Article

The Quantum Potential & the Bell Length of the 3D Quantum Vacuum as the Ultimate Parameters Generating the Avian Quantum Compass

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Abstract

A model of magnetoreception of birds in the picture of a three-dimensional quantum vacuum defined by energy fluctuations corresponding to elementary processes of creation/annihilation of virtual particles-antiparticles is proposed. In this approach, a quantum potential of the vacuum and its corresponding Bell length of the vacuum emerge as the ultimate physical parameters which generate the quantum correlations and thus the processes responsible of the avian quantum compass.

Keywords: Avian quantum compass, radical pair mechanism, three-dimensional quantum vacuum, Bell length of the vacuum.

1. Introduction

Magnetoreception is the ability of some migrating species to navigate using the Earth's magnetic field. Although the precise mechanism used, and its features, vary greatly from animal to animal, in the light of data we have got, it seems that quantum correlations help terrestrial creatures to find the right path, providing them a sort of compass to orient themselves.

Since the pioneering works of Alexander von Middendorf at mid of XIX century as regards the places and the dates of arrival of different species of migratory birds, which showed that these animals oriented themselves by the Earth's magnetic field, and of Yeagley in 1947 about the sense of orienting of homing pigeons, many scientists have established that several animals have an inner sensibility to the Earth's magnetic field, which gives them a strong sense of orienting [1, 2]. If the capacity of the animals of feeling the Earth's magnetic field is not in doubt, however one does not know how they manage in this: at the beginning of the '70s nobody knew how Earth's magnetic field, so weak, could influence animals' bodies and what were the place of the body in which there was the sensorial organ responsible of magnetoreception. In this regard, in the '70s an important discovery was the one of Wolfgang and Roswitha Wiltschko who showed that the avian compass of robins did not look like to conventional compasses, but was only a biologic inner compass "at inclination", which always points towards the nearer pole, whether it be [3]. Although at mid '70s nobody knew how a biological compass worked, in 1976 Karl Schulten published a fundamental paper in which he proposed an explanation of the avian

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compass based on a mechanism of a couple of free radicals generated by a fast triplet reaction which included the quantum correlation [4]. The radical-pair model suggested by Schulten can be summarized as follows, although the exact details and steps involved can be quite complex: a radical pair is (typically) a pair of bound molecules that each has an unpaired electron. These pairs are created, by a photochemical process, in spin-correlated states; that is, singlets or triplets. The state of these spins then evolves under the combined effect of the Earth's weak magnetic field and internal nuclear hyperfine interactions with the host nuclei. Finally, the rate of charge recombination depends on the spin of the separated charges, directly influencing the reaction products of these radical pairs. These differing reaction products are in principle biologically detectable. Thus, if the relative weights of the singlet and triplet states are sensitive to the angle of the external (geo-magnetic) field, the reaction products will be also, leading to a magnetic compass.

The idea of the quantum correlation as the fundamental element which generates the processes responsible of the avian compass, considered extravagant in the '70s, would have however received a bigger physical consistence few years later, when in 1982 the Alain Aspect group in Paris performed the first of a series of high-quality experiments which demonstrated in a clear way that non-locality constitutes an essential and inescapable property of quantum processes, that subatomic particles can communicate instantaneously information independently of their distance [5]. Thus, there was a renowned interest towards Schulten's theory and, in the light of successive important experimental results on migratory birds and, above all, of the discovery in 1998 that in the eyes of animals a protein is present, called cryptochrome, having an intrinsic ability to create couplet of radicals [6], Karl Schulten, Torsten Ritz and their group hypothesized that the cryptochrome were just the elusive receptor for the avian chemical compass, publishing their results in a magnificent 2000 paper which would become one of the classical references of quantum biology [7]. Besides proposing cryptochrome as the candidate for the chemical compass, the paper by Ritz and collaborators describes how the orientation of the bird with respect the Earth's magnetic field can influence what it sees. The key point of the theory is that, as a consequence of the absorb of a blue photon by a molecule sensible to light inside the protein cryptochrome, a couple of correlated electrons generates itself which can be in a superposition of triplet-singlet states, which is very sensible to the force and the angle of the Earth's magnetic field. Therefore the direction in which the bird flies creates a difference in the composition of the final chemical products generated in the reaction. Someway through a not better specified mechanism this difference generates a signal, which is sent to the brain and indicates to the bird where the nearer magnetic pole is.

Successively important proves accumulate that cryptochrome is implied in the perception of quantum fields, producing couples of radicals, by fruit midges, monarch butterflies and chickens. Experiments were performed too in order to verify if the ability of orientation of birds were disturbed by the application of oscillating magnetic fields from various directions and different frequencies.

But there remain many questions without answer yet. In particular, we do not have idea as regards what birds feel during these processes, i.e. how they manage to "see" the magnetic field, what allows their eyes to see the graphic of the Earth's magnetic field. And we do not know why the indigo compass have to be so ultra-sensible to oscillating magnetic fields, and how the free radicals act in order to remain in quantum correlation at long enough to make the difference from the biological point of view [8].

In this paper we propose ourselves to provide a new key of reading of the processes of magnetoreception of the birds on the basis of a model, proposed by the authors in some recent papers, of a three-dimensional (3D) timeless quantum vacuum as a fundamental arena of the universe, in which the quantum potential of the vacuum is the crucial entity which explains the origin of the quantum correlations. If on the basis of the fundamental Ritz's and Schulten's work the capacity of the animals to feel the terrestrial magnetic field is determined by the quantum correlations associated to a couple of free radicals and, in our model, at a fundamental level, the quantum correlations are linked with the action of the quantum potential of a 3D timeless quantum vacuum, we expect ourselves that the 3D timeless quantum vacuum have a significant role in the processes responsible of the avian compass. This is the main theme of this paper.

