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Speed of Light and Variable Energy Density of a Dynamic Three-Dimensional Quantum Vacuum

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Abstract: A model of a three-dimensional dynamic quantum vacuum with variable energy density and elementary reduction-state (**RS**) processes of creation/annihilation of virtual particles is considered. In this model, the origin of the speed of light from elementary fluctuations of the quantum vacuum energy density is analysed and, by using a perturbation theory in the quantum vacuum energy density, a calculation for the correction to the speed of light is provided.
Keywords: dynamic three-dimensional quantum vacuum, energy density of quantum vacuum, **RS** processes, speed of light, perturbation theory.

1 Introduction

The time delay of light signals in a gravitational field and the light deflection near a massive body can be considered two crucial predictions of general relativity (together with the gravitational redshift and the anomalous perihelion shift of the planet Mercury). In virtue of these predictions, which have been successfully tested in the slow-speed, weak-field limit within the solar system, general relativity turns out to be the first theory that predicts that a gravitational potential would reduce the speed of light [1].

According to general relativity [2, 3], the speed of light c as measured in a global reference frame is given by relation

$$c = c_0\left(1 + 2\frac{\Phi_G(\vec{r})}{c_0^2}\right) \quad (1)$$

where Φ_G is the gravitational potential and c_0 is the speed of light as measured in a local freely-falling reference frame. This reduction in the speed of light, which can be observed if a beam of light passes near a massive object such as the Sun, can reproduce the amount of the bending of light rays from a distant star which passes near a massive body, like in the classic general relativity test performed by Eddington's expedition during the solar eclipse in May 1919 and the optical measurement by the Texas Mauritanian Eclipse Team, during the solar eclipse of June 1973 in Mauritania. General relativity predicts that the light ray coming from a distant star, while passing close to the Sun, will be characterized by a gradual slowing of wavefront velocity when it is directing towards the Sun, and by a gradual increasing velocity when it is leaving the Sun's gravity field. The results from such experiments [4] regarding the deflection of starlight by a massive object are in excellent agreement with the prediction of equation (1) (and, furthermore, by 1995 the observations on light deflection had confirmed general relativity to an accuracy of 0.04%).

According to a model suggested recently by Franson in [5], by including the gravitational potential energy of massive particles in the Hamiltonian of quantum electrodynamics one obtains a correction to the speed of light that is proportional to the fine structure constant. In Franson's approach, as a photon travels through space, there is a finite chance that it will form an electron-positron pair which exists for only a brief period of time and then goes on to recombine creating another photon which moves along the same path. In these processes of vacuum polarization, the gravitational potential changes the energy of a virtual electron-positron pair, which in turn produces a small change $\delta E(k)$ in the energy of the photon with wave vector k as can be shown using perturbation theory. The dependence of the energy of the photon on k generates a small correction to its angular frequency $\omega(k)$ and thus to its velocity $c = \omega(k)/k$. Moreover, since the analogous effects for neutrinos – involving the weak interaction – are negligibly small in comparison, Franson's model predicts a small but observable reduction in the velocity of photons relative to that of neutrinos.

On the other hand, in [6] Urban and his collaborators propose a mechanism based upon a "natural" quantum vacuum description where the vacuum

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permeability, the vacuum permittivity and thus the speed of light in vacuum are not constant but fluctuate, in the sense that they are observable parameters of the quantum vacuum, which originate from properties of continuously appearing and disappearing pairs of virtual fermions. In Urban's model, the photon velocity in vacuum is then derived by interpreting its propagation as a series of interactions with these pairs.

In the light of the results of Franson's research and of Urban's approach, one arrives to the natural conclusion that a quantum vacuum intended as fundamental arena of processes can be considered as the ultimate physical structure which is responsible of the origin of the speed of light as well as of its correction linked to the fine structure constant. Making some considerations as regards the role of a dynamic quantum vacuum in determining the value of the speed of light as well as physical corrections to this physical value is the purpose of this paper.

In the effort to develop new perspectives as regards the fundamental background of physics, we have recently proposed a model of a three-dimensional (3D) dynamic quantum vacuum (DQV) in which general relativity emerges as the hydrodynamic limit of some underlying theory of a more fundamental microscopic 3D quantum vacuum condensate. In this model, which can also be called as "model of the 3D DQV", each elementary particle is determined by elementary reduction-state (**RS**) processes of creation/annihilation of quanta (more precisely, of virtual particles-antiparticles pairs) similar to the transactional processes invoked by Chiatti and Licata [7, 8] and corresponding to an opportune change of the quantum vacuum energy density. This model implies that the variable energy density of DQV is the fundamental energy which gives origin to the different physical entities existing in the universe [9-12]. The DQV energy density, as fundamental energy of the universe, cannot be created and cannot be destroyed and here time exists only as a mathematical parameter measuring the numerical order of changes.

In the absence of elementary particles, atoms and massive objects, energy density of quantum vacuum is defined by the following relation:

$$\rho_{pE} = \frac{m_p \cdot c^2}{l_p^3} \quad (2),$$

where m_p is Planck mass, and l_p is Planck length. The quantity (2) is the maximum value of the quantum vacuum energy density and physically corresponds to the total average volumetric energy density, owed to all the frequency modes possible within the visible size of the universe, expressed by

$$\rho_{pE} = \frac{c^7 h}{G^2} = 4{,}641266 \cdot 10^{113} J/m^3 \quad (3).$$

The Planck energy density (3) can be considered as the ground state of the same physical flat-space background.

Moreover, taking account of Rueda's and Haisch's interpretation of the inertial mass as an effect of the electromagnetic quantum vacuum (in which the presence of a particle with a volume V_0 expels from the vacuum energy within this volume exactly the same amount of energy as is the particle's internal energy, equivalent to its rest mass) [13], as well as Santos' explanation for the actual value

$$\rho_{DE} \cong 10^{-26} Kg/m^3 \quad (4)$$

of the dark energy density as the effect of the fluctuations of the quantum vacuum on the curvature of space-time [14-16], in our approach each elementary particle is associated with fluctuations of the quantum vacuum which determine a diminishing of the quantum vacuum energy density. Quantum vacuum, intended as a unified system governing the processes taking place in the micro and the macroworld, is dynamic in the sense that presence of a given stellar object or elementary particle reduces the amount of the quantum vacuum energy. The appearance of material objects and subatomic particles correspond to changes of the quantum vacuum energy density and thus can be considered as the excited states of the same DQV. Every particle can be considered as an excited state of the same DQV characterized by a lower energy density than the Planck energy density (2): each excited state of the DQV is defined by a diminished energy density which corresponds exactly to the energy of the particle under consideration.

