V 1 07/04/09

# A Discrete Model of the Dirac Electron

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**Abstract** The relativistic equation for the electron, when first developed by Dirac, had several problematic physical consequences. Among them were the physical reality of the allowed negative energy states of the electron. Dirac assumed that the problem was due to a mathematical shortcoming rather than the adequacy of the usual picture of physical reality and so he extended the mathematics in order to bring it into better agreement with reality. We return to the problem of the reality of mathematical models and entertain the proposition that Dirac's original mathematics is a satisfactory representation of Nature and turn our attention to the kind of physical reality of which the mathematics could be indicative. By subjecting the analysis to a broader than usual special relativistic constraint we are led to a picture of the electron whose chief feature is a continual actualisation of potential, of the Aristotelian type. The model is novel and contrary to the doctrine of continuity; it is parsimonious and conforms with the well-known counterintuitive quantum behaviour of elementary particles.

**Key words** Discrete Dirac electron   Physical model   Quantum theory   Special relativity • Mathematics and reality

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## 1 Introduction

Efforts to understand the electron within the framework of quantum theory have proceeded in the absence of underlying principles which lead naturally to the kinematics of quantum systems. Such principles might assist in making the distinction between classical and quantum concepts and their relevance to elementary particle behaviour. Einstein's opinion of the absence of a foundation for quantum mechanics and the limitation of classical theory as the source of those principles is well known:

> 'It is to be expected that behind quantum mechanics there lies a lawfulness and a description that refer to the individual system. That it is not attainable within the bounds or concepts taken from classical mechanics is clear.' [1].

Several fundamental questions about quantum mechanics, that have remained unresolved since the nineteen-thirties, go beyond an explanation for the strange and counterintuitive behaviour of quantum systems. For example, it is by no means settled whether quantum mechanics is a complete theory or not, or quite what it is a theory of [2], and it may be the case that the quantum analogues of the mathematical categories of classical physics are yet to be found [3]. And a description of individual quantum events is outside the scope of the quantum formalism [4].

The physical interpretation of the meaning of mathematical models and their relation to phenomena is not always simple or clear cut. The problem of the unreal consequences of the Dirac equation for the electron is an example of the difficulties that can arise when trying to gain a physical understanding of the mathematics. The equation is regarded, rightly, as a high point of achievement in the development of quantum theory, but three of its physical consequences were seemingly unreal: (i) energy values of less than zero, (ii) the motion of the electron at the speed of light and (iii) an equal role for time with space in its description have been generally regarded as inconsistent with physical reality.

Negative energy solutions have remained especially problematic and the numerous strategies used to avoid the complications they cause are well known. Dirac expressed the problem as follows: “These quantum equations are such that, when interpreted according to the general scheme of quantum dynamics, they allow as the possible results of a measurement of kinetic energy either something greater than $mc^2$ or something less than $-mc^2$” [5]. The difficulty was immediately apparent. The negative energy solutions were a challenge to the physical relevance of the equations. The mathematics and physical reality were inconsistent, which, on the face of it, could be interpreted to mean that either was a satisfactory representation of the electron and the other was not. It remains possible that neither were satisfactory representations of reality.

Dirac's response was to leave the prevailing picture of reality in place and to remove the inconsistency by extending the mathematics. He proved that by a unitary symmetry transformation negative energy solutions could be transformed into positive energy solutions with opposite charge and the same mass [6]. In taking the decision to extend the mathematics, Dirac made a choice between the alternatives of mathematics and reality and he chose in favour of the latter. The other alternative assumes that the original mathematics were an adequate representation of the quantum electron and that the problem arises from the inadequacy of the prevailing understanding of physical reality. The implication being that negative energy and the other two 'unreal' consequences of the equation, properly understood, are unproblematic elements of physical reality, which are consistent with quantum mechanics and special relativity. For this reason it is appropriate to reanalyse the problem physically with the aim of arriving at a logical and internally consistent model of electron behaviour that harmonises with the physical consequences of the Dirac equation and is (a) simple and clearly defined (b) economical of postulates and (c) in agreement with phenomena. Our approach may be summarised as follows:

