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Review

At the crossroad of the search for spontaneous radiation and the Orch OR consciousness theory

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Abstract

In this paper we perform a critical analysis of the Orch OR consciousness theory at the crossroad with the newest experimental results coming from the search for spontaneous radiation predicted by the simplest version of gravity-related dynamical collapse models. We conclude that Orch OR theory, when based on the simplest version of gravity-related dynamical collapse, is highly implausible in all the cases analyzed. We discuss the implications of our findings, the limitations, and future plans toward the development of more realistic gravity-related collapse models.

Keywords: Orch OR theory; Consciousness; Collapse models; Spontaneous radiation; Germanium detector

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1. Introduction

Since the 1990s, Stuart Hameroff and Roger Penrose (hereafter, HP) have sought to link microtubular neurobiological processes with quantum wave function collapse, as part of a comprehensive theory of how the (arguably) non-computable phenomenon of consciousness emerges from brain function [1,2]. They call their theory Orchestrated Objective Reduction (Orch OR) [2]. Crucial to Orch OR is the hypothesis, due to Roger Penrose, that wave function collapse is related to gravity in that quantum superpositions of matter degrees of freedom are accompanied by quantum superpositions of the curved spacetime geometries produced by the matter degrees of freedom, where the latter are unstable resulting in a random collapse of the total wave function in an average time τ given by the

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expression $\tau \approx \hbar/E_g$ [1,3–6,2]. Here $\hbar$ is the reduced Planck's constant and E_g is the gravitational self-energy of the difference between two (stationary) mass distributions of the superposition.

Another crucial (and highly controversial [7–10,2]) assumption needed by HP for the Orch OR mechanism to occur in brain microtubules is that quantum superpositions of gravitational self-energy E_g avoid environmental decoherence long enough to reach time τ [2]. Relatedly, HP argue that in order for Orch OR to be operative in the brain there would need to be coherent superpositions of sufficient amounts of microtubule material such that E_g, undisturbed by environmental entanglement, results in reduction on a timescale of the general order for a conscious experience [2]. For an ordinary type of experience, they note that this might be about $\tau = 0.5s - 10^{-2}s$, which concurs with neural correlates of consciousness, such as particular frequencies of EEG, visual gestalts, and reported conscious moments. Thus they take τ to correspond to the duration of, or possibly the interval between conscious moments. The assumption of coherent superpositions is important for HP as their hypothesis is that a moment of conscious experience emerges from (or is identical to) a collapse event that destroys coherence in a previously unitarily evolving coherent quantum state of tubulins in neurons. They also suggest that "coherent quantum processes correlate with, and regulate, neuronal synaptic and membrane activity" [2]. In other words, in Orch OR, coherent quantum processes are essential for regulating brain function while moments of conscious experience arise via gravity-related OR of coherently superposed states of tubulin.

HP propose to calculate E_g from the difference between the mass distributions between two states of tubulin in coherent superposition, but note that the use of an average density may not be adequate since the mass is concentrated in the nuclei [2]. There is also great uncertainty about how 'smeared out' these nuclei must be considered to be, which is related to how 'crystalline' the microtubules are. Accordingly, they calculate E_g for tubulin separated from itself at three possible levels of separation: (a) the entire smoothed-out protein (what they call "partial separation"), (b) its atomic nuclei, and (c) its nucleons (protons and neutrons). They say that, in their picture, the dominant effect is likely to be (b), i.e., separation at the level of atomic nuclei, or 2.5 Fermi for carbon nuclei. Why the emphasis on carbon nuclei? Two reasons, as far as we can tell. First, carbon is a substantial component of the chemical composition of tubulin. Second, HP have suggested [2] certain physical mechanisms in tubulin that may be able to dynamically prepare Carbon nuclei (and apparently only Carbon nuclei) into coherent spatial superpositions on the order of a Fermi. (In what follows, we quote several passages from [2] that explain the central role of Carbon nuclei: "The only tubulin conformational factor required in Orch OR is superposition separation at the level of atomic nuclei, e.g. 2.5 Fermi length for carbon nuclei (2.5 femtometers; 2.5×10^{-15} meters). This shift may be accounted for by electronic cloud dipoles with Mossbauer nuclear recoil and charge effects [90,91]", p. 68. And, "Electron dipole shifts do have some tiny effect on nuclear positions via charge movements and Mossbauer recoil [90,91]. A shift of one nanometer in electron position might move a nearby carbon nucleus a few femtometers ("Fermilengths", i.e. 10^{-15} meters), roughly its diameter", p. 48. And, "In our picture, the dominant effect is likely to be (2) separation at the level of atomic nuclei, e.g. 2.5 Fermi length for carbon nuclei (2.5 femtometers; 2.5×10^{-15} meters). This shift is the same as that predicted to be caused by electron charge separations of one nanometer, e.g. London force dipoles within aromatic amino acid rings", p. 61. And, "As electron movements may shift atomic nuclei by a distance of the order of a nuclear diameter, we assume that electron-superposition separations of around a nanometer could result in atomic (e.g. carbon) nuclear superposition separations of a few femtometers (Fermi lengths [85], which is about a nuclear diameter, thereby appearing to meet DP requirement for OR", p. 61.)