Each material object endowed with a mass m is produced by a change of the DQV energy density on the basis of equation

$$m = \frac{V \cdot \Delta\rho_{qvE}}{c^2} \quad (5),$$

where

$$\Delta\rho_{qvE} = \rho_{pE} - \rho_{qvE} \quad (6),$$

$$\rho_{qvE} = \rho_{pE} - \frac{m \cdot c^2}{V} = \rho_{pE} - \frac{3m \cdot c^2}{4\pi \cdot r^3} \quad (7),$$

where V is the volume of the object (and r is the radius of the material object, if we interpret it as a sphere).

Equation (7) expresses DQV energy density in the centre of the material object under consideration. On the basis of equation (7), DQV energy density constitutes an ontologically primary physical reality with respect to mass. Moreover, our model considers the possibility that relations (5)-(7) are valid both in macrophysics and in microphysics, in the sense that they describe baryonic matter both in macrophysics and in microphysics.

In the light of Santos' results [14-16], in the model of the 3D DQV the curvature of space-time characteristic of general relativity emerges as a mathematical value of a more fundamental actual energy density of quantum vacuum. The fluctuations of the quantum vacuum energy density generate a curvature of space-time similar to the curvature produced by a "dark energy" density [10]. In other words, one can say that, in this model, dark energy is energy of quantum vacuum itself, which originates from peculiar fluctuations of quantum vacuum. In this picture, a three-dimensional DQV (characterized by a symmetry between particles and variations of DQV energy density) can be considered as the fundamental arena of the universe. In particular, we have recently shown that both special relativity's Sagnac effect and significant general relativistic predictions (such as precession of the planets, the Shapiro time delay of light signals in a gravitational field, the geodetic and frame-dragging effect recently tested by Gravity Probe B) have origin in a "dragging" effect of DQV with the rotating earth, which allows us to obtain results in complete agreement with those of Einstein. Moreover, our model of variable energy density of a 3D DQV allows us to interpret and explain quantum behaviour of subatomic particles as well as the action of the Higgs boson as emergent properties which derive from the interplay of opportune fluctuations of the quantum vacuum energy density [11, 12].

Finally, another important feature of the 3D DQV lies in its superfluid nature. In this regard, we observe that, in a series of recent papers [17-20], Sbitnev introduced the perspective to describe the physical vacuum as a super-fluid medium, containing pairs of particles-antiparticles which make up a Bose-Einstein condensate, characterized by relativistic hydrodynamical equations which lead to the emergence of quantum equations (the Klein-Gordon equation and, in the non-relativistic limit, the Schrödinger equation) and provide a description of the motion of spiral galaxies. In epistemological affinity with Sbitnev's results, in our model, in presence of ordinary baryonic matter, the 3D quantum vacuum physically acts as a superfluid medium, which consists of an enormous amount of **RS** processes of creation/annihilation of particles-antiparticles with opposite orientations of spins (namely that these pairs possess zero spin, constitute an organized Bose ensemble, such as for example the case of the superfluid helium [21]). Because of the superfluid features of the 3D DQV, the diffusion flux vector can be seen as a result of scattering of the sub-particles of the **RS** processes characterizing the vacuum on each other and, as a consequence of the motion of the virtual particles corresponding to the elementary fluctuations of the quantum vacuum energy density, space-time is filled with virtual radiation with frequency given by the following relation

$$\omega = \frac{2\Delta\rho_{qvE}V}{\hbar n} \quad (8),$$

where n is the number of the **RS** processes of virtual sub-particles characterizing the vacuum medium.

According to our model, in GPS relativity of clocks rate (associated to a special relativistic effect and a general relativistic effect) also has origin in variable energy density of DQV. Less DQV energy is dense slower is rate of clocks, namely slower is the speed of material changes. Relativistic mass of a given particle is also a result of additional lower energy density of DVQ and additional absorption of quantum vacuum energy due to its high velocity. In this model velocity of light all over the universe is constant with a minimal variation which depends of the variable energy density of DQV (in agreement with Shapiro effect).

An important lesson which can be drawn from our model is that each given material object, stellar object or particle cannot be examined separately from the region of diminished quantum vacuum energy density which is moving with it. An extended region of diminished energy density of quantum vacuum around the Earth is moving with the Earth. In this picture, the null result of Michelson-Morley experiment is determined by the motion effect of the region of diminished quantum vacuum energy density around the Earth with the Earth [22].

On the other hand, according to Sato's recent research, GPS system functions because Earth rotates in the fixed ether. Sato showed that the complete ether-dragging hypothesis is compatible with the Michelson-Morley experiment in a picture where the speed of light c is not a fixed constant in each inertial reference frame [23]. Today, the GPS experiments show that if there is ether-dragging, it will be observed as an ether-wind more than 20,000 km from the ground level. Moreover, the ether is not only dragged but also modified by gravity. The values of the permittivity and permeability of the free space change in order to satisfy the effect of the gravitational field on the time dilation, and these modifications determine a decrease of the speed of light. In our model DQV is the medium of light propagation, which Sato names "ether". We propose Michelson-Morley experiment will not give null result on the satellite which is more than 20.000 km distant from the Earth (see figure 1).

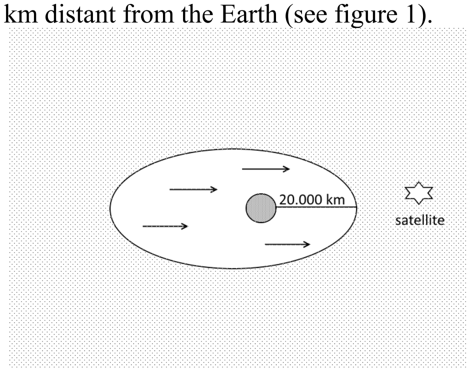

Figure 1.: Region of diminished energy density of DQV is moving with the Earth.

In this paper, by starting from the idea that the fundamental arena of the universe is represented by a variable quantum vacuum energy density corresponding to elementary **RS** processes of creation/annihilation of virtual sub-particles, we will show that, in the picture of the model of the 3D DQV, one can provide a new suggestive re-reading to Franson's and Urban's results regarding the origin of the value of the speed of light as well the correction to its physical value. This paper is structured in the following manner. In chapter 2, we will analyse the relation of vacuum permittivity and permeability with the fluctuations of the quantum vacuum energy density in the 3D DQV model. In chapter 3 we will perform a calculation for the correction to speed of light in a perturbation theory of the quantum vacuum energy density and we will conclude by making a comparison with experimental observations. Finally, in chapter 4 we will summarize the results of this paper, highlighting also some perspectives of our DQV model of the speed of light.

