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Theory of Brain Function, Quantum Mechanics and Superstrings^{*}

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Abstract

Recent developments/efforts to understand aspects of the brain function at the *sub-neural* level are discussed. MicroTubules (MTs), protein polymers constructing the cytoskeleton, participate in a wide variety of dynamical processes in the cell. Of special interest to us is the MTs participation in bioinformation processes such as *learning* and *memory*, by possessing a well-known binary error-correcting code $[K_1(13, 2^6, 5)]$ with 64 words. In fact, MTs and DNA/RNA are *unique* cell structures that possess a code system. It seems that the MTs' code system is strongly related to a kind of "*Mental Code*" in the following sense. The MTs' periodic paracrystalline structure make them able to support a *superposition* of coherent quantum states, as it has been recently conjectured by Hameroff and Penrose, representing an *external* or *mental order*, for sufficient time needed for *efficient* quantum computing. Then the quantum superposition collapses spontaneously/dynamically through a new, string-derived mechanism for collapse proposed recently by Ellis, Mavromatos, and myself.

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At the moment of collapse, organized *quantum exocytosis* occurs, *i.e.*, the simultaneous emission of neurotransmitter molecules by the synaptic vesicles, embedded in the “firing zone” of the presynaptic vesicular grids. Since in the superposition of the quantum states only those participate that are *related* to the “initial signal”, when collapse occurs, it only enhances the probability for “firing” of the *relevant* neurotransmitter molecules. That is how a “*mental order*” may be translated into a “*physiological action*”. Our equation for quantum collapse, tailored to the MT system, predicts that it takes 10,000 neurons $\mathcal{O}(1\text{ sec})$ to dynamically collapse, in other words to process and imprint information. Different observations/experiments and various schools of thought are in agreement with the above numbers concerning “*conscious events*”. If indeed MTs, with their fine structure, vulnerable to our quantum collapse mechanism may be considered as the *microsites of consciousness*, then several, unexplained (at least to my knowledge) by traditional neuroscience, properties of consciousness/awareness, get easily explained, including “*backward masking*”, “*referral backwards in time*”, etc. Furthermore, it is amusing to notice that the famous puzzle of why the left (right) part of the brain coordinates the right (left) part of the body, *i.e.*, the signals travel maximal distance, is easily explained in our picture. In order to have timely quantum collapse we need to excite as much relevant material as possible, thus signals have to travel the maximal possible distance. The *non-locality* in the cerebral cortex of neurons related to particular missions, and the related *unitary sense of self* as well as *non-deterministic free will* are consequences of the basic principles of quantum mechanics, in sharp contrast to the “sticks and balls” classical approach of conventional neural networks. The proposed approach clearly belongs to the *reductionist* school since quantum physics is an integrated part of our physical world. It is highly amazing that string black-hole dynamics that have led us to contemplate some modifications of standard quantum mechanics, such that the quantum collapse becomes a detailed dynamical mechanism instead of being an “external” ad-hoc process, may find some application to some quantum aspects of brain function. It looks like a big universality principle is at work here, because both in the black hole and the brain we are struggling with the way information is processed, imprinted, and retrieved.

“...*the Astonishing Hypothesis* – that each of us is the behavior of a vast, interacting set of neurons.”

Francis Crick in
The Astonishing Hypothesis

“...*what will they think?* – *What I tell them to think.*”

Orson Welles in
Citizen Kane

Prooimion

Theory of brain function, quantum mechanics, and superstrings are three fascinating topics, which at first look bear little, if any at all, relation to each other. Trying to put them together in a cohesive way, as described in this task, becomes a most demanding challenge and unique experience. The main thrust of the present work is to put forward a, maybe, foolhardy attempt at developing a new, general, but hopefully scientifically sound framework of Brain Dynamics, based upon some recent developments, both in (sub)neural science and in (non)critical string theory. I do understand that Microtubules [1, 2] are not considered by all neuroscientists, to put it politely, as the microsities of consciounes, as has been recently conjectured by Hameroff and Penrose [3, 4]. Also, I do know that, the *one interpretation* of non-critical string theory, put forward by Ellis, Mavromatos, and myself [5, 6], which has led to *not* just an incremental change, but a total rethinking of the Quantum Mechanics *doctrine(s)* from the ground up, is not universally, to put it mildly, accepted. Leaving that aside, and time will tell, the emerging big picture “*when microtubules meet density matrix mechanics*”, as the reader hopefully will be able to judge for her(him)self, is rather astonishing. It looks like the modified quantum dynamics [5, 6] of microtubules [1, 2] may indeed lead [3, 4] to a rather concise, experimentally verifiable (presently and in the immediate future) theory of brain function [7]. Since this is a rather vast, multidisciplinary, and multidimensional subject, I kept in mind that *potential* readers may include (high-energy) physicists, biologists, biochemists, neuroscientists, medical doctors, including psychiatrists, psychologists, and psychotherapists, etc. Thus, I have tried my best to obey the “*technical minimality*” principle, and at the same time, to make it as self-contained and informative, as possible, by not assuming that psychoanalysts know about “*quantum coherence*”, or formal string theorists know about the Freudian “*unconscious proper*”, even if, in the latter case, they believe that *they know everything, and so why bother?!*

A concrete, technically elaborated proposal materializing some of the general ideas that I have tried to put forward here, has been worked out by Mavromatos and myself [7], work that I strongly encourage the interested reader to consult. I am fully aware of the rather speculative nature of the ideas presented here *and* of the sometimes circumstantial looking experimental evidence used to support them. Nevertheless, the way that different structures/mechanisms, from completely disconnected fields of knowledge, *fit and bind* together to produce such a *coherent*, dynamical scheme of the Brain function, makes it very hard to ignore the whole thing, by just believing that it is all coincidental, and nothing more than a grand illusion! It goes without saying that the responsibility for all views expressed here is completely mine.

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1 Introduction

The brain is our most valuable asset. The workings of the brain enable us to *think*, a fundamental function that, among other things, make us aware of our own existence or self-aware: *cogito, ergo sum*. Our perceptions of the universe, concerning its physical structure, form and function according to the universal physical laws, emerge from processed-in-the-brain representations of, hopefully, objective physical reality. Understanding the way that the brain functions is the primordial prerequisite for a complete physical understanding of the dynamic universe that we are part of. Undoubtedly, the brain is a very complicated system and thus to understand its function we need a coordinated effort involving several, if not all, branches of natural sciences: biology, neuroscience, biochemistry, physics, information theory/computer science, medicine, pharmacology, etc. We may eventually need some well-organized excursions to the realms of the science of mental life or psychology, for some extra help. Alas, the compartmentalization of science in our epoch, the highly technical jargon used in every field today, and the endemic narrow mindness, expressed best by the dictum *scientific conformity means intellectual stultification*, make the study of brain function a titanic struggle. Nevertheless, we ought to try to figure out, as explicitly as possible, as detailed as possible, and as predictive as possible, what are the most fundamental brain constituents and how they interact, so that they eventually produce this miracle that is called brain function, or put it differently, what makes the brain *tick*! This kind of *reductionist* approach has turned out to be very successful in the past, both in biology and in physics. The discovery of the double-helical structure of DNA, its identification with the gene, and the subsequent breaking of the genetic code, three bases for one aminoacid, in biology, as well as the discovery of electroweak unification and its subsequent spontaneous breaking that led to the Standard Model of the strong and electroweak interactions, in particle physics, are glowing examples of applied reductionism. In the case of the brain function, things are a bit more complicated and delicate extra care is needed, because the *mind* pops into the picture and thus the workings of the associated *Mental World* have to be addressed one way or another!

There are two extremes in handling the mental world problem:

- *Strong Artificial Intelligence* (SAI), purporting that the brain is just a computer and the only thing we have to figure out is the algorithm.
- *Cartesian or dualistic view*, assuming that brain and mind are *two distinct entities*, in interaction with each other.

$$\begin{array}{ccc}
 \text{Brain} & \begin{array}{c} \longleftarrow \\ \longrightarrow \end{array} & \text{Mind} \\
 \cap & & \cap \\
 \text{(Attainable physical world)} & & \text{(Mental world)} \\
 \parallel & & \parallel \\
 W_1 & & W_2
 \end{array} \tag{1}$$

where the mental world contains perceptions, ideas, memories, feelings, acts of volition, etc. I believe that both the above extremes are needlessly exaggerated. Instead I would like to propose here a new *unified approach* in which there is an “effective” mental world *emerging* from the physical world, but with distinct qualities

$$\begin{array}{ccccccc}
 W & \supset & W_1 & \otimes & W_2 & \longrightarrow & W_1 \\
 ||| & & & & \downarrow & \uparrow & \\
 \text{physical world} & & & & \text{causes} & \text{“collapse”} &
 \end{array} \tag{2}$$

Hard-core *materialists* are very welcome to be W_2 -world “blind” and just concentrate on the transition $W \rightarrow W_1$, in a kind of “just the facts ma’am” attitude! The present approach combines two new ideas/mechanisms developed recently, one in biology/neuroscience and one in superstring theory:

- i. It has been suggested by Hameroff (for some time now) [1] that *MicroTubules* (MT), cytoskeletal protein polymer paracrystalline structures within the neurons [1, 2], may be the fundamental units or microsites where most of the brain function originates. Furthermore, Hameroff and Penrose argued very recently [3, 4] that quantum effects may play a central role in the MT functioning and they were *desperately* looking for an explicit “*collapse of the wavefunction*” mechanism, that would validate their claims.
- ii. It has been suggested by Ellis, Mavromatos and myself that, in *one interpretation* of non-critical string theory, one gets naturally modifications of Quantum Mechanics, leading among other things to a new explicit “*collapse of the wavefunction*” *mechanism* and a *microscopic arrow of time* [5, 6].

The present proposal is to combine (i) and (ii).

It is remarkable that the string-derived collapse of the wavefunction mechanism fits “hand-in-glove” to the MT hypothesis. Thus, by complementing (i) with (ii), a rather detailed and spelled out scenario of brain function *emerges*. Namely, because the stringy collapse of the wavefunction is due to the truncation of the unattainable global degrees of freedom, the scheme depicted as Eq. (2) naturally emerges. W_2 should be identified with the physical “global state space” *isomorphic* to the “effective” mental world in the following sense: the *collapse of the wavefunction* is what causes the system to “decide” its course of action, thus being completely identifiable with the Jamesian¹ view of *consciousness*, as a *selecting agency*. The W_2 global states are the agents of collapse!

In this approach, the “collapse of the wavefunction” will result in well-coordinated, organized *exocytosis*, *i.e.*, the *simultaneous* emission of neurotransmitter molecules by the synaptic vesicles, embedded in the “firing zone” of the presynaptic vesicular grids [9]. From then on, standard neurophysiology applies, *e.g.*, setting the motor in action, etc. Clearly, the strong correlation between the “effective” mental world

¹William James (1842–1910), the father of American (physiological) psychology, observed that consciousness is not a thing or a substance, but rather a *process* [8].

and the “collapse of the wavefunction” (through the “global state space”) makes it clear how a mental intention (*e.g.*, I wish to bend my index finger) is *physically* and *causally* related to the motor action (*e.g.*, bending my index finger). Eventually, we may even be able to develop a “*mental code*”, *i.e.*, a dictionary that would translate feelings, intentions, etc directly into specific neurochemical states charting out detailed neurotransmitter molecule topologies. Actually, even if this statement sounds extremely far-fetched speculation and off-the-wall, the *universality* of the “effective” mental world for all humans, with of course all its diversity, cries out for an objective mapping between mental and specific neurochemical processes. A good analogy here is the “*genetic code*”, a well-tabulated dictionary between “base” sequencing in DNA and aminoacid, thus protein, production on the ribosomes [10]. Proteins, of course, are our basic building blocks that are responsible for the way we look, move, etc.

In section 2, I will discuss *Brain Mechanics*, *i.e.*, some very general arguments of what the brain is supposed to do and how it does it, while in section 3, I will present some elements of *Quantum Mechanics*, useful in our subsequent discussions. Section 4 provides a view of some *Brain morphology and modeling*, based upon classical notions and some criticism and problems they are facing. Section 5 provides some elements of *string-derived density matrix mechanics*, an extension of orthodox Quantum Mechanics, while sections 6 and 7 discuss the *biochemical* and *physical profile* of *Microtubules* (MT) respectively, and their potentially important role in brain function. Section 8 shows how *microtubule* dynamics, in a stringy-derived *density matrix mechanics* framework, may yield a *unified model* of Brain and Mind, a *quantum theory of brain function*, while the final Section 9 covers the emerging *quantum psychophysics*.

2 Brain Mechanics

The brain is a rather complicated physical system in constant interaction with the external world or environment. Very generically and in *grosso modo* the brain functions as follows:

- (i) Imagine that the brain is in some state $|A\rangle$, when some *external stimulus* is applied, for some given period of time, then
- (ii) after the removal of the external stimulus, the brain is in some state $|B\rangle$, which in principle should have in some way *coded* (or recorded) the “message” that was carried by the external stimulus, in such a way that
- (iii) “later” it is possible to *retrieve* (or recall) the message directly from the state $|B\rangle$, keeping in mind that
- (iv) it is possible that the brain has not necessarily gone directly from $|A\rangle$ to $|B\rangle$, but many intermediate steps may have occurred: $|A\rangle \rightarrow |A_1\rangle \rightarrow |A_2\rangle \rightarrow \dots \rightarrow |B\rangle$, *i.e.*, the *information* (or message) has been *processed* in the brain before it was recorded.

There are some fundamental properties that characterize successful brain function, namely: *long-term stability* and *non-locality*, as strongly suggested by the plethora of experimental data. While the need for long-term stability is rather obvious, non-locality, *i.e.*, coherent neuronal activity at spatially remote cortical locations, makes the classical treatment of the brain function rather questionable. At the same time, non-locality is strongly suggestive of *quantum treatment* [11, 12, 13]. Since we are concerned here clearly with macroscopic states, and at the same time we need to invoke quantum treatment, we have to look at the so-called *Macroscopic Quantum States* (MQS), which are abundant in the quantum world. Superconductivity, superfluidity, magnetization, etc are typical examples of MQS with very specific characteristics:

- (i) For special “structures” and “conditions”,
- (ii) a critical degree of coherence may be achieved that leads to an
- (iii) *ordered state*, that is highly stable.

Consider for example *Magnetization*: the special “structures” are the *Weiss regions*, small regions in a ferromagnet within which all electron spins are polarized in a specific direction. Though, because there are many small regions and polarizations, on the average there is no magnetization visible in the ferromagnet. If we now apply a sufficiently strong magnetic field \vec{B} or we decrease sufficiently the temperature (below the P. Curie point), *i.e.*, the special “conditions”, the ferromagnet exhibits magnetization because now all electron spins in the whole *macroscopic* crystal, are polarized in the same direction, strongly correlated with each other, thus leading to a highly stable *macroscopic coherent* (or quantum) *state*, the *ordered state*.

In a more physical language, the transition from an unordered state (*e.g.*, many Weiss-regions) to an ordered state (*e.g.*, magnetization) is called a phase transition. The value(s) of the crucial parameter(s) (*e.g.*, the magnetic field \vec{B} or temperature T) at the transition point characterize the phase transition and define the *critical point* (*e.g.*, Curie temperature). It should be apparent that an ordered state contains some *information* (*e.g.*, all electron spins polarized in the same direction) than the unordered state (electron spins randomly polarized). On the other hand, the unordered state is more *symmetric* (randomly distributed electron spins are rotationally invariant, *i.e.*, there is no *preferred direction*), while the ordered state exhibits less symmetry (polarized electron spins have chosen spontaneously a specific direction, thus breaking the rotational symmetry). Thus, ordered states are the net result of *spontaneous symmetry breaking* that triggers the phase transition. There are certain characteristics of phase transitions very useful for our subsequent discussions

- (i) *Universality*: many, qualitatively and quantitatively different, systems can be described by the same phase transition.
- (ii) *Attractor*: by varying suitably the system parameters, they can be brought close to their *critical values*, so as to cause a phase transition. It is not necessary to be infinitesimally close to the critical point. The critical point acts as an

attractor for anything in its environment. In other words, we don't really need a *fine-tuning* of our system parameters to reach an ordered state.

- (iii) *Evolution equations*: All the basic properties of phase transitions (including (i) and (ii) above) can be encoded in a set of evolution equations called renormalization group equations (RGEs). They describe deviations (and approach) from (to) criticality, as well as other characteristics of phase transitions [14].

Macroscopic coherent (or quantum) states, or ordered states have some highly exclusive characteristics:

- (i) *Long-range/term stability*: highly stable, long-range correlations between the fundamental elements are maintained by wave-like, self-propagating excitation loops (*e.g.*: phonons, spin-waves, magnons, etc.) that *Regulate* the behavior of the “other” fundamental elements and *Feedback* to the original fundamental element that caused the “disturbance”. I will call this the *R+F* property of MQS.
- (ii) *Non-locality*: clearly MQS, as its very nature indicates may go beyond microscopic locality.
- (iii) *Emergence*: MQS have *new properties* that are *not* present at the fundamental elements level. The new properties characterize states at a *hierarchical level above* the level where the fundamental interactions among the fundamental constituents apply. For example, superconductivity is a new property/phenomenon, *i.e.*, emerging from a *collective treatment* of electrons under special circumstances, while of course each electron follows at the fundamental level the laws of quantum electrodynamics.

Let us use now the physical language of MQS and phase transitions to describe *by analogy*, for the time being, the basic functions of the Brain:

- (I) *Uncoded Brain*: random signals, unattended perception are some of the characteristics of this case. It corresponds to the random polarizations in the many, small Weiss regions of the ferromagnet.
- (II) *Learning*: An *external stimulus* is applied, say for a few seconds, that “straightens out” or “puts an order” to the random neuronal signals so that they are able to represent some *coherent piece* of information. It corresponds, in the case of the ferromagnet, to applying for some time an external magnetic field \vec{B} or lowering the temperature below the Curie point. They cause the *breaking* of the multi-domain small structures with their random polarizations, and thus they lead to the ordered state, where all electron spins, throughout the whole ferromagnet, are strongly correlated to all point in the *same direction*. We are talking about a phase transition or, in the spirit of the previous discussion, a spontaneous breaking of some symmetry. Clearly, it depends on the nature of

the external stimulus with which specific fundamental elements will interact and set them “straight”, so that a corresponding MQS, or ordered state, is created. Realistically, in order to be able to *encode* all qualitatively different signals and create a coherent *unitary sense of self*, a tremendous number of qualitatively different ordered states is needed, *i.e.*, practically an infinite number of qualitatively different spontaneously broken symmetries. Furthermore, these symmetries should be accompanied by a set of *selection rules*, thus providing a physical *filter* against undesirable, irrelevant “stray” signals. A very tall order indeed, if one recalls the fact that, until now, the only “known” (observable) spontaneously broken symmetry, at the fundamental level, is the one describing the electroweak interactions. Just *one*, which is kind of short with respect to the desirable *infinity* of spontaneously broken symmetries! We will see later how string theory takes care of this problem.

- (III) *Coded Brain or Memory*: the resulting, highly stable, coherent “*firing*” of a bunch of involved neurons, not necessarily localized, corresponding, in the case of the ferromagnet, to the stability and macroscopic nature (including non-locality) of the *emerging* magnetization (*ordered*) state. Such a kind of naturally organized, coherent neuron firing, not necessarily localized, may provide the solution to the so-called “**binding problem**”. More later.
- (IV) *Recall Process*: In this picture, a *replication weak* signal, *sufficiently* resembling the *learning* signal, may excite *momentarily* the ordered state, but, thanks to its R+F property, it will relax back to its previous form. It is this, ordered-state→excitation→ordered-state process that make us aware of recalling something, *i.e.*, we “feel” it! It corresponds in the case of the ferromagnet, to apply a *weak* magnetic field \vec{B}' , not necessarily exactly parallel to the original \vec{B} , which will force the electron spins to oscillate, *momentarily*, before they relax back to their equilibrium, *i.e.*, we recover the ordered state, thanks of course to the R+F property of MQS. It should be stressed that it is not necessary for the replication signal to be exactly identical to the learning signal in order to recall full information, thanks to the *attractor* property of the phase transitions, discussed above. In phase-transition language, the recall memory process corresponds to the act of an *irrelevant operator*. It should not escape our attention that the endemic, in the framework of phase transitions, R+F and *attractor* properties fascilitate tremendously the retrieving of information, without the need of *complete* identity of the replication and learning signal. Otherwise, it would take extraneous *fine-tuning*, which here translates to very long time periods, in order to retrieve information. Imagine what would happen if we need to see all the details of a fast approaching, hungry lion, including say the length and shape of its claws, before we run up a tree! Not very practical indeed.

The above presented generic picture for the brain function may sound plausible and promising. But, is there any “*experimental*” evidence for its support? The answer is *yes*. The main observational tool is the ElectroEncephaloGram (EEG). It is usually

assumed that the EEG waveforms emerge from the summation of local neuron firings, but things are a bit more complicated. One would expect that *asynchronous* firing of randomly distributed neurons would produce a zero net effect on the scalp electrodes. By studying electric potentials evoked during sensory stimulation and during learning trials, E. R. John has been able to show that these evoked potentials arise from the firing of large and disperse neural groups and that they are radically different from those obtained by the spontaneous random cortical activity [15]. *Temporal rearrangement* within the neural groups characterizes the externally evoked potentials. Furthermore, Sayers *et. al.*[16], presented independent evidence strengthening the temporal rearrangement case, by studying EEG *phase coherence*. Frequency components of the EEG spectrum obtained during spontaneous cortical activity show a random configuration of phase relations, which shifts to a distinct pattern of *phase coherence* immediately following sensory stimulation. Amazingly enough, imposing the *phase characteristics* of the evoked potential on the spontaneous waveform, we can reproduce the characteristic shape of the observed evoked waveform [16]. These findings support E. R. John's [15] case for temporal rearrangement, while at the same time it falsifies the kind of classical expectation that the EEG arises from the summation of neural firings, which would imply that just the *amplitude characteristics* is the only difference between spontaneous and evoked waveforms. Clearly, it seems that the external stimulus does not just add energy to the brain, but it organizes it in a *coherent way*, in a similar fashion that an external field \vec{B} acts on a ferromagnet! It seems that the analogy between brain function and critical phenomena dynamics may be quite useful and fruitful.

In the *unified approach* suggested here (see Eq. (2)) the “effective” mental world (W_2) is *actively* interacting with the emerging MQS, and thus through the R+F property of the MQS *and* the subsequent triggering by W_2 of the collapse of the MQS, it provides the solution to the age-old problem of how intentional/emotional acts are strongly correlated to body acts, as explained in the Introduction. It should be stressed that *emergence* here has a multi-valued meaning: it encompasses the natural (Darwinian [17]) evolution and selection, the development of brain in specific subjects and eventually the “conscious” moment under consideration.