The structure of the paper is the following. In chapter 2 we will review the fundamental features of our model of three-dimensional quantum vacuum in reference with quantum processes and quantum correlations. In chapter 3 we will propose a toy-model about how the quantum potential of the vacuum, and an opportune Bell length of the vacuum describing its fundamental geometry, allow us to explain the origin of the avian compass regarding the motion of migratory animals. In chapter 4 we will analyse the perspectives of this toy-model showing how it can answer some of the questions mentioned above in a picture where the Bell length of the vacuum is the ultimate parameter which allows us to explain the information which makes the bird realize where the nearer magnetic pole is.

2. The three-dimensional timeless quantum vacuum, the quantum potential of the vacuum and the Bell length of the vacuum

The 20th century theoretical physics replaced the notion of an "empty" space with the idea of a unified quantum vacuum as a fundamental medium subtending the observable forms of matter, energy and space-time and ruling the processes which take place in the micro- and the macroworld, which manifests itself on all space-time scales. We explored recently the possibility that the so called "empty space" is a type of energy "full" of itself by introducing, on the basis of the Planckian metric emerging, for example, from loop quantum gravity [9-11], a model of a three-dimensional (3D) timeless dynamic quantum vacuum which can create a bridge between quantum mechanics and general relativity.

In this model, the fundamental background space of physics is a 3D timeless quantum vacuum where each elementary particle is determined by elementary reduction-state (**RS**) processes of creation/annihilation of quanta (more precisely, of virtual pairs of particles-antiparticles) corresponding to opportune changes of energy density of space [12, 13]. In the outer intergalactic space, namely in the absence of material objects, the energy density of quantum vacuum is defined by the Planck energy density (and corresponds to the total average volumetric energy density, owed to all the frequency modes possible within the visible size of the universe):

$$\rho_{PE} = \frac{m_p \cdot c^2}{l_p^3} \tag{1}$$

where m_P is Planck's mass, c is the light speed and l_p is Planck's length, while the appearance of material objects derive from opportune diminishing of the quantum vacuum energy density. The Planck energy density (1) is the ground state of the vacuum: out of this fundamental energy pool of the universe particles and antiparticles continuously appear and disappear. In fact, each material particle is associated with fluctuations of the quantum vacuum which determine a diminishing of the quantum vacuum energy density. In our model energy E of a given physical object with mass m and volume V is proportional to the diminished energy density of quantum vacuum ρ_{qvE} in the centre of a given physical object:

$$E = mc^2 = (\rho_{PE} - q_{qvE}) \cdot V \tag{2}$$

where ρ_{qvE} is the energy density of quantum vacuum inside the physical object, ρ_{PE} is the Planck energy density (given by (1)) and V is the volume of the physical object. In other words, the mass of a physical object is produced by a variable quantum vacuum energy density on the basis of relation:

$$m = \frac{(\rho_{PE} - \rho_{qvE}) \cdot V}{c^2} \tag{3}$$

According to equation (3) there is a fundamental symmetry between the property of mass and the changes of the quantum vacuum energy density [14].

In this model the laboratory non-locality represents the essential, ultimate visiting card of quantum processes in the sense that it is an upper expression of the more fundamental 3D non-local quantum vacuum. By considering the action of Bohm's quantum potential inside the 3D isotropic quantum vacuum defined by elementary processes of creation/annihilation of quanta analogous to Chiatti's and Licata's transactions, our model provides an improvement and a completion of quantum theory in the sense that the behaviour of the electron can be seen as the effect of more elementary processes of formation and dissolving of quanta of the 3D quantum vacuum.

In a series of recent papers [15, 16], Chiatti and Licata proposed the idea that in the physical universe the ontologically primary events are the creation and annihilation of an elementary quantum, of an actualized transaction, and they correspond to a peculiar reduction of a state vector (which is constituted of interaction vertices in which real elementary particles are created or destroyed). In epistemological affinity with Chiatti's and Licata's transactional approach, our model postulates that the appearance of baryonic matter derives from an opportune excited state of the 3D quantum vacuum defined by opportune changes of the quantum vacuum energy density and corresponding to specific reduction-state (**RS**) processes of creation/annihilation of quanta [12]. The excited state of the quantum vacuum corresponding to the appearance of a material particle of mass (3) is defined (in the centre of that particle) by a diminishing with respect to the Planck energy density characterizing the ground state and its evolution is determined by opportune **RS** processes of creation/annihilation of quanta described by a wave function $C = \begin{pmatrix} \psi \\ \phi \end{pmatrix}$ at two components satisfying a time-symmetric extension of the Klein-Gordon quantum relativistic equation

$$\begin{pmatrix} H & 0 \\ 0 & -H \end{pmatrix} C = 0 \tag{4}$$

where $H = \left(-\hbar^2 \partial^\mu \partial_\mu + \frac{V^2}{c^2} \left(\Delta \rho_{qvE} \right)^2 \right)$ and $\Delta \rho_{qvE} = (\rho_{PE} - q_{qvE})$ is the change of the quantum vacuum energy density.