2 The origin of the speed of light in the three-dimensional dynamic quantum vacuum model

By describing the ground state of the unperturbed vacuum as containing a finite density of charged ephemeral fermion/antifermion pairs which are produced from the fusion of two virtual photons of the vacuum, Urban and his colleagues found that the vacuum permittivity and the vacuum permeability originate simply from the electric polarization and from the magnetization of these pairs when the vacuum is stressed by an electrostatic or a magnetostatic field respectively [6]. According to Urban's calculations, the vacuum permittivity is

$$\tilde{\varepsilon}_0 = \frac{(K_W^2-1)^{3/2}}{K_W}\frac{e^3}{3\pi^3\hbar c_{rel}} \quad (9)$$

while the vacuum permeability is

$$\tilde{\mu}_0 = \frac{K_W}{(K_W^2-1)^{3/2}}\frac{3\pi^3\hbar}{c_{rel}e^2} \quad (10)$$

where K_W is a constant assumed to be independent on the fermion type (and is linked with the energy spectrum of the virtual photons of the vacuum and their probability to create fermion pairs), c_{rel} is the maximum velocity used in special relativity. In this way, in Urban's approach, the average photon velocity regarding the propagation of a real photon in the vacuum (which implies the continue interaction of the photon with each ephemeral pair of the vacuum), can be expressed as

$$\bar{c}_{group} = \frac{K_W}{(K_W^2-1)^{3/2}}\frac{16e^2\pi}{k_\sigma \sum_i q_i^2}c_{rel} \quad (11)$$

where k_σ is a coefficient depending on the cross-section for a real photon to interact and be trapped by an ephemeral type of fermions.

If in Urban's model the permeability and the permittivity do not depend upon the masses of the fermions, in the sense that the electric charges and the number of species are the only important parameters, instead in our model of 3D DQV defined by a variable energy density associated with elementary **RS** processes of creation/annihilation of quanta, we consider the perspective that they are related with opportune fluctuations of the quantum vacuum energy density. In our model, we consider the possibility that fermion/antifermion pairs are produced out of the ground state defining the electromagnetic properties of the 3D quantum vacuum acting as a reservoir of photons. As we have shown in [24], the ground state of the 3D quantum vacuum acts just as a cosmic reservoir of photons, namely the ground state describing the electromagnetic properties of the 3D quantum vacuum represents the ultimate source from which photons are born, and thus through elementary processes regarding a timeless 3D quantum vacuum, a real particle such as an electron is just the "door" through which photon enters into existence and the door through which photon turns back into the quantum vacuum [24]. Moreover, this ground state of the vacuum acting as reservoir of photons is characterized by a zero-point energy density which is determined by the fluctuations of the quantum vacuum energy density and by the quantum potential corresponding to the **RS** processes on the basis of relation

$$W_{\rho_{qvE}} = 8\frac{(\Delta\rho_{qvE})^3 V^3 Q_{Q,i}}{\hbar^3\pi n^3 c_{rel}{}^3} \quad (12)$$

where

$$Q_{Q,i} = \frac{\hbar^2 c^2}{V^2(\Delta\rho_{qvE})^2}\left(\frac{\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)|\psi_{Q,i}|}{|\psi_{Q,i}|} - \frac{\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)|\phi_{Q,i}|}{|\phi_{Q,i}|}\right) \quad (13)$$

is the quantum potential of the vacuum choreographing the RS processes of the virtual particles of the medium, $\psi_{Q,i}$ and $\phi_{Q,i}$ being the wave functions describing creation events and destruction events respectively.

As a consequence, in our model we can associate the coefficient K_W of Urban's model with the rate of fluctuations of the quantum vacuum energy density (corresponding to a given excited state of the vacuum) with respect to the zero-point energy density defining the electromagnetic properties of the quantum vacuum $W_{\rho_{qvE}}$, namely:

$$K_W = \frac{\Delta\rho_{qvE}}{W_{\rho_{qvE}}} \quad (14)$$

which yields

$$K_W = \frac{\hbar^3\pi n^3 c_{rel}{}^3}{8(\Delta\rho_{qvE})^2 V^3 Q_{Q,i}} \quad (15).$$

Therefore, in our model of 3D DQV, the vacuum permittivity can be expressed as

$$\tilde{\varepsilon}_0 = \frac{\left[\left(\frac{\Delta\rho_{qvE}}{W_{\rho_{qvE}}}\right)^2 - 1\right]^{3/2}}{\frac{\Delta\rho_{qvE}}{W_{\rho_{qvE}}}}\frac{e^3}{3\pi^3\hbar c_{rel}} \quad (16),$$

namely

$$\tilde{\varepsilon}_0 = \frac{\left[\left(\frac{\hbar^3\pi n^3 c_{rel}{}^3}{8(\Delta\rho_{qvE})^2 V^3 Q_{Q,i}}\right)^2 - 1\right]^{3/2}}{\frac{\hbar^3\pi n^3 c_{rel}{}^3}{8(\Delta\rho_{qvE})^2 V^3 Q_{Q,i}}}\frac{e^3}{3\pi^3\hbar c_{rel}} \quad (17)$$

while the vacuum permeability is

$$\tilde{\mu}_0 = \frac{\frac{\Delta\rho_{qvE}}{W_{\rho_{qvE}}}}{\left[\left(\frac{\Delta\rho_{qvE}}{W_{\rho_{qvE}}}\right)^2 - 1\right]^{3/2}}\frac{3\pi^3\hbar}{c_{rel}e^2} \quad (18),$$

namely

$$\tilde{\mu}_0 = \frac{\frac{\hbar^3\pi n^3 c_{rel}{}^3}{8(\Delta\rho_{qvE})^2 V^3 Q_{Q,i}}}{\left[\left(\frac{\hbar^3\pi n^3 c_{rel}{}^3}{8(\Delta\rho_{qvE})^2 V^3 Q_{Q,i}}\right)^2 - 1\right]^{3/2}}\frac{3\pi^3\hbar}{c_{rel}e^2} \quad (19)$$

In this way, in our model, on the basis of equations (16) and (18), in epistemological affinity with Urban's treatment, the average photon velocity regarding the propagation of a real photon in the vacuum, becomes

$$\bar{c}_{group} = \frac{\frac{\Delta\rho_{qvE}}{W_{\rho_{qvE}}}}{\left[\left(\frac{\Delta\rho_{qvE}}{W_{\rho_{qvE}}}\right)^2 - 1\right]^{3/2}} \frac{16e^2\pi}{k_\sigma \sum_i q_i^2} c_{rel} \quad (20),$$

namely

$$\bar{c}_{group} = \frac{\frac{\hbar^3\pi n^3 c_{rel}{}^3}{8(\Delta\rho_{qvE})^2 V^3 Q_{Q,i}}}{\left[\left(\frac{\hbar^3\pi n^3 c_{rel}{}^3}{8(\Delta\rho_{qvE})^2 V^3 Q_{Q,i}}\right)^2 - 1\right]^{3/2}} \frac{16e^2\pi}{k_\sigma \sum_i q_i^2} c_{rel} \quad (21).$$

Here, as regards the values (16), (18) and (20) of the vacuum permittivity, vacuum permeability and average photon velocity, a compatibility with the observed values is assured if the following condition is satisfied:

$$\frac{\frac{\Delta\rho_{qvE}}{W_{\rho_{qvE}}}}{\left[\left(\frac{\Delta\rho_{qvE}}{W_{\rho_{qvE}}}\right)^2 - 1\right]^{3/2}} = \mu_0 \frac{c_{rel}e^2}{3\pi^3\hbar} = \frac{4}{3}\frac{\alpha}{\pi^2} \quad (22),$$

where α is the fine structure constant and μ_0 is the observed value of the vacuum permeability. Equation (22) provides the physical condition which constrains our model as regards the values of the vacuum permittivity, vacuum permeability and thus the speed of light. As regards the production of $e^+ e^-$ pairs, for example, it yields $\frac{\Delta\rho_{qvE}}{W_{\rho_{qvE}}} \approx 31{,}9$.

