Possible Roles of Neural Electron Spin Networks in Memory and Consciousness

(Dated: April 1, 2004)

Huping Hu[*1] **& Maoxin Wu**[†]

[*] Biophysics Consulting Group, 25 Lubber Street, Stony Brook, New York 11790, USA
[†] Department of Pathology, Mount Sinai School of Medicine, New York, New York 10029, USA

ABSTRACT

Spin is the origin of quantum effects in both Bohm and Hestenes quantum formulism and a fundamental quantum process associated with the structure of space-time. Thus, we have recently theorized that spin is the mind-pixel and developed a qualitative model of consciousness based on nuclear spins inside neural membranes and proteins. In this paper, we explore the possibility of unpaired electron spins being the mind-pixels. Besides free O_2 and NO, the main sources of unpaired electron spins in neural membranes and proteins are transition metal ions and O_2 and NO bound/absorbed to large molecules, free radicals produced through biochemical reactions and excited molecular triplet states induced by fluctuating internal magnetic fields. We show that unpaired electron spin networks inside neural membranes and proteins are modulated by action potentials through exchange and dipolar coupling tensors and spin-orbital coupling and g-factor tensors and perturbed by microscopically strong and fluctuating internal magnetic fields produced largely by diffusing O_2. We argue that these spin networks could be involved in brain functions since said modulation inputs information carried by the neural spike trains into them, said perturbation activates various dynamics within them and the combination of the two likely produce stochastic resonance thus synchronizing said dynamics to the neural firings. Although quantum coherence is desirable, it is not required for these spin networks to serve as the microscopic components for the classical neural networks. On the quantum aspect, we speculate that human brain works as follows with unpaired electron spins being the mind-pixels: Through action potential modulated electron spin interactions and fluctuating internal magnetic field driven activations, the neural electron spin networks inside neural membranes and proteins form various entangled quantum states some of which survive decoherence through quantum Zeno effects or in decoherence-free subspaces and then collapse contextually via irreversible and non-computable means producing consciousness and, in turn, the collective spin dynamics associated with said collapses have effects through spin chemistry on classical neural activities thus influencing the neural networks of the brain. Thus, according to this alternative model, the unpaired electron spin networks are the "mind-screen," the neural membranes and proteins are the mind-screen and memory matrices, and diffusing O_2 and NO are pixel-activating agents. Together, they form the neural substrates of consciousness.

[1] Correspondence Author. E-mail: drhu@quantumbrain.org. Voice/Fax: 212-898-1103.

I. INTRODUCTION

Tremendous progress has been made in neuroscience at cellular, molecular and atomic levels (1-3). However, what is and cause consciousness remains a mystery. Recently, we have explored the nature of consciousness based on a philosophical "map" on which consciousness is either associated with pre-spacetime or grounded at the bottom of physical reality but mediated by known physical process inside the brain (4,5). We have postulated that quantum spin is such process since spin is the origin of quantum effects in both Bohm and Hestenes quantum formulism and a fundamental quantum process associated with the structure of space-time (4-6). Applying these ideas to the particular structures and dynamics of the brain, we have developed a qualitative model of quantum consciousness based on nuclear spins inside neural membranes and proteins (4,5).

We have also shown that nuclear spin networks in neural membranes and proteins are modulated by action potentials through *J*-coupling, dipolar coupling and chemical shielding tensors and perturbed by microscopically strong and fluctuating internal magnetic fields produced largely by paramagnetic oxygen (7). Thus, we have suggested that these spin networks could be involved in brain functions since said modulation inputs information carried by the neural spike trains into them, said perturbation activates various dynamics within them and the combination of the two likely produce stochastic resonance thus synchronizing said dynamics to the neural firings. Although quantum coherence is desirable and may indeed exist, it is not required for these spin networks to serve as the subatomic components for the conventional neural networks (7).

On the other hand, neural membranes and proteins also contain various stable and unstable unpaired electron spins that may play the roles of mind-pixels. For example, many proteins contain unpaired electrons spins through covalent bonds, bound transition metal ions and absorbed small paramagnetic molecules such as O_2 and NO (8). Unstable unpaired electrons are also produced as free radicals through neural biochemical reactions and excited molecular triplet states through fluctuating internal magnetic fields induced singlet-triplet transitions (8). These unpaired electron spins form complex spin networks inside neural membranes and proteins. In this paper, we explore the possibility of unpaired electron spins being the mind-pixels.

II. NATURE OF SPIN, ANESTHESIA AND CONSCIOUSNESS

Spin reveals itself through the structure of the relativistic quantum equation for fermions such as electrons (9). Penrose had considered that spin might be more fundamental than space-time and invented spinor and twistor algebras for a combinatorial description of space-time geometry (10, 11). In Hestenes' geometric picture, the zitterbewegung associated with the spin of the Dirac electron is shown to be responsible for all known quantum effects of the electron (12). Second, Salesi and Recami has recently shown that the quantum potential in Bohmian mechanics is a pure consequence of "internal motion" associated with spin evidencing that the quantum behavior is a direct consequence of the fundamental existence of spin (13). Esposito has expanded this result by showing that "internal motion" is due to the spin of the particle, whatever its value (14). Recently, Bogan has further expanded these results by deriving a spin-dependent

gauge transformation between the Hamilton-Jacobi equation of classical mechanics and the time-dependent Shrődinger equation of quantum mechanics that is function of the quantum potential in Bohmian mechanics (15). Third, Kiehn has shown that the absolute square of the wave function could be interpreted as the vorticity distribution of a viscous compressible fluid that also indicates that spin is the process driving quantum effects (16). Sidharth has showed that spin is symptomatic of the non-commutative geometry of space-time at the Compton scale of a fermion and the three dimensionality of the space result from the spinorial behavior of fermions (17-18). He further showed that mathematically an imaginary shift of the spacetime coordinate in the Compton scale of a fermion introduces spin ½ into general relativity and curvature to the fermion theory (17-18). The reason why an imaginary shift is associated with spin is to be found in the quantum mechanical zitterbewegung within the Compton scale and the consequent quantized fractal space-time (17-18). Further, according to Sidharth, a fermion is like a Kerr-Newman Black Hole within the Compton scale of which causality and locality fails (17-18).

