Original Article

Synaptic Quantum Tunnelling in Brain Activity

Friedrich Beck

Abstract

In the struggle about the role of monism and dualism as basic concepts of the mind-brain relation, the indeterminacy of quantum events has led an increasing number of authors to postulate quantum brain dynamics as the key towards a scientific understanding of consciousness. In most cases some specific form of macroscopic quantum states in the brain are invoked without giving details for their occurrence or persistence. This raises immediately the question, how such states could survive thermal fluctuations in the hot and wet brain environment. In this paper we present a model for a quantum mechanical trigger which regulates synaptic exocytosis, the regulator for ordered brain activity. The model is based on a quantum mechanical tunnelling process which is stable against thermal fluctuations and consistent with the physiological conditions of the synaptic membrane.

Key Words: synaptic exocytosis, quantum trigger model, electron transfer in synaptic membranes

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1. Introduction

The last decades of the 20-th century have brought us tremendous progress in understanding complex biological structures. This has been achieved on one hand by refined microbiological experimental techniques and on the other by an increased understanding of complexity on the basis of nonlinear dynamics. In brain research this has led to new insight into the brain's topological structure during specific activities like attention, volition, ideation, or neurochemical abnormalities (Posner *et al.*, 1985; Corbetta *et al.*, 1990; Ingvar, 1990; Pardo *et al.*, 1991). One of the most intensely studied areas is the visual cortex, where pattern recognition techniques have revealed insight into the transformation of incoming nerve signals into coherent spatio-temporal patterns (Singer, 1990). These empirical studies have been accompanied by modelling of the neural net as a noisy and dissipative open system, leading to characteristic self organization processes (Freeman, 1996; Haken, 1996). Following these lines it is tempting to regard brain activity solely as a complicated and highly involved input-output process, moderated by the brain's memorial history, and working on similar lines as complicated artificial intelligence programs. Many neuroscientists adopt this concept, as, e.g., expressed in the works of (Crick and Koch, 1990), and of (Edelman, 1989). In their opinion *consciousness*, the special qualia of human responsive behaviour, finds here its natural physical explanation, avoiding the so-called *Cartesian dilemma.*[2]

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[2] Cartesian dualism (René Descartes, 1596-1650) postulates that the immaterial mind and the material brain, while being ontologically distinct substances, causally interact.

Despite the apparently convincing and scientifically satisfactory argumentation of these concepts of *identity theory* (Feigl, 1967), the problem of consciousness is far from being settled, since not everybody is willing to accept such a materialistic viewpoint. Too strong was at all times the believe, based on personal experience, that *self-consciousness* governs our actions in the world, and that this requires the ability for free, not completely pre-determined, activities. Natural scientists, however, were quite aware of the fact that this non-materialist view would cause an unsurpassable conflict with the laws of the completely deterministic classical physics, as formulated in Newton's mechanics and Maxwell's electrodynamics, which established the unambiguous description of the physical world by the end of the 19-th century. Undoubtedly, biological objects like human bodies, including the brain, underlay these laws of nature

An important qualitatively new aspect has been brought into the debate on the mind-brain problem when several authors realized that quantum physics frees physical processes from the strict determinism of the classical mechanistic picture. The quantum aspect, however, opened only rather late a new pathway to understand consciousness, pioneered by (Wigner, 1964), and later followed on by several authors (Margenau, 1984; Squires, 1988; Eccles, 1990; Donald, 1990; Stapp, 1991). Most influential in broader public discussions were the two books by (Penrose, 1984; Penrose, 1994).

In this contribution we present work which establishes a model for quantum brain dynamics, based on realistic and well established facts of neocortical activity. The model was originally introduced by (Beck and Eccles, 1992), and later on extended in (Beck, 1996) and (Beck and Eccles, 1998). The paper is organized as follows: Section 2 presents a numerical criterion for the persistence of quantum processes in thermal surroundings. Section 3 contains a brief introduction into the structure of the neocortex and the role of synaptic action. In section 4 we present the synaptic quantum trigger model and its possible biophysical realization, while section 5 discusses the problems of binding and large scale coherence. Section 6 gives our conclusions.

2. Quantum vs. Classical Brain Dynamics

In the brain there exists an interplay between micro- and macrostructures. The latter consist of pyramidal cells, dendrites and their bundles (*dendrons*), and electrochemical transitions in the neural net, while microstructures involve synaptic membranes and microtubules. Nerve impulses propagating along nerve cells are, independent of external stimuli or internal brain activity, always present and constitute a stochastic background in the brain. Recent investigations suggest that the neural net stays close to instability and in this way can be switched by minute action between different states (Freeman, 1996). In order to control such a system, a stable regulator has to be present which generates a coherent pattern in the active cortical unit. According to the cortical ultrastructure, as outlined in the next section, synaptic action qualifies as this regulator. This has also been demonstrated in various biochemical studies of the influence of drugs and anesthesia on the ion channel properties of the synaptic membrane (Flohr, 1995; Hameroff, 1998). We argue in the following that because of the stochastic thermal background quantum action could only be effective in brain dynamics if it establishes itself as a *quantum switch* within the microstructures.