3 Quantum Mechanics

The physical principles that govern the microworld, as provided by Quantum Mechanics (QM), are *profoundly* different from the ones that the macrocosmos obeys. The “microworld” here denotes anything at and below the molecular level: molecules, atoms, electrons, nuclei, protons, neutrons, quarks. As Linus Pauling taught us, chemistry is nothing else but applied quantum mechanics at the atomic and molecular level. Interestingly enough, Molecular Biology holds a very intriguing position between the macro and micro worlds in the following sense: *ab initio*, Molecular Biology is concerned with the structure and function of the cell [10], which is mainly composed of *macromolecular structures* (DNA, RNA, proteins, ...) and as such, *most*

of the time and for many purposes, are sufficiently and accurately described by classical physics. Nevertheless, we should not be carried away and discard QM from the picture by interpreting *most of the times* as implying *at all times!* After all, as Watson and Crick [18] taught us, the double helical structure of DNA, which is the source of DNA's fundamental genetic properties is due to the quantum mechanical H-bonds between purines (A,G) and pyrimidines (T,C): always a double H-bond for A=T and a triple H-bond for G ≡ C. It is in the *stability* and *universality* of these H-bonds, as verified experimentally by Chargaff [19], that the secret of the genetic code lies! Since my central thesis here, as emphasized earlier, is that quantum mechanics plays *also* a very fundamental role in the emergence of the mental world from the physical world, *i.e.*, in the brain-mind relation, I will discuss very briefly some elements of QM, that I will need later.

The central dogma of Quantum Mechanics is the *particle-wave duality*: it depends on the particular circumstances if a *quantum state* is going to express itself as a particle or as a wave [20]. Consider for example a particle travelling in spacetime. Its quantum state is described by a *wavefunction* $\Psi(\vec{x}, t)$ obeying a Schrödinger-type equation of the form

$$i\hbar \frac{\partial \Psi}{\partial t} = H\Psi \quad (3)$$

where \hbar ($\equiv 1$ in natural units) is the Planck constant, and H is a system-dependent operator, called the *Hamiltonian* of the system. It provides the *unitary, time-evolution* of the system, and with eigenvalues identifiable with the different energy levels of the system. A fundamental, and *immensely crucial* for us here, property of the quantum equation (3) is its *linearity*. Imagine that $\Psi_1, \Psi_2, \dots, \Psi_n$ are different solutions of (3), then clearly the *linear superposition*

$$\Psi = \sum_{i=1}^n c_i(t) \Psi_i, \quad (4)$$

with c_i arbitrary complex numbers, is also a solution of (3). This is the mathematical statement of *Quantum Superposition*. Let us discuss next its physical meaning. Suppose that we would like to describe quantum mechanically the following “history” of a particle, say an electron: it starts at some initial point around (\vec{x}_0, t_0) , it *goes through* a wall that contains n slits, say $1, 2, \dots, n$, *without us knowing which specific one*, and it ends up at some final point around (\vec{x}_f, t_f) . Let $\Psi_1, \Psi_2, \dots, \Psi_n$ denote the wavefunctions of the electron, referring to the case that the electron went through the slit $1, 2, \dots, n$, respectively. Since we don't know the specific slit that the electron went through, we are *obliged* to take as the wavefunction of the electron, a linear superposition of $\Psi_1, \Psi_2, \dots, \Psi_n$, *i.e.*, (4). The physical meaning then of the c_i 's becomes clear: $|c_i|^2$ is the *probability* that the electron went through the slit i , and thus c_i is referred to as the *the probability amplitude*. Notice that conservation of probability entails that at any time t

$$\sum_{i=1}^n |c_i(t)|^2 = 1 \quad (5)$$

The *probability density* to find the electron at some specific point (\vec{x}_a, t_a) , after it has passed through the slits and before it ends up at (\vec{x}_f, t_f) is given by

$$|\Psi(\vec{x}_a, t_a)|^2 = \left| \sum_{i=1}^n c_i \Psi_i \right|^2 . \quad (6)$$

Clearly, this is a standard *wave-like behavior* and (4) may be interpreted as describing a quantum state evolving in a *coherent way*, or obeying the fundamental quantum mechanical principle of *quantum coherence*, the physical meaning of *linear superposition*. Imagine now, that we would like to find out through which specific slit the electron went through. Then, we have to make a “*measurement*” or “*observation*”, *i.e.*, to concentrate on those aspects of the quantum system that can be *simultaneously magnified* to the classical level, and from which the system must then choose. In other words, we have to *disturb* the system (electron in our example) with the *magnifying device*, which results in *de-coherence*, thus (6) is replaced by

$$\begin{array}{ccc} & \text{“measurement”} & \\ |\Psi(\vec{x}_a, t_a)|^2 & \downarrow \longrightarrow & \sum_{i=1}^n |c_i|^2 |\Psi_i|^2 \\ & \text{“collapse”} & \end{array} \quad (7)$$

In other words, we get classical probabilities, highly reminiscent of a standard *particle-like behavior*. The “*measurement*”/“*observation*” process has caused decoherence of the wavefunction and thus led to its *collapse* to a *specific state*. Here are then, in a nutshell, our basic quantum mechanical rules, that constitute *quantum reality*:

- (i) A quantum system can, in principle, be in many states *simultaneously* $(\Psi_1, \Psi_2, \dots, \Psi_n)$ and its quantum state $\Psi = \sum_{i=1}^n c_i \Psi_i$, a *pure state*, evolves *coherently* and according to the quantum equation (3), *as long as* we don't *disturb* it. This is *quantum linear superposition* or *quantum parallelism*, leading to wave-like behavior.
- (ii) A “*measurement*”/“*observation*” forces the quantum state Ψ to *decide* what it wants to be, with probability $|c_i|^2$ that the Ψ quantum state will turn out to be the i -th state (described by Ψ_i), *after* the “*measurement*”/“*observation*”. This is the “*collapse of the wavefunction*”, leading to classical particle-like behavior.

Incidentally, the famous Heisenberg *uncertainty principle* [21] is nothing else but a quantitative expression of our intuitive statement above that a “*measurement*”/“*observation*” disturbs the system in an *uncontrollable way*, entailing always uncertainties in the outcome, *e.g.*,

$$\Delta x \cdot \Delta p \geq \hbar . \quad (8)$$

Clearly, (8) indicates the fact that it is impossible to “*measure*” *simultaneously*, at a desirable level, both the position and the momentum of a particle. Notice that this is a *fundamental principle*, and has nothing to do with the potentially difficult and

practical problems that face experimentalists. Whatever she does, she cannot beat the uncertainty principle.

The endemic, in the Quantum World, wave-particle duality is responsible for the necessity of the two-step approach to quantum dynamics discussed above. This kind of approach is very different from the deterministic approach of classical dynamics and, in a way, it creates a *schism* in our understanding of the Universe. There is the classical world and there is the quantum world, each following its own laws which, frankly, do not seem to have much common ground. It may even, sometimes, lead to some embarrassments [12], like *e.g.*, the *Schrödinger's cat* paradox, a peculiar situation where a quantum event may oblige us to treat a cat as 50% alive and 50% dead! Furthermore, in the passage from the quantum to the classical world it is not clear at all who is there to decide that we crossed the quantum-classical border!

This *dualistic* view of the world (classical versus quantum) is reminiscent of the ancient needs for heavenly-terrestrial dynamics, abolished by Galileo and Newton for universal dynamics, or for space and time dynamics, abolished by Einstein for spacetime dynamics, or for electromagnetic and weak interactions, abolished recently for electroweak interactions. It looks to me that this classical versus quantum dualistic view of the world *cries out*, once more, for a *unified approach* which for many practical purposes would *effectively* look like two separate worlds (classical and quantum). Any resemblance with the unified approach I discussed in the Introduction for the brain versus mind problem is *not* accidental! A *unified approach* for classical *and* quantum dynamics will be attempted in section 5, but let me prepare the ground here by generalizing a bit the notion of quantum state and the likes. What we are really after is some kind of formalism that enables us to express, at least in principle, the two-step process of quantum dynamics in a more uniform language. Let us represent a given quantum state α by a state vector $|\alpha\rangle$, while $\langle\alpha|$ denotes the complex conjugate state vector α^* , and let us assume that this state vector has “length” one: $\langle\alpha|\alpha\rangle = 1$. Consider now a complete set of orthonormal state vectors $|i\rangle$: $\langle j|i\rangle = \delta_{ij}$, implying that any *pure state* can be written as $|\Psi^a\rangle = \sum_i c_i^a |i\rangle$, with c_i complex numbers obeying the conservation of probability condition $\sum_i |c_i|^2 = 1$ (see (4),(5)). Then the *scalar product* $\langle\Psi^b|\Psi^a\rangle = \sum_i c_i^{*b} c_i^a$ expresses the *probability amplitude* that starting with the state vector $|\Psi^a\rangle$ we end up in the state $|\Psi^b\rangle$. Actually, we can consider all the tensor products $|\Psi^k\rangle\langle\Psi^l|$ with the understanding that $\langle\Psi^l|\Psi^k\rangle = \text{Tr}(|\Psi^k\rangle\langle\Psi^l|) = \sum_i c_i^{l*} c_i^k$. It is very convenient to introduce the notion of the *density matrix* $\rho \equiv |\Psi\rangle\langle\Psi|$ with matrix elements $\rho_{ij} = c_i c_j^* |i\rangle\langle j|$ and such that $\text{Tr}\rho = \text{Tr}(|\Psi\rangle\langle\Psi|) = \langle\Psi|\Psi\rangle = \sum_i c_i c_i^* = 1$, *i.e.*, the conservation of probability condition. Notice that, in the case of a *pure state*, the description of a quantum system by the state vector $|\Psi\rangle$ or by the density matrix ρ is *equivalent*. For example, the measurable quantities $\langle\Psi|A|\Psi\rangle$ correspond to $\text{Tr}(\rho A)$, with A denoting the quantum operator representing the “measurable quantity”, etc. The quantum equation (3) becomes in the density matrix approach

$$\dot{\rho} \equiv \frac{\partial\rho}{\partial t} = \frac{i}{\hbar} [\rho, H] , \quad (9)$$

which is nothing else but the *quantum analogue* of the classical statistical mechanics *Liouville equation*, describing the time evolution of the phase-space density function. The great advantage of the density matrix approach is its ability to describe not only *pure states*, but also *mixed states*. Imagine that for *practical reasons* it is impossible to know the exact *pure state* of our quantum system, *i.e.*, we only know that we have a combination of different *pure states* $|\alpha\rangle = \sum_i c_i^\alpha |i\rangle$, $\alpha = 1, 2, \dots$, each with *classical probability* p_i . Clearly, in this case we cannot use the quantum equations (3) or (9) because it is only applied for *single* pure states, but we can still use the density matrix approach. Write the density matrix of the system as a *mixed state*

$$\rho = \sum_a p_a |a\rangle \langle a| , \quad (10)$$

then the probability that a “measurement”/“observation” will find our system in some pure state $|\Psi\rangle = \sum_i d_i |i\rangle$ is given by

$$P_\Psi = \text{Tr}(\rho |\Psi\rangle \langle \Psi|) = \sum_a p_a |\langle \Psi|a\rangle|^2 , \quad (11)$$

which is a sum of products of classical and quantum probabilities! Notice that in the case of a single *pure state*, say $|b\rangle$, all $p_{a \neq b} = 0$ and $p_b = 1$ in (10), and a “measurement”/“observation” causes the “collapse of the wavefunction” $|b\rangle$, that implies turning a *pure state* $\rho = |b\rangle \langle b|$ into a *mixed state* $\rho = \sum_i |c_i^b|^2 |i\rangle \langle i|$, which is nothing else but (7)! Of course, in the case of a “measurement”/“observation” we *open* the system under consideration, and clearly (9) needs modification, *i.e.*, addition of extra terms that represent the “disturbances”. On the other hand, since the “collapse of the wavefunction” implies loss of quantum coherence, there is no way to use a wave equation like (3), or possible modifications, to represent the “disturbances”. The notion of description of a quantum state by state vectors or wavefunctions really gives in to the density matrix approach, thus the correct approach for a *unification* of classical and quantum dynamics. Usually, when we deal with realistic quantum systems, composed of different independent or loosely interacting parts, it helps to express the quantum state of the system as the product of different independent components. Imagine, for example, a particle called π^0 decaying into two photons γ_1 and γ_2 . Since π^0 has no spin, the most general description of the system of two photons is given by

$$|\Psi\rangle = c_1 |\gamma_1\rangle_+ |\gamma_2\rangle_- + c_2 |\gamma_1\rangle_- |\gamma_2\rangle_+ , \quad (12)$$

where the subscripts indicate the polarizations of the two photons, always opposite, such that the whole system has angular momentum zero, corresponding to the spinless π^0 . Imagine that a “measurement”/“observation” is done on the system by measuring say the polarization of γ_2 and found to correspond to the $-$ one. After the “measurement”/“observation” we know that $c_1 = 1$ and $c_2 = 0$, thus without “measuring” the polarization of γ_1 , we know it is the $+$ one. Einstein found it very disturbing, that some “measurement” on one part of the system has an “*instantaneous*” effect on some other *distant* part. Sometimes this is referred to as the *Einstein-Podolsky-Rosen* (EPR) puzzle [22, 12], and it is a very clear proof of the *non-local* nature of

the quantum world! Experiments done in the mid-80's have confirmed [23], beyond any shadow of doubt, the *non-local nature* of quantum mechanics, and the failure of classical spacetime notions to describe quantum reality.

The Macroscopic Quantum States (MQS), mentioned in section 2, correspond here to something like

$$|\Psi\rangle = \sum_i c_i |1\rangle_i |2\rangle_i \cdots |N\rangle_i , \quad (13)$$

where $|k\rangle_i$ refers to the quantum state of the k -th fundamental constituent in the i -th macroscopic quantum state. Of course, for a MQS N is $\mathcal{O}(N_{\text{Avogadro}} \approx 6 \times 10^{23})$, a rather larger number and in several occasions the index i can also run into large numbers. For example, in the case of a ferromagnet, the *ordered state* would be described by (13), and if $|k\rangle_i$ indicates the spin polarization of the k -th electron, then *only* one $c_i \neq 0$. While in the case of *quasicrystals*, describable also by (13), not only is N large ($\mathcal{O}(N_{\text{Avogadro}})$), but *also* the linear combinations may involve a huge number of *alternatives*, *i.e.*, the i -index can be also large. *Quasicrystals* are rather intriguing physical structures that may need quantum mechanics in an essential way for their understanding. According to Penrose [12], the quasicrystal assembly cannot be reasonably achieved by the local adding of atoms one at a time, in accordance with the *classical* picture of crystal growth, but instead there must be a non-local essentially quantum mechanical ingredient to their assembly. Instead of having atoms coming individually and attaching themselves at a continually moving growth line (standard classical crystal growth), one must consider using something like (13), an evolving quantum linear superposition of many different alternative arrangements of attaching atoms. There is not one *single* thing that happens, many alternative atomic arrangements must coexist! Some of these linearly superposed alternatives will grow to very large conglomerates, and at certain point the “collapse of the wavefunction” will occur and thus more specific arrangements will be singled out, and so on, until a good-sized quasicrystal is formed. But why is Nature employing such an intriguing mechanism? Penrose claims [12] that maybe “energetics” is the answer. Usually, crystalline configurations are configurations of *lowest energy*, and the correct arrangement of atoms can be discovered simply by adding one atom at a time, and solving its own minimizing problem, etc. In quasicrystal growth, finding the lowest energy state is a very complicated and difficult problem, because it involves a large number of atoms *at once*, and thus, we have a *global, non-local* problem to solve. Clearly, a quantum mechanical description, a la (13), seems appropriate where many different combined arrangements of atoms are being “tried” simultaneously, and eventually collapsing, through physical environment tangling, to the “energetically” and “environmentally” appropriate arrangements, the *observable* quasicrystal.

It should be stressed that the QM rules have been in place and in successful use for about 70 years now, and have led to a most deep understanding of the microworld. Nevertheless, the fundamental mechanism triggering the “collapse of the wavefunction” has escaped us, until I believe recently, when string theory enabled us to put a definite proposal on the table, to be discussed in section 5. Intriguingly enough, Molecular Biology and Neurobiology in particular, lies just in the classical-

quantum interface and thus very interesting phenomena may occur. So, let us turn our attention now to the detailed structure of the brain.

4 Brain Morphology and Modeling

The human brain is the most complicated object, as far as we know, in the Universe. At a first look, it is amazing that this seemingly amorphous mass is capable of executing all these miraculous operations that control our actions and make us aware of the world around. A closer look though points to a rather recursively hierarchical structure and a very elaborate organization [24, 12]. An average brain weighs about 1.3 kg, and it is made of: $\sim 77\%$ water, $\sim 10\%$ protein, $\sim 10\%$ fat, $\sim 1\%$ carbohydrates, $\sim 0.01\%$ DNA/RNA, and the rest other stuff. The largest part of the human brain, the *cerebrum*, is found on the top and is divided down the middle into left and right cerebral hemispheres, and front and back into *frontal*, *parietal*, *temporal*, and *occipital lobes*. Further down, and at the back lies a rather smaller, spherical portion of the brain, the *cerebellum*, and deep inside lie a number of complicated structures like the thalamus, hypothalamus, hippocampus, etc. It seems that what make humans more advanced than other animals is not only the largeness of the cerebrum, but also its proportion of brain as a whole, the largest in the animal kingdom!

Both the cerebrum and the cerebellum have comparatively thin outer surface layers of grey matter and larger inner regions of white matter. The grey regions constitute what is known as the *cerebral cortex* and the *cerebellar cortex*. It is in the grey matter where various kinds of computational tasks seem to be performed, while the white matter consists of long nerve fibers (axons) carrying signals from one part of the brain to another. It is the *cerebral cortex* that is central to the higher brain functions, speech, thought, complex movement patterns, etc. On the other hand, the *cerebellum* seems to be more of an “automaton”. It has to do more with precise coordination and control of the body, and with skills that have become “second nature”. Cerebellum actions seem almost to take place by themselves, without thinking about them. They are very similar to the unconscious reflex actions, *e.g.*, reaction to pinching, which may not be mediated by the brain, but by the upper part of the spinal column. Thus, it seems highly likely that the phenomena of consciousness, that we are mainly concerned here, have much more to do with the cerebrum than with the cerebellum or the spinal cord. So, from now on, we will concentrate on the cerebral cortex.

Various parts of the cerebral cortex are associated with very specific functions. We distinguish several regions. The *visual cortex*, a region in the occipital lobe at the back of the brain, is responsible for the reception and interpretation of vision. The *auditory cortex*, in the temporal lobe, deals mainly with analysis of sound, while the *olfactory cortex*, in the frontal lobe, deals with smell. The *somatosensory cortex*, just *behind* the division between frontal and parietal lobes, has to do with the sensations of touch. There is a very specific mapping between the various parts of the surface of the body and the regions of the somatosensory cortex. In addition, just in *front*

of the division between the frontal and parietal lobes, in the frontal lobe, there is the *motor cortex*. The *motor cortex* activates the movement of different parts of the body and, again here, there is a very specific mapping between the various muscles of the body and the regions of the motor cortex. All the above mentioned regions of the cerebral cortex are referred to as *primary*, since they are the one most directly concerned with the input and output of the brain. Near to these primary regions are the *secondary* sensory regions of the cerebral cortex, where information is processed, while in the *secondary motor* regions, conceived plans of motion get translated into specific directions for actual muscle movement by the primary motor cortex. But the most abstract and sophisticated activity of the brain is carried out in the remaining regions of the cerebral cortex, the *association cortex*. It is right here that information from various different sensory regions is analyzed in a rather complex way, memories are laid down, pictures of the outside world are constructed, general plans are conceived, etc. This is the anatomic, morphological structure of the brain, on which my observations of section 2 were based on! There is a rather well-known and extremely curious phenomenon that I call *X-ism*. It is the *right (left)* cerebral hemisphere which is concerned *exclusively* with the *left (right)* hand side of the body, so that virtually all nerves must *cross over* from one side to the other as they enter or leave the cerebrum! Furthermore, as I mentioned above, the vision cortex is right at the back, while the eyes are at the front, the feet-related region of the somatosensory cortex is at the top, whereas the feet are at the bottom, and the left (right) auditory cortex is related to the right (left) ear! It seems that the cerebral neurosignals prefer to follow the longest possible path, and since this X-ism is not observed in the cerebellum, whose action appears to be completely unconscious, it is not inconceivable that the emergence of consciousness is facilitated by the cerebral X-ism. In our unified scheme, such a strange correlation between consciousness and X-ism seems to be born out of the dynamics.

Let us now continue our fascinating trip inside the brain, and let us concentrate on its basic building blocks, the nerve cells or neurons. Among the about 200 types of different basic types of human cells, the neuron is one of the most specialized, exotic and remarkably versatile cell. The neuron is highly unusual in three respects: its *variation in shape*, its *electrochemical function*, and its *connectivity*, *i.e.*, its ability to link up with other neurons in networks. Let us start with a few elements of neuron microanatomy [24, 12]. There is a central starlike bulb, called the *soma*, which contains the nucleus of the cell. A long nerve fibre, known as the *axon*, stretches out from one end of the soma. Its length, in humans, can reach up to *few cm*, surprisingly long for a single cell! The *raison d'être* of the axon is to transmit the neuron's output signal, *i.e.*, it acts like a wire. The axon has the ability of multiple bifurcation, branching out into many smaller nerve fibers, and the very end of which there is always a *synoptic knob*. At the other end of the soma and often springing off in all directions from it, are the tree-like *dendrites*, along which input data are carried into the soma. The whole nerve cell, as basic unit, has a cell membrane surrounding soma, axon, synoptic knobs, dendrites. Signals pass from one neuron to another at junctions known as *synapses*, where a synaptic knob of one neuron is attached to

another neuron's soma or dendrites. There is very narrow gap, of a few nm, between the synaptic knob and the soma/dendrite to where the *synaptic cleft* is attached. The signal from one neuron to another has to propagate across this gap. The workings of the nerve signals are another wonder of Nature!

A nerve fiber is a cylindrical tube containing a mixed solution of NaCl and KCl, mainly the second, so there are Na^+ , K^+ , and Cl^- ions within the tube. Outside the tube the same type of ions are present but with more Na^+ than K^+ . In the *resting* state there is an excess of Cl^- over Na^+ and K^+ inside the tube, giving it a negative charge, while it has positive charge outside. A nerve signal is nothing else but a region of *charge reversal* travelling along the fiber. At its head, *sodium gates* open to allow the sodium to flow inwards and at its tail *potassium gates* open to allow potassium to flow outwards. Then, metabolic pumps act to restore order and establish the *resting state*, preparing the nerve fiber for another signal. Amazingly enough, there is no major material (ion) transport that produces the signal, just in and out local movements of ions, across the cell membranes, *i.e.*, a *small* and *local* depolarization of the cell! Eventually, the nerve signal reaches the attached synaptic knob, at the very end of the nerve fiber, and triggers it to emit chemical substances, known as *neurotransmitters*. It is these substances that travel across the synaptic cleft to another neuron's soma or dendrite. It should be stressed that the signal here is not electrical, but a chemical one. What really is happening is that when the nerve signal reaches the synaptic knob, the local depolarization cause little bags immersed in the *vesicular grid*, the *vesicles* containing molecules of the neurotransmitter chemical (*e.g.*, acetylcholine) to release their contents from the neuron into the synaptic cleft, the phenomenon of *exocytosis*. These molecules then diffuse across the cleft to interact with *receptor proteins* on receiving neurons. On receiving a neurotransmitter molecule, the receptor protein opens a gate that causes a local depolarization of the receiver neuron. The nerve signal has been transmitted!

