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Electric and Magnetic Fields Due to Massive Photons and Their Consequences

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Abstract—Allowing photons to bear mass, the electric and magnetic fields of a steadily moving charge are no longer perpendicular to each other, as anticipated from Biot-Savart law. The electric and magnetic fields of such a particle depend on the gauge potentials, φ and $\vec{A}$. The orthogonality relations of the particle fields and the direction of motion depend on the mass of the photon. The non-relativistic correction to the particle fields was found to be related to the Lorenz gauge condition. It is shown that the existence of magnetic monopoles inside matter is inevitable when magnetic field is applied in a conductor. Their existence is a manifestation of the massive nature of the photon inside matter. Neither electric nor magnetic current is separately conserved for photons, but their sum is. Massive photons are found to produce electric and magnetic fields. A force proportional to the square of the current is found to act along the wire, $F = \frac{1}{2}\mu_0 I^2$, where μ_0 is vacuum permeability.

1. INTRODUCTION

Modern physics relies entirely on the intimate relations between electricity and magnetism. Maxwell had already formulated the theory of electricity and magnetism. This theory, however, does not reflect all symmetry properties existing between electricity and magnetism. For instance, while isolated charges can exist in nature, magnet charges (poles) cannot be isolated. Therefore, within the framework of Maxwell theory, magnetic monopoles are not allowed to exist. Moreover, the electromagnetic field is carried by massless photons. A theory with massive photons brings about several difficulties [1–5]. Such a theory lacks gauge invariance that endows a theory a great power of predictability. Of these types is the Proca theory that extends Maxwell theory to include massive photons [6]. Though this theory is Lorentz invariant, it loses gauge invariance. Despite this impasse it finds application in physics in particular in superconductivity. In our present formulation, we consider the possibility and implication of massive photons, and explore their consequences in physics. A theory with massive photon can be achieved by invalidating the Lorenz gauge condition that is one of the cornerstones of Maxwell theory [7]. This invalidation is found to be associated with the photon mass [8]. Thus, a massive photon that is described by a modified Maxwell equation will render the photon be described by a quantum theory as well. Hence, a quantum mechanical representation for the photon is via its massive nature. One way to do that is to consider the vector and scalar potentials (φ and $\vec{A}$) as the corresponding wavefunctions of the massive photons. To this aim we employ a quaternionic Dirac equation [9]. In this formulation, we generalize the scalar and vector potentials, and treat them as the massive photon wavefunctions. It is not common in quantum mechanics formulation to represent a particle with a vector wavefunction. Recall that in Schrodinger's theory, a particle is represented by a scalar function, whereas in Dirac the particle is represented by a spinor, which has four components. These four components are found to represent a particle and its antiparticle.

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In this work, we assume that a quaternionic potential $\tilde{A}$ is the massive photon wavefunction, and consequently must satisfy Dirac equation. Recall that the spinors in Dirac equations are 4-components object, and a quaternionic scalar consists of 1 vector and a scalar (4-components object too). The group structure between these two objects is studied by [10, 11]. The full mathematical connection between the two groups, the spinor and quaternion groups, has to be investigated.

Some authors however adopt the idea that a proper photon wavefunction is a linear complex combination between the electric and magnetic fields, *viz.*, $\vec{F} = \frac{\vec{E}}{c} + i\,\vec{B}$ [12–15].

We have found that the photon mass significantly alters our fundamental picture we used to know about electromagnetism. Photons in vacuum are massless and massive in a conducting medium. Because of this property a magnetic charge is associated with massive photons. For every magnetic charge there is an electric dipole. Hence, the magnetic flux associated due to magnetic charge is related to twice an electric charge. This relation is revealed in superconductivity. The existence of monopoles is a consequence of violation of charge conservation in a conducting medium.

We proceed in this paper as follows: we introduce in Section 2 the equation for massive photon using quaternionic Dirac's equation, where $\vec{A}$, and φ, are now treated as quaternions. We found in Section 3 that this massiveness nature of photons had modified the ordinary Biot-Savart law. Owing to this, a longitudinal force arises. The massive photons are found to bring about their magnetic and electric currents. The magnetic current is carried by magnetic charges (monopoles). These monopoles (magnetic charges) are but these massive photons. The motion of these photons in a medium produces a magnetic current. The electric and magnetic charges of the photon are related by a Dirac-like quantization. We finally introduce in Section 4 the concept of quantum current, inductance and force. The force seen by a moving charge, where the electric and magnetic fields are generated by massive photon, is similar to the force experienced by a moving particle in a viscous (drag) fluid.

