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PLASMA BRAIN DYNAMICS (PBD): II. QUANTUM EFFECTS ON CONSCIOUSNESS[1]

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ABSTRACT: This article studies the quantum effect of the brain neuronal system on both normal and abnormal conscious states. It develops Plasma Brain Dynamics (PBD) to obtain a set of kinetic quantum-plasma Wigner-Poisson equations. The model is established under typical electrostatic and collision-free conditions in both the absence and presence of an external magnetic field. The quantum perturbation is solved analytically by employing a backward-mapping approach to the motion of electrons. Results expose that the quantum perturbation turns out to be zero at normal conscious states; but no more than 11% of the classical perturbation under assumed abnormal situations like a sudden head trauma, mood disorder, etc. The introduction of the magnetic field does not influence the results.

KEYWORDS: Plasma brain dynamics (PBD); Quantum effect; Wigner-Poisson equation

1. INTRODUCTION

In the mid-1960s, Ricciardi & Umezawa first suggested the Quantum Brain Dynamics (QBD).[2] The model has been developed over the last half century, and significant progress has been made in recent years to account for the neuro-and-cognitive

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[2] Ricciardi LM, Umezawa H 1967. Brain and physics of many-body problems. Kybernetik, 4, 2, pp.44-48.

mechanism of human consciousness,[3] a process dominated by the prefrontal cortex in the brain neuronal system to express the brain cognitive ability.[4] Among the achievements stand Penrose's neural "firing and not firing" model[5] and Penrose-Sameroff's neural "microtubule" one.[6] Nevertheless, studies on the neural de-coherence rates indicated that the consciousness should be thought of as a "classical rather than quantum" neural process, both for regular neuron firing and for kink-like polarization excitations in brain microtubules.[7] Consequently, the QBD paradigm have met serious challenges to provide not only convincing physical mechanisms but also qualitative or quantitative data-fit visualizations of holistic neuronal behaviours, particularly after the neuronal activities were found to adhere to long-range extracellular flows,[8] and the collective behaviour of the neuronal network to comply with stochastic movements.[9]

New advances in brain studies exhibit that the axonal actions of the neuronal system are similar to the scaled equivalents of plasma lightning,[10] while the cerebral cortex and its white matter system of the cortico-cortical fibres turn out to be a system somewhat analogous to the earth's ionospheric shell.[11] The research trend inspired us to develop an alternative model, namely, Plasma Brain Dynamics (PBD) which was proposed in the

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[3] E.g., (1) Başar E 2010. From quantum mechanics to the quantum brain. NeuroQuantology, 8, 3, pp.319-321. (2) Vitiello G 2011. Hiroomi Umezawa and quantum field theory. NeuroQuantology, 9, 3, pp.402-412. (3) Hameroff S 2012. How quantum brain biology can rescue conscious free will. Front Integr Neurosci. 6, 93, pp.1-17. (4) Sakane S, Hiramatsu T, Matsui T 2016. Neural network for quantum brain dynamics: 4D CP1+U(1) gauge theory on lattice and its phase structure. arXiv:1610.05443v1 [cond-mat.dis-nn].

[4] Gabi M, Neves K, Masseron C, et al 2016. No relative expansion of the number of prefrontal neurons in primate and human evolution. PNAS, 113, 34, 9617-9622.

[5] Penrose R 1989. The emperor's new mind: concerning computers, minds and the laws of physics. Oxford: Oxford University Press.

[6] Hameroff S, Penrose R 2003. Conscious events as orchestrated space-time selections. NeuroQuant. 1, pp.10-35.

[7] Tegmark M 2000. Importance of quantum de-coherence in brain processes. Phys Rev E 61, 4 Pt B, pp.4194-4206.

[8] (1) Linkenkaer-Hansen K, Nikouline VV, Palva JM, Ilmoniemi RJ 2001. Long-range temporal correlations and scaling behavior in human brain oscillations. J Neurosci, 21, 4, pp.1370-1377. (2) Vuksanovic V, Hövel P 2014. Functional connectivity of distant cortical regions: Role of remote synchronization and symmetry in interactions. NeuroImage, 97, pp.1-8.

[9] Touboul J 2012. Mean-field equations for stochastic firing-rate neural fields with delays: Derivation and noise-induced transitions. Phys D: Nonlin Phenomena, 241, 15, pp.1223-1244.

[10] Persinger MA 2012. Brain electromagnetic activity and lightning: potentially congruent scale-invariant quantitative properties. Front Integr Neurosci, 6, 19, pp.1-7.

