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Tripole Model for the Electron

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Abstract

A model for the structure of the electron is proposed, in which the electron is composed of electric tripole, *i.e.*, a +1 charge at the center and two −1 charges circulating around it and the Planck charge q_p is applied to these charges. The confinement force for the outer charges, which has been the essential issue in constructing electron models, is Coulomb attraction in this model. Calculation of the associated energies shows that the tripole structure is stable. The intrinsic magnetic moment corresponding to the Bohr magneton μ_B is formulated from the loop current of the two circulating charges and by converting q_p to e by a scaling factor $\sqrt{\alpha}$, where α is the fine-structure constant. In this formulation, it is shown that the electron g_e factor (=2) in the μ_B is inherently included in the tripole model without artificially introducing it. Also, it is shown that the associated magnetic flux Φ_0 generated by the loop current is equivalent to the magnetic flux quantum. Thus the tripole electron model naturally provides the quantized electric charge and the magnetic flux quantum in a self-consistent manner. An expression of the electron rest mass is derived from the relativistic energy-mass relation using the total energy of the internal and radial electrostatic energies and the magnetic energy, and the expression proves to be the same as the conventional expression deriving the classical electron radius. Furthermore, the multipole lepton concept, a wider concept including the tripole electron model, is presented, in which low energy leptons are composed of multiple electric poles originated from the dipoles existing in the Planck vacuum. Some specific processes associated with the electron can be elucidated and possible structures of neutrinos are proposed based on this concept.

Keywords

Electron Structure, Confinement Force, Electric Dipole, Planck Charge, Planck Vacuum, *g*-Factor, Magnetic Flux Quantum, Two-Turn Loop, Zitterbewegung, Electric Dipole Moment, Multipole Lepton Concept, Neutrino Structure

1. Introduction

The electron is the most familiar elementary particle providing great benefits to our life as electronics, while its true identity is still far from well-understood. In the Standard Model, it has been treated as a point particle with no dimension but possesses intrinsic properties such as mass, elementary charge and magnetic moment. Such characterization of the electron as well as other elementary particles has been sufficient for the moment in organizing and understanding the complicated reaction processes between the elementary particles systematically. However, the question of what is the "cause" of these intrinsic properties of the electron still remains. In spite of the firm assumption of the Standard Model that the electron is a point particle, various categories of extended electron models addressing the inner structure of the electron have been presented.

One category of models is ring or loop models [1] [2] and Zitterbewegung models [3] [4], in which an electric charge is circulating around a center of mass and generating the intrinsic magnetic moment. The ring or loop models have been extended to models in which a point charge moves in special orbits like a helical solenoid geometry [1] or a two-turn loop [2]. Other categories of models are photon or wave models [5] [6] motivated by the process of electron-positron pair production by photons (γ-ray), in which two photons combine to a self-confined photon, i.e., an electron [5]. As another category of models, a model constructed based on not electric charge but magnetic flux as the main framework of the electron has been presented [7]. Further, general relativistic models have been proposed in which the electron can be regarded as a solution of general relativistic theory [8] [9].

In the above loop current and loop wave models, the origin of the confinement force acting on the charge and the wave toward the center of mass has been the essential issue to be explained in constructing electron models. The confinement force has been attributed, for example, to locally curved space [5] [6], and the effect of gravity on the self-energy of the electron has been argued [8]. Nevertheless, this confinement problem is still an open problem despite its crucial importance in constructing electron structure models.

2. Background of the Tripole Electron Model

2.1. Electric Poles as the Building Blocks of the Electron

In the conventional theories of vacuum such as quantum electrodynamics (QED), the quantum vacuum (QV) is filled with virtual particles and antiparticles which appear and disappear at random by vacuum fluctuations (VF) [10] [11]. Our model for the electron is based on a new idea postulating that the positive and negative electric poles existing as dipoles in the vacuum are the most fundamental building blocks of leptons, namely, a particle-antiparticle pair is created by the positive and negative electric poles originated from the dipoles (Multipole Lepton concept) as will be elucidated later. There is a crucial difference between the "particle-antiparticle pair" in QED theory and the "positive and negative pole pair" in our model in more than terminology. The positive and negative pole pairs (electric dipoles) are produced in the Planck vacuum (PV) which is assumed to be the source of the QV [12]. The electric dipoles manifest themself experimentally as the Casimir effect [13] caused by their interactions through van der Waals forces [14]. Our idea further postulates that a dipole in the PV is momentary and has lifetime, while it is stabilized if certain momentum is transferred from another dipole and it becomes a real "particle" (a quantum dipole: a photon as will be explained next). In contrast, if a dipole was not transferred momentum during its lifetime, it recombines to disappear in the PV. From another point of view, the quantum dipoles are the carrier of momentum or energy.

The electron-positron pairs in the QV have ab initio the intrinsic properties mentioned above, and in other words, they are created as "finished products". It can be said that underlayer reaction processes between the electric poles, e.g., an electron and positron pair creation by photons, $2\gamma \rightarrow e^- + e^+$, are hidden under the QV processes as usually expressed by Feynman diagrams. It has been well established experimentally and theoretically how the creation and annihilation processes of the elemental particles conform to the conservation quantities such as total electric charge, momentum, angular momentum (spin), and various quantum numbers. However, fine physical mechanisms by which elementary particles transform to other particles is absolutely unknown.

2.2. Physical Structure of a Photon

A further postulation in the new idea is that an electric dipole, i.e., a positive and negative pole pair, is no other than the identity of a photon. The photon has been in general defined as a quantized EM wave, and further in QED, a quantized electric field or magnetic field has been referred to as the "virtual photon". Thus the physical definition of the "photon" which has been conventionally used is not unified. Here, the physical structure of a photon is identified as the quantum dipole with a pair of positive and negative electric poles which have a positive charge acting as a source diverging electric fields and a negative charge acting as a sink converging them, respectively.

Maxwell's equation connects the electric charges and the electric fields inseparably by Gauss's Law. However, the electric charges which should exist at the two transverse ends of an EM wave usually illustrated in text books have been treated as rather virtual entities or it has been silent on this point. It should be noted here that the motion of the real positive and negative charges in the travelling direction form parallel electric currents with opposite directions each other (i.e., neutral current in total), and they also induce a magnetic field normal to the transverse electric field between the charges, so that the assumption of the presence of the real charges (poles) at the transverse ends of the photon does not contradict Maxwell's equations. This postulation is similar to the preexisting model [15] in which a photon is a virtual "electron and positron" pair, however, it is physically different from our dipole of "positive and negative pole" pair.

With respect to the longitudinal size of a photon, it has been argued that the photon has a size of the wavelength of a half period [15] [16] or a single period [17]. We postulate here that a photon (a quantum dipole) rotates clockwise or counterclockwise around the travelling direction (spin) and that it has a longitudinal length λ_l in the travelling direction proceeded during a single rotation of the dipole, expressed by $\lambda_l = c\tau_l$, where c is the speed of light, τ_l is the period of the single rotation, and h/τ_l equals to the photon energy, where h is the Planck constant.