2. THE MODEL

Let us assume that the photon is massive (m), and satisfy the Dirac equation,

$$\gamma^\mu\, p_\mu \psi = mc\psi, \tag{1}$$

where the scalar and vector potentials ($\vec{A}$, φ) are its corresponding wavefunctions. In a quaternionic form, one has

$$\tilde{\gamma}\tilde{P}\tilde{A} = mc\tilde{A}, \quad \tilde{\gamma} = (i\beta, \vec{\alpha}), \quad \tilde{P} = \left(\frac{i}{c}E, -\vec{p}\right), \quad \tilde{A} = \left(\frac{i}{c}\,\varphi, \vec{A}\right). \tag{2}$$

The product of two quaternions, $\tilde{A} = (a_0,\, \vec{a})$ and $\tilde{B} = (b_0,\, \vec{b})$, is given by $\tilde{A}\tilde{B} = (a_0b_0 - \vec{a}\cdot\vec{b},\, a_0\vec{b} + \vec{a}b_0 + \vec{a}\times\vec{b})$. Applying this product in Equation (2), and equating the real and imaginary parts in the two sides of the first equation in Equation (2) to each other, yield

$$\vec{\alpha}\cdot\left(\vec{\nabla}\times\vec{A}\right) = -\frac{m}{\hbar}\varphi, \tag{3}$$

$$\beta\left(\frac{1}{c^2}\frac{\partial\varphi}{\partial t} + \vec{\nabla}\cdot\vec{A}\right) + \frac{\vec{\alpha}}{c}\cdot\left(\frac{\partial\vec{A}}{\partial t} + \vec{\nabla}\varphi\right) = 0, \tag{4}$$

$$-\hbar\beta\vec{\nabla}\times\vec{A} - \frac{\hbar\vec{\alpha}}{c}\times\left(\frac{\partial\vec{A}}{\partial t} + \vec{\nabla}\varphi\right) = mc\vec{A}, \tag{5}$$

and

$$-\frac{\beta\,\hbar}{c}\left(\frac{\partial\vec{A}}{\partial t} + \vec{\nabla}\varphi\right) - \vec{\alpha}\,\hbar\left(\frac{1}{c^2}\frac{\partial\varphi}{\partial t} + \vec{\nabla}\cdot\vec{A}\right) + \hbar\vec{\alpha}\times\left(\vec{\nabla}\times\vec{A}\right) = 0 \tag{6}$$

This formalism will produce the physics of massive photon. Some restricted forms of Maxwell's equations can describe spin-1/2 fields where the four-vector field combined the electric and magnetic fields [15]. Recently, Dvoeglazov modified Dirac formalism and considered a formalism for bosons and fermions [7].

3. THE ELECTRIC AND MAGNETIC FIELD OF A MOVING CHARGE: THE GENERALIZED BIOT-SAVART LAW

The electric and magnetic fields can be expressed in terms of $\vec{A}$ and φ as

$$\vec{E} = -\frac{\partial \vec{A}}{\partial t} - \vec{\nabla}\varphi, \quad \vec{B} = \vec{\nabla} \times \vec{A}. \tag{7}$$

The electric and magnetic fields of massive photons can be obtained if we use Equations (3)–(6). Apply Equation (7) in Equations (3)–(6) to obtain

$$\vec{\alpha} \cdot \vec{B}_s = -\frac{m}{\hbar}\varphi, \tag{8}$$

$$\frac{\beta\,\vec{\alpha}}{c} \cdot \vec{E}_s = \frac{1}{c^2}\frac{\partial \varphi}{\partial t} + \vec{\nabla} \cdot \vec{A}, \tag{9}$$

$$\vec{B}_s = \frac{\beta\,\vec{\alpha} \times \vec{E}}{c} - \frac{mc\beta}{\hbar}\vec{A}, \tag{10}$$

and

$$\vec{E}_s = -c\beta\vec{\alpha} \times \vec{B} + c\beta\vec{\alpha}\left(\frac{1}{c^2}\frac{\partial \varphi}{\partial t} + \vec{\nabla} \cdot \vec{A}\right). \tag{11}$$

