Quantum Vacuum Gravitation and Cosmology
The Electromagnetic Nature of Gravitation and Matter-Antimatter Antigravity

Constantin Meis
National Institute for Nuclear Science and Technology
CEA – Saclay, 91191 Gif-sur-Yvette, France.
constantin.meis@cea.fr

Abstract

We show that the electromagnetic quantum vacuum derives directly from Maxwell's theory and plays a primary role in quantum electrodynamics, particle physics, gravitation and cosmology. It corresponds to the electromagnetic field ground state at zero frequency, a zero-energy cosmic field permeating all of space. We show that the electromagnetic quantum vacuum is composed of real states, called *kenons* (κενο = vacuum), and that photons are local oscillations of kenons guided by a non-local vector potential wave function. They propagate at the speed imposed by the vacuum electric permittivity ε_0 and magnetic permeability μ_0, which are intrinsic properties of the electromagnetic quantum vacuum. The electron-positron elementary charge derives naturally from the electromagnetic quantum vacuum. We establish the masse-charge equivalence relation showing that the masses of all particles (leptons, mesons, baryons) and antiparticles are states of the elementary charges and their magnetic moments.

The equivalence between Newton's gravitational law and Coulomb's electrostatic law results naturally.

In addition, we show that the gravitational constant *G* is explicitly expressed by the electromagnetic quantum vacuum constants putting in evidence the electromagnetic nature of gravity. Furthermore, we draw that *G* is the same for matter and antimatter but gravitational forces should be repulsive between particles and antiparticles because their masses bear naturally opposite signs.
The electromagnetic quantum vacuum appears to be the natural link between quantum electrodynamics, particle physics, gravitation and cosmology and constitutes a basic step towards a unified field theory.

Dark Energy and Dark Matter might originate from the electromagnetic quantum vacuum fluctuations. The calculated electromagnetic vacuum energy density, related to the cosmological constant considered responsible for the cosmic acceleration, is in good agreement with the astrophysical observations. However, the cosmic acceleration may be due to both the quantum vacuum fluctuations as well as to the matter-antimatter gravitational repelling.

All the above results have been obtained without stating any assumptions or making postulates.

Next, we analyze the possibility that gravitation is due to the electromagnetic quantum vacuum pressure at the characteristic collective oscillation frequencies of the charge densities composing the bodies.
Finally, we advance the hypothesis that energy, matter and antimatter in the universe emerge spontaneously from the quantum vacuum fluctuations as residues that remain stable in space and we present the main principles upon which a new cosmological model may be developed overcoming the well-known Big Bang issues.

Key words: photons, electromagnetic waves, electromagnetic quantum vacuum, dark light, kenons, gravitation, matter-antimatter antigravity, electromagnetic push gravity, dark energy, cosmological constant, dark matter, elementary charges, mass-charge relation, cosmology, unified field theory.

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Introduction

The ΛCDM (Lambda – Cold Dark Matter) cosmological model is considered today as the most plausible theory that has the merit to provide satisfactory answers to a large number of astrophysical observations. It is based on the enhanced Big Bang concept according to which the universe is homogeneous and whose main components are Dark Matter and Dark Energy. The last one is associated to the cosmological constant Λ, which is considered responsible for the observed cosmic acceleration [1-4].
However, besides the difficulty to conceive that the whole universe emerged from a singular point, some upsetting issues still remain such as, why did the Big Bang occurred and what happened before? Furthermore, in order to explain the horizon problem as well as the fact that the geometry of the universe is Euclidean (flat), a cosmic inflation model has been introduced [5]. But, what are the physical reasons that inflation occurred in the very first 10^{-30} seconds of the Big Bang expanding the universe at a tremendous rate, many orders of magnitude faster than the speed of light in vacuum? What happened to antimatter?
Finally, quantum field theory fails by a factor of 10^{120} to give a precise estimation to the cosmological constant [6, 7], the worst discrepancy between theory and observation in the history of science.
The above drawbacks call the human intelligence to be humble in front of the immensity and complexity of the still unknown universe. All the cosmological theories, including the one presented here, are temporary attempts to explain the observations realized up to now using the present theoretical tools and they are finally condemned to be replaced in the future according to the new observations to come.

In what follows, we make an introduction to the fundamentals of Quantum Vacuum Gravitation and Cosmology. The electromagnetic quantum vacuum, namely Dark Light, corresponds to the electromagnetic field ground state and results naturally from Maxwell's theory by considering the vector potential quantization at a single photon level. It is a real field permeating all of space and has electric potential dimension. We show that photons are oscillations of the electromagnetic vacuum field while the lepton-antilepton elementary charges derive equally from this field.

The gravitational constant *G* is a vacuum property having electromagnetic nature and is the same for matter and antimatter. The masses of particles and antiparticles derive from elementary charges and their magnetic moments and have opposite sign entailing repulsive gravitational forces between matter and antimatter.

Fluctuations of the electromagnetic quantum vacuum generate transient states of photons that are plausible to compose the Dark Energy and transient pairs of charges (particles) that might compose the Dark Matter. A small fraction of the vacuum transient states might definitely remain stable in space composing the observed energy and mass in the universe.

1. The electromagnetic quantum vacuum, the Dark Light

The electromagnetic field vector potential $\vec{\alpha}_{k\lambda}(\vec{r},t)$ with quantized amplitude for a cavity free *k*-mode photon with angular frequency ω_k and polarization λ (circular left or right) writes [8-14]

$$\vec{\alpha}_{k\lambda}(\vec{r},t) = \xi\omega_k \left[\hat{\varepsilon}_{k\lambda}\, e^{i\left(\vec{k}\cdot\vec{r}-\omega_k t+\theta\right)} + cc \right] = \omega_k\, \vec{\Xi}_{k\lambda}(\vec{r},t) \qquad (1)$$

where $\hat{\varepsilon}_{k\lambda}$ is the complex polarization unit vector, $\vec{k}$ the wave-vector with amplitude $\left|\vec{k}\right| = 2\pi/\lambda_k$, λ_k is the wavelength of the mode *k*, θ phase parameter and *cc* the complex conjugate (see Appendix 1).
The vector potential amplitude quantization constant ξ may be positive or negative and is given by

$$\xi = \frac{\hbar}{4\pi ec} = \frac{1}{(4\pi)^2}\frac{e\mu_0}{\alpha} = \pm 1.747\,10^{-25}\; V\, m^{-1} s^2 \qquad (2)$$

where e is the electron or positron charge, $\hbar$ is Planck's reduced constant $(\hbar = h/2\pi)$, c the speed of light in vacuum, $\alpha \simeq 1/137$ is the fine structure constant and μ_0 the vacuum magnetic permeability.

It is straightforward to show that the vector potential function $\vec{\alpha}_{k\lambda}(\vec{r},t)$ is a natural wave function for a free *k*-mode photon satisfying the *vector potential – energy* (wave – particle) equation for the photon

$$i\begin{pmatrix}\xi\\ \hbar\end{pmatrix}\frac{\partial}{\partial t}\vec{\alpha}_{k\lambda}(\vec{r},t)=\begin{pmatrix}\tilde{\alpha}_0\\ \tilde{H}\end{pmatrix}\vec{\alpha}_{k\lambda}(\vec{r},t) \tag{3}$$

where

$$\begin{pmatrix}\tilde{\alpha}_0\\ \tilde{H}\end{pmatrix}=-i\begin{pmatrix}\xi\\ \hbar\end{pmatrix}c\vec{\nabla} \tag{4}$$

The constants $\hbar$ and ξ characterize respectively the energy and the vector potential field quantization for a single photon state. The perfect symmetry between the photon energy $E_k=\hbar\omega_k$ and the vector potential amplitude $\alpha_{0_k}=\xi\omega_k$ expresses the simultaneous wave-particle nature of the single photon through the *vector potential – energy* equation (3).

It is worthy noticing that the amplitude of the electric field of a cavity free *k*-mode photon is proportional to the square of the angular frequency [10, 12]

$$\left|\vec{\varepsilon}_{k\lambda}(\vec{r},t)\right|=\left|-\partial\vec{\alpha}_{k\lambda}(\vec{r},t)/\partial t\right|\propto\left|\xi\right|\omega_k^2 \tag{5}$$

Obviously, for $\omega_k=2\pi c/\lambda_k\rightarrow 0$ (that is for $\lambda_k\rightarrow\infty$**)** the photon energy, vector potential and electric field tend to zero. However, for $\omega_k=0$ the resulting electromagnetic field ground state does not correspond to a perfectly empty space because the fundamental function $\vec{\Xi}_{k\lambda}(\vec{r},t)$ in the vector potential expression (1) still subsists and writes in both classical electromagnetic theory and QED [14-17]

$$\vec{\Xi}_{0\lambda}=\xi\left[\hat{\varepsilon}_\lambda\, e^{i\theta}+\hat{\varepsilon}_\lambda^*\, e^{-i\theta}\right] \tag{6a}$$

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

where in the QED expression (6b) we have used the creation $a_{k\lambda}^{+}$ and annihilation $a_{k\lambda}$ non-Hermitian operators respectively for a *k*-mode and λ-polarization photon.

Hence, in total absence of energy, of vector potential as well as of electric and magnetic fields, $\Xi_{0\lambda}$ is the electromagnetic field ground state, the electromagnetic quantum vacuum corresponding to light at zero frequency, "Dark Light".

It is a real cosmic field permeating all of space $\left(\lambda_k\rightarrow\infty\right)$ and has electric potential nature according to the physical dimensions of ξ.