Moreover, the virtual particles-antiparticles corresponding to the **RS** processes of creation/annihilation of the 3D quantum vacuum give rise to a total zero spin, thus constituting an organized Bose ensemble, analogous to the superfluid helium [17]. As a consequence, in the light of recent results obtained by Sbitnev in a series of recent papers [18-21], regarding the role of the physical vacuum as a super-fluid medium containing pairs of particles-antiparticles which make up a Bose-Einstein condensate, our model implies that, in presence of ordinary baryonic matter, the 3D quantum vacuum – and thus the fundamental background which rules the behaviour of subatomic particles – physically acts as a superfluid medium, and thus can be characterized by the following Einstein energy-momentum tensor

$$T^{\mu\nu} = (\varepsilon + p) u^\mu u^\nu + p \eta^{\mu\nu} \tag{5}$$

In equation (5) ε and p are functions per unit volume expressed in units of pressure and the metric tensor $\eta^{\mu\nu}$ has the spacelike signature $(-,+,+,+)$. From the energy-momentum tensor (5), one obtains the following conservation law

$$\partial_\mu \left(V T^{\mu\nu} / n \right) = 0 \tag{6}$$

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

$$\omega = \frac{2 \Delta \rho_{qvE} V}{\hbar n} \tag{7}$$

In the light of equation (7), we can say that each elementary fluctuation of the quantum vacuum energy density in a given volume produces an oscillation of the vacuum at a peculiar frequency. This means that each material object given by mass (3) corresponds to oscillations of the vacuum given by equation (7).

The total effect of the motion of the virtual particles produced by the amount of **RS** processes characterizing a given region – in correspondence to changes of the quantum vacuum energy density – is to generate a dragging, pushing effect of the 3D quantum vacuum. In particular, one may describe the pushing effect of a region of volume V of the quantum vacuum in a given point at a distance R from the centre of that volume by defining a velocity of the 3D quantum vacuum on the basis of equation

$$v_{qv} = \frac{2\Delta\rho_{qvE} V}{\hbar n} R \tag{8}$$

The quantum vacuum velocity (8) is defined with respect to the special rest frame of the vacuum associated with the quantum vacuum energy density (1). In other words, the rest frame corresponding to the Planck energy density is a special frame in which the quantum vacuum velocity (8) is zero, all material objects (and thus all variations of the energy density of quantum vacuum) correspond to regions of the quantum vacuum endowed with a velocity (8) with respect to this special frame.

In our approach non-locality is embedded as the ultimate visiting card of processes by decomposing the real and imaginary parts of the fundamental equation ruling the **RS** processes, namely the Klein-Gordon equation (4) after writing the two components of the wave function in polar form. In fact, in this way one obtains a couple of quantum Hamilton-Jacobi equations in which the fundamental entity is a time-symmetric quantum potential of the vacuum given by

$$Q_{Q,i} = \frac{\hbar^2 c^2}{V^2 \left(\Delta\rho_{qvE}\right)^2} \left(\frac{\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\left|\psi_{Q,i}\right|}{\left|\psi_{Q,i}\right|} - \frac{\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\left|\phi_{Q,i}\right|}{\left|\phi_{Q,i}\right|} \right) \tag{9}$$

The non-locality characterizing laboratory subatomic processes can be thus considered as an upper effect of a more fundamental quantum potential of the vacuum (9), which represents the fundamental entity which guides the occurring of the processes of creation or annihilation events in space. In other words, according to our model, the quantum potential of ordinary quantum mechanics can be considered a consequence of the more fundamental quantum potential of the quantum vacuum (9). In particular, as regards the creation events, the quantum potential associated with the virtual particles of the **RS** processes of the 3D quantum vacuum may be written also as

$$Q = V\frac{p_1 + p_2}{n} = -\frac{\hbar^2 c^2 n^2}{4\Delta\rho_{qvE}{}^2 V^2}\left[\nabla^2\Delta\rho_{qvE} - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\Delta\rho_{qvE}\right] +$$

$$\frac{\hbar^2 c^2 n^2}{8\Delta\rho_{qvE}{}^3 V^2}\left[\left(\nabla\Delta\rho_{qvE}\right)^2 - \frac{1}{c^2}\left(\frac{\partial}{\partial t}\Delta\rho_{qvE}\right)^2\right] \tag{10}$$

where n is the number of virtual particles-antiparticles of the **RS** processes in the volume V of the 3D quantum vacuum into consideration [22]. Equation (10) shows that the quantum potential of the vacuum describes the geometry via the pressures p_1 and p_2 that arise by the collisions between the virtual particles-antiparticles populating the vacuum and corresponding to the **RS** processes.

In the model here analysed, the evolution of each subatomic particle (such as the electron in a double-slit interference) emerges from opportune elementary **RS** processes of creation/annihilation of quanta guided by the quantum potential of the vacuum. The behaviour of a subatomic particle as described by Bohm's approach to quantum mechanics can thus be seen as the result of a more fundamental evolution of fluctuations of the quantum vacuum energy density corresponding to elementary **RS** processes of creation/annihilation of quanta and ruled by the non-local quantum potential of the vacuum [23].

In virtue of the fundamental features of the 3D quantum vacuum, in our approach one can throw new light as regards the problem of the existence, in quantum physics, of different descriptive levels of physical reality, whether formal analogies exist between them or there is a deeper meaning. In fact, by using a Bohmian terminology, the reality constituted by the **RS** processes and their evolution through the non-local action of the quantum potential of the vacuum can be defined as the background from whose differentiation the foreground constituted by the events of a given subatomic particle or system (governed by the well-known laws of quantum theory) emerges. In this picture, the ordinary spacetime, as well as the background associated with the de Broglie-Bohm pilot-wave theory but also of Bohm's implicate order and Hiley's pre-space can be seen as manifolds deriving from this more fundamental arena represented by the three-dimensional non-local timeless quantum vacuum, are someway "materialized" by **RS** processes. In synthesis, our approach introduces a deeper meaning about the relationships between the different descriptive levels of physical reality, in the sense that here the ordinary quantum mechanics emerges directly from the 3D timeless non-local quantum vacuum [23].

