The Electromagnetic Field Ground State and the Cosmological Evolution

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The Electromagnetic Field Ground State and the Cosmological Evolution

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Abstract. The vector potential quantization procedure extended to a single free of cavity photon state issues to the zero-energy electromagnetic field ground state (EFGS), a quantum vacuum component, overcoming the vacuum energy singularity in quantum electrodynamics. We show that the EFGS oscillations generate photons and that the elementary electron/positron charge is expressed precisely by the EFGS quantized amplitude. We also show that the gravitational constant is equally expressed through the same EFGS quantized amplitude putting in evidence the electromagnetic nature of gravity and introducing the quantum vacuum influence in the cosmological equations. Fluctuations of the EFGS give birth to low energy transient photons as well as to particles/antiparticles which might be respectively at the origin of the dark energy and dark matter in the universe.

Keywords: Cosmological constant; Quantum vacuum; Photons; Vector potential quantization; Vacuum energy density, Electron/positron charge, Gravitational constant, Cosmological equations.

Introduction

Recent astrophysical observations revealed that the universe is speeding up rather than decelerating as it might be predicted by the general relativity theory in the standard matter sources universe [1-6]. The cosmological constant Λ , generally identified as the quantum vacuum energy density and as the principal component of the dark energy, is advanced as the most plausible physical explanation for the cosmic acceleration [4, 5, 7-9]. This theoretical hypothesis leads to the well-known serious problem related to the energy scale [4, 5, 10-12]. In fact, considering a reasonable cut-off for the upper limit frequency ~10^{43} Hz, corresponding roughly to Planck's energy 10^{19} GeV, the theoretical value obtained for the vacuum energy density is around 10^{110} J m^{-3}. Today, we have good evidence from the astrophysical measurements that the vacuum energy density should be close to 10^{-9} J m^{-3}. This huge discrepancy between the theoretical estimation and the experimental value, of the order of 10^{120}, has been characterized as the worst prediction in the history of physics and has been given the name "vacuum catastrophe" [5, 10-12]. The various theoretical studies carried out until now [13-33] on the physics of the dark energy and its relationship to the cosmological constant fail to provide a satisfactory answer to the energy scale problem.

Without using any assumptions, axioms or hypothetical models we show here that the quantization of the vector potential of a cavity free single photon leads naturally to the electromagnetic field ground state (EFGS), a vacuum universal field with zero-energy and zero vector potential overcoming the vacuum energy singularity. The EFGS is composed of an electric potential amplitude and it is expressed through the photon creation and annihilation operators involving both circular polarizations. Consequently, it is capable of generating photons (electromagnetic waves). Furthermore, it is shown that the electron/positron charge and mass are obtained exactly by the amplitude of the EFGS demonstrating that electrons/positrons (leptons/antileptons) and photons are expressions of the same vacuum field. The EFGS fluctuations in space can generate transient states of photons and leptons/antileptons (and probably other particles/antiparticles) that might contribute to the dark energy and dark matter respectively. Considering Planck's length we also show that the gravitational constant is equally expressed exactly through the amplitude of the EFGS putting in evidence the electromagnetic character of gravity whose nature can now be studied through a new approach, probably as a Casimir effect. It is therefore deduced that the EFGS plays a fairly important role in the cosmological evolution.

The photon wave-particle equation and the photon wave function. The Electromagnetic Field Ground State (EFGS) as a quantum vacuum component.

We have shown that for a free of cavity *k*-mode photon with angular frequency ω_k the vector potential amplitude writes as follows [13, 34]

$$\alpha_{0k} = \xi\omega_k \qquad \text{with} \quad |\xi| = \left|\frac{\hbar}{4\pi ec}\right| = \frac{1}{(4\pi)^2}\left|\frac{e\mu_0}{\alpha}\right| \tag{1}$$

where ξ is a constant characterizing the intrinsic electromagnetic nature of the photon, *c* is the speed of light in vacuum and *e* the electron charge. α is the fine structure constant and μ_0 the vacuum magnetic permeability. The vector potential of a free photon in the plane wave representation writes