It depends on the nature of the synaptic knob and of the specific synaptic junction, if the next neuron would be encouraged to *fire*, *i.e.*, to start a new signal along its own axon, or it would be discouraged to do so. In the former case we are talking about *excitatory synapses*, while in the latter case about *inhibitory synapses*. At any given moment, one has to add up the effect of all excitatory synapses and subtract the effect of all the inhibitory ones. If the net effect corresponds to a positive electrical potential difference between the inside and the outside of the neuron under consideration, *and* if it is bigger than a critical value, then the neuron *fires*, otherwise it stays mute.

For our concerns here, the fundamental dynamical process of neural communication can be summarized in the following three steps:

1. The neural axon is an *all* or *none* state. In the *all* state a signal, called a *spike* or *action potential* (AP), propagates indicating that the summation performed in the soma produced an amplitude of the order of tens of mV. In the *none* state there is no signal travelling in the axon, only the resting potential ($\sim -70\text{mV}$). It is essential to notice that the presence of a travelling signal in the axon, *blocks*

the possibility of transmission of a second signal.

2. The nerve signal, upon arriving at the ending of the axon, triggers the emission of neurotransmitters in the synaptic cleft, which in turn cause the receptors to open up and allow the penetration of ionic current into the *post synaptic* neuron. The *efficacy* of the synapse is a parameter specified by the amount of penetrating current per presynaptic spike.
3. The post synaptic potential (PSP) diffuses toward the soma, where all inputs in a short period, from all the presynaptic neurons connected to the postsynaptic are summed up. The amplitude of individual PSP's is about 1 mV, thus quite a number of inputs is required to reach the "firing" threshold, of tens of mV. Otherwise the postsynaptic neuron remains in the *resting* or *none* state.

The cycle-time of a neuron, *i.e.*, the time from the emission of a spike in the presynaptic neuron to the emission of a spike in the postsynaptic neuron is of the order of *1-2 msec*s. There is also some recovery time for the neuron, after it "*fired*", of about *1-2 msec*s, independently of how large the amplitude of the depolarizing potential would be. This period is called the *absolute refractory period* of the neuron. Clearly, it sets an upper bound on the spike frequency of 500-1000/sec. In the types of neurons that we will be interested in, the spike frequency is considerably lower than the above upper bound, typically in the range of 100/sec, or even smaller in some areas, at about 50/sec. It should be noticed that this rather exotic neural communication mechanism works very efficiently and it is employed *universally*, both by vertebrates and invertebrates. The vertebrates have gone even further in perfection, by protecting their nerve fibers by an *insulating coating* of *myelin*, a white fatty substance, which incidentally gives the *white matter* of the brain, discussed above, its color. Because of this insulation, the nerve signals may travel undisturbed at about 120 meters/second, a rather high speed!

A very important and significant anatomical fact for our discussion, is that each neuron receives some 10^4 synaptic inputs from the axons of other neurons, usually one input per presynaptic neuron, and that each branching neural axon forms about the same number ($\sim 10^4$) of synaptic contacts on other, postsynaptic neurons. A closer look at our cortex then would expose a mosaic-type structure of assemblies of a few thousand densely connected neurons. These assemblies are taken to be the basic cortical processing *modules*, and their size is about $1(\text{mm})^2$. The neural connectivity gets much sparser as we move to larger scales and with much less feedback, allowing thus for autonomous local collective, parallel processing and more serial and integrative processing of local collective outcomes. Taking into account that there are about 10^{11} nerve cells in the brain (about 7×10^{10} in the cerebrum and 3×10^{10} in the cerebellum), we are talking about 10^{15} synapses! Counting one synapse per second, you will find yourself counting past 30 million years after you started! Undoubtedly, the brain is very special, and it should not be unreasonable to expect it to give rise to mental properties [25].

While the dynamical process of neural communication suggests that the brain action looks a lot like a computer action, there are some fundamental differences having to do with a basic brain property called *brain plasticity*. The interconnections between neurons are not fixed, as is the case in a computer-like model, but are changing all the time. Here I am referring to the synaptic junctions where the communication between different neurons actually takes place. The synaptic junctions occur at places where there are *dendritic spines* of suitable form such that contact with the synaptic knobs can be made. Under certain conditions these dendritic spines can shrink away and break contact, or they can grow and make new contact, thus determining the *efficacy* of the synaptic junction. Actually, it seems that it is through these dendritic spine changes, in synaptic connections, that long-term memories are laid down, by providing the means of storing the necessary information. A supporting indication of such a conjecture is the fact that such dendritic spine changes occur within *seconds*, which is also how long it takes for permanent memories to be laid down [12].

Furthermore, a very useful set of phenomenological rules has been put forward by Hebb [26], the *Hebb rules*, concerning the underlying mechanism of brain plasticity. According to Hebb, a synapse between neuron 1 and neuron 2 would be strengthened whenever the firing of neuron 1 is followed by the firing of neuron 2, and weakened whenever it is not. A rather suggestive mechanism that sets the ground for the emergence of some form of *learning!* It seems that *brain plasticity* is not just an incidental complication, it is a *fundamental property* of the activity of the brain. Brain plasticity and its time duration (few *seconds*) play a critical role, as we will see later, in the present unified approach to the brain and the mind.

Many mathematical models have been proposed to try to simulate “learning”, based upon the close resemblance of the dynamics of neural communication to computers and implementing, one way or another, the essence of the Hebb rules. These models are known as *Neural Networks* (NN) [27].

Let us try to construct a neural network model for a set of N interconnected neurons. The activity of the neurons is usually parametrized by N functions $\sigma_i(t)$, $i = 1, 2, \dots, N$, and the synaptic strength, representing the synaptic efficacy, by $N \times N$ functions $j_{i,k}(t)$. The total stimulus of the network on a given neuron (i) is assumed to be given simply by the sum of the stimuli coming from each neuron

$$S_i(t) = \sum_{k=1}^N j_{i,k}(t)\sigma_k(t) \quad (14)$$

where we have identified the individual stimuli with the product of the synaptic strength ($j_{i,k}$) with the activity (σ_k) of the neuron producing the individual stimulus. The dynamic equations for the neuron are supposed to be, in the simplest case

$$\frac{d\sigma_i}{dt} = F(\sigma_i, S_i) \quad (15)$$

with F a non-linear function of its arguments. The dynamic equations controlling the time evolution of the synaptic strengths $j_{i,k}(t)$ are much more involved and only

partially understood, and usually it is *assumed* that the j -dynamics is such that it produces the synaptic couplings that we need or postulate! The simplest version of a neural network model is the Hopfield model [28]. In this model the neuron activities are conveniently and conventionally taken to be “*switch*”-like, namely ± 1 , and the time t is also an integer-valued quantity. Of course, this *all*(+1) or *none*(-1) neural activity σ_i is based on the neurophysiology discussed above. If you are disturbed by the ± 1 choice instead of the usual “binary” one ($b_i = 1$ or 0), replace σ_i by $2b_i - 1$. The choice ± 1 is more natural from a physicist’s point of view corresponding to a two-state system, like the fundamental elements of the ferromagnet, discussed in section 2, *i.e.*, the electrons with their spins up (+) or (-).

The increase of time t by one unit corresponds to one step for the dynamics of the neuron activities obtainable by applying (for all i) the rule

$$\sigma_i(t + \frac{i+1}{N}) = \text{sign}(S_i(t + i/N)) \quad (16)$$

which provides a rather explicit form for (15). If, as suggested by the Hebb rules, the j matrix is *symmetric* ($j_{i,k} = j_{k,i}$), the Hopfield dynamics [28] corresponds to a sequential algorithm for looking for the minimum of the Hamiltonian

$$H = - \sum_i S_i(t) \sigma_i(t) = - \sum_{i,k=1}^N j_{i,k} \sigma_i(t) \sigma_k(t) \quad (17)$$

Amazingly enough the Hopfield model, at this stage, is very similar to the dynamics of a statistical mechanics *Ising-type* [14], or more generally a *spin-glass*, model [29]! This *mapping* of the Hopfield model to a spin-glass model is highly advantageous because we have now a justification for using the statistical mechanics language of phase transitions, like critical points or attractors, etc, to describe neural dynamics and thus brain dynamics, as was envisaged in section 2. It is remarkable that this simplified Hopfield model has many *attractors*, corresponding to many different *equilibrium* or *ordered* states, endemic in spin-glass models, and an unavoidable prerequisite for successful storage, in the brain, of many different patterns of activities. In the neural network framework, it is believed that an internal representation (*i.e.*, a pattern of neural activities) is associated with each object or category that we are capable of recognizing and remembering. According to neurophysiology, discussed above, it is also believed that an object is memorized by suitably changing the synaptic strengths. *Associative memory* then is produced in this scheme as follows (see corresponding (I)-(IV) steps in section 2): An external stimulus, suitably involved, produces synaptic strengths such that a specific learned pattern $\sigma_i(0) = P_i$ is “printed” in such a way that the neuron activities $\sigma_i(t) \sim P_i$ (II *learning*), meaning that the σ_i will remain for all times close to P_i , corresponding to a stable attractor point (III *coded brain*). Furthermore, if a *replication signal* is applied, pushing the neurons to σ_i values *partially* different from P_i , the neurons should evolve toward the P_i . In other words, the memory is able to retrieve the information on the whole object, from the knowledge of a part of it, or even in the presence of wrong information (IV *recall process*). Of

course, if the external stimulus is very different from any preexisting $\sigma_i = P_i$ pattern, it may either create a new pattern, *i.e.*, create a new attractor point, or it may reach a chaotic, random behavior (I *uncoded brain*).

Despite the remarkable progress that has been made during the last few years in understanding brain function using the neural network paradigm, it is fair to say that neural networks are rather artificial and a very long way from providing a realistic model of brain function. It seems likely that the mechanisms controlling the changes in synaptic connections are much more complicated and involved than the ones considered in NN, as utilizing cytoskeletal restructuring of the sub-synaptic regions. *Brain plasticity* seems to play an essential, central role in the workings of the brain! Furthermore, the “*binding problem*”, alluded to in section 2, *i.e.*, how to *bind* together all the neurons firing to different features of the same object or category, *especially* when more than one object is perceived during a *single* conscious perceptual moment, seems to remain unanswered.

We have come a long way since the times of the “*grandmother neuron*”, where a *single* brain location was invoked for self observation and control, indentified with the pineal glands by Descartes [30]! Eventually, this localized concept was promoted to *homunculus*, a little fellow inside the brain which observes, controls and represents us! The days of this “*Cartesian comedia d’arte*” within the brain are gone forever!

It has been long suggested that different groups of neurons, responding to a common object/category, fire *synchronously*, implying *temporal correlations* [31]. If true, such correlated firing of neurons may help us in resolving the binding problem [32]. Actually, brain waves recorded from the scalp, *i.e.*, the EEGs, suggest the existence of some sort of *rhythms*, *e.g.*, the “ α -*rhythms*” of a frequency of 10 Hz. More recently, oscillations were clearly observed in the visual cortex. Rapid oscillations, above EEG frequencies in the range of 35 to 75 Hz, called the “ γ -*oscillations*” or the “*40 Hz oscillations*”, have been detected in the cat’s visual cortex [33, 34]. Furthermore, it has been shown that these oscillatory responses can become *synchronized* in a stimulus-dependent manner! Amazingly enough, studies of auditory-evoked responses in humans have shown inhibition of the 40 Hz coherence with *loss of consciousness* due to the induction of general anesthesia [35]! These remarkable and striking results have prompted Crick and Koch to suggest that this *synchronized* firing on, or near, the beat of a “ γ -*oscillation*” (in the 35–75 Hz range) might be the *neural correlate* of *visual awareness* [36, 32]. Such a behavior would be, of course, a very special case of a much more general framework where coherent firing of *widely-distributed* (*i.e.*, *non-local*) groups of neurons, in the “beats” of *x*-oscillation (of specific frequency ranges), *bind* them together in a mental representation, expressing the *oneness* of *consciousness* or *unitary sense of self*. While this is a remarkable and bold suggestion [36, 32], it should be stressed that in a physicist’s language it corresponds to a phenomenological explanation, not providing the underlying physical mechanism, based on neuron dynamics, that triggers the synchronized neuron firing. On the other hand, the Crick-Koch proposal [36, 32] is very suggestive and in compliance with the general framework I developed in the earlier sections, where macroscopic *coherent* quantum states play an essential role in awareness, and especially with respect to the “*binding*”

problem". We have, by now, enough motivation from our somehow detailed study of brain morphology and modeling, to go back to quantum mechanics and develop a bit further, using string theory, so that to be applicable to brain dynamics.

5 Stringy Quantum Mechanics: Density Matrix Mechanics

Quantum Field Theory (QFT) is the fundamental dynamical framework for a successful description of the microworld, from molecules to quarks and leptons and their interactions. The *Standard Model* of elementary particle physics, encompassing the strong and electroweak interactions of quarks and leptons, the most fundamental point-like constituents of matter presently known, is fully and wholly based on QFT [37]. Nevertheless, when gravitational interactions are included at the quantum level, the whole construction collapses! Uncontrollable infinities appear all over the place, thus rendering the theory inconsistent. This a well-known and grave problem, being with us for a long, long time now. The resistance of gravitational interactions to conventionally unify with the other (strong and electroweak) interactions strongly suggests that we are in for changes both at the QFT front and at the gravitational front, so that these two frameworks could become eventually compatible with each other. As usual in science, puzzles, paradoxes and impasses, that may lead to major crises, bring with them the seeds of dramatic and radical changes, if the crisis is looked upon as an opportunity. In our case at hand, since the Standard Model, based upon standard QFT, works extremely well, we had not been forced to scrutinize further the basic principles of the orthodox, Copenhagen-like QFT. Indeed, the mysterious "collapse" of the wavefunction, as discussed in section 3, remained always lacking a dynamical mechanism responsible for its triggering. Had gravity been incorporated in this conventional unification scheme, and since it is the *last known* interaction, any motivation for changing the ground rules of QFT, so that a dynamical mechanism triggering the "collapse" of the wavefunction would be provided, would be looked upon rather suspiciously and unwarranted. Usually, to extremely good approximation, one can neglect gravitational interaction effects, so that the standard QFT applies. Once more, *usually* should not be interpreted as *always*. Indeed, for most applications of QFT in particle physics, one assumes that we live in a *fixed, static, smooth* spacetime manifold, *e.g.*, a Lorentz spacetime manifold characterized by a Minkowski metric ($g_{\mu\nu}$ denotes the metric tensor):

$$ds^2 \equiv g_{\mu\nu} dx^\mu dx^\nu = c^2 dt^2 - d\vec{x}^2 \quad (18)$$

satisfying Einstein's special relativity principle. In such a case, standard QFT rules apply and we get the miraculously successful Standard Model of particle physics. Unfortunately, this is not the whole story. We don't live exactly in a *fixed, static, smooth* spacetime manifold. Rather, the universe is *expanding*, thus it is not *static*, and furthermore unavoidable *quantum fluctuations* of the metric tensor $g_{\mu\nu}(x)$ defy the

fixed and *smooth* description of the spacetime manifold, at *least* at very short distances. Very short distances here do not refer to the nucleus, or even the proton radius, of 10^{-13}cm , but to distances comparable to the Planck length, $\ell_{Pl} \sim 10^{-33}\text{cm}$, which in turn is related to the smallness of G_N , Newton's gravitational constant! In particle physics we find it convenient to work in a system of units where $c = \hbar = k_B = 1$, where c is the speed of light, \hbar is the Planck constant, and k_B is the Boltzman constant. Using such a system of units one can write

$$G_N \equiv \frac{1}{M_{Pl}^2} \equiv \ell_{Pl}^2 \quad (19)$$

with $M_{Pl} \sim 10^{19}\text{ GeV}$ and $\ell_{Pl} \sim 10^{-33}\text{cm}$.

It should be clear that as we reach very short distances of $\mathcal{O}(\ell_{Pl})$, fluctuations of the metric $\delta g_{\mu\nu}(x)/g_{\mu\nu}(x) \sim (\ell_{Pl}/\ell)^2 \sim \mathcal{O}(1)$, and thus the spacetime manifold is not well defined anymore, and it may even be that the very notion of a spacetime description evaporates at such Planckian distances! So, it becomes apparent that if we would like to include quantum gravity as an item in our unification program checklist, we should prepare ourselves for major revamping of our conventional ideas about quantum dynamics and the structure of spacetime.

A particularly interesting, well-motivated, and well-studied example of a *singular* spacetime background is that of a *black hole* (BH) [38]. These objects are the source of a singularly strong gravitational field, so that if any other poor objects (including light) cross their "horizon", they are *trapped* and would never come out of it again. Once in, there is no way out! Consider, for example, a quantum system consisting of two particles a and b in loose interaction with each other, so that we can describe its quantum *pure* state by $|\Psi\rangle = |a\rangle |b\rangle$. Imagine now, that at some stage of its evolution the quantum system gets close to a black hole, and that for some unfortunate reason particle b decides to enter the BH horizon. From then on, we have no means of knowing or determining the exact quantum state of the b particle, thus we have to describe our system not anymore as a *pure* state $|\Psi\rangle$, but as a *mixed* state $\rho = \sum_i |b_i|^2 |a\rangle \langle b_i|$, according to our discussion in section 3 (see (10,11)). But such an evolution of a *pure state* into a *mixed state* is not *possible* within the conventional framework of quantum mechanics as represented by (3) or (9). In conventional QM *purity* is eternal. So, something drastic should occur in order to be able to accomodate such circumstances related to singularly strong gravitational fields. Actually, there is much more than meets the eye. If we consider that our pure state of the two particles $|\Psi\rangle = |a\rangle |b\rangle$ is a quantum fluctuation of the vacuum, then we are in more trouble. The vacuum always creates particle-antiparticle pairs that almost momentarily, and in the absence of strong gravitational fields, annihilate back to the vacuum, a rather standard well-understood quantum process. In the presence of a black hole, there is a very strong gravitational force that may lure away one of the two particles and "trap" it inside the BH horizon, leaving the other particle hanging around and looking for its partner. Eventually it wanders away from the BH and it may even be detected by an experimentalist at a safe distance from the BH. Because she does not know or care about details of the vacuum, she takes it that the BH is decaying by emitting all these

particles that she detects. In other words, while *classical* BH is supposed to be stable, in the presence of quantum matter, BH do decay, or more correctly *radiate*, and this is the famous *Hawking radiation* [38, 39]. The unfortunate thing is that the Hawking radiation is *thermal*, and this means that we have lost vast amounts of *information* dragged into the BH. A BH of mass M_{BH} is characterized by a *temperature* T_{BH} , an *entropy* S_{BH} and a *horizon radius* R_{BH} [38, 39, 40]

$$T_{BH} \sim \frac{1}{M_{BH}}; \quad S_{BH} \sim M_{BH}^2; \quad R_{BH} \sim M_{BH} \quad (20)$$

satisfying, of course, the first thermodynamic law, $dM_{BH} = T_{BH}dS_{BH}$. The origin of the huge entropy ($\sim M_{BH}^2$) should be clarified. Statistical physics teaches us that the *entropy* of a system is a measure of the information *unavailable to us* about the detailed structure of the system. The entropy is given by the number of different possible configurations of the fundamental constituents of the system, resulting always in the same values for the macroscopic quantities characterizing the system, *e.g.*, temperature, pressure, magnetization, etc. Clearly, the fewer the macroscopic quantities characterizing the system, the larger the entropy and thus the larger the lack of information about the system. In our BH paradigm, the macroscopic quantities that characterize the BH, according to (20), is *only* its mass M_{BH} . In more complicated BHs, they may possess some extra “*observables*” like electric charge or angular momentum, but still, it is a rather small set of “*observables*”! This fact is expressed as the “*No-Hair Theorem*” [38], *i.e.*, there are not many different long range interactions around, like gravity or electromagnetism, and thus we cannot “*measure*” safely and from a distance other “*observables*”, beyond the mass (M), angular momentum (\vec{L}), and electric charge (Q). In such a case, it becomes apparent that we may have a huge number of different configurations that are all characterized by the same M, Q, \vec{L} , and this the huge entropy (20). Hawking realized immediately that his BH dynamics and quantum mechanics were not looking eye to eye, and he proposed in 1982 that we should generalize quantum mechanics to include the *pure state to mixed state* transition, which is equivalent to *abandoning* the quantum superposition principle (as expressed in (3) or (9)), for some more advanced quantum dynamics [41]. In such a case we should virtually abandon the description of quantum states by wavefunctions or state vectors $|\Psi\rangle$ and use the more accommodating density matrix (ρ) description, as discussed in section 3, *but* with a *modified* form for (9). Indeed, in 1983 Ellis, Hagelin, Srednicki, and myself proposed (EHNS in the following) [42] the following modified form of the conventional Eq. (9)

$$\frac{\partial \rho}{\partial t} = i[\rho, H] + \delta \mathbb{H} \rho \quad (21)$$

which accommodates the *pure state*→*mixed state* transition through the extra term $(\delta \mathbb{H})\rho$. The existence of such an extra term is characteristic of “*open*” quantum systems, and it has been used in the past for *practical reasons*. What EHNS suggested was more radical. We suggested that the existence of the extra term $(\delta \mathbb{H})\rho$ is

not due to *practical reasons* but to some fundamental, dynamical reasons having to do with quantum gravity. Universal quantum fluctuations of the gravitational field ($g_{\mu\nu}$) at Planckian distances ($\ell_{Pl} \sim 10^{-33}\text{cm}$) create a very *dissipative* and *fluctuating* quantum vacuum, termed *spacetime foam*, which includes virtual Planckian-size black holes. Thus, quantum systems *never* evolve undisturbed, even in the *quantum vacuum*, but they are continuously interacting with the spacetime foam, that plays the role of the *environment*, and which “opens” spontaneously and dynamically *any* quantum system. Clearly, the extra term $(\delta\mathcal{H})\rho$ leads to a *spontaneous dynamical decoherence* that enables the system to make a transition from a pure to a mixed state accomodating Hawking’s proposal [41]. Naive approximate calculations indicate that $\langle\delta\mathcal{H}\rangle \sim E^2/M_{Pl}$, where E is the energy of the system, suggesting straight away that our “low-energy” world ($E/M_{Pl} \leq 10^{-16}$) of quarks, leptons, photons, etc is, for most cases, extremely accurately described by the conventional Eq. (9). Of course, in such cases is not offensive to talk about wavefunctions, quantum parallelism, and the likes. On the other hand, as observed in 1989 by Ellis, Mohanty, and myself [43], if we try to put together more and more particles, we eventually come to a point where the decoherence term $(\delta\mathcal{H})\rho$ is substantial and decoherence is almost instantaneous, leading in other words to an instantaneous *collapse* of the wavefunction for large bodies, thus making the transition from quantum to classical *dynamical* and not by decree! In a way, the Hawking proposal [41], while leading to a major conflict between the standard QM and gravity, motivated us [42, 43] to rethink about the “collapse” of the wavefunction, and it seemed to contain the seeds of a dynamical mechanism for the “collapse” of the wavefunction. Of course, the reason that many people gave a “cold shoulder” to the Hawking proposal was the fact that his treatment of quantum gravity was semiclassical, and thus it could be that all the Hawking excitement was nothing else but an artifact of the bad/crude/unjustifiable approximations. Thus, before we proceed further we need to treat better Quantum Gravity (QG). String Theory (ST) does just that. It provided the *first*, and presently *only* known framework for a consistently quantized theory of gravity [44].