The phase parameter θ may take any value and consequently the electromagnetic quantum vacuum is composed of all possible states $\Xi_{k\lambda}(\vec{r},t)$ corresponding to all modes and polarizations that can be called "*kenons*" (from κενο = vacuum)

$$\vec{\Xi}_{k\lambda}(\vec{r},t)=\xi\left[\hat{\varepsilon}_{k\lambda}\, e^{i\left(\vec{k}\cdot\vec{r}-\omega t+\theta\right)}+cc\right] \tag{7a}$$

$$\tilde{\vec{\Xi}}_{k\lambda}(\vec{r},t)=\xi\left[\hat{\varepsilon}_{k\lambda}\, a_{k\lambda}e^{i\left(\vec{k}\cdot\vec{r}-\omega t+\theta\right)}+cc\right] \tag{7b}$$

From equation (4), an angular frequency operator $\tilde{\Omega}$ can be readily defined [17]

$$\tilde{\Omega}=-i\,c\vec{\nabla} \tag{8}$$

Using (3) and (8), we get the equation governing the kenons in vacuum

$$i\frac{\partial}{\partial t}\begin{bmatrix}\vec{\Xi}_{k\lambda}(\vec{r},t)\\ \tilde{\vec{\Xi}}_{k\lambda}(\vec{r},t)\end{bmatrix}=\tilde{\Omega}\begin{bmatrix}\vec{\Xi}_{k\lambda}(\vec{r},t)\\ \tilde{\vec{\Xi}}_{k\lambda}(\vec{r},t)\end{bmatrix}=\begin{bmatrix}\vec{\alpha}_{k\lambda}(\vec{r},t)\\ \tilde{\vec{\alpha}}_{k\lambda}(\vec{r},t)\end{bmatrix} \tag{9}$$

Obviously, according to the last equation, photons (electromagnetic waves) are generated by the action of the angular frequency operator $\tilde{\Omega}$ upon the kenons $\Xi_{k\lambda}(\vec{r},t)$ creating a real vector potential $\vec{\alpha}_{k\lambda}(\vec{r},t)$ of a *k*-mode photon. Consequently, photons are local oscillations of kenons over a wavelength, with circular polarization ($\lambda =$ Left or Right circular), guided by a non-local vector potential wave function with the real amplitude $\alpha_{0_k} = \xi\omega_k$ [10, 13, 14].

Thus, the electromagnetic quantum vacuum, that is Dark Light, is composed of kenons and Light (Electromagnetic Waves) is composed of photons which are kenons transformed by the angular frequency operator.

The vacuum electric permittivity ε_0 and magnetic permeability μ_0 are intrinsic physical characteristics of the electromagnetic vacuum and are expressed through the fundamental physical constants $\alpha, \xi, \hbar$ and the elementary charge e

$$\mu_0 = (4\pi)^2 \alpha \frac{\xi}{e} \qquad ; \qquad \varepsilon_0 = \frac{\mu_0}{(4\pi\alpha)^2} \frac{e^4}{\hbar^2} = \frac{\xi e^3}{\alpha \hbar^2} \tag{10}$$

It is straightforward to verify that the product of the last expressions gives directly the velocity of light in vacuum c.

$$\varepsilon_0 \mu_0 = \left(\frac{4\pi e \xi}{\hbar} \right)^2 = \frac{1}{c^2} \tag{11}$$

Finally, it can be easily demonstrated [17] that any particle moving in the electromagnetic quantum vacuum with an acceleration $\vec{\gamma}$ will experience the Fulling-Davies-Unruh temperature (Appendix 2)

$$T_H = \frac{\hbar}{2\pi c k_B} |\vec{\gamma}| \tag{12}$$

where k_B is Boltzmann's constant.

2. The electromagnetic quantum vacuum fluctuations, from QED to Cosmology

2.1 Transient photons from the electromagnetic quantum vacuum. Dark Energy and the cosmic acceleration.

Quantum field theory fails to evaluate the vacuum energy density by a factor of 120 orders of magnitude. In fact, the zero-point energy levels of all fields, corresponding to the fundamental eigenstate of the harmonic oscillator Hamiltonian, yield an infinite vacuum energy density which when upper limited to Planck's energy $(\sim 10^{19} GeV)$ gives the "astronomic" value ~ $10^{110} J\, m^{-3}$, while the observed one is roughly $\sim 10^{-10} J\, m^{-3}$ [1].

This unphysical theoretical result, the worst ever in the history of science, is mainly due to the mathematical ambiguity during the field quantization procedure according to the harmonic oscillator model consisting of replacing commuting classical variables of momentum and position by non-commuting quantum mechanics Hermitian operators [10, 14, 18]. Electromagnetic waves are not composed of harmonic oscillators and no experiment has ever demonstrated that a single photon state is a harmonic oscillator. It has to be emphasized that, in contrast with material oscillators, the zero-point energy in quantum field theory, $\sum_{k,\lambda} \hbar\omega_k / 2$, resulting from the harmonic oscillator Hamiltonian, does not correspond to a physical state and this is what indeed the astrophysical observations confirm.

As frequently pointed out [10, 18], we recall that the interpretations of the spontaneous emission and the Lamb shift in QED are not due to the zero-point energy term $\sum_{k,\lambda} \hbar\omega_k / 2$ but to the properties of the photon creation $a^+_{k\lambda}$ and annihilation $a_{k\lambda}$ operators respectively. As about the well-known Casimir effect, it has been demonstrated by different methods [14 and references therein] that it can be directly explained by using the source fields or Lorentz's forces without invoking at all the zero-point energy.

It has to be underlined again that the zero-point energy term $\sum_{k,\lambda} \hbar\omega_k / 2$, being a constant, commutes with all quantum mechanics Hermitian operators corresponding to physical observables and consequently has absolutely no influence to any physical process.

Conversely, it has been demonstrated [10, 14] that the electromagnetic quantum vacuum, composed of kenons (7a) and (7b), complements naturally the normal ordering Hamiltonian in QED and describes a real physical vacuum state in both classical and quantum electromagnetic theories. In addition, it explains directly the vacuum effects such as the spontaneous emission and the Lamb shift [10, 11, 14] as well as the Fulling-Davies-Unruh temperature [17] (see Appendices 2 and 3).
We have seen that photons are local oscillations of the electromagnetic quantum vacuum field, produced by the action of the angular frequency operator upon kenons, and propagate at the speed imposed by its intrinsic properties, the vacuum electric permittivity ε_0 and magnetic permeability μ_0. On the other hand, from Heisenberg's energy-time uncertainty relation we deduce that the vector potential amplitude is also subject to a fluctuation uncertainty [10, 16, 17]

$$\delta E_k \cdot \delta t \sim \hbar \quad \to \quad \delta\alpha_{0k} \cdot \delta t \sim \xi \quad \to \quad \delta\omega_k \cdot \delta t \sim 1 \tag{13}$$

Consequently, due to the electromagnetic vacuum fluctuations (Dark Light fluctuations), space is permanently full of transient photons at all frequencies underlying the cosmic radiation background.
Obviously, according to the uncertainty relation (13), the lower the frequency the longer the transient photons lifetime, which could explain the *1/f* ^{n} noise origin observed in astrophysical measurements.
We may assume that the probability for a transient *k*-mode photon spontaneous creation is proportional to $e^{-|\vec{\varepsilon}_k/\varepsilon_m|}$, where $|\vec{\varepsilon}_k|$ is the transient photon electric field amplitude generated in space and ε_m is a mean photon electric field amplitude over the electromagnetic spectrum. Using the result (5), that the photon electric field amplitude is proportional to the square of the angular frequency, we get the electromagnetic vacuum fluctuations energy density [19] weighing the integration by the transient photon spontaneous creation probability $e^{-|\vec{\varepsilon}_k/\varepsilon_m|} = e^{-\omega_k^2/\omega_m^2}$,

$$\rho_{vacuum} = \frac{\hbar}{\pi^2 c^3} \int_0^\infty e^{-\omega^2/\omega_m^2}\, \omega^3 d\omega = \frac{\hbar\,\omega_m^4}{2\pi^2 c^3} = \frac{2}{\pi}\varepsilon_0 \mu_0 e\,\xi\,\omega_m^4 \tag{14}$$

Note that the above calculation cannot be applied in the case of the zero-point energy term because it's an eigenvalue of the harmonic oscillator Hamiltonian corresponding to a stable eigenstate composed of all *k*-mode photons and consequently the weighing factor for all frequencies is 1.
Now, considering that ω_m is a logarithmic mean value for the angular frequency over the electromagnetic spectrum, that could be roughly in the THz region $\omega_m \sim 2\pi\, 10^{12}\, Hz$, we obtain $\rho_{vacuum} \sim 3\; 10^{-10}\; J\, m^{-3}$ which is in good agreement with the astrophysical observations.
Consequently, the energy density of the electromagnetic quantum vacuum fluctuations (Dark Light fluctuations) is quite plausible to represent the Dark Energy considered responsible for the cosmic acceleration.

2.2 Transient charges (particles and antiparticles) from the electromagnetic quantum vacuum. Mass-charge equivalence. At the origin of Dark Matter?

It has been established that the electron/positron elementary charge *e*, a fundamental physical constant, is obtained exactly from the electromagnetic vacuum quantized amplitude constant ξ [10, 17, 20]

$$e = (4\pi)^2\, \alpha \frac{\xi}{\mu_0} \tag{15}$$

Note that the last relation is neither a postulate nor a definition but derives naturally when considering the vector potential amplitude quantization at a single photon state (see Appendix 1).

