QED coherence in matter, syntropy and the coherent domains as storing "devices"

Luigi Maxmilian Caligiuri

Foundation of Physics Research Center (FoPRC), Cosenza, ITALY

E-mail: luigimaxmilian.caligiuri@foprc.org; max.caligiuri@gmail.com

Abstract. Several macroscopic systems, like in particular living organisms, are characterized by stability and high level of order at mesoscopic / macroscopic scale. These peculiar features cannot be explained by considering just short-range interactions among their elementary constituents (atoms / molecules) and the entropic dynamics governing it. The theory of QED coherence predicts that in condensed matter, when suitable boundary conditions about temperature and density are satisfied (as generally happens in living systems), a quantum phase transition spontaneously occurs, driving the system towards a macroscopic coherent quantum state in which phase tuned oscillations between matter and electromagnetic field take place and ensure long-range correlation and order. In 1944, the italian mathematician Luigi Fantappié formulated the "Principi di una teoria unitaria del mondo fisico e biologico", according to which living systems are governed by "syntropic" spontaneous phenomena, that are dual with respect the "entropic" ones, characterized by a reduction of entropy with time and whose causes are put in the future with respect the occurring events, able to ensure the organization and stability of living systems. In this paper we show how the results of QED coherence in matter are able to reproduce several of the main features of "syntropic" dynamics so giving it a support based on Quantum Field Theory. Finally, the role of water as a gatherer of quantum information, predicted by the QED coherence theory, is discussed as a possible practical realization of syntropic dynamics.

1. Introduction

In complex systems, the apparent macroscopic features are linked to the underlying collective properties of their microscopic components. Such link is provided by Quantum Field Theory (QFT) that is the equivalent to statistical mechanics for a system characterized by an infinite number of degrees of freedom. A distinguishing feature of complex systems is the emergence of order from the non-ordered set of their elementary components as well as their remarkable stability at mesoscopic and macroscopic space-time scales, despite the quantum fluctuations characterizing the components behaviour at microscopic scales.

Within the QFT, the request of ensuring the stability of the system out of the fluctuating components is expressed by the request of the Lagrangian $\mathcal{L}$ to be invariant under local phase transformation of the quantum component field $\psi(\vec{x},t)$, namely [1]

$$\psi(\vec{x},t) \to \psi'(\vec{x},t) = \exp\left[iq\theta(\vec{x},t)\right]\psi(\vec{x},t) \tag{1}$$

the invariance of the Lagrangian under the transformation (1) requires the introduction of a gauge field $A_\mu(\vec{x},t)$ that, at the scales of atoms and molecules is just the electromagnetic field, such that $\mathcal{L}$ be also invariant under the local gauge transformation

$$A_\mu(\vec{x},t) \to A'_\mu(\vec{x},t) - \partial_\mu\theta(\vec{x},t) \tag{2}$$

and we use, in $\mathcal{L}$, the covariant derivative

$$D_\mu\psi = (\partial_\mu + iqA_\mu)\,\psi \tag{3}$$

instead of the usual derivative so that it also transforms as equation (1)

$$D_\mu\psi \to \exp\left[iq\theta(\vec{x},t)\right] D_\mu\psi \tag{4}$$

Gauge invariance of the Lagrangian is the needed condition to tune together in a common oscillation the matter and e.m. fields. The gauge field then represents the required permanent background field in which the dynamics of elementary components manifests itself as new macroscopic quantum coherent phase of the system [2,3]. The phase transition from the uncoherent – perturbative ground state (in which all the components perform zero-point oscillations only) to the coherent one (characterized by the phased oscillation) is a spontaneous process, appearing as a spontaneous symmetry breaking (SSB) when suitable conditions about density and temperature are meet [2-4].

The coherent ground state (CGS) is characterized by a phase locking between the phase of the matter and e.m. fields and by the emergence of macroscopic quantum domains, called "coherent domains" (CDs), in which such tuned oscillation occurs [4]. More interestingly, such coherent states resemble, for example, the wavefunctions representing superfluid and superconductor physical systems.