Using $\tau \approx \hbar/E_g$, where they choose $\tau = 25$ ms for '40 Hz' gamma synchrony conscious moments, they calculate the number of required tubulins in coherent superposition, separated by the diameter of their (carbon) atomic nuclei. Because the carbon nucleus displacement is at the level of its radius, the gravitational self-energy E_c for superposition separation of one carbon atom is roughly given by $E_c = Gm_c^2/a_c$, where G is the universal constant of gravitation, m_c is the carbon nuclear mass, and $a_c = 2.5$ Fermi is the carbon nucleus radius. So the collapse timescale τ_c for a single carbon nucleus takes the form

$$\tau_c := \frac{\hbar a_c}{Gm_c^2} \tag{1}$$

and $\lambda_c = 1/\tau_c$ defines the collapse rate per nucleus. For a tubulin in superposition of size a_c, the collapse timescale, τ_{tub}, is obtained by multiplying λ_c by the number $N_{c/tub}$ of carbon nuclei in a given tubulin, and then taking the inverse:

$$N_{c/tub}\,\lambda_c \rightarrow \tau_{tub} := \frac{1}{N_{c/tub}\,\lambda_c} \tag{2}$$

where

$$N_{c/tub} := \frac{m_{tub}}{m_c} \tag{3}$$

If a number N_{tub} of tubulins are displaced in coherent superposition then the resulting collapse time is $\tau = \tau_{tub}/N_{tub}$. Hameroff and Penrose calculate that 2×10^{10} tubulins displaced in coherent superposition would be required for OR to happen on a time period of $\tau = 25$ ms. For $\tau = 500$ ms, $\sim 10^9$ tubulins would be required. (We can replicate the orders of magnitude of these numbers if we take $m_{tub} \approx 100\ \text{kDa} = 2 \times 10^{-22}$ kg, which appears to be about the mass of a typical tubulin, according to [11,12]. The carbon nuclear mass is $m_c = 2 \times 10^{-26}$ kg, hence $N_{c/tub} = 10^4$.)

They also note that neurons contain $\sim 10^9$ tubulins, but only a fraction per neuron are likely to be involved in consciousness (e.g., a fraction of those in dendrites and soma). If 0.1% of tubulins within a given set of neurons were coherent for 25 ms, they compute that 20,000 such neurons would be required to elicit OR.

As mentioned above, these calculations are based on Penrose's particular hypothesis of gravity-related wave function collapse. To the extent that Penrose lacks a general mathematical model that implements his proposed gravity-related collapse process valid for any initial state, including e.g. unbalanced and multiple superpositions, this can be regarded as a weak point of the Orch OR theory. This being said, there does exist a dynamical theory of gravity-related wave function collapse due to Lajos Diósi [13,14] which also predicts a collapse time of the form $\tau = \hbar/E_g$. After the coincidence of this major figure and the underlying structure of decoherence, the two theories are often called the "Diósi-Penrose" (DP) theory in the literature. Behind the joint name DP, there is a particular difference. Unlike Penrose's approach, which lacks general dynamics, Diósi's general dynamics predicts violations of energy conservation that are appreciable enough to be experimentally tested and constrained [15]. Indeed Penrose [16] has expressed to us that he regards this feature of the DP theory as unphysical, expects it to be definitively ruled out by future experiments, and seeks a physical theory of gravity-related wave function collapse that avoids this (in his view) unphysical feature of energy conservation violation. Equally dissatisfied is Diósi, thinking about new collapse dynamics to ensure energy-momentum conservation [17].

Nevertheless, the currently available (simplest) dynamics in DP theory, and recent experimental constraints on it, provide an occasion to examine and constrain a variant of Orch OR in which the collapse time for coherent superpositions of microtubule material (ignoring environmental decoherence effects) is determined by the DP equations and parameters.