It becomes evident that the photon vector potential amplitude $\alpha_{0_k} = \xi\omega_k$ and the elementary charge e are directly related to the electromagnetic quantum vacuum through the vacuum constant ξ demonstrating that photons and leptons/antileptons are physically strongly related entities and derive from the electromagnetic vacuum field, putting the basis for a physical comprehension of their mutual transformation mechanisms.
We recall that, from the historical experimental evidence, Planck's constant $\hbar$ is intrinsically related to the energy quantization of the electromagnetic field at a single photon state. Despite of this characteristic physical origin Planck's constant is used in quantum physics for the description of all particles.
Hence, we may guess that the electromagnetic nature should be an inherent property for any particle.
In addition, it is worthy to mention that the notion of mass introduced in the expression of Bohr's magneton μ_B is a classical concept associated to a quantum process for the description of the magnetic dipole moment $\vec{M}$ of a wave-particle with wave-vector $\vec{k}$ in a circular standing state of radius *r*. In fact, in a pure quantum description Bohr's magneton is simply the proportionality constant of the magnetic dipole moment $\vec{M} = \mu_B(\vec{k}\times\vec{r})$.
Now, the mass of the electron/positron m_{e^-,e^+} is expressed exactly through the vacuum constant ξ, the elementary charge e and its magnetic moment

$$m_{e^-,e^+} = 2\pi c\, e^2 \frac{\xi}{\mu_B} \tag{16}$$

with $\mu_B = 9.274\,10^{-24}\ J\,T^{-1}$ being the Bohr magneton.
Also, the proton/antiproton mass writes

$$m_{P^+,P^-} = 2\pi c\, e^2 \frac{\xi}{\mu_P} \tag{17}$$

where $\mu_P = 5.0508\,10^{-27}\ J\,T^{-1}$ is the proton magneton.
Similarly, the mass m_i of any elementary particle/antiparticle writes in a general way

$$m_i = 2\pi c\, e^2 \frac{\xi}{\mu_i} \tag{18}$$

where e is the electron charge for particles with $\xi < 0$ or the positron charge for antiparticles with $\xi > 0$ and μ_i is the magneton of the particle *i*.
On the other hand, the magneton μ_i of any particle/antiparticle can be expressed approximately through the Bohr magneton μ_B and the fine structure constant α

$$\mu_i \simeq \left(\frac{16\alpha}{n_i}\right)\mu_B \tag{19}$$

where n_i is simply a positive integer.
Thus, the mass of any particle i, other than the electron, that is lepton, meson or baryon, as well as of any antiparticle other than the positron, is expressed uniquely with a precision better than 0.5% through the electron/positron charge e [17]

$$m_i \simeq \sigma_m\, n_i e \tag{20}$$

where we have used (2).
The value of the proportionality constant is $\sigma_m = \hbar / 32\alpha\mu_B$ = 4.8696 10^{-11} $kg\ C^{-1}$.

In Table 1 are shown the masses obtained for different n_i values and the corresponding identified particles.
Obviously, the rest masses of all particles/antiparticles are purely of electromagnetic nature and the relations (18) and (20) express simply the mass-charge equivalence.

n_i	m_i calculated (MeV c^{-2})	m_i experimental (MeV c^{-2})	δ(%)	particle
24	105.0	105.65	-0.58	Muon (lepton), μ^-
31	135,6	134,97	0.46	Pion (meson), π^0
32	140.0	139.57	0.34	Pion (meson), π^+,π^-
113	494.5	493.68	0.17	Kaon (meson), K^+, K^-
114	498,9	497,70	0.24	Kaon (meson), K^0_s, K^0_L
125	547.1	547.75	-0.11	Eta (meson), η^0
177	774.7	775.8	-0.14	Rho (meson), ρ^0, ρ^+, ρ^-
179	783.4	782.59	0.10	Omega (meson), ω
214	936.6	938.27	-0.17	Proton (baryon), p^+
215	940.9	939.56	0.15	Neutron (baryon), n^0
255	1116.0	1115.68	0.03	Lambda (baryon), Λ^0
271	1186.0	1189.37	-0.28	Sigma (baryon), Σ^+
272	1190.4	1192.6	-0.18	Sigma (baryon), Σ^0
273	1198.9	1197.45	0.12	Sigma (baryon), Σ^-
300	1313.0	1314.8	-0.13	Xi (baryon), Ξ^0
302	1321.7	1321.7	0.00	Xi (baryon), Ξ^-
350	1531.8	1531.8	0.00	Xi (baryon), Ξ^0 resonance
351	1536.2	1535.0	0.07	Xi (baryon), Ξ^- resonance
382	1671.9	1672.45	-0.03	Omega (baryon), Ω^-
406	1776.9	1777.0	0.00	Tau (lepton), τ^-
426	1864.5	1864.8	-0.01	D Meson, D^0
450	1969.5	1968.4	0.05	Ds Meson, D_s^+
458	2004.5	2006.97	-0.12	D Meson, D^{*0}
459	2008.9	2010.27	-0.06	D Meson, D^{*+}
522	2284.6	2286.46	-0.08	Lambda c (baryon), Λ_c^+

n_i	m_i calculated (MeV c^{-2})	m_i experimental (MeV c^{-2})	δ(%)	particle
560	2451.0	2452.9, 2453.7	-0.08	Sigma c (baryon), Σ_c^+, Σ_c^0
561	2455.3	2453.9	0.05	Sigma c (baryon), Σc^{++}
564	2468.4	2467.9	0.02	Xi c (baryon), Ξ_c^+, Ξ_c^0
565	2472.8	2471.0	0.07	Xi c (baryon), Ξ_c^+, Ξ_c^0
588	2573.5	2575.7	-0.08	Xi c (baryon), Ξ_c^+ resonance
589	2577.9	2578.0	0.00	Xi c (baryon), Ξ_c^0 resonance
616	2696.0	2697.5	-0.06	Omega c (baryon), Ω_c^0
804	3518.9	3518.9	0.00	Xi cc (baryon), Ξ_{cc}^+
827	3619.5	3621.4	-0.05	Xi cc (baryon), Ξ_{cc}^{++}
1206	5278.3	5279.34 , 5279.65	-0.02	B Meson, B^+, B^0
1226	5365.8	5366.8	-0.02	Bs Meson, Bs0
1284	5619.7	5620.2	-0.00	Lambda 0s (baryon), Λ_b^0
1327	5807.9	5810,5	-0.04	Sigma b (baryon), Σ_b^+
1329	5816.6	5815,2	0.02	Sigma b (baryon), Σ_b^-
1356	5934.8	5935.0	-0.00	Xi' b (baryon), Ξ_b'
1361	5956.6	5955.3	0.02	Xi* b (baryon), Ξ_b*
1381	6044.2	6046.0	-0.02	Omega b (baryon), Ω_b^-
1423	6228.0	6226.9	0.01	Xi b (baryon), Ξ_b
1434	6276.2	6274.9	0.02	Bs Meson, B_c^+

Table 1. Identification of particle masses obtained using equation (20) with different values of integers n_i and comparison to the experimental values. The discrepancy is lower than 0.2% for roughly 90% of the identified particles.

According to the last equations, we draw that the electron/positron charge is related to photons and derive also from the electromagnetic vacuum while the particles/antiparticles masses are quantum states of the vacuum field originating from charges and their magnetic moment. In fact, the presence in equation (20) of the integer n_i characterizing the particles/antiparticles masses implies that the electromagnetic vacuum must have a complex structure of quantum levels yet to discover, which might be related to string theory. Quarks and antiquarks should be also states of the same vacuum field since they bear a fractional elementary charge and consequently, strong and weak forces should be particular manifestations of the electromagnetic vacuum field. Through this lens, all neutral elementary particles/antiparticles must be composed of positive and negative charges and consequently, gravity should have electromagnetic nature.

Finally, we draw that fluctuations of the electromagnetic vacuum may also give birth to transient states of positive and negative charges of matter and antimatter, corresponding to known and unknown particles. Halos of transient particles concentrations could be strongly favored near important real charges (mass) distributions and consequently might contribute to the Dark Matter.

2.3 Electromagnetic nature of the gravitational constant G. Newton's and Coulomb's laws equivalence. Matter-antimatter antigravity.

Considering Planck's length l_P = 1.616 10^{-35} *m*, which is the shorter possible wavelength for a single photon beyond which the electromagnetic energy density transforms to a black hole, the gravitational constant *G* is expressed exactly through the elementary charge *e* and the electromagnetic vacuum constants ξ, ε_0 and μ_0 [17]

$$G = \frac{l_p^2}{4\pi\,\varepsilon_0\mu_0 e\xi} = \frac{l_p^2}{(4\pi)^3\alpha\varepsilon_0\xi^2} \tag{21}$$

The masse-charge equivalence and the electromagnetic nature of the gravitation constant *G* imply the equivalence of Newton's gravitation law to Coulomb's electrostatic law. In fact, the well-known Newton's gravitational potential between two particles *i* and *j* with respective masses m_i and m_j separated by a distance r_{ij} writes [21]

$$U_{Newton} = G\frac{m_i m_j}{r_{ij}} = \frac{1}{4\pi\varepsilon_0}\frac{e_i e_j}{r_{ij}}\eta_{ij} = U_{Coulomb} \tag{22}$$

where we have used the relations (2), (18) and (21).

Note that e_i and e_j denote the electron charge for the particles or the positron one for antiparticles while η_{ij} is a dimensionless parameter characterizing the nature of the interacting particles and depending on their magnetic moments.

$$\eta_{ij} = \frac{\pi\hbar c l_P^2}{\mu_0\mu_i\mu_j} \tag{23}$$

Note also that, when considering the algebraic sign of charges, and not their absolute values as usually, a minus sign has to be considered in Coulomb's law in the electrostatic theory for the resulting positive potential to characterize attraction (as in gravitation) and the negative one repulsion (as in anti-gravitation).

According to equation (22) the gravitational potential writes now in pure electromagnetic terms

$$U = \frac{\hbar^2}{4} G \frac{e_i e_j}{r_{ij}\mu_i \mu_j} \tag{24}$$

and for a large number of particles

$$U = \frac{\hbar^2}{4} G \sum_{i,j(i<j)} \frac{e_i e_j}{r_{ij}\mu_i \mu_j} \tag{25}$$

We have used μ_B and l_p as intermediate constants in order to obtain physically meaningful relations expressing the mass-charge equivalence by equation (18) and the approximate expression (20), the electromagnetic nature of the gravitational constant *G* by equation (21) and the Newton-Coulomb potential equivalence by (22).

We recall here that Bohr's magneton μ_B is generally considered as a positive quantity so as the Larmor angular frequencies $\omega_L = \mu_B \left|\vec{B}\right| / \hbar$ for the elementary charge in a magnetic field $\vec{B}$ to be also positive and the corresponding absorbed and emitted photons to have positive energies $\hbar\omega_L$. Under this condition, considering that the magnetons μ_i of the particles are positive quantities we can draw a quite interesting feature concerning matter, antimatter and gravity. In fact, for ε_0 and μ_0 to be positive quantities in equations (10), e and ξ should have the same sign. In this way, the gravitational constant expressed by (21) is positive for both matter and antimatter. Gravitation forces are attractive between bodies of ordinary matter, as well as between bodies of antimatter, but they should be repulsive between matter and antimatter according to Newton's gravitational potential (22) since they have "positive" and "negative" masses following the mass-charge equivalence relation.