As its name indicates, in string theory one replaces *point like* particles by *one-dimensional, extended, closed, string* like objects, of characteristic length $\mathcal{O}(\ell_{Pl}) \sim 10^{-33}\text{cm}$. In ST one gets an *automatic, natural* unification of *all* interactions *including* quantum gravity, which has been the *holy grail* for particle physics/physicists for the last 70 years! It is thus only natural to address the hot issues of black hole dynamics in the ST framework [44]. Indeed, in 1991, together with Ellis and Mavromatos (EMN in the following) we started a rather elaborate program of BH studies, and eventually, we succeeded in developing a new dynamical theory of string black holes [45]. One *first* observes that in ST there is an *infinity* of particles of different masses, including the *Standard Model* ones, corresponding to the different excitation modes of the string. Most of these particles are unobservable at low energies since they are very massive $M \gtrsim \mathcal{O}(M_{Pl} \sim 10^{19}\text{GeV})$ and thus they cannot be produced in present or future accelerators, which may reach by the year 2005 about 10^4GeV . Among the *infinity* of different types of particles available, there is an *infinity* of massive “gauge-boson”-like particles, generalizations of the W -boson mediating the weak interactions, thus

indicating the *existence* of an *infinity* of *spontaneously broken gauge symmetries*, each one characterized by a specific *charge*, generically called Q_i . It should be stressed that, even if these stringy type, spontaneously broken gauge symmetries do not lead to long-range forces, thus *classically* their Q_i charges are unobservable at long distances, they do become observable at long distances at the *quantum level*. Utilizing the quantum Bohm-Aharonov effect [46], where one “measures” phase shifts proportional to Q_i , we are able to “measure” the Q_i charges from a desirable distance! This kind of Q_i charge, if available on a black hole, is called sometimes and for obvious reasons, *quantum hair* [47]. From the infinity of stringy symmetries, a relevant for us here, specific, *closed subset* has been identified, known by the name of $W_{1+\infty}$ *symmetry*, with many interesting properties [48]. Namely, these $W_{1+\infty}$ symmetries cause the mixing [49], in the presence of singular spacetime backgrounds like a BH, between the massless string modes, containing the *attainable localizable low energy world* (quarks, leptons, photons, etc), let me call it the W_1 -*world*, and the massive ($\geq \mathcal{O}(M_{Pl})$) string modes of a very characteristic type, the so-called *global states*. They are called *global states* because they have the peculiar and unusual characteristic to have *fixed* energy E and momentum \vec{p} , and thus, by employing the uncertainty type relations, ala (8), they are extended over *all* space and time! Clearly, while the *global states* are as *physical* and as *real* as any other states, still they are *unattainable* for *direct observation* to a *local observer*. They make themselves noticeable through their *indirect* effects, while interacting with, or agitating, the W_1 *world*. Let me call the global state space, the W_2 -*world*.

The *second* step in the EMN approach [45] was to concentrate on spherically symmetric 4-D stringy black holes, that can be *effectively* reduced to 2-D (1 space + 1 time) string black holes of the form discussed by Witten [50]. This effective dimensional reduction turned out to be very helpful because it enabled us to concentrate on the real issues of BH dynamics and bypass the technical complications endemic in higher dimensions. We showed that [45], as we suspected all the time, stringy BH are *endorsed* with W -hair, *i.e.*, they carry an *infinity* of charges W_i , corresponding to the $W_{1+\infty}$ symmetries, characteristic of string theories. Then we showed that [45] this W -hair was sufficient to establish *quantum coherence* and avoid *loss of information*. Indeed, we showed explicitly that [45] in stringy black holes there is no Hawking radiation, *i.e.*, $T_{BH} = 0$, and no entropy, *i.e.*, $S_{BH} = 0$! In a way, as it should be expected from a respectable quantum theory of gravity, BH dynamics is not in conflict with quantum mechanics. There are several intuitive arguments that shed light on the above, rather drastic results. To start with, the *infinity* of W -charges make it possible for the BH to *encode* any possible piece of information “thrown” at it by making a transition to an altered suitable configuration, consistent with very powerful selection rules. It should be clear that if it is needed an *infinite* number of *observable* charges to determine a configuration of the BH, then the “measure” of the unavailable to us information about this specific configuration should be virtually zero, *i.e.*, $S_{BH} = 0$! The *completeness* of the W -charges, and for that matter of our argument, for establishing that $S_{BH} = 0$, has been shown in two complementary ways. Firstly, we have shown that [45] if we *sum over* the W -charges, like being unobservables, we reproduce

the whole of Hawking dynamics! Secondly, we have shown that the $W_{1+\infty}$ symmetry *acts* as a phase-space volume (area in 2-D) preserving symmetry, thus entailing the *absence* of the extra $W_{1+\infty}$ symmetry violating $(\delta H)\rho$ term in (21), thus reestablishing (9), *i.e.*, safe-guarding quantum coherence. Actually, we have further shown that [45] stringy BHs correspond to “extreme BHs”, *i.e.*, BH with a harmless horizon, implying that the infinity of W -charges neutralize the extremely strong gravitational attraction. In such a case, there is no danger of seducing a member of a quantum system, hovering around the BH horizon, into the BH, thus eliminating the *raison d’être* for Hawking radiation! Before though icing the champagne, one may need to address a rather fundamental problem. The low-energy, attainable physical world W_1 , is made of electrons, quarks, photons, and the likes, all very well-known particles with well-known properties, *i.e.*, mass, electric charge, etc. Nobody, though, has ever added to the identity card of these particles, lines representing their W -charges. In other words, the W_1 -world seems to be W -charge blind. How is it possible then for an electron falling into a stringy BH, to excite the BH through $W_{1+\infty}$ -type interactions, to an altered configuration where it has been taken into account all the information carried by the electron? Well, here is one of the miraculous mechanisms, endemic in string theories. As discussed above, it has been shown [49] that in the presence of singular spacetime backgrounds, like the black hole one, a mixing, of purely stringy nature, is induced between states belonging to different “mass” levels, *e.g.*, between a *Local* (L) state $|a\rangle_L$ of the W_1 world, with the *Global* states (G) $|a_i\rangle_G$ of the W_2 world

$$\begin{aligned} |a\rangle &= |a\rangle_L + \sum_g |a_g\rangle_G \\ &\text{or} \\ |a\rangle_W &= |a\rangle_{W_1} \oplus |a\rangle_{W_2} \end{aligned} \tag{22}$$

Notice that any resemblance between the symbols in (22) and (2) is *not* accidental and will be clarified later. Thus, we see that when a low energy particle approaches/enters a stringy BH, its global state or W_2 components while *dormant* in flat spacetime backgrounds, get *activated* and this causes a quantum mechanical coherent BH transition, always satisfying a powerful set of selection rules. In this new EMN scenario [45] of BH dynamics, if we start with a *pure state* $|\Psi\rangle = |a\rangle_W |b\rangle_W$, we end up with a *pure state* $|\Psi'\rangle = |a'\rangle_W |b'\rangle_W$, even if our quantum system encountered a BH in its evolution, because we can *monitor* the $|b\rangle$ part through the Bohm-Aharonov-like W_i charges! So everything looks dandy.

Alas, things get a bit more complicated, before they get simpler. We face here a new purely stringy phenomenon, that has to do with the global states, that lead to some dramatic consequences. Because of their *delocalized* nature in spacetime, the global or W_2 -states can neither (a) appear as *well-defined asymptotic states*, nor (b) can they be integrated out in a *local path-integral formalism*, thus defying their detection in local scattering experiments!!! Once more, we have to abandon the language of the scattering matrix S , for the superscattering matrix $\mathcal{S} \neq SS^\dagger$, or equivalently abandon the description of the quantum states by the wavefunction or state vector $|\Psi\rangle$, for the density matrix ρ [51]. Only this time it is for real. While

string theory provides us with consistent and complete quantum dynamics, including gravitational interactions, it does it in such a way that *effectively* “opens” our low energy attainable W_1 world. This is not anymore a possible artifact of our treatment of quantum gravity, this is the *effective quantum mechanics* [51, 5, 6] that emerges from a consistent quantum theory of gravity. An intuitive way to see how it works is to insert $|a\rangle_W$ as given in (22) into (9), where $\rho_W \equiv |a\rangle_W \langle a|_W$, collect all the $|a\rangle_{W_2}$ dependent parts, treat them as *noise*, and regard (9) as describing *effectively* some quantum *Brownian* motion, *i.e.*, regard it as a *stochastic differential equation*, or *Langevin equation* for $\rho_{W_1} = \sum_i p_i |a_i\rangle_{W_1} \langle a_i|_{W_1}$ (see (10)), where the p_i 's depend on $|a\rangle_{W_2}$ and thus on the W_2 world in a *stochastic way* [52]. In the EMN approach [51, 52, 5, 6] the emerging equation, that reproduces the EHNS equation (21) with an explicit form for the $(\delta\mathbb{H})\rho$ term, reads (dropping the W_1 subscripts)

$$\frac{\partial \rho}{\partial t} = i[\rho, H] + iG_{ij}[\alpha_i, \rho]\beta^j \quad (23)$$

where G_{ij} denotes some *positive definite* “metric” in the string field space, while β^j is a characteristic function related to the field α_j and representing *collectively* the agitation of the W_2 world on the α_j dynamics and thus, through (22), one expects $\beta^j \approx \mathcal{O}((E/M_{Pl})^n)$, with E a typical energy scale in the W_1 -world system, and $n = 2, 3, \dots$

Before I get into the physical interpretation and major consequences of (23), let us collect its most fundamental, *system-independent* properties, following *directly* from its specific structure/form [51, 5, 6]

I) *Conservation of probability* P (see (5) and discussion above (9))

$$\frac{\partial P}{\partial t} = \frac{\partial}{\partial t}(\text{Tr}\rho) = 0 \quad (24)$$

II) *Conservation of energy, on the average*

$$\frac{\partial}{\partial t} \langle\langle E \rangle\rangle \equiv \frac{\partial}{\partial t}[\text{Tr}(\rho E)] = 0 \quad (25)$$

III) *Monotonic increase in entropy/microscopic arrow of time*

$$\frac{\partial S}{\partial t} = \frac{\partial}{\partial t}[-\text{Tr}(\rho \ln \rho)] = (\beta^i G_{ij} \beta^j) S \geq 0 \quad (26)$$

due to the positive definiteness of the metric G_{ij} mentioned above, and thus *automatically* and *naturally* implying a *microscopic arrow of time*.

Rather remarkable and useful properties indeed.

Let us try to discuss the physical interpretation of (23) and its consequences. In conventional QM, as represented by (9), one has a *deterministic, unitary* evolution of

the quantum system, and it is *only when* one feels compelled to “measure”/“observe” the system, that the probabilistic element of QM *emerges*. One, of course, tacitly assumes the existence of a fixed, smooth spacetime background that does not “disturb” the system, acting simply as the *arena* in which things are happening, and thus leaving the system “*closed*”. The characteristics of such “closed” systems include, of course, conservation of energy and no *definite arrow of time* or no *flow of time*, which is reflected in the forms of (9), (18), which are invariant under $t \rightarrow -t$! When we decide to “open” the system we basically perform a “measurement”, *i.e.*, we force the system to “decide” what it wants to be, by choosing a very specific state, out of many coexisting possible ones, *i.e.*, we are talking about the “collapse” of the wavefunction. That’s in a nutshell the Copenhagen interpretation of QM, leaving too much to be desired, and too much on the “eye” of the “observer”! We need to do better. In the *density matrix mechanics*, as represented by (23), and as emerged, in one *interpretation* from string theory, one has a *stochastic, indeterministic* evolution of the quantum system, *ab initio*, due to the *unavoidable* existence of *spacetime foam*. The *uncontrollable, universal* quantum fluctuations of the spacetime metric at very short distances ($\mathcal{O}(\ell_{Pl})$), containing creation and annihilation of virtual Planckian-size BH, *agitate* through the global or W_2 -world states, our low-energy quantum system, rendering it *dynamically* and *spontaneously* “open”. This is an *objective, universal* mechanism, independent of any “observer”, that is always “up and working”, thus *eroding* the quantum coherence and eventually leading to a *dynamical, spontaneous collapse*. It should be clear that the *natural “opening”* of our quantum system is due to our *inability* to take into account all the detailed effects of the global states, because of their delocalized nature, and thus we do *truncate* them, arriving at the *Procrustean Principle*, a *new universal principle* [6] that goes beyond the standard uncertainty principle (8). Furthermore, since this new dynamical mechanism of the “collapse” of the wavefunction, as emerged in the EMN approach [51, 5, 6], is an *objective spontaneous, time-ordered*, and thus an *orchestrated* one, I propose here to call it *synchordic collapse*.² Schematically, one can represent this new mechanism of the “collapse” of the wavefunction, by using (22), as follows

$$\begin{array}{ccccccc}
 W & \supset & W_1 & \otimes & W_2 \rightarrow & \text{cause} & \xrightarrow{\text{synchordic}} & W_1 \\
 ||| & & ||| & & ||| & & \xrightarrow{\text{collapse}} & \\
 \text{Physical World} & & \text{Attainable} & & \text{Global} & & & \\
 \text{(including all local} & & \text{Physical World} & & \text{States} & & & \\
 \text{and global states)} & & \text{(including all local,} & & \text{World} & & & \\
 & & \text{low-energy states)} & & & & & \\
 & & & & & & & (27)
 \end{array}$$

which makes it apparent that the *global* or W_2 -world states are the *agents* of the *synchordic collapse*, as being the *raison d’être* of *stochasticity* in quantum dynamics. Also, notice the similarity between (2) and (27), rather remarkable and very sugges-

²chord=string in greek; synchordia something like symphonia.

tive! The most *amazing* and *astonishing* thing is that, despite the well-known fact that usually open, dissipative systems defy quantization and energy conservation, our naturally “open” system, as represented by (23) and as explicitly indicated in (24), (25), and (26), is *different* [53, 54]. It is susceptible to quantization, it *conserves energy* in the mean, and *monotonically increases* its entropy, leading to loss of information, quantitatively expressed as *quantum decoherence*, and thus supplementing us with a very *natural, universal, objective microscopic arrow of time!* In the EMN approach [51, 5, 6], *time is a statistical measure of the interactions (quantum gravitational friction) between the local, low-energy world W_1 and the global or W_2 -world states, in the presence of singular spacetime backgrounds (spacetime foam).* The strong emerging correlation between loss of information, quantum decoherence leading to wavefunction collapse and the dynamical appearance of *flowing* time, I believe is unprecedented in physics.

Clearly, the role of the *magic* extra term proportional to β^j in (23), is multifunctional, as exemplified by making use of the *dissipation-fluctuation theorem* of statistical mechanics [14]. It can be viewed as a *dissipative term* that destroys quantum coherence, by damping the off-diagonal elements and *also* it can be seen as a *noise term* able to drive the system away from its equilibrium position and, after some time, bring it back to the same position or bring it to some other equilibrium position. In other words, we may interpret (23) as a renormalization group equation (RGE), as discussed in section 2, describing the evolution of the system between different *phases*, each corresponding to one of the *infinite* spontaneously broken $W_{1+\infty}$ symmetries. Clearly, at an *equilibrium position*, or at a *critical point*, all β^j do vanish, thus recovering naturally (9) from (23), or equivalently recovering standard QFT as applied to particle physics for the past 70 years. In principle, in fixed, smooth spacetime backgrounds, hopefully corresponding to *critical points* in our new stringy language, there is a *decoupling* of the global states from the local, low-energy states in (22), *i.e.*, all c_g 's do vanish, and thus implying vanishing β^j in (23). Before though, we are carried away from the highly promising stringy big quantum picture that emerges here, it should pay to have a closer look at some numerical details, if not for any other reason, just as a *reality check!* Indeed, one can work out, using (23), the time that it takes for quantum decoherence, or equivalently the quantum coherence lifetime τ_c , as defined by the off-diagonal elements damping factor [43]: $\exp[-Nt(m^6/M^3)(\Delta X)^2]$, for a system of N constituents of mass m , assuming that its center of mass gets finally pinned down within ΔX , and is given by

$$\tau_c = \frac{M^3}{Nm^6(\Delta X)^2} \quad (28)$$

where M stands for $M_{SU} \approx (1/10)M_{Pl} \approx 10^{18}$ GeV, the characteristic string scale [55]. What about the value of m ? The most natural value for it would be $m \approx m_{\text{nucleon}} \approx 1$ GeV for the following reason. Our attainable low-energy world, as far as we know is made up of electrons, protons, and neutrons: that is what constitute us, *i.e.*, our cells, our proteins, our DNA, etc, and also that is what everything else we

use, *i.e.*, the “apparatus”, is made of. Of course, protons and neutrons are mainly made of up (u) and down (d) constituent quarks, but for my arguments they are of comparable mass and thus would give the same results. Now, since the bulk of matter is due to nucleons, and not to electrons ($m_{\text{nucl}} \approx 1836m_e$), the shortest coherence lifetimes that we are interested in would be provided by $m \approx m_{\text{nucl}}$. Furthermore, independent of the complicated structure that you may consider, *e.g.*, a complicated protein polymer structure, a la Microtubules (MTs), the virtual Planckian BHs have such high energy that they “see” and interact/agitate with the most fundamental constituents of the complicated structure, *i.e.*, up and down quarks and electrons, thus as explained above, justifying the identification $m \approx m_{\text{nucl}} \approx 1 \text{ GeV}$ in (28). Thus, using $M \sim 10^{18} \text{ GeV}$, $m \sim 1 \text{ GeV}$, and $(\Delta x) \sim 1 \text{ nm} \equiv 10^{-7} \text{ cm}$, (28) yields

$$\tau_c = \frac{10^{16}}{N} \text{ sec} \quad (29)$$

a rather suggestive formula. In the case of a single ($N = 1$) hydrogen atom, (29) becomes $\tau_H \sim 10^{16} \text{ sec}$, the present age of the universe! In other words, standard QM applies extremely accurately in microsystems, as of course, we want, because of the spectacular successes of QM in the microworld. On the other hand, if we take a piece of ice, containing say $N \sim N_{\text{Avogadro}} \approx 10^{24}$ nucleons, then we get $\tau_c^{\text{ice}} \approx 10^{-8} \text{ sec}$, a rather short-lived quantum coherence implying that for macroscopic objects ($N \sim N_{\text{Avogadro}}$) QM rules fail and classical physics emerges *naturally, dynamically, spontaneously, and objectively!* The *Schrödinger’s cat* paradox is automatically resolved: within $\mathcal{O}(10^{-8} \text{ sec})$ the cat would be dead or alive, not the fifty/fifty stuff anymore. Furthermore, the “measurement”/“observation” problem gets a similar satisfactory resolution. Indeed, performing a “measurement”/“observation” on a quantum system implies bringing it in “*interaction*” with some suitable *macroscopic apparatus* ($N_{\text{macr}} \sim \mathcal{O}(N_{\text{Avog}})$), thus triggering an almost *instantaneous* “collapse” of the wavefunction of the quantum system, as suggested by (29) with $N \approx N_{\text{macr}} + N_{\text{quant.syst}} \sim \mathcal{O}(N_{\text{Avog}})$. The *magic step*, as indicated in (7), and which constitutes basically the one-half of quantum mechanics *it does need not to be postulated*, but it comes out from the stochastic dynamics, as provided by the agitating global or W_2 -world states. It should not escape our notice that there is no quantum-classical border, but a continuous and smooth transition. Furthermore, as (28) indicates, the Avogadro number, a measure of the macroscopicity of the system, is basically dynamically determined to be the inverse of the dimensionless product of the gravitational strength ($\sqrt{G_N}$) times the characteristic strong interaction scale ($\Lambda_{\text{QCD}} \sim \mathcal{O}(0.1 \text{ GeV})$) times the electromagnetic fine structure constant ($\alpha = 1/137$)

$$N_{\text{Avogadro}} \sim \frac{1}{\sqrt{G_N} \Lambda_{\text{QCD}} \alpha} \quad (30)$$

I do hope that I have convinced the reader that the performed *reality check* has been rather successful and illuminating.

It is highly remarkable that stringy modified QM or *density matrix mechanics* is offering us, see ((23),(27)), a new *unified approach* to quantum dynamics, by

turning a *deterministic* wave-type equation into a *stochastic differential* equation able to successfully describe *both* evolution and “measurement” of quantum systems. At the same time, a *unified picture* of the quantum and classical world is emerging, as promised in section 3, without the need of raising artificial borders between the quantum and the classical, the transition between them is dynamical and smooth. The fundamental property of string theory that allows all these “miraculous events” to occur is its defining property, *i.e.*, the need of 2-dimensions (1 space + 1 time) to describe a 1-dimensional (1-D) *extended* object and its accompanying *infinity* of excitation modes/particles, due exactly to its extended nature. While a pointlike particle “runs” on a *world-line*, a string sweeps a *world-sheet*. Eventually, all 4-D spacetime physics would be mappings of corresponding physics in the 2-D stringy world-sheet. The existence of the $W_{1+\infty}$ symmetry was first established in 2-D “world sheet” physics and then mapped into 4-D spacetime physics. The *infinity* of spontaneously broken stringy gauge symmetries, and the very existence of the *global states*, somehow can trace back their origin to the *2-dimensionality* of the world-sheet! In other words, the stringy nature of the modified quantum mechanics prevails, as should be apparent at each and every turn!

The alert reader may have already noticed the stunning similarity between the string dynamics in singular spacetime backgrounds, like black holes and spacetime foam, and the brain mechanics presented in section 2. Presence or lack of quantum coherence and its cause, the existence of an *infinite* number of possible equilibrium or critical points corresponding to an *infinite* number of spontaneously broken “gauge” (stringy) symmetries with *appropriate selection rules*, the possibility of “running” away from one equilibrium point, and eventually coming back to it, or end up at another equilibrium point, in a *timely* manner, etc, etc. If we could only find a structure in the brain that it renders the EMN string dynamics [45, 51, 52, 5, 6] applicable, we would then be able to provide a rather explicit answer to most of the problems raised in sections 2 and 4. Namely, the *binding problem*; how the brain represents a *physical, objectively real, flowing time? free will*, etc, etc.

Well, these brain structures *do exist* and they are called

6 MicroTubules (MT) I: The biochemical profile

Living organisms are collective assemblies of cells which contain collective assemblies of organized material, including membranes, organelles, nuclei, and the *cytoplasm*, the bulk interior medium of living cells. Dynamic rearrangements of the cytoplasm within *eucaryotic cells*, the cells of all animals and almost all plants on Earth, account for their changing shape, movement, etc. This extremely important cytoplasmic structural and dynamical organization is due to the presence of networks of interconnected protein polymers, which are referred to as the *cytoskeleton* due to their boneline structure [1, 2]. The cytoskeleton consists of *Microtubules* (MT’s), action microfilaments, intermediate filaments and an *organizing complex*, the *centrosome* with its chief component the *centriole*, built from two bundles of microtubules in a separated **T** shape.

