ESSAY ON MESOSCOPIC AND QUANTUM BRAIN

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The fox knows many things,

But the hedgehog knows one big thing,

Archilochus

... what about the grasshopper ?

Brooks has used the subsumption architecture to build insect-like robots.

But insect minds are not very interesting.

We are now exploring the space between the insect and the adult human.

D.C. Dennett, Phil. Trans. R. Soc. Lond. A **349**, 146 (1994)

In the pure essay style (no mathematical formulas), I present a number of speculative reflections and suggestions on possible applications of mesoscopic methods and of quantum mechanical concepts to as such a complex system as the human brain. As an initial guide for this essay I used "The Emperor's New Mind" of Roger Penrose.

I. INTRODUCTION

The almost one hundred years of historical development of quantum theory are a manifest proof of its viability and successfulness, despite a number of persisting conceptual and/or philosophical difficulties, e.g., measurement, quantum-Zeno, and EPR paradoxes, that may be considered ever-lasting open problems. Due to their versatility the quantum methods can be applied in principle to any space-time scale, when amended with corresponding innovations, usually by generalizing certain delicate interpretational aspects. For example, one may encounter ambitious programs such as describing the whole universe in quantum mechanical terms, a case in which the usual Copenhagen interpretation, apparently sufficient at microscales, have to be replaced by more general schemes, as for example, the "sum over histories" interpretation [1], a modern variant of Everett's "relative state" (1957) [2], or of the slightly different language of "many worlds" [3]. For a recent 'map' of the various interpretations and other issues of quantum mechanics, I recommend the paper of Sonego [4]. Unfortunately, what happens when one is trying to extend too much the usual domain of a theory, even if it is of the rank of quantum mechanics, which is *superb and useful* in Penrose's classification, is to turn it into a purely formal and almost unuseful scheme.

Since a common way of scientific reasoning in physics is that phenomena at normal macroscopic scales are to be explained in terms of concepts built up of quantities formally existing at microscopic scales, many people believe that quantum theory is a universal theory [5]. Therefore quantum theory/mechanics should have something to say regarding one of the most sophisticated systems, and actually for the time being, the most sophisticated we know about, which undeniably is the *human brain*. This "porridge-like" biological assemble is the command unit of the human body and of extreme importance to all of us for any need, including the scientific one. One can think of it at three spatial scales: the microscopic, the mesoscopic, and the macroscopic ones. By microscopic scales I would like to mean quantum length scales, i.e., $10^{-10} - 10^{-9}$ m, the mesoscopic scales, where according to Feynman [6] "there's plenty of room...", are those between $10^{-9} - 10^{-7}$ m, while beyond that one can say that we passed into the macroscopic realm, which in fact for the brain reduces to the centimeter scale. This division is of course not sharp and there are no well-established criteria for the relative separation. Most of the brain activity proceeds at the mesoscopic and macroscopic scales and it seems a priori unuseful to think of quantum features and quantum mechanics for such a complex self-organization. But for a physicist this is not so, and as a matter of fact, he/she should attempt at finding arguments for making relevant the quantum features of the human brain. Moreover, some of the quantum methods and ideas can find interesting applications in this field even at scales which are not properly quantum ones. The spatial scales mentioned above are standard ones in physics, i.e., they are the scales with which most of the physicists are dealing. Since human brain is a complex physical, biological, and information-processing system, one will expect multiple spatial and temporal scales to be mixed up, with interactions taking place at multiple hierarchical levels. Therefore the structural division of the brain activity usually considered by neuroscientists might look more natural, i.e., the microscopic scales are those of synaptic-neuronal interactions, the mesoscopic ones be-

long to minicolumns and macrocolumns of neurons, and the macroscopic scales are characterized by the regional activity over centimeters of neocortex (see [7] and the next section). The columns are defined as filamentary cluster structures of neurons in the (neo)cortex.

In the following, the reader will find several incipient and quite provisional opinions on the problem of the human brain at the mesoscopic and quantum level that I started to gather together mainly in the summer of 1992, when I began this essay while spending some really good time browsing in the ICTP-SISSA libraries and looking more carefully into *The Emperor's New Mind*. Being an essay, I escape any mathematical rigor, thus allowing me to utter, even though in a cursory manner, what might be some interesting and hopefully useful ideas for future analyses.

Previously to start reading this essay, I recommend the reader to take a look in Chapters 9 and 10, at least, in the aforementioned book of Penrose [8] for world-wide known opinions on the brain, to which I will frequently refer in the following. Philosopher Owen Flanagan has recently classified many of the scientists not belonging to the mainstream neuroscience as "the new mysterians". These are supposed to be people whose more or less declared beliefs are that topics such as *consciousness* and *free will* are too profound for scientific studies. Therefore what "the new mysterians" do is to mistify (consciously or unconsciously) those concepts, usually by relating them to other mysteries (of quantum mechanics in the case of Roger Penrose; recall that Chapter 6 in *Emperor's* has the title: *Quantum magic and quantum mistery*). I am negative to such an opinion, and I found in expressing my disagreement another motivation for the present essay. I think that scientists have the right to speculate. It is only a question of time for some small amount of their speculations to convert into scientific and even technologic truths. These were the main underlying arguments for writing the present essay.

II. WHAT IS THE HUMAN BRAIN ?

The brain is by itself a complex, i.e., self-organized quantum-meso-macro-scopic system/state of biological material which is more than a logical machine (composite- computer), showing some ability to react at phase correlations. J.J. Hopfield [9] remarked that the question "How does it work ?" is one of the best motivations for many scientists. In the case of the brain, an efficient answer is "it is doing computations", and this in its particular "biological" way. The powerful paradigm here is to view the brain composite-computers as input -output devices performing transformations on the input signals to generate the output ones. However, this in-out mapping is extremely complicated in the case of biological computers. It is also the main subject for the artificial

intelligence projects. Apparently, the paradigm of computing is at odd only with the concept of consciousness of the human brain. If a measure or a parametrization of the consciousness will be found, for human brains as well as for all biological computers, then this will make the difference between biological computers and electronic ones.

One defines a central nervous system to be a network of $\mathcal{N}$ interconnected neurons. The total number of neurons is approximately 10^{10}, each of which connects to a so called signal target $\mathcal{ST}$ made of a cluster of some $10^3 - 10^4$ neurons. The nearest neighbour connections are called synapses (Sy), by which neurons are sending electrical and chemical signals to their $\mathcal{ST}$ cluster. It is supposed that any Sy is in one of the two possible states: firing and non-firing. As such, a certain analogy with spin systems, the well-known Little-Hopfield model [9], has been developed for simulating the associative memory of neural networks [10] and constructing learning algorithms for artificial intelligence. I would like to suggest possible connections of the activity of neural networks with some of the self-organized criticality models, that clearly one can envision, especially with the forest-fire (FF) class of models [11]. By appropriately generalizing the automaton rules of the FF models one can put them in correspondence with the quasi-stable patterns (memory) of neuronal firing activity. On the other hand, the Hopfield model is based on a quasispin representation of the physical states of firing and nonfiring [12]: memories to be stored are just patterns of binary sequences of quasispin variables $S_i = \pm 1$ where the index i is running over the whole number $\mathcal{N}$ of neurons in the network. Such a sequence may be regarded as an $\mathcal{N}$-component vector, characterizing the patterns, which are stored if they are turned into attractors of the spin-flip dynamics. This dynamics is governed by the signs of the exchange sums, where the coupling constants are considered to be the synaptic strengths. One can turn given patterns into attractors by the Hebb's mechanism [13], i.e., by appropriate modifications of the synaptic strengths, known as learning algorithms. Major difficulties were surpassed by bounding the synaptic strengths (learning within bounds), and at the present time the "Ising-like" models with all the apparatus of spin-glass theory [14] are by far the most powerful paradigm of physics for studying the brain activity considered as sets of computations. These are, in a few words only, the basic facts required in order to proceed in a constructive-computing manner towards further understanding of the higher functions of human brain and/or the interconnections among its subsystems (visual cortex, somatosensory cortex, motor cortex, thalamus, peripheral cortex).