$$\vec{\alpha}_{k,\lambda}(\vec{r},t) = \omega_k\left(\xi\hat{\varepsilon}_\lambda e^{i\left(\vec{k}\cdot\vec{r}-\omega_k t+\theta\right)} + \xi^*\hat{\varepsilon}_\lambda^* e^{-i\left(\vec{k}\cdot\vec{r}-\omega_k t+\theta\right)}\right) = \omega_k\vec{\Xi}_{k,\lambda}(\vec{r},t) \tag{2}$$

where λ corresponds to the left (L) or right (R) circular polarization expressed by the complex unit vector $\hat{\varepsilon}_\lambda$.

The last relation can also be written with respect to the creation and annihilation operators $a_{k,\lambda}^+$ and $a_{k,\lambda}$ respectively for a *k*-mode and λ-polarization photon

$$\tilde{\alpha}_{k,\lambda}(\vec{r},t) = \omega_k\left(\xi\hat{\varepsilon}_\lambda a_{k,\lambda} e^{i\left(\vec{k}\cdot\vec{r}-\omega_k t+\theta\right)} + \xi*\hat{\varepsilon}_\lambda^* a_{k,\lambda}^+ e^{-i\left(\vec{k}\cdot\vec{r}-\omega_k t+\theta\right)}\right) = \omega_k\tilde{\vec{\Xi}}_{k,\lambda}(\vec{r},t) \tag{3}$$

It is straight forward to demonstrate that the photon vector potential function satisfies the *vector potential – energy* (wave – particle) equation for the photon [13, 34-37]

$$i\begin{pmatrix}\xi\\ \hbar\end{pmatrix}\frac{\partial}{\partial t}\vec{\alpha}_{k,\lambda}(\vec{r},t) = \begin{pmatrix}\tilde{\alpha}_0\\ \tilde{H}\end{pmatrix}\vec{\alpha}_{k,\lambda}(\vec{r},t) \tag{4}$$

where

$$\begin{pmatrix}\tilde{\alpha}_0\\ \tilde{H}\end{pmatrix} = -i\begin{pmatrix}\xi\\ \hbar\end{pmatrix}c\vec{\nabla} \tag{5}$$

with $\tilde{H}$ the relativistic massless particle Hamiltonian with eigenvalue $\hbar\omega_k$ and $\tilde{\alpha}_0$ the vector potential amplitude operator with eigenvalue $\xi\omega_k$. The insertion of the relation (5) in (4) yields the propagation equation in vacuum.

Thus, the vector potential function $\vec{\alpha}_{k,\lambda}(\vec{r},t)$ with the quantized amplitude can be considered as the photon wave function in a non-local representation that can be suitably normalized.

Now, from the vector potential relations (2) and (3) we draw that the photon wave function is mainly composed of the fundamental field $\Xi_{k,\lambda}(\vec{r},t)$ times the angular frequency ω_k. Obviously, a photon subsists only for a non-zero frequency. The zero-frequency level of the electromagnetic field, that is the Electromagnetic Field Ground State (EFGS), corresponds to an infinite spatial entity (infinite wavelength) with zero-energy and zero-vector potential as well as zero electric and magnetic fields. It is important to remark here that this physical state lays beyond the Ehrenberg-Siday and Bohm-Aharonov situations in which energy, electric and magnetic fields are zero but a vector potential is still present in space [38, 39]. However, the EFGS does not correspond to perfect inexistence since at zero frequency the fundamental field $\Xi_{k,\lambda}(\vec{r},t)$ does not vanish but reduces to $\vec{\Xi}_{0,\lambda}$ which also writes in the creation and annihilation operators representation $\tilde{\vec{\Xi}}_{0,\lambda}$ [13, 34, 35]

$$\vec{\Xi}_{0,\lambda} = \xi\hat{\varepsilon}_\lambda e^{i\theta} + \xi^*\hat{\varepsilon}_\lambda^* e^{-i\theta} \qquad \tilde{\vec{\Xi}}_{0,\lambda} = \xi\hat{\varepsilon}_\lambda a_{k,\lambda} e^{i\theta} + \xi^*\hat{\varepsilon}_\lambda^* a_{k,\lambda}^+ e^{-i\theta} \tag{6}$$