Parallel-arrayed MTs are interconnected by cross-bridging proteins (*MT-Associated Proteins*: MAPs) to other MTs, organelle filaments and membranes to form *dynamic networks* [1, 2]. MAPs may be contractile, structural, or enzymatic. A very important role is played by contractile MAPs, like dynein and kinesin, through their participation in cell movements as well as in intra-neural, or axoplasmic transport which moves material and thus is of fundamental importance for the *maintenance* and *regulation* of *synapses*. The structural bridges formed by MAPs stabilize MTs and prevent their disassembly. The MT-MAP “complexes” or *cytoskeletal networks* determine the cell architecture and dynamic functions, such a *mitosis*, or *cell division*, *growth*, *differentiation*, *movement*, and for us here the very crucial, *synapse formation and function*, all essential to the living state! It is usually said that *microtubules* and *ubiquitous* through the entire biology! [1, 2]

Microtubules [1, 2, 3] are hollow cylindrical tubes, of about 25 nm in diameter on the outside and 14 nm on the inside, whose walls are polymerized arrays of *protein subunits*. Their lengths may range from tens of nanometers during early assembly, to possible centimeters (!) in nerve axons within large animals. The protein subunits assemble in longitudinal strings called *protofilaments*, thirteen (13) parallel protofilaments laterally align to form the hollow “*tubules*”. The protein subunits are “barbell” or “peanut” shaped *dimers* which in turn consists of two globular proteins, *monomers*, known as *alpha* (α) and *beta* (β) *tubulin*. The α and β tubulin monomers are similar molecules with identical orientation within protofilaments and tubule walls. In the polymerized state of the MT, one monomer consists of 40% α -helix, 31% β -sheet and 29% random coil. The α -tubulin consists of four α -helixes, four β -sheets, and two random coils, while the β -tubulin has six α -helixes, one β -sheet, and seven random coils. Each *monomer* consists of about 500 aminoacids, is about 4nm \times 4nm \times 4nm, and weighs 5.5×10^4 daltons or equivalently its atomic number is 5.5×10^4 , and has a *local polarity*. Each *dimer*, as well as each MT, appears to have an electric polarity or dipole, with the negative end oriented towards the α -monomer and the positive end towards the β -monomer. The dipole character of the dimer originates from the 18 Calcium ions (Ca^{++}) bound within each β -monomer. An equal number of negative charges required for the electrostatic balance are localized near the neighboring α -monomer. Thus, MTs can be viewed as an example of *electret* substances, *i.e.*, oriented assemblies of dipoles, possessing *piezoelectric* properties, pretty important in their functions including their assembly and disassembly behavior. The dimers are held together by relatively weak Van der Waals hydrophobic forces due to dipole coupling. Each dimer has 6 neighbors which form slightly skewed *hexagonal lattices* along the entirety of the tube, with a “leftward” tilt, and several *helical patterns* may be “seen” in the relations among dimers. Imagine a MT slit along its length, and then opened out flat into a strip. One then finds that the tubulins are ordered in sloping lines which rejoin at the opposite edge 5 or 8 places displaced ($5+8=13$), depending on the line slope, it is to the right or to the left. The crystal-like symmetry packing of the tubulin in MTs is very suggestive for a possible use of MTs as “*information processors*”. It should be rather obvious that such a delicate, fine MT organization is there for some good reason.

Further evidence for the very special role that MTs are made to play is provided by the very interesting assembly and disassembly behavior. Dimers self-assemble in MTs, apparently in an *entropy-driven* process which can *quickly* change by MT disassembly and reassembly into *another orientation*. It seems that Guanosine TriPhosphate (GTP) hydrolysis to Guanosine DiPhosphate (GDP) provide the energy that binds the polymerizing tubulin dimers, while biochemical energy can also be pumped into MTs by phosphorylation/dephosphorylation of MAPs. In fact, each tubulin dimer, as a whole, can exist in two different geometrical configurations or *conformations*, induced, *e.g.*, by the GTP-GDP hydrolysis. In one of these they bend 29° to the direction of the microtubule. It seems that these two conformations *correspond* to two different states of the dimer's electric polarization, where these come about because an electron, centrally placed at the α -tubulin/ β -tubulin junction, may shift from one position to another, the textbook, gold-platted case of a *quantum-mechanical two-state system* [20]! Several "on-off" functions linked to Ca^{++} binding could do the job. The Ca^{++} concentration changes could alter the conformational states of certain tubulin subunits, which may be pre-programmed to undergo conformational changes in the presence of Ca^{++} , through GTP, glycosylation, etc. Furthermore, a calcium-calmodulin complex could facilitate charge and/or energy transfer, similar to the way acceptor impurities act in semiconductors! The Ca^{++} may delocalize an electron from its orbital spin mate, both electrons belonging to an aromatic aminoacid ring within a hydrophobic pocket, resulting in an unstable *electron "hole"*, and thus enhancing the probability for either a charge transfer from an adjacent subunit, and/or transfer of energy to an adjacent subunit. Tubulins in MTs may also be modified by binding various ligands, MAPs, etc. Then, given the fact that the genes for α and β tubulins are rather complex, providing a varying primary tubulin structure, *e.g.*, at least 17 different β -tubulins can exist in mammalian brain MTs, one easily sees that the number of different possible combinations of tubulin states and thus the *information capacity* within MTs may be very large indeed! It should be stressed that proteins undergo conformational motions over a wide range of time and energy scales. However, significant conformational changes related to protein function generally occur within the ($10^{-9} - 10^{-12}$) sec time scale. The conformational changes are related to cooperative movements of protein sub-regions and charge redistributions, thus *strongly linked to protein function* (signal transmission, ion channel opening, enzyme action, etc) and may be triggered by factors including phosphorylation, GTP hydrolysis, ion fluxes, electric fields, ligand binding, and neighboring protein conformational changes. In the case of MTs, the *programmable* and *adaptable* nature of the tubulin conformational states can be easily used to *represent* and *propagate* information. Further evidence for some of the extraordinary tasks that may be undertaken by the MTs, due to their specific fine structure, is their fundamental role in *mitosis*, or *cell division*. The *centriole*, as we discussed above, consists basically of two cylinders of nine triplets of MTs each, forming a kind of separated **T**. At some point, each of the two cylinders in the *centriole* grows another, each apparently dragging a bundle of MTs with it, by becoming a focal point around which MTs assemble. These MT fibers connect the centriole to the separate DNA strands in the nucleus, at the *centromeres*, and the

DNA strands separate, thus initiating cell division. Another, indeed extraordinary mechanism from the many contained in Nature's magic bag of tricks! The interrelation and parallelism between MTs and DNA goes much further. The *centriole*, a rather critical part of the *centrosome* or *MT's organizing center*, seems to be a kind of *control center* for the cytoskeleton. Thus, it seems that we have two *strategic centers* in a single cell: the *nucleus*, where all the fundamental genetic material of the cell resides, controlling the cell's heredity and governing the production of proteins, of which the cell itself is composed! On the other hand, the *centrosome*, with the MT-composed *centriole* as its chief component seems to control the cell's movements and its organization. As DNA is the common genetic database containing hereditary information, *microtubules* are *real time executives* of dynamic activities within living cells. One may wonder at this point, that while DNA's very suggestive double-helical structure enables it to possess a code, the *genetic code* [10], nothing of similar caliber occurs within microtubules. This is a false alarm! So, let us take things from the beginning. One nucleotide of DNA is composed of three elements: a *base*, ribose, and *phosphate group*. Four types of bases are present: Adenine (A), Thymine (T), Guanine (G), and Cytosine (C), belonging to two basic categories, a purine base (A,G) and a pyrimidine base (T,C). Nucleotides are interconnected by hydrogen bonds organizing them in a specific double-helix structure (A=T, G≡C). From the aspect of organization of structure, one such double-helix may be considered as an *aperiodic crystal*. "Aperiodic" signifies the irregular interchange of bases *inside* the helix, while the phosphates and riboses are located on the outside making up a *periodic crystal* structure. The irregular repetition of bases within the helix represents properties of the living beings which make sense, from an information point of view, only as *code system*. In the genetic code, one triplet of bases, the *codon*, codes one aminoacid. The basic genetic code is coded by 20 aminoacids and there exists a "stop" as three more codons. Thus, there exist 61 codons which code 20 aminoacids, from the $4^3 = 64$ possible combinations of four bases of triplets. Then, the messenger RNA (mRNA) is synthesized from the one strand of the DNA double helix, while the other strand of the double helix remains in the nucleus making possible the synthesis of another chain of DNA. The complete genetic information is preserved and remains inside the nucleus. From mRNA through carrier RNA (tRNA) to ribosomal RNA (rRNA) there is a continual transmission of the genetic information message, making in effect proteins, the other side of the genetic code. One crucial point to emphasize here is the following [56]: it is well known that the protein's catalytic or other functions strongly depends on its *exact 3-dimensional* structure, thus making it a Tantalian job to try to exactly reproduce genetically a protein! Nature, though, is more subtle. All a gene has to do is to get the *sequence* of the aminoacids correct in that protein. Once the correct polypeptide chain has been synthesized, with all its side chains in the right order, then following the laws of quantum mechanics, called Chemistry in this particular case, the protein would fold itself up correctly into a unique 3-D structure. A difficult 3-dimensional (reproduction) problem has been recast as a much easier attractable 1-dimensional one! A very good lesson to be appreciated and remembered and maybe to be used in other similar circumstances.

Until recently, it was widely believed that MTs were just base elements of the cytoskeleton and that they played a role in the mitotic spindle and active transport. More careful study of the MT's structure, notably by Koruga [57], showed that MTs possess also a *code system*! One should not be surprised by such a finding. Recall that the two different *conformational states* of a tubulin dimer can switch from one to the other, due to alternative possibilities for their *electric polarization*. Clearly, the state of each dimer would be influenced by the polarization states of each of its six neighbors, due to the Van der Waals forces between them, thus giving rise to certain specific rules governing the conformation of each dimer in terms of the conformations of its neighbors. This would allow all kind of messages to be propagated and processed along the length of each microtubule. These propagating signals appear to be relevant to the way that microtubules transport various molecules alongside them, and to the various interconnections between neighboring microtubules through MAPs. The repetitive geometric lattice array of MT units may serve as a *matrix* of directional transfer and transduction of biochemical, conformational, or electromagnetic energy. It seems highly plausible that the continuous grids of intramural MT could function as programable switching matrices capable of information processing. Within neurons, transfer of MT conformational charge or energy state could be driven by travelling nerve action potentials and/or associated transmittance Ca^{++} flux. Such a view is supported by the fact that velocities of action potentials and accompanying Ca^{++} flux $\mathcal{O}(10 - 100)\text{m/sec}$ would result in time intervals for 4nm tubulin subunit transfers of about 10^{-10} sec, consistent with the observed nanosecond range of protein conformational oscillations [58]! Taking into account the intraneural MT density, the neural fraction of the brain, and average neural firing rates, *parallel computing* in MT coupled to action potentials could reach 10^{28} transfers/sec (*bits*) in the human brain!

Koruga observed [57] that the hexagonal packing [59] of the α and β tubulin subunits in MT with *13 protofilaments* corresponds to *information coding*. He noticed that hexagonal packing and face-centered cubic packing of spheres have equal density and thus he used both to explain MT organization. It is known that the $\text{Oh}(\bar{6}/4)$ symmetry group describes face-centered-cubic sphere packing and *derives* information coding laws [60]. In the case of hexagonal packing, the centers of the spheres should lie on the surface of a cylinder (with radius equal to the $\text{Oh}(\bar{6}/4)$ unit sphere) and the sphere values in the axial direction (lattice) of the cylinder by order of sphere packing is the *same* as in the dimension in which face-centered-cubic packing is done. There should be two kinds of spheres (white and black) on the cylinder surface, but linked such that they have the dimension value in which the face-centered-cubic packing is done, leading to an "helical symmetry". Amazingly enough, the MTs satisfy all these desiderata! Thus, the MTs possess one of the best known [60] *binary error-correcting* codes, the 6-binary dimer $K_1[13, 2^6, 5]$, where the distance between spheres in order of packing is 5 and with $2^6 = 64$ *words*!!! It should be noticed that information theory suggests that the optimal number of spheres (white and black corresponding to, say, α and β *monomers*) for information processing is 11, 12, or 13! A rather amazing result, supported further by the fact that 13 (=5+8) seems to be almost universal

amongst *mammalian* MTs. Thus 13 is our lucky number! In addition, symmetry theory suggests that on the surface of a circular cylinder in axial direction of the MT, there must be a code of length of 24 monomer subunits (or 12 dimers), the code $K_2[24, 3^4, 13]$ corresponding to a 4-dimer ternary sequence [57]. It is under the influence of the above discussed Ca^{++} -calmodulin “complex” that 6-binary dimers of K_1 code give 4-dimer ternary sequence of K_2 code, corresponding to biophysical transfer of information from one point to other in MT, by transforming the hexagonal surface organization into a new cubic state. Undoubtedly, microtubule symmetry and structure are *optimal* for information processing. Thus microtubules along with DNA/RNA are *unique cell structures* that possess a *code system*, signifying their singularly important position. Like in the case of DNA/RNA, the specific structure of MTs led to the conclusion that they possess code systems which can be utilized in the neuron dynamic information activities, and other dynamical biological activities as well. It is very hard to believe that the detailed, fine, paracrystalline MT structure, which, among the many other useful functions, enables MTs to possess the K -codes, is just accidental and parochial. It is not very hard to speculate that, since the MTs are strongly involved in *exocytosis*, which is the most fundamental process that may somehow transform intentions/feelings/etc into neural action, the K -codes may be used as a dictionary translating *psychological “orders”* into *physiological actions!* In other words, the DNA/RNA provide the *genetic code*, while the MTs provide the *mental code* or *K-code*. As such, MTs become primary suspects for further investigations concerning their possible role as the *microsites of consciousness*. One should not worry that, at this stage of our investigation, the mechanism of “*real time*” *regulation* and *control* by MT or other cytoskeletal filaments seems to be missing, because it will be provided soon, once we study their physics in the light of *density matrix mechanics*, presented in the previous section. Before we get to this fascinating subject, let us provide some further phenomenological/experimental evidence that indeed neural MTs have to do a lot with learning, memory, cognition, and thus, eventually, with consciousness ...

Our story starts thousands of millions of years ago, when the then popular cytoskeleton-less *procaryotic* cells became entangled with spirochetes possessing whip-like tail composed of cytoskeletal proteins. This, fortunate for us, symbiosis produced the *eucaryotic* cells, possessing cytoskeletons [61, 3]. All this is well, but it has led to the following puzzle. *Single* eucaryotic cell organisms, the protozoa, like the amoeba and the paramecium, without possessing a single neuron or synapse, still appear able of cognitive and adaptive activities. Amoebae have been seen to hunt for food and paramecia to avoid obstacles! How is this possible? The only logical explanation left is that the *key structure* is the cytoskeleton, including MTs, that act as the *nervous system* of single cells, as has been observed almost half a century ago, by the famous neuroscientist C. S. Sherrington [62]. Indeed, the paramecium seems to use its cytoskeleton for coordinated action, in the form of *metachronal waves*. Furthermore, metachronal waves of ciliary beating in paramecia are *reversibly inhibited* by the general anesthetic, chloroform [63]. In addition, it has been shown that signal transduction in sensory cilia is due to propagating *conformational changes* along

ciliary microtubule subunits [64]!

Further evidence, in modern times, that links the cytoskeleton with cognitive function is provided by the following findings:

1. Experiments with trained goldfish show that the drug colchicine produces retrograde amnesia, by affecting memory fixation, through interference with the MTs responsible for the structural modification of certain synapses [65].
2. Production of tubulin and MT activities correlate with peak learning, memory and experience in baby chick brains [66].
3. Experiments with baby rats show that when they first open their eyes, neurons in their visual cortex begin producing vast quantities of tubulin [67].
4. Selective dysfunction of animal brain MTs by the drug colchicine causes defects in learning and memory which mimic the symptoms of Alzheimer's disease (AD). It has been reported that in rats, continuous MT disruption induced by chronic colchicine administration results in a dose-dependent learning deficit, and retention is also impaired. It has also been stressed that these colchicine-induced cognitive defects resemble those of AD, *i.e.*, amnesia of recent learning and loss of formerly established memories [68].
5. It has been hypothesized [69], and very recently supported by detailed experimental studies [70], that impairment of MTs, leading to tangled and dysfunctional neural cytoskeleton, may be one explanation for the pathogenesis of Alzheimer's disease (AD) [71].
6. In specific hippocampal regions of the brain of schizophrenic patients, neuronal distorted architecture found due to a lack of 2 MAPs (MAP-2 and MAP-5) [72].

Arguably, we have plenty of evidence that, the cytoskeleton, and in particular the microtubules, have been rather instrumental through the whole *natural evolution*, from the amoeba and paramecium to humans, and they even helped or were deeply involved in *natural selection*. All these facts, I believe, make it difficult to justify the rather popular attitude of taking the neuron as the fundamental, structureless unit and try to explain the brain function from there on. An analogous attitude would be to try to understand Chemistry by *only* accepting the existence of *structureless* a-toms, in their original Democritean form. We can make a bit of progress but we cannot go that far! The Pauli exclusion principle, of pure quantum mechanical origin, seems to play a rather fundamental role in understanding the periodic table, ... We should come to terms with the *complexity* of the neuron, and we should not treat it just as a *switch*. It will be wiser to concentrate on the *nervous system* of the *neuron*, namely the *microtubule network* [1, 3]. By avoiding taking this rather natural step, we are vulnerable to the accusations of being micro-behaviorists or micro-functionalists, by treating the whole neuron as a black box. Personally, I don't feel comfortable with such an accusation!

So, let us concentrate now on the detailed structure of the neural MTs. Each individual neuron, as being an eucaryotic cell, has its cytoskeleton. Due to the unfortunate for us, fact that neurons do not multiply after the brain is fully formed, there seems to be no role for a *centriole* in the neural cell. Indeed, centrioles seem to be absent in the neuron's centrosome, which as usual, is found close to the neuron's nucleus. Neural MTs can be very long indeed, in comparison with their diameter, of order of $\mathcal{O}(10\text{nm})$ and can reach lengths of mms or more! There are about 450 MTs/ μ^2 or about 7×10^5 tubulins/ μ^3 , along the neural axon. Furthermore, as we mentioned above, the potential *computing* brain power increases substantially if the tubulin dimers (of characteristic two-state conformational frequency of 10^{10}Hz) are taken to be the basic computational units. Indeed, in the case of the "neuron unit", we get something like 10^{14} basic operations per sec ($= 10^{11}$ neurons $\times 10^3$ signals/(neuron sec)), while in the case of the "tubulin dimer unit" we get something like 10^{28} basic operations per sec ($= 10^{11}$ neurons $\times 10^7$ tubulin/neuron $\times 10^{10}$ signals/(tubulin sec))! A rather remarkable gain on brain power by replacing "neuron-type" switches with "*microtubular information processors*", even if we reduce it for efficiency, non-participation, etc. down to, say, 10^{25} "bits". The neural MTs can grow or shrink, depending on the circumstances, they transport neurotransmitter molecules, they are running along the lengths of the axons and dendrites and they do form communicating networks by means of the connecting MAPs. Neural MTs seem to be responsible for *maintaining* the synaptic strengths, while they are able to effect *strength-alterations* when needed. It also seems that neural MTs play a fundamental role in organizing the growth of new nerve endings, piloting them towards their connections with other neuron, thus contributing or being mainly responsible for the formation of neural networks *in vivo*. Neural MTs extend from the *centrosome*, near the nucleus, all the way up to the presynaptic endings of the axon, as well as in the other direction, into the dendrites and dendritic spines, the postsynaptic end of the synaptic cleft. These dendritic spines are subject to growth and degeneration, a rather important process for *brain plasticity*, in which the overall interconnections in the brain are suffering continuous and subtle changes, and as we discussed in section 4, out of reach for the conventional neural networks (NN) approach to brain function. As a further indication for the involvement of neural MTs in *exocytosis*, or the release of neurotransmitter chemicals from the presynaptic vesicular grid, Penrose has emphasized [3] the existence and role of certain substances, called *clathrins*, found in the presynaptic endings of axons, and *associated* with MTs. Clathrins are built from protein trimers, known as *triskelions*, which form three-pronged structures. The clathrin triskelions fit together in an incredulous way, to form very beautiful configurations, basically identical in general organization to the carbon molecules known as "fullereness" or "bucky balls" [73], but much bigger, since the single carbon atoms are replaced by an entire clathrin triskelion involving several aminoacids. Thus, clathrins have a very fascinating geometrical structure, of a truncated icosahedron, that should be related to their important role in the release of neurotransmitter chemicals.

If what is happening in the synaptic clefts, involving always microtubule networks in a rather fundamental way both at the presynaptic and postsynaptic stage,

reminds you of the quasicrystals discussed at the end of section 3, you are right. Brain plasticity shares some similarities with quasicrystal growth [12]. Also, I do hope that I have presented significant evidence indicating the direct involvement of MTs in the control of brain plasticity, and thus coming to a point, where the physics of MTs needs to be discussed.

7 MicroTubules (MT) II: The physical profile

The remarkable biological/physiological properties of MTs discussed in the previous section is a typical example of the amazing *high degree of order* present in biological systems. Usually, bioscientists pay more attention to the functional organization rather than to the spatial/physical structure, but we should always remember that, if we would like to understand function we should study structure [56]. The DNA story is a good example at hand, emphasizing the strong structure-function correlation [18]. The basic physical framework for understanding biological order was put forward by Fröhlich [74]. As we discussed in the previous section, proteins are vibrant, dynamic structures in physiological conditions. A variety of recent techniques have shown that proteins and their component parts undergo conformational transformations, most significantly in the “nanosecond” $10^{-9} - 10^{-10}$ sec range, as predicted by Fröhlich. It should be stressed that these motions are *global changes* in protein conformation *rather than* rapid *thermal fluctuations* of side chains or local regions. About 25 years ago, Fröhlich suggested [74] that such *global* protein changes are *completely triggered* by charge redistributions such as dipole oscillations or electron movements within specific *hydrophobic* regions of proteins. Hydrophobic regions within proteins are comprised of non-polar side chains of aminoacids which exclude water. Incidentally, and for later use, general anesthesia gas molecules apparently act there to prevent protein conformational responsiveness [75]. Fröhlich’s basic conjecture was that quantum-level events such as the movement of an electron within these hydrophobic regions act as a *trigger/switch* for the conformational state of the *entire* protein. The movement of an electron among resonant bond orbitals of aminoacid and side chains such as aromatic rings of tyrosine, is a good example of Fröhlich’s electrons. Fröhlich considered an ensemble of high-frequency oscillators that can be subjected to an external electric field and allowed to strongly interact among themselves. He conjectured that, if biochemical energy such as ATP or GTP hydrolysis were supplied to the dipolar system, a new state would be formed that is characterized by a *long-range coherence*, as manifested by a macroscopic occupation of a single mode. He provided some physical evidence, that coherent excitation frequencies in the range $10^9 - 10^{10}$ Hz were possible in such biological systems. He further predicted metastable states (longer-lived conformational state patterns stabilized by local factors) and travelling regions of dipole-coupled conformations. Such global protein conformations appear suitable for computations: finite states which can be influenced by dynamic neighbor interactions. There is some experimental evidence for Fröhlich’s excitations in biological systems that include observations of GHz-range

phonons in proteins [76], sharp-resonant non-thermal effects of GHz irradiation on living cells [77], GHz-induced activation of microtubule pinocytosis in rat brains [78], Raman detection of Fröhlich frequency energy [79] and the demonstration of propagating signals in microtubules [80]. Fröhlich's basic physical ideas [74] seem to make a lot of sense, but is there any structure(s) that may realize them, or is it another theoretical pipedream? Lo and behold, microtubules just fit the bill. The entire MT may be viewed within the context of the Fröhlich framework, as a regular array of coupled dipole oscillators interacting through resonant long-range forces. Furthermore, as we discussed in the previous section in detail, in the case of MTs we have an explicit mechanism involving the calcium-calmodulin "complex" for the electron movement in the hydrophobic pocket. In addition, coherent vibrations within regions of an MT may take the form of *kink-like excitations* separating adjacent regions with opposite polarization vectors, with the dipole orientations in the direction of the MT axis. The extra energy needed for the creation of kink-like excitations may be provided by GTP hydrolysis, as discussed in the previous section. It is known that the energy produced during GTP hydrolysis is delivered to assembled MTs, although the precise manner in which this energy is utilized is still not understood. Amazingly enough, the free energy released in GTP hydrolysis is about 10Kcal/mole (0.42eV/molecule), or about the energy content of a kink-like excitation! Recently rather detailed and interesting studies of the physics of microtubules, at the *classical level*, have been undertaken by several groups [81, 82, 83], as it is discussed next.