Hopfield's paradigm is fine and quite efficient for artificial intelligence purposes. Nevertheless there is one really difficult question for it and this is the title of the first chapter in *Emperor's*: *Can a computer have a mind ?* In other words, what is the fact providing the distinc-

tion between a biological computer and an electronic one ? Is a biological computer just a more complicated electronic one or is there a fundamental difference ? Is this difference provided by quantum mechanics ? I shall try to formulate some arguments based on quantum ideas in Section IV below. Here I shall list other general properties of the brain that one can notice when is passing at the level of the higher brain functions:

(i) The higher functions are in general delocalized, display some degree of stochasticity, and are intercorrelated in parallel computing manner. There are many unresolved questions concerning the integration of cortical activity and the 'higher' integrative areas [15]

(ii) The neurons have the capacity of working out several inputs and are selecting the output signal and its frequency, the cooperative result of such a processing being a kind of generalized holographic recording of the outside world.

An interesting columnar self-organization of the neocortex is well-known: "minicolumns " of about 110 neurons (about 220 in the visual cortex) comprise modular units vertically oriented relative to the warped and convoluted neocortical surface through almost all the regions of the neocortex. The short-ranged fiber interactions (both excitatory and inhibitory) between neurons take place within about 1 mm, which is the extent of a "macrocolumn" comprising about one thousand minicolumns, whereas the long-ranged cortico-cortical excitatory fibers (the white matter) have an averaged length of several centimeters. This structural organization supports the idea of computing-oriented activity of the brain.

Shelepin, whom I cite in Section IV below, has suggested the theory of complex Markov chains as a sufficiently general mathematical description of the higher functions of the brain, which include quantum mechanics as a particular case, but in any case, one has to be aware of the impressive panoply of disciplines contributing to their understanding: neurobiology, computer science, biochemistry, artificial intelligence, molecular biology, mathematics, psychology, physics, and philosophy.

III. CONSCIOUSNESS AND MESOSCOPIA

Perhaps the most fundamental notion in neuropshycology is the global attribute of the brain known as consciousness. In general terms, what we usually call awareness or consciousness or "unique personality" might be considered a problem of spatio-temporal synchronization between the two cerebral hemispheres. This interpretation comes out from an interesting neuro-disease, which manifests itself by the so-called "multiple personalities" cases to be found for example in the book of Gazzaniga and LeDoux [17]. This neuro-disease is the result of the therapeutic operations (severing of the corpus callosum)

for some forms of epilepsy, and more generally can be considered as split-brain experiments. Such cases have the exterior data mapped only on one cerebral hemisphere without the other hemisphere being aware of them. Thus, one can think simply of a desynchronization of the two hemispheres at the level of their neuronal signals. This alone explains the attention paid to the synchronized oscillations in the cerebral cortex [18]. *Emperors's* p. 385 mentions also the interesting 'P.S.' split-brain case revealed by neurophysiologists, showing a transient phase in which only one hemisphere could speak, but both hemispheres could comprehend speech. For the cases with removed portions of visual cortex and comments on the phenomenon of *blindsight* as related to consciousness, see *Emperor's* pp. 386-387.

Clearly, it is extremely difficult to accept a definite physical base for such an esoteric concept as consciousness dealing mainly with the subjective activity of the brain. It may be called a sense for which the receptive organs are directly the neurons, in which all the other sense stimuli can be more or less included on a subjective base, that is with degrees of importance varying from one brain to another. The neuronal global response to such a brain activity is the personal representation of the exterior and interior world altogether and may be called consciousness. It is also a parameter of the evolution in time of an individual brain, obviously connected with both short-term and long-term memory. It is a direct neuronal "pshycological", and sometimes almost physiological sense that occurs as an outcome of all the mental functions of an individual brain working in *synergis*, and probably, from this standpoint, one can interpret it as an informational measure of the coupling between the 'subjectivity' and the 'objectivity' of a brain.

There are at least two physical phenomena contributing to consciousness in its objective form. One is the synchrony of the neurons. When synchrony is between the neurons of the two hemispheres it provides the 'unique personality' character of the brain. The other mechanism is the stationarity of the 40 Hz collective oscillations of the neurons as shown by experiments on animals. Synchrony and the 40 Hz oscillations together are related to the so-called 'binding problem' in neuroscience which is essentially the making of a unified perception. But what makes neurons to oscillate collectivelly at roughly 40 Hz. Is this a reflection of the nonlinear dynamics of the neuronal network as a result of functions such as memory and attention or it has to do with the microtubule architecture of the neuron skeletons ? Again cummulative effects can be invoked. The microtubules, which are long (350-750 microns in the axons), and rigid polymers made of a globular protein called tubulin, were suggested to generate quantum effects of importance for consciousness by Penrose [16]. I would like to come here with an argument of interest for microtubules taken from the mesoscopic phenomena recently put into evidence in the

realm of carbon nanotubes (for their history see [19]). Carbon nanotubes are thread-like structures forming in carbon deposition stimulated by an electron beam, and are pretty well observed in scanning transmission electron microscopy [20], and, as a matter of fact, they are amongst the few laboratory-produced structures covering the crossover from microscopic to the mesoscopic regime. In an interesting experiment, Kasumov, Kislov and Khodos [21] observed displacements of the free ends of threads of amorphous hydrocarbons of 200-500 $\mathring{A}$ in width and 0.2-2.0 μm in length relative to a fixed reference point on the screen of a transmission electron microscope. The minimal displacements were of about 5 $\mathring{A}$, and the observations were made in a stationary regime of the threads, i.e., very low density of the beam current (0.1 pA/cm^2). They observed random jumps of the free ends of the carbon threads of 10-30 $\mathring{A}$ in length with a frequency of 1 Hz. All the possible reasons of induced vibrations were taken into account by the authors with the conclusion that no classical external force can explain the jumps and finally they attributed the oscillations to jumping effects related to spontaneous localization ideas of Ghirardi, Rimini, and Weber [22]. In our opinion, the jumps in length of the carbon nanotubes can result from a mesoscopic Brownian motion in which there is a competition between some dynamical instability and damping, being different from the microscopic Brownian jumps which never damp out. If such jumps will be confirmed by other experiments, and their origin identified, there will be important consequences for neuronal microtubules too. For instance, one can associate the 40 Hz oscillations either with the frequency of the jumps of the network of neuronal microtubules due to a mesoscopic Brownian motion as mentioned above or with spontaneous localization ideas [22] as applied to microtubules. Actually, microtubules are already an active experimental and theoretical research field [23]. Their interesting growth properties have been recently under focus [24], and also non-linear energy-transfer mechanisms in microtubules have been proposed [25] making the field more physical. They may play an important role in the brain plasticity (*Emperor's* pp. 396-398). At the same time, it is quite obvious that graphene tubules can reveal many phenomena of worth for biological microtubules as well.