3. Tripole Model for the Electron

The tripole model which is a semiclassical model for the physical structure of the electron, constructed firstly so as to conform to the Breit-Wheeler process of electron-positron pair generation from photons, $2\gamma \to e^- + e^+$, as other models [5]. The basic structure of the electron by the tripole model consists of one positive charge at the center and two negative charges circulating around it, which makes the total charge one negative charge. These charges are originated from the source photons (quantum dipoles) and a proximate dipole. Here, each charge (pole) is assumed to be point-like and massless. The latter assumption is different from the preexisting three charge model for the electron [18], in which fractional charges (−1/3, +2/3) like quarks and intrinsic masses were assumed for each charge. In the tripole model, the rest mass of the electron is attributed to the EM energies associated with the three charges constituting it. Although we will elucidate only on the electron structure in the following, the structure of the positron can be quite similarly elucidated.

Based on the concept that a structure model for an elementary particle should be constructed from most elementary and smallest constituents, we adopted electric poles as the constituents in the tripole model. Further, we adopted the Planck charge q_p defined in the Planck vacuum [12] as the electric charge. The Planck charge is a bare charge not screened by vacuum polarization, while it is different from the bare charge used in the context of QED. The value of q_p (1.876×10^{-18} C) is greater than that of the experimentally determined elementary charge e (1.602×10^{-19} C) by a factor of 11.7. These two values are connected by the relation, $e = \sqrt{\alpha} q_p$ [12], where α is the fine structure constant (≃1/137).

An example of the creation mechanism of the electron according to the tripole model is schematically shown in **Figure 1**. The two photons (γ-rays) with total energy greater than 1.022 MeV/c^2 approach from opposite directions (**Figure 1(1)**), and when the distance between them becomes so near that the EM field between them becomes sufficiently strong, a new dipole would be induced between them to weaken the EM field (**Figure 1(2)**). As an alternative process, a dipole accidentally existed between the two approaching photons may play the same role in the creation process. Also, three photon Breit-Wheeler process [19] may be one special case of this situation. It is conjectured that the probabilities such events occur is very low, and acctually the experimental results suggest that these processes occur at low rates [20]. On the collision, these six poles will reconstruct and transform to a pair of electron and positron with the assist of driving forces by the momenta and angular momenta that the two dipoles possessed (Figure 1(3)). The created electron and positron will separate in different directions each with the momentum transferred from the incident photons.

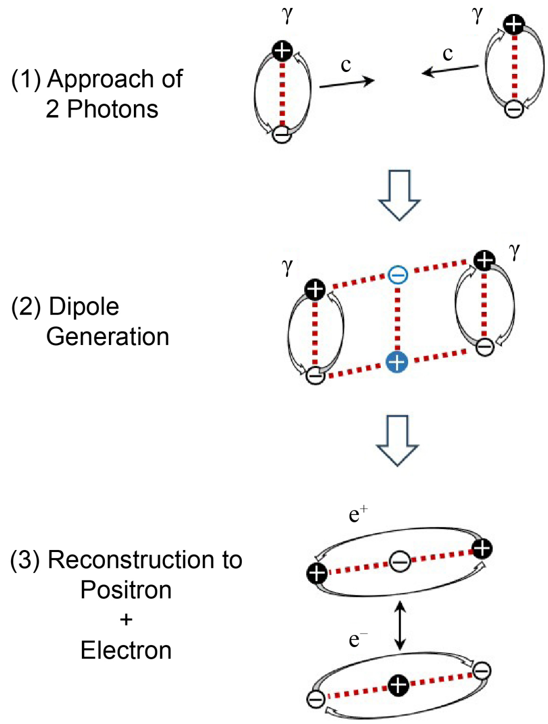

Figure 1. Schematic illustration of a creation process ((1) → (2) → (3)) of an electron-positron pair from two dipoles (photons). The blue dipole in (2) is a dipole induced by strong EM fields between the dipoles. The dotted lines indicate attractive electric fields and the semicircle arrows express the rotation of the poles though their directions are provisional.

Figure 2 illustrates the electron structure created in this manner from the two photons. Two negative charges q_1 and q_2 are circulating around the positive charge q_0 at the center. It is assumed that the orbital is a circle with radius a for simplicity, and that the q_1 and q_2 are arranged symmetrically with respect to the q_0. Although the arrangement that the three charges align in the x-y plane is obviously most favorable in reducing the repulsive force between q_1 and q_2, a more general arrangement is assumed in Figure 2(2), where the line connecting q_0 and q_1/q_2 and the line connecting q_1 and q_2 form an angle θ $(-\pi/2<\theta<+\pi/2)$.

In this arrangement, Coulomb attraction forces F_E act between the three charges, while since the mass of the charges (poles) are assumed to be zero, no centrifugal forces due to inertia acts on the rotating negative charges. In addition, a Lorentz force F_B acts on the moving q_1 as an outward force by the magnetic field $\boldsymbol{B}_2$ generated by the moving q_2, and conversely, the moving

q_2 is also exerted an outward force by the magnetic field $\boldsymbol{B}_1$ generated by the moving q_1 in the same manner. A preliminary calculation proved that the net force between q_1/q_2 and q_0 by the Coulomb forces F_{E} and the Lorentz forces F_{B} becomes centripetal (attraction) forces, and also has a z component as can be seen in **Figure 2(2)**. Accordingly, it is expected that the orbit plane and the central charge q_0 can oscillate mutually in the z direction as will be discussed later.

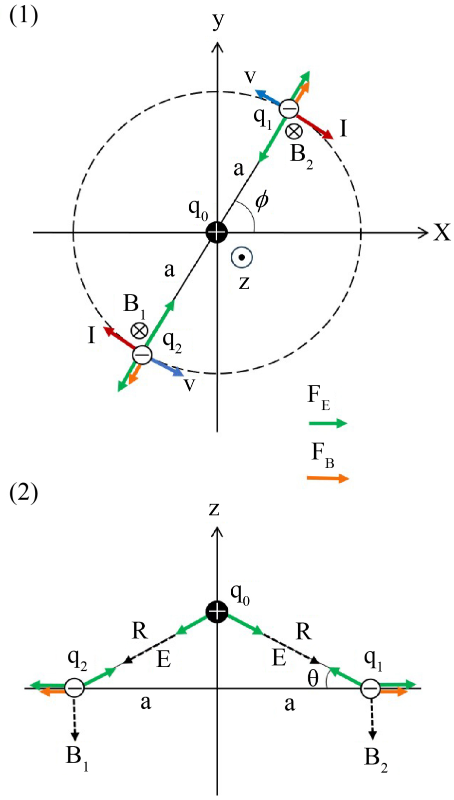

Figure 2. Arrangements of the three charges in the x-y plane (1) and in the *z* direction (2).

4. Electromagnetic Energies of the Tripole Structure

The Coulombic three-body systems composed of two negative charges and a positive charge have been investigated extensively. The positronium negative ion Ps^- [21] [22] is a typical example in the lepton level, and the negative hydrogen ion H^- is the smallest example in the atomic level [23]. It was shown that the Ps^- can exist though it is rather unstable [22]. The preexisting theories and experimental results showed that the stability of the three-body system significantly dependent on the mutual mass ratio of the elements [23]. As it is assumed that the charges are massless in our model, the above knowledge about the three-body system is only limited in applying to our model, however, calculation of the static binding energies of the three charges would be the first step to examine the stability of the tripole electron structure.