Microtubules are viewed as polymers of subunit proteins, the tubulins, and as such they may be considered as lattices of oriented dipoles. There are three types of arrangements of dipoles in lattices: (i) random, (ii) parallel-aligned or *ferroelectric*, and (iii) regions of locally frozen orientations or *spin-glass* [29]. As discussed in section 2, depending on the values of the parameters characterizing the system (temperature and external electric field look the most relevant here) the system may exhibit different phases. In the ferroelectric phase, there is a long range order (global dipole alignment), encouraging the propagation of kink-like excitations and thus able of MT signaling and assembly/disassembly. On the other hand, the spin-glass phase with its locally frozen dipole orientations seems to be useable for efficient information processing and computations. So, it seems that the MTs organize cell activities by operating in two different phases, accessible by slightly changing the temperature and the external electric field. A rather remarkable operational biological system [1, 57, 81, 82, 83].

The basic characteristics of the physical MT model, put forward in Ref. [81, 82], is that the MT's strong uniaxial dielectric anisotropy align the dipole oscillators so that they can be effectively described by *only one degree of freedom*! In fact, experiments have shown [84] that a tubulin undergoes a conformational change induced by GTP-GDP hydrolysis in which one monomer shifts its orientation by 29° from the dimer's vertical axis, as we discussed in the previous section. Thus, the relevant degree of freedom, identifiable with an "order parameter", is the projection on the MT cylinder's axis of the monomer's displacement from its equilibrium position. The mobile electron on each dimer, as discussed in the previous section, can be localized

either more toward the α -monomer or more toward the β -monomer. The latter possibility is associated with changes in dimer conformation, and thus we should identify the “order” parameter with the amount of β -state distortion when the latter is projected on the MT longitudinal axis. Using the language of Quantum Mechanics (see section 3) I will denote the two *conformational states* of the dimer as $|\alpha\rangle$ and $|\beta\rangle$ referring respectively to the cases of the mobile electron being on the α - or β -court and with $|\alpha\rangle \leftrightarrow |\beta\rangle$ the *quantum transition* triggered by the movement of the electron from the one court to the other. The archetypal of a two-state quantum system indeed! The remarkable inherent symmetry of a MT enables one to view it effectively as nearly perfect *one-dimensional crystal*, and thus including time, as a *highly symmetric 2-dimensional physical system*. Furthermore, one should take into account the fact that the whole MT cylinder represents a “*giant dipole*”. When the cross section of a MT is viewed using electron microscopy, the MT’s outer surfaces are surrounded by a “clear zone” of several nm which apparently represents the *oriented* molecules of cytoplasmic water called sometimes “*vicinal*” water, and enzymes. It seems that the MT produces an electric field. Therefore, it is assumed that, together with the polarized water surrounding it, a MT generates a nearly uniform intrinsic electric field parallel to its axis. The existence of a solvent in the environment of the MT, assumed for simplicity to be just water, has some further consequences. The water provides a dielectric constant ($\epsilon \sim 80$) that reduces the long-range electrostatic energy between the dimer dipoles, and at the same time, it provides a viscous medium that damps out vibrations of dimer dipoles.

All the above detailed physical structure is taken into account in a *classical* mean field theory approach to the dynamics of the MT [81, 82]. One mimics the overall effect of the surrounding dimer-dipoles on a *chosen site n*, by qualitatively describing it by a double-well quartic potential, a standard method, applied in the past rather successfully in similar systems, *e.g.*, in dipolar excitations of ferroelectrics [85]. The potential then, for the β -displacement $u_n(t)$ along the longitudinal symmetry (x) axis of the MT cylinder, in the continuous limit $u_n(t) \rightarrow u(x, t)$, where $u(x, t)$ represents a *1+1 dimensional classical field*, takes the form

$$V(u) = -\frac{1}{2}Au^2(x, t) + \frac{1}{4}Bu^4(x, t) \quad (31)$$

with $B > 0$ and $A = -(+\text{const})(T - T_c)$, where T_c denotes the critical temperature of the system. The equation of motion then reads

$$M\frac{\partial^2 u}{\partial t^2} - kR_0^2\frac{\partial^2 u}{\partial x^2} - Au + Bu^3 + \gamma\frac{\partial u}{\partial t} - qE = 0 \quad (32)$$

where M denotes the mass of the dimer, k is a stiffness parameter, R_0 is the equilibrium spacing between adjacent dimers, γ is the viscous water damping coefficient, and E is the electric field due to the “giant” MT dipole discussed above, with q the effective mobile charge of a single dimer. Detailed studies [81, 82] of the dynamical equation (32), in the appropriate parameter range, have revealed very interesting results/properties. Indeed, for temperatures below the critical temperature

$T_c \approx 300^\circ\text{K}$, the coefficient A in (31) is positive, thus putting the system into the ferroelectric phase, characterized by long-range order, *i.e.*, all dipoles aligned along the MT longitudinal direction. In this phase, Eq. (32) admits travelling waves in the form of displaced *classical* kink-like solitons with *no energy loss* [86]. The kink-like soliton propagates along the protofilament with a fixed velocity v , which for $T < T_c$, *i.e.*, in the ferroelectric phase is well approximated by [81, 82]

$$\vec{v} \approx 2 \times 10^{-5}(\text{m/sec})\vec{E}/(1\text{V/m}) \quad (33)$$

implying, for a characteristic average value of $E \approx 10^5\text{V/m}$, $v \approx 2\text{m/sec}$ and thus a propagating time, from one end to the other of an $\mathcal{O}(1\mu)$ MT, $\tau \approx 5 \times 10^{-7}$ sec. As (33) suggests, the kink-like soliton travels preferentially in the direction of the intrinsic electric field, thus transferring the energy that created it, *i.e.*, chemical GTP-GDP hydrolysis type energy, towards a specific end where it can be used to detach dimers from the MT, in accordance with experimental observations [87], concerning the assembly/disassembly of MTs [88]. The role of MAPs, the lateral cross-bridging proteins, as MTs *stabilizers* becomes clearer now. From the physical point of view, these bridges represent *lattice impurities* in the MT structure, and it is well-known that impurities play a very important role in soliton propagation. Kinks may be totally reflected by an attractive impurity, for a specific range of the kink propagating velocities, thus MAPs may significantly reduce the MT disassembly. Furthermore, the addition of an *external* electric field introduces a new control mechanism in the MT dynamics. As (33) suggests, depending on the relative direction and sign of the two fields (external versus internal) the kink-like solitons may travel faster or stop altogether! Here we have a mechanism that turns MTs to artificial information strings [81, 82, 83]. Each kink-like soliton can be viewed as a bit of information whose propagation can be controlled by an external electric field! Nevertheless, while the ferroelectric phase can be useful for signaling and the assembly/disassembly of MTs, it is to “straight” for *information processing* and *computation*! For such operations one has to move to the spin-glass phase [29]. Detailed studies show [82] that as we increase the temperature above the critical one T_c , while keeping the electric field at appropriate small values, the coefficient A in (31) becomes negative, signaling the formation of a *metastable* phase, the spin-glass phase, before eventually reaching the naively expected *random* phase, where all dipoles are distributed randomly. To understand the existence and properties of the spin-glass phase better, it helps to notice that an MT, as a regular array of coupled local dipole states, can be mapped to an anisotropic two-dimensional *Ising model* [14] on a *triangular lattice*, so that the effective Hamiltonian is

$$H = - \sum j_{ik}\sigma_i\sigma_k \quad (34)$$

with the effective spin variable $\sigma_i = \pm 1$ denoting the dipole’s projection on the MTs longitudinal axis, and the exchange constants j_{ij} , representing the interaction energy between two neighboring lattice sites, are given by

$$j_{ij} = \frac{1}{4\pi\epsilon} \left(\frac{3 \cos^2 \theta - 1}{r_{ij}^3} \right) p^2 \quad (35)$$

In (35), p is the dipole moment $p = qd$, where $d \approx 4\text{nm}$; r_{ij} is the distance between sites i and j , and θ is the angle between the dipole axis and the directions between the two dipoles. Explicit calculations using MT X-ray diffraction data, have succeeded to determine all relevant parameters (j_{ij} , θ , and r_{ij}) relevant to the MT system and be found in Ref. [82]. As is well-known [29], such a system is able to exhibit *frustration* in its ground state, *i.e.*, there will always be a conflict between satisfying all the *energy requirements* for the “+” bonds (two-parallel dipoles) and “-” bonds (parallel-antiparallel dipoles). That leads to the *spin-glass phase* where spin orientations are locally “frozen” in random directions due to the fact that the ground state has a multitude of equivalent orientations. For each triangle, reversing the spin on one side with respect to the remaining two leads to an equivalent configuration. In a MT with about 10^4 dipoles or dimers the degeneracy of the ground state is of the order of $6^{10,000}$, a very large number indeed! Small potential barriers separating the various equivalent arrangements of spins play a fundamental role. Relaxation times are very long for the various accessible states giving them *long-term stability*! All these properties of the spin-glass phase makes it optimal for computational applications. The spin-glass phases allow easy formation of *local* ordered states, each of which carries some information content and is relatively stable over time, thus the perfect candidate for information processing and computation. It is highly remarkable that tubulin subunits in closely arrayed neural MTs ($450\text{ MT}/\mu^2$) have a density of about $10^{17}\text{ tubulins}/\text{cm}^3$, very close to the theoretical limit for charge separation [89]. Thus, cytoskeletal arrays have *maximal* density for information storage via charge, and the *capacity* for *dynamically coupling* that information to mechanical and chemical events via *conformational states* of proteins. Furthermore, the switch between the different phases (*ferroelectric*, *spin-glass* and *random*) is achieved through various physical means, *e.g.*, temperature or electric field changes, both within easily attainable physiological conditions! For example, as the intrinsic electric field is raised above, about $10^4\text{V}/\text{m}$, easily attainable in MTs, the MT state switches from the spin-glass to the ferroelectric phase. While the similarities between the equations (34) and (17) as well as between the brain function phases of section 2 and the MT phases discussed here, are striking and rather suggestive, some further steps are needed before shouting *eureka*.

The treatment of MT dynamics [81, 82] presented above is based on *classical* (mean) *field theory*. For some physical issues this is an acceptable approximation, given the fact that MTs may sometimes have macroscopic dimensions. On the other hand, our main purpose would then evaporate, since the central issue of quantum coherence and its loss would remain mute and its relevance or not to brain function would remain unanswered. Usually, after the classical treatment of a system, one goes directly to *quantize* the dynamics of the system in a standard way. Alas, things here are not so easy. We have seen that there are very important, *dissipative*, *viscous* forces, due, for example, to the existence of water molecules that play a very important role in the support and propagation of classical kink-like solitons, but on the other hand, as is well-known, render the possible quantization of the dynamical system, rather impossible! Amazingly enough, very recently [7] together with N. Mavromatos we

have been able to map the 1+1 dimensional MT physical model discussed above to a 1+1 dimensional *non-critical* string theory [90, 91], the precursor of the 1+1 black-hole model [50] discussed in section 5. Should we be surprised by such a mapping? Probably, not that much. To start with, there are not that many different theories in 1+1 dimensions, and even seemingly completely different theories may belong to the same *universality class*, discussed in section 2, implying very similar physical, “*critical*” properties. In fact, the possibility of casting the 1+1 dimensional MT dynamics in the, rather simple, double-well quartic potential form (31), stems from the well-known equivalence [14] between such a quartic potential and the one-dimensional *Ising model*, *i.e.*, interacting one-dimensional “spin” chains, similar to the MTs protofilaments! Furthermore, one can “derive” [92] a 1+1-dimensional non-linear σ model (resembling the 1+1 dimensional, *non-critical* string theory [90, 91]) as the infrared limit of the Heisenberg (anti)ferromagnet model (resembling the 1+1-dimensional MT electret). The consequences of such a mapping of the 1+1 MT dynamics on to a suitable 1+1 *non-critical* string theory are rather far-reaching. All the interesting and novel results discussed in section 5, when appropriately translated, hold also true for the MT system, including the construction of a *completely integrable* 1+1 dimensional model for the MTs, admitting *consistent* (mean-field) *quantization*. Furthermore, the *completely integrable* nature of the MT system, implying the existence of an “infinity” of quantum numbers labelling the states of the system (like the Black-Hole $W_{1+\infty}$ *hair* discussed in section 5), make it possible to store and eventually retrieve information in a *coherent way*. The practically infinite dimensional degeneracy of the spin-glass ground state, discussed above with its remarkable information processing/computation abilities, is, of course, due to the available “infinity” of quantum numbers, characterizing the system. In any case, the *consistent quantization* of the MT-dynamics/system, make the possible appearance of large-scale coherent states, the MQS of section 2, not only plausible, but also feasible. But, as we discussed in detail in section 5, there is no “closed” system in Nature. Because of the *Procrustean Principle* [6], a concise, synoptic expression of the spacetime foam effects, all physical systems are rendered necessarily “open”, and thus eventually “collapse”. The MT system is no exception to the rule. On the contrary, the above discussed mapping of the 1+1-dimensional MT dynamics to a 1+1-dimensional *effective non-critical* string theory, as observed by N. Mavromatos and myself [7], simplify things considerably in this context too! After all, the central issue of section 5 was basically how to take into account space-time foam effects in string theory and their possible consequences, as coded in the EMN approach [51, 5, 6]. Let us give here a *very simplified* physical picture of what is going on.

More specifically, in the case of the MT system the *conformational, quantum* transitions of the dimers ($|\alpha\rangle \leftrightarrow |\beta\rangle$) create abrupt distortions of spacetime, thus enhancing the possibility of creation and annihilation of virtual, Planck-size black holes. The Planckian black holes interact with the MT system, through the global string states³ (the W_2 *world* of (27)), which *agitate* the MT system in a *stochastic way*,

³It should be remarked that the effective non-critical string picture advocated in Ref. [7], applies

as described by (23), but with a monotonic increase in entropy (26) supplying the MT system with a *microscopic arrow of time*, badly needed specifically in biological systems, while allowing for loss-free energy propagation (25). Furthermore, the W_2 global states lead to *synchordic collapse* (27) with a time period τ_c (29). While all these facts start painting a rather fascinating picture, one may justifiably wonder that the brain, being a hot, wet, noisy environment, is the complete *antithesis* of what is really needed for quantum effects to develop! In other words, even if we could be able to produce a macroscopic quantum state (MQS), would not be that *environmental effects* take over and “destroy” everything before any “useful” quantum effects take place? There are different ways/levels of answering this question in our framework here. The MT-dynamics, including viscous water and all, can be *mapped* to a *non-critical* string theory and as such MTs may be viewed as “open” systems obeying consistent quantum dynamics as contained in (23). One then is entitled, if so desired, to ignore completely the mapping, and just use (23) as a successful phenomenological equation describing the MT system, but with all parameters entering (23) determined appropriately by the *physical environment*. One then hopes to reproduce most of the interesting results mentioned above, without reference to the rather specific and detailed quantum gravitational framework used above. In principle, I don’t see anything wrong with such an *agnostic approach*, beyond losing some predictive power. Nevertheless, it should be stressed that the amazing shielding of the whole neuronal axon through the insulating coating of *myelin*, as discussed in section 4, and the whole astonishing fine paracrystalline structure of the MT network provide just the right environment for the flourishing of quantum effects. One may even wonder if Nature, or more precisely *natural selection* supported throughout evolution, all these fine structures in a random, parasitic way or, as I believe, because they were needed to perform useful work. *Survival of the finest!*

It is encouraging that further studies of the MT dynamics strongly indicate that the MT’s filamentous structure may be due to spontaneous symmetry breaking effects, a la superconductivity, and provided further evidence for the MTs’ usefulness to support and sustain quantum coherence. Indeed, considering the layer of ordered water outside and inside MTs, Del Giudice, *et. al.*[93] proposed that the formation of MT’s cylindrical structure from tubulin subunits may be understood by the concept of self-focusing of electromagnetic energy by ordered water. Like the Meissner (symmetry breaking) effect for superconducting media, electromagnetic energy would be confined inside filamentous regions around which the tubulin subunits gather. Del Giudice, *et. al.*[93] showed that this self-focusing should result in filamentous beams of radius 15nm, precisely the inner diameter of microtubules! Furthermore, Jibu, *et. al.*[94], have proposed that the quantum dynamical system of water molecules and the quantized electromagnetic field confined inside the hollow MT core can manifest a specific collective dynamical effect called *superradiance* [95] by which the MT can transform *any incoherent, thermal and disordered* molecular, atomic or electromag-

more generally to the case where the W_2 -world does not correspond *necessarily* to Planckian states but describes complicated, yet unknown, biological effects in the brain.

netic energy into *coherent photons* inside the MT. Furthermore, they have also shown [94] that such *coherent photons* created by superradiance penetrate perfectly along the internal hollow core of the MT as if the optical medium inside it were made “transparent” by the propagating photons themselves. This is the quantum phenomenon of *self-induced transparency* [96]. *Superradiance* and *self-induced transparency* in cytoskeletal MTs can lead to “*optical neural holography*” [1]. Neurons (and maybe other cells) may contain microscopic coherent optical supercomputers with enormous capacity. Thus Jibu, *et. al.*[94], suggest that MTs can behave as *optical waveguides* which result in coherent photons. They estimate that this quantum coherence is capable of superposition of states among MT spatially distributed over *hundreds of microns*! These in turn are in superposition with other MTs hundreds of microns away in other directions and so on...

It seems to me that we have accumulated enough evidence to safely assume that the MT structure and dynamics are not only, strongly supportive of the onset of long-range quantum coherence, but they are also very protective of quantum coherence, shielding it from standard physical environmental effects, modulo, of course, the menace of the spacetime foam. So, finally we have in place all the physical and biological facts needed to put forward our thesis about a *unified theory* of the Brain-Mind dynamics promised in the Introduction.

8 Microtubules and Density Matrix Mechanics (I): Quantum Theory of Brain Function

Let us assume that an “external stimulus” is applied to the brain. This, of course, means that some well-defined physical signal, presumably representing some form of information, interacts with the brain. The physical content of the signal (energy content, ...) starts to “straighten up” the *relevant* regions of the brain, as analyses of EEGs, discussed in section 2, have shown [16]. In our picture, the detailed microstructure, both physical and biological, of the MT network entails that this “external stimulus” would initially *trigger/cause coherent* vibrations of the *relevant* part of the MT network. Eventually, it is most probable that the “*prepared*”, by the external stimulus, quantum state of the system Ψ would be a quantum *superposition* of many states or many *alternatives*, all taking place at *once*. This is extremely likely to occur in the *spin-glass* phase with its huge degeneracy, thus basically allowing the *relevant part* of the MT network to perform many-many quantum (parallel) computations *at once*, while processing the data contained in the “external stimulus”. After some time τ_c , as given by (28) or (29), and because of the *global* or *W₂-world states* the *relevant* MT wavefunction would “*collapse*” to one specific state. The *W₂-world states* have forced the system to “decide” what it wants to be, by triggering it to *choose one* among many alternative states. Notice that since the MT network is rather *extensive*, from the “*sensory*” cortex to the *association cortex* to the *motor cortex* (see section 4), the whole process of *input*→*processing*→*output* is well-coordinated/correlated through

the *magic* properties of the *chosen* quantum state. The dynamically *emerging*, due to *synchordic collapse* (see (22)) *chosen* state has all the desirable properties (see section 2), like long-term stability and non-locality, as being one of the many possible states of the spin-glass phase, to be of primary importance in *brain function* and “*decision making*”! Indeed as we have stressed numerous times by now, one of the most important functional roles of the MTs, is their strong involvement in *brain plasticity* and *exocytosis* (see sections 4,6). MTs control the shrinkage or growth of dendritic spines (*brain plasticity*) and by triggering the “*unlocking*” of the presynaptic vesicular grid, thus allowing *one* vesicle to “fire” or emit its content of neurotransmitters towards the synaptic cleft, they control exocytosis. Certainly MTs are the *masters* of the *neurophysiological game*. The whole *neurophysiological response* to the “external signal” *depends* on the specific form of the *chosen* state of the *relevant part* of the MT network, which in turn, at least *partially* depends on the W_2 -world states in a *stochastic way* (see sections 5,7). That is how, finally they may lead to *learning* or *memory recall* or, through the motor cortex, to *action*, or *nothing*, as discussed in sections 2,4,6. It should be stressed that the biological/physical properties of the MTs, as discussed in sections 6 and 7, are rather suggestive of their important role in the brain function. The very existence of the K -codes [57], related to the MT *conformational states*, which in turn are *strongly correlated* to *protein function* (see section 6) make it apparent that *everything*, from bioinformation transmission to memories lay down, to decision making, to movement, is *MT-driven*, and thus, as mentioned above, at least *partially, global states* or W_2 -world states dependent! Actually, I cannot refrain from recalling here the analogy between *brain plasticity* and *quasicrystal growth* discussed in sections 3,4,6. In the case of quasicrystals, the ground state, *i.e.*, the state with *minimal energy*, is determined by employing many-many alternatives *at once, i.e.*, parallel “computations” of energy considerations *at once*, depending, of course, on the physical environment, *e.g.*, solvent, etc, until the quasicrystal grows enough, so that *synchordic collapse* occurs, with *one* final macroscopic state possible, the one that the experimentalists look at [12]! In the case of *brain plasticity*, including dendritic spine growth and shrinkage, a very similar situation occurs, though now we are dealing with a much more involved situation where many *minimization conditions* have to be satisfied simultaneously, corresponding to the very complex nature of the brain, and thus in a way, make *imperative* the possibility of *quantum computation*, as provided by the *MT network* in a *stringy modified quantum mechanics* or *density matrix mechanics framework*!