IV. HINTS FOR QUANTUM APPROACHES TO THE HUMAN BRAIN

I shall start this section by recalling Penrose's rather strong speculation on the existence of single-quantum sensitive neurons (*Emperor's* pp 400-401). Yet independently of this speculation, there are various other ideas concerning possible quantum treatments of the brain.

I would like to present shortly some facts from superfluorescence (SF) that might be of importance for Hop-

field's paradigm as I already mentioned at the end of Section II. Perhaps the simplest and probably useful way to think of quantum effects within human brain is to consider it as a kind of generalized Dicke superfluorescent (superradiant) system. This has been suggested by Shelepin [26] as an analogy for the two-position switch of axons. Four decades ago, Dicke has pointed out that $\mathcal{N}$ atomic oscillators interacting with a common radiation field are not independent and live in a correlated state [27] that, under certain conditions, can display a collective radiative deexcitation, with all $\mathcal{N}$ oscillators acting like a single rigid dipole. In the original treatment, the matter-radiation system is described by a Hamiltonian of three terms corresponding to a collection of two-level atoms, a one-mode field, and a one-photon Dicke interaction (a simple coupling between the transition operators and the absorption/emission operators of the photon). On these lines, particularly interesting would be to reveal counterpropagating correlations of the type recently put into evidence and discussed in solid-state superfluorescence [28] [29] with quasi-one-dimensional active volumes (pencil-shaped excitation volume) of length much longer than the emitted wavelength. Let me point out that even of more relevance to the problem of superradiant neurons is the observation of *hyperradiance* (HR) from phase-locked soliton oscillators in the setup of *long* Josephson junctions [30], because neurons are closer to soliton oscillators than to atomic ones. In any case, the *hyperradiance* phenomenon must be investigated in detail in the newly fabricated superconducting neural circuits [31]. To pass to neurons, one can simply assume that SF brain phenomena are induced by certain particular neurons acting similarly to the SF centres in crystals, whereas one can invoke some magnetic coupling between the synapses when the analogy with the Josephson junctions is pursued. In the first case for example, one is allowed to consider distributed-feedback structures due to density fluctuations of the SF neurons as the origin of the correlations.

Perhaps it is worthwhile to note that the strong correlations between counterpropagating one-dimensional pulses are absent in the gas phase. One might have in this way more than a naïve answer to the naïve question of why the brain is in a solid-state phase and not in a gas one. Clearly, it would be extremely interesting to look for counterpropagating correlations between the two cerebral hemispheres and to see the implications for brain synchronization. Their similarity with the EPR quantum correlations [32] should be investigated in order to get insight and provide good answers to the question: *Does quantum mechanics/quantum-like effects make us intelligent ?* It is worth mentioning at this point that some time ago, Vinduška [33] elaborated on the impossibility of creating quantum correlations with electronic computers. It might well be that a biological computer makes use of EPR-type correlations, thus promoting it-

self to a superior level of existence. What one should keep clear in his mind is that superfluorescence is a co-operative phenomenon, i.e., the output is proportional to the squared number of neurons involved, and it is due to some type of emission process and not to an amplification of an input signal. This implies a "laser"-like action of some brain activity.

On the other hand, there are many mathematical aspects involved in treating the human brain as a macroscopic quantum state. The first problem is to define rigorously the macroscopic brain quantum state. In this respect, we draw attention to the paper of Duffield, Roos, and Werner [34], who defined some notions of mean field limit for nets of states converging to a macroscopic limit state.

Of much relevance to the field of neuropsychology might be the experimental findings of Kelso *et al* [35] who put into evidence, by means of SQUID detectors, spontaneous transitions in the neuromagnetic field patterns. They claimed that such transitions are to be associated with the switching of the non-equilibrium patterns formed by the brain during the transition between coherent states, and so from one behavior to another one. One might guess that various types of coherent and squeezed states [36], when appropriately generalized, and within information-theoretic pictures [37], will have important applications in this field.

V. QUANTUM EFFECTS IN HUMAN RECEPTORS

We are interested in the human receptory organs since they are the places where manifestations of quantum effects from the standpoint of their sensitivity and response have been reported so far. At the cell scale, human brain has quantum (molecular) receptors of the outside fields. These receptors absorb electromagnetic radiation at the level of tens to thousands of quanta per mode as well as phonons in the same amount. More powerful fluxes are already damaging.

A. Visual or electromagnetic reception

Perhaps, the best sensory system in which one may have hopes for studying quantum correlation phenomena to be associated with the human brain is the visual system (from the eye up to the visual cortex). In fact, in this case one encounters experimental results on the rod sensitivity to single photons. Actually, biological photoreception has mesoscopic scale, and as such, is just at the transition point from quantum reception to classical one. For a good introduction to quantum fluctuations in the human vision we refer to the review paper of M.A. Bouman *et al* [38]. For the absorption of a single photon

by a rhodopsin pigment and its amplification ending up into a neural response see Lewis and Del Priore [39], and for the responses of the retinal rods of toads to single photons see Baylor, Lamb, and Yau [40]. Penrose is also citing Hecht, Shlaer, and Pirenne [41], who established in a famous experiment that an input signal of seven photons is required by humans for conscient perception.

I now address the relationship between the electromagnetic vacuum fluctuations and the possibility of four-dimensional and more-dimensional vision. My point is that the electromagnetic zero-point fluctuations are not very sensitive to the spatial dimensions of the macroscopic world. In other words, the number of spatial dimensions is a quite free parameter at the level of vacuum fluctuations [42]. Of course, the conversion of two-dimensional images into three-dimensional ones is well explained in the optics of the eye as a stereoscopic effect and it is for this reason that we need two eyes, but here I am referring to more-than-three spatial dimensions. In my opinion, the Regge calculus approach [43] to the more-dimensional manifolds, in its strict geometrical meaning, will be quite useful for the problem of producing vision in more dimensions, especially when the quantization of 4D Regge links will be properly understood [44]. The detailed features of the Regge quantum links will be essential in proceeding toward a biological more-than-three dimensional vision. Moreover, one should be aware of the experimental discovery of Hubel and Wiesel [45] who first observed that endstopped hypercomplex cells (that is, selective to moving-bar stimuli of specific lengths) in the visual cortex could respond to curved stimuli and sugessted they might be involved in the detection of curvature. More recently, Dobbins, Zucker and Cynader [46] provided both a mathematical model relating endstopping to curvature and physiological evidence that endstopped cells in area 17 of the cat visual cortex are selective for curvature.

There seems possible the implementation of multi-dimensional image construction as well as multi-dimensional photoreceptors at the mesoscopic level, either by using new types of "depth" effects or holographic methods. Also, more should be known on the connection between the internal representations of rigid transformations and cortical activity paths as suggested by Carlton [47].

Let me remark on another important feature of living creatures. While within the sonic world, the living creatures possess as a rule both receptory and emitting organs, this is not so in the electromagnetic world, where, in overwhelming majority, only receptors are present, and there is no electromagnetic 'mouth'. Moreover, if this is to exist, it should be a kind of biological laser [48], in order to be used for communication purposes. Although in the animal world there are certain species of fishes possessing organs recepting and emitting electrical pulses [49], it appears that the electric activity of the hu-

man brain, which is chemical in essence, is too weak to sustain a lasing activity of the brain, at least of the electromagnetic type. This looks frustrating, but we have to accept that it is much easier to build up mechanical organs than laser ones using biological materials.