• Return to the original 'unphysical' electron and its negative energy states (referred to as the Dirac electron)
• Suspend the natural prejudice in favour of what is physically real, leaving reality an open question
• Transform the 'troublesome' mathematical negative energy states into a physical analogue
• Analyse the electron physically, without recourse to mathematics or symmetry principles
• For the model to succeed it must be consistent with special relativity and Copenhagen quantum theory

The positive and negative energy states are given a logically equivalent although somewhat novel physical description. The other two 'unreal' physical consequences of the equation are initially set aside. The physical description is achieved by a transformation of mathematical opposites, as applied to the values of physical variables, expressed in the usual way by the use of the symbols (+) and (–), into a physical analogue. It is argued that the physical analogue refers not only to the value but also to the variable and by extension to the system itself. When combined with the oscillation of the Dirac electron the result is a serial coupling of elementary particle properties with their opposites that takes the form of the actualisation of potential. The concept of potential in the present scheme (see below) differs fundamentally from physical potentials such as potential energy or electric potential. It is similar to the 'potentialities' of the Aristotelian type, suggested by Heisenberg as an aid to understanding quantum mechanics [7]. The analysis, as it is applied to the Dirac electron, is in several ways a satisfying explanation of electron behaviour in terms of the process of the actualisation of potential.

## 2. The Physical Meaning of Positive and Negative Energy States

Energy for the present model is defined, as in classical physics, as: The quantity that is the measure of the capacity of a system for doing work. In addition, energy is always the energy of something; it always belongs to an object or system. Dirac introduced the concept of positive and negative energy states with his relativistic equation for the electron, which allows the possible results of a measurement of kinetic energy to be positive or negative. The mathematical representation of the allowed energy states, denoted in the usual way by positive (+) and negative (-) symbols, gives them the relation of opposites. The mathematical relation of opposites is here transformed into a physical analogue.

Positive energies are those associated with real, or actual, objects such as the classical electron—physical states have positive energy. The central postulate of the model is expressed as follows: the opposite of the energy of the actual electron is identical with the energy of the opposite of the actual electron. The opposite of the actual (or real) electron is the potential electron. Thus, the energy of the electron may be actual or potential dependent upon its being attributed to an actual or potential electron.

The transformation of the concept of opposites from mathematical to physical, in the present scheme, couples the variable with its value. Properties of an isolated system of equal magnitude but opposite sense are not attributable to a variable without consideration of the sense. For example, a co-ördinate system and a property of a quantum system are treated differently. The notion of opposite when applied to the value of a property variable of a quantum system extends to the variable and therefore to the system itself. Variables such as energy, mass and charge are autochthonous to the system; without them there is no system. We shall see, below, that from this analysis an important distinction arises between the opposite of the charge of the electron and the opposite of its polarity.

An additional physical consequence of the equation, that Dirac found remarkable, is the oscillation of the electron: "It is found that an electron which seems to us to be moving slowly, must actually have a very high frequency oscillatory motion of small amplitude superposed on the regular motion which appears to us." Since the oscillation is as much a part of the Dirac electron as its possible energy states, they are coupled in the present model. The physical consequence of the coupling is to transform the Dirac electron into serial phases of physical actuality and immaterial potential. The two phases of the oscillation are closely analogous to the Aristotelian concept of 'actual' and 'potential' as opposites when applied to physical objects [8].

For the potential phase of the electron oscillation, the values of all physical quantities, including energy, are zero. An energy of a magnitude of less than zero is a then taken to be a potential to achieve real energy of that magnitude in a subsequent actual phase. Thus, the physical meaning of the mathematical representation of positive and negative energy states is interpreted to be the mutual opposites of the energy states of an actual and a potential electron. The physical opposite of actual energy is the potential to achieve actual energy. The realisation of the energy potential is a component of the actualisation of the electron together with its other properties.