As well as the macroscopic model of superconductivity is based on the hypothesis that there is a macroscopic wave function $\Psi(\vec{x},t)$ which describes the whole ensemble of superconducting electrons, the theory of QED coherence in matter predicts a macroscopic wavefunction associated to the coherent domains which describes the collective coherent behavior of matter and e.m. field whose quanta can be considered as a condensate of quasiparticles that can be observed at a macroscopic scale, described by a macroscopic wavefunction given by

$$\Psi(\vec{x},t) = \Psi_0(\vec{x},t)\,e^{i\Theta(\vec{x},t)} \tag{5}$$

where $\Psi_0(\vec{x},t)$ is the wavefunction amplitude and $\Theta(\vec{x},t)$ its (well-defined) phase. As a consequence of coherent dynamics each coherent domain is characterized by an energy gap, with respect to the uncorrelated state, able to stabilize them against the thermal fluctuations (at least for not too high temperature) [4]. Furthermore, according to our results, the phase correlation ("phase-locking") among the elementary components and e.m. field, inside CD, gives rise to a long-range order at macroscopical scale that reduces the entropy, and can be then associated to a certain amount of information stored in the CD itself.

The coherent oscillation also implies a renormalization of the frequency of e.m. field that is "trapped" inside CD and characterized by a negative squared mass of the photons belonging to it [4]. QED coherent dynamics then leads to the spontaneous formation of macroscopic ordered domain, characterized by lower entropy (with respect to the environment) and by the presence of a massive coherent e.m. field. In the special case of water, which is the most abundant components in living systems, the coherent dynamics allows the formation of a spectrum of "excited" levels of the CD, in the form of "cold" vortices of quasi-free electrons, whose excitations are collective modes of oscillation of the whole CD, being coherent [5].

In this way water CDs are able to absorb high entropy energy from the environment transforming them into low entropy energy stored in a single coherent excited state of the CD as well as information in the form of negentropy. Within this framework, the phase transition from non-correlated ground state (perturbative ground state or PGS) to the coherent ground state (CGS) then acts as a self-organizing process in which the perturbative ground state undergoes a spontaneous symmetry breaking in which the symmetric (disordered) initial state evolves towards the coherent ordered state and the phase - locking among the matter and e.m. field naturally emerges from the dynamics itself in order to preserve the local gauge invariance of the theory and, then, the macroscopic stability of the system.

As we'll show in this paper, the above outlined features characterizing the phase transition to coherent state in condensed matter look to be intriguingly similar, at least from a phenomenological viewpoint, to those conjectured in 1949 by the italian mathematician Luigi Fantappié in his "*Principi di una teoria unitaria del mondo fisico e biologico*" [6], later generalized by S. and G. Arcidiacono [7]. According to this theory, the "anticipated" potentials (AP), that are solutions of undulatory fundamental equations of the Universe, have a physical reality and significance like the solutions of "retarded" potentials (RP) currently accepted as the only ones having physical meaning. Every physical phenomenon would then have a dualist intrinsic nature: the "*entropic*" one, associated to the RP, characterized by increasing entropy and disorder, depending on causes in the past and reproducibility (causality); the "*sintropic*" one, associated to AP, characterized by decreasing entropy and increasing order, depending on causes in the future and spontaneous occurrence (finality). This view then introduces a dual dependence of a given physical phenomenon both on the past and on the future so leading to a "global" concept of being. This supposed duality is based on the mathematical structures of the D'Alambert operator in the quantum-relativistic equations of motion that predicts the existence of waves moving backward in time from a source in the future. A similar idea was proposed by Feynman and Wheeler within the so-called "absorber-emitter" theory (AET) [8] according to which they assumed the solution of the Maxwell's equations to be invariant under time-reversal transformation, as are the field equations themselves, so avoiding any time-reversal symmetry breaking, that would appear just as an ad hoc assumption to select a preferential time direction that introduces a distinction between past and future.

