Chapter

Primary Role of the Quantum Electromagnetic Vacuum in Gravitation and Cosmology

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Abstract

The electromagnetic field ground state, a zero-energy vacuum component that issues naturally from Maxwell's theory and from the vector potential quantization at a single-photon level, overcomes the vacuum energy singularity in quantum electrodynamics which leads inevitably to the well-known "vacuum catastrophe" in cosmology. Photons/electromagnetic waves are oscillations of this vacuum field which is composed of a real electric potential permeating all of space. The Hawking-Unruh temperature for a particle accelerated in vacuum is readily obtained from the interaction with the electromagnetic field ground state. The elementary charge and the electron and proton mass are expressed precisely through the electromagnetic field ground state quantized amplitude entailing that photons, leptons/antileptons, and probably baryons/antibaryons originate from the same vacuum field. Fluctuations of the electromagnetic field ground state contribute to the cosmic electromagnetic background and may be at the origin of the dark energy which is considered to be responsible for the observed cosmic acceleration. Furthermore, the gravitational constant is also expressed through the electromagnetic field ground state quantized amplitude revealing the electromagnetic nature of gravity. The overall developments yield that the electromagnetic field ground state plays a primary role in gravitation and cosmology opening new perspectives for further investigations.

Keywords: vector potential quantization, zero-point energy singularity, vacuum catastrophe, cosmological constant, electromagnetic vacuum, photon-electron-positron relation, elementary charge, mass-charge relation, electromagnetic gravity, gravitational constant

1. Introduction

Following a large number of astrophysical observations, it is actually well-established that the cosmic expansion is accelerating. This conflicts with the fundamental predictions of general relativity according to which the universe should decelerate [1–6]. The most plausible physical explanation is the cosmological constant Λ which is identified as the quantum vacuum energy density. Recent studies generally consider the dark energy to be composed mainly of the vacuum energy [4, 5, 7–9]. The cosmic acceleration has been confirmed by multiple independent studies based on different observation methods such as Type Ia supernovae (SN) [1–3, 10–13], cosmic microwave background (CMB) anisotropies [5, 14–20], weak gravitational lensing [21–24], baryon acoustic oscillations (BAO) [25–29], galaxy clusters [30–32], gamma-ray bursts [33, 34], and Hubble parameter measurements [35, 36]. Hence, there is almost no doubt today that a cosmic field with low energy density and negative pressure may provide a satisfactory explanation to the observed accelerated expansion of the universe [5, 7]. However, the identification of the cosmological constant to the vacuum energy issued from the quantum field theory leads to a serious problem related to the energy scale [4, 5, 37–39], the origin of which we analyze briefly here.

The quantization process in quantum field theory following the harmonic oscillator representation leads to the well-known puzzling singularity of infinite zero-point energy (ZPE) [40, 41] corresponding to the vacuum energy. In the case of the electromagnetic field, for example [37, 38, 42–45], in a given volume V, the ZPE density is expressed in quantum electrodynamics (QED) by the well-known relation $\rho_{ZPE} = \frac{1}{V}\sum_{k,\lambda}\frac{1}{2}\hbar\omega_k$ where $\hbar$ is Planck's reduced constant and the summation runs over all possible angular frequencies ω_k and circular polarizations λ (right and left). Transforming the discrete summation into a continuous one, according to the density of state theory [42, 44], the ZPE density becomes $\rho_{ZPE} = \frac{\hbar}{2\pi^2 c^3}\int_0^\infty \omega^3 d\omega$ which is infinite at any point in space [41]. The frequency corresponding to Planck's energy of 10^{19} GeV [5, 37, 38], that is, roughly $\sim 10^{43}$ Hz, may reasonably assumed to be a physical cutoff for the upper limit of the integration. In this case, the theoretical value obtained for the ZPE density of the electromagnetic field is around 10^{110} J m^{-3}. When considering the quantization of all other known fields, the energy scale does not radically change even if the last value gets somehow higher [4, 5, 9, 37].