By using (16) and (18) with the constraint (20), one can easily verify that the phase speed of an electromagnetic wave in vacuum, given by $c_\phi = \frac{1}{\sqrt{\tilde{\mu}_0\tilde{\varepsilon}_0}}$ turns out to be equal to c_{rel} , the maximum velocity used in special relativity. Moreover, the average speed of photon (20) in the 3D DQV turns out to be equal to c_{rel} (and thus also to $c_\phi = \frac{1}{\sqrt{\tilde{\mu}_0\tilde{\varepsilon}_0}}$) if the following condition holds

$$k_\sigma = \frac{8}{3\pi}\alpha \quad (23)$$

which corresponds to a cross-section of $4 \cdot 10^{-26}\ m^2$ on an electron/positron pair. In summary, we can say that in the model of the 3D dynamic quantum vacuum, equations (16)-(23) indicate in what sense the variable energy density of the 3D DQV is the ultimate origin of the vacuum permittivity, vacuum permeability and therefore the speed of light.

Let us provide, now, a simple derivation of the formulas (16) and (18), by following the spirit of Urban's treatment in [6]. In this regard, we start from the hypothesis that the average energy of a fermion/antifermion pair, produced by the ground state of the vacuum acting as a reservoir of photons, may be expressed as follows:

$$W_i = 2V\frac{\Delta\rho_{qvE}{}^2}{W_{\rho_{qvE}}} \quad (24)$$

namely

$$W_i = \frac{\hbar^3\pi n^3 c^3}{4V^2 Q_{Q,i}} \quad (25).$$

As regards the derivation of the vacuum permeability, we observe that in the presence of an external magnetic field $\vec{B}$, the energy of the fermion/antifermion pair is modified by the coupling energy with the magnetic field and thus the pair lifetime is linked with the orientation of its magnetic moment with respect to the applied magnetic field:

$$\tau_i(\theta) = \frac{\hbar/2}{\frac{\hbar^3\pi n^3 c_{rel}{}^3}{4V^2 Q_{Q,i}} - 2\mu_i B\cos\theta} \quad (26),$$

where μ_i is the Bohr magneton and θ is the angle between the magnetic moment and the magnetic field. The resulting average magnetic moment, which is aligned with the magnetic field, is given by the integral over θ with a weight proportional to the lifetime, thus giving to the first order:

$$\langle M_i \rangle \cong \frac{4\mu_i^2}{3\frac{\hbar^3\pi n^3 c_{rel}{}^3}{4V^2 Q_{Q,i}}} B \quad (27).$$

Since the magnetic moment per unit volume produced by the i-type fermion is $2\left(\sqrt{\frac{\hbar\pi n^3 c_{rel}}{8VQ_{Q,i}}} - 1\right)^3 \frac{4\mu_i^2}{3\frac{\hbar^3\pi n^3 c_{rel}{}^3}{4V^2 Q_{Q,i}}} B$ and thus its contribution to the vacuum permeability is $2\left(\sqrt{\frac{\hbar\pi n^3 c_{rel}}{8VQ_{Q,i}}} - 1\right)^3 \frac{4\mu_i^2}{3\frac{\hbar^3\pi n^3 c_{rel}{}^3}{4V^2 Q_{Q,i}}}$, hence it derives that, by summing over all pair species, one obtains the estimation of the vacuum permeability given by (19):

$$\tilde{\mu}_0 = \frac{\frac{\hbar^3\pi n^3 c_{rel}{}^3}{8(\Delta\rho_{qvE})^2 V^3 Q_{Q,i}}}{\left[\left(\frac{\hbar^3\pi n^3 c_{rel}{}^3}{8(\Delta\rho_{qvE})^2 V^3 Q_{Q,i}}\right)^2 - 1\right]^{3/2}} \frac{3\pi^3\hbar}{c_{rel}e^2} \quad (19).$$

As regards the vacuum permittivity, in analogous way, one can say that it is produced by the polarization of the ephemeral fermion pairs in presence of an external electric field $\vec{E}$. The electric field modifies the pairs lifetimes according to their orientation on the basis of relation:

$$\tau_i(\theta) = \frac{\hbar/2}{\frac{\hbar^3\pi n^3 c_{rel}{}^3}{4V^2 Q_{Q,i}} - d_i E\cos\theta} \quad (28)$$

where θ is the angle between the ephemeral dipole and the field, d_i is the electric dipole moment carried by the fermion/antifermion pairs, which here is given by relation

$$d_i = q_i \frac{\hbar c_{rel}}{V\Delta\rho_{qvE}} \quad (29).$$

As in the magnetostatic case, one obtains an average dipole which is aligned with electric field and which, at the first order, is given by relation:

$$\langle D_i \rangle \cong \frac{d_i^2}{3\frac{\hbar^3\pi n^3 c_{rel}{}^3}{4V^2 Q_{Q,i}}} E \quad (30).$$

Thus, since the polarization produced by the i-type fermion is $2\left(\sqrt{\frac{\hbar\pi n^3 c_{rel}}{8VQ_{Q,i}}} - 1\right)^3 \frac{d_i^2}{3\frac{\hbar^3\pi n^3 c_{rel}{}^3}{4V^2 Q_{Q,i}}} E$ and thus its contribution to the vacuum permeability is $2\left(\sqrt{\frac{\hbar\pi n^3 c_{rel}}{8VQ_{Q,i}}} - 1\right)^3 \frac{d_i^2}{3\frac{\hbar^3\pi n^3 c_{rel}{}^3}{4V^2 Q_{Q,i}}} E$, by summing over all pair species of fermions, one obtains the estimation of the vacuum permeability given by (17):

$$\tilde{\epsilon}_0 = \frac{\left[\left(\frac{\hbar^3 \pi n^3 c_{rel}^3}{8(\Delta\rho_{qvE})^2 V^3 Q_{Q,i}}\right)^2 - 1\right]^{3/2}}{\frac{\hbar^3 \pi n^3 c_{rel}^3}{8(\Delta\rho_{qvE})^2 V^3 Q_{Q,i}}} \frac{e^3}{3\pi^3 \hbar c_{rel}} \quad (17).$$

We have thus demonstrated the origin of the vacuum permeability (19) and the vacuum permittivity (17) inside the model of the 3D DQV. The other equations, regarding the average photon velocity, (20) and (21), follow as a direct consequence.