With respect to anesthesia, there is no commonly accepted theory on how general anesthetics work (19,20). However, there are two schools of thoughts on the issue. The first and oldest is the "lipid theory" which proposes that anesthetics dissolve into cell membranes and produce common structural perturbation resulting in depressed function of ion channels and receptors that are involved in brain functions (19). The second, more popular and recent theory is the "protein theory" which suggests that anesthetics directly interact with membrane proteins such as ion channels and receptors that are involved in brain functions. But the protein theory doesn't seem to square well with the low affinity and diversity of the general anesthetics. There is no direct experimental evidence to support either theory (20). However, both theoretical and experimental studies have shown that many general anesthetics cause changes in membrane structures and properties at or just above the clinical concentrations required for anesthesia (19,21,22). Since both O_2 and general anesthetics are hydrophobic, we have proposed within the framework of conventional neuroscience that general anesthetic may cause unconsciousness by perturbing O_2 pathway in neural membranes and O_2-utilizing proteins, such that the availability of O_2 to its sites of utilization is reduced, which in turn triggers cascading cellular responses through O_2-sensing mechanisms, resulting in general anesthesia (20). We have also been asking the question whether anesthetic perturbations of neural membranes and oxygen pathways themselves are the direct cause of unconsciousness. This conjuncture requires that O_2 and neural membranes be directly involved in consciousness. Indeed, The low affinity, diversity and pervasiveness of general anesthetics point us to this direction. If we assume that consciousness is an emergent property of the brain and further liken consciousness to the formation of ice at 0 ^{o}C, the anesthetic action would be like the action of salt which prevents ice formation.

With respect to consciousness, there is no coherent view as to what is and causes consciousness (23-33). Some neuroscientists would say that it is the connections between the neurons and the coherent firing patterns thereof (24,28). Some physicists would propose that it is connected to the measurement problem in quantum theory and thus the solution lies there (23,25,27,29). A few philosophers would suggest that it is an emergent property of the complex brain (31) or a new kind of properties and laws are required (33). Philosophically, Searle argues that consciousness is an emergent biological phenomenon thus cannot be reduced to physical states in the brain (31). Chalmers argues that consciousness cannot be explained through reduction, because mind does not belong to the realm of matter (33). In order to develop a consciousness theory based on this

approach, Chalmers suggests expanding science in a way still compatible with today's scientific knowledge and outlines a set of fundamental and irreducible properties to be added to space-time, mass, charge, spin etc. and a set of laws to be added to the laws of Nature (33). On the theoretical front, there are quite a few quantum theories of mind (23,25-27,29,30). Among these, Penrose's Objective Reduction ("OR") together with Hameroff's microtubule computation is perhaps the most popular, and the combination of the two produced the Orchestrated Objective Reduction ("Orch OR") in microtubules (23,29,30). There are also a number of theories based on conventional neuroscience (24,28). Our view on these is that whatever the final accepted version based on neuroscience ("classical physics"), it could be accepted as classically correct. The reason is that we must rely on the classical parts of the brain working according to conventional neuroscience to provide us the necessary neural components and wirings such as coherent neural firings, neurotransmitter releases and neural plasticity to support any realistic quantum activities of the brain. The situation is much like that in quantum computation where classical components form the supporting system of a quantum computer. Without these classical components, quantum computation could not be implemented at all.

In comparison, our working philosophy in this paper is that consciousness is grounded at the bottom of physical reality and emerges from the collective dynamics of known physical candidates inside the brain. Next we ask "where" and "how." To answer these, we take the reductionist approach both down to the end of physics to see what is left there and to the microscopic domain of a neuron to see what may be really important for the functioning of a conscious brain. What we found is that there is almost nothing left at the end of physics except the fundamental ideas of quantized space-time and spin. On the other hand, we found that what may be really important in the microscopic domain of a neuron are the biologically available nuclear spins and unpaired electron spins. Naturally, we draw the conclusion that that quantum spin together with its connection to space-time dynamics is needed to ground consciousness in physical reality such that conscious experience emerges from the successive collapses of various entangled neural spin states. Specifically, we try to answer these questions: (a) what are the neural substrates of consciousness, (b) what physical processes are involved in conscious experience, (c) what physical and biochemical process are involved in connecting consciousness to the classical neural networks of the brain and, (d) what binding mechanism allows the mind to achieve unity.

III. ACTION POTENTIAL MODULATIONS OF ELECTRON SPIN NETWORKS

Neural membranes are the matrices of brain electrical activities. Figure 1 shows the range of electric field strength E_m inside the neural membranes during a typical action potential as calculated from $E_m = \frac{V_m}{d}$ where V_m and d are respectively the membrane voltage and thickness. It oscillates between -9 to +6 million volts per meter during the course of each action potential. These strengths are comparable to those causing electroporation of cell membranes and dielectric breakdown of many materials (34) at which the covalent bonds of the constituent molecules are torn apart. So it significantly affects the conformations and collective dynamics of the neural membrane components such as phospholipids, cholesterols and proteins. Indeed, voltage-

dependent ion channels perform their functions through electric field induced conformation changes of the constituent proteins (3) and studies on the effects of electric fields on lipids support the above conclusion (35,36).

The unpaired electron spins carried by neural proteins and membrane components form complex intra- and inter-molecular spin networks through various intramolecular exchange and dipolar couplings and both short- and long-range intermolecular dipolar couplings. Since exchange coupling is the interaction between two electron spins through orbital overlap and dipolar coupling is the direct interaction of two electron spins through space, their strengths and anisotropies strongly depend on the conformations of the neural protein and membrane components (8). Further, the g-factor and spin-orbital coupling of each electron spin also depend on the conformation of surrounding orbital configuration (8). Thus, when these spin networks are subjected to the enormous changing electric field produced during each action potential, the exchange and dipolar coupling tensors and g-factor and spin-orbital coupling tensors oscillate with it, although electron spins do not directly interact with electric fields.

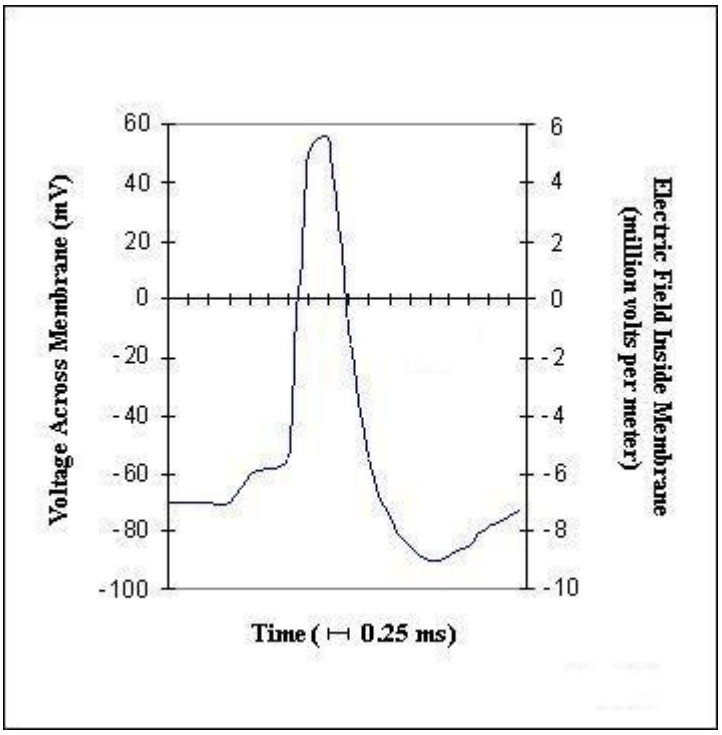

Figure 1. Electric field strength inside neural membrane during the course of an action potential. The calculation is down by assuming a typical membrane thickness of about 10 nm and the results are shown in the unit of one million volts per meter with "-" and "+" indicating that the direction of electric field is respectively pointing outward or inward inside the neural membrane.