[11] Kozlowski M, Marciak-Kozlowska J 2012. On the Temperature and Energy of the Brain Waves: Is there Any Connection with Early Universe? NeuroQuantology, 10, 3, pp.443-452.

early 1970s[12] to deal with the collective features of the brain consciousness. Our work set up a set of two-fluid, collision-free Vlasov-Maxwell equations to obtain self-similar differential equations which were used to simulate the excitation and propagation of nonlinear brain EEG waves.[13] Results show that the waves can be classified into two groups: Group-1, complex stormlike waves (α, β, and γ); Group-2, simple quasilinear waves (θ and δ). Group-1 packets are composed of three ingredients: high-frequency ion-acoustic (IA) mode, intermediate-frequency lower-hybrid (LH) mode, and, low-frequency ion-cyclotron (IC) mode; by contrast, Group-2 waveforms fall within the IA band, featured by one or a combination of the three envelopes: sinusoidal, sawtooth, and spiky/bipolar.

Though the PBD paradigm offered a more effective tool than the QBD one to expose the excitation and propagation of measurable brain waves, we notice that the human consciousness resides mainly in the outer layer of the cerebrum, cerebral cortex, with a thickness of $(2\sim5)\times10^{-3}$ m and a surface area of $0.16\sim0.4$ m^2,[14] giving a volume of $(3.2\sim20)\times10^{-4}$ m^3. Because the adult male human brain of an average of 1.5 kg has 86 billion neurons (nerve cells) and 85 billion non-neuronal cells,[15] the average volume density of neurons turns out to be in the order of 10^{14} neurons/m^3.[16] These neurons are interconnected with each other with each neuron to link with up to 10^4 other neurons, forming a highly intricate system to pass signals via as many as 1000 trillion synaptic connections.[17] What is more, in both the intracellular and extracellular spaces, the concentration of negative ions (124.0 mM) is far less than that of positive ones (317.5 mM), giving the charge number densities of $n_+ \approx 1.9\times10^{26}$ m^{-3}, and $n_- \approx 39\%\ n_+$,[18] with $n_+ \sim 1/1000$ of the molecular number density of water or the free electron density in copper, while the excess positive charges are balanced by the abundant electrons coming from the macromolecules such as nucleic acids and proteins in the brain to keep the brain

[12] Hokkyo N 1972. A plasma model of brain dynamics. Prog. Theoret. Phys., 48, 4, pp.1191-1195.
[13] Ma J 2017. Plasma Brain Dynamics (PBD): A Mechanism for EEG Waves Under Human Consciousness. Cosmos & History, 13, 2, pp. 185-203.
[14] Nunez PL, Srinivasan R. 2006. Electric fields of the brain: The neurophysics of EEG, 2nd ed. Oxford: Oxford University Press, p.6.
[15] Herculano-Houzel S. (1) 2009. The human brain in numbers: A linearly scaled-up primate brain. Front. Human Neurosci. 3, 31, pp.1-11; (2) 2016. The human advantage: A new understanding of how our brain became remarkable. Cambridge, MA: MIT Press, p.79.
[16] Teplan M 2002. Fundamentals of EEG measurement. Measurement Sci. Rev. 2, 2, pp.1-11.
[17] Mastin L 2010. Neurons & synapses. In: The human memory. http://www.human-memory.net/ brain_ neurons.html
[18] Phillips R, Kondev J, Theriot J 2013. Physical biology of the cell. 2nd Ed. Chapter 17: Biological electricity and the Hodgkin-Huxley model. New York: Garland Science. Table 17.1. p.685.

electrically neutral.[19]

Such a high charge density in the order of 10^{26} m^{-3} makes the brain plasma distinguishable from the classical low-density fusion or space plasmas which are characterized by the regimes in which the quantum effect can be totally negligible. It may be more appropriately defined as a new kind of so-called "quantum plasma" in which there coexists both the plasma and quantum effects, a state dwelled by some physical or astrophysical processes happening in, for example, the metallic nanostructure-arenas, semiconductors, or white dwarf stars.[20] Such a non-classical system should not still be treated by employing the Vlasov-Maxwell equations. In this case, the Wigner-Poisson or Wigner-Maxwell equations come to the stage by incorporating the quantum term into account in the Vlasov equations under electrostatic or electromagnetic conditions, respectively. This term may exert an ineligible impact on the plasma system if any or both of the following conditions of the two dimension-free parameters, χ_1 and χ_2, are satisfied:[21]

$$\chi_1 = \frac{4}{3}\pi(n_0\lambda_B^3) \geq 1; \;\; \chi_2 = \frac{T_F}{T_0} = \left(\frac{3}{8\pi}n_0\lambda_B^3\right)^{\frac{2}{3}} = 0.09\chi_1^{2/3} \geq 1 \qquad (1)$$