In particular, as regards the fundamental non-local geometry of the 3D timeless quantum vacuum, it can be characterized by introducing an appropriate Bell length of the 3D quantum vacuum given by relation

$$L_{quantum} = \frac{2\Delta\rho_{qvE}\sqrt{V}}{\sqrt{n\left[-\left(\nabla\Delta\rho_{qvE}\right)^2 + \frac{1}{c^2}\left(\frac{\partial}{\partial t}\Delta\rho_{qvE}\right)^2 - \Delta\rho_{qvE}\left(\nabla^2\Delta\rho_{qvE} - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\Delta\rho_{qvE}\right)\right]}} \tag{11}$$

The Bell length of the vacuum (11) can be considered the ultimate parameter that indicates the grade of non-locality of the fundamental level of the quantum reality, namely the 3D quantum vacuum defined by **RS** processes of creation/annihilation of virtual particles-antiparticles corresponding to fluctuations of the quantum vacuum energy density. And the laboratory non-locality here represents only a special case of the global non-locality and atemporality of the 3D quantum vacuum whose correlation degree is described by the Bell length of the vacuum (11).

Since, on the basis of recent research [24], the maximum value of the Bell length of the 3D quantum vacuum (11), which implies the maximum de-localization of a quantum system, is 1, one obtains the following simple relation satisfied by the number of virtual particles-antiparticles of the **RS** processes of the 3D quantum vacuum in the condition of maximum entanglement, of the maximum grade of non-locality and de-localization in a quantum system having the mass

$m=\frac{\Delta\rho_{qvE}V}{c^2 n}$ produced by the fluctuations of the quantum vacuum energy density corresponding to the same **RS** processes:

$$n^{1/2}=\frac{2\Delta\rho_{qvE}V^{1/2}}{\sqrt{\left[-\left(\nabla\Delta\rho_{qvE}\right)^2+\frac{1}{c^2}\left(\frac{\partial}{\partial t}\Delta\rho_{qvE}\right)^2-\Delta\rho_{qvE}\left(\nabla^2\Delta\rho_{qvE}-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\Delta\rho_{qvE}\right)\right]}} \tag{12}$$

Another relevant merit of the introduction of the Bell length of the vacuum lies in the possibility to provide a new key of re-reading of the well-known Bell inequalities investigating correlations between two particles who share a quantum state [25-27]. As regards the quantum dynamics of a general two qubits state, with vanishing total angular momentum projections, given by the following equation

$$|\psi\rangle=\cos\frac{\vartheta}{2}|\uparrow\downarrow\rangle+e^{i\varphi}\sin\frac{\vartheta}{2}|\downarrow\uparrow\rangle \tag{13}$$

where $|\uparrow\downarrow\rangle$ corresponds to the state of the system when the first qubit is in the "up" state and the second qubit is in the "down" state, while $|\downarrow\uparrow\rangle$ corresponds to the state of the system when the first qubit is in the "down" state and the second qubit is in the "up" state, in a bohmian framework the quantum potential is

$$Q=\frac{\left(\hat{M}_1^2+\hat{M}_2^2\right)R}{2IR} \tag{14}$$

where $\vec{M}_1=i\hat{\vec{M}}_1S$ and $\vec{M}_2=i\hat{\vec{M}}_2S$ are the angular momenta of the two qubits 1 and 2 respectively, S being the phase of the wave function of the system. The grade of non-locality in this system may be characterized by considering the following Bell length

$$L_{quantum}=\frac{1}{\sqrt{\frac{\left(\left(\hat{\vec{M}}_1^{\,2}+\hat{\vec{M}}_2^{\,2}\right)R\right)}{R}}} \tag{15}$$

In our approach, since each quantum system is the evolution of opportune **RS** processes of creation/annihilation of quanta corresponding to elementary fluctuations of the 3D quantum vacuum, the Bell length (15) regarding a system of two qubits in the entangled state (13) derives from a more fundamental Bell length of the vacuum (11). More precisely, one can say that the behaviour of a system of two qubits in the entangled state (13) described by the quantum laws is ultimately determined by **RS** processes of creation/annihilation of quanta corresponding to elementary fluctuations of the 3D quantum vacuum on the basis of equation:

$$\frac{1}{\sqrt{\frac{\left(\left(\hat{\hat{M}}_1^{\,2}+\hat{\hat{M}}_2^{\,2}\right)R\right)}{R}}}=\frac{2\Delta\rho_{qvE}\sqrt{V}}{\sqrt{n\left[-\left(\nabla\Delta\rho_{qvE}\right)^2+\frac{1}{c^2}\left(\frac{\partial}{\partial t}\Delta\rho_{qvE}\right)^2-\Delta\rho_{qvE}\left(\nabla^2\Delta\rho_{qvE}-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\Delta\rho_{qvE}\right)\right]}} \quad (16)$$

Now, in the light of these considerations, by following the philosophy underlying the approach of Hall's correlation distance developed in [28], in our model we can suggest that the standard Bell inequality in the form derived by Clauser, Horne, Shimony, and Holt (CHSH)

$$CHSH\equiv\langle AB\rangle+\langle AB'\rangle+\langle A'B\rangle-\langle A'B'\rangle\leq 2 \quad (17)$$

may be generalized as

$$\langle AB\rangle+\langle AB'\rangle+\langle A'B\rangle-\langle A'B'\rangle\leq\frac{4}{2-L_{quantum}^{\max}} \quad (18)$$

where $L_{quantum}^{\max}=1$ is the maximum value of the Bell length of the vacuum, that here is directly determined by opportune fluctuations of the quantum vacuum energy density on the basis of equation (11). By substituting equation (11) into equation (18) one obtains:

$$\langle AB\rangle+\langle AB'\rangle+\langle A'B\rangle-\langle A'B'\rangle\leq$$