In the simple case of two electron spins inside neural membranes or proteins coupled to each other through isotropic exchange coupling $J = J_{zz} = J_{xx} = J_{yy} = J_R + J_A$, the Hamiltonian of the system simply is $\hat{H} = h(J_R + J_A)(\hat{S}_{1z}\hat{S}_{2z} + \hat{S}_{1x}\hat{S}_{2x} + \hat{S}_{1y}\hat{S}_{2y})$ where J_R is the exchange coupling at

resting potential and J_A is the first-order contribution to J from action potential modulation thus it is a function of membrane voltage V_m. For a given value of V_m the two electron spins form a triplet consisting of $|1\rangle = |\uparrow\uparrow\rangle, |3\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle\right)$ and $|4\rangle = |\downarrow\downarrow\rangle$ and a singlet $|2\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$ with energies $E_1 = E_3 = E_4 = \frac{1}{4}h(J_R + J_A)$, $E_2 = -\frac{3}{4}h(J_R + J_A)$ thus an energy gap $J = h(J_R + J_A)$.

In the principal axes system of dipolar coupling tensor $\boldsymbol{D}$ for the two electron spins, $\hat{H} = h(J_R + J_A + D_R + D_A)\hat{S}_{1z}\hat{S}_{2z} + h(J_R + J_A - \frac{1}{2}D_R - \frac{1}{2}D_A)(\hat{S}_{1x}\hat{S}_{2x} + \hat{S}_{1y}\hat{S}_{2y})$ is the Hamiltonian with both isotropic exchange coupling $J = J_R + J_A$ and dipolar coupling $D = D_{zz} = -\frac{1}{2}D_{xx} = -\frac{1}{2}D_{yy} = D_R + D_A$ where D_R is the dipolar coupling at resting potential and D_A is the first-order contribution to D from action potential modulation thus it is also a function of membrane voltage V_m. It can be verified that $|1\rangle, |3\rangle$ $|4\rangle$ and $|2\rangle$ are also the eigenstates of the above Hamiltonian with energies $E_1 = E_4 = \frac{1}{4}h(J_R + J_A + D_R + D_A)$, $E_3 = \frac{1}{4}h(J_R + J_A) - \frac{1}{2}h(D_R + D_A)$ and $E_2 = -\frac{3}{4}h(J_R + J_A)$. Thus, dipolar coupling has no effect on the singlet state but partially removes the energy degeneracy of the triplet states thus producing zero-field splitting.

When the effects of both internal and external magnetic fields $\mathbf{B}_i$ and $\mathbf{B}_e$ are taken into accounts but g-factor anisotropies and spin-orbital couplings of both unpaired electron spins are neglected the total Hamiltonian for the two spin system in neural membranes and proteins is $\hat{H} = \hbar\gamma_1\hat{\mathbf{S}}_1 \cdot (\mathbf{B}_{1i} + \mathbf{B}_{1e}) + \hbar\gamma_2\hat{\mathbf{S}}_2 \cdot (\mathbf{B}_{2i} + \mathbf{B}_{2e}) + h\hat{\mathbf{S}}_1 \cdot (\mathbf{J}_R + \mathbf{J}_A) \cdot \hat{\mathbf{S}}_2 + h\hat{\mathbf{S}}_1 \cdot (\mathbf{D}_R + \mathbf{D}_A) \cdot \hat{\mathbf{S}}_2$ where $\mathbf{B}_{1i}, \mathbf{B}_{1e}, \mathbf{B}_{2i}$ and $\mathbf{B}_{2e}$ are respectively the internal and external magnetic fields at the locations of first and second electron spins and, γ_1 and γ_2 are respectively the gyromagnetic ratios of the said first and second electron spins. In general, microscopically $\frac{|\mathbf{B}_i|}{|\mathbf{B}_e|} >> 1$ at each spin location as shown later but macroscopically $\langle \mathbf{B}_i \rangle_{\mathbf{r}} = 0$, $\langle \mathbf{B}_e \rangle_{\mathbf{r}} \neq 0$, $\langle \mathbf{B}_i \rangle_t = 0$ and $\langle \mathbf{B}_e \rangle_t \neq 0$ where $\mathbf{r}$ and t respectively denote spatial and time average. So in many cases the effects of $\mathbf{B}_e$ on these electron spin networks are small.

These results from consideration of a simple two electron spin system in neural membranes demonstrate that the large neural electron spin networks inside the membranes can form complex modulated structures through action potential driven oscillations of exchange and dipolar couplings and g-factor and spin-orbital couplings. Thus, the neural spike trains of various frequencies can directly input information carried by them into these electron spin networks.

The fluctuating internal magnetic fields are produced by unpaired electrons such as those carried by O_2 and NO and spin-carrying nuclei such as ^1H, ^{13}C and ^{31}P. Table 1 shows the maximal magnetic field strengths produced by the magnetic dipoles of the unpaired electrons of O_2 and NO and the nucleus of ^1H along the axes of said dipoles at given distances. Because the magnetic dipole moment of an unpaired electron is 658 times larger than that of the ^1H nucleus, O_2 and NO can respectively produce magnetic fields 1,316 and 658 times larger than ^1H. As distance r increases, the strength of the magnetic dipole field quickly attenuate according to $B = \frac{\mu_0 m}{4\pi r^3}$ where μ_0 is the permeability of free space and m is the magnetic dipole moment. In addition, O_2 and NO are hydrophobic small molecules so their concentrations in neural membranes are much higher than in aqueous solutions such as cytoplasma (37). As they rapidly tumble and diffuse, they produce microscopically strong and fluctuating magnetic fields. Indeed, O_2 are the predominant sources of internal magnetic fields in neural membranes as evidenced by the strong effect of O_2 on spin-spin and spin-lattice relaxation rates (37,38).