3 The correction to the physical value of the speed of light in the three-dimensional dynamic quantum vacuum model

In this chapter, we will see in what sense the 3D DQV generates some physical corrections to the physical value of the speed of light, in terms of the polarization determined by the variable quantum vacuum energy density, and we will analyse these corrections in the context of a perturbative approach. In order to perform a calculation for the correction of the speed of light in the context of the 3D DQV model, from second-order perturbation theory one starts to express the change $\Delta E^{(2)}$ in the energy of a photon with wave vector $\vec{k}$ as

$$\Delta E^{(2)} = \sum_n \frac{\langle \vec{k} | \hat{H}' | n \rangle \langle n | \hat{H}' | \vec{k} \rangle}{E_0^{(0)} - E_0^{(n)}} \quad (31).$$

In equation (31) $|\vec{k}\rangle$ represents the unperturbed initial state containing only the photon and $|n\rangle$ indicates all the possible states of the vacuum which contain virtual electron-positron pairs created in the volume V under consideration; $E_0^{(0)}$ is the unperturbed energy of the initial state while $E_n^{(0)}$ is the unperturbed energy of the generic possible state of the electron-positron pairs generated in the volume *V*. Equation (31) corresponds to steady state perturbation theory, but the same results can be obtained using the forward-scattering amplitude from time-dependent perturbation theory [25].

By following the philosophy that underlies Franson's approach, in the calculation we can assume that the bare effects of the variable quantum vacuum energy density is contained in an unperturbed Hamiltonian $\hat{H}_0$ while the electromagnetic interaction terms (describing the electromagnetic properties of the vacuum) can be associated with a perturbation Hamiltonian $\hat{H}'$. The unperturbed Hamiltonian $\hat{H}_0$ at position ***r*** may be expressed as

$$\hat{H}_0 = -\frac{\hbar^2 c^2}{2\Delta\rho_{qvE} V}\nabla^2 - G\frac{(\Delta\rho_{qvE} V)^2}{c^4 r} \quad (32).$$

In the Lorentz gauge [26, 27], the interaction Hamiltonian $\hat{H}'$ is given by

$$\hat{H}' = -\frac{1}{c}\int d^3\vec{r}\hat{\vec{j}}_E(\vec{r},t)\cdot \hat{A}_E(\vec{r},t) + \int d^3\vec{r}\hat{\rho}_E(\vec{r},t)\hat{\Phi}_E(\vec{r},t) + -\frac{G}{c^2}\int d^3\vec{r}\hat{\rho}_G(\vec{r},t)\frac{\Delta\hat{\rho}_{qvE}V}{r} \quad (33)$$

where $\hat{\rho}_E(\vec{r},t) = q\hat{\psi}^+(\vec{r},t)\hat{\psi}(\vec{r},t)$ is the electromagnetic charge density, $\hat{\vec{j}}_E(\vec{r},t) = cq\hat{\psi}^+(\vec{r},t)\vec{\alpha}\hat{\psi}(\vec{r},t)$ is the current density, q is the charge of an electron, $\hat{\psi}(\vec{r},t)$ is the Dirac field operator, $\vec{\alpha}$ represents the Dirac matrices, $\hat{\rho}_G(\vec{r}) = \frac{\Delta\rho_{qvE}V}{c^2}\hat{\psi}^+(\vec{r})\beta\hat{\psi}(\vec{r},t)$ is the operator corresponding to the mass density of the particles, $\beta = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$ and, finally, $\hat{\vec{A}}_E(\vec{r},t)$ and $\hat{\Phi}_E(\vec{r},t)$ represent the vector and scalar potentials of the electromagnetic field. The first two terms in equation (33) correspond to the usual interaction between charged particles and the electromagnetic field. The third term represents the gravitational potential energy of any particles.

It must be emphasized here that the fields $\hat{\vec{A}}_E(\vec{r},t)$ and $\hat{\Phi}_E(\vec{r},t)$ appearing in (33) describe the electromagnetic properties of the vacuum as a consequence of the frequency (8) of the virtual radiation associated with the motion of the virtual particles corresponding to the elementary fluctuations of the quantum vacuum energy density. The link between $\hat{\vec{A}}_E(\vec{r},t)$ and $\hat{\Phi}_E(\vec{r},t)$ and the frequency (27) of the virtual radiation associated with the motion of the virtual particles of the vacuum, can be justified in the following way. On the basis of the results obtained in [11], in the 3D DQV model, the frequency (8) is the real origin of the electromagnetic effects of the 3D quantum vacuum. In particular, the electromagnetic field inside a cavity of perfectly reflecting can be seen as an expansion of infinite different modes of the fundamental 3D quantum vacuum where each mode corresponds to an independent oscillation defined by frequency (8) produced by a specific **RS** process of creation/annihilation of quanta in correspondence to elementary fluctuations of the 3D quantum vacuum. This means that the spectral energy density for the zero-point fluctuations characterizing the electromagnetic properties of the quantum vacuum is

$$\rho(\Delta\rho_{qvE}) = \frac{4(\Delta\rho_{qvE})^3 V^3}{\hbar^2\pi^2 n^3 c^3} \quad (34),$$

namely

$$\rho(\Delta\rho_{qvE}) = \frac{\omega\hbar}{2\pi^2 c^3} \quad (35).$$

To be explicit, in order to characterize the electromagnetic fields of the 3D quantum vacuum, by following Sunahata, Rueda and Haisch [28], let us consider an object, at rest at time $t_* = 0$ in the laboratory frame I_*, which is uniformly accelerated by an external force which produces a rectilinear motion along the x-axis with constant proper acceleration $\vec{a} = a\hat{x}$. By considering a Rindler frame S such that its x-axis coincides with that of I_* where the body is located at coordinates $(c^2/a, 0, 0)$ in S at all times, this point of S turns out to perform a hyperbolic motion and its acceleration in I_* is $\vec{a}_* = \gamma_\tau^{-3}\vec{a}$ at the body proper time τ. Consider also an infinite collection of inertial frames $\{I_\tau\}$ such that at the body proper time τ the body is located at point $(c^2/a, 0, 0)$ of I_τ. The I_τ frames have all axes parallel to those of I_* and their x-axes coincide with that of I_*. By setting the proper time τ such that at τ=0 the corresponding I_τ coincides with I_*, one has $I_{\tau=0} = I_*$ and thus the hyperbolic motion assures that

$$x_* = \frac{c^2}{a}\cosh\left(\frac{a\tau}{c}\right) \quad (36)$$

$$t_* = \frac{c}{a}\sinh\left(\frac{a\tau}{c}\right) \quad (37)$$

$$\beta_\tau = \frac{u_x(\tau)}{c} = \tanh\left(\frac{a\tau}{c}\right) \quad (38)$$

$$\gamma_\tau = \left(1-\beta_\tau^2\right)^{-1/2} = \cosh\left(\frac{a\tau}{c}\right) \quad (39).$$