In fact, particles and antiparticles having opposite charges are attracted by Coulomb forces overcoming naturally the weak gravitational repulsion and annihilate mutually giving generally birth to photons. Conversely, matter and antimatter neutral structures must be repelled due to repulsive gravitational forces. This result is in agreement with previous studies that have shown that CPT symmetry (Charge conjugation, Parity and Time reversal) and General Relativity cannot be compatible unless matter and antimatter are mutually repelled [22]. We expect the ALPHA-g, AEgIS and GBAR experiments at CERN to give a definite answer to that issue.

Note that, from equation (15) for the electron, ξ is negative and consequently the ordinary masses in equations (18) and (20) are negative and those of antimatter obtained from the positron charge are positive. This is because historically, a negative charge was conventionally attributed to the electron and a positive one to the positron. Inverting, eventually, the traditional convention and attributing a positive charge to the electron and a negative to the positron, which becomes a "negatron", results to positive mass for matter (positive ξ) and negative for antimatter (negative ξ).

Also, $\varepsilon_0, \mu_0, \mu_B, G$ as well as the photon frequencies and energies are positive and identical for matter and antimatter. However, due to ξ signs, the vector potential as well as the electric and magnetic fields of photons emitted by matter have opposite signs with respect to those emitted by antimatter, which might constitute an experimental criterion for exploring antimatter structures in the universe.

Planck's length l_P is a physical parameter corresponding to the shorter possible photon wavelength and consequently characterizes the granularity of the electromagnetic quantum vacuum. According to the established equations (2), (11), (15) and (21), the fundamental constants $c = (\varepsilon_0\mu_0)^{-1/2}$, $e = (4\pi)^2 \alpha\xi / \mu_0$, $\hbar = \alpha\xi^2 (4\pi)^3 \varepsilon_0^{-1/2} \mu_0^{-3/2}$ and $G = l_p^2 / (4\pi)^3 \alpha\varepsilon_0\xi^2$ are expressed uniquely through the vacuum physical parameters ε_0, μ_0, ξ and l_P entailing that electromagnetism and gravitation are natural manifestations of the electromagnetic quantum vacuum field that may constitute the basic step towards a unified field theory.

Now, it is important remarking that equation (22) simply transposes the problem of gravitation without giving a clear idea about its real physical origin. In other words, we have jumped from the unknown reason why masses attract (or repel) each other to the unknown reason why the ratios of charge to the magnetic moments should attract (or repel) each other.

In fact, using (20) the gravitational potential (25) writes

$$U \simeq \sigma^2 e^2 G \sum_{i,j(i<j)} \frac{s_{ij} n_i n_j}{r_{ij}} \qquad (26)$$

where s_{ij} is the sign of the product $e_i e_j$ and n_i, n_j are the corresponding integers.
Obviously, unless pure integers attract (or repel) each other, Newton's and Coulomb's law are phenomenological mathematical expressions describing "how" gravitation and electrostatic forces act but without explaining physically "why".

Consequently, it is worth investigating whether gravitation may originate from the radiation pressure of the electromagnetic quantum vacuum field (*Electromagnetic Push Gravity*) felt by the bodies in their own frame depending on the collective frequencies of their own charge densities [16].
In fact, a plasma is characterized by the plasma frequency ω_p corresponding to a collective oscillation frequency of the electron density n_e, whose well-known expression is

$$\omega_p = \left(\frac{n_e e^2}{\varepsilon_0 m_e} \right)^{1/2} \qquad (27)$$

Similarly, whatever the temperature, all the bodies are composed of charge densities whose collective oscillations yield characteristic global frequencies, analogue to the plasma frequency. For instance, the electron density in iron is roughly 2 10^{29} m^{-3}. Assuming that the plasma frequency expression (27) is valid, the frequency obtained for the iron is roughly $\omega_{iron} \approx 3 10^{16} Hz\ rad$, which lays in the UV region.

Thus, every mass is characterized by one or more charge density collective frequencies and the kenons of the electromagnetic quantum vacuum field are "seen" in the mass frame as photons at the same collective frequencies inducing a radiation pressure.

Considering that a mass is characterized by a collective frequency ω_c, taking into account the two circular polarizations of kenons and the fact that the photon electric field seen in the frame of the mass is proportional to $\xi \omega_c^2$, according to (5), the pressure dP exerted by the kenons upon the mass in a solid angle $d\Omega$ writes

$$dP_{vacuum} = \left(4 \varepsilon_0 \xi^2 \omega_c^4 \right) d\Omega \qquad (28)$$

The origin of gravitation appears to lay on the modification of the electromagnetic quantum vacuum field fluctuations due to the presence of localized charges (mass) which reduce locally the presence of the vacuum states that is kenons. Thus, a flow of kenons from the surrounding is induced towards the charge density (mass) which consequently experiences in its frame a radiation pressure at the characteristic frequency ω_c .

Variations to quantum vacuum fluctuations may be also due to the presence of electromagnetic waves (photons), which also reduce the presence of kenons since they are composed of kenons themselves, enhancing by this way the gravitational effect at short distance. For instance, the photospheres of stars increase the gravitational effect felt by the bodies moving closely (perihelion). By the same token, light rays should follow the paths in the electromagnetic vacuum imposed by the charge densities in space modifying locally the vacuum fluctuations and the refractive index.

As an example, we may attempt to evaluate in a first approximation what could be the characteristic frequency of the Earth's charge density by considering the system Sun-Earth.

The characteristic distances of the system are: Radius of the Earth $R_E = 6.37\,10^6 m$, Radius of the Sun $R_S = 6.96\,10^8 m$ and the mean distance Sun-Earth $R_{S-E} = 1.5\,10^{11} m$.

Let us denote the collective frequency of the charge densities of the Earth by ω_E.

Consequently, the screening of the Sun, being considerably more important than that of the Earth, induce a force on the Earth towards the Sun due to the radiation pressure of the kenons flux coming from the opposite side which writes in a first approximation

$$\delta F \approx 4\varepsilon_0 \xi^2 \omega_E^4 \left(\frac{\pi R_S^2}{R_{S-E}^2} \right) 2\pi R_E^2 = 8\pi^2 \varepsilon_0 \xi^2 \omega_E^4 \frac{R_S^2 R_E^2}{R_{S-E}^2} \tag{29}$$

Obviously, except the characteristic collective frequency, the geometry of the bodies plays also an important role.

We obtain a total attraction force exerted on the Earth due to the vacuum pressure induced by the presence of Sun equivalent to the Newtonian one $3.5\,10^{22} N$ for $\omega_E \sim 2\pi\,10^{17} Hz\ rad$ which lays in the far UV region.

Using the same formalism a similar result is obtained for the system Earth-Moon considering the lunar characteristic frequency ω_L. The distances are: Radius of the Earth $R_E = 6.37\,10^6 m$, Radius of the Moon $R_M = 1.74\,10^6 m$ and the mean distance Earth-Moon $R_{E-M} = 3.8\,10^8 m$. We get

$$\delta F \approx 8\pi^2 \varepsilon_0 \xi^2 \omega_L^4 \frac{R_L^2 R_E^2}{R_{E-L}^2} \tag{30}$$

The attraction force is equivalent to the Newtonian one $2\,10^{20} N$ for $\omega_L \sim 2\pi\,5 \cdot 10^{16} Hz\ rad$ which lays in the UV region.

Despite the extreme simplicity of the above calculations, the obtained results seem to be rather physical since the plasma frequency corresponding to the electron density in metals is also in the UV region.

The precise knowledge of the characteristic frequencies and the geometry could yield results that are more accurate by considering the mutual screening effects of all the interacting bodies.

Thus, a better-elaborated model of *Electromagnetic Push Gravity*, analogue to that developed recently [23] for the Push Gravity, could be interesting to be developed and tested. Thereon, the correspondence of "kenons" to "gravions would be also of great interest to be investigated in detail.

3. The electromagnetic quantum vacuum cosmic source of photons (energy) and charges (mass). Qualitative Principles of Quantum Vacuum Cosmology.

We have seen that transient states of the Dark Light fluctuations might be at the origin of Dark Energy and Dark Matter. Now, we may assume that a small part of the electromagnetic quantum vacuum fluctuations can indeed remain in space as residual real states. Certainly, this conflicts with the mass-energy and charge conservation laws but, as we will see later, these laws are satisfied between the initial and final states of the overall cosmic process. This statement constitutes the basis for a Quantum Vacuum Cosmological model whose main principles are described qualitatively below.

Real photons and charges (particles and antiparticles), can be created continuously in space as residues of the electromagnetic quantum vacuum fluctuations. Thus, the vacuum turns out to be a cosmic source of photons (energy) and charges (matter and antimatter). The particles generated by the vacuum fluctuations residues might be in thermal equilibrium at ~3 K, which could explain the homogeneous and isotropic Cosmic Microwave Background (CMB).

In the birth stage of the universe, the spontaneous energy-mass creation process dominates. Photons and charges (particles and antiparticles) are created continuously everywhere in an infinite and eternal space entailing that universe is homogeneous and flat. Some particle-antiparticles pairs annihilate producing photons, others combine progressively to electrons-protons and positrons-antiprotons forming respectively hydrogen and antihydrogen atoms, then molecules and gas which are progressively separated by gravitational repulsion to form distant accumulations, the first with ordinary matter and the second with antimatter. The presence of matter favors particles generation in space and that of antimatter antiparticles generation. Under the effect of gravity, following the well-known mechanisms, the increasing concentrations of hydrogen (antihydrogen) give birth to stars (antimatter stars, 'anti-stars'). Next, heavier elements (anti-elements) are produced in stars (anti-stars) by the also well-known baryon (anti-baryon) genesis process. Galaxies (antimatter galaxies, 'anti-galaxies') and clusters of galaxies (anti-galaxies) are formed progressively. Vacuum fluctuation residues are enhanced mostly near already generated massive structures entailing the formation of a local finite universe. If matter and antimatter structures are not separated completely since the beginning due to gravitational repulsion to form a local universe and a distant anti-universe, then remnants of antimatter (matter) might persist in the universe (antimatter universe, 'anti-universe'). Recent works have shown that antihydrogen atoms have the same properties with those of ordinary hydrogen atoms and particularly the same energy levels [24, 25]. We may reasonably assume that antimatter stars and galaxies should have the same birth, life and death as the ordinary matter ones, as well as similar radiation properties yielding a particular difficulty for their detection. Therein, as we mentioned above, an experimental device capable of distinguishing the opposite signs of the polarized photons vector potentials, and the resulting electric and magnetic fields, could eventually be useful for exploring the antimatter distributions in the universe.