Table 1. Magnetic Fields Produced by O_2, NO and ^1H

Distance (Å)	O_2 (Tesla)	NO (Tesla)	^1H (Tesla)
1.0	3.713940	1.856970	0.002821
2.0	0.464243	0.232122	0.000353
3.0	0.137553	0.068777	0.000104
4.0	0.058030	0.029015	0.000044
5.0	0.029712	0.014856	0.000023
10.0	0.003714	0.001857	0.000003

These fluctuating internal magnetic fields continuously perturb the neural electron spin networks. The intensities of said perturbations depend on the concentrations of O_2 and NO that are highly regulated in the brain. Thus, these perturbations not only activate various modulated dynamics within the neural electron spin networks but also are likely capable of enhancing the synchronization of these dynamics to the neural spike trains through non-linear processes such as stochastic resonance that is known to occur in the brain (39,40). So, stochastic resonance of dipolar splitting transitions and spin-forbidden singlet-triplet transitions are possible inside the neural membranes and proteins under said modulations and perturbations.

It is therefore possible that the collective dynamics of the neural electron spin networks under modulations by action potentials and perturbations by fluctuating internal magnetic fields represent meaningful information to the brain. An analogy to this suggestion is the mechanism of liquid crystal display (LCD) where information-carrying electric voltages applied to the pixel cells change the optical properties of the constituent molecules such that when lights pass through these cells their phases get rotated differently which in turn represent different information to the viewer of the LCD screen (41). According to this suggestion, large external disturbances to the collective dynamics of the neural electron spin networks will affect the

functional states of the brain to certain extent. Further, drug-induced large changes to membrane structures and O_2 pathways in neural membranes have similar adverse effects. These predications are testable and provide alternative interpretations to the causes of neural effects produced by some drugs and external stimulations. For example, the effect of transcranial magnetic stimulations (TMS) on cognitive functions (42) may be partly attributed to the direct disturbances of the dynamics of the said electron spin networks by TMS and the cause of unconsciousness by general anaesthetics may be explained as the direct consequence of their effects on neural membrane structures and O_2 pathways inside (20).

However, how can we explain based on the above suggestion that cognitive functions seem in general insensitive to environmental and even medical strength external magnetic fields such as those generated by the power lines and the ones used in MRI? First, the strengths of environmental magnetic fields are in the range of 10^{-4} -10^{-6} Tesla (43), For example, the magnetic field strength of the earth is about 5×10^{-5} Tesla. In comparison, the internal fluctuating magnetic fields can be as high as several Tesla as indicated by Table 1. Thus, the microscopically strong and fluctuating internal magnetic fields overshadow them. But the strengths of magnetic fields used in clinical and research MRI systems are in the range of 0.064 to 8.0 Tesla (44) that is comparable to or even higher than the strengths of said internal magnetic fields. So, additional explanations are called for. Indeed, the net magnetization of electron spins even by magnetic field of several Tesla very small at room temperature (8) that shows that even strong static magnetic fields only have small effects on the thermal dynamics of the neural spin networks. Third, to the extent that said electron spin networks are disturbed by external magnetic fields, it is argued that most of these disturbances do not represent meaningful information to the brain and, further, the brain likely have developed other mechanisms through evolution to counter the effects of external magnetic fields. In the cases where external magnetic disturbances were reported to have observable effects on cognition, the above suggestion provides a basis for interpreting these effects as said disturbances contain meaningful information to the brain.

Although quantum coherence is not required for the neural electron spin networks to serve as the subatomic components for the conventional neural network according to the above suggestion, it may exist within some parts of said electron spin networks as recent studies in other fields suggest. For example, long-lived (~ .05 *ms*) entanglement of two macroscopic electron spin ensembles in room temperature has also been achieved (45).

IV. ELECTRON SPIN MEDIATED CONSCIOUSNESS

With above discussions in mind, we present the following Postulates: (a) Consciousness is intrinsically connected to quantum spin; (b) The mind-pixels of the brain are comprised of the unpaired electron spins distributed in the neural membranes and proteins, the pixel-activating agents are comprised of the unbound O_2 and NO, and the neural memories are comprised of all possible entangled quantum states of the mind-pixels; (c) Action potential modulations of electron spin-spin interactions input information to the mind pixels and spin chemistry is the output circuit to classical neural activities; and (d) Consciousness emerges from the collapses of those entangled quantum states which are able to survive decoherence, said collapses are

contextual, irreversible and non-computable and the unity of consciousness is achieved through quantum entanglement of the mind-pixels.

In Postulate (a), the relationship between quantum spin and consciousness are defined based on the fact that spin is the origin of quantum effects in both Bohm and Hestenes quantum formulism (12-15) and a fundamental quantum process associated with the structure of space-time (9-11). Combining this fundamental idea with those stated in Postulates (b), (c) and (d) allows us to build a qualitatively detailed working model of quantum consciousness based on unpaired electron spins as discussed below. In Postulate (b), we specify that the unpaired electron spins in both neural membranes and neural proteins serve as the mind-pixels and propose that unbound O_2 and NO are the mind-pixel activating agents. We also propose that neural memories are comprised of all possible entangled quantum states of the mind-pixels. This concept of memory is an extension to the associative memory in neuroscience as will be discussed later. In Postulate (c), we propose the input and output circuits for the mind-pixels. As shown earlier, the strength and anisotropies of electron spin interactions through exchange and dipolar couplings and, indeed, the g-factors and spin-orbital couplings of electron spins are modulated by action potentials. Thus, the neural spike trains can directly input information into the mind-pixels. Further, spin chemistry can serve as the bridge to the classical neural activity since biochemical reactions mediated by free radicals are very sensitive to small changes of magnetic energies as mentioned earlier and further discussed later (46-48). In Postulate (d), we propose how conscious experience emerges. Since there are several interpretations of the measurement problem in quantum mechanics, we choose to accept the collapsing view (23,29). Thus, we adopt a quantum state collapsing scheme from which conscious experience emerges as a set of collapses of the decoherence-resistant entangled quantum states. We further theorize that the unity of consciousness is achieved through quantum entanglements of these mind-pixels (27).

Figure 2 is a highly schematic drawing of the overall picture of a spin-mediated consciousness model. At the top of Figure 2, a two-neuron network is shown. The connections are self-explanatory. The neural activities of the postsynaptic membrane are immediately shown below the neurons in Figure 2. These activities include biochemical reactions immediately following the release of neurotransmitters into the synaptic cleft, the ensuing collective activities of multiple ion channels and the action potentials and their propagations thereof, and other enzymatic activities. The present model is mainly concerned with the dynamics of the unpaired electron spin networks in neural membranes and proteins under modulations by action potentials and activations by rapidly tumbling and diffusing O_2 and neural transmitter NO, and the connections of such dynamics to conscious experience. The input and output interface of said spin networks are schematically shown in the middle of Figure 2. On the bottom of Figure 2, what the conscious brain perceives is schematically shown. The neural substrates and mechanism of the spin-mediated consciousness are described below.

