Is Matter Made of Light?

By Richard Gauthier, Ph.D.

"You know, it would be sufficient to really understand the electron." *
--Albert Einstein

$E = mc^2$. Einstein's equation relating energy, matter and the speed of light is probably the most famous scientific equation of all time. A book of this title by David Bodanis has been explaining the meaning, historical background and present implications of this equation to a large reading audience. A television program on this topic by the Public Broadcasting System brought this understanding to an even wider public audience.

This simple equation implies that an enormous quantity of energy is contained in a relatively small amount of matter, if that matter could be totally or even partly converted into energy. $E = mc^2$ means that a quantity of matter of mass *m* is to be multiplied by the square of the speed of light *c* in order to determine the total energy *E* contained in that quantity of matter. In atomic and hydrogen bombs, less than about 1% of the energy available in the mass of the active ingredients is actually converted into energy. The percentage is significantly higher in hydrogen bombs (which are based on fusion or joining of atomic nuclei of hydrogen) as compared to atomic bombs (which are based on the fission or splitting of atomic nuclei of uranium). Hydrogen bombs are therefore more powerful than atomic bombs of similar ingredient masses.

If 100% of the matter in a bomb could be converted into energy according to $E = mc^2$, such a bomb would be about 100 times as powerful as a hydrogen bomb of the same weight. Fortunately, these 100% mass conversion reactions can only take place when a quantity of matter, for example an electron, is combined with an equal amount of its corresponding antimatter, a positron. The electron and the positron mutually annihilate, releasing two or more highly energetic photons (particles of radiant energy) that travel off at the speed of light. According to $E = mc^2$, a millionth of a gram of positrons, when combining with the same mass of electrons, would release the energy equivalent of 83 pounds of highly explosive TNT. Antimatter is notoriously difficult to store since it is so reactive with ordinary matter. 100% matter-to-energy bombs do not appear to be feasible at present or in the foreseeable future. However, a Google search on "antimatter weapons" shows that the U.S. Air Force has invested millions of dollars to try to develop such weapons.

However, this article is not about applications of $E = mc^2$, of which there are many. It is about trying to understand why the speed of light *c* comes into the equation $E = mc^2$ when matter releases its stored energy. What is it about matter such as a rock, which may not seem to be moving at all or else is moving very slowly relative to the speed of light *c*, that requires the value of the speed of light *c* be used to calculate how much energy is contained in this rock?

Surprisingly, when Einstein derived the equation $E = mc^2$ in 1905, he didn't explain why matter itself is related to the speed of light. What he did was to show that when a certain amount of matter is converted to radiant energy such as light, the quantity of energy produced follows $E = mc^2$. But why matter itself, when it is still matter and not yet converted into radiant energy, should be related to the speed of light *c,* has never been satisfactorily explained. The explanation would likely require knowing the internal structure and inner motion, if any, of electrons as well as the nuclear particles like protons and neutrons (along with their constituent quarks and gluons) that compose the atoms and molecules of matter.

Leave aside the much heavier and more complicated nuclear particles. The inner structure and inner motion, if any, of even the electron, one of the least massive and most basic sub-atomic particles, has remained a deep mystery since its discovery by J.J. Thompson in 1897. Recent high energy experiments attempting to determine the size of an electron have shown that its size, if any, appears to be less than about a billionth of a billionth of a meter (10^{-18} meters). There are several other known facts about electrons. Each electron has a small but definite 'rest' mass *m*, which is about 1/1800 times that of a proton. The electron contains a small negative electric charge -*e* which produces electrical forces and effects in matter. The electron also has a constant measurable quantity of angular momentum. Angular momentum is normally associated with the rotation of an object. But the angular momentum or spin value of an electron is considered to be an intrinsic property of the electron, not associated with any actual physical rotation of the electron. The electron also acts like a tiny magnet with a fixed value of magnetism called its magnetic moment. Magnetism can be produced by the movement of electric charge through space, but the magnetic moment of an electron is also considered to be intrinsic to the electron. It is actually the organized arrangement of the magnetic moments of many electrons in magnetic materials that gives rise to their magnetic properties.

No accepted scientific theory has been able to explain the origin and values of all the properties of the electron in terms of its structure or internal motion, if any, though the electron's mass, charge, spin and magnetic moment have all been measured very precisely. There is also extremely good agreement between the measured value and theoretically predicted value of the electron's magnetic moment, based on the theory of quantum electrodynamics (QED).