Basing on a very similar concept, in 1986, G. Cramer [9] first proposed the so-called "transactional interpretation of quantum mechanics" (TIQM) in which any quantum interaction is described in terms of standing waves arising from the superposition between a retarded wave (propagating forward in time) and an advanced wave (propagating backward in time).

In this paper, without entering into the details of AET and TIQM and of their relationship with the theory of QED coherence in matter, that will be studied in forthcoming publications, we'll show how the occurrence and the features of some syntropic phenomena can be interpreted within the QED coherence framework, so giving a QFT support to this view especially with reference to the dynamics of macroscopic and complex quantum systems, as living organisms, characterized by stability, self-organization and spontaneous emerging of order at macroscopic level.

2. An overview of QED coherence in matter

According to the theory of QED coherence in matter (CQED) [4], under specific conditions on density and temperature, a condensed matter system experiences a spontaneous quantum phase transition to a new state in which a non-vanishing classic-like electromagnetic field, spontaneously generated, oscillates in tune with the matter system between its ground state and an excited state.

The stationary (long-time) dynamics of the system selects a couple of levels, involved in the transition itself, characterized by an energy difference given by

$$E = \hbar\omega_0 = \frac{hc}{\lambda} \tag{6}$$

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where λ is the wavelength of e.m. field, c the speed of light in vacuum and $\hbar = h/2\pi$ (from this point on we adopt the "natural units" $\hbar = c = 1$).

The system spontaneously evolves towards a more stable state (characterized by lower energy) in which all the matter components are phase correlated and oscillate in tune with an electromagnetic field confined within a defined spatial domain, called "Coherence Domain" (CD), whose dimension is given by the wavelength of the tuning electromagnetic field given by eq. (6). We then consider, for simplicity, a two-levels quantum system respectively described by the two wavefunctions $\psi_1(\vec{x}, t)$ and $\psi_2(\vec{x}, t)$ obeying the normalization condition

$$|\psi_1|^2 + |\psi_2|^2 = 1 \tag{7}$$

interacting with an electromagnetic field associated to a scalar field $A(\vec{x}, t)$. within a spatial region of size λ given by eq. (6). By introducing the adimensional time $\tau = \omega_0 t$, we can write the Eulero – Lagrange equations describing the evolution fo the system as [4]

$$\begin{array}{c} i\frac{\partial}{\partial\tau}\psi_1(\tau) = gA^*(\tau)\psi_2(\tau) \\ i\frac{\partial}{\partial\tau}\psi_2(\tau) = gA(\tau)\psi_1(\tau) \\ -\frac{1}{2}\ddot{A}(\tau) + i\dot{A}(\tau) - \mu A(\tau) = g\psi_1^*(\tau)\psi_2(\tau) \end{array} \tag{8}$$

where

$$g \equiv 2\pi(\omega_p/\omega_0) f_{01}^{\frac{1}{2}} \tag{9}$$

$$\omega_p = (e/\sqrt{m_e})(N/V)^{1/2} \tag{10}$$

m_e is the electron mass, f_{01} is the oscillator strength for the electronic transition from the ground state ψ_1 to the excited state ψ_2 and μ is the photon "mass" term [4]. The solution of the system (8) when $\tau \simeq 0$, with the initial conditions

$$A(0) \sim 0,\ \psi_1(0) \sim 1,\ \psi_2(0) \sim 0 \tag{11}$$

can be obtained by differentiating the third of eq. (8) and substituting it into the second one

$$-\frac{1}{2}\frac{\partial^3}{\partial\tau^3}A + \frac{\partial^2}{\partial\tau^2}A + i\mu\frac{\partial}{\partial\tau}A + gA^2 = 0 \tag{12}$$