It is important noticing that the EFGS expressed by $\Xi_{0,\lambda}$ is a real field permeating all of space, has an electric potential amplitude with units Volt $m^{-1}s^2$ and involves both circular polarizations as well as the creation and annihilation operators. Consequently the EFGS is capable of interacting with electrons (charges). Since it corresponds to a state with zero energy and zero vector potential the EFGS can be identified to a quantum vacuum component complementing the 'normal ordering' Hamiltonian in quantum electrodynamics. Hence, the vacuum is not an infinite sea of photons with all the wavelengths and polarizations, which leads to the well-known singularity in QED associated to the "vacuum catastrophe", but consists (probably among other components) of the EFGS which is capable of generating photons of all frequencies and polarizations.

Oscillation of $\Xi_{0,\lambda}$ at an angular frequency ω_k generates a photon, an integral entity extended over a wavelength with total energy $\hbar\omega_k$ and propagating with circular polarization (R or L) along a real wave function which is that of the vector potential $\vec{\alpha}_{k,\lambda}(\vec{r},t)$. Now, EFGS fluctuations imply that transient states of various photons can be generated spontaneously during a time interval. This may happen at the limits of Heisenberg's energy-time uncertainty relation $\delta E_k \cdot \delta t \sim \hbar \to \delta\alpha_{0k} \cdot \delta t \sim \xi \to \delta\omega_k \cdot \delta t \sim 1$. Obviously, the lower the frequency the higher the life-time δt of the transient photons generated by the EFGS fluctuations and consequently they may contribute to the long wavelength cosmic radiation background and to its associated anisotropies.

The electron-positron charge and the EFGS

Using the fine structure constant definition $\alpha = e^2/4\pi\varepsilon_0\hbar c$, where ε_0 is the vacuum electric permittivity, we draw directly from (1) that the electron/positron (and the proton/antiproton) elementary charge $e = \pm 1.602\ 10^{-19} C$, a fundamental physical constant, is expressed exactly through the EFGS amplitude ξ, the fine structure constant and the vacuum magnetic susceptibility [13, 40]

$$e = \pm(4\pi)^2 \alpha \frac{|\xi|}{\mu_0} \tag{7}$$

Using the relations (1) and (7) and recalling that the electron mass may be written $m_e = e\hbar/2\mu_B$, where μ_B is the Bohr magneton, we deduce that the electron mass is also expressed exactly as a function of the EFGS amplitude

$$m_e = 2\pi c\, e^2 \frac{|\xi|}{\mu_B} \tag{8}$$

entailing that the electron mass derives from the EFGS as a result of the magnetic moment and it is proportional to the square of the charge.
Equations (1), (7) and (8) show that the photon vector potential as well as the electron/positron charge and mass are related directly to the EFGS through the amplitude ξ. This may be at the origin of the physical mechanism governing the photon generation during the electron/positron (lepton/antilepton) annihilation and that of the electron/positron (lepton/antilepton) pair creation during the annihilation of high energy gamma photons in the vicinity of a heavy nucleus.
We de deduce that the EFGS fluctuations may be at the origin of spontaneous creation of lepton/antilepton pairs (and perhaps proton/antiproton and other types of known or unknown particle/antiparticle pairs) during very short time-intervals contributing to the cosmic matter that might be related to the dark matter [39].