In addition to these physical properties of the electron, it also has vibrational and wave-like properties. The first scientist to propose that the electron has an associated vibratory frequency and wavelength was Louis de Broglie. He proposed in 1924 that the electron's frequency *f* was proportional to its energy *E*. This is the same energy E of Einstein's equation $E = mc^2$. The energy of a photon, the quantum particle of radiant energy, had been previously been shown by Einstein to be $E = hf$ where *f* is its frequency and *h* is called Planck's constant, a very small number. De Broglie set the two energies for a photon and an electron equal, giving $hf = mc^2$ or equivalently $f = mc^2 / h$.

This frequency is around 10^{21}/sec or a billion trillion cycles per second for an electron. Based on this proposed proportional relationship of electron frequency to electron mass, de Broglie proposed that a moving electron has an associated wave motion, with a wavelength that is inversely proportional to the linear momentum (mass times velocity) of the electron. So slower electrons were predicted to have longer wavelengths and vice versa. This variable wavelength of the electron predicted by de Broglie was later precisely confirmed by experiments where electrons were found to scatter off of metal crystals very similarly to x-rays having similar wavelengths as electrons.

Interestingly, although de Broglie associated the frequency f of an electron at rest to an internal vibration within the electron using the same quantum equation $E = hf$ as for a photon, he never seems to have proposed that an electron is actually composed of a photon or a photon-like object. For de Broglie, a moving point-like electron having an internal frequency when at rest of $f = mc^2 / h$, is guided by a pilot wave having a corresponding frequency. The pilot wave's wavelength is given by his wavelength formula $\lambda = h / p$, where λ (Greek letter lambda or L) is the pilot wave's wavelength, h is Planck's constant and p is the electron's momentum ($p=mv$ for low velocity electrons of mass m moving at velocity v).

De Broglie's pilot wave concept never caught on due to some mathematical problems with his theory and its inability to explain certain physical reactions such as the deflection of one charged particle by another. However, the de Broglie wavelength of moving particles was successfully incorporated by Erwin Schrödinger into the Schrödinger equation in quantum mechanics, which makes many accurate predictions about atomic and molecular phenomena. But de Broglie's pilot wave approach was rediscovered and elaborated in 1952 by David Bohm. He resolved the earlier physical and mathematical difficulties of the pilot wave approach with a new approach where electrons are guided by a "quantum potential" to follow path trajectories showing the known wave-like properties of electrons.

The standard interpretation quantum mechanics, known as the Copenhagen interpretation, accurately predicts the probabilities of detecting and measuring electrons in atomic physics experiments. The Copenhagen interpretation cannot make precise predictions about the trajectory of an individual electron, and rejects the de Broglie/Bohm approach to describing the trajectory of an individual electron. Bohm's trajectory-oriented approach to quantum mechanics however has been proved to give the same statistical predictions for experiments as the widely-accepted Copenhagen approach to quantum mechanics. The Copenhagen approach, developed mainly by Niels Bohr, Werner Heisenberg, and Max Born, and including the quantum mechanical Schrödinger wave equation, rejects the idea that there can be completely precise images for particles and particle trajectories to describe atomic and sub-atomic reactions.

One reason for this rejection of 3D electron models to describe the electron was early calculations with spherical models of the electron that indicated that the surface of a rotating spherical electron would have to travel faster than the speed of light if the electron is to have the known experimental values for the electron's spin and magnetic moment. This result seemed to violate Einstein's theory of relativity which indicates that electrons must travel at less than the speed of light. Instead, the simple spinning 3D spherical model of the electron was rejected, and the electron's spin and magnetic moment were described as 'intrinsic' properties of the electron, not associated with any 3D spatial structure or internal movement.

Despite this generally effective 'ban' on particle images and precise particle trajectories in conventional quantum mechanics, some efforts continued towards finding an acceptable 3D spatial structure for the electron and explaining some of its enigmatic features.

The Dirac equation, proposed by English physicist Paul Dirac in 1928, is an equation for the electron that is consistent with Einstein's theory of special relativity theory (which doesn't include gravity). It also works for electrons traveling close to but less than the speed of light. It is more accurate than the non-relativistic Schrödinger equation for the electron, which is accurate for electron velocities only much less than the speed of light. Dirac thought of the electron as a point-like charged particle.

A first result found from the Dirac equation's solutions for a freely moving electron is that the speed of light c can be interpreted as the speed of an electron. This was quite a surprise because it was and still is experimentally observed that electrons always travel at less than c. Some physicists have proposed that this speed c found from the Dirac equation is an internal circulatory speed of an electron which has not been detected, while externally and measurably, the electron can move from one place to another at speeds less than c.