$\vec{E}_s$ and $\vec{B}_s$ are the electric and magnetic fields inside the medium generated by massive photons, while, $\vec{E}$ and $\vec{B}$ are those fields associated with massless photon. If we now define, as in Dirac theory, the velocity of the particle as $\vec{v} = c\beta\vec{\alpha}$, then Equations (8)–(11) become

$$\vec{v} \cdot \vec{B}_s = -\frac{mc\beta}{\hbar}\varphi, \tag{12}$$

$$\vec{v} \cdot \vec{E}_s = c^2\left(\frac{1}{c^2}\frac{\partial \varphi}{\partial t} + \vec{\nabla} \cdot \vec{A}\right), \tag{13}$$

$$\vec{B}_s = \frac{\vec{v} \times \vec{E}}{c^2} - \frac{mc\beta}{\hbar}\vec{A}, \tag{14}$$

and

$$\vec{E}_s = -\vec{v} \times \vec{B} + \vec{v}\left(\frac{1}{c^2}\frac{\partial \varphi}{\partial t} + \vec{\nabla} \cdot \vec{A}\right). \tag{15}$$

If we apply Equation (13) in Equation (15) we will get

$$\vec{E}_s = -\vec{v} \times \vec{B} + \vec{v}\left(\frac{\vec{v} \cdot \vec{E}}{c^2}\right). \tag{16}$$

Equations (14) and (16) are the electric and magnetic fields in a moving frame (charge at rest) with respect to the lab frame. These fields can be compared with those obtained by Dvoeglazov and Gonzalez using Lorentz transformation [7]. While they interpret the mass term to the mass of the particle, we relate this mass to that of the field (photon). Hence, a framework encompassing Lorentz transformations of massive field will give a full account on how the massive fields are transformed including their mass.

The force acting on the charged particle (q_e) in its rest frame can be written, employing Equation (16), in the form

$$\vec{F} = m\vec{a} = q_e\vec{E}_s + q_e\vec{v} \times \vec{B}_s.$$

Under certain conditions, Singh and Dadhich have obtained the field equation from the particle equation of motion [16]. They further asserted that the electric and magnetic charges can't exist independently, the existence of one would imply there other. In the same line we have recently derived particle equation (Lorentz force) from the field equations (Maxwell's equations) employing complex formulation [17]. Equation (13) states that the electric field of a moving charge is perpendicular to the particle velocity if Lorenz gauge condition is satisfied, otherwise a longitudinal component is anticipated. The second term in the right hand side of Equation (14) gives the contribution of magnetic field arising from the massive photon. The second term in Equation (16) appears to be a relativistic correction of the electric field produced by the massive photon. This term arises whenever the Lorenz gauge condition is not satisfied. It is absent when this condition is satisfied. It is also proportional to the velocity manifesting a longitudinal nature (along the direction of motion) of the electric field. Therefore, a longitudinal force will be associated with this term. This force appears like a second order correction to the electric force on a moving charge. This amounts to

$$\vec{F}_l = -q_e \vec{v} \left(\frac{\vec{v} \cdot \vec{E}}{c^2} \right). \tag{17}$$

This coincides exactly with our recent theory of longitudinal electroscalar wave described by the scalar function, $\Lambda = \varepsilon_0(\vec{E} \cdot \vec{v})$ [18]. Though it looks small but could be measurable for high electric fields. This force pushes electrons to move along the current direction. It exists only inside conductors and not in vacuum. The impulse imparted to electrons will thus be

$$\Delta p_\ell = F_\ell \, \Delta t = F_\ell \frac{\hbar}{2mc^2} = q_e \frac{\varepsilon_0}{\sigma} \frac{v}{c^2} \left(\vec{v} \cdot \vec{E} \right).$$

Evidently this quantity is significant when intensive field is used (e.g., LASER).