4.1. Electrostatic Energies

The electrostatic interaction energies between the three charges, q_0, q_1 and q_2 in the geometry shown in **Figure 2** were calculated by using the Planck charge q_p and setting $|q_i| = q_p$ ($i = 0,1,2$),

$$U_{01} = U_{02} = -\frac{kq_p^2}{R}$$
$$U_{12} = \frac{kq_p^2}{R} \cdot \frac{1}{2\cos\theta}, \left(\frac{1}{4\pi\epsilon_0} \equiv k\right) \tag{1}$$

where U_{01} and U_{02} are the interaction (attractive) energies between q_0 and q_1, and q_0 and q_2, respectively, U_{12} is the interaction (repulsive) energy between q_1 and q_2, and R is the distance between q_0 and q_1/q_2. The total electrostatic interaction energy U_{int} is given by

$$\begin{aligned} U_{\text{int}} &= U_{01} + U_{02} + U_{12} \\ &= -\frac{kq_p^2}{R}\left(2 - \frac{1}{2\cos\theta}\right). \end{aligned} \tag{2}$$

For small θ values, it follows that

$$\begin{aligned} U_{\text{int}} &\simeq -\frac{3kq_p^2}{2R}\left(1 - \frac{\theta^2}{18}\right) \\ &\geq -\frac{3kq_p^2}{2a}. \end{aligned} \tag{3}$$

It can be seen from Equation (3) that the total interaction energy U_{int} takes the form of a harmonic oscillation for small θ, and it takes a minimum at $\theta = 0$. In this case, $R\cos\theta = a$, *i.e.*, the three charges are aligned as expected. The U_{int} is negative similarly to the ground energies of the Ps^- or atomic systems [22] [23].

The other static energy is of the radial electric field, $\boldsymbol{E}(\boldsymbol{r}) = -kq_p\boldsymbol{r}/r^3$, spreading from the total charge $-q_p$ regarded as locating at the center. The radial electric fields would show spherical symmetry at distances sufficiently longer than the radius a, allowing us to calculate the radial electrostatic energy U_{rad} approximately by integrating the energy density $u_{\text{rad}} = \frac{1}{2}\boldsymbol{E}(\boldsymbol{r})\boldsymbol{D}(\boldsymbol{r})$ from a to ∞. The electrostatic energy inside the radius a is allocated by the above U_{int} in this model. Accordingly, the radial electrostatic energy U_{rad} is given by

$$\begin{aligned} U_{\text{rad}} &= \frac{1}{2}\int_a^\infty \boldsymbol{E}(\boldsymbol{r}) \cdot \boldsymbol{D}(\boldsymbol{r}) \mathrm{d}\boldsymbol{r} = \frac{\epsilon_0}{2}\int_a^\infty |\boldsymbol{E}(\boldsymbol{r})|^2 \mathrm{d}\boldsymbol{r} \\ &= \frac{\epsilon_0}{2}\left(\frac{q_p}{4\pi\epsilon_0}\right)^2 \int_a^\infty \int_0^\pi \int_0^{2\pi} \frac{1}{r^4} \cdot r^2 \sin\theta \mathrm{d}r\mathrm{d}\theta\mathrm{d}\phi \\ &= \frac{q_p^2}{4\pi\epsilon_0}\left[-\frac{1}{r}\right]_a^\infty = \frac{kq_p^2}{2a}. \end{aligned} \tag{4}$$

Historically, the origin of the electron mass has been interpreted as the EM energy [24] from more than one century ago, and in the tripole model, we also adopt the concept that the mass is originated entirely from the EM energy. The earliest model for the EM mass is the point charge model where its electrostatic potential energy (self-energy) is responsible for the electron mass. However, this point charge assumption introduced the infinity problem, *i.e.*, integrating the potential energy from ∞ to 0 diverges to infinity. In order to avoid this, the integration is truncated at such a radius that gives the measured electron mass (the classical electron radius: 2.818×10^{-15} m). As a next stage, models for the electron and its mass had been presented based on the postulation that the electron has spheric shape and the electric charge is uniformly spread over the sphere surface [24]. However, this postulation invited another puzzling problem that explaining the magnitude of the intrinsic magnetic moment requires a superluminal rotation of the surface charges. Moreover, it requires introducing some new confinement force acting on the surface charges such as the Poincaré stress [25].

However, for the first place, assuming electron charges distributed on the whole sphere surface implies the existence of fractional charges smaller than the "elementary charge" on the sphere surface, and such assumption appears to be inadequate for the model of an "elementary particle". The tripole electron model can essentially avoid such problem. Since our model is a multipole model, it is not required to integrate the potential energy from ∞ to 0. Also, since indivisible Planck charge is adopted as the constituting electric charge and two discrete negative charges are arranged at the opposite positions with respect to the central positive charge, it would minimize their repulsive forces than the early uniform-charge models. Furthermore, the other important advantage of this model is that the confinement force which has been the crucial issue of electron models can be attributed to the well-established Coulomb forces.

4.2. Magnetic Energy

The circulating negative q_1 and q_2 charges form a loop current I which has a steady state magnetic energy appearing as the electron magnetic moment. Generally, when a charge q moves with velocity $\boldsymbol{v}$, the magnetic flux $\boldsymbol{B}$ that the charge creates at position $\boldsymbol{r}$ is expressed by the Biot-Savart law,

$$\boldsymbol{B}(\boldsymbol{r}) = \frac{\mu_0}{4\pi} \cdot \frac{q\boldsymbol{v} \times \boldsymbol{r}}{r^3} = \frac{\mu_0}{4\pi} \nabla \times \frac{q\boldsymbol{v}}{r}, \tag{5}$$

where μ_0 is the permeability in vacuum. As we assume that the moving charges q_1 and q_2 are located opposite each other with respect to the origin as shown in **Figure 2(1)**, we can set the coordinates of q_0 at the origin of coordinate, q_1 at $a = (a\cos\phi, a\sin\phi, 0)$, and q_2 at $-a$. Then $\boldsymbol{r}$ in Equation (5) should be substituted by $-2a$ for q_1 and $2a$ for q_2. Also if we assume that the q_1 and q_2 move counterclockwise ($\mathrm{d}\phi/\mathrm{d}t = \omega_0 > 0$) in a circle orbit around the q_0, the velocity $\boldsymbol{v}$ can be defined as $v = \mathrm{d}a/\mathrm{d}\phi = a\omega_0(-\sin\phi, \cos\phi, 0)$, and the velocities of q_1 and q_2 are $\boldsymbol{v}_1 = \boldsymbol{v}$ and $\boldsymbol{v}_2 = -\boldsymbol{v}$, respectively, where $|\boldsymbol{v}| = a\omega_0 \equiv c$. Then the corresponding vector products $\boldsymbol{v} \times \boldsymbol{r}$ in Equation (5) for q_1, $\boldsymbol{v}_1 \times (-2\boldsymbol{a})$, and q_2, $\boldsymbol{v}_2 \times (2\boldsymbol{a})$, become the same $-2\boldsymbol{v} \times \boldsymbol{a}$. In this geometry, the moving q_2 generates a magnetic flux density $\boldsymbol{B}_2$ at q_1, while the moving q_1 generates a magnetic flux density $\boldsymbol{B}_1$ at q_2. Then each magnetic flux density $\boldsymbol{B}_i$ ($i = 1, 2$) is given by

$$\boldsymbol{B}_i = \frac{\mu_0}{4\pi} \cdot \frac{(-q_p)(-2\boldsymbol{v} \times \boldsymbol{a})}{(2a)^3} = \frac{\mu_0}{4\pi} \cdot \frac{(-q_p) 2a^2 \omega_0}{8a^3} \tilde{\boldsymbol{z}}, \tag{6}$$

$$B_{iz} = -\frac{\mu_0}{4\pi} \cdot \frac{q_p c}{4a^2}, \tag{7}$$

where $\tilde{z}$ is the unit vector in the z direction and B_{iz} is the z component of $\boldsymbol{B}_i$, indicating that the directions of $\boldsymbol{B}_i$ at the moving q_1 and q_2 are the same $-z$ direction, following that Lorentz forces exert them in the opposite outward directions (**Figure 2**).