## 3 The Discrete Electron Oscillation

### 3.1 The Potential Phase

The potential and actual phases of the electron are coupled, so as to form an oscillation of “very high frequency and small amplitude” [5]. The potential of the electron is motivated by a single imperative which is simply and entirely its own self-actualisation. This follows from the fact of the persistence of material reality. The imperative of the potential is the origin of the oscillation which gives rise to the actual phase. The potential does nothing beyond its self-actualisation. The content of the potential includes the capacity to achieve the realisation of every possible physical property that could characterise the actual event.[1] The potential of the oscillating electron is not exhausted by an individual actual event. In the case of an electron event there always remains scope to have been otherwise, within the constraint of its potential. For example, an electron event might be a particle-event or a wave-event. What is important about the wave–particle alternative is not the realised fact but rather the potential for the unrealised alternative that is not actualised. The possession of potential is a necessary but not a sufficient condition for its realisation in some event. It might be neither a particle- nor a wave-event. The properties of the event include its internal and external geometric relations.

The internal geometric relations of the electron chiefly concern the distance, duration and direction that separate its own contiguous actual events. External geometric relations are those that relate each event in the life of the electron to the actualisations of other elementary particles. Both sets of geometric relations arise within the constraint of the initial conditions, which are part of the potential for an actualisation that derives from its immediate antecedent event. The potential of the enduring oscillating electron is not static. Each actualisation in the series of oscillations contributes anew to the 'content' of the potential for the ensuing actualisation (see below).

The potential phase of the oscillation, being the opposite of the actual electron, is bereft of all space-time relations, both internal and external. Consistent with the absence of energy in any form, the potential electron has neither mass nor any other physical property, including position in space or time. Geometric relations, mass, energy and electric charge are all absent from the oscillating electron during its phase of pure immaterial potential; they are each energetically developed during the actualisation phase.

As a consequence of the oscillation between actual and potential states, every property of the real electron and its geometrical relations are rendered discrete in space and time. The process of the actualisation of potential is separated from its immediate antecedent event, not in space and time, but by

1 The event is the sum of the constituent variables realised during the process of the actualisation phase of one oscillation. 'Event' and 'actualisation' are synonyms insofar as they refer to the same thing.

the absence of space and time,[2] which characterised the intervening potential phase—it is nonlocal. The electron in its potential phase is in an immaterial vacuum state, which is complete and private.

By contrast with the present concept of the potential of an isolated system, the de Broglie Bohm potential is seemingly separate from both the wave function and the continuously moving particle. The motion of the particle is guided by the combined effects of the wave function and the potential [9, 10]. In the present scheme, wavefunctions are unreified mathematical objects which are concerned with the potential of the system for which they are written, not components of the oscillating physical system. The potential, in the present scheme, is inseparable from the particle whose kinematics do not involve real waves or fields.

### 3.2 The Actual Phase

The electron potential begins to actualise without any physical features or properties. The actualisation is energetic and it takes time. It culminates as an actual electron with the usual properties of electric charge, mass and internal and external geometric relations. The total energy of the ideal electron exclusively performs the work of its own actualisation. The completion of the event is the classical aspect of the discrete electron.

Properties such as mass, charge and position develop during the phase of actualisation, prior to the completion of the process of actualisation the electron has no properties. Each serial, complete actualisation of the electron is a motionless event, which is spatially and temporally separated by distance, direction and duration from its antecedent motionless, actual event. The geometric connection between a motionless events and its antecedent is realised only upon the completion of the event. The actualising electron has no position until its next event *arrives*, because it consists of actualising immaterial potential and therefore is not geometrically related to anything.

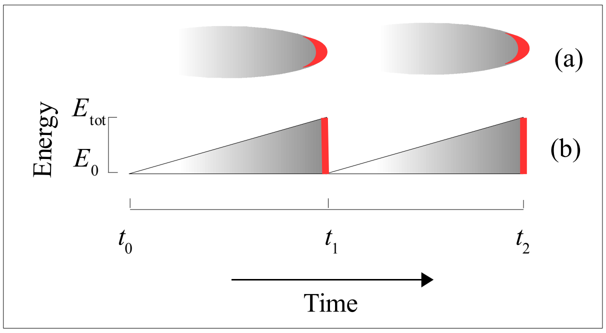



Fig. 1 (Colour online) Two oscillations of a single electron. At (a), the grey ovals depict the indefiniteness of the beginning and the gradual intensification of actualisation which terminates when fully actual, as depicted by the red crescents. Actualisation begins at $E_0$, $t_0$ (b). The total energy of two serial oscillations is represented by the grey triangles that terminate at $t_1$ and $t_2$. Red bands represent the classical culmination of the two serial events.