We are searching for solutions in the form

$$A = \exp(ip\tau) \tag{13}$$

that, inserted in eq. (12), gives the equation

$$\frac{p^3}{2} - p^2 - \mu p + g^2 = 0 \tag{14}$$

There is a value

$$g_{crit} = \left[\frac{8}{27} + \frac{2}{3}\mu + \left(\frac{4}{9} + \frac{2}{3}\mu\right)^{3/2}\right]^{1/2} \tag{15}$$

such that, when $g < g_{crit}$, equation (14) has three real solutions and the system performs periodic oscillations characterized by the amplitudes given by (11). When $g > g_{crit}$, eq. (14) has two complex conjugate solutions, apart one real root. The field A shows then a "runaway" solution of the type

$$A = \exp\left[\mathrm{Im}\left(p\right)\tau\right] \tag{16}$$

where p is the complex solution of eq.(14) for which $\mathrm{Im}\left(p\right) > 0$. This solution shows an exponentially increasing amplitude towards a non-vanishing value that implies an analogous increase of the matter field amplitude ψ_2. The system is then characterized, after a very short time [4], by a limit cycle defined by the fields ($0 < \gamma < \pi/2$)

$$\begin{array}{c} \psi_1\left(\tau\right) = \cos\gamma \exp\left[i\theta_1\left(\tau\right)\right] \\ \psi_2\left(\tau\right) = \sin\gamma \exp\left[i\theta_2\left(\tau\right)\right] \\ A\left(\tau\right) = A_0 \exp\left[i\varphi\left(\tau\right)\right] \end{array} \tag{17}$$

subject to the **phase-locking** constrain [2-4]

$$\frac{\partial\varphi}{\partial\tau} = \frac{\partial\theta_1}{\partial\tau} - \frac{\partial\theta_2}{\partial\tau} \tag{18}$$

Equations (17) and (18) describe the new state of the system, called "coherent ground state" (CGS), in which the matter and e.m. fields, oscillating in phase, assume non-vanishing stable amplitudes.

3. Phase transition toward coherent state as a spontaneous symmetry breaking and the case of water

The phase transition from PGS to CGS and the arising of coherent behavior can be also considered as the dynamical response of the system to the spontaneous breaking of global gauge invariance in order to recover the local gauge invariance needed to ensure the stability of the system on a macroscopic scale. To be more specific, we see that the initial state of the system can be an arbitrary symmetric and disordered state with arbitrary initial conditions only constrained by general physical principles as conservation of the constants of motions (as, for example, particle number and momentum, etc.). According to the field equations, giving rise to the equations of motion (8), the system then spontaneously undergoes a dynamical evolution towards the "true" ground state (the CGS) where $\left|\psi_{1,2}\left(t\right)\right|^2 \neq 0$ and the e.m. field amplitude $\left|A\left(t\right)\right|^2$ departs from its initial zero value according to equations (17).

The system then evolves, through a quantum phase transition (actually a succession of phase transitions), from the asymmetric vacuum (the PGS) in which $\left|A\left(t\right)\right|^2 \sim 0$ to the asymmetric vacuum (CGS) in which $\left|A\left(t\right)\right|^2 \neq 0$ (and the physical parameter of the system are fixed by dynamics) and the local phase symmetry is dynamically broken in the coherent state. In this process the phase locking condition (18), implied by the coherent regime, has just the "aim" to recover the needed gauge invariance of the theory. In fact, from a physical viewpoint, the introduction of the gauge field A_μ in eqs. (2) and (3) is needed to compensate the change of the phase of the matter field in eq. (1).

For this reason, any change in time in the phase of the fields $\psi_{1,2}$, or better in their difference, must be exactly compensated by the introduction of the suitable gauge field, namely by a corresponding change in the phase of e.m. field able to generate such a e.m. field, because of the relation (in the case of a pure gauge field) [2-4]

$$A_\mu = \partial_\mu\varphi \tag{19}$$

and this is just what the coherent dynamics does through the mechanism of phase-locking.

According to the coherent dynamics, the phase agreement between matter and co-resonating e.m. field define a new macroscopic quantum state (corresponding to a high number N of elementary components) characterized by a well-defined value of phase $\Theta\left(\vec{x}, t\right)$ which defines the rhythm of oscillation of whole the system according to eq. (5). From a quantum viewpoint this means the state vector of the system to be an eigenstate of a suitable quantum phase operator [5, 11].