Vacuum transient photons fluctuations are mostly enhanced near charge (mass) concentrations and consequently are higher within a local universe system than in the space outside contributing by this way to a smooth accelerated expansion [19]. The presence of antimatter structures in an ordinary mass universe would also contribute to the cosmic acceleration and it might probably play a dominant role through matter-antimatter gravitational repulsion that is worthy to be further investigated.

In a second stage, energy-mass annihilation mechanisms in the universe (anti-universe), like black holes (antimatter black holes, 'anti black holes') and probably other yet unknown cosmic structures, start appearing following the death of massive stars (anti-stars), mostly in the center of galaxies (anti-galaxies). Obviously, such annihilation mechanisms appear to older galaxies, which could explain why quasars are found in big distances. The cosmic energy-mass annihilation mechanisms transform the initially spontaneously generated energy-mass back to the quantum vacuum state, which also explains simply what the huge amounts of energy and mass absorbed by black holes become in the singularity.

A period of equilibrium might be eventually established in the local universe (anti-universe) during which the energy-mass annihilation and creation rates balance. In a later stage, the annihilation mechanisms might prevail the creation ones and the generated mass-energy returns progressively to the vacuum state. In the overall energy-mass creation and annihilation processes the energy-mass and charge conservation laws are respected between the initial and final state.

Conclusions

We have visited the basic physical features that derive naturally from the electromagnetic quantum vacuum, the cosmic Dark Light, composed of real states called kenons. Local oscillations of kenons over a wavelength at an angular frequency ω_k give birth to a real vector potential, thus to real photons (electromagnetic waves) guided by the non-local vector potential wave function with the quantized amplitude $\alpha_{0k} = \xi\omega_k$. The vacuum electric permittivity and magnetic permeability, ε_0 and μ_0 respectively, are intrinsic properties of the electromagnetic quantum vacuum and fix the speed of photons in vacuum c.

Positive and negative elementary charges are states of the same vacuum field and are strongly related to photons vector potential through the vacuum constant ξ. The masses of all particles and antiparticles originate from charges and their magnetic moment. Hence, the electromagnetic vacuum should have a complex structure with quantum levels that may be related to the string theory.
The mass-charge equivalence relation results directly expressing that the masses of all particles-antiparticles are proportional to the electron-positron elementary charge respectively. The gravitational constant *G* derives also from the vacuum electromagnetic properties ε_0, μ_0, ξ implying that Newton's gravitational potential is equivalent to Coulomb's electrostatic potential. We deduced that gravitation has electromagnetic nature and the gravitational constant *G* is the same for matter and antimatter. However, the masses of particles and antiparticles bear naturally opposite signs entailing a mutual gravitational repulsion. Matter-antimatter antigravity may play a dominant role in the cosmic acceleration and has to be investigated experimentally.

Finally, the electromagnetic quantum vacuum is a cosmic field permeating everything in the universe and whose fluctuations last longer the lower the frequency. This could also explain the origin of the $1/f^n$ noise observed not only in astrophysics but also in many other technological fields.

It is of high importance to mention that we have made no hypothesis and advanced no axioms or postulates in order to obtain the above results. Everything derives naturally from Maxwell's theory once the vector potential amplitude is normalized at a single photon level. The simplicity of the established formalism relating the electromagnetic vacuum to electromagnetism, particle physics and gravitation signifies that there should be a real physical background behind the equations. Consequently, the electromagnetic quantum vacuum field may constitute the physical basis for the development of a coherent unified field theory.

Dark Energy and Dark Matter might both originate from transient states of Dark Light fluctuations. The first due to transient photons and the second to transient pairs of known and unknown particles. Weighing the electromagnetic vacuum fluctuations energy density, we deduced that the electromagnetic energy density of the quantum vacuum fluctuations should have a pic in the THz region. Under these conditions, free space is not Lorentz invariant and an observer with uniform velocity, in absence of any other reference frame, would be able to detect his motion from the Doppler shift of the electromagnetic vacuum fluctuations spectrum.

We have drawn that transient photons due to vacuum fluctuations, that we identified to Dark Energy, and matter-antimatter antigravity represent the physical mechanisms that might be at the origin of the observed cosmic acceleration. A detailed experimental investigation could conclude which of these mechanisms plays the dominant role in this process.

Next, we advanced two hypothesis:

a. *Gravitation is due to the electromagnetic quantum vacuum (kenons) radiation pressure (Electromagnetic Push Gravity) seen by the charge densities (mass) in their frame at their own collective oscillation frequencies.*

Using a simple screening model, we have analyzed in a first approximation the possibility of the "*Electromagnetic Push Gravity*" due to the electromagnetic quantum vacuum (kenons). The modification of the vacuum field fluctuations due to the presence of a localized charge density (mass), which reduces the vacuum states (kenons), induces a flux of kenons towards the mass which in its frame experiences a radiation pressure at the characteristic frequency of the charge density collective frequency.

Photons (electromagnetic waves) may also induce a modification to the quantum vacuum fluctuations since they are composed of kenons reducing locally the vacuum states. Light rays follow the paths in the electromagnetic vacuum imposed by the charge densities in space reducing locally the vacuum states (kenons) and modifying consequently the vacuum fluctuations and the refractive index.

The approximated characteristic frequencies calculated for Earth and Moon lay in the far UV spectrum and are slightly higher than the plasma frequencies attributed to metals.

b. *Photons as well as matter and antimatter in universe emerge spontaneously from the electromagnetic quantum vacuum as residues of its associated fluctuations.*

Thus, Dark Energy, Dark Matter, photons, matter and antimatter, all derive from the electromagnetic quantum vacuum, the Dark Light composed of kenons.

Energy-mass annihilation mechanisms, such as black holes, appear naturally in the later stage of the evolution of the universe transforming the initially generated energy-mass back to the vacuum state. This also provides a satisfactory explanation to what the tremendous quantities of energy-mass swallowed by black holes become in the singularity.

A large number of finite universes, as ours, and anti-universes might be born, extend, live and die in an infinite and eternal space. Energy-mass and charges are conserved between the initial and final states of the overall cosmic creation-annihilation processes.

A new cosmological model could be developed on this basis overcoming the well-known Big Bang inconveniences such as, initial state, faster than the speed of light inflation, as well as the horizon, flatness and antimatter issues.

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The **appendices** below are joint with the aim to help the reader understanding better the theoretical background used in this paper.
Developments that are more extensive can be found in:

- *Light and Vacuum*, Constantin Meis, 2nd Edition, World Scientific, Singapore (2017).

- *Quantized field of single photons*, Constantin Meis, in Single Photon Manipulation, IntechOpen, London (2019), Ed. Prof. Keyu Xia, Nanjing University, China. DOI: 10.5772/intechopen.88378, ISBN: 978-1-83880-353-7. Open Access. https://www.intechopen.com/online-first/quantized-field-of-single-photons

- *Primary role of the quantum electromagnetic vacuum in Gravitation and Cosmology*, Constantin Meis, in Cosmology 2020 – The Current State, IntechOpen, London (2020), Ed. Michael L. Smith, USA. DOI: 10.5772/intechopen.87805. ISBN: 978-1-83968-267-4. Open Access https://www.intechopen.com/online-first/cosmology-2020-the-current-state

APPENDIX 1

- *Vector potential amplitude operator and photon wave-particle equation*

A general solution of the vector potential $\vec{A}(\vec{r},t)$ is obtained from Maxwell's equations and writes

$$\vec{A}(\vec{r},t)=\frac{\mu}{4\pi}\int\frac{\vec{J}(\vec{r}',t-\frac{|\vec{r}-\vec{r}'|}{c})}{|\vec{r}-\vec{r}'|}d^3r \qquad (1.1)$$

A simple dimension analysis of the last expression shows that the vector potential is proportional to a frequency. Hence, we may write for the vector potential amplitude $\alpha_{0k}(\omega_k)$ of a single *k*-mode photon with angular frequency ω_k

$$\alpha_{0k}(\omega_k)=\xi\omega_k \qquad (1.2)$$

where ξ is a constant to be determined.
Thus, the equation with the fundamental physical quantities characterizing both the particle (energy and momentum) as well as the wave (vector potential, wave vector and dispersion relation) nature of a single *k*-mode photon is now completed by introducing the missing electromagnetic nature of a single photon through the vector potential amplitude

$$\frac{E_k}{\hbar}=\frac{|\vec{p}_k|}{\hbar/c}=\frac{\alpha_{0k}}{\xi}=\frac{|\vec{k}|}{\sqrt{\varepsilon_0\mu_0}}=|\vec{k}|c=\omega_k \qquad (1.3)$$

An interesting feature results by considering that the photon momentum $|\vec{P}_k|$ has the units of a mass m_k times the velocity *c* in vacuum so we may write $|\vec{P}_k|=\hbar k=m_k c$. Of course, m_k is simply a dimensional parameter here since the photon is generally considered to be a massless particle. Using $E_k=\hbar\omega_k=\hbar\, k\, c$ one gets directly $E_k=m_k c^2$ showing that the energy-mass equivalence is a direct result of the wave-particle double nature of light since we have used the wave dispersion relation $\omega_k=|\vec{k}|c$ and the momentum $|\vec{P}_k|=\hbar|\vec{k}|$ which is a particle property.