$$\frac{2}{1-\frac{\Delta\rho_{qvE}\sqrt{V}}{\sqrt{n\left[-\left(\nabla\Delta\rho^{\max}{}_{qvE}\right)^2+\frac{1}{c^2}\left(\frac{\partial}{\partial t}\Delta\rho^{\max}{}_{qvE}\right)^2-\Delta\rho_{qvE}\left(\nabla^2\Delta\rho^{\max}{}_{qvE}-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\Delta\rho^{\max}{}_{qvE}\right)\right]}}} \quad (19)$$

where here $\Delta\rho_{qvE}^{max}$ are the opportune quantum vacuum energy fluctuations determining the maximum degree of non-local correlations in a quantum system. Therefore on the basis of the Bell length of the vacuum (11), a quantum vacuum inequality can be introduced of the form

$$CHSH_{vacuum}\leq 0 \quad (20)$$

where

$$CHSH_{vacuum}=\langle AB\rangle+\langle AB'\rangle+\langle A'B\rangle-\langle A'B'\rangle-$$

$$\frac{2}{1-\frac{\Delta\rho_{qvE}\sqrt{V}}{\sqrt{n\left[-\left(\nabla\Delta\rho^{\max}{}_{qvE}\right)^2+\frac{1}{c^2}\left(\frac{\partial}{\partial t}\Delta\rho^{\max}{}_{qvE}\right)^2-\Delta\rho_{qvE}\left(\nabla^2\Delta\rho^{\max}{}_{qvE}-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\Delta\rho^{\max}{}_{qvE}\right)\right]}}} \quad (21)$$

In our approach, the violation of the quantum vacuum inequality (20) essentially coincides with the one of the standard CHSH inequality. However, the measurements that maximize the violation of CHSH are not the ones which give the maximal violation of $CHSH_{vacuum}$. In general, for the standard Bell-CHSH scenario, the violation of the standard inequality (17) is a necessary but not sufficient condition for the violation of (20). The advantage of the quantum vacuum inequality (20) lies in the fact that the results depend causally on the Bell length of the vacuum which emerges directly as the ultimate parameter determining, at the fundamental level of the 3D quantum vacuum defined by **RS** processes of creation/annihilation of quanta corresponding to elementary fluctuations of the quantum vacuum energy density, the correlation degree in quantum systems [29].

3. A toy-model about the link between the three-dimensional quantum vacuum and the avian compass in animals' motions

As regards the use of Earth's magnetic field for orientation and navigation by birds, insects and mammals, it was recently demonstrated in spin chemistry experiments that a photochemical reaction can act as a compass even in a magnetic field as weak as the geomagnetic field [30]. The underlying mechanism in such a chemical compass turns out to be of quantum mechanical nature but the specific role of quantum interactions, in determining entanglement and (de-)coherence, are little understood [31]. In the recent paper "Quantum control and entanglement in a chemical compass", Cai, Guerreschi and Briegel show that several quantum control protocols can be applied to study the magnetoreception of certain animals, in order to either enhance or suppress the function of a chemical compass [32]. Cai's, Guerreschi's and Briegel's calculations demonstrate that the radical pair mechanism firstly proposed in the pioneering work by Schulten *et al.* in 1976, can not only detect weak magnetic fields, but it is also sensitive to quantum control even without the presence of a static magnetic field. In Cai's, Guerreschi's and Briegel's model quantum entanglement, rather than mere quantum coherence, is the contributing factor that allows the avian compass to achieve its high level of sensitivity. Recently, Kominis [33] also argued that spin-selective radical-ion-pair reactions are able to offer an exquisite magnetic sensitivity. In the light of these results, the following questions become natural: does the duration of the entanglement last long enough to impact biological processes and is the duration of entanglement sensitive to the inclination of the radical pair with respect to the earth's magnetic field? To answer these questions, after revisiting the standard radical-pair mechanism with the candidate chemical reaction [34], we take under consideration a model recently proposed by Pauls, Zhang, Berman and Kais in which the entanglement displays both directional sensitivity and a sufficiently long duration of entanglement [35].

The basic idea of the radical-pair approach is the following: there are molecular structures in the bird's eye which can each absorb an optical photon and originate a spatially separated electron pair in a singlet spin state, and then the avian neurons react to the signal. More precisely, inside the radical-pair model the process of magnetoreception may be divided into three fundamental stages. In the first stage, the photons with enough energy activate a certain type of molecules located in the birds' eye, inducing an electron transfer reaction and generating the radical pairs in their excited singlet states. After the pair is generated, under the influence of the external magnetic field (the geomagnetic field) and the internal magnetic field (the hyperfine coupling effect), the state of the pair can remain a singlet state or become a triplet state. This means, in other words, that, by virtue of the differing local environments of the two electron spins, a singlet-triplet evolution takes place. This evolution is strictly tied with the inclination of the molecules with respect to the Earth's magnetic field. Different inclination angles, associated with the external magnetic field, can induce different ratios of the singlet and triplet states. These molecules give rise to a pattern, discernible to the bird, which indicates the orientation of the field. Recombination happens either from the singlet or triplet state, yielding different chemical end products. The concentration of these products forms a chemical signal correlated to the Earth's field orientation. In the last stage, the molecules in different states will generate different chemical products which can induce a detectable signal that the birds can use to recognize the direction they need to go [36].