The all important regulatory function of spine synapses results from the fact that exocytosis, the release of transmitter molecules across the presynaptic membrane, occurs only with probabilities much smaller than one upon each incoming nerve impulse (Redman, 1990). We therefore regard exocytosis as a candidate for quantum processes to enter the network, and thus regulating its performance (Beck and Eccles, 1992).[3]

[3] An alternative regulating process by tubulin molecules comprising the cylindrical walls of microtubules has been proposed by (Hameroff and Penrose, 1996). We would like to emphasize that the basic quantal event postulated by them, a two state conformational transition in the tubulin molecule, is

Micro- and macrostructures in the brain are clearly separated by time-, or correspondingly, energy scales. The macrostructure is typically characterized by the fact that the brain lives in *hot and wet* surroundings of $T \approx 300°K$. This raises immediately the question of quantum coherence vs. thermal fluctuations. As is well known, as soon as thermal energies surpass quantal energies classical thermal statistics prevails.

To answer this question, two characteristic energies can be defined:

(i) the thermal energy per degree of freedom

$$E = \frac{1}{2} k_b T$$

with k_b : Boltzmann's constant.

(ii) the quantal energy, defined as zero point energy of a quasiparticle of mass m_{eff} which is localized over a distance Dq**.** From Heisenberg's uncertainty relation $\Delta p \cdot \Delta q \geq 2\pi\mathbf{h}$ it follows (using the equal sign)

$$E_{qu} = \frac{(\Delta p)^2}{2m_{eff}} \cong \left(\frac{2\pi\mathbf{h}}{\Delta q}\right)^2 \frac{1}{2m_{eff}}$$

with $\mathbf{h}$: Planck's constantdivided by 2 π.

These relations define *two energy regimes*:

$E_{qu} << E_{th} = E_c$: *the thermal regime, with* E_c*, the thermal energy at brain temperature*

$E_{qu} >> E_{th}$: *the quantal regime*

with the breaking point E_c separating the two regimes, which at physiological temperature of T» 300 K amounts to a thermal energy $E_{th} = E_c \sim 1.3 \times 10^{-2}$ eV.

Evaluation of the relation between the localization distance Δq and the effective mass m_{eff} shows that for moderate Δq of about 1–3 nm and effective masses below 10 m_e (m_e: electron mass) the quantal energy E_{qu} is well above the thermal regime $E_{th} = E_c$, (Fig. 1 A).

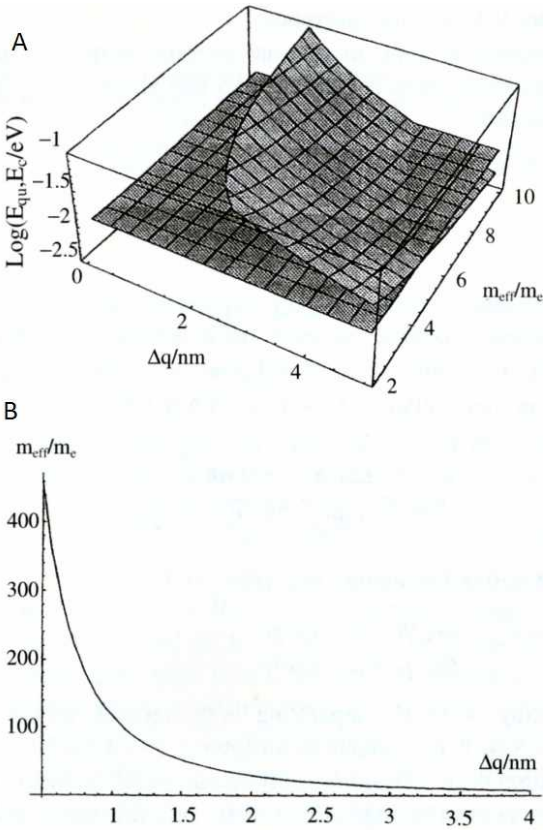

Figure 1. (A), three-dimensional plot of the logarithm of the quantal energy E_{qu} in its dependence on the localization dimension Δq and on the effective mass m_{eff} in units of the electron mass m_e. Also shown is the plain of the breaking point E_c=*const.* between the quantal and the thermal regimes. (B), the allowed effective mass m_{eff} in units of the electron mass m_e as function of the localization length Δq.

This means that the dynamical mass of a quantum transition, if robust against thermal fluctuations, has to be of the order of a few electron masses (Fig. 1 B). Biomolecules whose mass is in the range of kD, do not qualify *as a whole*. We can also derive a *critical frequency*, $\mathbf{h}\ \omega_c\ E_c$, and a critical *signal time*, $\tau_c = 2\pi/\omega_c$. With $E_c = 1.3 \times 10^{-2}$ eV one obtains

$$\omega_c \approx 2 \cdot 10^{13}\ s^{-1}\ ;\quad \tau_c \approx 0.3\ ps$$

These results show unambiguously that quantum processes at room temperature involve signal times smaller than the picosecond scale. This, in turn, means they correspond to electronic transitions, like electron transfer or changes in molecular bonds (e.g., breaking of a hydrogen bridge).

Our analysis leads to the consequence that in brain dynamics two well separated regions with different time scales

rather similar to the synaptic quantum trigger model presented here. We do not follow, however, these authors in their postulate of a macroscopic coherent quantum state along the microtubules, nor in their quantum gravitational arguing for *'orchestrated (state) reduction'* (OR).

exist: (*i*) The *macroscopic*, or cellular, dynamics with time scales in the milli-, and down to the nanosecond range. (*ii*) The *microscopic*, or quantal, dynamics with time scales in the pico- to femtosecond range. The large difference in time scales makes it possible to deal with quantum processes in the individual microsites, and decoupled from the neural net. On the other hand, it explains why the usual biochemical and biophysical studies do not show the need for introducing quantum considerations. To uncover them one has to employ ultra-short time spectroscopy (Vos et al., 1993)

3. Neurocortical Brain Activity

Fig. 2 a illustrates the universally accepted six laminae of the neocortex (Szentagothai, 1978) with two large pyramidal cells in lamina V, three in lamina III, and two in lamina II. The pyramidal apical dendrites finish in a tuft-like branching in lamina I (Fig. 3 a). There is agreement by Fleischhauer, Peters and their associates (Schmolke and Fleischhauer, 1984; Peters and Kara, 1987) that the apical bundles of dendrites, schematically shown in Fig. 3 b, are the basic anatomical units of the neocortex.