in which χ_1 and χ_2 are the two dimension-free parameters; $n_0 = n_+ \approx n_-$ is the mean-field plasma density; $\lambda_B = h/(m_e v_{Te})$ is the electron thermal de Broglie wavelength in which $h = 6.63 \times 10^{-34}$ J·s is the Planck's constant, $m_e = 9.11 \times 10^{-31}$kg, v_{Te} is the most-probable speed of the thermal-equilibrium electrons which follow the Maxwell-Boltzmann distribution, satisfying $\frac{1}{2}m_e v_{Te}^2 = k_B T_e$ where $k_B = 1.38 \times 10^{-23}$ J/K is the Boltzmann constant and T_e is the electron temperature; T_F is the Fermi temperature; and T_0 is the plasma thermal temperature with $T_0 \approx T_e$ for a locally thermodynamical quasi-equilibrium plasma system. For typical parameters of $n \sim 10^{26}$ m^{-3} and $T_0 \sim 300$ K, we obtain $\lambda_B = 7.28$ nm, $v_{Te} = 100$ km/s, $n_0\lambda_B^3 = 38.55$, and $\chi_1 = 161.46 > 1$, $\chi_2 = 2.77 > 1$. As a result, the brain plasma is non-classical and may be influenced by the quantum effect, if there are no additional factors to mitigate or cancel the effect.

Albeit the fact mentioned above, our data-fitting EEG simulations were carried out within the reliable classical regime where the quantum interference was not encountered by the plasma brain dynamics. We therefore postulated that the quantum effect appeared not playing a significant role in brain consciousness. This means that there might exist

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[19] C.f., Jibu M, Yasue K 1995. Quantum brain dynamics and consciousness: an introduction. Amsterdam: John Benjamins Publishing. p.685.

[20] Manfredi G 2005. How to model quantum plasmas. Fields Inst. Commun., 46, pp.263-287.

[21] Ibid.

some kind of mechanism which acts against the quantum uncertainty and damps out or neutralizes the quantum effect. This paper focuses on investigating the role played by the quantum term in the brain consciousness by generalizing PBD's Vlasov-Maxwell equations with the extra quantum term, thus forming the Wigner-Maxwell equations. Its purpose is to give a clear answer to the dilemma of whether the quantum effect has an impact on the mental activities of the human brain.

The layout of the paper is as follows: Section 2 introduces the quantum plasma model. A set of electrostatic Wigner-Poisson equations are given in the absence of an external magnetic field, B_0, where an additional quantum term comes into being relative to the classical Vlasov-Maxwell equations under electrostatic conditions. Section 3 solves the Wigner-Poisson equations by applying the linearization approach. The perturbation of the quantum term is obtained to show the quantum effect on the unperturbed mean-field property, and the results are extrapolated to a generalized case in the presence of B_0. Section 4 gives the conclusions of the study. SI units are used throughout the paper.

2. QUANTUM PLASMA: WIGNER-POISSON EQUATIONS

In classical plasmas at the sites of, such as, fusion, ionosphere or stars, constituent particles obey classical laws of physics, and it is unnecessary to consider their quantum nature. However, as the density increases or the temperature decreases to such a degree that the interparticle distance becomes comparable to the thermal de Broglie wavelength, the quantum effect starts to affect the properties and dynamics of the classical plasmas which are now known as quantum plasmas. With following assumptions, [22]

(1) an ideal plasma;
(2) particle interaction via the classical electrodynamics only;
(3) collision-free;
(4) non-relativistic; and,
(5) spin-free,

the quantum plasmas can be described by either Wigner-Poisson or Wigner-Maxwell equations under the self-consistent collective electrostatic or electromagnetic conditions, respectively. To reduce the complexity of solving the problem while still being able to develop a tenable approach, we consider the simpler electrostatic case in the present study, and take it for granted that the plasma consists of only electrons of mass m_e, charge $-e$, and density $n_e = n_-$, and one-species positively charged ions of mass m_i, charge $+e$,

[22] (1) Tyshetskiy YO, Vladimirov SV, Kompaneets R 2013. Unusual physics of quantum plasmas. ISSN 1562-6016, 1-83/19, pp.76-80. (2) Vladimirov SV, Tyshetskiy YO, 2011. On description of a collisionless quantum plasma. Physics-Uspekhi, 54, 12, pp.1243-1256.

and density $n_i = n_+ = n_0$, while ions are immobile but constitute the neutralizing background for the active electrons. In addition, as done in the previous work,[12] we suggest that all the test particles of the brain quantum plasma under modeling are well inside the extracellular space thereby being able to neglect all the edge effects.