A second result from the Dirac equation is that there is an oscillatory frequency associated with an electron that is twice the frequency for the electron that was proposed earlier by de Broglie. This double-sized frequency $f = 2mc^2 / h$ from the Dirac equation was named the electron's *Zitterbewegung* ("trembling motion" in German) frequency. It is around 10^{21} (a billion trillion) vibrations per second. This *Zitterbewegung* frequency has so far not been measured in the electron. But it is taken seriously because it comes from the successful Dirac equation (and because Dirac considered it important) and because it also comes into the theory of quantum electrodynamics, developed after the Dirac equation. This theory describes how the electron interacts with photons, and gives very precise results.

A third result from the Dirac equation for a free electron is that the electron has a certain amplitude or size associated with its *Zitterbewegung* vibratory motion, given by the size $R = \frac{1}{4\pi}\frac{h}{mc}$ or about 1.9×10^{-13} meters. This is around 200,000 times larger than the experimentally measured maximum size of the electron found in high energy electron-electron collision experiments mentioned earlier. The huge difference between this theoretical Dirac value and the experimentally measured value has not yet been resolved.

A fourth result of the Dirac equation was its prediction of negative energy solutions for the electron. A later development from Dirac's results, called second quantization, predicted the existence of antimatter. For example, the antimatter particle for the electron is the positron, as mentioned earlier. Dirac at first thought this predicted antiparticle was the much more massive proton, since a positive electron was not known at that time. The positron was experimentally detected in a cosmic ray detection experiment in 1932 and was found to have the same mass but the opposite charge as the electron. A particle and its antiparticle can mutually annihilate, leaving pure radiant energy in the form of at least two photons. Second quantization predicted the positron but did not assign a particular structure to either an electron or a positron. Today electrons and positrons are still generally not considered to have any internal structure.

A fifth result of the Dirac equation is that it predicts a spin value for the electron of $\frac{1}{2}\hbar$ (pronounced h-bar), (where $\hbar = h/2\pi$ and h is Planck's constant), which is the experimentally measured spin of the electron. Although the electron's spin value was already known experimentally, it is a main result of the Dirac equation also.

A sixth result of the Dirac equation is that the value of the electron's magnetic moment M, is found to be $M = e\hbar/2m$, which is close to the presently accepted experimental and theoretical value for the electron's magnetic moment.

A seventh result of the Dirac equation is that it gives the de Broglie wavelength for a moving electron. According to de Broglie's prediction, the wavelength λ (lambda, the Greek letter for L) of a moving electron is experimentally found to be inversely proportional to the momentum p of the electron, that is, $\lambda = h/p$. When the velocity of the electron is small compared to the speed of light, the momentum p is given by $p = mv$ where m is the electron's rest mass and v is its velocity, so in this case $\lambda = h/mv$. For speeds approaching the speed of light, the correct momentum p is obtained by multiplying the value mv by a correction factor γ (gamma) which starts at one when the electron's velocity is zero, and increases rapidly as the electron's velocity approaches the speed of light c. The momentum formula for the electron then becomes $p = \gamma mv$. So the precise relation for the electron's wavelength λ to its velocity becomes $\lambda = h/\gamma mv$. The exact formula for γ is $\gamma = \frac{1}{\sqrt{1-v^2/c^2}}$. It can be seen in this formula that when the electron's velocity $v = 0$, then $\gamma = 1$, and as v becomes near to but less than c, γ becomes very large.

An eighth result, or rather an important property of the Dirac equation is that it was designed by Dirac to be consistent with Einstein's theory of special relativity. The Schrödinger equation for the electron is not consistent in this way, though it is still very useful for electrons having velocities that are small compared with the velocity of light, such as the speed of most electrons in an atom. This property that the Dirac equation has is known as relativistic covariance. Basically this means that the Dirac equation will apply equally well in any measurement frame (the coordinate system used to measure the position of the electrons) that is moving at a constant velocity (less that the speed of light c) with respect to the electrons. It also means that the total energy E of a moving electron is larger in a specific way than the electron's energy $E = mc^2$ at rest, where m is the electron's rest mass. The total energy E of a moving electron is given by $E = \gamma mc^2$, where γ is defined previously. An equation (called the Einstein/de Broglie equation) containing this same information but explicitly containing the electron's momentum p is $E^2 = p^2c^2 + m^2c^4$. When $p = 0$ (for an electron having no measured velocity and no linear momentum), this formula reduces to $E^2 = m^2c^4$ which simplifies to $E = mc^2$, the relationship for an electron at rest. When p is greater than zero (for a moving electron), the Einstein/de Broglie formula shows that E for a moving electron is also greater than mc^2, where m is the rest mass.