The electric power delivered by the electric field, as seen from Equation (13), is

$$P_e = q_e \vec{v} \cdot \vec{E} = q_e c^2 \left(\frac{1}{c^2} \frac{\partial \varphi}{\partial t} + \vec{\nabla} \cdot \vec{A} \right). \tag{18}$$

As evident from Equations (12) and (13), it is clear that the electric and magnetic potentials influence our physical world. They are physical and not mere mathematical construct. This is in agreement with the Aharonov-Bohm effect where he demonstrated that the phase difference associate with these potentials is physically measurable [19]. Recall that the force acting on a wire bar (of length l) with resistance R drawn in a magnetic field yields a force that is proportional to the velocity, i.e., $F = \frac{l^2 B^2}{R} v$. This is a drag-like force. It thus seems that when moving an object in a static magnetic field, the magnetic fields act as if it were fluid. Hence, the static electric and magnetic fields behave as fluid of massive photons. As a result a longitudinal viscous force would act on the moving charge. Because of this force, some observational effects can be detected.

The magnetic moment associated with orbital motion of photons can interact with the photon magnetic field (second term in Equation (14)) giving an energy of

$$U_l = -\vec{\mu} \cdot \vec{B} = \frac{mc\beta}{\hbar} \vec{\mu} \cdot \vec{A} = -\frac{qc\beta}{2} \vec{r} \cdot \vec{B}, \quad \vec{\mu} = \frac{gq}{2m} \vec{L}, \tag{19}$$

where g is a g-factor for the massive photon, and that $\vec{L} = \vec{r} \times \vec{p}$ (where in quantum mechanics $\vec{p} = -i\hbar\vec{\nabla}$) is the orbital angular momentum. We deduce from Equation (19) that the magnetic dipole moment of massive photons is

$$\vec{\mu} = \frac{g q_e c}{2} \, \vec{r} \, i, \tag{20}$$

where $\vec{r}$ is the radial vector [20]. The magnetic moment described in Equation (20) is referred to as a *longitudinal magnetic moment*. This magnetic moment is found to show up in a giant enhancement of the exciton magnetic moment due to its motion [21]. Since in Dirac theory β is a 4×4 matrix, we expect that magnetic and electric fields in Equations (14) and (15) represent the magnetic and electric fields due to the electric and magnetic charges of a particle and an antiparticle.

We have recently shown that for massive photons the Lorenz gauge condition become [8]

$$\frac{1}{c^2} \frac{\partial \varphi}{\partial t} + \vec{\nabla} \cdot \vec{A} = -\frac{2m}{\hbar} \varphi, \tag{21}$$

and that

$$\vec{A} = -\frac{\mu_0 \hbar^2}{m^2 c^2} \vec{J}, \quad \varphi = -\frac{\mu_0 \hbar^2}{m^2} \rho. \tag{22}$$

Upon applying Equation (21) in Equation (13) we find

$$\vec{v}\cdot\vec{E}_s=-\frac{2mc^2}{\hbar}\varphi, \tag{23}$$

and that Equation (12) becomes

$$\vec{v}\cdot\vec{B}_s=-\frac{mc\beta}{\hbar}\varphi. \tag{24}$$

Multiply Equation (16) by $\vec{B}_s$ and use Equations (23) and (24) to obtain

$$\vec{E}_s\cdot\vec{B}_s=\frac{2m^2c\beta}{\hbar^2}\varphi^2, \tag{25}$$

This equation shows that the departure of the orthogonality of the electric and magnetic fields is a measure of the massiveness of the photon. Using Equation (22), Equations (23) and (24) become

$$\vec{v}\cdot\vec{E}_s=\frac{2\hbar}{\varepsilon_0 m}\rho, \tag{26}$$

and

$$\vec{v}\cdot\vec{B}_s=\frac{c\mu_0\hbar\beta}{m}\rho. \tag{27}$$

Now apply Equation (22) in Equation (25) to obtain

$$\vec{E}_s\cdot\vec{B}_s=2c\beta\frac{\mu_0^2\hbar^2}{m^2}\rho^2. \tag{28}$$

Equation (25) reveals that the electric and magnetic fields of a steadily moving charged particle are perpendicular to the particle motion for massless photons ($m=0$) only. If photons are massive then a longitudinal component between the fields and the velocity direction is inevitable. Moreover, Equations (23) and (24) indicate that work is done by both electric and magnetic fields. But, massless photons don't show such an effect and the two contributions would vanish. This energy dissipation can be converted into heat or other mechanical energy inside the medium.