The gravitational constant and the EFGS

It is actually well established that Planck's length (l_P = 1.6162 10^{-35} m), corresponding physically to the wavelength of a photon whose energy density transforms to a black hole, appears to be a characteristic distance in the space-time continuum [4, 9, 12]. At the present state of knowledge and technology Planck's length is unattainable by the experimental methods and is generally advanced that below this characteristic distance physical notions have no sense. It is easily established that the gravitational constant G = 6.674 10^{-11} $m^3\,kg^{-1}s^{-2}$ can be expressed exactly using Planck's length l_P and the EFGS amplitude ξ,

$$G = \frac{1}{4\pi}\frac{l_P^2\,c^2}{|e\xi|} \tag{9}$$

Consequently, the electromagnetic character of gravity lays in the nature of the EFGS opening perspectives for studies of the gravitational field through a new approach. In fact, following the relations (2) and (3) any charge undergoing a periodic motion at a given angular frequency ω experiences in its frame the presence of "vacuum photons" due to the EFGS. For a physical system characterized by a mean electron density $<n_e>$ it is usual to attribute a plasma frequency ω_p which writes

$$\omega_p = e<n_e>^{1/2}(\varepsilon_0 m_e)^{-1/2} \tag{10}$$

Therein, it might be interesting to investigate whether the gravity is an analogue of Casimir effect due to the EFGS radiation pressure at roughly the plasma frequencies felt by the charge densities of the bodies in their own frame.

The Electromagnetic Field Ground State and the Cosmological Equations

The field equations of general relativity applied to the Friedmann-Lemaitre-Robertson-Walker (FLRW) space-time metric

$$ds^2 = c^2dt^2 - a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2d\theta^2 + r^2\sin^2\theta\, d\varphi^2\right) \tag{11}$$

lead to the FLRW equations which are presently considered as the principal equations of cosmology [4, 5]

$$\frac{1}{c^2}\left(\frac{1}{a(t)}\frac{d\,a(t)}{dt}\right)^2 + \frac{k}{R_0^2a^2(t)} = \frac{8\pi G}{3c^4}\rho + \frac{\Lambda}{3} \tag{12}$$

$$\frac{1}{c^2}\frac{1}{a(t)}\frac{d^2a(t)}{dt^2} = -\frac{4\pi G}{3c^4}(\rho + 3P) + \frac{\Lambda}{3} \tag{13}$$

where the factor $a(t)$ characterizes the cosmic expansion ($a(t)$ = 1 in our epoch), k denotes the 3-dimensional space curvature (-1 for negative curvature, 0 for flat Euclidean space, 1 for positive curvature), $\{r,\theta,\varphi\}$ are the coordinates in the spherical system, ρ is the total energy density of the universe composed of all the components

(matter, radiation, dark matter, dark energy…), P is the total pressure of the components, R_0 is the present radius of the space curvature and Λ is the cosmological constant.

The last one was introduced by Einstein in the general relativity equations in order to obtain a static model of the universe. Shortly after, the astronomical observations confirmed the expansion of the universe and the cosmological constant was abandoned. In recent years, the cosmic expansion acceleration has justified again its reintroduction. Today, we have good evidence that the cosmological constant should correspond to the vacuum energy density ρ_{vacuum} resulting to a negative vacuum pressure P_{vacuum} expressed as follows [5]

$$\Lambda c^4 = 8\pi G \rho_{Vacuum} = -8\pi G P_{Vacuum} \tag{14}$$

Denoting by ρ_{Ξ_0} the energy density due to the EFGS fluctuations generating transient photons we may assume that $\rho_{Vacuum} \approx \rho_{\Xi_0}$ so that taking into account the relations (9) and (14) the FLRW equations write in terms of the EFGS amplitude ξ, the electron charge e and Planck's length l_P

$$\left(\frac{1}{a(t)}\frac{da(t)}{dt}\right)^2 + \frac{k c^2}{R_0^2 a^2(t)} = \frac{2}{3}\frac{l_P^2}{|e\xi|}\left[\rho + \rho_{\Xi_0}\right] \tag{15}$$

$$\frac{1}{a(t)}\frac{d^2a(t)}{dt^2} = -\frac{2}{3}\frac{l_P^2}{|e\xi|}\left[\frac{1}{2}(\rho + 3P) - \rho_{\Xi_0}\right] \tag{16}$$

where ρ and P also involve the contributions of the EFGS fluctuations contributing to the Dark Energy and Dark Matter. Apparently, the influence of the EFGS to the cosmic evolution appears to be fairly important, linking quantum electrodynamics to cosmology.