The calculation of the magnetic energy is difficult by integrating the magnetic energy density $u_{\text{mag}} = \frac{1}{2}(\boldsymbol{H} \cdot \boldsymbol{B})$ all over the space, and instead, it is easier to calculate it by using the vector potential $\boldsymbol{A}$ and the current density $\boldsymbol{j}$ of the loop current, since a moving charge has a well-defined EM momentum, $\boldsymbol{p} = q\boldsymbol{A}$. The magnetic energy of a charge can be calculated by the next formulas,

$$U_{\text{mag}} = \frac{1}{2}\int \boldsymbol{H}(\boldsymbol{r}) \cdot \boldsymbol{B}(\boldsymbol{r}) \mathrm{d}V = \frac{1}{2\mu_0}\int |\boldsymbol{B}(\boldsymbol{r})|^2 \mathrm{d}V$$

$$= \frac{1}{2\mu_0}\int \left[\boldsymbol{A}(\boldsymbol{r}) \cdot (\nabla \times \boldsymbol{B}(\boldsymbol{r})) + \nabla \cdot (\boldsymbol{A} \times \boldsymbol{B}(\boldsymbol{r}))\right] \mathrm{d}V \tag{8}$$

$$\simeq \frac{1}{2}\int \boldsymbol{A}(\boldsymbol{r}) \cdot \boldsymbol{j}(\boldsymbol{r}') \mathrm{d}V' = \frac{1}{2} I \oint \boldsymbol{A} \cdot \mathrm{d}\boldsymbol{l}. \tag{9}$$

In Equation (8), the second volume integral for large r becomes zero, and in Equation (9), the volume integral can be replaced with a line integral along the current loop.

In the tripole model, q_1 (q_2) feels the vector potential $\boldsymbol{A}_2$ ($\boldsymbol{A}_1$) associated with the magnetic flux density $\boldsymbol{B}_2$ ($\boldsymbol{B}_1$) generated by q_2 (q_1). From Equation (5) and the formula $\boldsymbol{B} = \nabla \times \boldsymbol{A}$, the vector potential $\boldsymbol{A}(\boldsymbol{r})$ can be inferred to be

$$\boldsymbol{A}(\boldsymbol{r}) = \frac{\mu_0}{4\pi} \cdot \frac{(-q_p)\boldsymbol{v}}{r}. \tag{10}$$

Then the vector potential for both q_1 and q_2 is given by

$$\boldsymbol{A} = -\frac{q_p \boldsymbol{v}}{8\pi\epsilon_0 c^2 a}, \tag{11}$$

using the relation $\mu_0 = 1/\epsilon_0 c^2$.

The magnitude of the loop current I_1 by the q_1 is given by $I_1 = -q_p/T$, where T is the period of one cycle ($= 2\pi a/c$), following that $I_1 = -q_p c/2\pi a$. The loop current I_2 by the q_2 is the same as I_1, and the total loop current I becomes $-q_p c/\pi a$. Noting that $|\boldsymbol{v}| = a\omega_0 = c$, the magnetic energy U_{mag} is calculated by substituting these terms to Equation (9),

$$
\begin{aligned}
U_{\text{mag}} &= \frac{1}{2} I \oint \boldsymbol{A} \cdot \mathrm{d}\boldsymbol{l} = \frac{1}{2}\left(-\frac{q_p c}{\pi a}\right) \cdot \left(-\frac{q_p}{8\pi\epsilon_0 ca}\right) \cdot \pi a \\
&= \frac{q_p^2}{8\pi\epsilon_0 a} = \frac{kq_p^2}{2a}.
\end{aligned} \tag{12}
$$

It is interesting to note that the derived form of U_{mag} is the same as U_{rad} (Equation (4)), namely, the magnitudes of the radiating electric and magnetic energy of the electron are equal.

4.3. Total Energy and Electron Mass

From the above arguments, we obtain the total energy of the electron U_{tot},

$$
\begin{aligned}
U_{\text{tot}} &= U_{\text{int}} + U_{\text{rad}} + U_{\text{mag}} \\
&= \frac{kq_p^2}{a}\left(-\frac{3}{2} + \frac{1}{2} + \frac{1}{2}\right) = -\frac{kq_p^2}{2a}.
\end{aligned} \tag{13}
$$

The total energy is negative, indicating that the tripole electron structure is stable.

As the above U_{tot} is derived in terms of the Planck charge q_p, it can be converted to the expression using the elementary charge e by applying the relation between the two charges,

$$
\alpha = \frac{e^2}{4\pi\epsilon_0 c\hbar} = \frac{e^2}{q_p^2}. \tag{14}
$$

Thus the square root of the fine-structure constant $\sqrt{\alpha}$ is regarded as a scaling factor converting q_p to e as mentioned earlier. The elementary charge e is the reduced value of q_p due to the screening by vacuum polarization. In the Bohr's atom model, the shortest distance between the circulating electron and the nucleus is 5.29×10^{-11} m (the Bohr radius). Further, from the well-known relations, $r_e = \alpha\lambda_C / 2\pi = \alpha^2 b$, where r_e is the classical electron radius (in the tripole model, r_e corresponds to $2\alpha a$), λ_C is the Compton wavelength (=2.43×10^{-12} m) and b is the Bohr radius, indicating that the radius a ($= r_e/2\alpha = 1.93\times10^{-13}$ m) is much smaller than the Bohr radius. Accordingly, the space as wide as the Bohr radius would possibly contain a large number of dipoles by vacuum polarization that screen the electric field of the bare charge q_p. This may also be interpreted that the effective dielectric constant of the space is equivalent to $1/\sqrt{\alpha}$ [12]. In the tripole model, it is postulated that the radius a is sufficiently small such that the probability of dipole creation in the tripole structure is low to ensure the stability of the structure. Finally, Equation (13) can be expressed using Equation (14) as

$$
U_{\text{tot}} = -\frac{ke^2}{2\alpha a}. \tag{15}
$$

We can now derive the rest mass of the electron from this total energy and using the relativistic energy-mass relation, $\left(m_0 c^2\right)^2 = E^2 - |c\boldsymbol{p}|^2$, where m_0 is the rest mass and E is the total energy of the electron. At rest, as the kinetic energy $|c\boldsymbol{p}|$ is zero, the energy-mass relation becomes

$$\left(m_0c^2\right)^2 = U_{\text{tot}}^2 = \left(-\frac{ke^2}{2\alpha a}\right)^2. \tag{16}$$

Then we obtain the rest mass energy U_{rm} (>0) as

$$U_{\text{rm}} = m_0c^2 = \frac{ke^2}{2\alpha a}. \tag{17}$$

The negative solution ($U_{\text{rm}} < 0$) of Equation (16) corresponds to the rest mass energy of the positron. Since this expression is similar to the conventional formula defining the classical electron radius r_e, the product $2\alpha a$ in Equation (17) can be regarded as r_e. It is interesting to note that the derived value of U_{rm} is the same as both U_{rad} (Equation (4)) and U_{mag} (Equation (12)), and this coincidence may be the cause for that the theoretical attribution of the EM mass has been unsettled so far.