It can be seen in Fig. 1 that there is no definite energy at an instant between $t_0$ and $t_1$, because that

2 In the present scheme, consistent with the economy of introduced postulates, there is no space or time apart from geometric relations among objects. The physical domain that is bereft of space and time is the vacuum. Like distance, direction and duration, 'vacuum' only makes sense in terms of a system that occupies such a state. Vacua do not contain objects.

duration only arises upon energy decay at $t_1$. Observation of the electron during actualisation is not possible in principle. There can only be a definite energy value for the duration of the whole actualisation phase and it cannot be determined before it is complete.[3] The oscillation is an instance of the Heisenberg time–energy uncertainty relation.

In accordance with the matter–force distinction, denoted by the terms 'fermion' and 'boson', the former being a matter particle and the latter a force or binding particle, the postulated oscillation may be analysed in terms of fermionic and bosonic elements. The fermionic element belongs to the termination of the oscillation as the physical electron. The bosonic element is immaterial potential. Successive pairs of fermionic termini are separated and *connected* by an intermediate nonlocal bosonic element.

The transition between successive fermionic termini, including their relative positions in space and time, is indistinguishable from the concept of a quantum jump. The jump is usually employed to explain transitions between states of different values of a variable and the realisation of a fact from among a set of predictions. Here the jump occurs between separate space-time loci and discrete stationary states of the same or different values of all variables. Every oscillation entails a jump between stationary states that is motivated by the imperative for self-realisation.

The fundamental and indivisible ideal electron of continuous physics is thereby divided into discrete motionless events, separated by nonlocal immaterial potential. Stationarity applies to the value of all variables, without qualification. Neither angular momentum, usually referred to as 'spin', nor linear momentum are the result of classical motion against a background of space. The stationary state of the electron in a hydrogen atom does not extend to include the classical concept of a continuous orbit. The oscillation as it is applied to the electron is likewise applied to the photon.

## 4 The Special Relativistic Constraint

Special relativity is the source of the constraint on the model of the oscillating electron. In the discrete scheme, the constraint supplied by special relativity divides naturally into two parts, a geometric part and a kinematic part.

### 4.1 The Geometric Constraint

According to Einstein, in the absence of matter there is neither space nor time [11]. In classical physics space and time seemingly extend continuously throughout the universe, so the above assertion is essentially inconceivable, but it is a necessary element of the discrete model. Following the completion of actualisation, the oscillating electron consists entirely of immaterial potential because its energy has decayed to zero. Since space is simply the distance and direction that relate the matter particles of the

3 The fundamental reason that nothing of the actualisation is observable prior to its completion is that the photons that enable the observation are only emitted following the termination of the event to be observed.

universe and time is the set of temporal relations among their serial actualisations, there is neither space nor time for the electron other than when it is approaching complete actualisation; then it begins to possess its classical properties, which include its geometrical relations with all the actualisations of the universe.

For the oscillating electron, the Lorentz transformation becomes relevant upon the completion of actualisation, when the classical, material electron occupies a fixed position and is at zero energy and the geometry of its space-time relations is therefore flat. It is at that stage of the oscillation that charged particles emit the photons that enable their observation (see below). Thus the geometric conditions for the applicability of the Lorentz transformation to the co-ordinate system of the electron arise with flat Minkowski space-time together with the creation of the photons that enable its observation. It does not follow from this argument that special relativity is irrelevant to the process leading up to complete actualisation—it is.

### 4.2 The Kinematic Constraint

The rules that relate to the speed of light, mass and the mass–energy transformation relation provide the special relativistic constraints on the actualisation phase of the oscillation. Those three elements of special relativity all concern the concept of mass. It is of interest that Einstein considered the new concept of mass to be the most important result of special relativity [12].

