BRAINS AS QUANTUM MECHANICAL SYSTEMS – A NEW MODEL

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Abstract

We consider the possibility that the brain functions somewhat in the manner of a quantum mechanical system. The processes that instantiate its consciousness – the physical correlates of consciousness – are suggested to be partly quantum mechanical in nature rather than entirely classical. This idea is by no means new. But specific physical models are hard to come by. We begin by approximating a synapse as a small, parallel-plate capacitor. We find that the classical electromagnetic energy stored in such a synapse corresponds closely to the spacing of energy levels we would obtain were the capacitor to be treated as a quantum mechanical system. Intrigued by this surprising observation, we propose a new model of the brain as a partially quantum mechanical system. Its potential evolutionary benefits are discussed briefly.

Keywords: Brains and Quantum Mechanics, Quantum Measurements, von Neumann-Wigner Interpretation, Synapses.

Introduction.

The author (Broka, (2019), (2020), (2023)) has recently suggested a variant of the von Neumann-Wigner Interpretation of Quantum Mechanics (Schrödinger (1935), Wigner (1961), von Neumann (1932)). It is described in the language of field theory where the state of the entire universe, at time t, $|\Psi(t)\rangle$, is a vector in the Fock space of the Standard Model. Consciousness is, here, assigned the role of "classifier." Some $|\Psi(t)\rangle$s are classified as admissible. The others are inadmissible. We gave a simple example where an electron is passed through a Stern-Gerlach apparatus. If it comes in spin-up a green light is triggered. If it is down we get a red light. A conscious observer watches all of this. Were the electron to come in in a superposed spin-state unitary evolution would have our observer seeing a 'green-red' qualia. Wigner called this situation "absurd" and we call it inadmissible. $|\Psi(t)\rangle$ can never enter into such a state. To ensure that it does not we introduce a new operator – S – and demand that $\mathsf{S} \, | \Psi(t) \rangle \, = \, |\Psi(t)\rangle$ always. If $|\Psi(t)\rangle$ is admissible S does nothing. If it is not, S looks at all the amplitudes $\langle\Psi_a|\Psi(t)\rangle$ for every admissible $\langle\Psi_a|$. It will square these amplitudes and, using these values as *relative* probabilities, convert $|\Psi(t)\rangle$ into one of the $|\Psi_a\rangle$ at random.

This takes care of the "absurd" 'green-red' qualia. But we wondered whether S might not perform another – and more important – function. Let $|\Psi(t)\rangle$ describe a simple universe consisting of a single conscious brain that is experiencing qualia. Suppose, further, that the brain instantiates its consciousness through a physical mechanism that it, in one way or another, quantum mechanical in nature – it does not behave as a totally classical system. $|\Psi(t)\rangle$ starts out in an admissible state. But the brain is a warm, wet, noisy environment. It may be that, as $|\Psi(t)\rangle$ evolves unitarily, interaction with the environment begins to carry it into an inadmissible state no longer compatible with consciousness or its functioning as a workable "quantum computer." S then projects it back into an admissible state. It then evolves unitarily with no trouble until, after a while, it tries to, once again, become inadmissible. We (rather loosely) described this process as quantum decoherence. There are not a great many *physical* theories of brains as quantum mechanical and we used, as an example, the Hameroff-Penrose Microtubule Hypothesis (Hameroff (2014)). Tegmark (Tegmark (2000)) has calculated that their model would decohere in about 10^{-13} - 10^{-20} sec. This is quite rapid relative to the time-scales normally associated with

conscious processes. We did not, ourselves, propose any physical model of the brain as a quantum mechanical thing. But we will try to do so here.

The Independent Oscillator Model.

We begin by approximating a synapse as a capacitor consisting of two circular, parallel, plates of radius R separated by a gap of width d (which they do, somewhat, resemble). In chemical synapses R and d are about 0.5 μm and 30 nm, respectively. This system is studied in every introductory course on electromagnetism. Between the plates is a potential difference φ. There will be a uniform electric field $(-\varphi/d)$ between the plates. Assume this varies. A circulating magnetic field $(\frac{1}{2c^2} r\, \partial_t E)$ will be induced between the plates. As this changes, a correction will be introduced into the electric field. This will, in turn, induce a new correction to the magnetic field. We could carry this process on indefinitely but we will not do this. We will drop all but the original (homogeneous) electric field, its first-order magnetic correction, and the first-order magnetic field. As long as the potential is not varying quickly, we are justified in doing this. As a practical matter, potentials in synapses do not change much over time-scales less than about 10^{-5} sec. Given the dimensions of a typical synapse, the higher-order corrections drop to zero very quickly. We know that the Lagrangian density for this system is given by $\frac{\epsilon_0}{2}\left(E^2 - c^2 B^2\right)$.