In the next section, we will reexamine the above Orch OR calculations using the DP theory along with recent experimental constraints on the DP cutoff parameter R_0 [15]. We will show, perhaps unsurprisingly, that the variant of Orch OR based on the DP theory, upon taking into account the experimental constraint on R_0 from [15], is definitively ruled out for the case of atomic nuclei level of separation (case (b) above), without needing to consider the impact of environmental decoherence; we will also show that the case of partial separation (case (a) above) requires the brain to maintain coherent superpositions of tubulin of such mass, duration, and size that vastly exceed any of the coherent superposition states that have been achieved with state-of-the-art optomechanics and macromolecular interference experiments.

2. Orch OR bounds from the new DP experimental limits

2.1. DP basics

We first recall that in the DP theory, the formula for the gravitational self-energy E_g of the difference between two mass distributions of a quantum superposition is given by [13,3]

$$E_g = \frac{G}{2} \int \int d^3r d^3r' \frac{\left[f(r|X) - f(r|X')\right]\left[f(r'|X) - f(r'|X')\right]}{|r - r'|} \tag{4}$$

where $f(r|X)$ is the mass density at a point r for a system with position coordinate X, and E_g is the Newtonian gravitational self-energy difference between the superposed $X \neq X'$ and the trivial $X = X'$ configurations. When the two component states of the superposition do not differ but by their center-of-mass positions $X \neq X'$, E_g takes the simple form $U(X - X') - U(0)$ and the collapse timescale becomes

$$\tau = \frac{\hbar}{E_g} = \frac{\hbar}{U(X - X') - U(0)} \tag{5}$$

where U is the gravitational potential energy between two identical systems, one at X and the other at X'.

The above two expressions have been shared by both Penrose and Diósi. The self-interaction $U(0)$ is divergent if pointlike constituents are present. Penrose gave a theoretical answer: let $f(r|X)$ and $f(r|X')$ be calculated for stationary mass distributions corresponding to unsuperposed solutions of the Schroedinger-Newton equation [18,5,2], smearing-out the pointlike mass densities. However, this concept does not apply to the tubulin. Instead, HP consider the finite size of the nuclei to avoid pointlikeness-related divergence. This was Diósi's original concept as well [cf. [14]]. Later on, he considered the standard way to resolve this divergence for point masses [19]. That is the introduction of a minimum length R_0 which limits the spatial resolution of the mass density $f(r)$, thereby acting as a short-length cutoff to regularize the mass density and kinetic energy increase due to the collapse dynamics. This implies that E_g becomes a function of R_0. The larger R_0 the longer the collapse time.

Note that the mentioned levels of (spatial) *separation* contemplated by HP, do correspond to the levels of (spatial) *resolution* ruled by the parameter R_0. Accordingly, partial separation level (a), atomic nuclei separation (b), and nucleon separation (c) correspond respectively to internuclear (or larger), nuclear, and deep subnuclear levels of R_0. The results of HP for option (b), summarized in the Introduction, require mass density resolution as fine as $R_0 \approx 2.5$ Fermi.

2.2. Gran Sasso test of spontaneous radiation: new $\mathbf{R_0}$

So far we have discussed the role of spatial resolution (separation, for HM) R_0 in calculating the decay time. If we invoke the dynamical equation as well, we face energy-nonconservation that results in faint spontaneous electromagnetic radiation [15]. Just as the DP spontaneous collapse rate depends on R_0 so does the rate of spontaneous radiation. The larger R_0 the longer the collapse time and the lower the rate of spontaneous radiation emission. Conversely, if the resolution is fine, i.e., R_0 is chosen small like 2.5 Fermi then the predicted radiation becomes high enough to fall into the regime of experimental sensitivity.

In [15] the predicted spontaneous radiation emission rate was compared with the measured radiation emitted by an ultra-pure germanium crystal and by the surrounding shielding materials. The experiment was performed in the low-background environment of the underground Gran Sasso National Laboratory of INFN. The experimental setup was based on a coaxial p-type high-purity germanium detector, surrounded by a complex shielding structure. A dedicated Monte Carlo characterization of the whole detector system made it possible to calculate the expected spontaneous radiation emission energy spectrum, by weighting the theoretical rate with the efficiency/acceptance functions, for each component of the system. The background, mainly originated by residual radio-nuclides emission, was carefully characterized and an upper limit:

$$R_0 > 5.4 \times 10^{-11}\ \mathrm{m} \tag{6}$$

was extracted, with a probability of 0.95, corresponding to a total exposure of about 124 kg·day.