Special relativity requires that mass limit the rate at which a particle can change its position; which in continuous physics is the speed at which it moves. A particle with mass cannot change its position as fast as a massless photon; which is interpreted to mean, it cannot overtake a photon that it has emitted. The difference between their speeds remains absolute, irrespective of the speed of the charged particle.

According to this analysis, the nineteenth-century field theory requirement that a particle interact with itself, which is absolute, is rendered relative by the twentieth-century advent of special relativity. Indeed, there never was a consistent theory of the action of a particle on itself [13]. In the present model a charged particle cannot interact with itself via its emitted electromagnetic boson—the photon. By contrast, an elementary particle can interact with itself via a boson it emits if it has mass [14]. The relative–absolute distinction is an effect of the concept of mass, as understood in the theory of special relativity.

The speed at which a particle changes its position, in the discrete scheme, is inversely related to the duration of its actualisation. This follows because the zero-energy, nonlocal component of the oscillation makes no contribution to the duration of the journey of the particle, whether it has mass or not. The particle tunnels instantaneously from the locus of one motionless event to the next [15, 16]. The photon, being the fastest moving component particle of the atom, therefore has the shortest duration of actualisation, which follows from its being uniquely without mass.

## 4.3 The Real Photon and Electric Charge

Consistent with the adoption of a minimum of postulates, charge is defined to be a property of some elementary particles that enables them to exert forces on one another. In the present scheme, it is primarily the property that enables charged particles to annihilate photons. The physical interpretation of the concept of opposites is applied to charge in the same manner that it is applied to energy. Therefore, the opposite of the charge of the electron is the charge of the opposite of the electron, which is zero charge of the potential electron. Energy and charge are each properties of a single oscillating electron that actualise and then decay to the opposite status of immaterial potential.

By contrast, among the low-energy components of the atom, the opposite of the *polarity* of the charge of the electron is the polarity of the charge of the proton. Charge of either polarity is simply the property, for the present model, of individual electrons and protons that enable photon annihilation. Photons do not distinguish the polarity of the charges of the electron and proton. For a photon, the opposite of the electron charge is the absence of charge because the opposite of annihilation is endurance.

If the space separation and phases of the oscillations of a charged particle and a photon are suitably related, both potentials will couple in the actualisation of a single event. Such a charge-dependent co-actualisation (which energises the photon) is photon annihilation. The annihilation of the photon by the electron is dependent upon them being propitiously separated in space and time at the termination of the immediate antecedent actualisation of each. The ensuing potential phase of such an excited actual electron consists in the double potential of a photon and an electron without any quantum properties, including charge. Each potential begins to actualise at the termination of the actual phase of the excited electron. The duration of actualisation of the electron is absolutely greater than that of a photon. Because they begin to actualise simultaneously, the absolute difference in the duration of their actualisation decouples the photon potential from that of the electron. The photon potential actualises before that of the electron.

The crucial consequence of the absolute difference in the rates of actualisation of the photon and electron potentials is, heuristically, that the charge of the electron does not actualise in time to effect the capture of the actualising photon; their phase relations are no longer propitious for their co-actualisation. Photon creation, or emission, by an oscillating electron occurs in the potential phase and photon annihilation, or absorption, occurs during the actual phase. Photon creation always follows the decay of the energy of its creator. For photons and charged particles, electric charge is the discrete property which enables photon annihilation and their absolute mass difference is the physical basis for photon creation. For a single electron, the oscillating phases of photon creation and annihilation relate serially to one another; therefore they cannot occur simultaneously.

### 4.4 The Virtual Photon

Real photons oscillate between actual and potential phases when alone and effectively isolated from charged particles during journeys of indefinite distance and duration, across a room or across a galaxy. The sum of the durations of the actual phases gives the photon the finite value of the speed of light; the nonlocal potential phases make no contribution to the duration of the journey.