In this way, by using Lorentz transformations from the laboratory frame I_* into an instantaneously comoving frame I_τ, the electromagnetic zero-point field vectors – deriving from the fluctuations of the 3D quantum vacuum – $\vec{E}_{zp}$ and $\vec{B}_{zp}$ of I_* as represented in I_τ are given by relations

$$\vec{E}_\tau^{zp}(0,\tau) = \sum_{\lambda=1}^2 \int dk^3\, H_{zp}(\omega)\left\{\hat{x}\hat{\varepsilon}_x + \hat{y}\cosh\left(\frac{a\tau}{c}\right)\left[\hat{\varepsilon}_y - \tanh\left(\frac{a\tau}{c}\right)\left(\hat{k}\times\hat{\varepsilon}\right)_z\right] + \hat{z}\cosh\left(\frac{a\tau}{c}\right)\left[\hat{\varepsilon}_z + \tanh\left(\frac{a\tau}{c}\right)\left(\hat{k}\times\hat{\varepsilon}\right)_y\right]\right\}\left\{\vec{\alpha}(\vec{k},\lambda)e^{i\theta} + \vec{\alpha}^+(\vec{k},\lambda)e^{-i\theta}\right\} \quad (40)$$

$$\vec{B}_\tau^{zp}(0,\tau) = \sum_{\lambda=1}^2 \int dk^3\, H_{zp}(\omega)\left\{\hat{x}\left(\hat{k}\times\hat{\varepsilon}\right)_x + \hat{y}\cosh\left(\frac{a\tau}{c}\right)\left[\left(\hat{k}\times\hat{\varepsilon}\right)_y - \tanh\left(\frac{a\tau}{c}\right)\hat{\varepsilon}_z\right] + \hat{z}\cosh\left(\frac{a\tau}{c}\right)\left[\left(\hat{k}\times\hat{\varepsilon}\right)_z + \tanh\left(\frac{a\tau}{c}\right)\hat{\varepsilon}_y\right]\right\}\left\{\vec{\alpha}(\vec{k},\lambda)e^{i\theta} + \vec{\alpha}^+(\vec{k},\lambda)e^{-i\theta}\right\} \quad (41).$$

In relations (40) and (41) we have defined

$$\theta = \hat{k}_x\frac{c^2}{a}\cosh\left(\frac{a\tau}{c}\right) - \omega\frac{c}{a}\sinh\left(\frac{a\tau}{c}\right) \quad (42),$$

$\hat{\varepsilon}_i$ are the polarization components, $\vec{k}$ is the polarization wave vector such that $|\vec{k}| = \omega/c$, λ is the polarization index, $\vec{\alpha}(\vec{k},\lambda)$ and $\vec{\alpha}^+(\vec{k},\lambda)$ are annihilation and creation operators and, by using QED, the spectral energy density for the zero-point fluctuations characterizing the electromagnetic properties of the quantum vacuum is $H_{zp}^2(\omega) = \frac{\Delta\rho_{qvE}V}{2\pi^2 n}$ namely $H_{zp}^2(\omega) = \frac{\hbar\omega}{4\pi^2}$. Equations (40) and (41) indicate clearly that electric and magnetic fields are two different kinds of polarization of the 3D quantum vacuum produced by the frequencies of the radiation associated with the motion of the virtual particles of the **RS** processes, namely by the fluctuations of the quantum vacuum energy density. Thus, taking account of equations (40) and (41), the vector and scalar potentials of the electromagnetic field $\hat{\vec{A}}_E(\vec{r},t)$ and $\hat{\Phi}_E(\vec{r},t)$ appearing in equation (33) (and therefore also in the fundamental equation (31)) may be seen as consequences of the electromagnetic zero-point field vectors – deriving from the frequencies (8) of the radiation associated with the motion of the virtual particles of the **RS** processes, namely from the fluctuations of the 3D quantum vacuum – $\vec{E}_{zp}$ and $\vec{B}_{zp}$ on the basis of equations

$$-\nabla\hat{\Phi}_E - \frac{1}{c}\frac{\partial}{\partial t}\hat{\vec{A}}_E = \sum_{\lambda=1}^2 \int dk^3\, H_{zp}(\omega)\left\{\hat{x}\hat{\varepsilon}_x + \hat{y}\cosh\left(\frac{a\tau}{c}\right)\left[\hat{\varepsilon}_y - \tanh\left(\frac{a\tau}{c}\right)\left(\hat{k}\times\hat{\varepsilon}\right)_z\right] + \hat{z}\cosh\left(\frac{a\tau}{c}\right)\left[\hat{\varepsilon}_z + \tanh\left(\frac{a\tau}{c}\right)\left(\hat{k}\times\hat{\varepsilon}\right)_y\right]\right\}\left\{\vec{\alpha}(\vec{k},\lambda)e^{i\theta} + \vec{\alpha}^+(\vec{k},\lambda)e^{-i\theta}\right\} \quad (43)$$

$$\nabla\times\hat{\vec{A}}_E=\sum_{\lambda=1}^{2}\int dk^3\,H_{zp}(\omega)\left\{\hat{x}\left(\hat{k}\times\hat{\varepsilon}\right)_x+\hat{y}\cosh\left(\frac{a\tau}{c}\right)\left[\left(\hat{k}\times\hat{\varepsilon}\right)_y-\tanh\left(\frac{a\tau}{c}\right)\hat{\varepsilon}_z\right]+\hat{z}\cosh\left(\frac{a\tau}{c}\right)\left[\left(\hat{k}\times\hat{\varepsilon}\right)_z+\tanh\left(\frac{a\tau}{c}\right)\hat{\varepsilon}_y\right]\right\}\left\{\vec{\alpha}\left(\vec{k},\lambda\right)e^{i\theta}+\vec{\alpha}^{+}\left(\vec{k},\lambda\right)e^{-i\theta}\right\}$$

(44).

Now, in the light of these considerations, let us see the calculation, in a perturbation approach till the second-order, of the change $\Delta E^{(2)}$ in the energy of a photon, given by (31). In this regard, before all, on the basis of the unperturbed Hamiltonian (32), the unperturbed energy of the intermediate state containing an electron-positron pair becomes

$$E_n^{(0)}=E_q+E_p-2G\frac{(V\cdot\Delta\rho_{qvE})^2}{rc^4} \quad (45)$$

where $\vec{p}$ and $\vec{q}$ are the momenta of the virtual electron and positron respectively, while $E_p=\left(p^2c^2+V^2\left(\Delta\rho_{qvE}\right)^2\right)^{1/2}$ (46).