The transition from the uncoherent state to the coherent one is associated to the arising of an energy gap per molecule $\Delta E/N < 0$ (whose value depends on the energy levels involved in the coherent oscillations) that makes it more stable with respect the uncoherent state.

If the system temperatures is different than $T = 0$, thermal collisions are able to transfer to molecules an energy sufficiently high to push them out of tune. So, if we define the coherent fraction $F_c\,(T)$ and the non - coherent fraction $F_{nc}\,(T)$, respectively as the average fractions of the total atoms / molecules belonging, at a given temperature, to the coherent and non - coherent phases, the following relation holds:

$$F_c\,(T) + F_{nc}\,(T) = 1 \tag{20}$$

The QED coherent dynamics of water is particularly significant even because water is the fundamental constituent of living systems in which self-organization, long-range order and stability represent essential features.

If coherent water is close to a surface, as always occurs in living systems, the effect of thermal collisions is counteracted by the attraction of the water molecules to the wall [12,13]. The coherent fraction of water is then stabilized to a value close to the unity so that water can be considered as fully coherent even at room temperature.

4. Information stored in a QED coherent system

The quantum phase transition from perturbative symmetrical ground state (PGS) to the ordered coherent ground state (CGS) leads to an energy release towards the environment, due to achieve the energy gap per elementary components needed to ensure the stability of the CGS. The process then appears as a "condensation" of the initial quantum state in the new coherent one. On the other hand, it also is characterized by a decrease of the entropy of the system since the final state is an ordered coherent state, in which all the elementary quantum components oscillate in phase among them and with the e.m. field and are described by the same macroscopic wavefunction given by eq. (5).

In order to roughly estimate the amount of information stored in the coherent state of the system, we remember the information can be defined as [14]

$$I = K \ln\left(\frac{P_0}{P_1}\right) \tag{21}$$

where P_0 is the number of possibilities for the system in the initial state characterized by $I_0 = 0$ (no information), P_1 ($P_1 < P_0$) the number of possibilities in the finale state characterized by $I_1 > 0$, given by eq. (21), and K is a constant that, in thermodynamical units, is equal to Boltzmann constant k_B. In order to apply eq. (21) we'll consider the so-called "bound information", namely the information associated to the system when we consider the number of possible cases as the complexions of the physical systems. By assuming that the change in entropy is fully converted into information, we can estimate the maximum information that can be stored in a coherent system, due to the phase transition from PGS to CGS, as

$$-\Delta S = (k_B \ln 2)\, I \tag{22}$$

where $\Delta S = S_1 - S_0$ is the change of entropy due to the phase transition and I is the corresponding information in bits. The entropy variation ΔS associated to the phase transition can be evaluated by considering the transformation to be isothermal (we can assume the system to be in contact with a thermal bath), and then we have

$$\Delta S = \frac{\Delta Q}{T} \simeq \left(\frac{\Delta E}{\Delta N}\right)_{coh} \frac{N_{coh}\,(T)}{T} \tag{23}$$

where ΔQ is the (latent) heat exchanged by the system with the environment during transition, T the absolute temperature, $(\Delta E/\Delta N)_{coh}$ the energy gap per particle (atom/molecule) carachterizing the CGS, N_{coh} is the overall number of particles in the coherent state. By introducing the coherent fraction of particles F_{coh} we can rewrite eq. (23) as

$$\Delta S \simeq \left(\frac{\Delta E}{\Delta N}\right)_{coh} \frac{F_{coh}\,(T)\,N}{T} \tag{24}$$

The use of eq. (22) in eq. (24) allows to calculate the information in bits as

$$I = -\left(\frac{\Delta E}{\Delta N}\right)_{coh} \frac{F_{coh}\,(T)\,N}{\ln 2 k_B T} \tag{25}$$

In the case of a single water CD at room temperature [5] ($T = 293.15\ K$), by assuming $(\Delta E/N \simeq -0.26\ eV)_{coh}$, $N \simeq 2 \cdot 10^5$, $N \simeq 2 \cdot 10^5$ and $F_{coh} \sim 0.4$ we obtain, for water

$$I_{CD} \simeq 1.2 \cdot 10^6\ bits \tag{26}$$

In the case of interfacial water, as always is the case inside living organisms, we can assume $F_{coh} \sim 1$ and $I_{CD} \simeq 3 \cdot 10^6 bits$, namely a noticeable quantity of information per single CD.