By contrast, a virtual photon is created in the potential phase of one energised, charged particle and is annihilated by its co-actualisation with another charged particle, without achieving photonic actualisation between its creation and annihilation; virtual photon transfer is effected 'during' one potential phase of a single oscillation. Such a photonic potential, is a virtual photon tunnelling between two charged particles, the one which created it and the one which annihilated it. Because the virtual photon tunnels during a single potential phase, from which space-time relations are absent, it does so instantaneously; which is the discrete Hartman effect [17]. The special relativistic mass effect that prevents the photon emitter from recapturing its own photon paves the way for the one-way transfer of a photon between two charged particles. There is no difference between individual potential phases of a real photon and the single potential phase of a virtual photon and neither is there a difference between their creation or annihilation.

## 5 The Bond Between Events

### 5.1 Isolated Systems

In continuous physics, there is no concept of a bond that maintains the enduring electron because the electron has no parts to be bound. By contrast, the observable, classical aspect of the discrete electron consists of a series of motionless events. Those actual events are individual parts of the electron, separated equally in time and space. Therefore, the discrete electron requires a bond between the contiguous events of which it is comprised in order to explain its endurance. That bond is the potential (bosonic) phase of its own oscillation, which binds a pair of contiguous actualisations of the enduring electron. The same analysis applies to the real photon.

The principle of elementary particle endurance is that each motionless event that comprises the particle is bound to the source of the potential which it actualises; the bosonic potential forms the bond between contiguous actual events. The bond is the immaterial nonlocal actualisation of the potential derived from the immediate antecedent event. The potential, which includes the geometrical component of its initial conditions, provides the constraint upon where and when the event occurs. The potential of an elementary particle does not enable its constituent events to avoid compliance with Newton's laws of motion, or to behave chaotically.

### 5.2 The Electron and the Real Photon

The potential of the oscillating real photon consists of two elements. The first is its energy potential, which actualises each of its constituent events. That component of its potential has its origin with the actual event that created the enduring photon, at the other side of the room or galaxy. The energy potential is repeatedly realised with each event in the life of the real photon. The second element of its potential is the geometric component of its initial conditions and it originates with the source of the potential each event actualises; which is its immediate antecedent event.

When eventually the real photon is annihilated by a charged particle, e.g. an electron, both components of its potential co-actualise with the potential of the electron. The photon contribution to the event is supplied by both components of its potential. The photon energy excites the electron to a higher energy level and contributes to the energy that is converted into the mass of the event (see below). The geometric component contributes to where and when the event actualises. The internal geometric relations of the actual event are subject to the constraint of the geometric relations of the two sources of the potential it actualised, viz. the immediate antecedent electron event and the immediate antecedent photon event; the latter is the last event in the life of the photon. The actual event is thus bound to its two antecedent events.

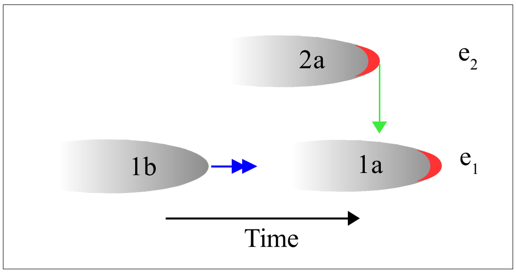
From the standpoint of the electron, the geometrical element brought to the event by the real photon is random with respect to the relative direction of its origin. The influence of the photon on the geometric locus of the electron event will therefore depend upon the geometry of the separation of the two antecedent events, which were the sources of the potential it actualised. Where and when contiguous electron events occur will be randomly influenced by the geometry of the origin of the photon potential. The outcome is consistent with a more literal meaning of 'zitterbewegung', viz. trembling motion, rather than the more usual connotation of angular momentum.

### 5.3 The Virtual Photon-Mediated Bond

The single principle that explains the bond for the enduring one-particle electron system and the interaction of the two-particle, real photon-electron system also explains the electromagnetic bond between two electrons. The co-actualisation of the potential of a virtual photon with the potential of an electron binds the resultant event to the sources of the two potentials it actualises. In contrast with the origin of the transferred potential of a real photon, which is an isolated photonic event, the transferred potential of a virtual photon has its origin with a charged particle. The contribution by a virtual photon to the potential of the event consists of (i) an energy contribution to the generation of the electron mass and (ii) the constraint of the geometrical relations of the charged-particle event that created the photon.