Now, the photon vector potential may be written in a general plane wave expression with the quantized amplitude

$$\vec{\alpha}_{k\lambda}(\vec{r},t) = \omega_k \left(\xi \hat{\varepsilon}_\lambda e^{i\left(\omega_k t - \vec{k}\cdot\vec{r} + \varphi\right)} + cc\right) = \omega_k \vec{\Xi}_{k\lambda}(\omega_k, \vec{r}, t) \qquad (1.4)$$

with λ the polarization (circular left or right), $\hat{\varepsilon}_\lambda$ the polarization complex unit vector, φ a phase parameter and *cc* the complex conjugate.

It is physical for the photon vector potential function $\alpha_{k\lambda}(\vec{r},t)$ to satisfy the wave propagation equation in vacuum

$$\vec{\nabla}^2 \vec{\alpha}_{k\lambda}(\vec{r},t) - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\vec{\alpha}_{k\lambda}(\vec{r},t) = 0 \qquad (1.5)$$

The second derivative with respect to time is proportional to the square of the amplitude and we get

$$\frac{\partial^2}{\partial t^2}\vec{\alpha}_{k\lambda}(\vec{r},t) = -\omega_k^2 \vec{\alpha}_{k\lambda}(\vec{r},t) = -\left(\frac{\alpha_{0k}}{\xi}\right)^2 \vec{\alpha}_{k\lambda}(\vec{r},t) \qquad (1.6)$$

The propagation equation now writes

$$\left[\alpha_{0k}^2 + \xi^2 c^2 \vec{\nabla}^2\right] \vec{\alpha}_{k\lambda}(\vec{r},t) = 0 \qquad (1.7)$$

entailing that the photon vector potential amplitude can be expressed as an operator $\tilde{\alpha}_{0k}$ proportional to the constant ξ

$$\tilde{\alpha}_{0k} = -i\xi c\vec{\nabla} \qquad (1.8)$$

which is valid for any mode *k*. Obviously, the established vector potential amplitude operator is quite symmetrical with the relativistic Hamiltonian for a massless particle

$$\tilde{H} = -i\hbar c\vec{\nabla} \qquad (1.9)$$

Application of $\tilde{\alpha}_{0k}$ upon $\alpha_{k\lambda}(\vec{r},t)$ along the propagation axis induce a phase variation getting

$$\tilde{\alpha}_{0k}\,\vec{\alpha}_{k\lambda}(\vec{r},t,\varphi) = i\xi ck\,\vec{\alpha}_{k\lambda}(\vec{r},t,\varphi + \frac{\pi}{2}) \qquad (1.10)$$

However, for the time variation we also get

$$\frac{\partial}{\partial t}\vec{\alpha}_{k\lambda}(\vec{r},t,\varphi) = \omega_k\,\vec{\alpha}_{k\lambda}(\vec{r},t,\varphi + \frac{\pi}{2}) \qquad (1.11)$$

Combination of the last two equations gives a linear time differential equation for the photon vector potential

$$i\xi\frac{\partial}{\partial t}\vec{\alpha}_{k\lambda}(\vec{r},t) = \tilde{\alpha}_{0k}\,\vec{\alpha}_{k\lambda}(\vec{r},t) \qquad (1.12)$$

Consequently, the *vector potential – energy* (wave – particle) equation for the photon is obtained straight forward by associating Schrödinger's equation and writes

$$i\begin{pmatrix}\xi\\ \hbar\end{pmatrix}\frac{\partial}{\partial t}\vec{\alpha}_{k,\lambda}(\vec{r},t) = \begin{pmatrix}\tilde{\alpha}_0\\ \tilde{H}\end{pmatrix}\vec{\alpha}_{k,\lambda}(\vec{r},t) \qquad (1.13)$$

where

$$\begin{pmatrix}\tilde{\alpha}_0\\ \tilde{H}\end{pmatrix} = -i\begin{pmatrix}\xi\\ \hbar\end{pmatrix}c\vec{\nabla} \qquad (1.14)$$

are the photon vector potential amplitude and the Hamiltonian operators.

- *Definition of the vector potential amplitude quantization constant* ξ
- *Electron charge from the electromagnetic quantum vacuum*

Considering the photon as an integral particle, the integration of the energy density should give the single photon energy $E_k = \hbar\omega_k$, so we have

$$\int \varepsilon_0 \omega_k^2 \alpha_{0k}^2(\omega_k)\left[\hat{\varepsilon}_\lambda e^{i(\omega_k t - \vec{k}\cdot\vec{r}+\varphi)} + c.c\right]^2 d^3r = \hbar\omega_k \qquad (1.15)$$

For the last relation to hold at any instant *t* the photon polarization unit vector $\hat{\varepsilon}_\lambda$ should have at least two orthogonal components, $\hat{e}_1$ and $\hat{e}_2$, such as $\hat{\varepsilon}_\lambda = \sigma_1\hat{e}_1 + \sigma_2\hat{e}_2$ with $|\sigma_1|^2 + |\sigma_2|^2 = 1$ and $\hat{e}_1 \cdot \hat{e}_2 = 0$. Accordingly, right (R) and left (L) hand circular polarization unit vectors, $\hat{\varepsilon}_{L,R} = \frac{1}{\sqrt{2}}\left(\hat{e}_1 \pm i\hat{e}_2\right)$ are naturally appropriate to satisfy this condition and equation (1.15) becomes

$$\int 2\varepsilon_0 \omega_k^2\, \alpha_{0k}^2(\omega_k) d^3r = \hbar\omega_k \qquad (1.16)$$

It has been demonstrated that a *k*-mode photon cannot be considered as an integral entity within a length smaller than its wavelength λ_κ [1.1]. Furthermore, Compton has demonstrated the directional character of photons experimentally. Thus, the integration of the left hand side of equation (1.16) may be carried out in cylindrical coordinates (ρ, θ, z), where *z* is the propagation axis along which the vector potential rotates perpendicularly. In a full period interval, $0 \le z \le \lambda_k$, the angular coordinate θ is related to *z* by $\theta = 2\pi z / \lambda_k$ and the integration may be reduced to the variables, *z* and ρ in the limits $0 \le z \le \lambda_k$ and $0 \le \rho \le \eta\lambda_k$, with η a positive dimensionless constant characterizing the radial spatial extension of the photon.

Using (1.2) we get

$$2\varepsilon_0\omega_k^2\alpha_{0k}^2(\omega_k)\left(\frac{\eta^2}{2}\lambda_k^3\right) = (2\pi c)^3\varepsilon_0\xi^2\eta^2\omega_k = \hbar\omega_k \qquad (1.17)$$

Hence, the product of the two constants η and ξ has the value

$$\eta\xi = \frac{1}{(2\pi)^{3/2}}\sqrt{\frac{\hbar}{\varepsilon_0 c^3}} \qquad (1.18)$$

Now, equation (1.17) can be written with a slight rearrangement as follows

$$4\pi c\left(\frac{1}{4\pi c}2\varepsilon_0\omega_k^2\alpha_{0k}(\omega_k)\left(\frac{\eta^2}{2}\lambda_k^3\right)\right)\alpha_{0k}(\omega_k) = 4\pi c\, Q\, \alpha_{0k}(\omega_k) = \hbar\omega_k \qquad (1.19)$$

making to appear a parameter *Q* which has charge units.

Considering the square of *Q* and using (1.2) and (1.18) we get

$$Q^2 = \left(\frac{1}{4\pi c}2\varepsilon_0\omega_k^2\alpha_0(\omega_k)\left(\frac{\eta^2}{2}\lambda_k^3\right)\right)^2 = \frac{\eta^2}{4}\left(\varepsilon_0 h\, c\right) \qquad (1.20)$$

where *h* is Planck's constant.

Using for η the experimental approximate value of ~1/4 [1.2-1.4] we obtain directly the numerical value $Q \sim 1.6\ 10^{-19}$ Coulomb, which is the electron charge, a physical constant, appearing naturally here when considering the quantization of the vector potential amplitude at a single photon level.

This signifies that the physical origin of the electron charge is strongly related to photon vector potential. Based on this result we can go further in the definitions of both η and ξ constants by the intermediate of the electron charge expressed through the fine structure constant $\alpha = e^2 / 4\pi\varepsilon_0\hbar c$

$$\frac{\eta^2}{4}\left(\varepsilon_0 h c\right) = 2\alpha\left(\varepsilon_0 h c\right) \qquad (1.21)$$

getting

$$\eta = \sqrt{8\alpha} \tag{1.22}$$

Consequently, from (1.18) we get the value of ξ

$$\xi = \pm \frac{1}{(2\pi)^{3/2}} \sqrt{\frac{\hbar}{8\alpha\ \varepsilon_0 c^3}} = \frac{\hbar}{4\pi ec} = 1.747\ \ 10^{-25}\ Volt\ m^{-1} s^2 \tag{1.23}$$

The single *k*-mode photon quantization volume writes

$$V_k = \left(\frac{\eta^2}{2} \lambda_k^3 \right) = 4\alpha\lambda_k^3 \tag{1.24}$$

A similar result for the single photon quantization volume can be obtained from the density of states theory. In fact, the number of photons $dn(\omega)$ in the quantization volume *V* in the frequency interval between ω and $\omega + d\omega$ is

$$dn(\omega) = V \frac{\omega^2}{\pi^2 c^3} d\omega \tag{1.25}$$

Thus,

$$n(\omega) = 4V \frac{\omega^3}{3\pi^2 c^3} \tag{1.26}$$

where the factor 4 takes into account the two possible values of spin ($\pm\hbar$) and the propagation directions ($\pm z$). For $n(\omega) = 1$ the corresponding quantization volume for a k-mode photon writes

$$V_k = \left(\frac{3}{4} \pi^2 c^3 \right) \omega_k^{-3} \tag{1.27}$$

With $\lambda_k^3 = (2\pi c)^3\ \omega_k^{-3}$ we get

$$V_k = \frac{3}{32\pi} \lambda_k^3 \simeq 4\alpha\lambda_k^3 \tag{1.28}$$

Finally, from (1.20), (1.22) and (1.23) it is straightforward to obtain the electron charge depending uniquely on the electromagnetic quantum vacuum constants

$$e = (4\pi)^2\ \alpha \frac{\xi}{\mu_0} \tag{1.29}$$

The last relation demonstrates that the elementary charge is a state of the electromagnetic quantum vacuum strongly related to the single photon vector potential amplitude.