Under the above simplifications, the set of kinetic Wigner-Poisson equations for electrons is as follows in the absence of an external magnetic field, B_0:[23]

$$\begin{cases} \dfrac{Df}{Dt} = \dfrac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f + \dfrac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} \cdot \nabla_{\mathbf{v}} f = \dfrac{e\hbar^2}{24m_e^3} \nabla^3 \varphi \cdot \nabla_{\mathbf{v}}^3 f \\ \nabla^2 \varphi = \dfrac{e}{\varepsilon_0} \left(\displaystyle\int f \mathrm{d}\mathbf{v} - n_0 \right) \end{cases} \quad (2)$$

where the upper and the lower equations are the Wigner and Poission ones, respectively, while f is the distribution function, t is time, $\mathbf{v}$ is electron velocity, φ is the self-consistent electrostatic potential, $\hbar = h/(2\pi)$ is the Dirac constant, and $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m is the permittivity of free space. Relative to the classical Vlasov-Maxwell equations under electrostatic conditions, this set of equations includes an additional quantum term. Note that the acceleration term, $\mathrm{d}\mathbf{v}/\mathrm{d}t$, is equivalent to $e\nabla\varphi/m_e$ in the absence of an external magnetic field. Adopting a slab model with the only spatial variable, x, reduces Eq.(2) to the following, where v is the electron speed along x:

$$\begin{cases} \dfrac{Df}{Dt} = \dfrac{\partial f}{\partial t} + v\dfrac{\partial f}{\partial x} + \dfrac{e}{m_e}\dfrac{\partial \varphi}{\partial x}\dfrac{\partial f}{\partial v} = \dfrac{e\hbar^2}{24m_e^3}\dfrac{\partial^3 \varphi}{\partial x^3}\dfrac{\partial^3 f}{\partial v^3} \\ \dfrac{\partial^2 \varphi}{\partial x^2} = \dfrac{e}{\varepsilon_0}\left(\displaystyle\int f \mathrm{d}v - n_0 \right) \rightarrow \dfrac{\partial^3 \varphi}{\partial x^3} = \dfrac{e}{\varepsilon_0}\dfrac{\partial n_e}{\partial x} \end{cases} \quad (3)$$

In the above, substituting the 3rd-order partial derivative of φ in the RHS term of the upper equation with the RHS term of the lower equation yields

$$\frac{Df}{Dt} = \frac{\hbar^2}{24m_e^2}\frac{\partial \omega_{pe}^2}{\partial x}\frac{\partial^3 f}{\partial v^3} \xrightarrow{\text{mean-field: uniform } \omega_{pe}} f_0 = \frac{n_0}{\sqrt{\pi} v_{Te}} e^{-v_0^2/v_{Te}^2} \quad (4)$$

in which $\omega_{pe} = \sqrt{n_e e^2/(\varepsilon_0 m_e)}$ is the electron plasma angular frequency the mean-field value of which is spatially uniform to give a mean-field thermal-equilibrium

[23] Shukla PK, Eliasson B 2010. Nonlinear aspects of quantum plasma physics. Physics-Uspekhi, 53, 1, pp.51-76.

Maxwell–Boltzmann distribution,f_0; it is 5.66×10^{14} rad/s for a typical value of $n_e \sim 10^{26}$ m^{-3}. The electron plasma frequency, f_{pe}, and electron quantum energy, E_{qe}, can be given as $f_{pe} = \omega_{pe}/(2\pi) = 9 \times 10^{13}$ Hz, and $E_{qe} = \hbar\omega_{pe} = 6 \times 10^{-20}$ J, respectively. Here, E_{qe} is a newly introduced parameter to evaluate the order of the electron quantum energy relative to the electron thermal energy, $E_{te} = k_B T_e$, which turns out be $E_{te} = 0.41 \times 10^{-20}$ J for a typical value of $T_0 \sim 300$ K. Clearly, the ratio, η, of the two energies is $\eta = E_{qe}/E_{te} \sim 15$. Besides, the electron thermal potential, $\varphi_e = E_{te}/e$, is 26 mV, and the electron Debye length, $\lambda_e = \sqrt{\varepsilon_0 E_{te}/(n_e e^2)}$, is 1.2 Å (the same order of the radii of isolated neutral atoms; note that the classical electron radius is $\sim 10^{-5}$ Å). Note that there exists a relation that $v_{Te} = 2\sqrt{2\pi}\, f_{pe}\lambda_e$.

This equation is a semi-classical quantum Vlasov equation. However, unlike the classical case that $Df/Dt \neq 0$ owing to the RHS quantum $\hbar$-term in Eq.(4), the distribution function f is not preserved, except for linear electric fields that leads to a vanishing $\hbar$-term due to $\partial^3\varphi/\partial x^3 = 0$, along with the classical characteristic equations of the electrons:

$$\frac{\mathrm{d}x}{\mathrm{d}t} = v \text{ and } \frac{\mathrm{d}v}{\mathrm{d}t} = \frac{e}{m_e}\frac{\partial\varphi}{\partial x} \quad \rightarrow \quad \frac{1}{2}m_e v_0^2 = \frac{1}{2}m_e v^2 - e\varphi \tag{5}$$