1) $\int \frac{\epsilon_0}{2}\left(E^2 - c^2 B^2\right) dV = -\frac{\mu}{2}\varphi_{,t}^2 + \frac{\mu\alpha^2}{2}\varphi^2 + \mu\varphi\varphi_{,tt}$ where $\mu = \frac{\pi R^4 \epsilon_0}{8 c^2 d}$ and $\alpha = \frac{\sqrt{8}\, c}{R}$. The Euler-Lagrange equation, and hence the physics, is unchanged if we subtract the (useless) total derivative $\mu\,\partial_t\left(\varphi\,\varphi_{,t}\right)$ from the above. We could just as well have written our result as: $-\frac{3\mu}{2}\varphi_{,t}^2 + \frac{\mu\alpha^2}{2}\varphi^2$.

Either way, variation of 1) by φ leads to a harmonic oscillator solution with a resonant frequency equal to $\alpha/\sqrt{3}$. This is the same result we would obtain were we to write :

2) $\mathcal{H} = \frac{1}{2m}p^2 + \frac{m\omega^2}{2}\varphi^2$ where $m = \frac{3\pi R^4 \epsilon_0}{8 c^2 d}$ and $\omega = \frac{\sqrt{8/3}\, c}{R}$.

We have a classical harmonic oscillator with resonant frequency ω and the inconvenient $\varphi_{,tt}$ term has disappeared. Of course, we do not know over what range φ oscillates. It would oscillate quickly, however; $\omega \approx 10^{15}$ sec^{-1}.

We will proceed to quantize our system. p and φ are, now, to be interpreted as operators where $[\varphi, p] = i\,\hbar$. This leads to a wave function for φ:

3) $\psi(\varphi, t) = \sum_n c_n \psi_n(\varphi, t)$ where the $\psi_n(\varphi, t)$ are the familiar energy eigenfunctions for a quantized harmonic oscillator.

We now make a very interesting observation: We look at $\hbar\omega$ (the energy of a quantized excitation of our oscillator) and compare it to the total classical energy in our synapse which is equal to $\frac{\epsilon_0}{2}\frac{\pi R^2}{d}\varphi_{max}^2$ where φ_{max} is the greatest classical potential difference achieved by our oscillator. If the latter is vastly greater than the

former, we know we are *not* dealing with a quantum mechanical problem. Equating the two gives us $|\varphi_{max}| \approx$ 30 mV. This is exactly similar to the potential differences typically seen in real synapses and neurons. Resting potentials, for instance, are generally about -70 mV in magnitude and this can change to about +40 mV with the appearance of an action potential. We could, I suppose, write this off as a strange coincidence. But we could, also, suspect that Nature has engineered this result carefully and for a purpose.

We are no longer interested in the classical physics and are, certainly, not trying to suggest that there is a classical φ in the synapse that oscillates $\sim 10^{15}$ times a second. That would be ridiculous. $\psi(\varphi, t)$ simply tells us the likelihood of finding a particular value of φ were it to be measured. And this will affect how the brain functions.

Let us imagine a scenario in which there is an action potential propagating down an axon towards a synapse that is in $\psi(\varphi)$. We envision action potentials as purely classical things. When it arrives at the synapse it must decide what to do. Since it is a classical object it will have to perform a quantum measurement to determine the value of φ. If it finds a very small value, things go on as usual. But suppose it measures a φ that is large and opposite in sign. The net potential difference would then be reduced. The action potential may find itself unable to fire the synapse and will stop there. If the synapse does fire, the resulting synaptic potential would, likewise, be augmented or reduced. The value found for φ is, of course, determined randomly. The overall effect is to introduce an element of randomness into the process of neurotransmission. Action potentials will, sometimes, fail to cross a synapse although we would expect them to. Other times they would get across even though we might not expect them to.

When a measurement is performed and φ found to be φ_0, the wave function of the synapse will want to collapse into a state with no uncertainty in φ. The uncertainty in p would then be infinite. The state of the synapse would instantly evolve into one where there would be an equal probability of a new measurement giving *any* result for φ (even physically impossible ones). This situation is almost as "absurd" as the 'green-red' qualia. Let $\{\psi_a(\varphi)\}$ denote the set of all admissible $\psi(\varphi)$s. $\mathfrak{S}$ would project the (inadmissible) state into one of the $\psi_a(\varphi)$ with a relative probability given by $|\psi_a(\varphi_0)|^2$. Since each synapse constitutes its own, independent, Hilbert space, we do not think that $\mathfrak{S}$ would affect any other synapses (provided they were already in admissible states). Here we encounter a real example where $\mathfrak{S}$ does, in fact, function to allow the brain to continue its quantum mechanical operations (although quantum decoherence is not involved). There are thought to be up to 10^{15} synapses in a human brain. If each synapse encounters an action potential 10 times a second, $\mathfrak{S}$ would have to project the system every 10^{-16} sec. We note that what we propose is not particularly sensitive to the details of the wave function's collapse. Some readers may have no use for the $\mathfrak{S}$ operator, preferring other collapse mechanisms. Regardless, as long as the system is prevented from entering the "absurd" state described above, our argument should go through. We also mention that several other models have been proposed that try to impute quantum mechanical properties to synapses (Beck (1992), Georgiev (2018)).