Finally, we recall that according to Chomski [50], the fisiology of the eye-brain system is essential in interpreting the various trajectories we are observing in our visual field. Such an argument is put forth as a consequence of the so-called "rigidity principle" in human vision, that is the interpretation of the visual scene in terms of rigid objects in motion. On the other hand, the animal visual systems are projected to react to other types of movements.

B. Hearing or sonic reception

Quantum detection can be looked for in other sensory systems, in particular in the hearing system, where by quantum one should mean the phonon, although one can immediately estimate that the thermal environment actually forbids single phonon detection for humans [51]. In this subsection I would like to draw attention to an ethnological claiming I heard about in Trieste. Some time ago, the ethnomusicologist Mantle Hood wrote an essay on a ... quantum theory of music [52]. He advocates the idea that a manifestation of Bohr complementarity principle is to be encountered in this discipline of arts as *the continuity of the first partial of a tone sounded and the discontinuity of constantly shifting energies in the distribution of upper partials.* These ethno-concepts are not clear to the present author who is merely quoting the paper as a curiosity. According to Hood, *Musics*, as a form of cognitive learning, is based on physiological responses to aural stimuli transcending any mechanical differences in construction between the musical instruments. I remember that, during my stay in Trieste, I participated in Prof. Hood's ethno-experiment, which meant just hearing successively as diverse instruments as: Scotish bagpipe, flute, tambura, mridangam, Tibet funeral horns, Korean kayagam, Japanese gagaku, Irish tin whistle, and so on, in order to test his assumption, but frankly I was not capable of saying anything interesting about my aural stimuli.

As for the mesoscopic musical scales to which some technologies are already knocking the door, one can foresee the numerous applications of wavelets in processing musical sounds [53]. The wavelet approach [54] looks already essential for studying the hearing system of the brain, as well as the visual system and other brain phenomena, at the mesoscopic scale.

C. Uncertainty principles

The usage of wavelet principles is not at all new for psychophysical experiments, especially in models of vision. The old Gabor functions (harmonic oscillations within Gaussian envelopes) [55] are in fact wavelets, and have been introduced by applying arguments from quantum mechanics. Gabor demonstrated that this class of "modulated probability pulses" is optimal in the sense that it possesses the smallest product of effective duration (or alternatively spatial extent) by effective frequency width. In the eighties, Daugman extended Gabor's work to two dimensional filters [56]. For linear filters there is an "uncertainty relation" which limits the resolution simultaneously attainable in space and frequency. In the past decade 2D Gabor functions have been applied to receptive fields of neurons in the striate cortex by many authors. They concluded that this filters provide a good description for the receptive field structure of simple cells in the cat striate cortex. In the words of Daugman "... the visual system is concerned with extracting information jointly in the 2D space domain and in the 2D frequency domain, and because of the incompatibility of these two demands, has evolved towards the optimal solution via 2D channels that roughly approximate 2D Gabor filters." The problem of 'energetic' uncertainty principles in human visual perception has recently been tackled by Trifonov and Ugolev [57]. Moreover, in their paper there is a good historical account of the problem. The main a good historical account. The main idea is that since the human eye responds to the emitted luminescence, one may be endowed to look for an uncertainty principle involving the luminescence threshold and the spatial resolution.

One can foresee that more complicated families of wavelets and wavelet-based representations of the signals will be involved in reproducing the signal processing of more complicated visual and auditory receptive fields of neurons. In this case, the detailed study of new types of uncertainty relations will be of great importance. The interested reader is referred to the literature [58].

D. Quantal synaptic transmission ?

There is considerable debate in neurophysiology on the problem of quantal synaptic transmission. This is a dominant hypothesis concerning the chemical transmission, which is the principal means of neuronal communication in the central nervous system. The debate centers around statistical analyses of recorded histograms of excitatory postsynaptic currents, whose quantal nature means demonstration of successive peaks, ideally evenly spaced, which are thought to be of biological and not of statistical origin [59]. My opinion is that whenever one is facing statistical treatment of data one should proceed

with extreme care since there may occur unexpected statistical artefacts. I agree more with the demonstration provided by Clements [60] that regularly spaced peaks in a synaptic amplitude histogram can arise from sampling error than with the answer of Larkman, Stratford, and Jack [61].

VI. LIMITATIONS OF THE HUMAN BRAIN TO THE QUANTUM KNOWLEDGE

Recently, James D. Edmonds Jr. [62] examined the human brain limitations to quantum knowledge, citing Bohr's opinion that the task of physics is to reveal what we can say about Nature and not what is Nature [63]. According to this conjecture, which seems quite reasonable, "we only do brain-limited physics !". Hence, our theories are only strategies, i.e., decision making in the face of uncertainties. However, the crucial assumption which determines the structure of a strategy is due to dynamics and not to probabilities and is based on microscopic reversibility. This fundamental assumption gives rise to the equation of detailed balance, which is, as a matter of fact, Bayes's postulate in probability theory, i.e., the common way of conditioning for macroscopic probabilistic thinking. It is well-known that microscopic reversibility does not imply necessarily time reversal invariance [64]. On the other hand, the main components of logical reason are cause-effect relationships. By their very nature cause-effect correlations involve dynamics with a prefered direction of time. It would be therefore interesting to develop non-Bayesian strategies, since they might find a direct experimental field in the mesoscopic world. Such strategies will be applicable whenever one will take into account violations of microscopic reversibility and the activity related to some mesoscopic agent working like a Maxwell demon [65]. An interesting discussion of the breakdown of microscopic reversibility in enantiomorphous systems in the context of chemical evolution and origins of life has been provided by L. D. Barron [66], who introduced the concept of enantiomeric detailed balancing, that can be of interest to neuronal networks too.

The common logic of human thinking seems to be in difficulty whenever probabilistic reasoning is coming into play. It is not at all an easy matter to elaborate languages and appropriate terminology for generalized probability judgements [67]. Indeed, Arthur Miller attributed to Heisenberg the following remarkable recollection of the years 1926-1927: "we couldn't doubt that quantum mechanics was the correct scheme but even then we didn't know how to talk about it, and the discussions left us in a state of almost complete despair". As a matter of fact we are at this point very close to the theories of language formation, which predict a period of chaotic dynamics both in groups of cerebral neurons and in the thalamocortical pacemaker [68]. According to Damasio & Damasio [69]:

"A large set of neural structures serves to represent concepts; a smaller set forms words and sentences. Between the two lies a crucial layer of mediation..." and I would say of "meditation". It is this layer of mediation that one can associate with the period of chaotic dynamics.

At a more physical level, let's touch upon Zipf's principle of minimal effort in speaking [70] or, equivalently, Mandelbrot's condition of minimal cost of information transmission [71]. Such variational principles or conditions can be associated with 1/f noise in speaking and writing as a manifestation of information transmission in normal human communication. For a recent derivation of a universal 1/f noise from an extremized physical information see Frieden and Hughes [72]. Recall now that a 1/f noise is only one of the two requirements of the self organized criticality (SOC) paradigm. The second one is a fractal or multifractal spatial structure of the region producing the 1/f noise, i.e., for speech, Broca's area, and for understanding languages, Wernicke's area. What we suggest here is self organized critical states of these brain areas as possible non-equilibrium dynamical brain states for normal verbal communication. Passing to an electromagnetic (nonverbal) communication, and accepting the idea of an electromagnetic lasing organ as alluded above, the information transmission would be through the vortex patterns in the transverse plane of the laser beam [73], but again taking into account the result of Frieden and Hughes [72], one can claim that a SOC paradigm will still be at work, however at much superior levels of information rates.