Using $1/f_{pe}$, λ_e, v_{Te}, n_0 and φ_e as the units of t, x, v, n_e and φ, respectively, in Eq.(4) produces a dimension-free Wigner-Poisson equation as follows, in which $\alpha = \sqrt{2}\pi\eta^2/48$ is a quantum coefficient:

$$\frac{Df}{Dt} = \frac{\partial f}{\partial t} + 2\sqrt{2}\pi\, v\frac{\partial f}{\partial x} + \sqrt{2}\pi\, \frac{\partial\varphi}{\partial x}\frac{\partial f}{\partial v} = \alpha\, \frac{\partial^3\varphi}{\partial x^3}\frac{\partial^3 f}{\partial v^3}\left(= \alpha\frac{\partial n_e}{\partial x}\frac{\partial^3 f}{\partial v^3}\right) \tag{6}$$

Similarly, Eq.(5) becomes

$$v_0^2 = v^2 - \varphi \tag{7}$$

In Eq.(6), the contribution of the quantum effect depends not merely on α, but is determined by the product of α, the partial derivative of ω_{pe}^2 over x, and the the 3$^{\text{rd}}$-order partial derivative of f over v. That is, only $\mathcal{E}$ itself is unable to govern the contribution of the quantum effect on any brain system. More importantly, the presence of the quantum effect makes it impossible to take the too spiky Wigner functions as the solution of the distribution function, f, which would be against the uncertainty principle, $\int f^2 \mathrm{d}x\mathrm{d}v \leq m_e N_e^2/h$ (where N_e is the total electron number); instead, the solution should take the form of $f = f_0 + f_1$, where f_0 is the exact solution of Eq.(6) in the absence of the RHS quantum term; and, f_1 is the leading quantum correction.[24] Adopting the previously developed backward-mapping approach[25] to the motion of electrons which follow an initial Maxwellian function, together using Eq.(7), yields the mean-field f_0 as follows:

$$f_0 = \frac{n_0}{\sqrt{\pi}} e^{-v_0^2} = \frac{n_0}{\sqrt{\pi}} e^{\varphi - v^2} \rightarrow \frac{\partial f_0}{\partial v} = -2v f_0 \text{, and, } \frac{\partial^3 f_0}{\partial v^3} = 4v(3 - 2v^2) f_0 \quad (8)$$

3. MAGNITUDE OF QUANTUM PERTURBATION

3.1 In the absence of external magnetic field, B_0

In the electrostatic brain, the electric potential φ comes into being as a perturbation φ_1 of the mean-field state at which the electron characteristics of motion is determined by the integrated acceleration $\mathrm{d}v/\mathrm{d}t$. In the absence of an external magnetic field, B_0, replacing f with $f_0 + f_1$ and $\varphi = \varphi_1$ in the Wigner-Poisson equation, Eq.(6), offers the linearized semi-classical quantum Vlasov equation in which Eq.(5) is kept unchanged:

$$\frac{Df_1}{Dt} = \frac{\partial f_1}{\partial t} + 2\sqrt{2\pi}\, v \frac{\partial f_1}{\partial x} + \frac{\mathrm{d}v}{\mathrm{d}t}\frac{\partial f_1}{\partial v} = \alpha \, \frac{\partial^3 \varphi_1}{\partial x^3}\frac{\partial^3 f_0}{\partial v^3} - \sqrt{2\pi} \, \frac{\partial \varphi_1}{\partial x}\frac{\partial f_0}{\partial v} \quad (9)$$

In this equation, there are two RHS terms, one is quantum term, a product of the two 3rd-order derivatives of both φ and f_0; the other one is the classical term, a product of the two 1st-order derivatives of φ and f_0. Using the above estimated η value, the ratio of the two coefficients of the two terms is $\alpha/(\sqrt{2\pi}) = \eta^2/48 = 4.69$. Clearly, it is the competition between the quantum and the classical terms which determines the contribution of the quantum effect.

Using the Fourier transform in time and space and expressing any perturbations to vary with $\sim e^{i(kx - \omega t)}$ where k and ω are the electrostatic wave number and angular frequency in units of λ_e^{-1} and f_{pe}, respectively, we have the dimension-free potential perturbation as follows:

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[24] Haas F 2011. An introduction to quantum plasmas. Brazilian Journal of Physics, 41, 4–6, pp.349–363.

[25] Ma J, St.-Maurice JP 2015. Backward mapping solutions of the Boltzmann equation in cylindrically symmetric, uniformly charged auroral ionosphere. Astrophys. Space Sci., 357: 104, 10.1007/s10509-015-2331-6.

$$\varphi_1(x,t) = \varphi_{10}e^{i(kx-\omega t)} \ \rightarrow \frac{\partial\varphi_1}{\partial x} = ik\varphi_1, \text{and,} \frac{\partial^3\varphi_1}{\partial x^3} = -ik^3\varphi_1 \tag{10}$$

Here, φ_{10} is the dimension-free amplitude of the potential normalized by the electron thermal potential, φ_e.