2.3. Orch OR for atomic nuclei level of separation

The finest sensible not yet relativistic resolution is $R_0 \approx 10^{-15}\ \mathrm{m} = 1$ Fermi. This is of the order of HP's separation $|X - X'| = a_c = 2.5$ Fermi. Hence, for a carbon nucleon, both $U(X - X')$ and $U(0)$ are of the order of Gm_c^2/a_c so we have the collapse time

$$\tau_c^{a_c \approx R_0} \approx \frac{\hbar a_c}{Gm_c^2} \tag{7}$$

However, the experimental results of [15] constrain R_0 well above 10^{-15} m, equation (6).

Given this new constraint, the dynamics of DP theory predicts an extremely slow collapse of a tubulin superposition state of size a_c **since** $\mathbf{R_0 \gg a_c}$, as we show below. Due to $R_0 \gg a_c$, the contribution of mass m_c of a carbon nucleus to E_g is concentrated no longer in spheres of radius a_c but in spheres of radius $\sim R_0$. Since the separation $|X - X'| = a_c$ is kept small, the potential $U(X - X')$ starts quadratically to grow with $X - X'$. In particular, we have

$$\lambda_c^{a_c \ll R_0} = \frac{Gm_n^2}{\hbar R_0}\left(\frac{a_c}{R_0}\right)^2 \approx 10^{-26}\ \mathrm{s}^{-1}, \tag{8}$$

$$\tau_{tub}^{a_c \ll R_0} := \frac{1}{N_{c/tub}} \frac{1}{\lambda_c^{a_c \ll R_0}} \approx \left(10^{-4}\right)\left(10^{26} s\right) = 10^{22} \text{ s} \tag{9}$$

For 2×10^{10} tubulins in superposition state of **size a_c, we have**

$$\tilde{\tau}^{a_c \ll R_0} := \frac{\tau^{a_c \ll R_0}}{2 \times 10^{10}} = \frac{10^{22} s}{2 \times 10^{10}} \approx 5 \times 10^{11} \text{ s} \tag{10}$$

which is not realistic. For a collapse time of 25 ms = .025 s, the number of tubulins needed is

$$N_{tub}^{25ms} = \frac{\tau^{a_c \ll R_0}}{.025 s} = \frac{10^{22} s}{.025 s} = 4 \times 10^{23} \tag{11}$$

Is this possible? Recall that each neuron has $\sim 10^9$ tubulins and there are $\sim 10^{11}$ neurons in a human brain. HP say that only a fraction of tubulins per neuron are likely to be involved in consciousness. If 0.1% of tubulins were coherent for 25 ms, then we would need

$$N_{neur}^{25ms} = \frac{\left(4 \times 10^{23}\right)}{(.001)\left(10^9\right)} = 4 \times 10^{17} \tag{12}$$

Clearly this is far too many neurons!

Even if we assume that all tubulins are involved in the coherent superposition, there are only $(10^9)(10^{11}) = 10^{20}$ tubulins in the brain, which is more than a factor of 10^3 short of our estimate above. But even if we assume that our order of magnitude estimate is off by a factor of 10^3, this would mean that the entire brain is involved in the coherent superposition. Clearly not a plausible assumption!

These considerations seem to rule out (b), tubulin separation at the level of the atomic nuclei (and it certainly also rules out (c), separation at the level of the nucleons).

2.4. Orch OR for partial separation of tubulins

The only tubulin separation possibility left seems to be (a), the entire smoothed-out protein (partial separation). For this possibility, we will approximate the entire smoothed-out protein as a homogeneous bulk of mass $m_{tub} = 2 \times 10^{-22}$ kg and characteristic size L. Let us also consider two cases, first, $\Delta X \ll L$, and then the second one $\Delta X \approx L$ with $\Delta X > L$ included, where $\Delta X := \left|X - X'\right|$. We shall proceed by first ignoring environmental entanglement for calculating the number of tubulin and neurons that must be prepared in coherent superpositions of the necessary sizes and timescales. Then we shall comment on the (im)plausibility of such coherent superposition states in light of inevitable environmental entanglement.