Furthermore, in the calculation of (31), we consider periodic boundary conditions with a unit volume V [29]. In this regard, by following [30] and [5] in the Schrödinger picture the Dirac field operators are given by

$$\hat{\psi}(\vec{r})=\sum_{p,s}\sqrt{\frac{\Delta\rho_{qvE}V}{E_p}}\left[\hat{b}(\vec{p},s)u(\vec{p},s)e^{i\vec{p}\cdot\vec{r}}+\hat{c}^{+}(\vec{p},s)v(\vec{p},s)e^{-i\vec{p}\cdot\vec{r}}\right] \quad (47)$$

where $\hat{b}^{+}(\vec{p},s)$ is the operator which creates an electron with momentum $\boldsymbol{p}$ and spin s, whose values will be denoted by ± to indicate spin up or down, while $\hat{c}^{+}(\vec{p},s)$ is the operator that creates a positron with momentum $\boldsymbol{p}$ and spin s. The Dirac spinors $u(\boldsymbol{p},s)$ and $v(\boldsymbol{p},s)$ are defined by the following relations [31, 30, 25]

$$u(\vec{p},+)=\sqrt{\frac{E_p+\Delta\rho_{qvE}\cdot V}{2\Delta\rho_{qvE}\cdot V}}\begin{bmatrix}1\\0\\\frac{p_3c^2}{E_p+\Delta\rho_{qvE}\cdot V}\\\frac{(p_1+ip_2)c^2}{E_p+\Delta\rho_{qvE}\cdot V}\end{bmatrix} \quad (48),$$

$$u(\vec{p},-)=\sqrt{\frac{E_p+\Delta\rho_{qvE}\cdot V}{2\Delta\rho_{qvE}\cdot V}}\begin{bmatrix}0\\1\\\frac{(p_1-ip_2)c^2}{E_p+\Delta\rho_{qvE}\cdot V}\\\frac{-p_3c^2}{E_p+\Delta\rho_{qvE}\cdot V}\end{bmatrix} \quad (49),$$

$$v(\vec{p},-)=\sqrt{\frac{E_p+\Delta\rho_{qvE}\cdot V}{2\Delta\rho_{qvE}\cdot V}}\begin{bmatrix}\frac{p_3c^2}{E_p+\Delta\rho_{qvE}\cdot V}\\\frac{(p_1+ip_2)c^2}{E_p+\Delta\rho_{qvE}\cdot V}\\1\\0\end{bmatrix} \quad (50),$$

$$v(\vec{p},+)=\sqrt{\frac{E_p+\Delta\rho_{qvE}\cdot V}{2\Delta\rho_{qvE}\cdot V}}\begin{bmatrix}\frac{(p_1-ip_2)c^2}{\Delta\rho_{qvE}\cdot V}\\\frac{-p_3c^2}{\Delta\rho_{qvE}\cdot V}\\0\\1\end{bmatrix} \quad (51).$$

Here, if one makes the integral over $\boldsymbol{r}$ in the interaction Hamiltonian combined with the exponential factors in $\hat{\psi}^{+}(\vec{r})$, $\hat{\psi}(\vec{r})$, and assumes that the energy of the photon is sufficiently small that $\hbar kc<<\Delta\rho_{qvE}\cdot V$, in which case $E_q\doteq E_p$ (i.e., the recoil momentum from absorbing the photon has a negligible effect on the virtual particle energies), one obtains

$$\langle n|H'|\vec{k}\rangle=\frac{q}{2}\sqrt{\frac{\pi\hbar^2nc^2}{\Delta\rho_{qvE}\cdot V}}\left(\frac{E_p+\Delta\rho_{qvE}\cdot V}{E_p}\right)\left(1+\frac{\left(p_1^2+p_2^2-p_3^2\right)c^2}{\left(E_p+\Delta\rho_{qvE}\cdot V\right)^2}\right)$$

(52).

Inserting equation (52) into equation (31) and summing over all of the intermediate spin states gives the correction to the photon energy as

$$\Delta E^{(2)}=\frac{1}{16\pi^3}\frac{\alpha\pi c^3n}{\Delta\rho_{qvE}^{(0)}V}\int_{-\infty}^{+\infty}d^3\vec{p}\,\frac{1}{\left(\frac{2\Delta\rho_{qvE}^{(0)}V}{\hbar n}-2E_p+2G\frac{(\Delta\rho_{qvE}V)^2}{r_0c^4}\right)}\times\left(\frac{E_p+\Delta\rho_{qvE}V}{E_p}\right)^2\frac{\left[\left(E_p+\Delta\rho_{qvE}V\right)^4+\frac{2}{3}\left(E_p+\Delta\rho_{qvE}V\right)^4p^2c^2+p^4c^4\right]}{\left(E_p+\Delta\rho_{qvE}V\right)^4}$$

(53)

where $\alpha=\frac{q^2}{\hbar c}$ is the fine structure constant and $\Delta\rho_{qvE}^{(0)}$ is the unperturbed quantum vacuum energy density.

Now, by making the assumption $\Delta\rho_{qvE}^{(0)}V<<E_p$

and $\left|G\frac{(\Delta\rho_{qvE}V)^2}{rc^4}\right| << E_p$, one may expand the denominator in the first term inside equation (53) in a Taylor series to first order in $G\frac{(\Delta\rho_{qvE}V)^2}{rc^4}$ and to second order in $\Delta\rho_{qvE}^{(0)}V$. In this way, one obtains

$$\left(\frac{2\Delta\rho_{qvE}^{(0)}V}{\hbar n}-2E_p-2G\frac{(\Delta\rho_{qvE}V)^2}{rc^4}\right)=-\frac{G}{E_p}\frac{(\Delta\rho_{qvE}V)^2}{rc^4E_p}\left[\frac{1}{2}+\frac{1}{2}\frac{\Delta\rho_{qvE}^{(0)}V}{nE_p}+\frac{3}{8}\left(\frac{\Delta\rho_{qvE}^{(0)}V}{nE_p}\right)^2+...\right]$$

(54).

As regards the first two terms on the right-hand side of equation (54), their contributions to the correction to the speed of light are proportional to $\left(\frac{\hbar n}{2\Delta\rho_{qvE}^{(0)}V}\right)^2$ and $\left(\frac{\hbar n}{2\Delta\rho_{qvE}^{(0)}V}\right)$ respectively. By taking account of Franson's results in [5], these two terms constitute non-physical terms that become infinite in the limit of long wavelengths, in analogy to the usual infrared divergences present in quantum electrodynamics.