Integrating Eq.(9) gives

$$f_1(x,v,t) = \int_{-\infty}^{t} \mathrm{d}t' \left[\alpha \frac{\partial^3\varphi_1}{\partial x^3}\frac{\partial^3 f_0}{\partial v^3} - \sqrt{2}\pi \frac{\partial\varphi_1}{\partial x}\frac{\partial f_0}{\partial v}\right]_{x=x(t'),v=v(t')} \tag{11}$$

By applying Eqs.(7,8,10) and considering the electron kinetic energy of the unperturbed orbits is a constant of motion for $\varphi_0 = 0$, Eq.(11) is

$$\frac{f_1}{f_0} = 2\varphi_{10}\left[\sqrt{2}\pi - 2\alpha k^2(3-2v^2)\right]\cdot I \tag{12}$$

where the derivation of I is obtained by reducing a generalized 3D case[26] to the present 1D case with

$$I = \int_{-\infty}^{t} ikv'e^{i(kx'-\omega t')}\mathrm{d}t' = e^{i(kx-\omega t)}\frac{kv}{kv-\omega} \tag{13}$$

Therefore, Eq.(12) becomes

$$\frac{f_1}{f_0} = \frac{2\left[\sqrt{2}\pi - 2\alpha k^2(3-2v^2)\right]}{1-\omega/(kv)}\varphi_1(x,t) \tag{14}$$

In the above, the ω-k relation is determined by the dispersion relation obtained from solving the electrostatic wave equations of electrons:[27]

$$\omega^2 = \omega_{pe}^2 + \frac{\gamma_e}{2}k^2v_{Te}^2 \ \rightarrow \ \omega^2 = 4\pi^2(1+\gamma_e k^2) \ \text{(dimension-free)} \tag{15}$$

[26] Bellan PM 2006. Fundamentals of Plasma Physics. Cambridge: Cambridge University Press. pp.266-270.

[27] E.g., Baumjohann W, Treumann RA 1997. Basic Space Plasma Physics. London: Imperial College Press, p.202.

where γ_e is the ratio of specific heats; here, $\gamma_e = 3$ because the density compressions are one-dimensional in *x* only. Eq.(15) is the dispersion relation of the Langmuir waves. It determines the dependence of the wave frequency on the wavenumber. Obviously, the electron thermal motion leads to a dispersion of the electron plasma oscillations by introducing the dependence of the wave frequency ω on wavenumber k. In general, k (equivalently, the wavelength) is not stable and able to vary in the range from zero to $1/\sqrt{\gamma_e} = 0.58$, resulting in a change in the frequency of the electron plasma waves, roughly speaking, between ω and $\sqrt{2}\omega$.

Using Eq.(15) in Eq.(14) gives

$$\frac{f_1}{f_0} = \frac{2kv\left[\sqrt{2}\pi - 2\alpha k^2(3 - 2v^2)\right]}{kv - 2\pi\sqrt{1 + \gamma_e k^2}}\varphi_1(x,t) \tag{16}$$

In this equation, the quantum effect is expressed by the α-term, and parameter v is the speed of the electrons which obey the Maxwell-Boltzmann distribution as given in Eq.(8). Although every electron is most likely to have the most-probable speed, v_{Te}, which is used for the unit of the speed in this paper, it is always in a random motion and can move at various speeds. Thus, the average speed of all the electrons equals zero since the distribution function, f_0, is symmetric to $v = 0$. However, all the electrons have kinetic energies, as expressed by the dimension-free v^2, which are determined by the internal thermal energy dependent of their temperature, T_e, irrelevant of the directions the speeds are in. The collective average kinetic energy of v^2, and the root-mean-square speed of v provided by this energy, are 3/2 and $\sqrt{3/2}$, respectively, for the given electron Maxwell-Boltzmann distribution of Eq.(8) at the normal brain states. Using $v = \sqrt{3/2}$ in Eq.(16) makes the quantum α-term become zero, that is, the quantum effect does not exist in brain activities in general cases where the brain thermal equilibrium is only disturbed by electrostatic perturbations under normal conscious conditions.

However, the brain temperature is not always stable but fluctuates within, say, a few degrees as measured in laboratory experiments, especially in situations like a sudden head trauma, stroke, headache, mood disorder, etc.[28] For a serious deviation of $\pm 5°C$ relative to $T_0 \sim 300$ K, the variation above and below $v^2 = 3/2$, Δv^2, is $\pm 1.67\%$. In this case, the ratio, *R*, of the quantum α-term to the classical perturbation for $k = 1/\sqrt{\gamma_e}$ is

$$R \leq \frac{2\alpha k^2(3 - 2\Delta v^2)}{\sqrt{2}\pi} = \pm 10.63\% \tag{17}$$

[28] Wang H, Wang B, Normoyle KP, et al. 2014. Brain temperature and its fundamental properties: a review for clinical neuroscientists. Frontiers in Neuroscience, 8, 307, pp.1-17.

Thus, in the absence of an external magnetic field, B_0, the quantum effect contributes no more than 11% of the classical electrostatic perturbation even in the unusual circumstances.

