be proposed. As discussed by Barut, earlier models were proposed.[7] Lorentz and Abraham tried to model the electron as an extended charge distribution with its mass purely electromagnetic. Later workers determined that the electron could not be totally electromagnetic in nature. However as the derivation of the de Broglie wavelength in section 8 suggests, unless the electron is totally electromagnetic in origin, its wavelength will not be that as postulated by de Broglie and verified experimentally.

The electron is literally a photon generating entity. Its existence and properties depend upon the emission and absorption of photons required to enable the rotating primary photon that is the electron to travel in a closed loop trajectory. It is that property, the generation of electric charge by movement, that gives the electron its magnetic moment. From this model, the electron's magnetic moment is the Bohr magnetron, which makes up almost 99.89% of the electron's intrinsic magnetic moment. By accurately calculating all possible photon paths from the electron to their final destination, QED theory can exactly calculate the remaining ≈ 0.11% of the electron's magnetic moment.

Some of the inexplicable and apparently contradictory properties of the electron are understandable from this rotating photon model. As can be seen from their derivations, properties such as $E = mc^2$, the relativistic corrections of mass, length and time with velocity, the Bohr magnetron, the de Broglie wavelength, the dimensions of the electron and how its radius changes with velocity, are automatic consequences of the model. As well as matching the electron's properties, this model also predicts properties that have not been recognized before, namely the electron is totally electromagnetic in nature, it is a hoop of rest radius $\hbar/2m_0c$ that diminishes with increasing velocity, while its length increases with velocity and the charge on the electron originates at its circumference and is planar in nature, at least close to it. These are not predictions of other models. It is hoped they will be checked experimentally to verify the validity of the model.

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Disclosures

This manuscript has been read and approved by the author. This paper is unique and not under consideration by any other publication and has not been published elsewhere. The author reports no conflicts of interest. The author confirms that there is no copyrighted material in this presentation.

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Appendix 1

Fundamental differences between the Einstein-de Broglie and Copenhagen Convention interpretations of the photon—a brief presentation.

If there was one property that separates the Einstein-de Broglie model of the photon from the Copenhagen Convention interpretation, it is the assignment of mass to a photon. Both models are very complex and this is neither the time nor place for a full treatment of their differences. When it comes to mass, there is a clear difference, which can be summed up by any person who asks the question "What is the mass of an electron?" Asked that question, most physicists would respond with something like 9.109382. $\times 10^{-31}$ kg. Or perhaps they would say 0.5109989. MeV/c^2. But that is the rest mass of the electron. The mass of a moving electron is a combination of its rest mass and its energy.

Photons behave sometimes like a particle and sometimes like a wave.[39] In the Copenhagen Convention interpretation, a photon is considered to behave like a particle similar to an electron. And just as in the case of an electron, which is known to have a rest mass, a photon is likewise considered to have a property known as rest mass. But according to equation 9 (and the earlier derived Lorenz/Lorentz and special relativity corrections) a particle having a finite mass at rest will have an infinite mass when traveling at the speed of light c. The Copenhagen Convention interpretation of the photon states that it has zero mass because it has zero rest mass. On the other hand, photons under the Einstein-de Broglie model only exist as long as they are traveling at the speed of light and therefore have mass at that velocity. In support of this, one can only quote Einstein again,[30] when he concluded: "*If the theory corresponds to the facts, radiation conveys inertia between the emitting and absorbing bodies*". Inertia implies mass. Photons may indeed have no rest mass, but they have relativistic mass when traveling at c, which mass is given by $m = hf/c^2$.

That summarizes the different approaches to modeling a photon. It is the 1926 Copenhagen Convention interpretation of the photon that receives the widest acceptance. But it is also that model that makes it difficult for physicists to perceive of the possibility of photons having mass and has led to many physicists believing that photons do not have any mass.