Figure 2. Illustration of electron spin mediated consciousness theory. The drawing is self-explanatory except the part dealing with conscious experience See text for detailed explanations.

The mechanism of electron spin mediated consciousness is concisely stated here and the related issues such as decoherence effect are discussed later. Through action potential modulated electron spin-spin interactions and fluctuating internal magnetic field driven activations, the neural electron spin networks inside neural membranes and proteins form various entangled quantum states some of which survive decoherence through quantum Zeno effects or in decoherence-free subspaces and then collapse contextually via irreversible and non-computable means producing consciousness and, in turn, the collective spin dynamics associated with said collapses have effects through spin chemistry on classical neural activities thus influencing the

neural networks of the brain. It is also argued that the unpaired electron spins inside a network of large molecules may be able to form long-lived macroscopic quantum coherence through tunneling since they are insulated to certain extent from the noisy brain environment. Thus, according to this alternative approach, the unpaired electron spin networks are the "mind-screen," the neural membranes and proteins are the mind-screen and memory matrices, and unbound paramagnetic small molecules such as O_2 and NO are pixel-activating agents. Together, they form the neural substrates of consciousness.

This mechanism is illustrated at the bottom of Figure 2. The geometry inside the spinning circle represents conscious experience and is part of a Penrose tiling (23). It symbolizes that consciousness emerges from the non-computable collapses of entangled quantum states of the mind-pixels under the influence of spacetime dynamics schematically shown as the spinning circle. The edges in the Penrose tiling represent the unpaired electron spins in neural membranes and proteins as mind-pixels, the nodes represent interactions between these electron spins through exchange and dipolar couplings and the colors represent activations of mind-pixels by the fluctuating internal magnetic fields largely generated by diffusive O_2. The whole tiling pattern in Figure 2 represents conscious experience and the underlying spacetime geometry. This pattern successively evolves under repeated activations representing successive collapses of the entangled quantum states of the mind-pixels that have survived decoherence as a stream of conscious experience.

We adopt Penrose's long-standing view that human thought may involve non-computable processes, as Gödel's theorem of incompleteness would suggest (23,29). According to Gödel, any consistent system of axioms beyond a certain basic level of complexity yields statements that cannot be proved or disproved with said axioms. Yet human can decide whether those statements are true, thus human thought cannot be reduced to a set of rules or computations (23,29). So where can one find non-computable process in physics? Obviously it cannot be found in classical physics because classical physics is deterministic so, in principle, can be simulated by a computer (23,29). Thus, Penrose reasoned that some kind of non-computable quantum process must be involved in consciousness and further suggested gravity-induced reduction ("R") process of quantum state superposition to be the candidate (23,29). One may recall that, according to Einstein's theory of general relativity, gravity is space-time geometry and, further, as we have discussed before quantum spin is associated with the structure of space-time. Therefore, the quantum state of spin must be connected to the underlying space-time geometry. However, we still have the task of working out the details in future research. This will be especially difficult because at the present we do not have a satisfactory theory of quantum gravity.

The decoherence effect which causes a quantum system to lose quantum coherence through interactions with its environment is a major concern for any quantum theory of the brain and is hotly debated (49-50). Because the high mobility of the electrons and strong interactions of electron spins with their environments, electron spins have very short relaxation time after excitations (8). This property of electron spins seems to be a major problem for them to serve as the mind-pixels. These electron spins can form various intra/inter-molecularly entangled quantum states under different external activations through exchange coupling and dipolar couplings (8). The diffusing O_2 and NO can strongly interact with the unpaired electron spins

bound/absorbed to large molecules through their large magnetic dipoles and collision-induced exchange couplings (8) thus activating the neural electron spin networks. Paradoxally, the interactions of the neural electron spin networks with their noisy brain environments may enhance quantum coherence through quantum Zeno effect which prevents a quantum system to evolve/decohere through repeated collisions with their environments (27). Further, studies show that decoherence-free subspaces can exist within the Hilbert space of a complex quantum system (51). Indeed, Julsgaard *et al* have first theoretically predicted and then experimentally demonstrated at room temperature a long-lived entanglement of two macroscopic spin ensembles formed by two caesium gas samples each of which contains about 10^{12} atoms (45). The entangled spin-state can be maintained for 0.5 milliseconds and was generated via interactions of the samples with a pulse of light (45). The state they demonstrated is not a maximally entangled "Schrödinger cat" state but a state similar to a two-mode squeezed state; thus, it is an example of a non-maximally entangled state (45). In addition, Kun *et al* have theoretically predicted a "Schrödinger cat" state to be found in highly-excited and strongly-interacting many-body system (52). These results apparently contradict the claim that there is no large-scale quantum coherence in the noisy brain (49).

If there is no large-scale quantum coherence in the noisy brain because of decoherence (49), how can consciousness still emerge from the statistically mixed quantum states of the electron spin networks in neural membranes and proteins? There are indeed at least two ways out. The first is to adopt an emergence theory (31) and the second is to take a dualistic approach (26,33). Here, we will focus our discussion on the dualistic approach. In such approach we could propose that mind has its own independent existence and reside in a pre-spacetime domain. Then, the question becomes how would mind process and harness the information from the brain so that it could have conscious experience? We could theorize that conscious experience emerges from those quantum states of the mind-pixels in the statistical mixtures that have grabbed the attention of the mind through quantum Zeno effect (27) or some non-local means in pre-spacetime. Indeed, the many-mind interpretation of quantum theory as proposed by Donald seems to support this type of formulation (25). Thus, in this scenario, mind does not depend on large quantum coherence to work.

We have suggested that action potential modulations of electron spin interactions could input information to the mind pixels and spin chemistry could be the output circuit to classical neural activities. With respect to the input circuit, we have shown that the strength and anisotropies of electron spin interactions through exchange and dipolar couplings are modulated by action potentials. Thus, the neural spike trains could directly input information into the mind-pixels made of unpaired electrons spins in neural membranes and proteins. Secondly, the weak magnetic field produced collectively by all neural activities may also directly serve as the input. However, the magnitude of said magnetic field is only in the order of 10^{-12} Tesla (53). In comparison, diffusing O_2 and NO can produce a fluctuating local magnetic field as high as a few Tesla as discussed earlier. Thus, the effect of said weak magnetic field on the dynamics of mind-pixels is probably small unless non-linear processes such as stochastic resonance are involved. Further, we have already pointed out earlier that spin chemistry can serve as the output circuit to classical neural activities because biochemical reactions mediated by free radicals are very sensitive to small changes of magnetic energies as discussed previously. Indeed, many biochemical reactions mediated by radical pairs and biradicals, such as those dual path radical

reactions driven/initiated by NO and active oxygen species, have been found to be influenced by the magnetic field in their local environment (46-48). Thus, the functional output of the mind-pixels, being the varying local magnetic field generated by the dynamics of the electron spin networks, could directly affect classical neural activities. Further, there may be other mechanisms through which the mind-pixels could influence the classical neural activities of the brain.