The predictions of the radical–pair mechanism are consistent with behavioral findings: the reaction yield is independent of the polarity of the magnetic field [37, 38], reception of magnetic information takes place in the eye [39, 40], reception is strongly influenced by the environment light conditions [41–45], and reception turns out to be coherent with the postulated function of ocular photoreceptors in generating magnetosensitive radical pairs [46]. As regards the specific biological magnetosensitive radical pairs which can satisfy and reproduce these processes, according to the current approach cryptochrome 1a (Cry1a) seems a promising candidate [36, 47–52]. Although the matter of the electron transfer path has been studied [53, 54], the neural path is still unknown, even if a vision-based hypothesis was put forward by Ritz et al. in the classic 2000 paper [7].

Despite all of the theoretical arguments, the ultimate goal of studying the mechanisms of bird navigation is to learn from nature and to design highly effective devices that can make biological systems to detect weak magnetic fields, and to use the geomagnetic field to navigate. On the basis of previous literature, it seems that the anisotropic hyperfine coupling plays a crucial role in the magnetic field sensitivity of the avian compass, allowing also the design of biologically inspired magnetic compass sensors [55–64]. Scientists have exploited many practical methods to realize a device based on the avian chemical compass.

The Hamiltonian of a radical pair is of the form [65]

$$H = g\mu_B \cdot \sum_{i=1}^{2} \vec{S}_i \cdot \left(\vec{B} + \hat{A}_i \cdot \vec{\mathrm{I}}_i\right) \tag{22}$$

where the first term accounts for the Zeeman interaction and the second term reproduces the hyperfine interaction, μ_B is the Bohr magneton of the electron, $\hat{A}_i$ denote the hyperfine coupling tensor (a 3X3 matrix) and $\vec{S}_i$, $\vec{I}_i$ are the electron and nuclear spin operators respectively and the g-values are chosen to be g=2 for both radicals. The radical-pair dynamics is ruled by a Liouville equation of the form

$$\dot{\varphi}(t) = -\frac{i}{\hbar}[H, \varphi(t)] - \frac{k_S}{2}\{Q^S, \varphi(t)\} - \frac{k_T}{2}\{Q^T, \varphi(t)\} \tag{23}$$

where H is the Hamiltonian of the system, Q^S is the singlet projection operator, Q^T is the triplet projection operator, $\varphi(t)$ is the density matrix for the system, and k_S and k_T are the decay rates for the singlet state and triplet states, respectively. Moreover, the external weak magnetic field $\vec{B}$, representing the Earth's magnetic field in equation (22), depends on the angles θ and ϕ with respect to the reference frame of the immobilized radical pair, i.e., $\vec{B} = B_0(\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$, where $B_0 = 0{,}5G$ is the magnitude of the local geomagnetic field (and where, without losing the essential physics, ϕ can be assumed to be 0).

By utilizing the standard Ritz's model, the authors Pauls, Zhang, Berman and Kais have recently found that the dynamics of entanglement does not change with angle, namely that entanglement is not sensitive to the angle between the *z* axis of the radical pair and the Earth's magnetic field (and this seems to be in contrast with the expectations because in order for entanglement to also act as a signal of direction, the entanglement must be angle dependent). This physically means that the entanglement of the radical pair of Ritz's model cannot provide the same information as the vision-based signal, namely that inside Ritz's model the entanglement of the system cannot directly influence the birds' ability to orient themselves. In the light of these results, Pauls, Zhang, Berman and Kais have considered what happens by replacing the symmetric hyperfine tensor with an asymmetric hyperfine tensor, finding that the dynamics of the entanglement in this way turned out to be clearly dependent on the system's orientation. As a consequence they have proposed a new model in which each electron interacts with additional local magnetic fields $\vec{B}_i$ rather than with the hyperfine interactions. The Hamiltonian for Pauls', Zhang's, Berman's and Kais' model is then given by equation (22), but with $\hat{A}_i \cdot \vec{\mathrm{I}}_i$ replaced by $\vec{B}_i$, the local magnetic field for the *i*th electron spin, and thus is of the form:

$$H = g\mu_B \cdot \sum_{i=1}^{2} \vec{S}_i \cdot \left(\vec{B} + \vec{\mathrm{B}}_i\right) \quad (24)$$

In this picture by taking the local fields to be $\vec{B}_1$=(0,0,5) and $\vec{B}_2$=(0,5,0), we assume to consider the violation of the quantum vacuum inequality (20) as the metric of entanglement and thus as origin of the correlations generating the avian compass in animals' motions. In the light of the quantum vacuum inequality (20), we can say that, for the opportune changes of the quantum vacuum energy density which make the quantity $\langle AB\rangle + \langle AB'\rangle + \langle A'B\rangle - \langle A'B'\rangle - \dfrac{2}{1-\dfrac{\Delta\rho_{qvE}\sqrt{V}}{\sqrt{n\left[-\left(\nabla\Delta\rho^{\max}{}_{qvE}\right)^2 + \dfrac{1}{c^2}\left(\dfrac{\partial}{\partial t}\Delta\rho^{\max}{}_{qvE}\right)^2 - \Delta\rho_{qvE}\left(\nabla^2\Delta\rho^{\max}{}_{qvE} - \dfrac{1}{c^2}\dfrac{\partial^2}{\partial t^2}\Delta\rho^{\max}{}_{qvE}\right)\right]}}}$ exceeding 0, then the correlations between the two spins can no longer be explained classically, so the system is entangled. In other words, we can say that the correlations responsible of the avian quantum compass in animals' motion as regards the magnetoreception are determined by the opportune values of the Bell length of the vacuum, ultimately associated with the quantum potential of the vacuum and associated with specific values of the quantum vacuum energy density, which satisfy the following relation:

$$\langle AB\rangle + \langle AB'\rangle + \langle A'B\rangle - \langle A'B'\rangle -$$

$$1-\frac{\frac{2}{\Delta\rho_{qvE}\sqrt{V}}}{\sqrt{n\left[-\left(\nabla\Delta\rho^{\max}{}_{qvE}\right)^2+\frac{1}{c^2}\left(\frac{\partial}{\partial t}\Delta\rho^{\max}{}_{qvE}\right)^2-\Delta\rho_{qvE}\left(\nabla^2\Delta\rho^{\max}{}_{qvE}-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\Delta\rho^{\max}{}_{qvE}\right)\right]}}\geq 0 \quad (25)$$