Since the rest mass m_0 is a constant and the radius a is the only one variable with the dimension of length in Equation (17) determining the electron mass in the tripole model, when the center of mass moves with velocity w, the variable a will contract according to the Lorentz contraction and should be expressed as $a\sqrt{1-(w/c)^2} \equiv a/\gamma$. Then the energy of the electron E can be transformed as,

$$\begin{aligned} E &= \frac{ke^2}{2\alpha a} \simeq \frac{ke^2}{2\alpha a}\left(1+\frac{w^2}{2c^2}\right) \quad (w \ll c) \\ &= m_0c^2 + \frac{1}{2}m_0w^2. \end{aligned} \tag{18}$$

This indicates that the Lorentz contraction of the radius a directly induces the relativistic expression of the energy of the electron E. Therefore, the presence of a finite dimension for the electron is consistent with the theory of relativity. In this regard, it should be noted that the dimension of electron can decrease to less than 10^{-18} m in the high energy range of 100 - 200 GeV where the experiments to determine the size of electron were conducted [2].

5. Magnetic Properties

5.1. Angular Momentum

According to the Bohr's atom model in which an electron with mass m moves in a circle orbit around a central positive charge with radius b and velocity v, the orbital angular momentum L and the magnetic moment μ_e are expressed as

$$L = mvb \equiv \hbar \tag{19}$$

$$\begin{aligned} \mu_e &= IS = -\frac{ev}{2\pi b}\cdot \pi b^2 = -\frac{1}{2}evb \\ &= -\frac{e\hbar}{2m} = -\frac{g_e e}{2m}\cdot\frac{\hbar}{2}\left(\equiv -\mu_{\text{B}}\right), \end{aligned} \tag{20}$$

where I is the magnitude of the current, S is the area surrounded by the orbit, g_e is the Landé g factor of the electron (≃2) and μ_{B} is the Bohr magneton.

On the other hand, in the tripole model, the orbital angular momentum J_i of q_i, ($i = 1,2$) is expressed using the vector potential (Equation (11)) and Equation (14) as

$$\begin{aligned} J_i &= (-q_p)Aa = (-q_p)\cdot\left(-\frac{q_p}{8\pi\epsilon_0 ca}\right)\cdot a \\ &= \frac{q_p^2}{4\pi\epsilon_0 c\hbar}\cdot\frac{\hbar}{2} = \frac{\hbar}{2}, \end{aligned} \tag{21}$$

$$J = J_1 + J_2 = \hbar. \tag{22}$$

In the Bohr model, the angular momentum L was "postulated" to be quantized as the reduced Planck constant $\hbar$ (Equation (19)), while the tripole structure of the electron "naturally" derives $\hbar$ as the total angular momentum. This natural derivation of $\hbar$ is due to the use of the bare charge q_p instead of the elementary charge e, since q_p is equivalent to a universal constant $\sqrt{\hbar/c \times 10^7}$ [26]. The total angular momentum $\hbar$ derived from the tripole model (Equation (22)) is the same as in the Bohr's model (Equation (19)), whereas it is twice the spin angular momentum $\hbar/2$ (spin-half) which is commonly accepted as the spin angular momentum of the electron. In this connection, it is noted that the spin-half was theoretically derived based on the result of the Stern-Gerlach experiment which showed that a silver beam was split "twofold" by a nonuniform magnetic field [27] and the magnetic quantum number of the electron was formulated as $(2s+1)$ analogously to the form of orbital angular momentum $(2l+1)$. However, it should be noted that the spin-half has brought a new enigma that the observed magnetic moment of the electron is twice the value expected from the spin-half, which required the introduction of the g factor of 2.

The total angular momentum J (Equation (22)) can be formally rewritten as follows analogously to the Bohr model (Equation (19)),

$$J = \hbar = \tilde{m}ca, \tag{23}$$

where $\tilde{m}$ is a virtual mass associated with the two negative charges as explained below. Equation (23) expresses the quantum mechanical constant in terms of classical mechanics where a point mass is circulating around a fixed center. The energy of the electron with rest mass m_0 (Equation (17)) can also be derived from Equation (23) by equating $\tilde{m}$ with $2m_0$ and using Equation (14),

$$\begin{aligned} m_0c^2 &= \frac{\tilde{m}}{2}c^2 = \frac{c\hbar}{2a} = \frac{q_p^2}{4\pi\epsilon_0 c\hbar}\cdot\frac{c\hbar}{2a} \\ &= \frac{kq_p^2}{2a} = \frac{ke^2}{r_e}. \end{aligned} \tag{24}$$

The worked replacement of $\tilde{m}$ with $2m_0$ suggests that m_0 corresponds to each charge. If we rearrange the right side of Equation (23) as $J = 2m_0c\cdot a = m_0c\cdot 2a$, the second term simply expresses the angular momentum of two particles each with mass m_0 and radius a rotating around a fixed center of mass. On the other hand, the third term can be regarded as the angular momentum of a single particle with mass m_0 rotating around a fixed center with radius $2a$, which is the same geometry as the Bohr model. The latter interpretation is possible if we regard the mass m_0 as the reduced mass of the two particles and the radius $2a$ as the distance between one rotating particle and the other fixed particle.

5.2. Intrinsic Magnetic Moment

In the tripole model, the magnetic moment μ_m generated by the loop current shown in Figure 2 is expressed using Equation (23) as

$$\begin{aligned}\mu_\text{m} &= IS = 2\cdot\frac{q_p c}{2\pi a}\cdot\pi a^2 \\ &= q_p ca = \frac{q_p \hbar}{2m_0}.\end{aligned} \tag{25}$$

The expression of μ_m becomes identical to the μ_B by multiplying the scaling factor $\sqrt{\alpha}$.

$$\sqrt{\alpha}\mu_\text{m} = \frac{e\hbar}{2m_0} = 2\cdot\frac{e}{2m_0}\cdot\frac{\hbar}{2} = \mu_\text{B}. \tag{26}$$

Although the magnetic moment is a magnetic quantity, its origin is the motion of the negative charges. The value of μ_B (5.788×10^{-5} eV/T) is a measured one at distances much greater than the atomic size, so that the value can be influenced by vacuum polarization. Accordingly, the μ_m value must be converted to the μ_B value by multiplying the scaling factor $\sqrt{\alpha}$.

In the usual formula of μ_B (Equation (20)), it is necessary to introduce the g_e factor (=2) to match it with the μ_B value which is twice the value expected from the value of $\hbar/2$ commonly accepted as the spin angular momentum. In contrast, based on the tripole model, the formula of μ_B can be naturally derived without introducing the g_e factor, since the factor of 2 is potentially included in the angular momentum $\hbar$ as shown in Equation (26).