Figure 3. Illustration of neural memory. **a** shows a neural membrane containing only the same phospholipids. **b** shows the neural membrane after cholesterols are added. **c** shows the chemical structure and atomic model of a stearic acid molecule and **d** shows the chemical structure and atomic model of oleic acid molecule.

We have proposed that neural memories are comprised of all possible entangled quantum states of the unpaired electron spins inside neural membranes and proteins. This proposal calls for extension of the existing associative memory concept in neuroscience to include all possible conformations of neural membranes and proteins in a single neuron (1). A few illustrations are given here. Figure 3 (a) schematically shows a patch of neural membrane containing only the same phospholipids. Such a membrane is much like a blank tape. Figure 3 (b) shows the same neural membrane after cholesterols are added. The changes in membrane configuration are quite noticeable (54-55). These changes can represent memory or information. Figure 3 (c) shows the chemical structure and atomic model of a stearic acid molecule - a saturated fatty acid. Figure 3 (d) shows the chemical structure and atomic model of oleic acid molecule – an unsaturated fatty acid. The only difference between the two fatty acids is that the latter contains a double bond in the middle that causes its kink formation when the double bond is the cis form. When the double bond is in the trans form, the chain is doubly bent so there is no kink. Certainly insert either one of the fatty acids into the membrane shown in Figure 3 (b) would further increase its complexity

thus information content. Furthermore, insertions of proteins to neural membranes also significantly change their conformation and dynamics surrounding the inserted proteins (56). Thus, inserting different proteins to neural membranes both in numbers and types can significantly increase the information content of the neural membranes.

As mentioned earlier in this paper, the mechanism of anesthetic action is closely related to the inner workings of consciousness (20). We describe here said mechanism in accordance with our spin-mediated consciousness theory. Figure 4 (a) schematically shows the normal diffusion of O_2 and NO without anesthetics dissolved into the neural membranes and proteins. As these molecules rapidly diffuse through the membranes, they collide with the neural membrane components and generate strong and fluctuating internal magnetic fields thus activating the electron spin networks inside these membranes and proteins. Figure 4 (b) schematically shows anesthetic perturbations of O_2 and NO pathways and neural membranes themselves by anesthetic molecules and the resulting distortion and/or obstruction of these pathways. Such perturbations render O_2 and NO not able to perform their normal activation functions thus resulting in unconsciousness.

Figure 4. Illustration of anesthetic action. **a** shows the normal diffusion of O_2 without anesthetics dissolved into neural membranes. **b** shows anesthetic perturbations of O_2 pathways and neural membranes themselves.

V. PREDICTIONS AND SUPPORTING EVIDENCE

Several experimentally verifiable predictions can be drawn from our alternative model in which unpaired electron spins play the roles of mind-pixels: (a) Significant eliminations of unpaired electrons in neural membranes and proteins will affect or disrupt consciousness; (b) Significant external disturbances to the dynamics of the electron spin networks in neural membranes and proteins will interfere with normal conscious functions; (c) Significant drug-induced disturbances to the structure and dynamics of the neural membranes and protein themselves will affect or disrupt consciousness; (d) Significant drug-induced disturbances to the O_2 pathways inside the neural membranes will diminish or block consciousness; and (e) Significant lack of O_2

in neural membranes will directly affect or disrupt consciousness even if everything else in the brain functions normally. Of course, other predictions and inferences can also be drawn from the present theory. But we will focus our discussions on the above listed a few to see whether there are any experimental evidence supporting these predictions.

With respect to prediction (a), new experiments need to be designed and conducted. On prediction (b), there are quite a few published studies based on transcranial magnetic stimulation ("TMS") that could be partially explained based on our alternative model (57,58), although common wisdom is that TMS induces electrical currents in the brain, causing depolarization of cellular membranes and thereby neural activation (57). It has been found that depending on the locations of stimulation TMS affects the test subject's verbal ability, visualization and other conscious functions (58). According to our alternative approach, TMS could directly affect the dynamics of electron spin networks in neural membranes and proteins which in turn result in altered, diminished and/or disrupted conscious functions of the brain. With respect to predictions (c) and (d), many general anesthetics have been found to disturb the structures and dynamics of neural membranes (20-22). Thus, the mechanism of their action could be interpreted, according our electron spin basewd model, as caused by their direct effects on O_2 pathways and electron spin networks inside the neural membranes and proteins. One of our papers contains a detailed treatment on anesthetic perturbations of oxygen pathways and membranes themselves (20). Here we will focus on one particularly small anesthetic agent, the nitrous oxide (N_2O), also known as the laughing gas. Indeed, the size of N_2O is similar to that of O_2 but it does not contain unpaired electrons and is not reactive. It has low polarity that makes it soluble in both water and lipid. Thus, it can be carried to the brain through blood stream and accumulate in the neural membranes. Inhalation of N_2O will cause disorientation, euphoria, numbness and ultimately loss of consciousness if the inhalation dosage is high. The cellular mechanism of these actions by N_2O is so far unknown but seems confined to postsynaptic targets (59). On the other hand, its closely related "cousin" NO contains one unpaired electron and has been discovered as the first small and highly diffusive neural transmitter produced in the brain through enzymatic reactions (60). According to our theory, there indeed exist a natural and straightforward explanation. By dissolving into neural membranes in an inhalation-dose-dependent fashion, N_2O gradually displace O_2 in the neural membranes thus diminish or disrupt the activating function of O_2. With respect to prediction (e), it is probably very hard to deprive brain O_2 and yet at the same time require its neurons to keep their metabolic functions normal since O_2 is an essential component of brain energy production. However, according to our theory in the case of temporary-hypoxia-induced unconsciousness such as that due to sudden loss of air pressure on an airplane, the actually cause may not be the depletion of brain energy resources because of the lack of O_2 but the direct loss of O_2 as the activating agents.

Finally, we briefly turn our attention to the associative memory model proposed herein. There are tens of thousands of research papers on the subject of synaptic plasticity/modification (61). The commonly accepted assumption in neuroscience is that synaptic efficacy is both necessary and sufficient to account for learning and memory (62). Our associative memory model does not conflict with the synaptic efficacy view but extend it to the sub-neural and microscopic domain. Studies show that neural activities modify not only the synaptic efficacy but also the intrinsic properties of the neuron (62).

