Perception Constraints on Mass-Dependent Spontaneous Localization

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Some versions of quantum theory treat wave function collapse as a fundamental physical phenomenon to be described by explicit laws. One motivation is to find a consistent unification of quantum theory and gravity, in which collapse prevents superpositions of space-times from developing. Another is to invoke collapse to explain our perception of definite measurement outcomes. Combining these motivations while avoiding two different collapse postulates seems to require that perceptibly different physical states necessarily create significantly different mass distributions in our organs of perception or brains.

Bassi, Deckert and Ferialdi investigated this question in the context of mass density dependent spontaneous collapse models. By analysing the mechanism of visual perception of a few photons in the human eye, they argued that collapse model parameters consistent with known experiment imply that a collapse would take place in the eye within the human perception time of \( \approx 100 \text{ ms} \), so that a definite state of observing some or no photons would be created from an initial superposition.

I reanalyse their arguments, and note a key problem: they treat the relevant processes as though they take place in vacuo, rather than in cytoplasm. This makes a significant difference, since the models imply that superpositions collapse at rates that depend on the difference between the coarse grained mass densities of their components. This increases the required collapse rate, most likely by at least an order of magnitude and plausibly by significantly more. This casts some doubt on the claim that there are collapse model parameters consistent with known experiment that imply collapse times of \( \leq 100 \text{ ms} \) within the human eye. A complete analysis would require a very detailed understanding of the physical chemistry and biology of rod cells at microscopic scales.

INTRODUCTION

Finding a theory that unifies quantum theory and gravity is universally agreed to be a fundamental unsolved problem in physics. Finding a theory that explains the apparent emergence of classicality from quantum theory, resolving the so-called “measurement problem” or “reality problem” is thought by many to be another, and there are several well-known lines of thought on possible solutions. Explaining the emergence of consciousness from either classical or quantum physics is also thought by many to be a fundamental problem; those who think this mostly think we do not currently have lines of thought that promise anything like a complete solution.

One popular approach to the measurement problem is to propose explicit laws governing wave function collapse. Wigner [1] considered the possibility that collapses take place when observations are made by conscious observers. Diosi [2] and Penrose [3] suggested that unifying quantum theory and gravity may require that superpositions collapse whenever they would otherwise create superpositions of distinguishable spacetimes. Ghirardi-Rimini-Weber-Pearle [4] developed spontaneous collapse models, in which unitary quantum dynamics are replaced by stochastic differential equations that are proposed as fundamental laws, from which the unitary Hamiltonian evolution of micro-systems and the effective collapse of macroscopic superpositions emerge as special cases. In the currently preferred versions of these models, collapse rates are proportional to mass densities. This avoids the need to treat composite particles such as nucleons as composed of definite numbers of elementary particles, which would be difficult to reconcile with current theory. It also maintains consistency with current experiments, which appear to exclude the original GRW [4] model. Moreover, appealingly, it suggests a link with gravity.

Although all of these justifications are certainly questioned, collapse hypotheses thus also risk over-motivation. It is not immediately obvious that a collapse law designed to prevent spacetime superpositions necessarily also explains the appearance of classical outcomes of all measurements, or even that it is possible to find a single law that does both and remains consistent with known experiment. In principle, of course, one could postulate two or even more collapse laws: Wigner and Diosi-Penrose could be pointing to independent fundamental collapse phenomena, for example. For most theorists, though, this seems at least one law too many. We would like any alternatives to unitary quantum dynamics to be as simple and elegant as possible and to explain as much as possible.

To define and analyse the question quantitatively, we need to consider specific dynamical collapse models. I focus here on mass-dependent spontaneous collapse models, and on a pioneering paper [6] by Bassi, Deckert and
Ferialdi (BDF) which considered the implications of these models for events associated with visual perception. These are certainly not the only models linking gravity with collapse, and indeed do so less directly than other proposals. However, they are better developed than most, their experimental implications have been carefully analysed, and they include two parameters that allow the predictions of other models to be compared and fitted in a given experimental regime.

On this complex topic, it is natural that some assumptions may be debatable, and progress is likely to be incremental. Indeed, reanalysing BDF’s arguments, I note some problems both with the calculations and the approximations. These make a significant enough difference – a factor of at least \( \approx 10 \) and perhaps significantly more in the lower bound on the collapse rate – that they cast doubt on the conclusion that the relevant collapse models can be consistent both with known experiment and with collapse taking place within human perception times.

That said, a definitive conclusion would require a very complicated analysis, including a detailed understanding of physical chemistry, microscopic cell biology and the correlates of conscious visual perception in the human brain. I am unable to present such an analysis, and indeed not certain that the present state of understanding of these topics will allow precise and reliable estimates of collapse rate bounds from perception. Nonetheless, more progress can surely be made, and I hope that this discussion will stimulate further work.