In the first case, we take $L = 3$ nm, which is the radius of the smallest tubulin structure comprising a microtubule, the so-called actin filament [11,12]. For the tubulin coherent superposition size, we take $\Delta X = R_0 = 5.4 \times 10^{-11}$ m. Hence, $L \gg \Delta X$. Using the tubulin mass $m_{tub} = 2 \times 10^{-22}$ kg, we find a tubulin collapse rate of

$$\lambda_{tub}^{\Delta X \ll L} := \frac{1}{\tau_{tub}^{\Delta X \ll L}} := \frac{G m_{tub}^2}{\hbar L} \left(\frac{\Delta X}{L}\right)^2 = 3 \times 10^{-15} \text{ s}^{-1} \tag{13}$$

hence

$$\tau_{tub}^{\Delta X \ll L} = 3 \times 10^{14} \text{ s} \tag{14}$$

The collapse rate scales with the number of tubulins N_{tub}. How many tubulins would need to be involved for a collapse time of 25 ms?

$$N_{tub}^{25ms} = \frac{\tau_{tub}^{\Delta X \ll L}}{(.025 s)} \approx 10^{16} \tag{15}$$

Assuming that only 0.1% of tubulins per neuron are involved in the coherent superposition, how many neurons need to be involved?

$$N_{neur}^{25ms} := \frac{N_{tub}^{25ms}}{(.001)(10^{9)}} = 10^{10} \tag{16}$$

Since there are roughly 10^{11} neurons in the human brain, this means roughly 10% of the neurons comprising the brain would have to be involved. For a collapse time of 500 ms, we would need roughly 1% of the brain involved. In our view, both of these findings stretch credulity when one considers the physical implausibility of biological shielding of (roughly) 10% or 1% of the brain from environmental entanglement for 25 ms or 500 ms, respectively.

In the second case, we take $\Delta X \approx L$ with $\Delta X > L$ included. Then we have the rate

$$\lambda_{tub}^{\Delta X \approx L} := \frac{1}{\tau_{tub}^{\Delta X \approx L}} \simeq \frac{G m_{tub}^2}{\hbar L} \approx 10^{-11}\ \mathrm{s}^{-1}. \tag{17}$$

For a collapse time of 25 ms, the number of tubulins needed is

$$N_{tub}^{25ms} = \frac{\tau_{tub}^{\Delta X \approx L}}{(.025s)} = 4 \times 10^{12} \tag{18}$$

Assuming that only 0.1% of tubulins per neuron are involved in the coherent superposition, the number of neurons that need to be involved is

$$N_{neur}^{25ms} := \frac{N_{tub}^{25ms}}{(.001)(10^{9})} = 4 \times 10^{6} \tag{19}$$

For a collapse time of 500 ms, the number of neurons is roughly 10^5.

We are talking about the brain maintaining coherent superpositions of (tubulin) masses of 10^{-16} kg (10^{-17} kg) for durations of 25 ms (500 ms) over separations of around .01 microns. This vastly exceeds any of the coherent superposition states achieved with state-of-the-art optomechanics [20,21] or macromolecular interference experiments [22]. One should, in principle, not exclude that some particular forms of biological matter, like tubulins, might find some different way for long term superpositions to develop. (For a discussion of possible mechanisms how this might happen, we refer the reader to section 4.5, "OR and Orch OR" in [2].) Even if so, our assessment is that such signatures have not definitively or plausibly appeared so far, either in theory or in experiments.

3. Conclusion

We have considered a variant of the Orch OR theory of consciousness that's based on the simplest version of the DP theory of gravity-related dynamical wavefunction collapse, at the crossroad of the search for spontaneous radiation providing recent experimental constraints on this simplest version of DP theory from [15]. After reanalyzing the most plausible tubulin superposition scenarios described by HP in [2], using the framework of this Orch OR theory variant, along with the recent experimental constraints, we are led to conclude that none of the scenarios (with possible exception to the case of partial separation of tubulins) are plausible.

To be sure, the results in this paper do not rule out Orch OR theory in general. Rather, they rule out variants of Orch OR based on the simplest version of the DP theory of gravity-related dynamical wavefunction collapse. As mentioned earlier, Penrose [16] and Diósi [17] seek alternative theories of gravity-related dynamical wavefunction collapse that do not imply energy-nonconservation. It is possible that, if such a theory is ever found, it will make the tubulin superposition scenarios considered by HP in [2] and this paper seem far more plausible than they currently appear to be on the basis of the simplest DP theory. It is also possible that, when the DP collapse dynamics is modified to include dissipation and/or non-Markovianity, the scenario may change. In future work, we intend to develop such variants of the DP collapse dynamics and then reexamine the tubulin superposition scenarios discussed above. Of course, objections to the Orch OR theory based on environmental decoherence considerations will likely still remain, barring unexpected discoveries in neurobiology showing decisively that microtubules can maintain coherent tubulin quantum states on scales required by Orch OR theory.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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