Evolution.

If the model we have suggested above is valid, Evolution seems to have put a great deal of effort into optimizing it. It must confer a significant benefit upon animals. What could this be? At first glance it might be hard to see how what we have proposed would be useful at all. As mentioned, it leads to a certain randomization of neurotransmission and this might appear to be detrimental. But suppose there were a primitive animal in which a particular stimulus resulted in the firing of a synapse between neurons A and B. This, in turn, leads to a

behavior and an outcome. If the brain were a completely classical system this behavior would always result from the stimulus. But, if we are right, on some random occasions the synapse will fail to fire. The result would be a different behavior and outcome. If the different outcome was favorable the brain would "notice" this and be inclined to weaken or delete the synapse so as to ensure that the favorable outcome always occurred. Or suppose the different outcome was unfavorable. The brain would try to strengthen the synapse or, perhaps, create more synapses between A and B to make sure that the unfavorable outcome never occurred again. The animal will, therefore, have *learned* something. We think the advantage of our proposed model lies in its ability to allow the animal to (randomly) experiment with a wider range of behaviors than would otherwise be possible. Learning would take place and the animal's survival chances would be improved.

Thermodynamics and Equilibrium.

Since the phenomenon we are proposing is fundamentally electromagnetic in nature, we might wonder whether it could interact with photons in its environment. Given ω , these photons would lie in the near-infrared region. At such frequencies the brain may be considered a black body at about 310 K so there would be a considerable number of such photons present. If an electromagnetic wave were to pass through a synapse its electric field would contribute to φ. We can re-write 2) as:

4) $\quad \mathcal{H} = \frac{1}{2m}p^2 + \frac{m\omega^2}{2}\varphi^2 - m\omega^2\varphi\, d\, E_0\, (\epsilon \cdot k)\, \mathrm{Cos}(\omega_\gamma t)$ where E_0 is the strength of the electric field and ϵ the unit vector in its direction. k is the unit vector perpendicular to our plates. We have dropped the $E_0{}^2$ term and regard the above addition as a small perturbation.

Since the wavelength of our photon is about 4 R the electric field inside the synapse will, at least, be somewhat homogeneous some of the time. We can, therefore, employ Fermi's 2nd Golden Rule to very roughly estimate the rate of spontaneous decay of a $\psi_1(\varphi)$ state into the ground state. We find:

5) $\quad Rate_{1\rightarrow 0} \approx \frac{d^2\, m\, \omega^6}{6\,\pi\, c^3\, \epsilon_0} = \frac{32\, c\, d}{27\, R^2} \approx 5\, \mathrm{X}\, 10^{13}\, \mathrm{sec}^{-1}$.

This is extremely rapid relative to the brain processes we are interested in. And, if the photons were in thermal equilibrium with our oscillators, we would expect the energies of the latter to constitute a Boltzmann distribution. This would imply that, at any given time, only about 10^5 of the 10^{15} synapses would be in their first excited state with almost none in the higher states. This is not, necessarily, a bad situation for the above-mentioned animal that benefits from learning things. Even in the ground state there would be a 4% chance of measuring a $|\varphi|$ greater than 30 mV and a .004% chance of finding it greater than 60 mV. This may be quite sufficient for our animal.

It also occurs to us that, if what we have just suggested is correct, it might be possible to dispense with wave function collapse altogether. Regardless what kind of state a measurement projects $\psi(\varphi)$ into, it may very quickly revert to the ground state by itself, thus avoiding any problems.

Conclusion.

In (Broka (2023)) we speculated that the brain functions as a partly quantum mechanical system and that $\mathfrak{S}$ may be necessary for this to be possible. We mentioned the Microtubule Hypothesis but were unable to offer

any model of our own. We have now provided one.

By far the strongest evidence suggesting that our model might be on the right track comes from the "coincidental" agreement between the classical energy stored in our capacitor-like synapse and the quantum mechanical spacing of the energy levels obtained by quantizing it. This is a truly peculiar result and hints at some very clever evolutionary design-work. Neurons, given their small size and metabolic limitations, probably, have more-or-less to function with potential differences of about 30 mV. It is hard to see how they could generate hugely greater potentials. This being the case, were the radius of the synapse to be ten times larger than it is, the synaptic cleft would have to be 30 μm wide for our "coincidental" equality to hold. Neurotransmitters would be unable to diffuse across it quickly or in significant concentrations. And the synapse would no longer much resemble a parallel-plate capacitor. If the radius were ten times smaller, the synaptic cleft would have to be narrower than an atom.

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