Conclusion

The vector potential amplitude quantization for a single free of cavity photon leads to the definition of a zero-energy and zero-vector potential electromagnetic field ground state $\Xi_{0,\lambda}$ (EFGS) permeating all of space and identified as a vacuum component with the real amplitude $\xi = e\mu_0 / (4\pi)^2 \alpha$. Photons, thus electromagnetic waves, are oscillations of this vacuum field. Fluctuations of the EFGS generate low energy transient photons that may contribute to the observed vacuum energy density considered responsible for the cosmic acceleration.

The lepton/antilepton charge is expressed exactly through the EFGS amplitude ξ demonstrating the physical relationship between photons and leptons/antileptons. It is worthy to investigate further this aspect in order to understand the mechanisms governing the photons transformation to leptons/antileptons and inversely. Transient pairs of leptons/antileptons and probably other pairs of known (or unknown) particles/antiparticles may be issued from the EFGS fluctuations at the limits of Heisenberg's energy-time uncertainty that might contribute to the dark matter in the universe.

We have finally shown that the gravitational constant is equally expressed through the EFGS amplitude entailing that the electromagnetic character of gravity can now be studied through a new approach.

To finish, according to all the above considerations we have expressed the contribution of the EFGS in the FLRW cosmological equations revealing the decisive role that it plays in the cosmic evolution.

References

[1] A.G. Riess et al., *Observational evidence from supernovae for an accelerating universe and a cosmological constant. Astron. J.* 116 (1998)1009-38.

[2] S. Perlmutter et al.,*Measurements of Ω and Λ from 42 High Redshift Supernovae*. *Astrophys.J*. 517(1999)565.

[3] R.F.L Holanda and S.H. Pereira, *Can galaxy clusters, type Ia supernovae, and the cosmic microwave background rule out a class of modified gravity theories. Phys. Rev. D* 94, (2016) 104037.

[4] V. Mukhanov, *Physical foundations of Cosmology*; Cambridge University Press, Cambridge, U.K. 2005.

[5] J.A. Frieman, M.S. Turner and D. Huterer, *Dark Energy and the Accelerating Universe.*