On the experimental front, following the well-validated astrophysical observations mentioned above, we have good evidence today that the vacuum energy density should be approximately 10^{-9} J m^{-3}. The discrepancy between the experimental value and the different theoretical estimations is 10^{120}, the worst ever observed in science. Not surprisingly, the problem related to the quantum vacuum energy scale has been called "vacuum catastrophe" and constitutes a major challenge in modern physics [5, 37–39].

The most elaborated theoretical models on the dark energy developed up to now [45–64] are unable to resolve satisfactorily the energy scale problem. Hence, new models based on modified gravity have been advanced [65–67] obtaining interesting results although many scientists were skeptical since the beginning regarding the physical validity of such a hypothesis. Indeed, recent studies [68] of over 193 high-quality disk galaxies have finally ruled out with a high degree of statistical accuracy all modified Newtonian dynamic models. Other particular developments have been based on phenomenological assumptions [69], in particular arbitrary axioms [7], or even on the hypothesis that the physical constants like the electron charge or the fine structure constants vary with time [70] but they have not obtained any significant advancements on the problem. Finally, it is worthy to mention that the introduction of the classical notion of spin in stochastic electrodynamics (SEDS) using the real zero-point field (that is non-renormalized) yields naturally an upper frequency limit [71]. Furthermore, in this development, when approaching the upper frequency limit, the zero-point energy density is no more proportional to ω^4 but increases much slower. Consequently, SEDS has opened interesting perspectives for further studies in this field though the real energy scale problem finally remains.

The theoretical concept in QED leading to the vacuum energy singularity is based on the ZPE issued from the quantization process of the harmonic oscillator energy [40–45, 72]. It is well-known that in material harmonic oscillators, e.g., phonons in solid-state physics, the ZPE is obtained directly without any commutations of the position and momentum operators during the quantization process [41, 42, 45, 72]. Consequently, in this case a ZPE term represents a quite physical result with a direct influence on the thermodynamic properties of materials, e.g., the specific heat. Conversely, during the quantization process of the electromagnetic field, commutations between the position and momentum operators occur unavoidably leading to the "normal ordering" Hamiltonian without the ZPE and to the "anti-normal ordering" one involving a ZPE term [40–45, 72]. It has been pointed out [42, 45] that this mathematical procedure suffers from the fundamental ambiguity consisting of replacing products of naturally commuting classical canonical variables by products of non-commuting quantum mechanics operators and consequently may lead to unphysical results [42, 73]. In fact, no experiments have ever demonstrated that a single-photon state is a harmonic oscillator. Hence, in QED the "normal ordering" Hamiltonian, which is not a harmonic oscillator, is the only principally employed in all calculations dropping aside the ZPE singularity.

Regarding the vacuum effects, like the spontaneous emission and the Lamb shift, they are interpreted in QED [41, 42, 44] based on the fundamental commutation properties of the creation $a^{+}_{k\lambda}$ and annihilation operators $a_{k\lambda}$ of a k-mode and λ-polarization photon without invoking the harmonic oscillator ZPE expression. The reason is simply that the ZPE term is a constant and has absolutely no influence in the QED calculations because it commutes with all Hermitian operators $\tilde{Q}$ corresponding to physical observables $\left[\tilde{Q}, \sum_{k,\lambda} \frac{1}{2}\hbar\omega_k\right] = 0$.

Finally, due to the unobserved impact of the zero-point energy singularity in cosmology, it becomes progressively more and more accepted today that the direct interpretation of the Casimir effect based on the source fields [74, 75] or Lorentz forces [76] without invoking at all the electromagnetic field zero-point energy should be the real physical explanation of this effect [77]. In fact, from the historical point of view, the interpretations of the Casimir effect based on the ZPE had been carried out well before the astrophysical observations [1, 2, 5, 10] have ruled out the corresponding vacuum concept.