- *Photon wave-particle properties and Heisenberg's uncertainty*

The particle properties, energy, momentum and spin of a *k*-mode photon are not carried by a point particle but by a wave-corpuscle and can be expressed in terms of the quantisation volume.
As we have seen above, the energy of a single photon can be obtained as follows

$$E_k = \int_{V_k} 2\varepsilon_0 \alpha_{0k}{}^2 \omega_k^2 d^3 r = \int_{V_k} 2\varepsilon_0 \xi^2 \omega_k^4 d^3 r = 2\varepsilon_0 \xi^2 \omega_k^4 V_k = \hbar\omega_k \tag{1.30}$$

With the same token considering a circular polarization the momentum writes

$$\vec{P}_k = \int_{V_k} \varepsilon_0 \vec{\varepsilon}_{k\lambda} \times \vec{\beta}_{k\lambda} d^3 r = \varepsilon_0 \left(\sqrt{2}\omega_k \alpha_{0k} \right) \left(\frac{1}{c} \sqrt{2}\omega_k \alpha_{0k} \right) V_k \frac{\vec{k}}{|\vec{k}|} = \hbar\vec{k} \tag{1.31}$$

where $\vec{\varepsilon}_{k\lambda}$ and $\vec{\beta}_{k\lambda}$ denote the electric and magnetic fields of a single mode *k*.

According to the classical electromagnetic theory the spin can be written through the electric and magnetic fields components

$$\left|\vec{S}\right| = \int_{V_k} \varepsilon_0 \left|\vec{r} \times \left(\vec{\varepsilon}_{k\lambda} \times \vec{\beta}_{k\lambda}\right)\right| d^3 r = \varepsilon_0 \left(\frac{c}{\omega_k}\right)\left(\sqrt{2}\omega_k \alpha_{0k}\right)\left(\frac{1}{c}\sqrt{2}\omega_k \alpha_{0k}\right) V_k = \hbar \tag{1.32}$$

where we have considered the property [1.6] that the mean value of the length in a *k*-mode photon state is c/ω_k .

The quantization volume V_k appears to be an intrinsic property for a single photon and defines the minimum space in which the quantized electric and magnetic fields oscillate at the frequency ω_k over a wavelength λ_k along the propagation axis. It may also ensure the link with the particle representation. In fact, when introducing the particle operators single photon vector potential amplitude operators expressed through the creation and annihilation non-Hermitian operators

$$\tilde{\alpha}_{0k} = \xi \omega_k a_{k\lambda} \quad ; \quad \tilde{\alpha}^*_{0k} = \xi \omega_k a^+_{k\lambda} \tag{1.33}$$

into the quantum electrodynamics position and momentum operators, one directly gets the corresponding position $\hat{Q}_{k\lambda}$ and momentum $\hat{P}_{k\lambda}$ operators,

$$\hat{Q}_{k\lambda} = \sqrt{\varepsilon_0 V_k}\left(\tilde{\alpha}_{0k} + \tilde{\alpha}^*_{0k}\right) \qquad \hat{P}_{k\lambda} = -i\omega_k \sqrt{\varepsilon_0 V_k}\left(\tilde{\alpha}_{0k} - \tilde{\alpha}^*_{0k}\right) \tag{1.34}$$

The demonstration of Heisenberg's commutation relation, a fundamental concept in quantum theory, is straightforward

$$\left[\hat{Q}_{k\lambda}, \hat{P}_{k'\lambda'}\right] = -i\varepsilon_0 \omega^2_{k'} \omega_k \sqrt{V_k V_{k'}}\left[\left(\xi a_{k\lambda} + \xi^* a^+_{k\lambda}\right), \left(\xi a_{k'\lambda'} - \xi^* a^+_{k'\lambda'}\right)\right] = i\hbar \delta_{kk'} \delta_{\lambda\lambda'} \tag{1.35}$$

showing the consistency of the above formalism.

Appendix 1 - References

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APPENDIX 2

- *Fulling-Davies-Unruh temperature in the electromagnetic quantum vacuum*

Any particle moving in the electromagnetic field ground state with an acceleration $\vec{\gamma}$ experiences an electric potential

$$U = |\xi\,\vec{\gamma}| \qquad (2.1)$$

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

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

$$E = |e\,\xi\,\vec{\gamma}| = \frac{1}{2} k_B T \qquad (2.2)$$

where k_B is Boltzmann's constant.

Replacing ξ in the last equation by the expression, $\xi = \hbar / 4\pi ec$ we get directly the Fulling-Davies-Unruh temperature

$$T = \frac{\hbar}{2\pi c k_B} |\vec{\gamma}| \qquad (2.3)$$

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

APPENDIX 3

In the following, we calculate the vacuum effects, spontaneous emission and Lamb shift, due to the electromagnetic quantum vacuum $\Xi_{0\lambda}$. We do not deal with the Casimir effect since it has been clearly demonstrated [3.1 – 3.3] that its physical origin lays on the source fields and Lorentz's forces. However, the Casimir effect may also be interpreted as the radiation pressure difference between the inner and outer space of the conducting plates due to photons "seen" in the electromagnetic quantum vacuum field by the electrons having a periodic motion on the inner and outer surfaces of the plates.

- *The electromagnetic quantum vacuum and the spontaneous emission*

We recall the total Hamiltonian of an atom in the presence of an electromagnetic field in the dipole approximation writes:

$$H_{tot} = H_{Electromagnetic\_Field} + H_{\text{interaction}} + H_{atom} = \sum_{k,\lambda} \hbar\omega_k \left(\tilde{n}_{k\lambda} + \frac{1}{2} \right) - \vec{D}\cdot\vec{E}(\vec{r},t) + \sum_i \hbar\omega_i \left|\Psi_i\right\rangle\left\langle\Psi_i\right| \qquad (3.1)$$

Where we have used the harmonic Hamiltonian representation for the electromagnetic field including the zero-point energy, $\vec{D} = e\vec{r}$ is the dipole moment of an atomic electron of charge e and $|\Psi_i\rangle$ the atomic levels with the corresponding energies $\hbar\omega_i$.

The spontaneous emission rate is always calculated in QED <u>neglecting</u> $\sum_{k,\lambda}\frac{1}{2}\hbar\omega_k$ in $H_{Electromagnetic\_Field}$ (since it is an infinite quantity) and using the following expression for the electric field $\vec{E}(\vec{r},t)$ resulting from Heisenberg's equation of motion.

$$\vec{E}(\vec{r},t) = -\frac{\partial \vec{A}(\vec{r},t)}{\partial t} = \frac{i}{\hbar}\left[\vec{A}(\vec{r},t), \sum_{k,\lambda} \hbar\omega_k \left(\tilde{n}_{k\lambda} + \frac{1}{2} \right) \right] \tag{3.2}$$

Consequently, for the calculation of the electric field attributed to the vacuum state the term $\sum_{k,\lambda} \frac{1}{2}\hbar\omega_k$ should be the principal contribution to the interaction Hamiltonian. However, the commutation operator of the vector potential and the vacuum zero-point Hamiltonian cancels

$$\left[\vec{A}(\vec{r},t), \sum_{k,\lambda} \frac{1}{2}\hbar\omega_k \right] = 0 \tag{3.3}$$

because the zero-point energy $\sum_{k,\lambda} \frac{1}{2}\hbar\omega_k$ is a constant and consequently this term has absolutely no contribution in the general expression of the quantized electric field used to calculate the spontaneous emission in QED.

Indeed, in a rigorous calculation the interaction Hamiltonian between an atomic electron and the vacuum writes

$$H_{\text{interaction}} = -\vec{d} \cdot \frac{i}{\hbar}\left[\vec{A}(\vec{r},t), \sum_{k,\lambda} \frac{1}{2}\hbar\omega_k \right] = 0 \tag{3.4}$$

which also vanishes in QED as in the semi-classical description and this fact is scarcely quoted in the literature.

The physical reason is that in QED the vacuum state Hamiltonian is not described by a function of $a_{k\lambda}$ and $a_{k\lambda}^{+}$ operators and consequently it is impossible to define an interaction Hamiltonian for the description of the electron-vacuum interaction processes. Conversely, the electromagnetic field ground state (described by equation 7b in this paper) does indeed depend on the photon creation and annihilation operators permitting to define a "vacuum action" operator corresponding to an interaction Hamiltonian per angular frequency between the vacuum field $\tilde{\tilde{\Xi}}_{0\lambda}$ and an atomic electron of mass m_e and charge e [3.4]

$$H_{\omega_k} = \frac{\hbar e}{m_e c} \tilde{\tilde{\Xi}}_{0\lambda} \tilde{\Omega}_k = -i\hbar \frac{e}{m_e} \tilde{\tilde{\Xi}}_{0\lambda} \cdot \vec{\nabla} \tag{3.5}$$

Thus, the amplitude of the transition probability per angular frequency between an initial state $|\Psi_i, 0\rangle$ with total energy $E_i = \hbar\omega_i$, corresponding to an atom in the state $|\Psi_i\rangle$ with energy E_i in vacuum $|\ldots, 0_{k\lambda}, \ldots, 0_{k'\lambda'}, \ldots\rangle$, and a final state $|\Psi_f, n_{k\lambda}\rangle$ with total energy $E_{f,n_{k\lambda}} = \hbar\omega_f + n_{k\lambda}\hbar\omega_k$ representing the atom in the state $|\Psi_f\rangle$ with energy $E_f = \hbar\omega_f$ in the presence of $n_{k\lambda}$ photons, can be expressed in first order time dependent perturbation theory

$$c_{\omega_k}^{(1)}(t) = -\frac{e}{m_e} \int_0^t \Big[\langle \Psi_f, n_{k\lambda} | \xi \vec{\varepsilon}_{k\lambda} \cdot \vec{\nabla} a_{k\lambda} | \Psi_i, 0 \rangle e^{i(\omega_i - \omega_f - n_{k\lambda}\omega_k)t'} + \langle \Psi_f, n_{k\lambda} | \xi^* \vec{\varepsilon}^{\,*}{}_{k\lambda} \cdot \vec{\nabla} a_{k\lambda}^{+} | \Psi_i, 0 \rangle e^{-i(\omega_i - \omega_f - n_{k\lambda}\omega_k)t'} \Big] dt' \tag{3.6}$$