Ann. Rev. Astron. Astrophys. 46, (2008) 385-432.
[6] E.V. Linder, *Mapping the cosmological expansion*. *Rep. Prog. Phys.* 71, (2008) 5.
[7] C. Beck, *Axiomatic approach to the cosmological constant*. *Phys.A* (2009), 3384. arXiv:0810.0752.
[8] P.J.E. Peebles and B. Ratra, *The cosmological constant and dark energy*. *Rev. Mod. Phys*. 75 (2003) 559.
[9] T. Hey, *The New Quantum Universe*, Cambridge University Press: New York, U.S. 2003.
[10] R.J. Adler, B. Casey and O.C. Jacob, *Vacuum catastrophe: An elementary exposition of the cosmological constant problem. Ann. J. Phys.* 63, (1995) 620-626.
[11] T. Padmanabhan, *Cosmological constant: the weight of the vacuum, Phys. Rept.* 380 (2003) 235
[12] M.P. Hobson, G.P. Efstathiou and A.N. Lasenby, *General Relativity*: *An introduction for physicists;* Cambridge University Press: New York, U.S., 2006.
[13] C. Meis, *Light and Vacuum, 2nd Edition;* World Scientific: Singapore, 2017.
[14] A.Sangwan, A.Mukherjee and H.K.Jassal, *Reconstructing the dark energy potential .JCAM* 01 (2018) 018.
[15] R. Caldwell and E. V. Linder, *The Limits of quintessence Phys.Rev.Lett.* 95 (2005) 141301.
[16] I. Zlatev, L.-M. Wang, and P. J. Steinhardt, *Quintessence, cosmic coincidence, and the cosmological constant, Phys.Rev.Lett.* 82 (1999) 896-899.
[17] C. Armendariz-Picon, V. F. Mukhanov, and P. J. Steinhardt, *A Dynamical solution to the problem of a small cosmological constant and late time cosmic acceleration, Phys.Rev.Lett.* 85 (2000) 4438-4441.
[18] J. Garriga and V. F. Mukhanov, *Perturbations in k-ination, Phys.Lett.* B458 (1999) 219-225.
[19] E. Babichev, V. Mukhanov, and A. Vikman, *k-Essence, superluminal propagation, causality and emergent geometry*, JHEP 0802 (2008) 101
[20] C. Wetterich, *The Cosmon model for an asymptotically vanishing time dependent cosmological constant, Astron.Astrophys*. 301 (1995) 321-328.
[21] L. Amendola, *Coupled quintessence, Phys.Rev*. D62 (2000) 043511
[22] R.-G. Cai and A. Wang, *Cosmology with interaction between phantom dark energy and dark matter and the coincidence problem*, *JCAP* 0503 (2005) 002.
[23] E. J. Copeland, A. R. Liddle, and D. Wands, *Exponential potentials and cosmological scaling solutions, Phys.Rev.* D57 (1998) 4686-4690.
[24] A.Y. Kamenshchik, U. Moschella, V. Pasquier, *An Alternative to quintessence, Phys.Lett.* B511 (2001) 265.
[25] S. Capozziello, S. Carloni, and A. Troisi, *Quintessence without scalar felds, Recent Res.Dev.Astron.Astrophys*. 1 (2003) 625,
[26] M. Bento, O. Bertolami, and A. Sen, *Generalized Chaplygin gas, accelerated expansion and dark energy matter unification, Phys.Rev.* D 66 (2002) 043507
[27] S. Nojiri and S. D. Odintsov, *Introduction to modified gravity and gravitational alternative for dark energy, Int.J.Geom.Meth.Mod.Phys.* 4 (2006) 06
[28] Y.-S. Song, W. Hu, and I. Sawicki, *Large scale structure of f(r) gravity*, Phys. Rev.D 75 (2007) 44004.
[29] S. Tsujikawa, *Matter density perturbations and effective gravitational constant in modified gravity models of dark energy*, *Phys.Rev.* D 76 (2007) 023514,
[30] S. Tsujikawa, *Observational signatures of f(R) dark energy models that satisfy cosmological and local gravity constraints*, *Phys.Rev*. D 77 (2008) 023507,
[31] H. Alnes, M. Amarzguioui, and O. Gron, *An inhomogeneous alternative to dark energy?, Phys.Rev.* D 73 (2006) 083519.
[32] H. Iguchi, T. Nakamura, and K.-i. Nakao, *Is dark energy the only solution to the apparent acceleration of the present universe?, Prog.Theor.Phys.* 108 (2002) 809-818.
[33] A.A. Starobinsky, *A new type of cosmological models without singularity, Phys.Lett*. B 91 (1980) 99,102.
[34] C. Meis, C. *Vector potential quantization and the quantum vacuum*. *Phys. Res. Int.* (2014) ID 187432.
[35] C. Meis and P.R. Dahoo, *Vector potential quantization and the photon wave-particle representation. Jour. Phys.* Conf. Series 738 (2016) 012099. DOI: 10.1088/1742-6596/738/1/012099.
[36] C. Meis and P.R. Dahoo, *Vector potential quantization and the photon intrinsic electromagnetic properties: Towards nondestructive photon detection. Int. Jour. Quantum Information.* 15, N°8, (2017) 1740003. DOI: 10.1142/S0219749917400032
[37] C. Meis and P.R. Dahoo, *Vector potential quantization and the photon wave function. Jour. Phys.* Conf. Series 936 (2017) 012004. DOI :10.1088/1742-6596/936/1/012004
[38] W. Ehrenberg and R.E. Siday, *The refractive index in electron optics, Proc. Phys. Soc. B* 62 (1949) 8-21.
[39] Y. Aharonov and D. Bohm, *Significance of electromagnetic potentials in the quantum theory. Phys. Rev.* 115 (1959) 485-491.
[40] C. Meis and P.R. Dahoo, *American Institute of Physics Publications* (AIP), 2018, in press.