An interesting debate concerns the non-verbality of thought (*Emperor's* pp 423-425). There is the remarkable phrase of Henry Adams in his *Education*: "No one means all he says, and yet very few say all they mean, for words are slippery and thought is viscous." Many artists certainly don't think their masterpieces in words, at least during the creative instants, and also a number of eminent scientists were completely against words and insisted on their drawback and even damaging effect with respect to thoughts (for examples, see *Emperor's* pp 423-425). However, as Penrose mentions, there are persons managing to process a rapid and efficient transcription of their thoughts into words such as philosophers, and this certainly with no less merits. Admittedly, there are ways of thinking, like artistic and/or scientific ones, for which words are not so much useful. So what are thoughts really ? Can they be associated with various transport phenomena of nerve signals, like various types of solitons and other non-linear wave structures in neuronal nets ? For example, one can work out a simple non-linear Schrödinger equation, either discrete or continuous, for the propagation of thought interpreted as an envelope soliton and discuss "collapse"- like and/or "blow-up"-like phenomena corresponding to various phases of the creativity processes. Moreover, non-linear extensions of the quantum mechanics, not fulfilling the second law of

thermodynamics [74], may well be at their home inside the human brain, which being a living system does not obey the usual formulation of the second law of thermodynamics.

Penrose's discussion of the nerve signals (*Emperor's* pp 389-392) is very short. Hodgkin-Huxley oscillator model and the FitzHugh-Nagumo one are two well-established nonlinear models for this phenomenon. To fully be aware of the importance of non-linear partial differential equations for pulselike voltage waves carrying information along a nerve fiber I refer the reader to the review paper of Scott [75].

I also quote as being very close to Bohr's conjecture, Wolfram's point of view [76] who, in a cellular automaton context, claimed that physical processes are only computations, whence the difficulty of answering physical questions is directly connected to the difficulty of performing the computations. At the quantum level of the human brain, it will be of interest to obtain further insight into its "quantum computer" aspects [77], taking into account the recent claims of improved efficiency for certain algorithms [78], and also for reasons implied by quantum logic theories [79].

VII. CONCLUSIONS

In this essay, I expressed a range of speculative ideas that resulted from the notes I used to make during my first reading of *The Emperor's New Mind* and my simultaneous random jumping from shelf to shelf in the ICTP-SISSA libraries. One warning for the reader is that none of those ideas may be truly of worth, although my feeling is that human brain can support phenomena described by generalized quantum methods, other than the usual Ising-like transcription of memory patterns in neural networks. Particularly interesting would be a generalized brain superradiance. Also direct vision (not by projections) in more than three dimensions is another interesting issue.

Quantum mechanics *per se* seems to be a weak theory and not a proper scientific language when confronting it with the complexity of the brain activity, and also when compared with other methods put forth in tackling this highly interdisciplinary research field. However, the progress in our technologies and the advancement of our understanding of the functioning of the human brain at quantum and mesoscopic levels may well have important consequences in the future. It is somewhat amasing yet not surprising, that while the most advanced tomographic techniques of visualising the brain activity are based on quantum mechanical phenomena, we have so little to say about the quantum-mechanical brain. For the time being, the main doctrine that brain activity is entirely computation is dominating the field despite a few metaphysical objections related for example to the

consciousness issue, and I am afraid that even the microtubules and their infrastructure can be included in a computational scheme (according to the principle that digital computing can be used to model and/or to describe most physical systems). Indeed, M.P. Barnett [80] has already suggested that microtubules are processing channels along which strings of bits are propagating from one place to another, and they may well be the material base for the *ultimate computing* [81] in the molecular framework. Microtubule networks may turn into a major research field in the near future. For example, they are predicted to possess piezoelectric properties allowing a possible application of recently proposed experimental techniques called two-photon diffraction and holography [82].

Finally, whether or not the quantum features of the human brain will prove difficult to reveal, this does not mean at all that a quantum brain cannot be fabricated.

• 1. Introduction

[1] M. Gell-Mann and J.B. Hartle, in *Proceedings of the 3rd International Symposium Foundations of Quantum Mechanics*, S. Kobayashi et al., eds., (Physical Society of Japan, Tokyo, 1990), p. 321

[2] H. Everett, Rev. Mod. Phys. **29**, 454 (1957)

[3] B.S. DeWitt, Phys. Today **23**, 30 (September 1970); B.S. DeWitt and N. Graham, eds., *The Many-Worlds Interpretation of Quantum Mechanics* (Princeton University Press, Princeton, 1973)

[4] S. Sonego, Ann. Fond. L. de Broglie **17**, 405 (1992); **18**, (1993) for Erratum

[5] A. Peres and W.H. Zurek, Am. J. Phys. **50**, 807 (1982); D. Deutsch, Int. J. Theor. Phys. **24**, 1 (1985)

[6] R.P. Feynman, "There's plenty of room at the bottom", talk given on December 26, 1959 at the annual meeting of AIP at Caltech and republished in J. Microelectromechanical Systems **1**, 60 (1992)

[7] L. Ingber, Phys. Rev. A **44**, 4017 (1991); Phys. Rev. E **49**, 4652 (1994)

[8] R. Penrose, *The Emperor's New Mind* (Oxford University Press, first printed 1989, reprinted with corrections 1989 and 1990)

• 2. What is the human brain ?

[9] J.J. Hopfield, Proc. Natl Acad. Sci. USA **81**, 2554 (1982); **79**, 2554 (1982); Phys. Today **47**, 40 (Febr. 1994); W.A. Little, Math. Biosci. **19**, 101 (1974); G. Parisi, J. Phys. A **19**, L617 (1986)

[10] For an introductory book see: T. Khanna, *Foundations of Neural Networks*, (Copyright Addison-Wesley, 1990)

[11] P. Bak, K. Chen, and C. Tang, Phys. Lett. A **147**, 297 (1990); K. Christensen, H. Flyvbjerg, and Z. Olami, Phys. Rev. Lett. **71**, 2737 (1993); C.L. Henley, Phys. Rev. Lett. **71**, 2741 (1993)

[12] W.S. McCulloch and W. Pitts, Bull. Math. Biophys. **5**, 115 (1943)

[13] D.O. Hebb, *The Organization of Behaviour* (Wiley, New York, 1949)

[14] M. Mézard, G. Parisi, and M. Virasoro, *Spin Glass Theory and Beyond*, (World Scientific, Singapore, 1987); D.J. Amit, *Modeling Brain Function*, (Cambridge Univ. Press, Cambridge, 1989); D.L. Stein, *Spin Glasses and Biology*, (World Scientific, Singapore, 1992)

[15] F. Crick, Proc. Natl. Acad. Sci. USA, **81**, 4586 (1984); A.R. Damasio, Semin. Neurosci. **2**, 287 (1990)

• **3. Consciousness and mesoscopia**

[16] J. Horgan, Scientific American **271**, 72 (July 1994)