They are observed in all areas of the cortex that have been investigated in all mammals, including humans. It has been proposed that these bundles are the cortical units for reception, which would give them a preeminent role. Since they are composed essentially of dendrites, the name *dendron* was adopted (Eccles, 1990).

Figure 2b illustrates a typical spine synapse that makes an intimate contact with an apical dendrite of a pyramidal cell. The ultrastructure of such a synapse has been intensively studied by Akert and his associates (Pfenninger et al., 1969; Akert et al., 1975). The inner surface of a bouton confronting the synaptic cleft (d in Fig. 2 b, the active zone (AZ) in Fig. 4) forms the presynaptic vesicular grid (PVG). Fig. 4 shows the dense projections in triangular array, and with the faint synaptic vesicles fitting snugly in hexagonal array; the front ones in the process of exocytosis. The spherical synaptic vesicles, 50–60 Å in diameter, with their content of transmitter molecules, can be seen in the idealized drawings of the PVG (Fig. 4). They arrange themselves in a hexagonal array on the active zone AZ.

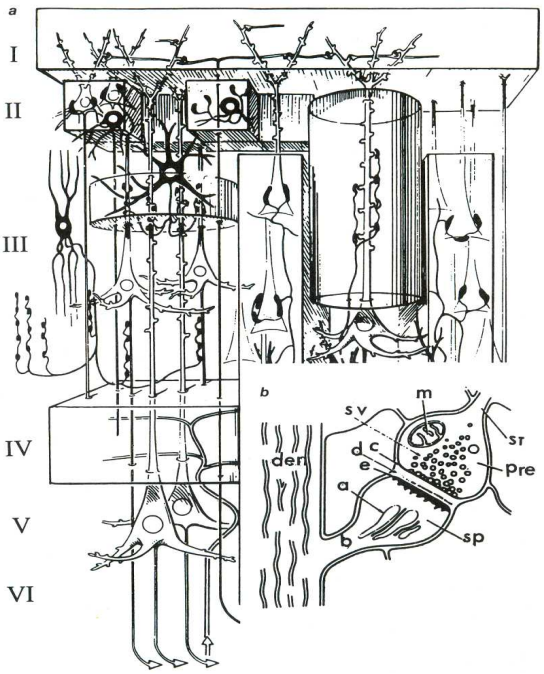

Figure 2. a, three-dimensional construct by (Szentagothai, 1978) showing cortical neurons of various types. There are two pyramidal cells in lamina V and three in lamina III, one being shown in detail in a column to the right, and two in lamina II. b, detailed structure of a spine (sp) synapse on a dendrite (den); st, axon terminating in the synaptic bouton or presynaptic terminal (Pre); sv, synaptic vesicles; c, presynaptic vesicular grid (PVG in text); d, synaptic cleft; e, postsynaptic membrane; a, spine apparatus; b, spine stalk; m, mitochondrion (Gray, 1982).

A nerve impulse propagating into a bouton causes a process called *exocytosis*. A nerve impulse evokes at most a single exocytosis from a PVG (Figs. 4 and 5). Exocytosis is the basic unitary activity of the cerebral cortex. Each all-or-nothing exocytosis of synaptic transmitter substance results in a brief excitatory postsynaptic depolarization (EPSP). Summation by electrotonic transmission of many hundreds of these milli-EPSPs is required for an EPSP large enough (10–20 mV) to generate the discharge of an impulse by a pyramidal cell (Fig. 6). This impulse will travel along its axon to make effective excitation at its many synapses. This is the conventional macro-operation of a pyramidal cell of the neocortex, and it can be satisfactorily described by conventional neuroscience,

even in the most complex design of neural network theory and neural group selection (Mountcastle, 1978; Szentagothai, 1978; Edelman, 1989).

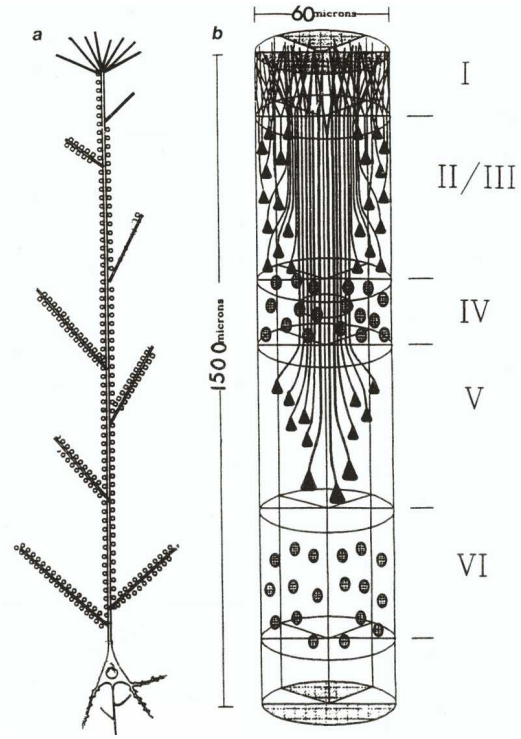

Figure 3. a, drawing of a lamina V pyramidal cell with its apical dendrite showing the side branches and the terminal tuft, all studded with spine synapses (not all shown). The soma with its basal dendrites has an axon with axon collaterals before leaving the cortex. b, drawing of the six laminae of the cerebral cortex with the apical dendrites of pyramidal cells of laminae II, III and V, showing the manner in which they bunch in ascending to lamina I, where they end in tufts (Peters and Kara, 1987).