5.3. Magnetic Flux Quantum

In connection with the magnetic moment, the magnetic flux Φ_0 generated by the loop current can be derived using the vector potential (Equation (11)) and using Equation (14) as

$$\begin{aligned}\Phi_0 &= 2\oint A\text{d}l = 2\cdot\frac{q_p}{8\pi\epsilon_0 ca}\cdot 2\pi a \\ &= \frac{q_p^2}{4\pi\epsilon_0\hbar c}\cdot\frac{2\pi\hbar}{q_p} = \frac{h}{q_p}.\end{aligned} \tag{27}$$

This relation is similar to the definition of the Dirac's quantization condition of the electron charge as expressed by the next formula [28] except for that the electron charge is not e but q_p,

$$\frac{eg_\text{m}}{\hbar} = 2\pi n \quad (n = 0, \pm 1, \pm 2, \cdots), \tag{28}$$

where $g_{\rm m}$ is the magnetic charge of the magnetic monopole. In the case of $|n|=1$, this formula becomes $g_{\rm m}=h/e$. So the magnetic flux h/q_p derived in Equation (27) is regarded as a modification of the magnetic flux quantum. It is notable that this derived value h/q_p is consistent with the theoretical conclusion in a topological theory discussing the discretization of the electric charge [29], in which the discretized charge proved to be q_p which is greater than e by a factor of $1/\sqrt{\alpha}$ (3.3 in natural units and 11.7 in SI units). Accordingly, the magnetic flux generated by the loop current of the tripole structure shown in Equation (27) can be regarded as the magnetic flux quantum. Hence, the tripole electron structure naturally provides the quantized electric charge and the magnetic flux quantum in a self-consistent manner with the use of q_p.

6. Oscillation of the Current Loop

From Equation (24), the intrinsic momentum m_0c at rest is given by

$$m_0c=\frac{\hbar}{2a}=\frac{h}{4\pi a}. \tag{29}$$

One possible interpretation of the angular momentum by classical mechanics was shown in the subsection 4.4, which is a rotating single particle with the reduced mass m_0 of the two particles and radius $2a$ around the other particle in the rest frame. Here we will show another interpratation conforming specifically to the geometry of the tripole structure shown in **Figure 2**. According to the conventional interpretation, the denominator $4\pi a$ is the Compton wavelength of the electron, and the length $2a$ may be assigned to the radius of a circle with the Compton radius, *i.e.*, the reduced Compton wavelength $\bar{\lambda}_{\rm C}$ (=3.86×10^{-13} m). However, this length is twice the radius a shown in **Figure 2**, and it appears to be difficult to give a simple explanation from a geometrical point of view.

An alternative interpretation is that $4\pi a$ is the one-cycle length of a two-turn loop (Hubius Helix) with curvature radius a [2]. In the tripole model, such trajectory is possible if the center of the current loop oscillates in the z direction relatively with respect to the positive charge, as suggested in the subsection 4.1. On the oscillation, the negative charges q_1 and q_2 draw two-turn loops symmetrically each other with respect to the q_0, *i.e.*, "twin two-turn loops" as illustrated in **Figure 3**. The relative position of the two negative charges and the central positive charge changes with the cycle (1) → (2) → (3) → (4) → (1), returning to their start points with a rotation angle of 4π. One cycle by 4π rotation is a nature of spinors.

The frequency of the oscillation is ω ($=c/2a$) and it is half the angular frequency ω_0 ($=c/a$) of one circular rotation of each negative charge in the absence of the oscillation, *i.e.*, $\omega=\omega_0/2$. From this relation, we can interpret the frequency ω ($=m_0c^2/\hbar$) as the Compton frequency $\omega_{\rm C}$, while the frequency ω_0 as the Zitterbewegung frequency ($=2m_0c^2/\hbar$) [4] [5]. If this interpretation is adopted, the rest mass energy $U_{\rm rm}$ can be written also as

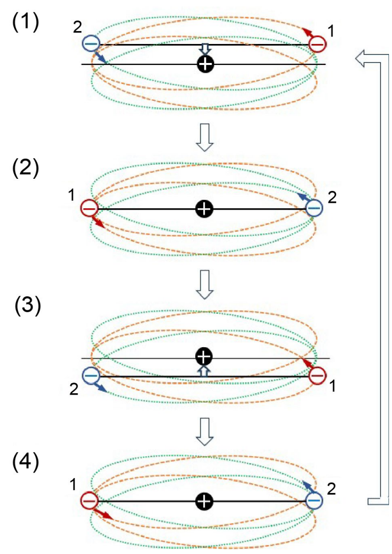

Figure 3. Schematic illustration of the potential *z*-oscillation of the tripole structure. The two negative charges are tentatively denoted by 1 and 2 for an easier understanding and their orbits are shown in different colors. The transition, (1) → (2) → (3) → (4) → (1), corresponds to one cycle.

$$U_{\mathrm{rm}} = \hbar\omega = \frac{\hbar}{2}\cdot\omega_0. \tag{30}$$

As the frequency ω is also of the z direction oscillation, it can be said that it is quantized also in the z direction. It is interesting to note that we can express the rest mass energy in two ways using the two different frequencies, *i.e.*, as the product of unit $\hbar$ and the Compton frequency [5] and as the product of $\hbar/2$ equivalent to the one charge angular momentum (Equation (21)) and the Zitterbewegung frequency. In addition, it is to be indicated that the tripole structure includes an electric dipole moment in the $\pm z$ direction alternatively with the frequency of ω_{C}, so that its observed value will be extremely small, in agreement with the experimental result [30].

7. Multipole Lepton Concept

7.1. The Concept

As shown earlier, the tripole electron model could be constructed to fully conform to the main electron-positron pair creation process (the Breit-Wheeler process). Further to this, we mentioned that the tripole electron model is based on the wider concept which can be extendable to other various elementary particle reactions. The basic concept is that the elementary particles (mainly leptons here) are composites of multiple poles, and we will refer to it as the multipole lepton (MPL) concept. Here we mean the "pole" as a topological singular point of the electric fields which has ± polarity in units of unity, and define the electrical charge as the product of the pole and the unit charge (q_p or e). According to the concept, the positive and negative poles generated from the dipoles in the PV are the building blocks of leptons such as electrons and neutrinos and their antileptons.

Similar ideas that the existing elementary particles are the composites of tiny two or three kinds of building blocks (preons) [31] has been presented so far as various specific models. Each model intended to reproduce all the known elementary particles (fermions of three flavors and bosons) in a unified manner with satisfying the conservation of the various quantum numbers that those elementary particles have. However, they have not succeeded in explaining the mass difference or the reaction dynamics between the particles.

In contrast, the tripole model of the electron and positron ($q_p^- q_p^+ q_p^-$, $q_p^+ q_p^- q_p^+$) are to be understood rather as the lepton counterpart of the nucleon (proton, neutron) structures composed of three quarks (uud, udd). Further, the MPL concept would be only applicable to light mass leptons, where EM forces are the confinement force working on the circulating electric charges. In the high energy (heavy mass) region, the quarks are regarded as the constituent particles which have a different type of charges (color charges) with different symmetry and fractional values (±1/3, ±2/3), and the gluons confine the quarks by the strong force. Therefore, it would not succeed in accounting for the structures of all elementary particles only by a single class of constituents.