Instead, as regards the last term of equation (54), it produces a contribution of the form

$$\Delta E^{(2)}=-\frac{G}{8\pi}\alpha c\frac{\Delta\rho_{qvE}^{(0)}V}{n}\frac{(\Delta\rho_{qvE}V)^2}{rc^4}{}_G\int_0^{+\infty}dp\frac{p^2c^2}{E_p^4}\left(\frac{E_p+\Delta\rho_{qvE}V}{E_p}\right)^2$$
$$\times\frac{\left[(E_p+\Delta\rho_{qvE}V)^4+\frac{2}{3}(E_p+\Delta\rho_{qvE}V)^4p^2c^2+p^4c^4\right]}{(E_p+\Delta\rho_{qvE}V)^4}$$

(55).

Evaluating the integral yields

$$\Delta E^{(2)}=-\frac{9G}{32}\alpha c\frac{(\Delta\rho_{qvE}^{(0)}V)^2}{n}\frac{1}{rc_0^4}\quad(56).$$

Taking account that the speed of light is given by $c=\omega/k$ namely

$$c=\frac{2\Delta\rho_{qvE}V}{\hbar nk}\quad(57),$$

one directly obtains the correction Δc to the speed of light

$$\Delta c=\frac{\Delta E^{(2)}nc_0}{2\Delta\rho_{qvE}^{(0)}V}\quad(58).$$

Therefore, by inserting the value of $\Delta E^{(2)}$ from equation (74) into equation (76) one obtains

$$\frac{\Delta c}{c}=-\frac{9G}{64}\alpha\frac{(\Delta\rho_{qvE}V)}{rc^4}\quad(59)$$

which is the correction to the physical value of the speed of light in the context of the 3D DQV model. The result (59) turns out to be in agreement with the results obtained in the context of Franson's model.

In the context of the 3D DQV model developed by the authors of this paper, the correction (59) to the speed of light determined by the fluctuations of the quantum vacuum energy density can explain the longstanding anomaly regarding the huge delay of 7.7 hours between the first burst of neutrinos and the arrival of the optical photons from Supernova 1987a (in fact, neutrinos and photons both travel at the speed of light and should therefore arrive simultaneously). This anomaly regarding the time of arrival of neutrinos and optical photons cannot receive a satisfactory explanation in the currently accepted interpretation and yet remains an open question [32-37].

In the approach proposed in this paper, the gravitational potential Φ_G/c^2 is associated with a corresponding change of the quantum vacuum energy density on the basis of equation

$$\Phi_G/c^2=-\frac{G\Delta\rho_{qvE}V}{Rc^4}\quad(60)$$

where G is the gravitational constant, and thus the fluctuations of the quantum vacuum energy density determining the gravitational potential (60) can be considered the ultimate entities required in order to compare the predicted correction to the speed of light with experimental observations such as those from Supernova 1987a. In this regard, one can invoke the perspective of a double collapse of the core – where the second collapse of the core would have produced an increase in the intensity of the visible light approximately 4.7 hours after the arrival of the first photons – which emerges as a consequence of the processes of the fundamental DQV, leading thus to an alternative explanation for the observations associated with Supernova 1987a.

In summary, we can say that the correction to the speed of light, given by equation (59) – and where the gravitational potential is determined by a corresponding change of the quantum vacuum energy density on the basis of equation (60) – obtained in the picture of the 3D DQV model, turns out to be in reasonable agreement with the experimental observations as well as with Franson's results and it provides a possible explanation for the first burst of neutrinos that is inconsistent with the conventional model of the Supernova.

4 Conclusions and perspectives

Vacuum, as a unifying system ruling the processes taking place on all space-time scales, can be considered one of the most intriguing concepts in physics. When observed at the quantum level, vacuum is not empty and exhibits zero-point fluctuations everywhere in space, even in regions which are devoid of matter and radiation. In particular, it is filled with continuously appearing and disappearing particle pairs such as electron-positron or quark-antiquark pairs. These virtual particles are real particles, but their lifetimes are extremely short by virtue of the uncertainty principle, which prevents their observation. Although the virtual particles of the vacuum are not observable, the vacuum state has nontrivial properties in the sense that it produces observable effects in the behaviour of physical systems, such as the Lamb shift and the Casimir effect to name a few.

In recent years, some authors have shown that also the speed of light has its ultimate origin in properties of the quantum vacuum. In particular, we have seen that, on one hand, in Franson's model the physical vacuum, as a consequence of the action of the gravitational potential on the energy of electron-positron pairs (created in the motion of a photon), determines a correction to the speed of light [5] and, on the other hand, according to Urban's model, the speed of light is an observable parameter of the quantum vacuum, fluctuates as a consequence of the origin of the vacuum permeability and the vacuum permittivity from the magnetization and the polarization of continuously appearing and disappearing fermion pairs [6]. Now, the model provided in this paper of a three-dimensional dynamic quantum vacuum defined by elementary reduction-state processes of creation/annihilation of quanta (more precisely, of virtual pairs particles-antiparticles) corresponding to opportune changes of a fundamental quantum vacuum energy density, suggests that the physical value of the speed of light, as well as its corrections owed to action of the vacuum, are determined by the fluctuations of the quantum vacuum energy density. This model allows us thus to unify Franson's results and Urban's approach into a more general unifying scheme justifying in what sense the speed of light depends on variations of the quantum vacuum properties: the ultimate visiting card of these processes is the variable quantum vacuum energy density.

Finally, at the end of this paper we mention that, in a recent work, H. Razmi, N. Baramzadeh and H. Baramzadeh, by analysing the influence of the quantum vacuum acting as a polarized medium in the light propagation, have shown, on one hand, that in the standard linear theory of quantum electrodynamics, although the electric permittivity and the magnetic permeability of the vacuum are changed due to the polarization made by the propagation of a real photon, the speed of light remains unchanged, and, on the other hand, that taking into account nonlinear effects in the context of Euler-Heisenberg Lagrangian, the speed of light is modified by the dispersive property of the quantum vacuum medium [38]. This result of H. Razmi, N. Baramzadeh and H. Baramzadeh, regarding the modification of the value of the speed of light produced by the action of the quantum vacuum as a dispersive medium, is compatible, from an epistemological point of view, with the treatment of the corrections of the speed of light inside a perturbative approach in our theory of three-dimensional quantum vacuum characterized by a variable energy density. The perspective to find a more unifying re-reading between our theory of dynamic three-dimensional quantum vacuum and the view of H. Razmi, N. Baramzadeh and H. Baramzadeh, is therefore opened. As regards the connections, both from the conceptual point of view and from the mathematical point view, between the calculations of the corrections provided by the three-dimensional dynamic quantum vacuum as regards the value of the speed of light in a perturbative approach provided in this paper and the corresponding results of H. Razmi, N. Baramzadeh and H. Baramzadeh in their model of the physical vacuum endowed with dispersive properties based on the Euler-Heisenberg Lagrangian, further research will give you more information.

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