While the above emerging quantum theory of brain function has several suggestive and *qualitatively* sound features, it would be nice to be able to make some *quantitative statements* as well, in other words work out some predictions or even postdictions! Indeed, this is possible. To start with, in order for this new dynamical theory to “hold water” at all, we first have to check whether the very phenomenon of *exocytosis* is of quantum nature, as we claim, or whether it can be explained on the basis of statistical or thermal fluctuations. Well, the answer is on our favor. Eccles [9] and Beck and Eccles [97] have shown that *exocytosis* is a *quantum phenomenon* of the presynaptic vesicular grid. They noticed that the synaptic vesicles forming an

hexagonal array, are packaged between the presynaptic dense projections in a triangular array, composing the presynaptic vesicular grid, having *paracrystalline properties* [98]. Any similarity with the MT hexagonal paracrystalline structure is not accidental, since the *boutons* are the end points of MTs! There are about *10,000 vesicles* per synaptic unit or *bouton*, of which only (30–80) belong to the “*firing zone*” of the paracrystalline presynaptic vesicular grid [98] and of which, *only one* (1) “fires” about (5,000–10,000) neurotransmitter molecules, in a *probabilistic* ($\sim 0.3 - 0.4$) way. Thus, the probability of quantum (vesicular) emission is a *holistic* property of the presynaptic vesicular grid of the bouton! Actually, they further noticed [9, 97] that this probability *is not a fixed number*, but can be increased or decreased by physiological or pharmacological treatment [99]! This is exactly what the doctor ordered. Indeed, one can *schematically* identify the *prepared state* Ψ , discussed with the one represented by (13), where the $|k\rangle_i$ refers now to the specific $|\alpha\rangle$ or $|\beta\rangle$ conformational state of the k -th tubulin dimer in the i -th relevant macroscopic (MT-network) quantum state, and N is the number of tubulins involved. Then, the system suffers *synchordic collapse*

$$|\Psi\rangle = \sum_i c_i |1\rangle_1 |2\rangle_i \cdots |N\rangle_i \longrightarrow \rho_{W_1} = \sum_{i=1} p_i |1\rangle_i \cdots |N\rangle_i \langle N| \cdots \langle 1| \quad (36)$$

where ρ_{W_1} has been discussed in Section 5 (just above (23)), with the p_i denoting *probabilities* depending in an *stochastic way* on the W_2 -world states. Since, the MT network extends all the way to the relevant vesicular grids, it becomes apparent that we expect a *synchordic, simultaneous* (EPR-like [22, 12]), *probabilistic* “firing” of all the *boutons* involved, triggering thus the appropriate standard neurophysiological action! Thus, not only do we expect *quantum exocytosis* to occur, but we also do expect to be able to *influence*, through the *stochasticity* brought by the *global* or W_2 -world states, the probabilistic outcome, allowing thus for (see below) *free-will*! And indeed it is happening [9, 97, 98, 99]. So far so good. Another immediate prediction or natural expectation, that one has in this new dynamical theory, concerns the *time difference* between say an “*external order*” and “*action*”. According to our new picture advanced here, there is some time-lapse between the input and the output, characterized *mainly* by τ_c , the quantum coherence lifetime, as given by (28),(29), *i.e.*, the time that takes for information processing and quantum computation. The way that (29) has been derived should make it clear that it was meant to apply in the MT network system! The only thing we are missing is the value of N . It seems to be a consensus, very rare in Brain Science, that the basic *module* of 10^4 neurons, discussed in section 4, should be able to “decide” something useful! In this case

$$N \approx 10^4 \frac{\text{neurons}}{\text{module}} \cdot 10^8 \frac{\text{tubulins}}{\text{neuron}} \cdot 10^5 (Z_{\text{tubulin}}) (10\% \text{ efficiency}) \approx 10^{16} \quad (37)$$

implying, when inserted in (29)

$$\tau_c^{\text{“Brain”}} \approx \mathcal{O}(1 \text{ sec}) , \quad (38)$$

a rather long time compared to the neuron cycle-time of about (1–2) msec and to *neurosignal* velocity of about 100 m/sec, as discussed in section 4. Let me stress at this point that the rather long time of $\mathcal{O}(1\text{ sec})$ should not be compared with *cerebellum* guided reflections, as discussed in section 4, of much smaller reaction time, since they have become of second nature and there is no “*thinking*” or “*decision making*” involved. For the skeptical reader, who may feel queasy with our philosophy to use the nucleon mass ($m_{\text{nucleon}} \approx 1\text{ GeV}$) as the fundamental mass unit (m) in (28) and thus yielding (29), we offer the following hopefully soothing remarks. It has been noticed in [7] that it is reasonable, in the case of an assembly of tubulin dimers as in microtubules, to assume that the pertinent moving mass is the effective mass M^* of the kink background. This effective mass M^* has been estimated to be [81] $M^* \approx 3m_{\text{nucleon}}$! By inserting now M^* as the fundamental mass unit in (28), where N denotes, in this interpretation, the number of tubulin dimers $N_T \approx 10^{12}$, as provided by (37), we get *again* $\tau_c^{\text{“Brain”}} \approx \mathcal{O}(1\text{ sec})$! For yet another way, the third way of reproducing (38) see [7]. So, we feel kind of confident that (38) provides indeed a rather indicative, *canonical* value of the time lapse needed, in our scheme, for an “*event*” to be perceived *consciously*, under normal circumstances. Clearly, (28),(29) and (37) spell out *explicitly* the dependence on different parameters involved in getting (38) and thus enabling us to derive estimates for $\tau_c^{\text{“Brain”}}$ in circumstances different that the normal/canonical one discussed above. Individual *conscious events* may occur at different time scales depending on the number (N), effective mass (M^*), etc, of the tubulin dimers involved in the *prepared* coherent state Ψ (36). For example, the “ γ -oscillations” (or “40 Hz oscillations”) [33, 34] discussed at the end of section 4, *may be* due to the successive, synchronic collapses of an *extended* MT-network. Indeed, it is plausible that the *relevant* MT-network involves either a bigger number of, or longer, neurons than the *canonical* values used in (28),(29), (37) to yield (38), thus enabling us to get in this case $\tau_c^{\text{“Brain”}} \approx \mathcal{O}(1/50\text{ sec})$, without much sweat and pain. It is too early yet, to get down to such specifics, and would be foolhardy to claim that everything has been explained! Simply, it does not seem inconceivable to be able to accommodate such “ γ -oscillations” in our scheme, thus providing a microscopic, physical explanation to the phenomenological Crick-Koch proposal [36, 32] that synchronized firing in the “ γ -range” might be the neural correlate of visual awareness. Generalizing this notion to other “ x -oscillations” we may naturally lead to the solution of the *binding problem* or *unitary sense of self*! It is highly remarkable and astonishing the *synergy*, in our scheme, between *Planck scale physics, atomic and subatomic physics* providing the relevant parameters in (28), thus leading to (29), *and Neurobiology* (37), to eventually yield the estimate (38), seemingly in the right ballpark! Indeed, as discussed in sections 4 and 6, *learning* or *memory laydown*, closely related to *brain plasticity*, involving shrinkage or growth of dendritic spines are supposed to occur [100] within $\mathcal{O}(\text{seconds})$, in amazing agreement with our prediction (38)!

Further evidence that our prediction (38), and more generally, that our new quantum theory of brain is making sense relies upon rather complicated experiments, including clinical studies, that have been discussed in detail by Penrose [12, 3], so I will be rather concise. These are experiments that have been performed on *hu-*

man subjects, and have to do with the time that *consciousness* takes to act and to be enacted, *i.e.*, they are concerned with the *active* and *passive* role of *consciousness* respectively. In the first one, performed by Kornhuber, *et. al.*[101] on a number of human subjects volunteered to have electrical signals recorded at a point on their heads, *i.e.*, EEGs, and they were asked to flex their index finger of their right hands suddenly at various times, at *free-will*. Averaged over many trials, Kornhuber's experiments showed that the decision to flex the finger appears to be made a *full second* or even *1.5 seconds before* the finger is actually flexed. Furthermore, if *free-will* is replaced by reponse to the flash of a light signal, then the reaction time for finger flexing is, at least, five times shorter than the *free-will* one! In the second experiment, by Libet, *et. al.*[102], subjects who had to have brain surgery consented to having electrodes placed at points in the brain, in the somatosensory cortex. The upshot of Libet's experiment [102] was that when a stimulus was applied to the skin of the patients, *skin-touch*, it took about $\mathcal{O}(\text{second})$ before they were *consciously aware* of that stimulus, despite the fact that the brain itself would have received the signal of the stimulus in about *0.01 sec*, and a pre-programmed "reflex" response to such a stimulus could be achieved by the brain in about *0.1 sec*! Furthermore, cortical stimuli of less than $\mathcal{O}(\text{sec})$ are not perceived at all, and a cortical stimulus over $\mathcal{O}(\text{sec})$ is perceived from $\mathcal{O}(\text{sec})$ onwards! It is even possible that a cortical stimulus can even "*backward mask*" an earlier skin stimulus, indicating that *awareness* of the skin stimulus had actually not yet taken place by the time of cortical stimulus. The *conscious perception* can be prevented ("masked") by a later event, provided that the event occurs within $\mathcal{O}(\text{sec})$. In addition, when a cortical stimulation lasting for more than $\mathcal{O}(\text{sec})$ is followed by a skin stimulation, within the original $\mathcal{O}(\text{sec})$, *both signals* were perceived, but in *reversed order*! The subject would think that first was the skin-touch, followed by the cortical stimulation, *i.e.*, a *referral backwards in time* for the skin stimulus of about $\mathcal{O}(\text{sec})$. Though for the cortical stimulation, assumed to occur this time after the skin-touch, there is no *referral backwards in time*, implying that this is *not* simply an overall error in the internally perceived time. These are rather dramatic results with far-reaching consequences for the understanding of *consciousness* [103, 12, 3]. In our new dynamical theory they admit a rather simple and straightforward explanation. Indeed, the Kornhuber type experiments [101], concerning *active* consciousness, imply that indeed there is a time-lapse between input→output of about $\mathcal{O}(\text{sec})$ as suggested by (38), and not in the naively expected $\mathcal{O}(\text{msec})$ range from simplistic "neurosignal" analysis. One may imagine, as discussed in detail above, that the external stimulus, flex the finger at *free-will* in this particular case, sets the *relevant preconscious state* "*in gear*", and eventually, through the involvement of *global or W_2 -world states*, the "collapse" of the wavefunction occurs, leaving only one specific state, the *conscious state*, that carry the order to *physiologically* flex the index finger! The strong correlation between *free-will* and the *global or W_2 -world states* should be apparent. Clearly, if *free-will* is replaced by *reflective response* to an external stimulus, then we expect much smaller reaction time, since basically there is no conscious thinking involved and thus the situation is very similar to cerebellum reflective actions. Concerning the Libet type experiments [102], involving *passive consciousness*, again we can pro-

vide simple explanations. Since it takes about $\mathcal{O}(\text{sec})$ for *conscious perception* in our new dynamical theory, if the cortical stimulus is removed in time less than $\mathcal{O}(\text{sec})$, we feel nothing, since presumably it did not succeed to “prepare” the *preconscious states*, thus it acts simply like random noise. On the other hand, if it lasts about $\mathcal{O}(\text{sec})$, then it is able to “straighten” the *relevant* states up, and thus it is able to create *conscious perception*, that we “feel” it! On the other hand, the skin-touch, as more “*real*” and *effective*, would always be felt after $\mathcal{O}(\text{sec})$, *except* when, during the $\mathcal{O}(\text{sec})$, a *relevant* cortical stimulus is applied that *eliminates* the skin-touch’s efforts to “prepare” a *preconscious state* and let it “run” or “*compute*”, to be more specific. In a way, since the cortical stimulus is applied before the “collapse” of the skin-touch related wavefunction, quantum superposition, even if it is approximate, suggests that indeed something like $|\Psi_{\text{skin-touch}} + \Psi_{\text{cort.stim.}}|^2 \approx 0$ is possible, thus providing a possible quantum explanation to the “*backwards masking*” effect! Concerning the *referral backwards in time* puzzle, one should recall that a *microscopic arrow of time*, presumably responsible for the *consciously perceived time ordering*, past, present, future, is *only* present in the EMN approach [5, 6, 51], and as such is strongly correlated with the spontaneous collapse. The skin-touch case as more “effective”, involving more “mass”/“energy” movement in its process (*longest way*) may have a “collapse” characteristic time τ_c , as given in (29), smaller than the cortical stimulus case (*shortest way*), thus because $(\tau_c)_{\text{s-t}} < (\tau_c)_{\text{c-s}}$, *independently* of the time of their application, we always feel that the skin-touch occurred always first! A rather interesting application of the EMN approach [5, 6, 51]. Incidentally, if this new approach to brain dynamics is right, one may understand the famous *X-ism* phenomenon, referred to in section 4. The neurons seem to follow the principle of the *longest possible path*, because in such a case they *activate* the most “mass”/“energy” movement possible, thus *shortening* the “decision” time τ_c given by (28) or (29), thus contributing better to hierarchical and non-local actions of the brain. This kind of microphysical explanation is, of course, supportive of an evolutionary natural selection, where in this case survival of the fittest reads survival of the longest neuron ... It should not be very surprising that the modern man is around only 50,000 years and that the dawn of civilizations was about 10,000 years ago! It is a lot of fine-complicated structure to put together, starting from the very simple amoeba or paramecium and eventually evolving to humans with their extremely long microtubule networks.

Another very suggestive key feature, supporting further the eminent direct connection between coherent MT conformational oscillations and the emergence of *consciousness*, is the fact that *absence* of conformational oscillations, as caused by general anesthesia molecules, leads to *loss* of consciousness [75, 3]. We have already discussed in section 6 the case of *reversible inhibition* of paramecium’s methachronal waves by chloroform [63]. *Metachronal waves* are paramecium’s best shot for a conscious event! What about higher organisms? It is rather well-known that brains of patients under general anesthesia are commonly quite active: EEG, evoked potentials and other brain functions persist despite lack of consciousness. In a way, general anesthesia, at the right level, implies *absence* of consciousness. It has been suggested [75, 3] that, as *anesthetic gas* diffuse into individual nerve cells, their electric dipole

properties (unrelated, in principle, to their ordinary chemical properties) can interrupt the actions of MTs. They interfere through weak Van der Waals forces, with the normal switching actions of the tubulins, “blocking” the crucial tubulin electrons, as discussed in section 6. It should be stressed that although there seems to be no generally accepted *detailed* picture of the action of anesthetics, it is widely believed that it is the Van der Waals interactions of these substances with the conformational dynamics of the brain proteins that do the job. Here, the relevant brain proteins are identified with the tubulin dimers consisting the MT network. Such a detailed scenario for the workings of general anesthesia seem to explain easily some of its key features. For example, it is a rather remarkable fact that general anesthesia can be induced by a large number of completely different substances of no chemical affinity whatsoever, *e.g.*, from ether to chloroform to xenon! In our case it is just the electric dipole properties of these substances that need to be similar and not necessarily their chemical properties. Furthermore, if the general anestheson concentrations are not too high, complete reversibility or recovery of consciousness is achieved, indicating that the temporary Van der Waals “blocage” of the crucial tubulin electron has ended and conformational oscillations reoccur. On the other hand, general anesthetics, which are known to bind to microtubules, at high enough concentrations cause their depolymerization [104], implying in our picture partial or total *irreversible* loss of consciousness. It is also known that anesthetics may disrupt hydrophobic links among MAPs which interconnect MTs into functional coherent networks [105]. These, rather simple, in our framework, explanations of certain *puzzling* features of general anesthesia provide further positive evidence and credibility to our central thesis here, that MTs are the microsities of consciousness. We have argued before that quantum coherence in MT networks leads eventually, through synchordic collapse, to conscious events, while we see here that *systematic, organized, prevention* of quantum coherence, a la general anesthesia, leads to *loss* of consciousness!

It is remarkable how well the MT’s biological/physical structure fits within the density matrix mechanics framework. We were able not only to derive several qualitatively interesting results, but as I showed above, we were able to get some highly desirable *numbers* too! Nevertheless, we should not be carried away and we should also not lose perspective of what we want to achieve, *i.e.*, how the *whole* brain works and what is *consciousness*, etc. There is a cognitive hierarchy, and what we have showed is that the MT information processing may provide the basement level, implying that everything else is build upon it. The neuron synapse is the next layer up leading to yet another layer, the *neural synaptic network* or *module*, that it is able to operate cooperatively by utilizing dense interconnectedness, parallelism, associative memory and learning due to synaptic plasticity, as we explained above. At intermediate cognitive levels the motor and sensor *maps* represent the body and the outside world, while the next to highest cognitive level appears to be comprised of anatomically and functionally recognizable brain systems and centers (*i.e.*, respiratory center, ...). The highest cognitive level is *global brain function*, which *correlates* with awareness, thought or *consciousness*. Clearly, this hierarchical structure is *susceptible* to *quantum treatment*, because of the very special dynamics that characterize the MT

network. In a way, one may consider the conformational ($|\alpha\rangle$ or $|\beta\rangle$) states of the tubulin dimers assembled in microtubules, as the basic units of the quantum system. While the more evolved hierarchical structures comprised of neurons, modules, modules of modules, and, eventually the whole brain, may be viewed as the “measuring apparatus” providing the bulk of the “mass”/“energy” needed in *synchordic collapse*. Recall that, in the case of quantum mechanics discussed in section 3 (around (7)), it is only after the “collapse” of the wavefunction has occurred that we are able to discuss with certainty, “observable” properties of the system. Likewise, in our case here, it is only after the *synchordic collapse* has occurred that we can “*feel*” *consciously an event*. As we discussed above, it depends on the individual conscious event, *i.e.*, on the specifics of the *relevant* MT-network involved, of how long it is going to take before we “*feel*” it. Thus, we get in our scheme a dynamically organized *time-ordered* appearance of conscious events, corresponding to the synchordic collapse of the *relevant* MT-network involved, representing the very nature of the event under consideration. At each instant, and in a *cohesive way*, the “*sum*” of the conscious events consists of what we call *consciousness*! If $c_i(t)$ refers to the i -th conscious event at time t , then consciousness C at time t may *symbolically* be represented by $C(t) = \sum_i c_i(t)$. This is how *consciousness emerges hierarchically* in our dynamical scheme. It looks like, at each moment, we “*read*” the outputs ($c_i(t)$) of the different “*microscopic measuring apparatus*”, we “*decide*” ($C(t)$) and we *proceed* accordingly, and so on, ad infinitum, meaning here our lifetime span! A very simplistic analogy would be the way we use the panel of our cars, with all its numerous indicators, showing us, at each moment, how we are doing with gas, oil, temperature, water, etc, and thus, “*forcing*” us to “*decide*” if we have to stop or not for gas, etc. As I mentioned above, while discussing the phenomenon of “*backwards masking*” and “*referral backwards in time*”, *conscious time, i.e.*, past, present, future make sense only when it refers to *conscious events*. In our scheme, conscious events are due to synchordic collapse which, as discussed in section 5, introduces a microscopic arrow of time, providing thus, naturally, time-ordering! It is amazing that the mechanism that we have proposed [52] to explain the origin and arrow of cosmic time, applies all the way down to the MT-networks, explaining the origin and arrow of consciousness. Putting it differently, in our scheme, the notions of cosmic and conscious time are naturally identified as one may naively expect, and as it was, since long, suspected.

So, we expect to see a kind of *fractal phenomenon* occurring in which we have quantum coherence (and synchordic collapse) extended over a MT, over hundreds of MTs comprising the neuron, over thousands of neurons comprising the module, over tens of modules (incidentally explaining the “40 Hz oscillations” discussed above and in section 4), etc. Actually, there is enough space in our dynamical, hierarchical scheme to accommodate *neural networks* [28, 27], attempts to use *synchronized neural firing* [33] in explaining the *binding problem* [36, 32], and eventually Neural Darwinism [25]. Eventually the whole brain is involved, one way or another, but coherently and in a correlated way, subjected to *synchordic collapse*, thus explaining the “*binding problem*” or the “*unitary sense of self*” problem. Furthermore, the *stochastic nature* of the synchordic collapse, due to the existence of the *global or W_2 -world states*,

provides a very plausible explanation of *free-will*.

In order to see how our new dynamical theory of brain function, spelled out in a rather detailed manner above, would work in practice, it would be interesting and perhaps amusing to present a very simple example. Let us consider (36), in the admittedly very unrealistic, case of only two superimposed quantum states: $\Psi = c_1(t)\Psi_1 + c_2(t)\Psi_2$, where Ψ_i stands for $|1\rangle_i |2\rangle_i \cdots |N\rangle_i$, and with $c_1(0) = c_2(0) = \frac{1}{\sqrt{2}}$. Then, if we denote by γ the synchordic collapse frequency ($\gamma \equiv 1/\tau_c$ (28)), and assume that the finally *chosen* state will be, say Ψ_1 , then one may deduce that [42, 43] $|c_1|^2 = (1 + e^{-2\gamma t})^{-1}$. In Fig. 1, $|c_1|^2$ is plotted against time (t), for different values of γ , corresponding, in our scheme, to rather indicative *psychological* or *personality* states, providing thus our *psychological* or *personality profile*! Depending on the value of γ , the curves are *schematically* denoted as “*visible*”, “*violet*”, “*ultraviolet*”, and “*infrared*”. A common feature of all these curves is the increase with time of $|c_1|^2$, until it reaches some rather big (close to 1) value (say ≈ 0.9), at which point one safely may assume that synchordic collapse is occurring. At this moment, we pass from the *superimposed* ($c_1\Psi_1 + c_2\Psi_2$) quantum state, identified here with the *preconscious state*, to the *chosen* (Ψ_1) state, identified here with the *conscious state* or *event*, *i.e.*, we “*feel*” it! Fig. 1(a) indicates a *normal psychological state*, in which things happen in a straightforward way as represented by the canonical, standard (“*visible*”) value of $\gamma = 1$ Hz, corresponding to $\tau_c^{\text{“Brain”}} \approx \mathcal{O}(1 \text{ sec})$ (38). Fig. 1(b) indicates *excitement* (“*violet*”), in other word things are happening quicker by involving, maybe, more tubulins (increase N in (37) and thus (28,29) increasing γ , say $\gamma = 2$ Hz or $\tau_c^{\text{“Brain”}} \approx \mathcal{O}(0.5 \text{ sec})$. Clearly, in this case there is less time for quantum computations, and maybe, not enough time for very wise “*decisions*”, thus we may start acting a bit incoherent in the social sense! This case gets much worse in the presence of “*stimulants*”, where maybe many more than the usual tubulins get involved and thus the synchordic collapse frequency gets much bigger (“*ultraviolet*”) disrupting, eventually, complete “*collapse*”, as schematically indicated in Fig. 1(c). In this “*high*” state [106], while we are “*closer*” to a coherent quantum superposition, we clearly act in a completely incoherent, and thus unacceptable, social way. On the other end of the *synchordic collapse* frequency sector, in the “*infrared*” limit, lies the *dream state* as indicated in Fig. 1(d). Indeed, during our sleep, basically by definition, the brain is working in a very slow, subnormal mode entailing thus rather small values of γ (see Fig. 1(d)). In such a case, a quantum superposition, initiated presumably in a *parasitic* way, may last much longer than a *normal state* case, and thus, eventually, may get lost in the *environmental* background, one way or another, before suffering our specific *synchordic collapse*, the agent of *conscious events*. That is why in most cases, we don’t *remember* our dreams! Furthermore, as we all know, when we dream of someone, the person in the dream is usually a *mixture* of two or three rather similar people, read quantum superposition of *relevant* quantum states in our scheme, and eventually disappear without leaving any strong imprint in our memory, read absence of complete synchordic collapse in our scheme! Of course, it may happen, as in the case of not being quite asleep, that γ gets close to its “*normal*” value (*e.g.*,

$\gamma \approx 0.9$ in Fig. 1(d)), in which case complete synchordic collapse is achievable and we do, then, vividly remember our dream or nightmare! It is amazing and worth mentioning, that a similar, but phenomenologically postulated picture explaining the *Dream states*, or *Rapid-Eye-Movement (REM) sleep state*, has been put forward in Ref. [107],[32](p.161-2). There, words like “disturbed”, “superimposed”, “condensation” are used to describe *Dream states* in a generic way, without any reference to Quantum Physics. Here we see that such an explanation [107, 32] seems to emerge naturally from the quantum aspects of our dynamical scheme.