**BDF ON CONTINUOUS SPONTANEOUS LOCALIZATION**

To ensure that we represent BDF accurately, we quote directly from their analysis in this and the next section. BDF begin by presenting the stochastically modified Schrödinger equation that defines the mass proportional version of the Ghirardi-Pearle-Rimini \([5]\) continuous spontaneous localization model:

\[
|\psi_t\rangle = \left( -\frac{i}{\hbar}H + \sqrt{\gamma} \int d^3x(M(x) - \langle M(x) \rangle_t) dW_t(x) - \frac{\gamma}{2} \int d^3x(M(x) - \langle M(x) \rangle_t)^2 dt \right) |\psi_t\rangle .
\]  

Here \( H \) is the Hamiltonian and \( M(x) \) is a smeared mass density operator. It takes the form

\[
M(x) = \frac{1}{m_N} \int d^3y g(x-y) \sum_s m_s a^\dagger_s(y) a_s(y),
\]

where the sum is over particle species \( s \) with mass \( m_s \). BDF take \( m_N \) to be the mass of a nucleon, in an approximation in which the difference between the proton and neutron masses is negligible. The smearing function is taken to be

\[
g(x) = \frac{1}{(2\pi r_C^2)^{3/2}} \exp(-x^2/(2r_C^2)).
\]

Here the coupling constant \( \gamma \) and the length scale \( r_C \) are parameters of the collapse model. These may be varied independently, and a complete analysis would consider all ranges of both. In their analysis BDF set \( r_C \approx 10^{-5}\text{cm} \) and consider the bounds implied for \( \gamma \), or equivalently for the collapse rate

\[
\lambda = \frac{\gamma}{8\pi^{3/2} r_C^3}.
\]

BDF then consider a superposition of states of \( N \) particles, of the form

\[
\alpha'|\vec{x}'\rangle + \alpha''|\vec{x}''\rangle ,
\]

where \( \vec{x}' = x'_1, x'_2 \ldots x'_N \) and \( \vec{x}'' \) is similarly defined. (Here BDF implicitly assume that each particle has the nucleon mass \( m_N \): an atom with atomic mass \( x \) Daltons is effectively treated as a system of \( x \) tightly bound nucleons in their discussion.) They set the Hamiltonian to zero, and writing the stochastic average density matrix as

\[
\rho_t = \overline{[|\psi_t\rangle\langle\psi_t|]} .
\]

They then give the time evolution of the off-diagonal elements:

\[
\frac{\partial}{\partial t} (\rho_t |\vec{x}'\rangle |\vec{x}''\rangle) = -\Gamma(\vec{x}', \vec{x}'') (\rho_t |\vec{x}'\rangle |\vec{x}''\rangle).
\]
Here

$$\Gamma(x', x'') = \frac{\gamma}{2} \sum_{i,j=1}^{N} \left[ G(x'_i - x'_j) + G(x''_i - x''_j) - 2G(x'_i - x''_j) \right],$$

(8)

and

$$G(x) = \frac{1}{(4\pi r_C^2)^{3/2}} \exp(-x^2/(4r_C^2)).$$

(9)

Now if $|x'_i - x''_i| \ll r_C$ for all $i$, then the first two terms in each summand in Eqn. (8) cancel the third, up to negligible contributions, and so the decay rate is negligible. If $|x'_i - x''_i| \geq 3r_C$ for all $i$ while $|x'_i - x'_j| \ll r_C$ and $|x''_i - x''_j| \ll r_C$ for all distinct $i, j$, then $\Gamma \approx \gamma(4\pi r_C^2)^{-3/2}(N^2 - 2N)$ and so $\Gamma \approx \gamma(4\pi r_C^2)^{-3/2}N^2 = \lambda N^2$ to leading order in $N$. If first and second (or third) conditions hold, while the third (or second) set of separations are larger than $3r_C$, then $\Gamma \approx \frac{\lambda}{2}(4\pi r_C^2)^{-3/2}N^2 = \frac{\lambda}{2}N^2$, again giving a quadratic leading order dependence. If $|x'_i - x'_j| \geq 3r_C$ and $|x''_i - x''_j| \geq 3r_C$ for all distinct pairs $(i, j)$, while $|x'_i - x''_j| \geq 3r_C$ for all $(i, j)$ then only the terms with $i = j$ in the first two sums contribute, giving $\Gamma \approx \gamma(4\pi r_C^2)^{-3/2}N = \lambda N$, i.e. a linear dependence.