Using Equation (13) and (23), Equation (17) can be written as

$$F_l=\frac{2m\,q_e\varphi}{\hbar}\,\vec{v}. \tag{29}$$

Applying Equation (21) in Equation (15) yields

$$\vec{E}_s=-\vec{v}\times\vec{B}-\frac{2m\vec{v}}{\hbar}\varphi, \tag{30}$$

and Equation (14)

$$\vec{B}_s=\frac{\vec{v}\times\vec{E}}{c^2}-\frac{mc\beta}{\hbar}\vec{A}. \tag{31}$$

Using Equation (22), Equation (31) can be written as

$$\vec{B}_s=\frac{\vec{v}\times\vec{E}}{c^2}+\frac{\mu_0\hbar\beta}{mc}\vec{J}_e, \tag{32}$$

where $\vec{J}_e$ is the photonic electric current. These fields have four components representing a charge (particle) and anticharge (antiparticle). Equations (30) and (31) extend the Biot-Savart equations to include massive photons. Equations (12)–(15) describe the electric and magnetic fields of a charge moving at constant velocity assuming that the photons of the electromagnetic field are massive. These equations extend the Biot-Savart law. Since these equations represent 4-components, they may be considered, as in Dirac theory, the fields of a particle and antiparticle. It is evident from Equations (30) and (31) that even in a region where no electric or magnetic field ($\vec{E}=0,\vec{B}=0$), effective electric and magnetic fields could be present arising from the scalar and vector potentials. A charged particle at rest will have effective electric and magnetic fields. These fields can be related to the electric and magnetic fields due to photons themselves, hence Equations (30) and (31) point to $\vec{E}_{ph} = -\frac{2m\vec{v}}{\hbar}\varphi$ and $\vec{B}_{ph} = -\frac{mc\beta}{\hbar}\vec{A}$. These latter fields are not gauge invariant. The photon electric field is parallel to the particle direction of motion, and the photon magnetic field is parallel to the vector potential. These fields can also be considered as due to vacuum fluctuation of electric and magnetic fields providing energy to the vacuum state. At a universal level, they may have significant contribution to the overall vacuum energy density that is assumed nowadays to give rise to cosmic acceleration.

The appearance of the gauge fields in Equations (14) and (15) would make the line integral of these fields have physical significance, as demonstrated in the Aharonov-Bohm effect [19]. These fields are coupled to photon mass. Their effect will vanish (in vacuum) when $m = 0$. Notice that the vacuum is characterized by either $m = 0$ or, $\varphi = 0$ & $\vec{A} = 0$. It can be stated that electric and magnetic fields associated with massive photons also exhibit wave-particle duality. These photons permeate the space surrounding the moving charged particle in question.

4. MAGNETIC CHARGE AND MAGNETIC CURRENT

Let us consider here the magnetic charge and current arising from the motion of massive photons. Using Equation (22), Equation (21) can be written as

$$\vec{\nabla}\cdot\vec{J}_e + \frac{\partial\rho_e}{\partial t} = -\frac{2mc^2}{\hbar}\rho_e, \tag{33}$$

where $\vec{J} \equiv \vec{J}_e$ and $\rho \equiv \rho_e$, are the photon electric current and charge densities, respectively. Taking the divergence of Equation (32) using Faraday's equation, and Equation (27), yield

$$\vec{\nabla}\cdot\vec{B}_s = \frac{\mu_0\hbar\beta}{mc}\left(\frac{\partial\rho_e}{\partial t} + \vec{\nabla}\cdot\vec{J}_e\right) = -2\mu_0 c\beta\,\rho_e. \tag{34}$$