Exocytosis has been intensively studied in the mammalian central nervous system, where it is meanwhile possible to refine the study by utilizing a single excitatory impulse to generate EPSPs in single neurons that are being studied by intracellular recordings. The initial studies were on the monosynaptic action on motoneurons by single impulses in the large Ia afferent fibres from muscle (Jack et al., 1981). More recently it was found that the signal-to-noise ratio was much better for the neurons projecting up the dorso-spino-cerebellar tract (DSCT) to the cerebellum (Wamsley et al., 1987).

This successful quantal resolution for DSCT neurons and motoneurons gives confidence in the much more difficult analysis of neurons of the cerebral cortex, which provide the key structures of neural events, relating to consciousness. The signal-to-noise ratio was so low in the studies of CA1 neurons of the hippocampus that so far only three quantal analyses have been reliable (Sayer et al., 1990). In the alternative procedure the single CA3 impulse projecting to a CA1 pyramidal cell was directly stimulated in the stratum radiatum. For a systematic review, see (Redman, 1990). *Key result of these observations is the fact that exocytosis occurs with probabilities much smaller than one per each impulse reaching the synapse.*

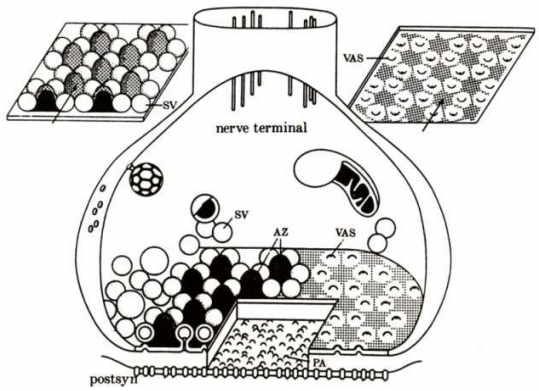

Figure 4. Scheme of a nerve terminal, or bouton, of a mammalian central synapse. The active zone (AZ) is formed by presynaptic dense projections spacing synaptic vesicles (sv). The synaptic vesicles are in hexagonal array and their attachment sites (vas) are shown on the right. PA: paricle aggregations in the postsynaptic membrane (postsyn), shown below cut-out. The insert to the left shows the presynaptic vesicular grid and the insert to the right shoes the vesicle attachment sites (vas), (Akert, et al., 1975).

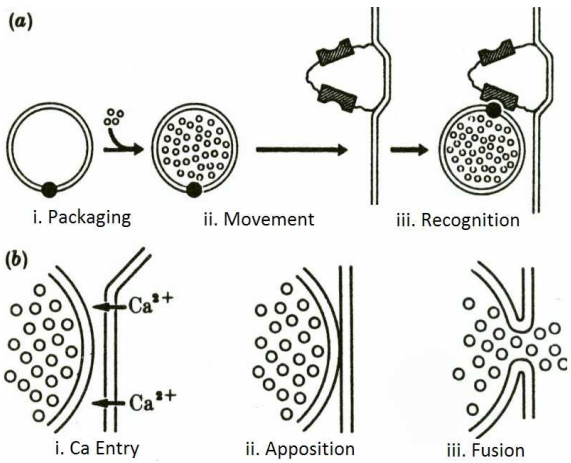

Figure 5. Different stages of synaptic vesicle propagation: (a), filling, movement towards the presynaptic membrane, docking. (b), stages of exocytosis. Note the essential role of Ca^{2+} after depolarization by a nerve impulse (Kelly et al., 1979

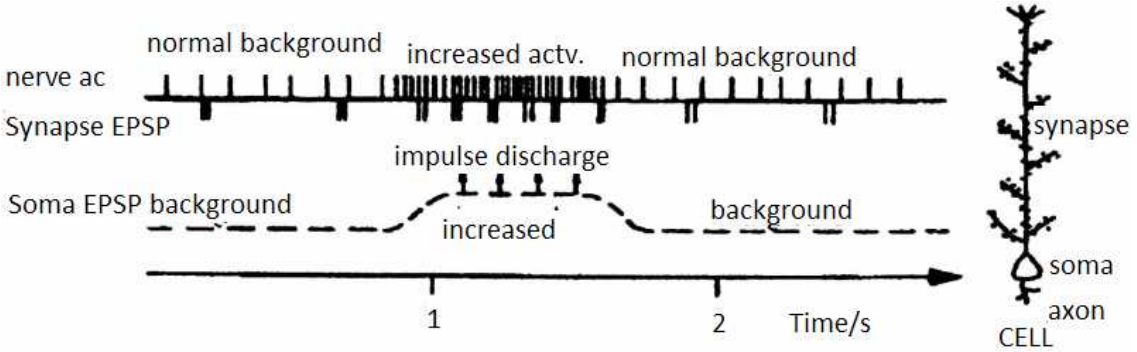

Figure 6. Impulse processing in a pyramidal cell (shown to the right). Upper trace: normal background and increased nerve activity. By filtering via synaptic exocytosis it produces reduced EPSPs, shown in the lower trace. The summed EPSP at the soma (excitation curve in the lower part) is not strong enough in normal background activity to produce an impulse discharge. This happens only with increased activity (Beck and Eccles, 1992; sketch due to Helena Eccles).