In what follows we show that the vacuum energy singularity is overcome by enhancing the vector potential amplitude quantization to a single-photon state. This procedure issues naturally from Maxwell's theory and yields a zero-energy electromagnetic field ground state capable of generating photons. The lepton/antilepton and proton/antiproton charge, the electron and proton mass, and the gravitational constant are expressed exactly through the quantized amplitude of the electromagnetic field ground state putting in evidence that it plays a fairly important role in cosmology.

2. Vector potential amplitude of a cavity-free photon

A detailed dimension analysis of the vector potential general solution obtained from Maxwell's equations shows that it is proportional to a frequency [42, 72, 78, 79]. Consequently, we may write the vector potential amplitude α_{0k} for a single free k-mode photon with angular frequency ω_k as follows [45, 80–84]:

$$\alpha_{0k}(\omega_k) = \xi\,\omega_k \tag{1}$$

where ξ is a constant.

It is worthy to notice that Eq. (1) is not an arbitrary hypothesis but a mathematical representation resulting directly from Maxwell's equations [45, 72]. The normalization of the energy of a single k-mode plane electromagnetic wave over a wavelength to Planck's experimental expression for the photon energy $\hbar\,\omega_k$ leads to the evaluation of the constant ξ [45, 80]:

$$|\xi| = \left|\frac{\hbar}{4\pi e c}\right| = 1.747\ \ 10^{-25}\ \ \mathrm{V\,m^{-1}s^2} \tag{2}$$

where c is the speed of light in vacuum and e is the electron/positron charge.

Eq. (2) expresses the physical relation between Planck's constant and the electromagnetic nature of the photon through the vector potential amplitude.

By this way, Eq. (1) permits to complement the fundamental physical properties relation characterizing the *wave-particle* nature of a single k-mode photon in vacuum by introducing the missing electromagnetic nature through the quantized vector potential amplitude:

$$\frac{E_k}{\hbar} = \frac{\left|\vec{p}_k\right|}{\hbar/c} = \frac{\alpha_{0k}}{|\xi|} = \left|\vec{k}\right| c = \omega_k \tag{3}$$

The last relation signifies that the particle properties of the photon, that is, energy E_k and momentum $\vec{p}_k$, and the electromagnetic wave properties, that is, vector potential amplitude α_{0k} and wave vector $\vec{k}$, are all related to the angular frequency ω_k.

Thus, the vector potential function of a free single photon can now be written in the plane wave representation [45, 80, 81]:

$$\vec{\alpha}_{k\lambda}\left(\vec{r},t\right) = \xi\omega_k\left(\hat{\varepsilon}_{k\lambda}e^{i\left(\vec{k}\cdot\vec{r}-\omega_k t+\theta\right)} + \hat{\varepsilon}^*_{k\lambda}e^{-i\left(\vec{k}\cdot\vec{r}-\omega_k t+\theta\right)}\right) = \omega_k\vec{\Xi}_{k\lambda}\left(\vec{r},t\right) \tag{4}$$

where λ denotes a circular polarization (left or right), $\hat{\varepsilon}_{k\lambda}$ is the corresponding complex unit vector, and θ is a phase parameter.

The last equation can also be written in QED representation as a function of the creation and annihilation operators $a^+_{k\lambda}$ and $a_{k\lambda}$, respectively, for a k-mode and λ-polarization photon:

$$\tilde{\alpha}_{k\lambda}\left(\vec{r},t\right) = \xi\omega_k\left(\hat{\varepsilon}_{k\lambda}a_{k\lambda}e^{i\left(\vec{k}\cdot\vec{r}-\omega_k t+\theta\right)} + \hat{\varepsilon}^*_{k\lambda}a^+_{k\lambda}e^{-i\left(\vec{k}\cdot\vec{r}-\omega_k t+\theta\right)}\right) = \omega_k\tilde{\Xi}_{k\lambda}\left(\vec{r},t\right) \tag{5}$$

Notice that the main function $\Xi_{k\lambda}\left(\vec{r},t\right)$ of the vector potential expressed in both representations constitutes the physical "skeleton" of photons/electromagnetic waves.