Is an electron composed of a photon-like object?

It has been known for many years that an electron and a positron annihilate each other to create photons. But it was only demonstrated in 1997 that photons can also combine together to create an electron and a positron. This was demonstrated by a scientific team using the 2-mile-long Stanford Linear Accelerator in California.

Electrons and photons are two of the simplest physical particles, with photons probably being the simpler of the two. Since electron-positron pairs are interconvertable with photons, this strongly suggests that an electron or a positron may be composed of or contain a photon or a photon-like object. However, electrons and photons differ in many respects. An electron is electrically charged, while a photon is electrically neutral. An electron moves at less than the speed of light c and can be relatively stationary, while a photon normally moves at c. An electron has a spin or angular momentum equal to $\frac{1}{2}\hbar$, where $\hbar = h/2\pi$ is the basic unit of angular momentum, while the photon has a spin of $1\hbar$. An electron has a rest mass m and contains a specific rest energy $E = mc^2$, while a photon has a rest mass of zero and can have any energy $E = hf$ where f is its frequency. Furthermore, when any particle such a proton mutually annihilates with its antiparticle such as an antiproton, photons are also produced. Yet protons are known to be composed of other particles called quarks and gluons (gluons also travel at the speed of light) and not photons. Electrons are called fermions, and obey one type of statistical properties called Fermi-Dirac statistics, while photons are called bosons and obey a different type of statistical properties called Bose-Einstein statistics. Despite all these differences, could an electron be composed of a photon or something like it?

Here's an interesting quote from Isaac Newton, who did fundamental studies of light as well as gravity in the 1600's and 1700's and speculated on light as follows:

"Are not gross Bodies and Light convertible into one another, and may not Bodies receive much of their Activity from the particles of Light which enter their Composition? The changing of Bodies into Light, and Light into Bodies, is very conformable to the Course of Nature, which seems delighted with Transmutations. [...] And among such

various and strange transmutations, why may not Nature change Bodies into Light, and Light into Bodies?" – Isaac Newton , Opticks, 1704, Book Three, Part 1 Query 30 (quoted from http://www.tardyon.de)

A number of authors have proposed that matter is composed of light-speed particles or waves. This website proposes that there are two types of physical particles—tardyons which travel at less than the speed of light and luxons which travel at the speed of light, and that all tardyons are composed of luxons.

According to http://www.tardyon.de , the first person to propose that matter is composed of light-speed entities was H. Ziegler. In 1909 he wrote, "If one thinks about the basic particles of matter as invisible little spheres which possess an invariable speed of light, then all interactions of matter-like states and electrodynamics phenomena can be described and thus we would have erected the bridge between the material and immaterial world that Mr. Planck wanted." (Max Planck was one of the founders of quantum theory. The quantum constant h is named after him: Planck's constant.)

This web site lists other web sites containing proposals for models of particles with mass, like electrons, composed of speed-of-light entities. However, none of the proposed models seen here or elsewhere appears to have all eight characteristics of the Dirac results listed previously:

1) The electron a point-like particle with speed equal to speed of light c
2) The *Zitterbewegung* frequency $f_z = 2mc^2/h$
3) The *Zitterbewegung* amplitude $R = \frac{1}{2}\frac{\hbar}{mc}$
4) The positron prediction
5) The electron spin $s = \frac{1}{2}\hbar$
6) The electron magnetic moment $M = e\hbar/2m$
7) The de Broglie wavelength $\lambda = h/\gamma mv$ for an electron having rest mass m that is moving with velocity v.
8) The total energy $E = \gamma mc^2$ of a moving electron, where m is the rest mass.

Perhaps the greatest stumbling block for producing a 3D model of the electron is the combined properties of the electron having spin $s = \frac{1}{2}\hbar$ and magnetic moment $M = e\hbar/2m$. This is because the measured value of M for an electron is about twice as large as it would be if its spin and magnetic moment are calculated in the normal or classical way (i.e. without using quantum mechanics which is considered to be unvisualizable in the Copenhagen interpretation of quantum mechanics). A successful model of the electron needs to deal with this problematic factor of 2.