Since $a_{k\lambda}\left|\Psi_i,0\right\rangle = 0$, using the fundamental definition of the momentum operator $\vec{P} = -i\hbar\vec{\nabla}$ as well as Heisenberg's equation of motion $\vec{p} = m\frac{d}{dt}\vec{r} = -m\frac{i}{\hbar}\left[\vec{r}, H_0\right]$ the scalar product of the equation (1.6) corresponding to the creation operator $a^+_{k\lambda}$ writes

$$\left\langle \Psi_f, n_{k\lambda}\left|\xi^*\vec{\varepsilon}^*_{k\lambda}\cdot\vec{\nabla}a^+_{k\lambda}\right|\Psi_i,0\right\rangle = -\xi^*\delta_{1,n_{k\lambda}} m_e\omega_{if}\vec{\varepsilon}^*_{k\lambda}\cdot\vec{r}_{if}/\hbar \qquad (3.7)$$

with $\vec{r}_{if} = \left\langle\Psi_f\left|\vec{r}\right|\Psi_i\right\rangle$, $\omega_{if} = \omega_i - \omega_f$ and considering the expression of $\xi = \hbar/4\pi ec$ we obtain the spontaneous emission rate in the elementary solid angle $d\Omega$

$$T^{\text{spontaneous}}_{emission} = \frac{e^2}{8\pi^2\hbar\varepsilon_0 c^3}\omega^3_{mi}\int d\Omega\sum_\lambda\left|\vec{r}_{mi}\right|^2_\lambda\cos^2\theta = \frac{e^2}{3\pi\varepsilon_0\hbar c^3}\omega^3_{mi}\left|\vec{r}_{mi}\right|^2 \qquad (3.8)$$

where $\cos^2\theta$ has been replaced by the mean value

$$<\cos^2\theta> = \frac{1}{4\pi}\int\cos^2\theta\, d\Omega = \frac{1}{4\pi}\int_0^{2\pi}d\phi\int_{-1}^{+1}\cos^2\theta\, d(\cos\theta) = \frac{1}{3} \qquad (3.9)$$

Getting finally the well-known expression of the spontaneous emission rate within a solid angle $d\Omega$

$$W_{if} = \frac{1}{3\hbar c^3}\frac{e^2}{4\pi\varepsilon_0}\omega^3_{if}\left|\vec{r}_{if}\right|^2 d\Omega \qquad (3.10)$$

- *The electromagnetic quantum vacuum and the Lamb shift.*

Precisely W.E. Lamb and R.C. Rutherford measured the energy difference between the levels 2S1/2 and 2P3/2 of the atomic hydrogen in 1947 using microwave technics. They obtained a value of 4.5 10^{-5} eV, which was not explained by Dirac's theory which predict these two levels to have the same energy. From a theoretical point of view, although by introducing the kenon function in Bethe's calculations instead of the vector potential we get identical results we will not reproduce those calculations here. The reason is that Bethe's non-relativistic calculations for the Lamb shift, which many authors have discussed and commented, are based on a quite original method consisting of obtaining finite quantities by subtracting and neglecting infinite quantities. Therein, Dirac was the first to argue that *intelligent mathematics consists of neglecting negligible quantities and not infinite quantities because, simply, you do not want them*. Indeed, many authors remarked that in Bethe's method what is quite puzzling is that after manipulating and ignoring infinite quantities, after imposing arbitrary integration limits, after considering mean logarithmic values over an infinity of atomic energy levels near the continuum,…"the final result compares "remarkably" well to the experiment".

Henceforth, we can now have a different look to the Lamb shift by applying a physically comprehensive method (without infinities and singularities) for the description of the interaction of the electromagnetic quantum vacuum state with the atomic energy levels [3.4].

The energy shifts of the electron-bounded states can be seen as a topological effect of the vacuum radiation pressure upon the electronic orbitals. In fact, the vacuum is not composed of photons but of kenons. Thus, the motion of a bounded state electron with charge *e*, whose energy is E_{nlj}, in the vacuum field $\Xi_{0\lambda}$ is characterised by Bohr's angular frequency

$$\omega_{nlj} = \frac{E_{nlj}}{\hbar} = \frac{R_\infty}{n^2\hbar} \tag{3.11}$$

where *n,l,j* are the quantum numbers of the corresponding orbital, R_∞ is Rydberg's constant and *n* an integer, the principal quantum number. This periodic motion of the electron in the field $\Xi_{0\lambda}$ yields the rise in its frame of a vector potential amplitude

$$\alpha_{0(nlj)} = \xi\omega_{(nlj)} \tag{3.12}$$

corresponding to "vacuum photons" with energy

$$4\pi ec\xi\omega_{nlj} = \hbar\omega_{nlj} \tag{3.13}$$

Hence, despite the fact that the vacuum state has no photons in the normal ordering Hamiltonian representation, an electron experiences in its frame vacuum photons due to its periodic motion whose radiation pressure per unit surface writes

$$dP_{vacuum} = \sum_{\lambda} \varepsilon_0 \left|\vec{\varepsilon}_0^{(R,L)}\right|^2 d\Omega \tag{3.14}$$

where $\left|\vec{\varepsilon}_0^{(R,L)}\right|$ is the electric field amplitude of the left and right hand polarized vacuum photons seen by the electron in its frame.

Using the circular polarization components, we obtain for the square amplitude of the electric field

$$\left|\vec{\varepsilon}_0^{(R)}\right|^2 = \omega_{nlj}^2\left(\left|\alpha_{x_0}^{(R)}\right|^2 + \left|\alpha_{y_0}^{(R)}\right|^2\right) = \omega_{nlj}^2\left(\left|\alpha_{x_0}^{(L)}\right|^2 + \left|\alpha_{y_0}^{(L)}\right|^2\right) = \omega_{nlj}^2\left(2\xi^2\omega_{nlj}^2\right) \tag{3.15}$$

Consequently, from (3.14) the summation over the two circular polarizations λ, R and L, and the summation over the whole solid angle gives the total vacuum radiation pressure

$$P_{vacuum} = 4\pi\varepsilon_0\left(4\xi^2\omega_{nlj}^4\right) = \frac{\hbar\omega_{nlj}^4}{4\alpha\,\pi^2c^3} \tag{3.16}$$

Where α is the fine structure constant. Hence, if the electron moves in the effective volume $V_{nlj}(eff)$ of the *nlj* orbital the corresponding energy shift due to vacuum radiation pressure writes

$$\delta E = P_{vacuum}V_{nlj}(eff) \approx \frac{\hbar\omega_{nlj}^4}{4\alpha_{FS}\pi^2c^3}V_{nlj}(eff) \tag{3.17}$$

A delicate operation consists of defining $V_{(nlj)}(eff)$. The *nS* electronic orbitals for example are characterised by a density probability distribution decreasing smoothly with an exponential expression. Furthermore, for the excited electronic *nS* states the radial wave functions contain negative values and the electron probability density distribution involves a significant space area with zero values. Hence, in the case of atomic hydrogen for the spherically symmetrical electronic orbitals *nS*, in order not to take into account the space regions where the probability density is zero, the effective volume may be written in a first approximation

$$V_{(nS)}(eff) \approx \frac{1}{n}\frac{4}{3}\pi\left|\langle\psi_{ns}|\ r\ |\psi_{ns}\rangle\right|^3 \tag{3.18}$$

and following the last two equations the corresponding frequency of the energy shift

$$\nu_{nS} = \frac{\delta E_{(nS)}}{h} \simeq \frac{\omega_{nS}^4}{6\alpha\,\pi^2c^3}\frac{1}{n}\left|\langle\psi_{ns}|\ r\ |\psi_{ns}\rangle\right|^3 \tag{3.19}$$

Putting $\omega_{nS} = \dfrac{R_\infty}{n^2\hbar}$ with $R_\infty = 13.606\ eV$, and considering the cube of the mean value of the distance in the hydrogen electronic orbitals *nS*

$$\left|< r >\right|_{n,l=0}^3 = \left|\int \Psi_{(n,l=0)}\, r\, \Psi^*_{(n,l=0)} d^3r\right|^3 = a_0^3\left(\frac{3n^2}{2}\right)^3 \tag{3.20}$$

with $a_0 = 0.53\ 10^{-10}\ m$ being the first Bohr radius, the frequency of the energy shift writes

$$\nu_{nS} \simeq \frac{1}{n^3}\frac{9\,R_\infty^4 a_0^3}{16\alpha\ \pi^2 c^3 \hbar^4} \qquad (3.21)$$

Significant Lamb shifts have been observed for the *nS* orbitals (*n* being the principal quantum number) having a spherical density probability distribution and zero orbital momentum $l = 0$.
We obtain the Lamb shifts frequencies for the hydrogen *nS* levels:

1S: ~7.96 GHz (8.2 GHz), 2S: ~ 1000 MHz (1040 GHz), 3S: ~ 296 MHz (303 MHz), 4S: ~124 MHz

where the experimental values are given in parenthesis.
Consequently, the energy shifts of the *nS* levels of the hydrogen atom interacting with vacuum can be estimated with a rather good approximation for such a simple calculation by considering the radiation pressure of the vacuum "seen" in the frame of the electrons due to their periodic motion in the vacuum field $\vec{\Xi}_{0\lambda}$.
The above demonstrate that the electromagnetic quantum vacuum, the Dark Light composed of kenons, complements remarkably well the normal ordering Hamiltonian of the electromagnetic field and lifts the corresponding ambiguities in QED.

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