3.2 In the presence of external magnetic field, B_0

It is worth to see the influence of B_0 on the above results. Although B_0 may contributes to an extra acceleration in $\mathrm{d}\upsilon/\mathrm{d}t$ in Eq.(9) due to a possible Lorentz force, $-(e/m_e)\mathbf{v}\times\mathbf{B}_0$, it does not cause any gains or losses in electron energy but only changes the velocity direction. Neglecting non-electromagnetic components, Eq.(7) is still valid. However, both Eq.(9) and Eq.(5) are generalized in a 3D (x,y,z)-frame, respectively, where $\mathbf{B}_0$ is assumed along z:

$$\begin{cases}\dfrac{\mathrm{d}f_1}{\mathrm{d}t}=\dfrac{\partial f_1}{\partial t}+\mathbf{v}\cdot\nabla f_1+\dfrac{\mathrm{d}\mathbf{v}}{\mathrm{d}t}\cdot\nabla_\mathrm{v}f_1=-\dfrac{e}{m_e}\nabla\varphi_1\cdot\nabla_\mathrm{v}f_0+\dfrac{e\hbar^2}{24m_e^3}\nabla^3\varphi_1\cdot\nabla_\mathrm{v}^3f_0\\ \nabla^2\varphi_1=\dfrac{e}{\varepsilon_0}\displaystyle\int f_1\mathrm{d}\mathbf{v}\end{cases}\tag{18}$$

and

$$\frac{\mathrm{d}\mathbf{x}}{\mathrm{d}t}=\mathbf{v}\ \text{ and }\ \frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t}=-\frac{e}{m_e}\mathbf{v}\times\mathbf{B}_0\tag{19}$$

in which $\varphi_0=0$ is also considered. Define subscripts "$\perp$" and "$\parallel$" to denote the components perpendicular and parallel to $\mathbf{B}_0$, respectively. After adopting the backward-mapping technique again to express $\mathbf{v}=\{\mathbf{v}_\perp,\upsilon_\parallel\}$ (in which $\mathbf{v}_\perp=\{\upsilon_x,\upsilon_y\}$) and $\mathbf{x}=\{x,y,z\}$ at the initial state, t', by those at the final state, *t*, and, let $\Omega=eB_0/m_e$, we have

$$\mathbf{v}(t')=\begin{cases}\upsilon_x(t')=\upsilon_x\cos[\Omega(t'-t)]+\upsilon_y\sin[\Omega(t'-t)]\\ \upsilon_y(t')=-\upsilon_x\sin[\Omega(t'-t)]+\upsilon_y\cos[\Omega(t'-t)]\\ \upsilon_z(t')=\upsilon_z=Const.\end{cases}\tag{20}$$

and,

$$\mathbf{x}(t') = \mathbf{x}(t) + \frac{1}{\Omega} \times \begin{cases} x(t'-t) = \upsilon_x \sin[\Omega(t'-t)] - \upsilon_y\{\cos[\Omega(t'-t)] - 1\} \\ y(t'-t) = \upsilon_x\{\cos[\Omega(t'-t)] - 1\} + \upsilon_y \sin[\Omega(t'-t)] \\ z(t'-t) = \Omega\upsilon_z(t'-t) \end{cases} \quad (21)$$

Writing a 3D wavenumber $\mathbf{k} = \{\mathbf{k}_\perp, k_\parallel\}$. The generalized 3D expression of the perturbed potential is

$$\varphi_1(\mathbf{x},t) = \varphi_{10} e^{i(\mathbf{k}\cdot\mathbf{x}-\omega t)} \rightarrow \nabla\varphi_1 = i\mathbf{k}\varphi_1, \text{and}, \nabla^3\varphi_1 = -i\mathbf{k}^3\varphi_1 \quad (22)$$

which reduces to Eq.(10) in the 1D case. In addition, the generalized Eq.(11) is

$$f_1(\mathbf{x},\mathbf{v},t) = \int_{-\infty}^{t} \mathrm{d}t' \left[\alpha\, \nabla^3\varphi_1 \nabla_{\mathbf{v}}^3 f_0 - \sqrt{2}\pi\, \nabla\varphi_1 \nabla_{\mathbf{v}} f_0\right]_{\mathbf{x}=\mathbf{x}(t'),\mathbf{v}=\mathbf{v}(t')} \quad (23)$$

where f_0 in Eq.(8) is in a generalized 3D form:

$$f_0 = \frac{n_0}{\sqrt{\pi^3}} e^{-\mathbf{v}_0^2} = \frac{n_0}{\sqrt{\pi^3}} e^{\varphi-\mathbf{v}^2} \rightarrow \nabla_{\mathbf{v}} f_0 = -2\mathbf{v} f_0\,, \text{and}, \nabla_{\mathbf{v}}^3 f_0 = 4\mathbf{v}(3-2\mathbf{v}^2) f_0 \quad (24)$$