[17] M.S. Gazzaniga, J.E. LeDoux, *The Integrated Mind* (Plenum, New York, 1978)

[18] R.R. Llinas, Science **242**, 1654 (1988)

[19] J.A.E. Gibson, Nature **359**, 369 (1992)

[20] S. Iijima, Nature **354**, 56 (1991); **356**, 776 (1992); P.M. Ajayan and S. Iijima, Nature **358**, 23 (1992); T.W. Ebbesen and P.M. Ajayan, Nature **358**, 220 (1992); S. Iijima, P.M. Ajayan, and T. Ichihashi, Phys. Rev. Lett. **69**, 3100 (1992); L.A. Chernozatonskii, Phys. Lett. A **166**, 55 (1992); M.R. Pederson and J.Q. Broughton, Phys. Rev. Lett **69**, 2689 (1992)

[21] A.Yu. Kasumov, N.A. Kislov and I.I. Khodos, "Vibration of cantilever of a supersmall mass", unpublished (1992); see also, V.V. Aristov, N.A. Kislov and I.I. Khodos, "Direct electron beam-induced formation of nanometer carbon structures in STEM", in IOP Conf. Series # 117 (1992)

[22] G.C. Ghirardi, A. Rimini, and T. Weber, Phys. Rev. D **34**, 470 (1986); This is a simple model within the Schrödinger interpretation of the wave function, attempting at solving the measurement paradox. This is done by postulating a non-unitary evolution law in the form of a discontinuous localization at the mesoscopic scale. The authors assume a normalized Gaussian jump factor with the frequency of the jumps (10^8 years^{-1}) and the localization parameter of the Gaussian (10^{-5} cm) considered to be new fundamental constants of Nature. This model can be modified and adjusted for the purposes of explaining the experimental results of Kasumov, Kislov, and Khodos. In fact, GRW model belongs to the set of extensions of quantum mechanics to simulate dissipative processes (there are two classes of models called quantum- state diffusion and state-vector Monte Carlo, respectively), which have already found many applications in quantum optics. For details see B.M. Garraway and P.L. Knight, Phys. Rev. A **49**, 1266 (1994)

[23] P. Dustin, *Microtubules* (Springer-Verlag, New York, 1984), 2nd ed.

[24] M. Dogterom and S. Leibler, Phys. Rev. Lett. **70**, 1347 (1993)

[25] M.V. Satarić, J.A. Tuszyński, and R.B. Žakula, Phys. Rev. E **48**, 589 (1993)

• **4. Hints for quantum approaches to the human brain**

[26] L.A. Shelepin, Proc. Lebedev Phys. Inst., vol. **173**, 1, (1988) [Copyright 1988 Nova Science Publishers Inc.]

[27] R.H. Dicke, Phys. Rev. **93**, 99 (1954); For an excellent review see M. Gross and S. Haroche, Phys. Rep. **93**, 301 (1982); for the automaton theory applied to the brain see: J.D. Victor, Physica D **45**, 205 (1990); Considerations of mental events as Heisenberg events are to be found in: H.P. Stapp, "Mind, Matter, and Pauli", Invited Lecture at the Symposium on the Foundations of Modern Physics 1992: The Philosophic Thought of W. Pauli. Helsinki, Aug. 10-12, 1992 [LBL-32761, February 10, 1993]

[28] D. Jansen and A. Stahl, Europhys. Lett. **18**, 33 (1992)

[29] R. Bausch et al., Europhys. Lett. **10**, 445 (1989); see also: L.O. Schwan et al., Phys. Rev. A **40**, 7093 (1989)

[30] T.F. Finnegan and S. Wahlsten, Appl. Phys. Lett. **21**, 541 (1972); C. Varmazis et al, Appl. Phys. Lett. **33**, 357 (1978); M. Cirillo et al, Phys. Lett. A **167**, 175 (1992); N. Gronbech-Jensen and J.A. Blackburn, Phys. Rev. Lett. **70**, 1251 (1993)

[31] Y. Mizugaki et al., Appl. Phys. Lett. **62**, 762 (1993)

[32] A. Einstein, B. Podolsky, and N. Rosen, Phys. Rev. **47**, 777 (1935); J.S. Bell, Physics **1**, 195 (1964); *Speakable and Unspeakable in Quantum Mechanics* (Cambridge Univ. Press, UK, 1987); for an elementary discussion see D. Harrison, Am. J. Phys. **50**, 811 (1982)

[33] M. Vinduška, preprint Dubna E5-91-485 (1991); see also: P.J. Bussey, Phys. Lett. A **123**, 1 (1987); T.F. Jordan, Phys. Lett. A **94**, 264 (1983); H. Scherer and P. Busch, Phys. Rev. A **47**, 1647 (1993)

[34] N.G. Duffield, H. Roos, and R.F. Werner, Ann. Inst. H.P., Phys. Théor. **56**, 143 (1992)

[35] J.A.S. Kelso et al., Phys. Lett. A **169**, 134 (1992); Also Oshins used a SQUID to study mental rotations, see E. Oshins, "Searching for spinor representations of global symmetry in mental rotations using a SQUID: An informal seminar." (delivered at Stanford University, August 14, 1984)

[36] D.A. Trifonov, Phys. Lett A **187**, 284 (1994)

[37] R. Horodecki, Phys. Lett. A **187**, 145 (1994)

• **5. Quantum effects in human receptors**

[38] M.A. Bouman et al., *Progress in Optics XXI-I*, 79, E. Wolf (ed) (Elsevier, 1985)

[39] A. Lewis, L. Del Priore, Physics Today **41**, 38 (January 1988)

[40] D.A. Baylor, T.D. Lamb, and K.-W. Yau, J. Physiol. **288**, 613 (1979)

[41] S. Hecht, S. Shlaer, and M.H. Pirenne, J. Gen. Physiol. **25**, 891 (1941)

[42] The fundamental problem of the number of spatial dimensions can be traced back to H. Poincare, Rev. metaphys. et morale **20**, 483 (1912) and P. Ehrenfest, Proc. Amsterdam Ac. **20**, 200 (1917); Ann. Physik **61**, 440 (1920). For more recent papers on the bounds on deviations from three spatial dimensions, see: M. Hayashi, K. Katsuura, and H. Vera Mendoza, Rev. Mex. Fis. **37**, 712 (1991); J.L. Torres and P.F. Herrejón, Rev. Mex. Fis. **35**, 97 (1989) and references therein.

[43] T. Regge, Nuovo Cimento **19**, 558 (1961); for a recent review see: R.M. Williams and P.A. Tuckey, Class. Quantum Grav. **9**, 1409 (1992)

[44] V. Khatsymovsky, Phys. Lett. B **323**, 292 (1994)

[45] D.H. Hubel and T.N. Wiesel, J. Neurophysiol. **28**, 229 (1965)

[46] A. Dobbins, S.W. Zucker, and M.S. Cynader, Nature **329**, 438 (1987)

[47] E.H. Carlton, Biol. Cybern. **59**, 419 (1988) and references therein.

[48] In the literature one can find speculations on lasing actions and/or long-range coherence in living matter. E. Del Giudice, G. Preparata, and G. Vitiello, Phys. Rev. Lett. **61**, 1085 (1988) developed an analogy with free electron lasers for the interaction of the electric dipole of water molecules with the quantized electromagnetic radiation field and introduced the idea of water as a free electric dipole laser. On the other hand, Fröhlich's theory of long-range coherence of longitudinal-polarization modes is well-known for explaining some of the dielectric properties of biological cells (for a review, see H. Fröhlich, Int. J. Quantum Chem. **2**, 641 (1968)).