It is a straightforward calculation to show [45, 82, 83] that the photon vector potential function $\vec{\alpha}_{k\lambda}\left(\vec{r},t\right)$ satisfies the classical wave propagation equation in vacuum:

$$\vec{\nabla}^2\vec{\alpha}_{k\lambda}\left(\vec{r},t\right) - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\vec{\alpha}_{\kappa\lambda}\left(\vec{r},t\right) = 0 \tag{6}$$

as well as the *vector potential energy* (wave-particle) equation for the photon

$$i\left(\frac{\xi}{\hbar}\right)\frac{\partial}{\partial t}\vec{\alpha}_{k\lambda}\left(\vec{r},t\right) = \left(\frac{\tilde{\alpha}_0}{\tilde{H}}\right)\vec{\alpha}_{k\lambda}\left(\vec{r},t\right) \tag{7}$$

where $\tilde{H} = -i\hbar c\vec{\nabla}$ is the relativistic massless particle Hamiltonian having eigenvalue the single-photon energy $\hbar\omega_k$ and $\tilde{\alpha}_0 = -i\xi c\vec{\nabla}$ is the vector potential amplitude operator having eigenvalue the single-photon vector potential amplitude $\xi\omega_k$.

Eq. (7) is simply a combination of Schrödinger's equation for the energy to a symmetrical wave equation for the vector potential [45, 72, 82] expressing the simultaneous wave-particle nature of the photon.

From the operator expressions and the corresponding eigenvalues for the energy and the vector potential amplitude, we readily define an angular frequency operator $\tilde{\Omega}$ which writes

$$\tilde{\Omega} = -ic\vec{\nabla} \tag{8}$$

so that the Hamiltonian and the vector potential amplitude operators can be expressed simply as

$$\tilde{H} = \hbar\tilde{\Omega}; \quad \tilde{\alpha}_0 = \xi\tilde{\Omega} \tag{9}$$

We can thus obtain the equation governing the main function $\vec{\Xi}_{k\lambda}\left(\vec{r},t\right)$ of the vector potential in vacuum by introducing the angular frequency operator in the *vector potential-energy* Eq. (7):

$$i\frac{\partial}{\partial t}\vec{\Xi}_{k\lambda}\left(\vec{r},t\right) = \tilde{\Omega}\vec{\Xi}_{k\lambda}\left(\vec{r},t\right) \tag{10}$$

Consequently, photons/electromagnetic waves are generated by the action of the angular frequency operator $\tilde{\Omega}$ upon the fundamental function $\vec{\Xi}_{k\lambda}\left(\vec{r},t\right)$ creating a real vector potential:

$$\tilde{\Omega}\vec{\Xi}_{k\lambda}\left(\vec{r},t\right) = -ic\vec{\nabla}\vec{\Xi}_{k\lambda}\left(\vec{r},t\right) = \omega_k\vec{\Xi}_{k\lambda}\left(\vec{r},t\right) = \vec{\alpha}_{k\lambda}\left(\vec{r},t\right) \tag{11}$$

The vector potential function $\vec{\alpha}_{k\lambda}\left(\vec{r},t\right)$ expressed in Eq. (4) can be considered as a real wave function for the photon [45, 82–84]. In fact, previous attempts based on the electric and magnetic fields failed to define satisfactorily a photon wave function [85–89]. Here, the vector potential function $\vec{\alpha}_{k\lambda}\left(\vec{r},t\right)$ with the quantized amplitude $\xi\omega_k$ expresses a real probability amplitude entailing that the probability for localizing a photon is proportional to the square of the angular frequency:

$$P_k\left(\vec{r}\right) \propto \left|\vec{\alpha}_{k\lambda}\left(\vec{r},t\right)\right|^2 \propto \xi^2\omega_k^2 \tag{12}$$

This is in agreement with the experimental evidence following which the higher the frequency, the better the localization probability for a single photon [42, 44, 78].