The condition (25) determined by opportune energy fluctuations of the 3D timeless quantum vacuum allows us to explain what is the ultimate origin, at a deep level of physical reality, of the ability of orientation of birds Earth's magnetic field. It allows us to introduce suggestive perspectives of explanation of the problem regarding how birds manage to "see" the magnetic field, what allows their eyes to see the graphic of the Earth's magnetic field: the ultimate key of reading lies just in the fundamental properties of the 3D non-local timeless quantum vacuum, namely its elementary fluctuations acting in a non-local way described by the Bell length of the vacuum.

Now, if one studies the quantum vacuum inequality as a function of time for various orientations of the system in a magnetic field of 0.5 G, one finds that, as θ increases from 0° to 180°, the time for which the electron pair is entangled increases from roughly 60 ns to nearly 90 ns, while for φ from 0° to 150° the variation of time of entanglement is restricted to an interval of less than 10 ns, and that changing the relative angles and strengths of the local magnetic fields has a dramatic impact on the angular sensitivity, in the sense that a change in the field strength of the first electron from 4 G to 5 G is enough to dramatically increase both the azimuthal and angular sensitivity of the entanglement.

If indeed magnetoreception is caused in part by a protein such as cryptochrome, a directional orientation of the protein should play an important role, which could be provided by embedding within the membrane layers of photoreceptor cells. This form of embedding leaves the protein free to rotate about one axis [66], but greatly restricts the rotation about its second axis [51]. For this reason the radical-pair compass must be sensitive to rotation about one axis, while the rotation about the second axis should not influence it.

At the present time little is known about how cryptochrome is situated within the retina, in particular how it embeds onto or within the cell membrane [67]. There is no reason to assume that the z axis of the radical-pair model coincides with the fixed rotational axis of the embedded protein. As a consequence, a configuration such as $\vec{B}_1$=(0,0,4) and $\vec{B}_2$=(0,5,0) might still produce a strong directional response under a coordinate transformation to the axis of protein rotation.

It should be pointed out that the angular dependence of entanglement in this model is not invariant under a reversal of the external magnetic field and that the net signal generated by the cryptochrome cannot discern the polarity of the geomagnetic field. In this picture, one obtains therefore that, once the radical pair is generated in a spin-correlated state, its singlet and triplet states will be interconverted by the local magnetic fields $\vec{B}_i$ appearing in equation (24). This singlet-triplet interconversion, representing the second step in the radical-pair reaction scheme, can be influenced by a magnetic field $\vec{B}$ too. Then, singlet and triplet pairs will react to provide distinct products, thus depleting the population of radical pairs with respective recombination rates k_S and k_T with $k_T < k_S$.

The charge recombination of the radical pair follows different channels, which depend on the electron-spin state (singlet or triplet). In particular, by considering [65] the yield of products formed by the reaction of singlet radical pairs can be computed as

$$\Phi_s(t) = \int_0^t r_c(t) f(t)\, dt \tag{26}$$

where $r_c(t)$ is the radical re-encounter probability distribution, and $f(t) = \langle S|\varphi_s(t)|S\rangle$ is the fidelity between the electron spin state $\varphi_s(t)$ at time t and the singlet state. According to the model of Ritz et al., the ultimate activation yield $\Phi_s(t) = \Phi_s(t \to \infty)$ in cryptochrome is believed to influence the visual function of animals [7]. In our approach, we assume that the re-encounter probability distribution $r_c(t)$ appearing in the function (26) is directly determined by the Bell length of the vacuum, and thus by opportune elementary fluctuations of the quantum vacuum energy density, on the basis of equation (11). In other words, since here the violation of the quantum vacuum inequality (20) represents the metric of entanglement and thus the origin of the correlations generating the avian compass in animals' motions, the re-encounter probability distribution $r_c(t)$ can be associated to the distribution of probability that the $CHSH_{vacuum}$ exceeds zero:

$$r_c(t) = P\left(CHSH_{vacuum} > 0\right) \tag{27}$$

Equation (27) provides the fundamental condition which generates the strong quantum correlations which are responsible of the generation of the ultimate activation yield $\Phi_s(t) = \Phi_s(t \to \infty)$ which in cryptochrome is invoked to explain the visual function of animals.

As a consequence of the role of the distribution of probability that the $CHSH_{vacuum}$ exceeds zero as the radical re-encounter probability distribution, the magnetic field sensitivity of the radical pair reaction, which in the original model by Ritz et al. [7] is measured by the derivative of the activation yield (26) with respect to the magnetic field strength $\vec{B}$, here can be expressed as

$$\Lambda(B) = \frac{\partial \Phi_s}{\partial B} = \int_{t_0}^{t_0+\tau} P(CHSH_{vacuum} > 0) \frac{\partial \mathrm{f_s(t)}}{\partial B} \tag{28}$$

According to equation (28), the magnetic field sensitivity is ultimately generated by the distribution probability of the exceeding of the quantum vacuum inequality. Therefore, in this model, the avian compass in animals' motions turns out to be ultimately produced by opportune energy density fluctuations of a fundamental 3D timeless quantum vacuum which determine an exceeding of a fundamental quantum vacuum inequality describing the origin of quantum correlations.