A superluminal model of the electron and the photon

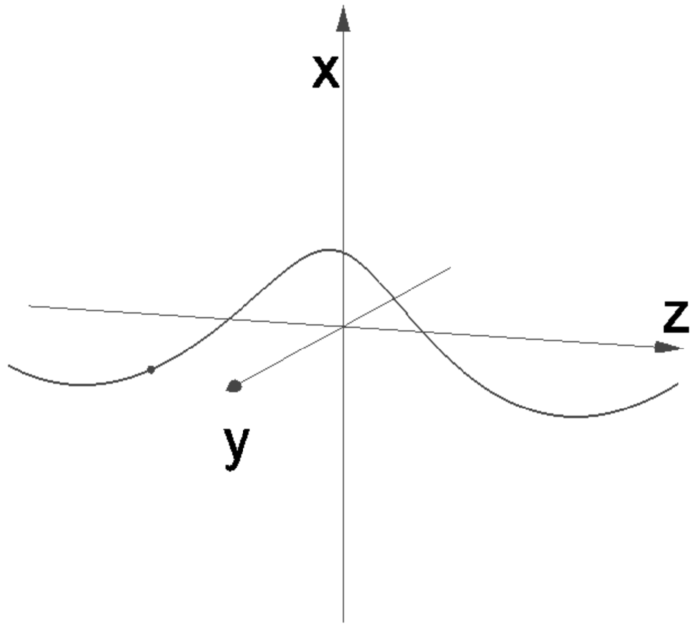
So far, there is no generally accepted 3-D model of the electron that contains the 8 features listed earlier that are characteristic of solutions to the Dirac electron for a single electron. As previously mentioned, an early model of an electron as a spinning charged sphere was rejected because for it to have the right physical properties of spin value and magnetic moment, its surface would have to move faster than light. This was not considered allowable in an electron model at that time because according to Einstein's theory of special relativity, no signal can travel faster than light.

But perhaps the idea of internal faster-than-light motion for an electron model was rejected prematurely. As long as an electron as a whole travels at less than the speed of light *c*, why can't the electron have an internal speed that is equal to or even faster than *c*? It is the external speed of an electron that can carry a signal from place to place, not its internal movement.

If we admit to the possibility that an electron, and even a photon, can have an internal speed which is faster than light, new possibilities open up for describing the structure of an electron or a photon. It is this new possibility that is introduced in the present superluminal models of the electron and the photon. How would these models work?

It's known that a photon has a certain amount of spin or angular momentum, the measure of an object's momentum of rotation. We can conceive of a photon as composed of a quantum or bundle of energy that is moving rapidly along a helical path. This helical motion would produce the photon's angular momentum. Since a photon travels forward at the speed of light, the quantum of energy composing a photon would have to move along its helical path at a speed greater than the speed of light in order to produce the photon's forward speed *c*. So it's easy to conceive of a photon as having an internal speed greater than the speed of light, that is, having an internal superluminal speed.

A photon's linear or forward momentum is known to vary inversely with its wavelength—the longer its wavelength, the smaller its forward momentum. This is a precise experimentally verified relationship. When this mathematical momentum relationship for a photon is combined with the mathematical relationship for the photon's angular momentum based on the proposed model of a photon as a helical movement of energy and momentum, it turns out that the angle that the helical path makes with the forward direction of the photon is 45 degrees. It is also found in this model of the photon that the energy and the total momentum of the photon move helically at 1.414 (or more precisely $\sqrt{2}$) times the speed of light *c*. And the distance around a photon's helix (the circumference of the helix) is found to equal the wavelength of the photon (where one turn of the photon's helix corresponds to one wavelength). So in the superluminal model of the photon, the superluminal speed of the quantum of energy composing a photon is very exact, and doesn't depend on the wavelength or the energy of the photon. The figure below is the superluminal model of the photon, with a superluminal quantum particle following this helical path:



The superluminal quantum model of a photon. An uncharged superluminal point-like quantum particle travels at $1.414c$ along an open 45-degree helical trajectory with radius $R = \lambda / 2\pi$.