This can be written as

$$\vec{\nabla}\cdot\vec{B}_s = \rho_m \quad \rho_m = -\frac{2\beta\rho_e}{\varepsilon_0 c}, \tag{35}$$

where ρ_m is the magnetic charge density. This clearly shows that the existence of monopole is a consequence of charge non-conservation expressed in Equation (33) owing to the massive nature of the photon. Equation (35) fixes the electric to magnetic charges ratio to $(2c\mu_0)^{-1}$. Similarly, if we take the divergence of Equation (30), and employ Equations (26), (35) and Ampere's equation, we will obtain

$$\vec{\nabla}\cdot\vec{E}_s = -\frac{\hbar}{mc}\left(\frac{\partial\rho_m}{\partial t} + \vec{\nabla}\cdot\vec{J}_m\right) = \frac{\rho_e}{\varepsilon_0}, \tag{36}$$

which can be written as

$$\frac{\partial\rho_m}{\partial t} + \vec{\nabla}\cdot\vec{J}_m = -\frac{mc}{\hbar\varepsilon_0}\rho_m, \quad \vec{J}_m = \rho_m\vec{v}, \tag{37}$$

where $\vec{J}_m$ is the photon magnetic current. Hence, the photon has electric current as well as magnetic current. The electric and magnetic currents are consequences of the scalar and vector potentials, respectively. In vacuum both currents vanish. It can be seen from Equations (33), (35) and (37) that the total current is conserved. It is interesting to see that while, $\vec{\nabla}\cdot\vec{B} = 0$, for massless photon, Equation (35) reveals that $\vec{\nabla}\cdot\vec{B}_s \neq 0$ for massive photons. This is so since massive photons have magnetic charges, which are assumed only inside conducting matter. The magnetic charges are effective charges and are acquired only inside conducting matter. Hence, the second term in Equation (14) is responsible for generating magnetic charges in the system. Thus, even if we don't assume magnetic charge to exist in vacuum, its presence inside matter is inevitable. An electric dipoles is associated with every magnetic charge. This why the factor 2 in Equation (35) appears. Equations (22) and (35) reveal that no magnetic monopole can exist in vacuum ($m = 0$ or, $\varphi = 0$ & $\vec{A} = 0$). Note from Equations (35) and (22) that no monopole can exist when φ or $m = 0$. The magnetic density of the monopole depends on the mass of the photon, or on the charge density in which the photon travels. A recent theoretical proposal suggested that defects in the spin alignment of certain oxide magnets can create separated effective magnetic monopoles [22]. Using Equation (33) and (34), Equation (30) can be written as

$$\vec{E}_s = -\vec{v} \times \vec{B} - \frac{\hbar}{mc}\vec{J}_m, \tag{38}$$

together with Equation (32)

$$\vec{B}_s = \frac{\vec{v} \times \vec{E}}{c^2} + \frac{\mu_0 \hbar \beta}{mc}\,\vec{J}_e. \tag{39}$$

It is interesting that the electric and magnetic fields, $\vec{E}_s$ and $\vec{B}_s$, in Equations (38) and (39) are symmetric. These fields should give rise to symmetric Maxwell's equations. The second terms in these equations represent the quantum correction to the ordinary (vacuum) fields mediated by massless photons.

Integrating Equation (35) with respect to volume element dV, and using the divergence theorem, yield the magnetic flux due to massive photons

$$\phi_B = \mp\frac{2q_e}{\varepsilon_0 c} = q_m, \quad q_m = \int \rho_m dV, \quad q_e = \int \rho_e dV, \tag{40}$$

where q_m and q_e are the total magnetic and electric charges in the system. It was shown by Singh and Dadhich that both of these charges cannot exist independently [16].

It is apparent from Equation (35) that the magnetic charge is associated with twice electric charge. This relation is manifested in superconductivity where the charge is related to the charge of the Cooper pairs [23, 24]. The electric and magnetic charges of massive photon can be obtained from Equation (40) as

$$q_e q_m = \mp\frac{2q_e^2}{\varepsilon_0 c}. \tag{41}$$

Dirac has found that the charge of the monopole is related to electric charge by the relation $q_e q_m = \frac{n}{2}\hbar$, where $n = 1, 2, 3, \ldots$ [16, 25].

Using Equation (22), the longitudinal force, Equation (29), can be written as

$$\vec{F}_l = -\frac{2q_e \mu_0 \hbar \rho_e}{m}\vec{v}. \tag{42}$$

This is similar to a drag (viscous) force that a particle experiences when traveled in a fluid. In the resent case the space around a moving object filled with massive photons behaves like a fluid. This is similar also to a drag force that experienced by a bar drawn in a magnetic field. It is thus the effect of magnetic field (magnetic charges) associated with the massive photon that induces this force. This may imply that the massive photos are dragged by the particle motion creating them, or equivalently the particle moves in photon fluid and so is dragged.