Weighting the vector potential function by $\omega_k\sqrt{2\varepsilon_0}$ and considering both circular polarizations ($\lambda = L, R$), a six-component general wave function can be defined for the photon:

$$\Phi_{k,(L,R)}\left(\vec{r},t\right) = \omega_k\sqrt{2\varepsilon_0}\begin{pmatrix}\vec{\alpha}_{kL}\left(\vec{r},t\right)\\ \vec{\alpha}_{kR}\left(\vec{r},t\right)\end{pmatrix} \tag{13}$$

which is now suitably normalized in order to get the energy density of the electromagnetic field composed of a single k-mode

$$\left|\Phi_{k,(L,R)}\left(\vec{r},t\right)\right|^2 = 2\varepsilon_0\xi^2\omega_k^4 \tag{14}$$

From the photon vector potential, we also deduce that a single photon has intrinsic electric $\vec{\varepsilon}_k$ and magnetic $\vec{\beta}_k$ fields whose amplitudes in vacuum are proportional to the square of the angular frequency [45, 82, 83]:

$$\left|\vec{\varepsilon}_k\right| = \left|-\frac{\partial}{\partial t}\vec{\alpha}_{k\lambda}\left(\vec{r},t\right)\right| \propto \xi\omega_k^2 \text{ and } \left|\vec{\beta}_k\right| \propto \sqrt{\varepsilon_0\mu_0}\,\xi\omega_k^2 \tag{15}$$

where ε_0 and μ_0 are the vacuum electric permittivity and magnetic permeability, respectively.

Eqs. (3), (14), and (15) clearly show that all the physical properties characterizing a single k-mode photon as an integral wave-particle entity of the electromagnetic field depend directly on the angular frequency ω_k.

3. The electromagnetic field ground state as a vacuum field and the Hawking-Unruh temperature

From Eqs. (4) and (5) appears clearly that the photon vector potential is mainly composed of the fundamental field $\Xi_{k\lambda}\left(\vec{r},t\right)$. As developed in the previous section, a photon subsists only for a non-zero angular frequency ω_k characterizing the rotation (left or right) of the vector potential perpendicularly to the propagation axis generating an electric and magnetic field whose amplitudes are given in Eq. (15). Now, it is interesting to investigate what happens at zero frequency. Following Eqs. (3), (14), and (15), we can draw that the zero-frequency level ($\omega_k \to 0$) of the electromagnetic field corresponds to a cosmic state (the wavelength $\lambda_k = \frac{2\pi c}{\omega_k} \to \infty$) characterized by the complete absence of the photon physical properties: energy, energy density, vector potential, and electric and magnetic fields are all zero. This state lays beyond the Ehrenberg-Siday and Bohm-Aharonov physical situation in which the electric and magnetic fields are zero but space is filled by a real vector potential [90, 91].

However, at $\omega_k = 0$ the resulting electromagnetic field state is not synonym to perfect vacuum because the fundamental function $\Xi_{k\lambda}\left(\vec{r},t\right)$ of the vector potential gets reduced to the field $\Xi_{0\lambda}$ which writes in both representations:

$$\vec{\Xi}_{0\lambda} = \xi\left(\hat{\varepsilon}_\lambda e^{i\theta} + \hat{\varepsilon}_\lambda^* e^{-i\theta}\right); \tilde{\Xi}_{0\lambda} = \xi\left(\hat{\varepsilon}_\lambda a_{k\lambda} e^{i\theta} + \hat{\varepsilon}_\lambda^* a_{k\lambda}^+ e^{-i\theta}\right) \tag{16}$$

Electromagnetic fields are real [79, 92], and the reality of the vector potential has been well established experimentally [90, 93–95]; consequently the fundamental function $\Xi_{k\lambda}\left(\vec{r},t\right)$ in Eqs. (4) and (5) is also real. At the limit $\omega_k \to 0$ the residual field $\Xi_{0\lambda}$ is a real field permeating all of space ($\lambda_k \to \infty$) and according to Eq. (2) has an electric potential amplitude with units V m^{-1} s^2. Thus, $\Xi_{0\lambda}$ corresponds physically to the electromagnetic field ground state, a dark cosmic field capable of generating any k-mode photon with left or right circular polarization and which in absence of energy and vector potential can be considered as a vacuum component, identical in both classical electromagnetic theory and QED.