VI. DISCUSSIONS AND CONCLUSIONS

In this paper, we have explored the possibility of unpaired electron spins being the mind-pixels instead of nuclear spins as proposed in our primary model (4-7). Our working philosophy has been that consciousness is grounded at the bottom of physical reality and emerges from the collective dynamics of known physical candidates inside the brain. We strongly believe that quantum spins are such candidates because they are one of the most fundamental entities in modern physics and, on the other hand, neural membranes and proteins not only are saturated with spin-carrying nuclei but also contains various unpaired electron spins. The main sources of unpaired electron spins in neural membranes and proteins, besides free O_2 and NO, are transition metal ions and O_2 and NO bound/absorbed to large molecules, free radicals produced through biochemical reactions and excited triplet states induced by fluctuating internal magnetic fields. We have made important predictions based on this alternative model and presented some experimental evidence in support of the same.

However, our electron spin based model as it stands now is highly speculative. In contrast to nuclear spins that have after excitation relaxation times comparable to the dynamic time scales of relevant neural activities (milliseconds or longer), electrons in excited spin states relax back to thermal equilibrium in microseconds or shorter in room temperature. Thus, the effect of decoherence is a major concern in this model. It is suggested that the interactions of the neural electron spin networks with the noisy brain environments may enhance quantum coherence through paradoxal quantum Zeno effect and decoherence-free subspaces may exist within the Hilbert space of the complex electron spin networks in the brain. Further, it is plausible that the unpaired electronic spins caged inside a network of large molecules could form long-lived macroscopic quantum coherence through tunneling since they are insulated to certain extent from the noisy brain environment.

In conclusion, we have represented an alternative model of consciousness in which unpaired electron spins play the central role as mind-pixels and the unity of mind is achieved by entanglement of these mind-pixels. To justify such a choice, we have shown that spin is the origin of quantum effects in both Bohm and Hestenes quantum formulism and a fundamental quantum process associated with the structure of space-time. Applying these ideas to the particular structures and dynamics of the brain, we have speculated on how consciousness might emerge from the collapse of the decoherence-resistant entangled electron spin states via contextual, non-computable and irreversible processes. We have suggested that these entangled electron spin states could be formed through action potential modulated exchange and dipolar interactions plus O_2 and NO driven activations and survive rapid decoherence through quantum Zeno effects or in decoherence-free subspaces. We have further suggested that the collective electron spin dynamics associated with said collapses could have effects through spin chemistry on classical neural activities thus influencing the neural networks of the brain. Our proposals imply the extension of associative encoding of neural memories to the dynamical structures of neural membranes and proteins. Therefore, according our electron spin based model the neural substrates of consciousness are comprised of the following: (a) electron spin networks embedded in neural membranes and proteins which serve as the “mind-screen” with unpaired electron spins as the pixels, (b) the neural membranes and proteins themselves which serve as the matrices for

the mind-screen and neural memories; and (c) free O_2 and NO which serve as the pixel-activating agents.

REFERENCES

1. Marder, E., Abbott, L. F., Turrigiano, G. G., Liu, Z. & Golowasch, J. Memory from the dynamics of intrinsic membrane currents. *Proc. Natl. Acad. Sci. USA.* 1996; **93,** 13481–13486.

2. Hunt, S. P. & Mantyh, P. W. The Molecular dynamics of pain control. *Nature Rev. Neurosci.* 2001; **2,** 83–91.

3. Morais-Cabral, J. H., Zhou, Y. & MacKinnon, R. Energy optimisation of ion conduction rate by the K selectivity filter. *Nature* 2001; **414,** 37–42.

4. Hu, H. P., & Wu, M. X. Spin-Mediated Consciousness Theory: possible roles of oxygen unpaired electronic spins and neural membrane nuclear spin ensemble in memory and consciousness. *arXiv e-print* 2002; quant-ph/0208068.

5. Hu, H. P., & Wu, M. X. Spin-Mediated Consciousness Theory: an approach based on pan-protopsychism. *Cogprints* 2003; ID2579.

6. Hu, H. P., & Wu, M. X. Spin as primordial self-referential process driving quantum mechanics, spacetime dynamics and consciousness. *NeuroQuantology* 2004; 1:41-49.

7. Hu, H. P., & Wu, M. X. Action Potential Modulation of Neural Spin Networks Suggests Possible Role of Spin. *Cogprints* 2004; ID3458.

8. Wertz, J. E., Bolton J. R. Electron Spin Resonance: Elementary theory and practical application (New York: McGraw-Hill Book Company, 1972).

9. Dirac, P. A. M. The quantum theory of the electron. *Proc. R. Soc.* A , 1928; **117**: 610-624.

10. Penrose, R. A spinor approach to general relativity. *Ann. Phys.*, 1960; **10**: 171.

11. Penrose, R. Twistor algebra. *J. Math. Phys.*, 1967; **8**: 345.

12. Hestenes, D. Quantum mechanics from self-interaction. *Found. Physics*, 1983; **15**: 63-87.

13. Salesi, G. and Recami, E. Hydrodynamics of spinning particles. *Phys. Rev. A*, 1998; **57**: 98.

14. Esposito, S. On the role of spin in quantum mechanics. *Found. Phys. Lett*., 1999; **12**: 165.

15. Bogan, J. R. Spin: the classical to quantum connection. http://www.arxiv.org/pdf/quant-ph/0212110, 2002.

16. Kiehn, R. M. An extension to Bohm's quantum theory to include non-gradient potentials and the production of nanometer vortices. http://www22.pair.com/csdc/pdf/bohmplus.pdf, 1999.

17. Sidharth, B. G. Issues and ramifications in quantized fractal space-time: an interface with quantum superstrings. *Chaos Solitons Fractals*, 2001 **12**: 1449-1457.

18. Sidharth, B. G., Chaotic Universe (New York: Nova Science, 2001).

19. Cantor, R. S. The lateral pressure profile in membranes: a physical mechanism of general anesthesia. *Biochem.*, 1997; **36**: 2339-2344.

20. Hu, H. P., Wu, M. X. Mechanism of anesthetic action: oxygen pathway perturbation hypothesis', *Med. Hypotheses*, 2001; **57**, 619-627.

21. Tu, K. Effect of anesthetics on the structure of a phospholipid bilayer: molecular dynamics investigation of halothane in the hydrated liquid crystal phase of dipalmitoyl-phosphatylcholine. *Biophys. J.*, 1998; **75**: 2123-2134.

22. Koubi, L. Distribution of halothane in a dipalmitoylphosphatidylcholine bilayer from molecular dynamics calculations. *Biophys. J.*, 2000; **78**: 800-811.