4. The Quantum Trigger Model

Experimental analysis of transmitter release by spine synapses of hippocampal pyramidal cells has revealed a remarkably low exocytosis probability per excitatory impulse (see sction 3). This means that there must exist an activation barrier against opening of an ion channel in the PVG. Activation can either occur purely stochastically by thermal fluctuations, or by stimulation of a trigger process. Here we propose a two-state quantum trigger which is realized by quasi-particle tunneling. This is motivated by the predominant role of exocytosis as the synaptic regulator of cortical activity which is certainly not completely at random. On the other hand, primary electron transfer processes play a decisive role in membrane transport phenomena (Vos et al., 1993).

Exocytosis as a whole certainly involves macromolecular dynamics (Fig. 5). We propose, however, that it is initiated by a *quantum trigger mechanism*: An incoming nerve impulse excites some electronic configuration to a metastable level, separated energetically by a potential barrier $V(q)$ from an unstable state which leads in a *unidirectional* process to exocytosis. Here, q denotes a *collective coordinate* representing the path along the coupled electronic and molecular motions between two states. The motion along this path is described by a *quasiparticle* of mass m_{eff} which is able to tunnel through the barrier quantum-mechanically. As has been shown in the previous section, m_{eff} can be in the range of tens of electron masses, or less, in order to survive thermal fluctuations. This implies that ion channel dynamics as a whole does not qualify for significant quantum processes in the brain.

The quasiparticle assumption allows the treatment of the complicated molecular transition as an effective one-body problem whose solution follows from the time dependent Schrödinger equation

$$i\mathbf{h}\frac{\partial}{\partial t}\Psi(q;t) = -\frac{\mathbf{h}^2}{2\,m_{eff}}\frac{\partial^2}{\partial q^2}\Psi(q;t) + V(q)\cdot\Psi(q;t).$$

Fig. 7 shows schematically the initial state at $t = 0$ (after activation by the incoming impulse), and at the end of the activation period, $t = t_1$. Here it is assumed that the activated state of the presynaptic cell lasts for a finite time t_1 only before it recombines. t_1, however, is of the macroscopic time scale (micro- to nanosecond), as discussed in the previous section. At $t = t_1$ the state has evolved into a part still sitting to the left of the barrier in region I, while the part in region III has tunneled through the barrier. Recombination of the activated state defines the *measurement process*, leading to von Neumann collapse of the tunneling state (von Neumann, 1955).

We can now separate the total wave function at time t_1 into two components, representing left and right parts:

$$\Psi(q;t_1) = \Psi_{left}(q;t_1) + \Psi_{right}(q;t\ )$$

and this constitutes the two *amplitudes* for the *alternative results of the same process*: which, after collapse, determine: *either* exocytosis *has happened* (Ψ_{left}), *or* exocytosis *has not happened* (Ψ_{right}) (inhibition).
State collapse transforms this into the probabilities

Exocytosis: probability

$$p_{ex}(t_1) = \int |\Psi_{right}|^2 \, dq$$

Inhibition: probability

$$p_{in}(t_1) = \int |\Psi_{left}|^2 \, dq$$

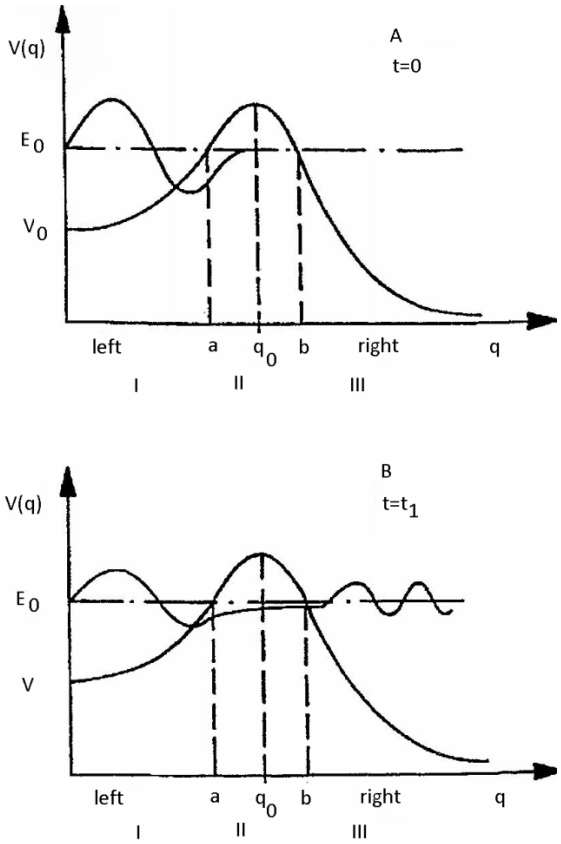

Figure 7. (Upper), the initial state (t=0) of the quasiparticle in the potential V(q). The quasiparticle wave function is located to the left of the barrier. E_0 is the energy of the activated state which starts to tunnel through the barrier. (Lower), after time t_1 the wave function has components on both sides of the barrier. a, b: classical turning points of the motion inside and outside the barrier (Beck and Eccles, 1992).