Heisenberg's energy-time uncertainty relation applied in Eq. (3) entails directly that the vector potential amplitude is also subject to a fluctuation uncertainty:

$$\delta E_k \cdot \delta t \approx \hbar \rightarrow \delta \alpha_{0k} \cdot \delta t \approx \xi \tag{17}$$

Consequently, fluctuations of the electromagnetic field ground state in space imply that transient states of various k-mode and λ-polarization photons can be generated spontaneously during time intervals respecting Heisenberg's relation contributing to the cosmic radiation background and to its associated anisotropies and might be at the origin of the dark energy. From Eq. (17), we deduce that the lifetime is longer for the low-frequency transient photons and consequently we can expect a quite important contribution in the cosmic radio background at long wavelengths. It would be extremely worthy to investigate experimentally the very low frequency cosmic radiation background spectrum.

The phase parameter θ in Eq. (16) can take any value, and consequently the electromagnetic field ground state contains all possible main functions $\Xi_{k\lambda}$ corresponding to all modes and polarizations. Hence, according to Eq. (10), any perturbation expressed through an angular frequency operator may create real photons in space. It can be easily demonstrated [45, 80] that the electromagnetic field ground state complements the normal ordering Hamiltonian representation in QED by getting a direct interpretation of the vacuum effects. Indeed, an interaction Hamiltonian between the electrons and the vacuum field $\Xi_{0\lambda}$ can be readily defined resulting precisely to the spontaneous emission rate. Also, it is important to notice that the vector potential operator in the interaction Hamiltonian used in Bethe's [96] and Kroll's [97] calculations for the Lamb effect can be replaced by that of Eq. (5) yielding exactly the same energy shifts.

We have mentioned previously that the vacuum effects, that is, the spontaneous emission and the Lamb shift, are interpreted in QED [41, 42, 44, 96, 97] without invoking the ZPE of the electromagnetic field. The Casimir effect is equally well explained [74–77] without invoking at all the ZPE which inevitably leads to the "vacuum catastrophe." Now, it can be easily demonstrated that the Hawking-Unruh temperature [98], associated to the Fulling-Davies-Unruh effect [99–101] for a charge accelerated in vacuum, can also be deduced without invoking the ZPE. In fact, any particle moving in the electromagnetic field ground state with an acceleration $\vec{\gamma}$ experiences an electric potential:

$$U = \left|\xi \vec{\gamma}\right| \tag{18}$$

Notice that even for high relativistic values, of the order of $\left|\vec{\gamma}\right| \propto 10^{7}\,\mathrm{m\,s^{-2}}$, the electric potential felt by the accelerated particle is very low $U \propto 10^{-18}\mathrm{V}$.

For a charge e, the corresponding energy along a given degree of freedom is equivalent to a thermal energy according to the equipartition theorem:

$$E = \left|e\,\xi\,\vec{\gamma}\right| = \frac{1}{2}k_B T \tag{19}$$

where k_B is Boltzmann's constant.

Replacing ξ in the last equation by the expression of Eq. (2), one gets directly the Hawking-Unruh temperature:

$$T = \frac{\hbar}{2\pi c k_B}\left|\vec{\gamma}\right| \tag{20}$$

This extremely simple calculation shows that an accelerated charge in the electromagnetic field ground state will "feel" the Hawking-Unruh temperature.

In fact, there are many experimental controversies in the literature related to the measurement of the Hawking-Unruh temperature and to the physical reality of the Fulling-Davies-Unruh effect [102, 103]. Following the above calculation, the measure of the electric potential energy variation of the accelerated particle could be more affordable experimentally than the direct measure of such a low temperature and could consequently lead to a real validation of Eq. (19).