Finally, the *I*-integration in Eq.(13) has a generalized form given as[25]

$$I = \int_{-\infty}^{t} i\mathbf{k}\cdot\mathbf{v}(t') e^{i[\mathbf{k}\cdot\mathbf{x}(t')-\omega t']} \mathrm{d}t' = e^{i(\mathbf{k}\cdot\mathbf{x}-\omega t)} X \quad (25)$$

in which

$$X = 1 - e^{-\frac{ik_\perp \upsilon_\perp \sin\phi}{\Omega}} \sum_n \frac{\omega e^{in\phi} J_n\left(\frac{k_\perp \upsilon_\perp}{\Omega}\right)}{\omega - k_\parallel \upsilon_\parallel + n\Omega} \xrightarrow{B_0=0,n=0} X = \frac{k\upsilon}{k\upsilon - \omega} \quad (26)$$

where ϕ is the angle between $\mathbf{k}_\perp$ and $\mathbf{v}_\perp$; and J_n is the Bessel function. Thus, the generalized form of Eq.(14) is:

$$\frac{f_1}{f_0} = 2X \cdot \left[\sqrt{2}\pi - 2\alpha\mathbf{k}^2(3-2\mathbf{v}^2)\right]\varphi_1(\mathbf{x},t) \quad (27)$$

On the one hand, for $B_0 = 0$ and $n = 0$, Eq.(27) recovers the solution given by Eq.(14) after taking into account the reduced expression of X in Eq.(26). On the other hand, because $\Omega{\sim}8{,}800$ krad/s $\ll \omega{\sim}k_\perp v_\perp{\sim}k_\| v_\|$ of the order of $\omega_{pe}{\sim}10^{11}$krad/s, equivalent to $B_0 \to 0$ and $n = 0$, X in Eq.(26) approach to $[1-\omega/(kv)]^{-1}$. Thus,

$$\frac{f_1}{f_0} = \frac{2\left[\sqrt{2}\pi - 2\alpha\mathbf{k}^2(3-2\mathbf{v}^2)\right]}{1-\omega/(kv)}\varphi_1(\mathbf{x},t) \tag{28}$$

A comparison between Eq.(28) and Eq.(14) shows that the external magnetic field modulates neither the relative amplitude of the perturbation to the mean-field, nor the quantum effect obtained in the absence of the magnetic field, except that the 1D scalar k and v are substituted by the 3D vector $\mathbf{k}$ and $\mathbf{v}$ in the quantum α-term.

4. CONCLUSION

The classical PBD theory[11] was proven to provide a useful tool in the data-fit modelling of measured brain EEG signals, regardless of either the highly nonlinear structures featured by a train of storm-like wave packets, or the quasilinear envelops featured by deformed linear waves.[12] However, it is important to make use of the quantum mechanics to explain the neuro-and-cognitive mechanism of human consciousness.[29] This paper takes into account the quantum behaviour of electrons to investigate the quantum role played in brain consciousness.

Unclassical quantum effects arise when particle density is too high or temperature is too low. In human brain, the charge density is in the order of 10^{26} m^{-3}, so high enough to give two dimension-free parameters, χ_1 and χ_2 much larger than 1. No doubt, the brain plasma is non-classical and may be influenced by the quantum effect if it is not mitigated or cancelled by some mechanism(s). This paper formulates a quantum plasma model by generalizing PBD's Vlasov-Maxwell equations with the extra quantum term. The obtained electrostatic electron Wigner-Poisson equations are solved in both the absence and presence of an external magnetic field by applying a backward-mapping approach to the motion of Maxwellian electrons. The perturbation of the quantum term is obtained to superimpose on the classical perturbation of the mean-field property. Main results include:

(1) Different from the classical perturbation which is determined by the 1st-order derivatives of both φ and f_0, the quantum perturbation is dependent of the 3rd-order derivatives of the two parameters;

(2) In the absence of an external magnetic field, the quantum perturbation competes with the classical electrostatic perturbation, and is determined by the difference

[29] E.g., Vitiello G 2011. Hiroomi Umezawa and quantum field theory. NeuroQuantology, 9, 3, pp.402-412.

between 3 and the dimensional magnitude of $2(\upsilon/\upsilon_{Te})^2$;

(3) Under the same condition, the quantum perturbation has no effects at the normal brain states where the collective speed υ of all the Maxwell-Boltzmann electrons takes the dimensional root-mean-square speed, $\sqrt{3/2}\upsilon_{Te}$;

(4) Under the same condition, if brain temperature fluctuates, a serious deviation of ± 5 K relative to ~ 300 K causes the quantum effect to contribute no more than 11% of the classical perturbation;

(5) In the presence of the external magnetic field, the above results are not influenced, except the 1D scalar parameters substituted by corresponding 3D vectors in the quantum α-term.

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