We see from eq. (25) that the quantity of information storable by the system increases with the level of coherence of the system as well as with the number of particles participating in the common coherent oscillations. It is interesting to recall, as already shown in a previous works [15,16], the possibility for the excited coherent domains of water to interact each other through the exchange of evanescent photons due to quantum tunneling effect.

Such interaction between CDs could give rise, under suitable conditions, to a synchronized oscillation between CDS at higher space-time scales, named "supercoherence" (i.e. a coherence between coherent domains), able to further increase the coherence level of the overall systems composed by the oscillating CDs and, consequently, the energy gap characterizing it so giving to such systems, composed by many water coherent domains (to which living systems can be assimilated) the possibility to "memorize" high quantities of low entropy information.

In summary water CDs act as negentropic "devices" able to collect high entropy energy contributions from the environment and convert them into the energy of a single macroscopic low entropy coherent state. The use of water coherent CDs as a physical substrate for quantum (hyper)computation [16,17] and information storage [18] has been already studied in previous publications. In particular it has been shown that such information can be stored in the quantum phase associated to the macroscopic wavefuntion describing a CD as a whole that can be retrieved by exploiting, for example, the electric version of the Aharonov-Bohm effect and/or Josephson effect [18].

5. Conclusions and outlook

The theory of QED coherence in matter predicts that in condensed matter, when suitable conditions about temperature and density are met, a quantum phase transition occurs from a symmetric perturbative ground state (PGS), in which all the elementary components of the system perform uncorrelated zero-point oscillations, towards a new ordered macroscopic quantum state, the coherent ground state (CGS), in which the elementary components oscillate in tune with a permanent non-vanishing e.m. field within spatially defined domains called "coherent domains". Such coherent state is described by a macroscopic wavefunction and characterized by an energy gap per particle able to make it stable with respect the quantum fluctuations of matter and e.m. fields with respect to the PGS.

The arising of such coherent behavior and, in particular, the related phase-locking between matter and e.m. quantum fields can be also interpreted as the dynamical response of the system to the spontaneous symmetry breakdown of PGS needed to restore the local gauge invariance of the theory, so appearing like a "finalistic" phenomenon.

The quantum phase transition towards CGS is accompanied by a decrease of entropy during the formation of each coherent domain, so that the CGS turns out to be "informed" by the quantum phase transition.

In the particular case of water, coherent domains are characterized by an excited energy spectrum allowing them to interact each other and perform, in turn, tune oscillations giving rise to a coherence between coherent domains realizing a nested arrangement of coherent domains at different scales.

In summary, the above dynamics spontaneously leads to the formation of macroscopic, self-organizing and stable structures capable to store a potentially high quantity of information. All these features look extraordinarily consistent with those predicted by L. Fantappiè in his "Principi di una teoria unitaria del mondo fisico e biologico" as regards as the existence of syntropic phenomena, dual with respect to the entropic ones, marked by spontaneous occurrence, decreasing entropy, order and information at macroscopic scales as happens, in particular, in the case of the living systems. These results also put some of the most interesting and intriguing prediction of the Fantappié - Arcidiacono theory on a firm theoretical ground, based on QFT.

Obviously, although in a preliminary stage, our results open the door to the formulation of a novel unitary theory of the Universe (including physical as well as biologic phenomena), based on the occurrence of coherent dynamics at different space-time scales from micro to macro cosmos, in which a key role is played by the concept of quantum information stored in the coherent domains and its "manipulation" throught the interaction between them.

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