Where and when the co-actualisation terminates will be subject to the constraints of the geometric relations of the two electron events, which were the origins of the two components of the potential.

**Fig. 2** The discrete two-electron interaction. The co-actualisation at event 1a of the electron potential derived from event 1b of electron $e_1$ (double blue arrow) and the photon potential derived from event 2a of electron $e_2$ (single green arrow) forms the discrete bond between electrons $e_1$ and $e_2$.




Pairs of discrete charged particles bind by a one-way transfer of virtual photons between the motionless events of which they are composed. There is no physical connection between the bound electrons at any time; the bond is nonlocal. And neither are there any classical effects such as momentum transfers due to collisions of electrons and photons. Each event is where and when it is because it is subject to the constraint of its own potential, which includes its initial conditions that are derived from the two sources of the potential it actualises.

It can be seen from Fig. 2 that the two electrons that interact by photon transfer are not simultaneously actual (depicted by the two red crescents); thus Pauli exclusion is not violated. In order for a photon transfer to occur, the two-electron ensemble has to be antisymmetrical with respect to their fermionic states. If, in the discrete model of the electron, a two-particle quantum system is formed by the electromagnetic interaction then the special relativistic constraint on the kinematics manifests as an instance of the Pauli exclusion principle. The special relativistic constraint also prevents the simultaneous two-way exchange of photons between two charged particles.

**6 The Mass–Energy Transformation Relation and the Origin of the Electron Mass**

The relativistic mass–energy transformation relation is important, not for the conversion of mass into energy, but the reverse—the conversion of energy into mass. The energy of the electron exclusively performs the work of its actualisation during each of its oscillations. From the imposed simplicity of the postulated oscillation process it is inferred that the energetic actualisation of particles with and without mass must differ fundamentally and absolutely. The need for an absolute difference arises from the observation that the quantity of energy of an elementary particle is unrelated to its transformation into mass, since photons of the highest and lowest energies have zero mass. Regardless of the energy of the photon, none is converted into mass at the serial events between its creation and annihilation.

Each actualisation, between creation and annihilation, of an isolated, and therefore real, photon is the realisation of a single potential. Therefore, there is no co-actualisation with additional potential, and coincidentally, no conversion of its energy into mass; the two are correlated. Of the oscillations of the three matter particles and the photon of the low-energy atom only that of the photon occurs without co-actualisation and without conversion of energy into mass. The exception for the photon is its annihilation by a charged particle when the potential of each combines to form the double potential of the photon and the particle. The two co-actualise as a single event and energy is converted into the mass of the charged particle. This suggests that the energy of the real photon, which in isolation is solely the energy of its own actualisation, does not lack the capacity to contribute to the production of mass, but does not do so in isolation.

The electron, although without constituent parts, in the classical sense, is expected to continually co-actualise with and therefore annihilate photons of its immediate environment, whether as a single particle or part of an atom or electron plasma.[4] Co-actualisation is thus correlated with the conversion of energy into mass. Heuristically, in the sense of the Standard Model, the continual co-actualisation of the electron with photons is a quasi-collision between two potentials, which results in the mass of each actual event. The photon has zero mass, because prior to its annihilation it does not collide with anything. The special relativistic mass–energy transformation is continually realised as part of the oscillation of the discrete Dirac electron.

## 7 Discussion

The present approach to the apparent inconsistency of the untransformed Dirac equation with physical reality, which is the alternative to that taken by Dirac, is to entertain the proposition that the original mathematics provides an adequate model of electron behaviour, together with the suspension of the general preconception of how the electron is supposed to behave. By this analysis we arrive at a synthesis of special relativity and quantum mechanics, which requires negative energy electrons that change their position at the speed of light and whose description gives equal roles to time and space. It is both satisfying and surprising that a physical model of the electron is able to apparently accommodate special relativity and the tenets of quantum theory without employing either mathematics or symmetry principles.