According to our new concept, the leptons are created by the reconstruction of the poles which are produced from the dipoles in the PV when they collide or by strong EM fields. If there are n poles of + polarity and m poles of − polarity involved in a reaction process, where n, m are positive integers, we define the total pole number N as $n+m$, and the net charge Γ as $(+1)n+(-1)m = n-m$. The Γ value may be in units of q_p or e. Although the reconstruction would occur under the above-mentioned various conservation rules, the conservation of the net charge Γ under the restriction of $|n-m| \le 1$ is the first basic rule to be satisfied in this concept. In contrast, the total pole number N involved in a reaction process may be increased by the participation of dipoles in units of one pair ($n = m = 1$).

According to these definitions, we can assign $N = 2$ and $\Gamma = 0$ ($n = m = 1$) to the photon, and $N = 3$ and $\Gamma = -1$ to the electron, where we adopted the minimum numbers $n = 1$, $m = 2$ for the electron ($n = 2$, $m = 1$ for the positron) for simplicity. The composite of $N = 5$ also makes a $\Gamma = -1$ particle when $n = 2$, $m = 3$, which can be speculated to be another flavor electron like muon. When $N = 1$ ($n = 1$, $m = 0$ or $n = 0$, $m = 1$), it is an electric monopole. It is expected that it has a large self-energy due to its strong electric field so that it would attract surrounding dipoles to mitigate it.

7.2. Other Electon Creation Processes

The other creation and annihilation processes of the electron and positron other than the above two-photon process may be explained based on the MPL concept with wider flexibility by the participation of adjoining dipoles existing in the PV. For example, the three-photon annihilation of an electron-positron pair (positronium) $e^- + e^+ \to 3\gamma$ can be intuitively understood as the reconstruction of an electron ($q_p^- q_p^+ q_p^-$) and a positron ($q_p^+ q_p^- q_p^+$) to three photons 3($q_p^+ q_p^-$) as can be seen from **Figure 1**. Although the preexisting models conformed to the pair creation process $2\gamma \to e^- + e^+$ [5] [6] may also account for the two-photon annihilation process $e^- + e^+ \to 2\gamma$ as the reverse process of the creation process, it would be difficult to give an explanation for the three-photon annihilation process.

Further, the MPL concept can address processes involving nucleons (quarks), for example, the well-known β^- decay which is another process creating an electron,

$$n \to p^+ + W^-,\ W^- \to e^- + \bar{\nu}_e, \tag{31}$$

where n is the neutron, p is the proton, W^- is the negative weak boson and $\bar{\nu}_e$ is the electron anti-neutrino. In the quark level, a down quark d in the neutron (udd) transforms to an upp quark u to produce a proton (uud). The excess −1 charge of the quark is released as the weak boson W^- and this becomes the source of the e^- and $\bar{\nu}_e$. Interpretation of this process according to the MPL concept is as follows: Since the quark charges and the dipole charges are quite different in their symmetry and nature, the weak boson W^- can be regarded as a transient state which involves charge conversion processes from the fractional (color) charges to the integer (electric) charges. This transient state may take a form of plasma with a very short lifetime equivalent to the great mass of ~80 GeV/c^2. Following the charge conversion process, a cluster of poles with the Γ of −1 is generated and reconstructed to form the e^- and $\bar{\nu}_e$.

7.3. Photon Radiation Process

Other than the electron creation processes, the phenomenon of the creation and radiation of photons by accelerating an electron is easily explained based on the MPL concept. The accelerated electron by an outer EM field will gain translational momentum and transfer part of the gained momentum to a collided dipole temporary existing in the PV. The dipole that acquired the momentum by the collision becomes a stable quantum dipole, *i.e.*, a photon, and will be flicked off in a certain direction. In this way, a shower of collided dipoles (photons) with transferred kinetic momentum and energy will be radiated toward the directions around the acceleration direction.

7.4. Pole Clusters with $N > 3$

By the previous subsection, the cases that the total pole number N is 2 (photon) and 3 (electron and positron) have been argued. Further to these, it is interesting to consider the cases of N greater than 3. In the case of $N = 4$, the only possible combination that satisfies $|\Gamma| \le 1$ is $n = m = 2$ with $\Gamma = 0$, and we suggest that this quadrupole may correspond to the electron neutrino as will be argued in the following. If assuming a simplest square geometry of ($q_p^+ q_p^- q_p^+ q_p^-$) with vertexes of alternatively positioned q_p^+ and q_p^-, its structure does not change even if the polarity of the charges are interchanged, indicating that its antiparticle is the same as itself, *i.e.*, a Majorana neutrino. The electron capture process may directly support that N is 4 for the neutrino. In the electron capture process (32) [32], an orbit electron in an atom is absorbed into its nucleus, and a proton p transforms to a neutron n with producing a neutrino through the process,

$$p + e^{-} \to n + \nu_e. \tag{32}$$

The simplest interpretation of this process based on the MCL model is that the total charge of the nucleon reduces from +1 to 0 and the released +1 charge (pole) increases the N of the lepton from $N = 3$ ($\Gamma = -1$) of the electron to $N = 4$ ($\Gamma = 0$) of the neutrino.

Further, if assuming that the quadrupole rotates around an axis perpendicular to the square, the axis direction component of the magnetic field generated by each loop current of q_p^{+} and of q_p^{-} will be canceled because the directions of the two currents are opposite, so that the magnetic moment will be zero or significantly small. This conjecture agrees with the experimental result that the magnetic moment of the electron neutrino is significantly small ($< \sim 3 \times 10^{-11} \mu_{\text{B}}$) [33]. With regard to the mass, it is difficult to directly conjecture the very small estimated mass (< 2.2 eV/c^2) [34] from the quadrupole neutrino model. However, according to the theoretical derivation that the neutrino masses are proportional to the magnetic moment [33], the nearly-zero magnetic moment of the quadrupole model agrees with the very small mass.

When N is an even number and $n = m$, a pole cluster with $\Gamma = 0$ can be formed with a ($-q_p^{+} - q_p^{-} -$) ring geometry, though as N becomes larger, its generation probability will get smaller. In the case of $N = 6$ (hexapole), it may exist as a six-membered ring geometry, as it is one of the most stable configuration at least in the molecule level. Also, this structure provides the property of zero or very small magnetic moment. Further, in the case of $N = 8$ (octupole), it may exist as a hexahedron geometry with opposite charges alternately positioned at the eight vertexes of the hexahedron. This structure may also provide the property of zero or very small magnetic moment. Thus these $\Gamma = 0$ pole clusters remain as candidates for the neutrinos.

8. Conclusions

We have proposed the tripole electron model in which the electron is composed of a positive charge and two negative charges circulating around it. In the tripole model, the confinement force for the outer charges, which has been a crucial issue in the modeling of the electron structure, is the well-established EM centripetal force. In the calculations of various energies associated with the charges, the Planck charge, a bare charge unscreened by vacuum polarization, was used instead of the elementary charge. Under these postulations, the tripole electron structure was found to be stable and could provide the formulations for the intrinsic properties of the electron such as charge, intrinsic magnetic moment, and rest mass.

The total angular momentum of the circulating charges was derived to be $\hbar$ which is the same as the Bohr's atom model, meaning that the g_e factor (=2) in the Bohr magneton is potentially included in the framework of the tripole electron model without artificially introducing it. This derivation differs from the currently accepted spin angular momentum of $\hbar/2$, while it can naturally account for that the measured intrinsic momentum is twice the value expected from the $\hbar/2$.