According to a recent study by Cai and Plenio, by introducing the viewpoint of chemical magnetoreception as a quantum interferometer, a direct relation between the global electron-nuclear spin coherence and the magnetic sensitivity of chemical magnetoreception for general molecules emerges, and this allows the development of a quantitative connection between compass sensitivity and the global coherence with respect to the eigenbasis of the hyperfine Hamiltonian of the combined system of radical pair electrons and the surrounding nuclei [60].

Therefore, since in our approach the hyperfine Hamiltonian of the combined system of radical pair electrons and the surrounding nuclei must be replaced by the Hamiltonian (24) in which each electron interacts with the additional local magnetic fields $\vec{B}_i$, Cai's and Plenio's result may be conveniently re-read and generalized by considering that the link between global coherence and magnetic sensitivity in a chemical compass for general molecules is directly determined by the local magnetic fields $\vec{B}_i$ as well as by the distribution probability of the exceeding of the quantum vacuum inequality on the basis of equation (28).

Moreover, it must be remarked that, since a chemical compass shall work under ambient conditions, the noise from the environment of the core system (namely the radical pair and the surrounding nuclear spins) will inevitably influence its function: quantum effects, such as coherence and entanglement, can be easily destroyed by interactions with the environment. In this regard, there is a rule, the k_{BT} argument, which states that when the interaction energy is smaller than ambient temperature, then quantum coherent phenomena cannot persist. As regards biological systems, since the temperature is around 300K, which is hot, the quantum coherent effects are then destroyed by thermal fluctuations. However, for living systems like birds the k_{BT} argument can break down because it is true only for the equilibrium state, which the system approaches for relatively long times. If the system reaches equilibrium rapidly, coherent quantum effects can survive (at equilibrium) even at room temperatures [68–75]. Another possibility is that the quantum coherent effects, including the quantum entanglement, are used before the system approaches the equilibrium with the surrounding environment, which is the situation which happens in the radical pair mechanism of the avian compass.

On the other hand, dephasing noise can only influence the coherences between singlets and triplets. Many papers discuss the effects of dephasing noise on the radical pair mechanism in terms of Lindblad operators, showing that the effect of the dephasing noise depends on the model [58, 76, 77]. For example, in Gauger's model, the compass mechanism is almost immune to pure phase noise [77]. Cai showed that correlated dephasing noise could even enhance the chemical compass in their model [75]. Both models give us positive perspectives concerning dephasing noise. In our approach, we propose that the noise effects can be described by the generalized Lindblad type quantum master equation of the following form

$$\frac{d}{dt}\rho = -i[H,\rho] - \frac{k_S}{2}[Q_S,\rho]_+ - \frac{k_T}{2}[Q_T,\rho]_+ + L(\rho) \qquad (29)$$

where $L(\rho)$ is a dissipator representing the environmental noise and H is the Hamiltonian given by equation (24). In the light of equation (29) as well as of Cai's and Plenio's results, the concept of global coherence turns out to offer a unified perspective to predict the magnetic sensitivity of a chemical compass in a picture where the Hamiltonian (24) and the distribution probability of the exceeding of the quantum vacuum inequality are the ultimate physical elements.

4. Some perspectives of this toy-model

As regards the investigation of a possible primary magnetoreception in animals, according to the original model proposed by Ritz *et al* in [7], the following essential criteria must be satisfied by a good candidate for a photoreceptor-based magnetoreceptor:

- the magnetoreceptor should contain a pair of molecules capable of a radical-pair reaction that can be influenced by weak magnetic fields;

- the magnetoreceptor should be linked to a photoreceptor that starts the radical-pair process upon excitation. In addition, the magnetoreceptor has to be connected to a nervous transduction chain, such as, e.g., the visual transduction chain;

- the receptors have to be arranged in an ordered way to provide the orientational dependence necessary for the compass to work, namely their orientation should vary over a wide angular region.

Whether an amplification of this primary magnetoreception effect is then needed to provide magnetic compass information depends not only on the strength of the effect, but also on the way the primary reception process is connected to the nervous system. By considering, in line with the original Ritz's proposal, that a photoreceptor in the visual pathway, such as retinal, is part of the radical-pair system involved in the magnetoreception, we suggest that, as regards the modulation of the sensitivity of a visual receptor, the Hamiltonian (24) and opportune behaviours of the distribution probability of the exceeding of the quantum vacuum inequality play a crucial role.

As regards the role of the radical pair mechanism in the birds' navigation, in the recent paper [78] Y. Zhang, G. P. Berman, S. Kais conclude their analysis with the following sentences: "The radical pair mechanism is a promising hypothesis to explain the mystery of the navigation of birds. This theoretical study has demonstrated the role of weak magnetic fields play in the product yields of the radical pairs. In addition, this type of study has inspired scientists to design highly effective devices to detect weak magnetic fields and to use the geomagnetic fields to navigate. [...] By studying the role of intensity of the magnetic field in avian navigation, we find that birds could be able to detect the change of the intensity of geomagnetic fields and the approximate direction of parallels instead of sensing the exact direction. However, the mechanism in which birds can utilize the signal remains unknown at this time". In the light of the treatment made in this paper, here we emphasize that suggestive perspectives are opened as regards the problem of the mechanism in which birds use the change of the intensity of the geomagnetic fields: the turning key is represented by the Bell length of the vacuum associated with opportune fluctuations of the energy density of a 3D quantum vacuum and thus on the probability distribution of the exceeding of the quantum vacuum inequality. As regards the precise mechanism through which the fluctuations of the quantum vacuum energy density and thus the probability distribution of the exceeding of the quantum vacuum inequality act in reference to the use of birds of the change of the intensity of the geomagnetic fields, further research will give you more information.

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