4. The electromagnetic field ground state, the charge-mass relation, and the gravitational constant

When replacing Planck's constant in the photon energy $E_k = \hbar\omega_k$ by an equivalent expression obtained from the fine structure constant $\alpha = e^2/4\pi\varepsilon_0\hbar c \approx 1/137$, which is dimensionless, then the energy of a free photon depends directly on the electron charge. This was always quite puzzling, and it has been often advanced [42, 43, 78] that photons and electrons/positrons should be strongly related physical entities.

Now, from Eq. (2) and the fine structure constant expression, we straightforward draw that the lepton/antilepton and the proton/antiproton elementary charge, a fundamental physical constant, is expressed exactly through the electromagnetic field ground state quantized amplitude constant ξ:

$$e = \pm(4\pi)^2\alpha\frac{|\xi|}{\mu_0} = \pm 1.602\ 10^{-19}\mathrm{C} \tag{21}$$

where α is the fine structure constant, $\mu_0 = 4\pi\ 10^{-7}\mathrm{H\,m^{-1}}$ is the vacuum magnetic permeability, and $|\xi| = 1.747\ 10^{-25}\mathrm{V\,m^{-1}s^2}$.

The last relation shows that the single-photon vector potential and the elementary charge are related directly to the electromagnetic field ground state through the quantized amplitude constant ξ. This supports further the strong physical relationship between photons and electrons/positrons which appear to originate from the same vacuum field being consequently at the origin of their mutual transformation mechanism.

Recalling that the electron and proton mass at rest are expressed as $m_e = e\hbar/2\mu_B$ and $M_P = e\hbar/2\mu_P$, respectively, where $\mu_B = 9.274\ \ 10^{-24}\ \ \mathrm{J\,T^{-1}}$ is the Bohr magneton and $\mu_P = 5.0508\ \ 10^{-27}\ \ \mathrm{J\,T^{-1}}$ is the proton magneton, and using again Eq. (2), we deduce the relations of the electron and proton mass depending also on the constant ξ:

$$m_e = 2\pi c\,e^2\left|\frac{\xi}{\mu_B}\right| = 9.109\ \ 10^{-31}\mathrm{kg} \tag{22}$$

$$M_P = 2\pi c\,e^2\left|\frac{\xi}{\mu_P}\right| = 1.672\ \ 10^{-27}\mathrm{kg} \tag{23}$$

Notice that the ratio of the proton-to-electron mass equals the ratio of the electron-to-proton magneton $M_P/m_e = \mu_e/\mu_P = 1836.15$ according to the experimental evidence. Eqs. (22) and (23) show that the electron and proton mass is also related directly to the electromagnetic field ground state through the vector potential amplitude constant ξ yielding the quite interesting conclusion that the electron and proton mass are equally manifestations of this field and depend on the elementary charge and on the associated magnetic moments.

It has been shown [104] that the masses of all the fundamental elementary particles can be obtained from the electron mass and the fine structure constant with a precision of roughly 1%.

Consequently, the mass m_i of any elementary particle i can be expressed using Eq. (22)

$$m_i = 2\pi c\, e^2 \left| \frac{\xi}{\mu_i} \right| \tag{24}$$

with $|\mu_i| = \mu_B$ for the electron and $|\mu_i| = \left(\frac{2\alpha}{n_i}\right)\mu_B$ for other particles where n_i is simply an integer and α is the fine structure constant.

This formalism is valid for leptons (e.g., muon for n_i = 3, tau for n_i = 51), mesons (e.g., pion for n_i = 4, kaon for n_i = 14, rho for n_i = 22, … etc.) as well as baryons (e.g., nucleon for n_i = 27, lambda for n_i = 32, sigma for n_i = 34, … etc.).

A generalization of these results means that:

- charges are states of the electromagnetic field ground level,
- particle masses issue from charges and their corresponding magnetic flux; hence, all the neutral particles should be composed of positive and negative charges,
- gravitation is consequently an electromagnetic effect.