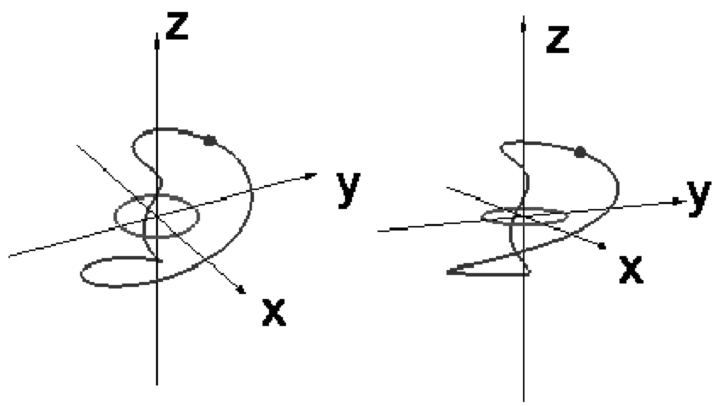
Now think of the superluminal electron model as a kind of a charged, curled-up superluminal photon model. The electron model will have an internally moving superluminal quantum of energy like with the photon, but the electron's superluminal quantum of energy will carry the charge of the electron. The electron model's point-like quantum of energy and charge also circulates along a helical path (just like for a photon). However, the superluminal electron model's helical path is closed rather than open as with the superluminal photon model. The path of the photon's quantum of energy will close on itself after it travels only one full turn of its helical path (that is, one wavelength). But the spin of an electron is known to be exactly one-half of the spin of a photon. So in order to get this correct spin in the superluminal electron model, the axis of the circulating superluminal charged energy quantum has to make a double circular loop before the path of the superluminal charged energy quantum closes on itself. The charged superluminal quantum then continues to circulate along its closed double-looped helical path. This double loop of the closed helical path of the superluminal electron's quantum of energy and electric charge ensures that the calculated spin of the superluminal model of the electron will give the correct spin value, which is half that of a normal photon.

The superluminal model of the electron may be hard to visualize from this verbal description. But the path of the superluminal quantum of energy and electric charge is a precise trajectory in space and time and has a precise mathematical formula based on this description. The position of the charged superluminal quantum as it changes with time is expressed with three spatial coordinates -- *x*, *y* and *z*-- and the time *t*:

$$x(t) = R_0(1+\sqrt{2}\cos(\omega_0 t))\cos(2\omega_0 t)$$
$$y(t) = R_0(1+\sqrt{2}\cos(\omega_0 t))\sin(2\omega_0 t)$$
$$z(t) = R_0\sqrt{2}\sin(\omega_0 t)$$

where ω_0 (omega-zero, an angular frequency) is 2π times the electron's de Broglie frequency $f = mc^2/h$, and $R_0 = \frac{1}{2}\frac{\hbar}{mc}$ is the radius of the circular axis of the electron's closed double-looped helix. $R_0\sqrt{2}$ is the radius of the superluminal charged energy quantum's helical path, in comparison to the radius R_0 of the closed double-looped helical axis of the superluminal electron model. The helical radius $R_0\sqrt{2}$ is set to this value in order to give the superluminal electron model the Dirac value of the electron's magnetic moment $M = e\hbar/2m$. The quantum particle moving in this trajectory sometimes moves faster than light. Its maximum speed, which can be derived from these three equations, is 2.515 *c* when it is at its maximum distance from the *z*-axis. Its speed halfway along its closed helical trajectory, when it is nearer the z axis is however only .819*c*.

Using these three equations, the superluminal model of the electron looks like this, from two different angles:



Two views of the 3D superluminal quantum model of the electron. A point-like charged quantum particle travels with a maximum speed 2.515 *c* in a closed double-looped helical trajectory. The circle is the axis of this helical trajectory.

This superluminal model of the electron satisfies all eight mathematical features of the Dirac electron that were previously mentioned:

1) The electron model's energy quantum circulates along its circular axis at a forward speed of the speed of light *c* (although its actual helical speed is sometimes greater than the speed of light.
2) The double-looping helical motion gives the *Zitterbewegung* double frequency $f_z = 2mc^2 / h$.
3) The radius of the circular axis of the closed helix is the *Zitterbewegung* amplitude $R = \frac{1}{2}\frac{\hbar}{mc}$.
4) The two possible directions of internal helical rotation correspond to the electron and the electron's antiparticle, the positron.
5) The electron model's radius and rotational frequency give it the known spin of the electron of $\frac{1}{2}\hbar$.
6) The radius of the helix, along with the charge of the electron and its frequency of rotation, give the electron model the Dirac equation magnetic moment of the electron $M = e\hbar / 2m$.
7) The normal internal de Broglie frequency of the electron $f_{dB} = mc^2 / h$ along with a Doppler shift and mutual interference of the wavelengths on the opposite sides of a moving electron model results in the electron's de Broglie wavelength $\lambda = h / \gamma mv$. (A Doppler shift in frequency or wavelength is produced when a moving object, having its own frequency value, gets its observed frequency shifted to a higher or lower pitch or frequency due to the movement of the source towards or away from an observer.)
8) A Doppler shift of the internal frequencies of a moving electron model cause the electron to gain energy in accordance with Einstein's energy equation for a moving electron $E = \gamma mc^2$.