To estimate numbers using physically meaningful parameters we can evaluate the tunneling process using the Wentzel-Kramers-Brillouin (WKB) approximation (see, e.g., Messiah, 1961}. This results for the barrier transmission coefficient *T* in the form

$$T = \exp\left\{-2\int_a^b \frac{\sqrt{2m_{eff}\,[V(q)-E_0\,]}}{\mathbf{h}}\right\} dq$$

with E_0 , the energy of the activated initial state. For barrier widths slightly above 1 nm and effective heights of 0.05 to 0.1 eV (which lies well above the energy of thermal fluctuations, cf. Section 2) one obtains transmission coefficients in the range 10^{-10} to 10^{-1} (*see footnote*[4]). Using an intermediate value of $T = 10^{-7}$, activation times t_1 in the macroscopic time scale of a few ns, and excitation energies (the energies of the activated quantum state before tunneling starts) between 0.5 and 1 eV, Fig. 8 (A), the probability for exocytosis $p_{ex}(t_1)$ covers the range between 0 and 0.7, Fig. 8 (B), in agreement with measured values (Jack et al., 1981). *Realistic numerical input leads to meaningful results for the quantum trigger which regulates exocytosis!*

As a consequence we can describe brain dynamics by two time scales:
- microscopic scale (femtosecond): *quantum synaptic dynamics*
- macroscopic scale (nanosecond): (**c***oherent*) *cell dynamics,*
and
- the *coupling between micro- and nonlinear macrostructures.*

As a *possible realization* of the trigger model we can consider *electron transfer* (ET) between biomolecules (Beck, 1996). In biological reaction centers such processes lead to *charge transfer* across *biological membranes* (Vos et al., 1993). The quasiparticle describes the electron coupled to nuclear motion according to the Franck-Condon principle. The theory has been worked out by (Marcus, 1956), and was later put into quantum mechanical version by (Jortner, 1976). The initializing step of ET is excitation of *donor* D, usually a dye molecule, with subsequent transport of an electron to *acceptor* A, producing the polar system D^+A^-.

[4]The large difference in the values of *T* reflect the exponential dependence of *T* from the effective barrier height $V(q) - E_0$.

This is accompanied by rearrangement of the molecular coordinates leading to unidirectional charge separation and, over several further electronic transitions with increasing time constants, to the creation of an electrostatic potential across the membrane. The energetics is shown in Fig. 9. Fig. 9 (A) presents the potential energy curves separately for electrons and nuclear conformations, Fig. 9 (B) gives the combined potential in the quasiparticle picture (Marcus and Sutin, 1985). This latter form resembles closely the effective potential assumed in our quantum trigger model presented earlier in this section.

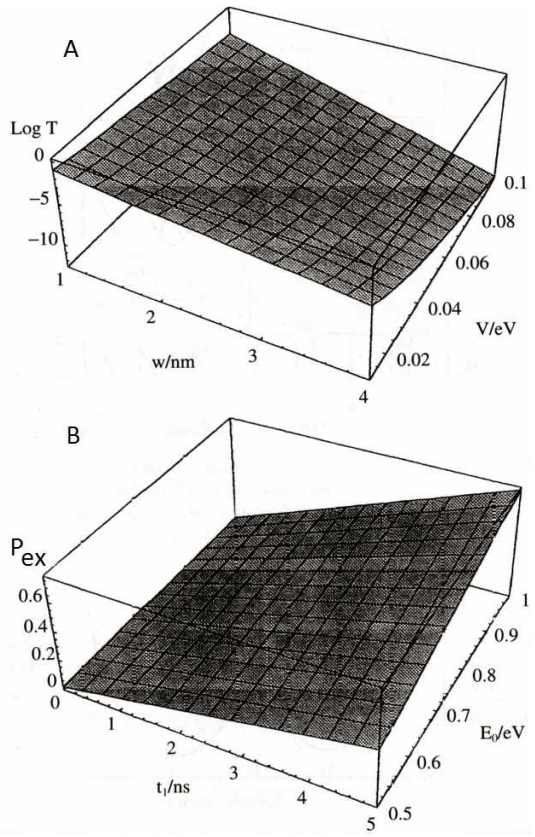

Figure 8. (A), 3D-plot of the logarithm of the transmission coefficient T in its dependence on the width w of the tunneling barrier, and on the effective barrier height $V_{eff} = V(q)_{max} - E_0$. (B), exocytosis probability P_{ex} calculated with fixed transmission coefficient $T=10^{-7}$ in its dependence on the (macroscopic) activation time t_1, and on the excitation energy E_0 of the activated trigger state before tunneling.

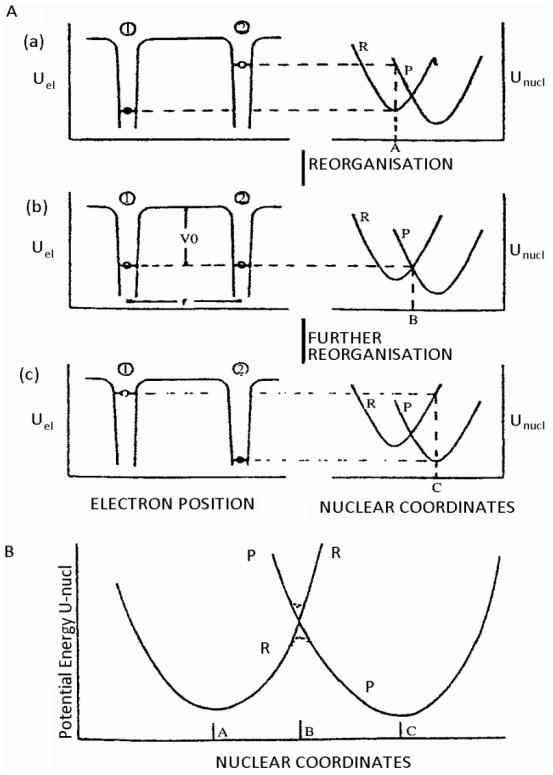

Figure 9. (A), electron transfer coupled to nuclear motion. Left: electronic potential energy curves, right: corresponding nuclear potential curves. (a), (b), (c): electronic energies in the two wells for the nuclear positions A, B, C. The transition proceeds from (a) over the barrier (b) to the final state (c). (B), the same situation in the quasiparticle picture. The potential energy surfaces of donor (R) and acceptor (P) are shown. The positions correspond to (A), (B), (C) in part (A). The dotted lines indicate splitting due to electron interactions between donor and acceptor (Marcus and Sutin, 1985).