It should be strongly emphasized that in order to be able to provide positive evidence or refute our scheme, further experiments are badly needed and their results eagerly awaited. MT dynamics have to be studied in *vivo* and in *vitro*. We need to have a clear experimental picture about their assembly and disassembly properties, including their growth; we also need to have experimental information on which specific mechanism, if any, of the ones that have been suggested, is responsible for sustaining quantum coherence of the conformational states. We need further clinical studies of the “*funny*” time related phenomena. We also need to understand experimentally *and* theoretically, the role played by the K-code(s) in bioinformation processing, and their connection to the genetic code. Is it accidental that both codes have 64 words? Is it accidental that MT-networks look suspiciously similar to “quantum computers”? Can we use them in *vitro* for quantum computing? Is it accidental that microtubules, as participants in centrioles, are partially responsible for *mitosis* or cell division, thus “*interacting*” directly with the DNA, maybe thus being able to bring in *environmental information*, since MT-networks extend all the way to the cell membrane? Is it accidental that both *DNA* and MTs, the unique cellular structures known to possess a code system, are *effectively* 1+1 dimensional? Is it accidental that as we move from micro-organisms to macro-organisms, the amount/length of *normal* and *selfish or junk* DNA and the length of MTs do increase? Probably not, but we have to, and we are going to find out.

9 Microtubules and Density Matrix Mechanics (II): Quantum Psychophysics

Any scientifically sound theory of brain function, by its very nature, has not only to provide a credible picture of what is happening at the very microscopic (basic) level but it should also accommodate naturally all phenomena observed at the very macroscopic (top) level, *i.e.*, *personality* level as described by *psychology*. Psychology is usually defined as the science of mental life, where the latter includes feelings, desires, intentions, cognitions, reasonings, decisions, and the like. It is advisable and useful, for our purposes here, to distinguish between *Jamesian psychology* [8], or psychology of the *conscious*, and *Freudian*⁴ *psychology* [108, 109] or psychology

⁴Sigmund Freud (1856-1939), founder of psychoanalysis and arguably the single most important figure in pointing out the role of *unconscious processes* in our behavior and feelings.

of the *unconscious*. I use here the term *Freudian psychology* instead of the, maybe, more proper one *psychoanalysis* for the following reasons. As defined by Freud [108], *psychoanalysis* falls under the head of psychology, not of medical psychology, nor of the psychology of the morbid processes, but simply psychology. Psychoanalysis is certainly not the whole psychology, but its substructure and perhaps its entire foundation (unconscious→conscious)! But, *psychoanalysis* is also a method of psychotherapy, *i.e.*, it consists of techniques for treating emotionally disturbed people. Since this last property of psychoanalysis is, commonly, the prevailing one, and since the therapy shouldn't swallow up the science, I prefer to stick to the term Freudian psychology, as the theoretical system, background of psychology, and view psychoanalysis strictly as a method of psychotherapy. We describe next the essentials of Jamesian psychology [8] and how they fit in (or are explained) within our scheme, which also seems able to accommodate the basics of Freudian psychology [108, 109], *i.e.*, we will move from the *conscious* to the *preconscious* to the *unconscious*! The relevance of the connection of Jamesian views of consciousness to Copenhagen Quantum Mechanics has been *repeatedly* and *forcefully* emphasized by H. Stapp [13].

The brain-mind interaction is of central importance in Jamesian thought [8]. James opposed, vigorously, sterile, (pseudo)scientific, prevailing at his time, views purporting that feelings, no matter how intense that may be present, can have *no causal efficacy* whatever. He counterattacked by making a positive argument for the efficacy of consciousness by considering its distribution. For James, consciousness is at all times primarily a *selecting agency*, being present when choices must be made between different possible courses of action [8]. Clearly, such distribution makes sense *only* if consciousness plays a role, one way or another, in making these selections. James went even further, developing his principal claim about the unity of each conscious thought [8]. It is the whole thoughts, he argued, that are the proper fundamental elements of psychology, not some collection of elementary components out of which thoughts are assumed to be formed by aggregation. In other words, even if each thought has components, these component thoughts are experienced together in a particular way that makes the experienced whole an essentially new *emerging* entity! He even had the courage to speculate that if all these properties were not to be born out of his contemporary physics (what we now call Classical Physics), physics has to be modified! All this activity was taking place in the 1890's!! [8] What a *wise* man, indeed. Coming back to the 1990's, it is striking to notice that James' views of consciousness are *mapped*, almost *one-to-one* to our dynamical theory of brain function. Our *central thesis* suggest, that every *conscious event* is the *psychological counterpart* of a *related, specific synchordic collapse event* in the brain, that triggers a specific neural activity, described here by MT-dynamics, strongly correlated and *quantum computably*, responding to stimuli. An *isomorphism*, or a *one-to-one mapping* seems to emerge between *conscious events*, in a generic sense, and *specific neural patterns*, described by *specific* MT-networks, generated by, and thus strongly dependent on, synchordic collapse. By, just, recalling that it is synchordic collapse that causes the quantum MT-system to "*decide*" its course of action in a fundamentally *integrative character*, EPR-like [22, 3] way, and using the isomor-

phism available in our scheme, one should be able to reproduce, almost *verbatim*, the Jamesian views of consciousness. If, James' proposal about consciousness is not the mental or psychological version, or counterpart, of our physical/physiological views about consciousness, frankly, I don't know what would ever be. However, in order to complete our *isomorphism* between mental events and neural patterns described by MT-network states, we clearly have to discuss the preliminary phase that "*prepares*" the specific set of superimposed MT quantum states, of which *only one* is going to be selected or *chosen*. But then, we naturally have been led to the domains of the other great master of modern psychology.

Freud [108] felt that consciousness was only a *thin slice* of the total mind, that like an iceberg, the larger part of it existed below the surface of awareness. He said that scientific work in psychology will consist in *translating* unconscious processes into conscious ones, and thus filling the gaps in conscious perceptions! He argued that the *personality* is a complex and intricate *energy system* [109]. The form of energy that operates the personality and enables it to perform work is called *psychic energy*. He assumed that *psychic energy* comes from the energy of the body, but he was agnostic on how this transformation takes place. He insisted, though, that there is nothing mystical, vitalistic or supernatural about the concept of *psychic energy* [109]. It performs work as does any other form of energy, but in this case is psychological work, thinking, perceiving, and remembering. There is a continuously transformation taking place of bodily energy to psychic energy and viceversa.

A mental event is conscious or not, according to Freud [108, 109], depending upon the magnitude of energy invested in it and the intensity of the resisting force! A person feels pain or pleasure when the magnitude of the pain or pleasure exceed a certain *cathexis* value which is called the *threshold value*. Likewise, (s)he perceives an object in the world when the perceptual process is energized beyond a threshold value. Sometimes even when the *cathexis* exceed the treshold, the feeling or perceptions may not become *conscious* because of the inhibiting effects of an *anti-cathexis* which prevents it from becoming conscious! Freud [108, 109] differentiated between two qualities of *unconsciousness*, the *preconscious* and *unconscious proper*. A *preconscious state* is one which can become *conscious* quite easily because of weak resistance, and in sharp contrast, to an *unconscious proper state* where the opposing force is rather strong! Actually, there is a continuous *spectrum of unconsciousness*. At the one end, ending at the *unconscious proper state*, there is memory that can never become conscious, because it has no association with language, while at the other end, including the *preconscious state*, there is memory which is "on the tip of the tongue".

Freud assumed that, since a relatively large concentration of energy in a mental process is required in order for it to become conscious, we can be conscious of only one thing at a time [109]. However, the rapid shifting of energy from one idea, memory, perception or feeling to another provides for a wide range of conscious awareness within a *short time-lapse*! The perceptual system is like a radar mechanism which rapidly scans and takes many quick pictures of the world. When the perceptual system discovers a needed object, or apprehends potential danger in the external

world, it comes to rest and focuses its attention upon the object or danger. Ideas and memories, *i.e.*, mental representations of past experiences, are summoned from the *preconscious* to help the person adjust to the situation confronting him. When the danger is past or the need is satisfied, the mind turns its attention to other matters [108, 109].

Concerning the nature of the “*unconscious proper*”, Freud suggested [109] that “*threatening*” events could be *repressed* in memory so that they were not ordinarily available for conscious recall. Freud’s analysis of *repression*, the selective inability to recall, is a form of Darwinism (survival of the fittest) as applied to the mental world to become the Freudian *suppression of the “threatening”*. “Threatening” events belong to the set of the “*unconscious proper events*”. Freud developed further [108, 109] a theory about the fate of the repressed events, connecting them, partially, to *dreams!* Dreams are filled with *disguised* or *symbolic* representations of repressed desires. When the disguise becomes too transparent, the dreamer usually wakes up. Anxiety dreams and nightmares, for example, are caused by the emergence of repressed desires which makes the person anxious. He noticed that somatically, sleep is an act which reproduces intra-uterine existence,⁵ fulfilling the condition of repose, warmth and absence of stimulus. The feature characterizing the mind of a sleeping person is an almost complete withdrawal from the surrounding world and the cessation of all interest in it. Freud pictured [109] the situation which leads to dream formation as follows: the *preconscious* dream-wish is formed, which expresses the *unconscious* impulse in the material of the *preconscious* day-residues. This dream-wish must be sharply distinguished from the day-residues, it need not have existed in waking life and it may already display the *irrational character*, *e.g.*, a person in the dream is the *mixture* of two or three rather similar people, etc, noticeable in all that is unconscious when we come to translate it into terms of consciousness! The logical validity, freshness, and stunning resemblance to our presently holding views about brain function, characterizing *Freudian psychology* [108, 109], are properties very hard to miss. Since his time, ample evidence has accumulated from the study of neurosis, hypnotism, and parapraxes to show that his basic views about the action of the unconscious and its role in behavior, were essentially correct.

After our, hopefully, enjoyable and useful excursion to Freud-land, we have all that is needed to complete the above-discussed *isomorphism* between mental events and neural patterns, described by MT-quantum states. Freud’s *psychic energy* as opposed to *bodily energy* and the transformation into each other, corresponds to the exchange of energy/interactions between the W_1 -world or *attainable physical world localizable states* and the W_2 -world or *global states*, as explicitly indicated in (27). Notice, as (25) explicitly shows, that there is *conservation of energy* in our scheme! Furthermore, the “preparation” of the *relevant superimposed* MT-quantum states depends on the *nature* and *intensity* of the stimulus, as discussed in sections 2,4,7,8, *i.e.*, if it can “easily” “straighten up” the *relevant states*, corresponding to a *precon-*

⁵There is, presently, evidence to suggest that in the *womb*, especially in the third trimester, *Dream or REM sleep* occurs more than 8 hours a day [107].

scious state, or if, it can “hardly” have any effect on the states, corresponding to “*unconscious proper*” states. In the case of *preconscious states*, identifiable with the *relevant superimposed quantum states*, synchordic collapse follows easily, turning it into a *conscious state*! In the case of “*unconscious proper*” states, identifiable with either isolated, not easily reproduced, or random states, nothing happens! Clearly, there is a continuous spectrum of quantum states from the “*preconscious*” to the “*unconscious proper*”. In the case that an “*unconscious proper*” state gets “prepared”, then synchordic collapse leads to Freud’s “threatening events”. For example, while we sleep being “off guard”, “*unconscious proper*” states may be partially and *parasitically* prepared, even in disguised form, and may lead to nightmares! On the other hand, synchordic collapse, of variable effectiveness, of presumably partially *parasitically prepared preconscious dream-states*, as discussed in the previous section (see Fig. 1(d)) reproduces Freud’s basic views about dream formation discussed above. If our dynamical theory of brain function, with its now completed *isomorphism* between mental events and MT-quantum dynamics states has not reproduced, almost *verbatim* the basic elements of Freudian psychology, I don’t know what would ever do. Needless to say, Freud’s terms are psychological, while ours are structural. It is in this sense that we consider the *mental world* somehow *isomorphic* to the W_2 -world of *physical global states* that help to “*prepare*” and eventually dismantle, by “*synchordic collapse*”, the *relevant superimposed* MT-quantum states of the W_1 -attainable physical world constituted by tubulin-dimer conformational states, as depicted clearly in (2) and (27). It should be mentioned here (see relevant discussions in sections 6,8) the rather fundamental role played by the K-code(s) [57] possessed by the microtubules, in advancing and completing our *isomorphism* between the mental world and the W_2 -world, by acting as a dictionary translating *psychological orders* into *physiological actions*. It is in this sense that I propose to call the K-code(s), the *Mental Code*, playing in a way the role of the *genetic code*, but in the mental world. It should be stressed once more here (see the appropriate discussion in section 5, between (22) and (23), that there is nothing mystical or supernatural about the W_2 world *global states*, or the way they interact with the W_1 -world *attainable physical states*, except that, due to their *delocalized nature*, sometimes, a bit different than normal, novel properties may emerge! Through the above mentioned *isomorphism*, these novel properties are transmitted to the mental world, which thus is an (*emerging*) part of the physical world, but with (*inherited*) distinct qualities. Notice further, that in particle physics at very high energies, we only talk about electroweak interactions, and only at low energies we may talk about “*effective*” electromagnetic and weak interactions. Similarly here and in a *unified theory sense*, we should talk only about the *physical world* (W) when *all states, localized and delocalized* are accounted for (2,27), and only talk about the *attainable physical world* (W_1) and the *mental world* and their interactions, *i.e.*, an *effectively emerging dual world* (1), *only* when the delocalized states get truncated, which happens realistically most of the time! Incidentally, if all these kind of (post) modern views sound pretty drastic, let me remind you that *Empedocles* (490-430 B.C.), the famous, ancient greek, presocratic philosopher, in his “cosmic phantasy”, ascribed to the whole universe the same animistic principle as is mani-

fested in each individual organism! If he was not describing, in his way, the W_2 -world global, delocalized states, I don't know whatever would do better. He certainly was the first complete *effective* dualist! Hopefully, this emerging compromising resolution of the age-old problem concerning the brain-mind relation, will bring peace, once and for all, to the different quarters of *dualists* and *non-dualists*, and avoid further *duels*! Nevertheless, as I already mentioned in the Introduction (just after (2)), hard-core *materialists* may, if they so wish, concentrate their attention on the physical relation/transition between the *W-physical world* and the W_1 -attainable *physical world*. It is *immaterial* to me!

The interface between psychology and physics (*psychophysics*) has always been rather interesting, though-provoking, challenging, sometimes controversial, but certainly not dull. Before Darwin, man was set apart from the rest of the animal kingdom by virtue of having a soul. The evolutionary doctrine made man a part of nature, an animal among other animals. Man became an object of scientific study, no different save in complexity, from other forms of life. Literally at the same time (1860), Fechner founded the science of psychology, by showing that the mind could be studied scientifically and that it could be measured quantitatively. At about the same time, the physical formulation of the *principle of conservation of energy*, notably by Helmholtz, stating that energy is a quantity that can be transformed, but it cannot be destroyed, had rather far reaching consequences for biology and psychology. It made possible an even more radical view of man. This is the view that man is an *energy system* which obeys the same physical laws that regulate, say, the fall of an apple or electromagnetic phenomena. Thanks to Freud's genius, the physical dynamics extended to apply to man's *personality*, and not only to her/his body. This really amazing visionary step, as taken by Freud, led to *dynamical psychology* [108], *i.e.*, one that studies transformation and exchanges of energy within the *personality*, as well as between the *personality* and the body. It is an amusing coincidence to notice that Freud's chef d'oeuvre "*The Interpretation of Dreams*" [108], and Planck's revolutionary paper on energy quantization, *both* appeared in 1900 (!), and *both* after considerable hesitation and self-doubt!!! The dynamical scheme presented here, is nothing more than a supermodest attempt to continue the psychophysical tradition described above, by combining the most recent advances in quantum dynamics, as described in non-critical superstring theory [5, 6, 7], with the amazing progress in microtubules and their dynamics [1]–[4]. A *unified scheme* of brain-mind dynamics emerges, consistent with all known laws of physics, notably including the law of conservation of energy, and at the same time, providing satisfactory answers to age-old problems such as what is *consciousness*, the *binding problem* or *unitary sense of self*, *free-will* and the like, involving parts or the entire activity of the brain. Indeed, *conscious thoughts* seem to correspond to metastable states of the brain associated with particular integrated patterns of neural excitations, that are *selected* by *synchordic collapse*, from among a plethora of such neural patterns described by MT-network states (quantum) mechanically generated according to (3,4). Since *synchordic collapse* is due to the truncation of *global delocalized* states, our *consciousness* is nothing else but a *localized* aspect of a global, integrative process. There is a new image of man emerging, in which hu-

man consciousness is placed in the inner workings of a non-local global process that link the whole universe together, defying classical physics and observations of usual everyday life. It seems, that we are *intimately* and *integrally* connected into the same global process that is actively creating the form of the universe, as we suggested in [52], thus providing a whole new meaning to the, presently fashionable, expression *global village*. There seems to be a *central organizing principle* at work, essentially what I called *the Protean Principle* at the end of my review “As time goes by ...” [6]. This new view of man’s place in the universe is an essential “*paradigm shift*”. We are not *just* small, irrelevant, struggling for survival creatures in a meaningless universe, but through our dynamically created consciousness, *we participate actively* in the intrinsically global process that forms the world around us. *We are brains with strings attached!* I do believe that this, scientifically geared, “paradigm shift” in our *Weltanschauung*, or “world view”, is bound to have a tremendous impact, but mostly presently unimaginable, in all forms of human behavior from the individual to the social level. Some visionary people have already started talking about the dawn of the *brain man*, at the dawn of *third wave* [110] of civilization, characterized by strongly declining muscle work and fastly increasing brain work, that succeeds the “*second wave*” related to the industrial revolution of 300 years ago, and which in turn succeeded the “*first wave*” related to the agricultural revolution of 10,000 years ago, This is just the *dawn* of the *Homo Quantum* ...

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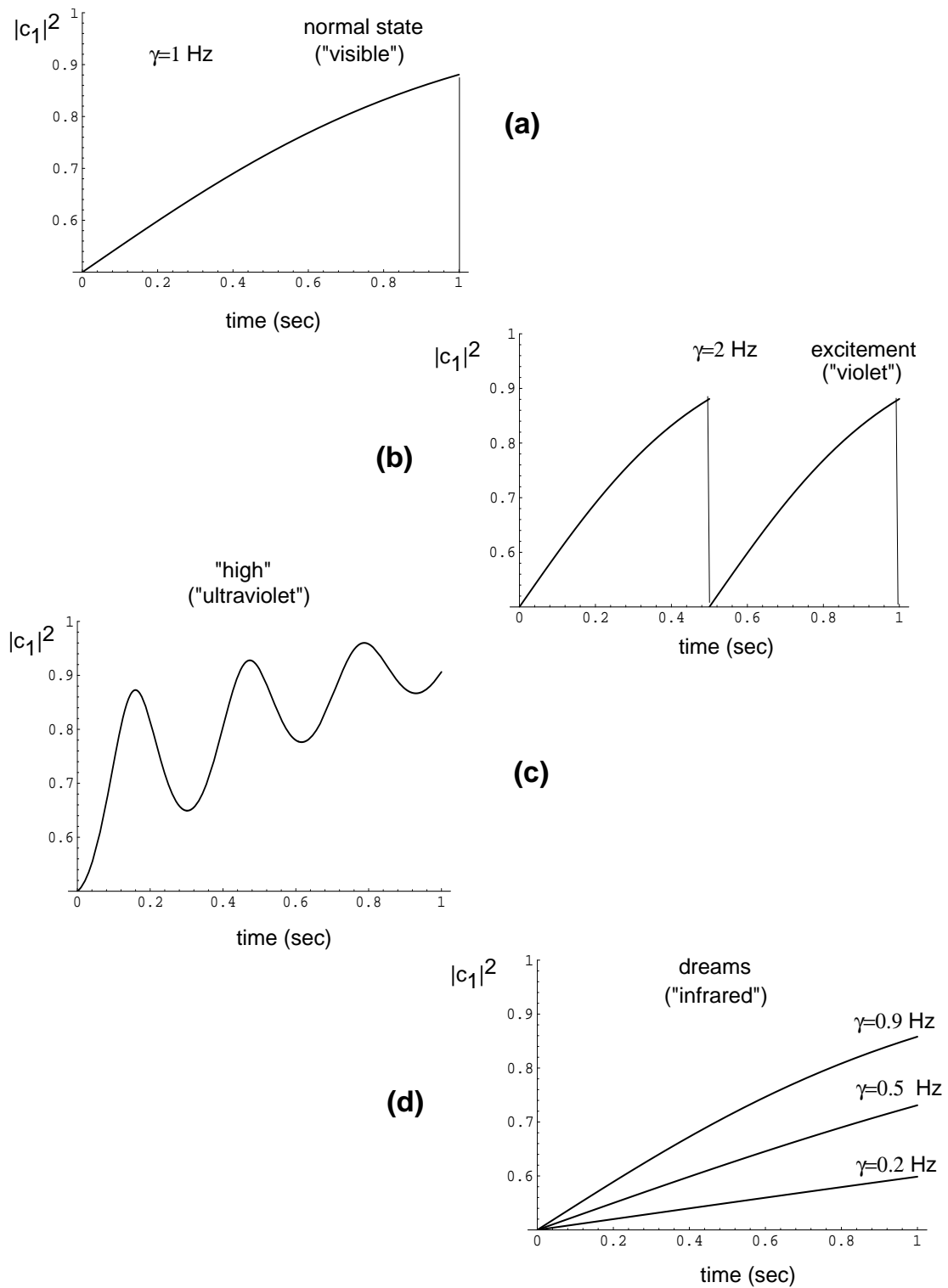


Figure 1: *Psychological* or *Personality* profile as a function of time, parametrized by different values of the MT-network synchronic collapse frequency γ ($\equiv 1/\tau_c^{\text{Brain}}$), as indicated in (a) through (d).