The superluminal model of the electron indicates there does exist a 3D model of the electron which has many of the physical (both particle-like and wave-like) properties of the electron. These include the Dirac electron's values of spin *s* and magnetic moment *M*, which have usually not been considered to be both representable in a viable 3D model of the electron. The result was achieved using a superluminal quantum of energy and electric charge, but as the superluminal motion is internal to the electron and does not transmit a signal faster than light, the superluminal electron model is not in violation of Einstein's theory of special relativity, which says that an electron itself must travel at less than the velocity of light *c*.

The superluminal electron model, quantum wave-particle duality and Heisenberg's Uncertainty Principle

Whenever the electron is detected in an experiment, it always a point-like particle. But when the electron is traveling from one place to another without being detected, it acts like a wave. This has led to what has been called wave-particle duality of the electron—is the electron a particle or a wave or both?

The proposed superluminal model of the electron has wave properties, as indicated by its two internal frequencies (the de Broglie frequency and the *Zitterbewegung* frequency), its internal Compton wavelength and its external de Broglie wavelength. The model also has particle properties, indicated by it moving as a charged point-like particle carrying energy and momentum along its closed double-looped helical trajectory. When the superluminal electron model is detected, it is its internal point-like charged quantum particle that is detected, but when it is traveling, it moves with its quantum wave properties. The superluminal model of the electron may therefore help to clarify the nature of wave-particle duality.

Another remarkable aspect of the superluminal electron model is that it may help explain the famous Heisenberg Uncertainty Principle. This principle says that there is sometimes a fundamental limitation on the accuracy of simultaneously measuring two related physical properties of an elementary particle or other physical object, such as its position and its momentum. Greater accuracy in measuring one of the two properties entails a corresponding lesser accuracy in measuring the other property. The Heisenberg Uncertainty relationship for the x coordinate of a particle is stated precisely as $\Delta x \, \Delta p_x \ \geq h/4\pi$, where Δx is the standard error (the square root of the statistical variance) in measuring the position of the particle along the x direction , Δp_x is the standard error in measuring the particle's momentum along the same x dimension, "$\geq$" means "greater than or equal to", and *h* is Planck's constant, an extremely small quantity. How does the Heisenberg Uncertainty relation apply to detecting a photon in the superluminal photon model?

In the superluminal model of the photon, it would be the superluminal quantum that is actually detected when a photon is detected in an experiment. Consider detecting the vertical or x position of the superluminal quantum in a photon that is moving horizontally in the z direction. From the results for the superluminal quantum model of the photon obtained earlier, the radius of the superluminal quantum's helical trajectory is $R = \dfrac{\lambda}{2\pi}$ where λ is the photon's wavelength (corresponding to the axial length for one turn of the superluminal quantum's helical trajectory). So for a photon moving in the z direction, the superluminal quantum's position in the x direction has a value $x = R\sin(\omega t) = \dfrac{\lambda}{2\pi}\sin(\omega t)$ where $\omega = 2\pi f$ is the angular frequency of the photon. Also from our earlier results, the superluminal quantum for the photon also has a transverse component of momentum in the x direction of $p_x = h/\lambda$ which is 90 degrees out of phase with its x position value, so that $p_x = \dfrac{h}{\lambda}\cos(\omega t)$. In this example the standard error Δx is the square root of the average value of x^2 over one cycle while the standard error Δp_x is the square root of the average value of $p_x{}^2$ over one cycle. So $x^2 = (\dfrac{\lambda}{2\pi})^2 \sin^2(\omega t)$ while $p_x{}^2 = (\dfrac{h}{\lambda})^2 \cos^2(\omega t)$. The average value of $\sin^2(\omega t)$ and $\cos^2(\omega t)$ over a cycle is ½ for each. So the average value of x^2 is $\frac{1}{2}(\frac{\lambda}{2\pi})^2$ and the average value of $p_x{}^2$ is $\frac{1}{2}(\frac{h}{\lambda})^2$.