[49] J. Bastian, Phys. Today **47**, 30 (February 1994)

[50] N. Chomski, *Language and Problems of Knowledge. The Managua Lectures*, (Cambridge, MIT Press, 1988)

[51] W. Denk and W.W. Webb, Phys. Rev. Lett. **63**, 207 (1989)

[52] M. Hood, "The quantum theory of music II", The Inaugural Address read at the founding of the Jaap Kunst Stichting, Amsterdam, Oct. 3, 1991.

[53] D.E. Newland, Proc. R. Soc. Lond. A **444**, 605 (1994). Newland is also quoting an old book of Sir James Jeans with the interesting title *Science and Music* (Cambridge Univ. Press, 1937).

[54] For a book see: C.K. Chui, *An Introduction to Wavelets*, (Copyright Academic Press, 1992); see also H.H. Szu Ed., SPIE **2242**, *Wavelet Applications, Orlando, Fl*, (April 1994)

[55] D. Gabor, "Theory of communication", J. IEE (London) **93**, 429 (1946)

[56] J.G. Daugman, Vision Res. **20**, 847 (1980); J. Opt. Soc. Am. A **2**, 1160 (1985)

[57] M.I. Trifonov and D.A. Ugolev, in SPIE Vol. **2179**, pp. 60-69 (1994)

[58] M.J.W. Hall, Phys. Rev. A **49**, 42 (1994); R. Balian, C.R. Acad. Sc. Paris **292**, série ll, 1357 (1981); G.W. Wornell, Proc. IEEE **81**, 1428 (1993)

[59] Guosong Liu and J.L. Feldman, J. Neurophysiology **68**, 1468 (1992)

[60] J. Clements, Nature **353**, 396 (1991)

[61] A. Larkman, K. Stratford, and J. Jack, Nature **353**, 396 (1991)

• 6. Limitations of the human brain to the quantum knowledge

[62] J.D. Edmonds Jr, Speculations in Science & Techn. **14**, 231 (1991)

[63] N. Bohr, *Atomic Physics and Human Knowledge* (John Wiley, New York, 1985)

[64] D.N. Page, Phys. Rev. Lett. **70**, 4034 (1993)

[65] R. Bhandari, Pramaña **6**, 135 (1976); L.G.M. Gordon, Found. Phys. **13**, 989 (1983)

[66] L.D. Barron, Chem. Phys. Lett. **135**, 1 (1987)

[67] G. Shafer and A. Tversky, Cognitive Science **9**, 309 (1985); a bit more literature is: J.T. Cushing, Philosophy of Science **58**, 337 (1991); W. Mückenheim, Phys. Rep. **133**, 337 (1986); L. Accardi, Phys. Rep. **77**, 169 (1981); S. Youssef, "Quantum mechanics as Bayesian complex probability theory", preprint FSU-SCRI-93-77 (June 1993); S. Guiasu, Phys. Rev. A **36**, 1971 (1987); Y.F. Orlov, "The Logical Origins of Quantum Mechanics", preprint CLNS 93/1208 (1993)

[68] J.S. Nicolis and I. Tsuda, Prog. Theor. Phys. **82**, 254 (1989)

[69] A.R. Damasio and H. Damasio, Scientific American **268**, 63 (September 1992)

[70] G.K. Zipf, *Human behavior and the principle of least effort* (Addison Wesley, Cambridge, Mass., 1949)

[71] B. Mandelbrot, *Jeux de communication*, Publ. de l'Inst. de Statistique de l'Univ. de Paris (1953)

[72] B. Roy Frieden and Roy J. Hughes, Phys. Rev. E **49**, 2644 (1994)

[73] M. Brambilla et al., Phys. Rev. A **43**, 5090 and 5114 (1991)

[74] A. Peres, Phys. Rev. Lett. **63**, 1114 (1989)

[75] A.C. Scott, Rev. Mod. Phys. **47**, 487 (1975)

[76] S. Wolfram, Phys. Rev. Lett. **54**, 735 (1985)

[77] D. Deutsch, Proc. R. Soc. Lond. A **400**, 97 (1985)

[78] P.W. Shor, AT & T Bell Labs preprint May 1994; see also W.G. Unruh, hep-th/9406058

[79] The classic paper is: G. Birkhoff and J. von Neumann, Ann. Math. **37**, 823 (1936). There are hundreds and hundreds of papers in the field. For a recent paper see: C.J. Isham, "Quantum Logic and the Histories Approach to Quantum Theory", J. Math. Phys. **35**, 2157 (1994)

• 7. Conclusions

[80] M.P. Barnett, in *Proceedings of the Third Molecular Electronic Device Conference*, ed F. Carter (Naval Research Laboratory, Washington, DC, 1987)

[81] S.R. Hameroff, *Ultimate Computing* (North-Holland, Amsterdam, 1987)

[82] A.V. Belinskiĩ and D.N. Klyshko, JETP **78**, 259 (1994) [Zh. Eksp. Teor. Fiz. **105**, 487 (1994)]

More references

• Consciousness, Microtubules, Robot, Thought, Quantum Mechanics, Perception

I. Marshall, "Consciousness and Bose-Einstein condensates", New Ideas in Psychol.**7**, 73-83 (1989)

P. Pérez, "Physics and Consciousness", quant-ph/9510017

F. Crick and C. Koch, "Towards a neurobiological theory of consciousness", *seminars in The Neurosciences* **2**, 263-275 (1990) [visual awareness (VA)- the favorable form of consciousness to study neurobiologically is proposed to be made of a very fast form associated to iconic memory whose neural basis is difficult to study experimentally, and a slower form based on visual attention and short-term memory. In the slower VA, the iconic memory is due to an attention mechanism which binds togheter a cluster of neurons whose activity is related to the main features of the visual object on which the attention is paid. It is suggested that the cluster's collective activity is done by generating coherent semi-synchronous oscillations, probably in the 40-70 Hz range. These oscillations

are the source of a transient short-term memory. Several lines of experimental work are outlined that might help to understand the neural mechanism involved.]

Lester Ingber, "Statistical mechanics of neocortical interactions: Constraints on 40-Hz models of short-term memory", Phys. Rev. E **52**, 4561-63 (1995)

J.E. LeDoux, "Emotion, memory and the brain", Scientific American , June issue of 1994

D.N. Page, "Attaching theories of consciousness to Bohmian quantum mechanics", quant-ph/9507006 [theories of conscious perceptions are attached to Bohmian QM turning it into Sensible Bohmian QM. Previously, Don Page introduced the SQM concept, see "SQM: Are only perceptions probabilistic", quant-ph/9506010 and references therein.]

G. Vitiello, "Dissipation and brain", and the extended version with the title "Dissipation and memory capacity in the quantum brain model", Int. J. Mod. Phys. B **9** (1995) [the quantum model of the brain proposed by Ricciardi and Umezawa is extended to dissipative dynamics. Consciousness emerges as a manifestation of the brain dissipative dynamics.]