Choosing a mathematical scheme to represent what is a non-classical, unobservable process is bound to be problematic. There is a sense, however, in which the mathematics has already been done by the creators of Copenhagen quantum mechanics and special relativity and the present exercise is an effort to try to understand what it means. The use of additional mathematics to gain a physical understanding of the original equations provides no guarantee of a wholly satisfactory outcome.

4 The annihilation of a real photon by an electron, in contrast to a virtual photon, does not form a bond between the charged particle that created the photon and the electron that annihilated it. Because an actual event of the energised electron is bound to the source of the potential it actualised; the electron is bound to the last isolated actualisation of the photon and is unaffected by the photon's creator. The consequent electron behaviour is consistent with the concept of Zitterbewegung.

The discrete model of the electron described here is radical in many ways; it is also clearly defined and simple. Much of the counterintuitive quantum behaviour of the electron is inherent in the model and energy is bounded from below. The nonlocality of the oscillation does not violate causality and elementary particles change their positions without moving through space or time. Central to the model is the physical interpretation of a quantum system in terms of the Aristotelian concept of the actualisation of potential, which Heisenberg suggested as a means of understanding quantum mechanics. The strange behaviour of the electron, that Heisenberg sought to make more comprehensible by the use of the Aristotelian model of matter, arises naturally from the application of Aristotle's physics to Dirac's relativistic quantum mechanics.

The type of behaviour attributed to the electron by the model is completely at odds with quantum field theory and yet there is no clash with Copenhagen quantum mechanics or special relativity. The quantum features of the model include:

• Nonlocality which characterises the quantum process that terminates in the emergence of the material electron into the classical domain.
• A single principle explains the endurance of the discontinuous, material electron and the virtual photon-mediated electromagnetic interaction.
• Jumps, without interphenomena, extend to every property and property value of the whole electron.
• Like quantum angular momentum, linear momentum is not due to classical motion. The distinction between quantum angular momentum and classical motion about an axis or point is extended in the model to the separation of linear momentum from the classical concept of continuous rectilinear motion through fixed space. The non-classicality of angular momentum generalises naturally to include the linear case.
• Time–energy uncertainty is integral to the model. The model does not admit of a prediction of an exact energy value at a precise time.
• Quantum and classical regimes are naturally related. Quantum mechanical *work* creates the classical particle.
• Bohr's complementarity is accommodated by the electron being greater than the sum of the parts that comprise any one of its individual events. Each event retains the potential to have been otherwise. The electron cannot be said to have properties without interactions. The fact of wave–particle duality explains the non-actualisation of the potential for the counterfactual event. If the electron does not interact with either a wave or particle detector at an event, and if waves and particles exhaust the forms of its manifestation, then the event has no properties.
• The zero-energy residue of the electron oscillation forms one tiny component of the observable classical world, in which the symmetries of flat space-time obtain. The model is not inconsistent with the matter-induced space-time tension of General Relativity. The electron forms rather than deforms its own space-

time locus during the phase of energetic actualisation of its geometric connection to every other event in the universe.

• The geometry of electron pairing, which is a special relativistic imperative of the oscillation, gives rise naturally to the Pauli exclusion principle. The electrons form a two-particle antisymmetrical ensemble that obeys Pauli exclusion, not because of their relative spin orientations or relative energy differences, but because one electron is energised and the other is not; the energy difference is absolute rather than relative and brings with it all the qualitative states of the particle. Nothing is put in by hand.

Finally, the model is capable of an expanded development among the charged particles of the atom in the low-energy sector. One consequence of the model, not developed here, is the special relativistic constraint that only allows a one-way transfer of virtual photons among bound electrons. Such a kinematic constraint offers the interesting possibility of the single interaction principle extending naturally to include indefinite numbers of electrons in the formation of bound plasmas and to the well-known electron pairs of classical chemistry. In both cases, the one-way transfer of virtual photons requires a photon source external to the antisymmetrical two-particle ensemble. Such a development will be the subject of a later paper.

**Acknowledgement** The author thanks Vincent Powell for helpful discussions.

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