In the quantum mechanical electron transfer picture (Jortner 1976) the transition process is described via product states in the electronic coordinates r_e, coupled to the nuclear motion (coordinates q):

$$\Psi_i(r_e)\otimes\chi_i(q)\rightarrow\Psi_f(r_e)\otimes\chi_f(q)$$

with Ψ, χ: electronic and nuclear states, respectively. The transition $i \rightarrow f$ is given by *Fermi's Golden Rule*

$$w_{fi}=\frac{2\pi}{\mathbf{h}}\left|H_{fi}\right|^2\times FC$$

with H_{fi}, the transition matrix element, which is determined by the electron-ion couplings. *FC*, the Franck-Condon factor, defined as the overlap integral between initial and final wave functions, χ_i, χ_f. This calculation would, however, require a specific knowledge of the

coupling structures in the presynaptic membrane.

The important role of quantum events does, however, not depend on the exact nature of this large scale structures, but it relies on the concept of state superposition in microscopic molecular transitions.

Finally, a word concerning the *qualia* of consciousness may be added. Science can not, by its very nature, present any answer to the philosophical, ethical or religious questions related to the mind. It can, however, and it does, provide the *openness* which is essential to make discussions beyond the limitations of science possible.

5. Neural Coherence

Neural activity in processes of perception or intention is characterized by coherent action of specific areas in the brain (Singer, 1990; Pardo et al., 1991; Eccles, 1994). Activated areas are characterized by an increase in regional cerebral blood flow, as demonstrated in radio-xenon technology (Roland, 1981), or more recently by positron emission tomography (PET; Posner et al., 1985; Corbetta et al., 1990). Activation generates most complex spatio-temporal patterns which characterize the specific perception (visual, audible, taste or touch) or intention (silent thinking, moves). These patterns are intimately related to memory and the learned inventory of pyramidal cells (Kandel and Schwartz, 1982). Since in the neural bundles ('dendrons', cf. Fig. 3) which comprise the active area, there are thousands of modifiable synapses which have to act cooperatively to generate the increased action potential needed to bring out the observed activity (Fig. 6). Since the synapses can only modify (increase or decrease) their exocytosis probability upon incoming nerve impulses, there has to be a constant background activity which will be modulated *coherently* by a large number of synapses.

Long range coherence in biological systems at room temperature can either be established by self-organization in classical nonlinear dynamics, or by macroscopic quantum states (*Fröhlich coherence*, Fröhlich, 1968). The necessary ingredients for macroscopic quantum states at room temperature are *dissipation* and *energy supply* (*pumping*). Pumping *stabilizes* against thermal fluctuations, and phase synchronization (coherence) is achieved by *self organization*. The latter is mediated by nonlinear couplings to classical fields (electromagnetic, phonons, molecular) which implies that the quantal spectrum becomes *quasi-continuous.* *Quantum* state interference and subsequent state reduction, however, need a few well separated discrete states (like the two states in the synaptic trigger model), and consequently is not possible with quasi-continuous macroscopic quantum states at room temperature.

From empirical evidence (Freeman, 1996, Spitzer and Neumann, 1996), and from successful modeling (Haken, 1996), we would rather attribute long range cooperative action in the active zones of the brain to nonlinear dynamics of a driven open system. Such a system is far from thermal equilibrium and close to instability, and it can organize itself by external stimuli in a variety of synchronous activity patterns (Gray et al., 1989). Synaptic exocytosis in such a system serves as *regulator*, and the cooperation of the many synapses in the dendrons (active area) produce the spatio-temporal patterns above noise (limit cycles: the coherent structures in a chaotic environment). Quantum action and subsequent state reduction in the individual synapse produce the *non-algorithmic binding* (Penrose, 1994) in cortical units.

Fig. 10 presents a schematic sketch of three bundles of pyramidal cells (dendrons) surrounded by their spatial pattern which are produced temporarily by cooperation within the individual cells. Since these patterns are activated by *perception, intention* as well as in *ideation* (Ingvar, 1990) they establish the basic *units of consciousness*. To give them a name which expresses their outstanding importance, we may call them *psychons* (Eccles, 1990). The physiological mechanism of pattern formation and signal transduction in the brain are not yet fully understood. Recent rapid progress in understanding many facets of nonlinear dynamics in biological systems (Goldbeter, 1996) gives, nevertheless, hope to proceed substantially

in understanding large scale brain dynamics in the near future.

A most promising approach to combine noisy structures with the enhancement of regular signals is presented by the observation of *stochastic resonance* (Gammaitoni et al., 1998). A recent study of stochastic resonance in a neural net is presented in Fig. 11 (Jung and Mayer-Kress, 1995). It shows for increasing noise level the time development (left to right) of spiral waves in thr excitable medium, generated by an initially firing column of elements. The results show clearly the constructive influence of noise on coherent pattern formation ('stochastic resoance'). The combination of quantum tunneling states with noisy surroundings has recently also been studied by (Grifoni and Hänggi, 1990).