More generally, consider a superposition of two states, in each of which the particles are clustered in groups, with separations $\ll r_C$ within the clusters and $\gg r_C$ between the clusters. Suppose that the separations between the states of each cluster in the two components are $\gg r_C$ and that there are $n_i$ particles in cluster $i$. Then to leading order the collapse rate is

$$\Gamma = \lambda \sum_i n_i^2.$$

(10)

As noted above, an atom of mass $x$ is treated as a cluster of $x$ nucleons. As this suggests, one can extend the result to the general case in which particle type $i$ has mass $m_i$, giving

$$\Gamma = \frac{\lambda}{m_N^2} \sum_i m_i^2 n_i^2.$$

(11)

**BDF ON VISUAL PERCEPTION**

BDF consider a human observing a superposition state of a few photons, arranged so that one component causes the photons to impinge on the retina while the other does not. The components of the photon state may be very widely separated: non-relativistic collapse models generally do not assume any spontaneous collapse of photon states, and in any case the collapse rate for a few particles is negligible and effectively independent of the state separation $l$ in the regime $l \gg r_C$.

The goal of collapse models is to explain the appearance of classicality. Humans do indeed perceive definite outcomes – namely, observing photons or not – when observing such states. Hence, BDF argue, a plausible collapse model must imply that a superposition reaching the eye must collapse before it is transformed into a perception in the brain. Human reaction time for weak light perceptions is $\approx 100$ms, so, BDF argue, this requires a collapse within that time. This appears reasonable, though of course there is room for discussion. Three points seem worth elaborating on.

First, our reports and memories of perceptions might not be entirely reliable. Theoretically, one could imagine that collapses take place at a much later point – hours or days after the interaction – leaving us with post-collapse memory states indistinguishable from memories of a (near) real time observation. However, if we are happy to accept theories in which the appearance of classicality is a false post hoc construct, we may struggle to explain why we are not happy with some version of many-worlds quantum theory [8], undercutting entirely the motivation for considering collapse models.

Second, one could imagine that collapse takes place not as a result of events within the brain, but as a result of our physiological responses to these events. Perhaps neither the eye detecting the photons, nor our visual cortices processing the information, are sufficient to cause collapse. Perhaps, instead, collapse only takes place when we blink, or subtly shift position, or report our observation orally or in writing. This is not so ridiculous a hypothesis, but nor is it completely evident that it is consistent with our perception of the appearance of classicality. It feels to me quite plausible that I would notice the photons even if my head and body were completely immobilized. That might be wrong: perhaps there are subtle but significant involuntary responses to any photon detection. But this does not
seem a hypothesis we should accept without good evidence. If a purportedly fundamental physical theory such as a CSL model can only be kept alive by invoking the hypothesis, then (a) anyone advocating the theory should be very clear about this, and (b) we need to test the hypothesis directly. At present, my impression is that advocates of CSL do not rely on this line of thought, and would generally be reluctant to. So I will ignore it in the present discussion.

Third, one could imagine that collapse takes place as a result of events within the brain, but not necessarily within the eye. As BDF note, some authors have produced bounds for CSL models on this hypothesis. BDF consider it dubious: they argue that it would imply that “animals with a simpler visual apparatus could perceive . . . superpositions which we consider rather unlikely”. Here, if I understand BDF correctly, I disagree. Animals with simpler brains would not necessarily perceive superpositions if no collapse took place as a result of events in their brains before their reaction time. They might have no conscious perception at all of these observations, or they might have delayed perceptions. They might not necessarily have conscious memories of these perceptions, and if they do these may not necessarily give them the same impression of time sequencing that our memories give us. So I consider the hypothesis that collapse takes place within the human brain, but not necessarily within the human eye, within \( \approx 100 \text{ms} \), perfectly reasonable. However, my aim here is to discuss BDF’s arguments. These assume that collapse takes place within the eye, and this is certainly an interesting and prima facie plausible hypothesis. I will argue that there are problems with those arguments, which make it very hard to produce precise bounds for mass-dependent CSL collapse rates. The same issues arise in considering information processing elsewhere in the brain, and so I will not pursue this hypothesis further here.

BDF’s account of the biochemical processes involved in photodetection in the eye considers the following stages. Each photon is absorbed by a rhodopsin molecule, transforming it. The transformed molecule interacts with \( \approx 20 \) transducin molecules, splitting off \( \alpha \)-subunits from each. Each subunit diffuses over the rod disc and binds to a phosphodiesterase (PDE) molecule, activating it. Each active PDE converts a cyclic guanosine monophosphate (cGMP) molecule to guanosine monophosphate (GMP). The reduction in cGMP causes the closure of \( \approx 300 \) ionic channels on the rod cell membrane, each preventing \( \approx 10 \) sodium ions (Na\(^+\)) from entering the rod. This generates an electric signal which is transmitted to the optic nerve.