23. Penrose, R. The Emperor's New Mind (Oxford: Oxford University Press, 1989).

24. Edelman, G. M. The Remembered Present: A Biological Theory of Consciousness (New York: Basic Books, 1989).

25. Donald, M. J. Quantum theory and the brain. *Proc. R. Soc.* A. 1990, **427**: 43-93.

26. Beck, F., Eccles, J. C. Quantum aspects of brain activity and the role of consciousness. *Proc. Natl. Acad. Sci. USA*, 1992; **89**: 11357-11361.

27. Stapp. H. P. Mind, Matter and Quantum Mechanics (New York: Springer-Verlag, 1993).

28. Crick, F. The Astonishing Hypothesis (New York: Simon & Schuster, 1994).

29. Penrose, R. Shadows of the Mind (Oxford: Oxford University Press, 1994).

30. Hameroff, S., Penrose, R. Conscious events as orchestrated spacetime selections. *J. Conscious Stud.*, 1996; **3**: 36-53.

31. Searle, J. The Rediscovery of the Mind (Cambridge, MA: MIT Press, 1992).

32. Churchland, P.S., Sejnowski, T. J. The Computational Brain, 2d. ed. (Cambridge, MA: MIT Press, 1993).

33. Chalmers, D. The Conscious Mind (Oxford: Oxford University Press, 1996).

34. Barnet, A. & Weaver, J. C. Electroporation: a unified, quantitative theory of reversible electrical breakdown and mechanical rupture in artificial planar bilayer membranes. *Bioelectrochem. Bioenerg.* 1991; **25,** 163–182.

35. Sargent, D. F. Voltage jump/capacitance relaxation studies of bilayer structure and dynamics. *J. Membr. Biol.* 1975; **23,** 227–247.

36. Saux, A. L., Ruysschaert, J. M. & Goormaghtigh, E. Membrane molecule reorientation in an electric field recorded by attenuated total reflection Fourier-transform infrared spectroscopy. *Biophys. J.* 2001; **80,** 324-330–125.

37. Marsh, D. Polarity and permeation profiles in lipid membranes. *Proc. Natl. Acad. Sci. USA.* 2001; **98,** 7777–7782.

38. Prosser, R. S., Luchette, P. A., Weterman, P. W., Rozek, A. & Hancock, R. E. W. Determination of membrane immersion depth with O_2: A high-pressure ^{19}F NMR study. *Biophys. J.* 2001; **80,** 1406–1416.

39. Bezrukov, S. M. & Vodyanoy, I. Noise-induced enhancement of signal transduction across voltage-dependent ion channels. *Nature* 1995; **378,** 362–364.

40. Simonotto, E., Riani, M., Seife, C., Roberts, M., Twitty, J. & Moss, F. Visual perception of stochastic resonance. *Phys. Rev. Lett.* 1997; **78,** 1186–1189.

41. Bryan-Brown, G. P., Brown, C. V., Sage, I. C. & Hui, V. C. Voltage-dependent anchoring of a nematic liquid crystal on a grating surface. *Nature* **392,** 365–367 (1998).

42. Walsh, V. & Cowey, A. Transcranial magnetic stimulation and cognitive neuroscience. *Nature Rev. Neurosci.* **1,** 73–79 (2000).

43. Marino, A. A. Environmental electromagnetic fields and public health. *In Foundations of Modern Bioelectricity Marino, A. A., ed.* (Marcel Dekker, New York, 1988).

44. Shellock, F. G. Magnetic Resonance Safety Update 2002: Implants and Devices. *J. Magn. Resonan. Imaging* 2002; **16,** 485–496.

45. Julsgaard, B., Kozhekin, A. & Polzik, E. S. Experimentally long-lived entanglement of two macroscopic objects. *Nature* 2001; **413,** 400–403.

46. Nagakura, S., Hayashi, H. and Azumi, T. Dynamic Spin Chemistry (New York: Wiley, 1998).

47. Hayashi, H. Advent of spin chemistry. *RIKEN Review*, 2002: **44**: 7-10.

48. Minaev, B. F. Intermolecular exchange in the system $O_2 + H_2$ as a model of spin-catalysis in radical recombination reaction. *Theor. Experimental Chem.*, 1996; **32**: 229.

49. Tegmark, M. The importance of quantum decoherence in brain processes. *Phys. Rev.*, 2000; **61E**: 4194.

50. Hagan, S., Hameroff, S. R. and Tuszynski, J. A. Quantum computation in brain microtubules: decoherence and biological feasibility', *Phys. Rev. E.*, 2002; **65**: 061901(1-10).

51. Lidar, D. A., Whaley, K. B. Decoherence-free subspaces and subsystems. In *Irreversible Quantum Dynamics*, Benatti , F., Floreanini, R. (Eds.), 83-120 (Springer Lecture Notes in Physics vol. 622, Berlin, 2003).

52. Kun, S. Y., *et. al*. Schrodinger cat states in highly-excited strongly-interacting many-body system', http://www.arxiv.org/pdf/quant-ph/0205036, 2002.

53. Wikswo, J. P. Biomagnetic sources and their models. In *Advances in Biomagnetism, Williamson, S. J., et al (Eds)* (New York: Plenum, 1990).

54. Raffy, S., Teissie, J. Control of membrane stability by cholesterol content. *Biophys. J.*, 1999; **76**: 2072-2080.

55. Smondyrev, A M., Berkowitz, M. L. Structure of Dipalmitoylphosphatidylcholine-cholesterol bilayer at law and high cholesterol concentrations: molecular dynamics simulation', *Biophys. J.*, 1999; **77**: 2075-2089.

56. Woolf, T. B., Roux, B. Structure, energetics, and dynamics of lipid-protein interactions: A molecular dynamics study of the gramicidin a channel in a DMPC bilayer. *Proteins: Struct. Funct. Gen.*, 1996; **24**: 92-114.

57. Limoniemi, R. J. Neuronal responses to magnetic stimulation reveal cortical reactivity and connectivity. *NeuroReport*, 1997; **8**: 3537-3540.

58. Chicurei, M. Magnetic mind games. *Nature*, 2002; **417**: 114-116.

59. Mennerick, S. Effect of nitrous oxide on excitatory and inhibitory synaptic transmission in Hippocampal cultures. *J. Neurosci.*, 1998; **18**: 9716-9726.

60. Philippides, A., Husbands, P., and O'Shea, M. Four-dimensional neural signaling by nitric oxide: A computer analysis. *J. Neurosci.*, 2000; **20**: 1199-1207.

61. Fu, Y. X., et al. Temporal specificity in the cortical plasticity of visual space representation. *Science*, 2002; **296**: 1999-2003.

62. Marder, E. *et. al*. Memory from the dynamics of intrinsic membrane currents. *Proc. Natl. Sci. USA*, 1996; **93**: 13481-13486.