The important role of quantum events does, however, not depend on the exact nature of this large scale structures, but it relies on the concept of state superposition in microscopic molecular transitions.

Finally, a word concerning the *qualia* of consciousness may be added. Science can not, by its very nature, present any answer to the philosophical, ethical or religious questions related to the mind. It can, however, and it does, provide the *openness* which is essential to make discussions beyond the limitations of science possible.

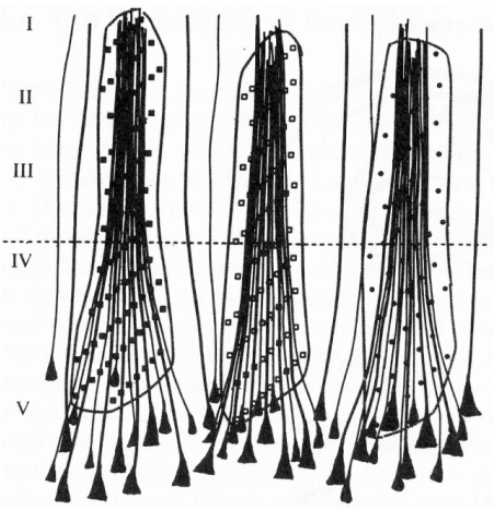

Figure 10. Coherent couplings of bundles of dendritic pyramidal cells (dendrons) to form spatio-temporal patterns (Eccles, 1990).

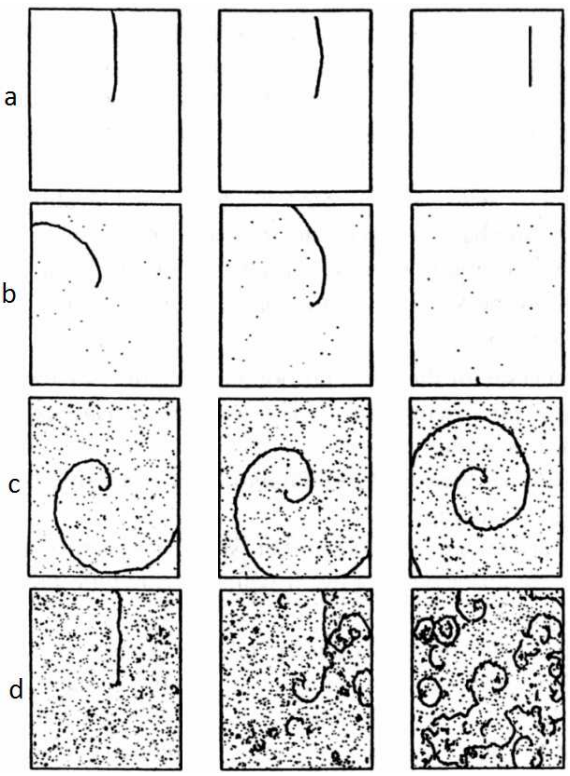

Figure 11. Spatio-temporal pattern formation in a two-dimensional excitable neural net model by stochastic resonance. Shown is the formation of spiral waves out of an initially firing column osf elements. From left to right: snapshots of firing patterns of elements in position (i,j) with i,j = 1, …,400 as time evolves. a, noise turned off, b to d, increasing noise level (Jung and Mayer-Kress, 1995).

6. Conclusions

Quantum *state collapse* is the decisive process which distinguishes quantum mechanics from classical physics. In a *single event* it is *non-predictable* (von Neumann, 1955). By this it qualifies for the *indecisive and non-computable nature* of brain functioning (Penrose, 1994). It should be emphasized that this introduces a new logical concept, different from classical determinism, underlying the struggle between dualism, identity theory, and the call for 'free will'. The interpretation of quantum mechanics as a succession of *single events* produces in a natural way the fundamental difference between past and future, in so far as the past is *known* (by events having manifestly could, however, object to this interpretation by arguing that the Schrödinger equation is *causal*, and consequently describes the time evolution of the probability amplitudes unambiguously. Thus, the *probabilities* for

future events are *completely determined*. This, however, relates to *ensemble averages*, for a large number of identical systems under identical initial conditions. Such ensembles can be realized in the material world of microscopic atomic systems but they are never realized in the world of complex objects such as the brain. Each new event finds itself borne in a new initial state. For these the non-predictability for single events prevails.

In view of these new and important concepts for elevating consciousness finally up to a scientific basis, we present evidence for a *realistic* implementation of quantum events into brain dynamics. It is based on our present knowledge of cortical structure and the synaptic regulation of neural impulses. Basic assumptions and results are:

- Quantum processes in the wet and hot surroundings of the brain are only possible at the microscopic level of (electron) transitions in the pico- to femtosecond time scale.
- Spine synapses are important regulators in brain activity, filtering the ever present firings of nerve impulses.
- Exocytosis, the release of transmitter substance across the presynaptic membrane, is an all-or-nothing event which occurs with probabilities much smaller than one.
- A model, based on electron transfer, relates exocytosis with a two-state quantum trigger, leading by quantum tunnelling to the superposition of two states, followed by state reduction (collapse into one definite final state).
- The coherent coupling of synapses via microtubular connections is still an open problem. Quantum coherence ('macroscopic quantum state') is not needed to couple microsites, which exhibit quantum transitions with their definite phase relations, to produce spatio-temporal patterns. The quantum trigger can, however, initialize transitions between different macroscopic modes (stochastic limit cycles, Grifoni and Hänggi, 1996).

The quantum trigger opens a doorway for a better understanding of the relation between brain dynamics and consciousness.

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