Spontaneous creation of particle/antiparticle pairs during short time-intervals due to the electromagnetic field ground state fluctuations may occur in space. We can make the hypothesis here that other type of unknown particle/antiparticle pairs could also emerge from the electromagnetic field ground state so that the overall process in the universe may contribute to the cosmic mass background and eventually to the dark matter [4, 9]. Hence, the electromagnetic field ground state appears to be a cosmic source of energy (photons) and charges (mass).

Recent observations [105, 106] have indicated that space granularity should be many orders of magnitude less than Planck's length, usually denoted as l_P and having the value of l_P = 1.616 10^{-35} m. However, Planck's length is generally considered as a characteristic physical parameter for the electromagnetic field corresponding theoretically to the shorter possible wavelength of a photon [4, 9]. This corresponds to a photon frequency close to 10^{43} Hz. Although we have not yet observed photons with such a high energy, no photon can be conceived, at least theoretically, beyond this upper frequency limit.

Therefore, we can draw now another result related to the gravitational constant G which can be expressed exactly by the square of the ratio of Planck's length l_P to the electromagnetic field ground state quantized amplitude ξ:

$$G = \frac{1}{(4\pi)^3 \alpha\, \varepsilon_0} \left(\frac{l_P}{\xi} \right)^2 = 6.674\ \ 10^{-11} \mathrm{m}^3\ \ \mathrm{kg}^{-1}\ \ \mathrm{s}^{-2} \tag{25}$$

where α is the fine structure constant and $\varepsilon_0 = 8.854\ \ 10^{-12} \mathrm{F\,m}^{-1}$ is the electric permittivity of vacuum. Introducing the complete expression of α in the last equation and taking into account Eq. (2), we deduce that the gravitational constant G, the elementary charge e, and the vector potential amplitude constant ξ are directly related as follows:

$$G = \frac{l_P^2 c^2}{4\pi e\, \xi} \tag{26}$$

According to the last equation, the electromagnetic character of gravity appears clearly entailing new possibilities for theoretical and experimental investigations in this field [107].

5. Conclusions

The vacuum concept initially identified as the zero-point energy singularity of the quantized fields has been ruled out by recent well-validated astrophysical observations. Instead, the electromagnetic field ground state $\Xi_{0\lambda}$, a zero-energy cosmic dark field permeating all of space and having the real amplitude $\xi = \hbar/4\pi e c$, issues naturally from Maxwell's theory and is compatible with the observational evidence. It is readily deduced that photons/electromagnetic waves, are oscillations of this vacuum field which is identical in classical electromagnetic wave theory and QED. Thus, the electromagnetic field ground state naturally complements the normal ordering Hamiltonian in QED overcoming the zero-point energy singularity.

Fluctuations of the electromagnetic field ground state may give birth to transient photons contributing to the observed vacuum energy density, considered responsible for the cosmic acceleration, as well as to the cosmic radiation background and to its anisotropies.

The elementary charge issues from the electromagnetic field ground state and is expressed exactly through the constant ξ. This demonstrates the strong physical relationship between photons and leptons/antileptons. The mechanisms governing their mutual transformations are directly related to the nature of the electromagnetic field ground state. Furthermore, it is shown that a charge accelerated in the electromagnetic field ground state will experience the Hawking-Unruh temperature.

Like photons, transient pairs of particles/antiparticles may emerge from the electromagnetic field ground state fluctuations contributing to the cosmic matter background and eventually to the dark matter.

It is also drawn that mass issues from charges which appear to be states of the electromagnetic field ground state revealing that the last one is a cosmic source of energy (photons) and charges (mass). Finally, the gravitational constant can be expressed exactly through the elementary charge and the electromagnetic field ground state amplitude entailing that gravitation has an electromagnetic nature and putting in evidence the primary role the electromagnetic vacuum might play in gravitation and cosmology.

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