Therefore $\Delta x = \sqrt{\frac{1}{2}(\frac{\lambda}{2\pi})^2} = \frac{1}{\sqrt{2}}\frac{\lambda}{2\pi}$ while $\Delta p_x = \sqrt{\frac{1}{2}(\frac{h}{\lambda})^2} = \frac{1}{\sqrt{2}}\frac{h}{\lambda}$. Multiplying Δx by Δp_x we get $\Delta x \Delta p_x = (\frac{1}{\sqrt{2}}\frac{\lambda}{2\pi})(\frac{1}{\sqrt{2}}\frac{h}{\lambda}) = \frac{h}{4\pi}$. Comparing this result with the Heisenberg Uncertainty relation $\Delta x \Delta p_x \geq \frac{h}{4\pi}$ we see that the uncertainty product of position and momentum for the superluminal quantum in the photon model is exactly at the minimum value allowed by the Heisenberg Uncertainly Principle. This result is either a remarkable coincidence or could indicate that, in the case of the photon, the Uncertainty Principle for a photon could be related to the position and momentum relationship in the superluminal model of the photon.

The equations for the superluminal model for the electron are:

$$x(t) = R_0(1+\sqrt{2}\cos(\omega_0 t))\cos(2\omega_0 t)$$
$$y(t) = R_0(1+\sqrt{2}\cos(\omega_0 t))\sin(2\omega_0 t)$$
$$z(t) = R_0\sqrt{2}\sin(\omega_0 t)$$

With the superluminal model of the electron, it is the electron's superluminal point-like quantum particle that would be detected in an experiment. That would be why the electron always is point-like when it is detected. Since that point-like quantum particle is moving around in its double-looped helical trajectory at an extremely high frequency, around 10^{21} /sec (a billion trillion times per second – too high to measure directly), there will be an uncertainty in where the quantum particle is detected along this internal trajectory. This uncertainty Δx in its position in the *x*-dimension is the standard error of its superluminal trajectory in the *x*-dimension, which, using the equation above for *x(t)* is found to be $\Delta x = R_0 = \frac{1}{4\pi}\frac{h}{mc}$. Since the x component of internal momentum of the superluminal electron p_x varies as $p_x = mc\sin(2\omega_0 t)$ where $\omega_0 = mc^2/\hbar$, the standard error Δp_x of p_x is $\Delta p_x = \frac{1}{\sqrt{2}}mc$. Multiplying these values of Δx and Δp_x for the superluminal electron model gives $\Delta x\ \Delta p_x = (\frac{1}{4\pi}\frac{h}{mc}) \times \frac{1}{\sqrt{2}}mc = \frac{1}{\sqrt{2}} \times \frac{h}{4\pi} = .707\frac{h}{4\pi}$.

Compare this result with the Heisenberg Uncertainty relation: $\Delta x\ \Delta p_x \geq \frac{h}{4\pi}$. Since the Uncertainty product for the superluminal electron model is .707 times the minimum Uncertainty product allowed by the Heisenberg Uncertainty relation, this indicates that the position/momentum relations of the superluminal quantum model of the electron may not be experimentally detectable if the Heisenberg Uncertainty relation is correct. Another way to view this result is that the Heisenberg Uncertainty relation for an electron may actually be partly due to the current experimental inability to simultaneously measure both the position and momentum of the electron's quantum along its closed helical trajectory due to its extremely high circulating frequency $f = 2mc^2 / h = 2.5 \times 10^{20}$ cycles per second.

In conclusion, the structure of the electron, if any, has eluded physicists for more than a hundred years. The proposed 3D superluminal model of the electron includes a number of the electron's experimental and theoretical features, while relating the electron to a proposed superluminal model of the photon. These models offer the possibility of better understanding quantum wave-particle duality. They also may help explain the Heisenberg Uncertainty Principle. Experimental tests of these models could be developed to test whether they have predictive value and may therefore be helpful in more deeply understanding the still-mysterious electron.

"A thing should be as simple as possible, but no simpler." ** -- Albert Einstein

"If I can't picture it, I can't understand it." -- Albert Einstein

*Einstein quote recollected and explained by Valentine Bargmann. In H. Woolf (ed.) "Some strangeness in proportion, a Centennial symposium to celebrate the achievements of Albert Einstein", p. 418 Addison-Wesley, Reading, MA (1980)

** Einstein quote from J. Wheeler (1991) Scientific American 257(6), 36.

More articles on this subject can be found at the author's web site http://www.superluminalquantum.org including the more detailed articles "Superluminal Quantum Models of the Electron and the Photon" and "FTL Quantum Models of the Photon and the Electron".

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