L.M. Ricciardi and H. Umezawa, Kibernetic **4**, 44 (1967)

V.E. Tarasov, "Strings and dissipative mechanics", hep-th/9506053

D.V. Nanopoulos, "Theory of brain function, quantum mechanics and superstring", hep-ph/9505374 [Fig. 1: Psychological or Personality profile as a function of time, parametrized in terms of the so-called synchordic collapse frequency $\gamma \equiv 1/\tau_c$ of the microtubule-network.]

N.E. Mavromatos and D.V. Nanopoulos, "Non-critical string theory formulation of MT dynamics and quantum aspects of brain function", ACT-09/95, CTP-TAMU-24/95, ENSLAPP-A-524/95; "On a possible connection of non-critical strings to certain aspects of quantum brain function", quant-ph/9510003

R. Penrose and S. Hameroff, "Orchestrated reduction of quantum coherence in brain MTs: A model of Consciousness", Mathematics and Computers in Simulation **40**, 453-480 (1996)

J.W. Griffin et al.,in *Molecular biology of the human brain* (1988 Alan R. Liss, Inc.), pp 141-145. [Excerpt: MTs in neurons, as in other cells, are composed of alpha and beta subunits. MTs are found throughout the neuron. They are the major cytoskeletal element in dendrites. In the axon, they are arranged as parallel, strictly longitudinal rods, with the length of individual MTs estimated to be 350-750 microns in length. They are uniformly polarized with the minus end toward the periphery.... MTs provide the essential structural substrate for fast axonal transport within the axon.]

H.P. Stapp, "Why classical mechanics cannot naturally accommodate consciousness but quantum mechanics can", LBL-36574 (February 8, 1995), prepared for a special issue of *Psyche*. "Quantum mechanical coherence,

resonance, and mind", quant-ph/9504003; "Values and the quantum conception of man", quant-ph/9506035; "The hard problem: A quantum approach", LBL-37163 (June 1, 1995). "Quantum propensities and the brain-mind connection", Found. Phys. **21**, 1451 (1991)

J.C. Eccles, "Do mental events cause neural events analogously to the probability fields of quantum mechanics ?", Proc. R. Soc. Biol. **227**, 411-428 (1986)

D.C. Bennett, "The practical requirements for making a conscious robot", Phil. Trans. R. Soc. Lond. A **349**, 133 (1994) [longterm project to design and build a humanoid *protein-free* conscious robot named Cog]

W.A.N. Ellis, "A theory of thought", Spec. in science and techn. **16**, 181 (1993)

A. Rose, "Quantum effects in human vision", in Adv. in Biol. and Medical Physics **5**, 211-242 (1957)

J.A. Wheeler and W.H. Zurek (eds), *Quantum theory and measurement*, Princeton series in Physics, (Princeton University Press, Princeton, New Jersey, 1983), section *Questions of principle* at pp. 769-771.

D.L. Gonzalez et al., "Pitch perception of complex sounds: Nonlinearity revisited", chao-dyn/9505001

• The Neuron: Some experiments

P. Fromherz and A. Stett, "Silicon-Neuron junction: Capacitive stimulation of an individual neuron on a silicon chip", PRL **75**, 1670 (1995)

G. De Stasio et al., "Scanning photoemission spectromicroscopy of neurons", PR E **48**, 1478 (1993)

R. Uma Maheswari et al., "Observation of subcellular nanostructure of single neurons with an illumination mode photon scanning tunneling microscope", Opt. Commun. **120**, 325-334 (1995)

• Stochastic Resonance, Complexity, Firing, Noise, Chaos, Fractal, Dendritic Tree, Neural Computation

P.C. Bressloff, "Average firing rate of a neural network with dynamical disorder", J. Phys. A **28**, 2457-2469 (1995)

P. Jung, "Threshold devices: Fractal noise and neural talk", Phys. Rev. E **50**, 2513 (1994)

L.A. Lipsitz and A.L. Goldberger, "Loss of 'complexity' and aging", J. Am. Med. Association (JAMA) **267**, 1806 (1992). [Fig. 3 in this paper, which is reprinted with permission from WB Saunders Co., shows an age-related loss of fractal structure in the dendritic arbor of giant pyramidal Betz cell of the motor cortex.]

T. Fukai, "Metastable states of neural networks incorporating the physiological Dale hypothesis", J. Phys. A **23**, 249 (1990)

J.A. Scott Kelso and A. Fuchs, "Self-organizing dynamics of the human brain: Critical instabilities and

Sil'nikov chaos", Chaos **5**, 64-69 (1995) and references therein.

S.J. Schiff et al., "Controlling chaos in the brain", Nature **370**, 615 (1994)

J.K. Douglass, L. Wilkens, E. Pantazelou and F. Moss, "Noise enhancement of information transfer in crayfish mechanoreceptors by SR", Nature **365**, 337 (1993) [SR observed in experiments with hydrodynamically sensitive hair mechanoreceptors in the tailfan of the crayfish *Procambarus clarkii-* termed also crayfish neuron experiment]

A. Longtin, A. Bulsara and F. Moss, "Time-interval sequences in bistable systems and the noise-induced transmission of information by sensory neurons", Phys. Rev. Lett. **67**, 656 (1991) [simulations of the effect of the noise intensity on the interspike interval histograms]

A.R. Bulsara, R.D. Boss, and E.W. Jacobs, "Noise effects in an electronic model of a single neuron", Biol. Cybern. **61**, 211 (1989)

A.R. Bulsara, A.J. Maren, G. Schmera, "Single effective neuron: dendritic coupling effects and SR", Biol. Cybern. **70**, 145-56 (1993)

A. Longtin, A. Bulsara and F. Moss, "Sensory information processing by noisy bistable neurons", Mod. Phys. Lett. B **6**, 1299 (1992)

A.R. Bulsara, S.B. Lowen and C.D. Rees, "Cooperative behavior in the periodically modulated Wiener process: Noise-induced complexity in a model neuron", Phys. Rev. E **49**, 4989 (1994)

K. Wiesenfeld, "SR on a circle", Phys. Rev. Lett. **72**, 2125 (1994) [electronic Fitzhugh-Nagumo neuron model, which essentially describes a threshold-plus-reinjection dynamics].

M.C. Teich, "Fractal neuronal firing patterns", in *Single neuron computation. Neural nets: Foundations to applications* (Academic Press, 1992) pp. 589-625.

J.G. Elias, "Artificial dendritic trees", Neural Computation **5**, 648 (1993)

P. Ling, "Neurocomputation by reaction diffusion", PRL **75**, 1863 (1995)

Á. Tóth and K. Showalter, "Logic gates in excitable media", J. Chem. Phys. **103**, 2058 (1995)

N. Suga, "Biosonar and neural computations in bats", Scientific Am. (June 1990)

J.A. Simmons, D.J. Howdell and N. Suga, "Information content of bat sonar echoes", Am. Scientist **63**, 204 (1975)

H.C. Tuckwell, *Stochastic processes in the neurosciences*, (SIAM, Philadelphia, 1989)

● **Laser-type phenomena**

G. Alli and G.L. Sewell, "New methods and structures in the theory of the multimode Dicke laser model", J. Math. Phys. **36**, 5598 (1995)

S.T. Zavtrak, "Generation conditions for an acoustic laser", Phys. Rev. E **51**, 3767-69 (1995)

● **Encephalograms**

N. Pradhan and P.K. Sadasivan, "Relevance of surrogate-data testing in electroencephalogram analysis", Phys. Rev. E **53**, 2684 (1996)