5. QUANTUM CURRENT, INDUCTANCE AND FORCE

In this section, we would like to find the current, inductance, and longitudinal force induced by the motion of magnetic charges in a conductor. To this aim, we multiply (dot product) Equation (14) with $d\vec{\ell}$ and integrate the resulting equation using Stokes' theorem and Ampere's law to obtain

$$I = -\frac{mc\beta}{\mu_0 \hbar}\,\phi_B, \tag{43}$$

where ϕ_B is the magnetic flux, and I is the induced electric current in a conductor. We have found recently that photon mass is related to electric conductivity as [8]

$$m = \frac{\mu_0 \sigma \hbar}{2}. \tag{44}$$

The Compton wavelength and frequency associated with this mass, are

$$\lambda_m = \frac{c}{k\sigma}, \quad f_m = k\sigma, \tag{45}$$

where k is the Coulomb constant. Hence, massive photons move inside conductors like matter (de Broglie) wave. Equation (43) permits us to define a self-inductance quantum

$$L_q = \pm\frac{\mu_0\hbar}{mc} = \frac{2}{\sigma c}, \tag{46}$$

as a fundamental inductance associated with massive photons resulting from the motion of the magnetic charges. Allowing the magnetic flux to be quantized in units of $\frac{\hbar}{2e}$, i.e., $\phi_B = n\frac{\hbar}{2e}$, leads to

$$I_q = \pm\frac{mc}{\mu_0(2e)}n, \quad n = 0, 1, 2, \ldots. \tag{47}$$

Hence, applying Equation (44) in Equation (47) yields

$$I_q = \pm\frac{c\sigma\hbar}{2(2e)}n. \tag{48}$$

The current quantum, I_q, represents the quantum current that can be developed from magnetic charge moving inside conductors. It is interesting to see that I_q is quantized, while L_q is not.

Now taking the dot product of Equation (16) with $d\vec{\ell}$ (unit displacement along the wire), using Stokes' theorem and Faraday's law show that the electric voltage is zero, i.e.,

$$V = 0. \tag{49}$$

This is so because the electric field of massive photons vanishes inside a conducting medium. Using the force law on a wire in a magnetic field, $dF_\ell = \ell B dI$, one finds a force (longitudinal force)

$$F_l = \frac{1}{2}\mu_0 I^2, \tag{50}$$

where $\phi_B = BA$ is defined in Equation (43), $A = \ell\lambda_L$, the area the magnetic flux contained, and $\lambda_L = \frac{\hbar}{mc}$ the penetration depth of the magnetic field in the material. Therefore, Equation (50) is the longitudinal (tangential) force acting on a wire when a current I is passed on it. Apparently this force doesn't depend on the current direction. And because of the smallness of μ_0, this force is effective when a large current is used. Moreover, one can relate the inductance in Equation (46) to that of a solenoid consisting of one loop, i.e., $L = \mu_0\frac{A}{\ell} = \frac{\mu_0\hbar}{mc}$. It is found that the magnetic field due to a current-carrying conductor interacts with its own magnetic field producing a longitudinal mechanical force in the conductor [26]. The longitudinal force stretches the conductor and the resulting tension is referred to Ampere tension.

Applying Equation (50) in (48) yields the force quantum

$$F_q = \pm\frac{1}{8\,\varepsilon_0}\left(\frac{\sigma\,\hbar}{2e}\right)^2 n^2. \tag{51}$$

It is apparent that the physical nature of the scalar and vector potentials of the electromagnetic fields relies crucially on the existence of quantum values as advised by Equations (48) and (51).

6. CONCLUDING REMARKS

We study in this paper the effects of massive photons on the electric and magnetic fields produced by a moving electric charge (current). We find that because of this massive nature of photons, these photons produce their own electric and magnetic fields. These photons then become the monopoles satisfying a Dirac-like quantization rule. Since massive photons carry electric and magnetic charges, they will then be scattered by the electron of the medium in which the move. They also generate their own currents. Because of this current, a longitudinal force along the particle (charge) direction arises leading to significant force, when a large current is passed in a wire. This generated current further leads to quantum current, inductance and force.

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