The intrinsic magnetic moment μ_{m} generated by the loop current by the circulating charges was derived, and it was transformed to the μ_{B} value by multiplying the scaling factor $\sqrt{\alpha}$. Furthermore, the associated magnetic flux Φ_0 generated by the loop current proved to be equivalent to the magnetic flux quantum derived based on the topological theory.

Also, the expression of the rest mass was derived from the total energy of the static interaction, electrostatic and magnetic energies of the tripole system using the relativistic energy-mass equation, which proved to be the same as the conventional expression giving the classical electron radius. Further, the possibility of the oscillation of the tripole structure in the z direction was indicated, which provides a twin two-turn loop orbit to the moving charges and a 4π period of rotation for each charge.

The extended idea of the multipole lepton (MPL) concept on which the tripole electron model was based was also presented. The concept is that the light mass leptons are composed of multiple electric poles originated from the electric dipoles existing in the vacuum. We showed that some examples of reactions associated with the electron can be elucidated at least qualitatively by the MPL concept, e.g., other reactions to produce electrons such as the β^- decay process which involves the transformation of the quarks to the leptons. Furthermore, possible multipole structures were presented for other leptons such as neutrinos, which can give a semiquantitative elucidation for the basic properties of the neutrino. Exploring the elementary particles based on the MPL concept will provide a new path to understand the elementary particle physics in a deeper layer.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] Consa, O. (2018) Helical Solenoid Model of the Electron. *Progress in Physics*, **14**, 80-89.

[2] Hu, Q. (2004) The Nature of the Electron. *Physics Essays*, **17**, 442-458. https://doi.org/10.4006/1.3025708

[3] Hestenes, D. (2020) Zitterbewegung Structure in Electrons and Photons. arXiv: 1910.11085.

[4] Barut, A.O. and Bracken, A.J. (1981) Zitterbewegung and the Internal Geometry of the Electron. *Physical Review D*, **23**, 2454-2463. https://doi.org/10.1103/physrevd.23.2454

[5] Williamson, J.G. and van der Mark, M.B. (1997) Is the Electron a Photon with Toroi-

dal Topology? *Annales de la Fondation Louis de Broglie*, **22**, Article 133.

[6] Bowen, D. and Mulkern, R.V. (2015) An Electron Model Consistent with Electron-Positron Pair Production from High Energy Photons. *Journal of Modern Physics*, **6**, 1334-1342. https://doi.org/10.4236/jmp.2015.69138

[7] Markoulakis, E. and Antonidakis, E. (2022) A ½ Spin Fiber Model for the Electron. *International Journal of Physical Research*, **10**, 1-17. https://doi.org/10.14419/ijpr.v10i1.31874

[8] Blinder, S.M. (2001) General Relativistic Models for the Electron. arXiv: math-ph/0105029.

[9] Burinskii, A. (2008) The Dirac-Kerr-Newman Electron. arXiv: hep-th/0507109.

[10] Mainland, G.B. and Mulligan, B. (2020) Polarization of Vacuum Fluctuations: Source of the Vacuum Permittivity and Speed of Light. *Foundations of Physics*, **50**, 457-480. https://doi.org/10.1007/s10701-020-00339-3

[11] Leuchs, G., Hawton, M. and Sanchez-Soto, L.L. (2021) Physical Mechanisms Underpinning the Vacuum Permittivity. arXiv: 2110.07223.

[12] Daywitt, W.C. (2009) The Planck Vacuum. *Progress in Physics*, **1**, 20-26.

[13] Wikipedia. Casimireffect. https://en.wikipedia.org/wiki/Casimireffect

[14] Fleming, R. (2018) Electron Properties Explained as Quantum Field Effects. https://www.researchgate.net/publication/327835183

[15] Fleming, R. (2017) Photons as Quantum Electron-Positron Composites. https://www.researchgate.net/profile/Ray-Fleming/publication/335319213

[16] Drozdov, I.V. and Stahlhofen, A. A. (2018) How Long Is a Photon? arXiv: 0803.2596v1.

[17] Xu, W. (2013) Light: Duality or Discontinuity? *Optics and Photonics Journal*, **3**, 98-101. https://doi.org/10.4236/opj.2013.31016

[18] Vic Dannon, H. (2012) Electron's Spin, Diffraction, and Radius. *Gauge Institute Journal*. http://www.gauge-institute.org/wave-particle/ElectronRing.pdf

[19] Wikipedia. Breit-Wheeler Process. https://en.wikipedia.org/wiki/Breit-Wheelerpro-cess

[20] Yu, J.Q., Lu, H.Y., Takahashi, T., Hu, R.H., Gong, Z., Ma, W.J., *et al.* (2019) Creation of Electron-Positron Pairs in Photon-Photon Collisions Driven by 10-PW Laser Pulses. *Physical Review Letters*, **122**, Article 014802. https://doi.org/10.1103/physrevlett.122.014802

[21] Mills, A.P. (1981) Observation of the Positronium Negative Ion. *Physical Review Letters*, **46**, 717-720. https://doi.org/10.1103/physrevlett.46.717

[22] Bressanini, D. (2021) Internal Structure of the Positronium Ion Ps−. *Physical Review A*, **104**, Article 022819. https://doi.org/10.1103/physreva.104.022819

[23] Armour, E.A.G., Richard, J.M. and Varga, K. (2024) Stability of Few-Charge Systems in Quantum Mechanics. arXiv: physics/0411204.

[24] Feynman, R.P., Leighton, R.B. and Sands A. (1977) The Feynman Lectures on Physics. Chap. 28-3. Addison-Wesley.

[25] Jiménez, J.L. and Campos, I. (1999) Models of the Classical Electron After a Century. *Foundations of Physics Letters*, **12**, 127-146. https://doi.org/10.1023/a:1021656906106

[26] Haug, E.G. (2022) Potential Simplification of Charge and the Coulomb Force without Affecting Predictions. *Journal of Applied Mathematics and Physics*, **10**, 3003-3015. https://doi.org/10.4236/jamp.2022.1010201

[27] Wikipedia. Stern-Gerlach Experiment. https://en.wikipedia.org/wiki/Stern-Gerlachexperiment

[28] Jackson, J.D. (2019) Classical Electrodynamics. 3rd Edition, Wiley.

[29] Rañada, A.F. and Trueba, J.L. (1998) A Topological Mechanism of Discretization for the Electric Charge. *Physics Letters B*, **422**, 196-200. https://doi.org/10.1016/s0370-2693(98)00071-9

[30] Hudson, J.J., Kara, D.M., Smallman, I.J., Sauer, B.E., Tarbutt, M.R. and Hinds, E.A. (2011) Improved Measurement of the Shape of the Electron. *Nature*, **473**, 493-496. https://doi.org/10.1038/nature10104

[31] Dugne, J-J., Fredriksson, S., Hansson, J. and Predazzi, E. (1999) Preon Trinity—A New Model of Leptons and Quarks. arXiv: hep-ph/9909569.

[32] Wikipedia. Electron Capture. https://en.wikipedia.org/wiki/Electroncapture

[33] Alexander, S. (2016) Status and Perspectives of Neutrino Magnetic Moments. *Journal of Physics*: *Conference Series*, **718**, Article 062076. https://doi.org/10.1088/1742-6596/718/6/062076

[34] Dev, A. (2023) Neutrino Oscillations and Mass Models. arXiv: 2310.17685.