Using the approximations described in the previous section, BDF argue that there are three relevant components in the superposition state of detecting and not detecting a photon. First, the \( \approx 20 \) \( \alpha \)-subunits either remain attached to the transducins or diffuse over the rod disc surface, in which case they become separated from one another by \( > r_C \). They then bind to PDE. Second, in the absence of photons cGMP molecules bind to the ion channels, while converted GMP molecules diffuse in the cytoplasm. Third, \( \approx 10^3 \) Na\(^+\) ions either enter or fail to enter the rod membrane through ion channels.

BDF argue that Eqn. (10) can be applied to obtain contributions to the collapse rate from each of these three components. They take the first component as effectively giving a contribution of \( n_1^2 N_1 \), where \( n_1 = 3.9 \times 10^4 \) is the molecular weight of the \( \alpha \)-subunits in daltons, and \( N_1 = 20 \) is the number of subunits separated by \( > r_C \). The second component is taken to give a contribution \( n_2^2 N_2 \), where \( n_2 = 363 \) is the molecular weight of GMP and \( N_2 = 2000 \) the number of molecules.

The third component is taken to give a contribution \( n_3^2 N_3 \), with two different hypotheses assigning different values. One (BDF’s “most likely case”) takes \( n_3 = 5 \times 3 \times 23 \), corresponding to 5 channels within distance \( r_C \), clusters of 3 ions separated by \( < r_C \), each with molecular weight 23. In this case there are \( \approx 60 \) groups of 5 channels, and \( \approx 333 \) clusters of ions, and BDF take \( N_3 = 60 \times 333 \). The second (BDF’s “extreme case”) assumes all ions passing through a channel are separated by \( < r_C \), giving them \( 10^3 \) ions for each of 5 channels in a cluster and \( n_3 = 5 \times 10^3 \times 23 \), and 60 groups of 5 channels, giving \( N_3 = 60 \).

Accepting these values for the moment, this gives

\[
\begin{align*}
n_1^2 N_1 & \approx 3 \times 10^{10}, \\
n_2^2 N_2 & \approx 3 \times 10^8, \\
n_3^2 N_3 & \approx 2 \times 10^9 - 8 \times 10^{11}.
\end{align*}
\]

and two estimates defining a range for the third contribution

\[
n_3^2 N_3 \approx 2 \times 10^9 - 8 \times 10^{11}.
\]

Summing these, BDF argue, gives the effects of one photon, and multiplying by 6 gives the effects of 6 photons, which they take to be the fewest detectable by the human eye. Thus their final estimate is

\[
6 \times \sum_{i=1}^{3} n_i^2 N_i,
\]

with the \( n_i \) and \( N_i \) given above.
PROBLEMS IN THE BDF ANALYSIS

Problems in BDF’s calculations

The second term in BDF’s sum is dominated by the first and third, and so may be neglected. The first term lies within the range of estimates for the third, so that the sum lies in a compressed range

\[ 6 \times \sum_{i=1}^{3} n_i^2 N_i \approx 2 \times 10^{11} - 5 \times 10^{12}. \]  

(15)

BDF’s estimates for \( \lambda \) appear, however, to be based only on their estimates for the range of \( n_3^2 N_3 \), neglecting the contribution of \( n_i^2 N_i \). This gives them a larger range than should follow from their assumptions and estimates.

BDF adopt the criterion that a superposition is taken to have collapsed when \( \Gamma t \approx 10^2 \), meaning that one term is \( \approx e^{100} \) times smaller than the other. As they note, this is reasonable but arbitrary, and a factor of 10 either way could reasonably be included. The equation \( \Gamma t = 10^2 \), with a time \( t = 100 \text{ms} \), implies \( \Gamma = 10^4 \text{s}^{-1} \).

Using the corrected range, we find from BDF’s estimates and Eqn. (10) a range for the collapse rate given by

\[ \lambda \approx 5 \times 10^{-9} - 2 \times 10^{-10}, \]  

(16)

rather than BDF’s estimate of

\[ \lambda \approx 5 \times 10^{-9} - 2 \times 10^{-11}, \]  

(17)

As BDF note, both ranges could reasonably be multiplied by \( 10^{\pm 1} \) given the arbitrariness noted in the previous paragraph.

Allowing for the cytoplasm

BDF’s calculations effectively model visual perception as though the only relevant massive particles are the specific particles they discuss: the \( \alpha \)-subunits, the GMP molecules, and the Na\(^+\) ions. Their estimates of the collapse rate are thus derived from Eqns. (8) and (10), where the sums include these particles and no others.

This would be a valid approximation if the interactions between incoming photons and these three types of particles took place in otherwise empty space. In fact, of course, they take place within rod cells, which have membranes and other structures filled with cytoplasm, a gel-like substance containing many proteins and ions.

To see immediately that this is likely to affect the calculations significantly, note that Eqn. (1) depends on \( (M(x) - \langle M(x) \rangle_i) \), and that \( M(x) \) itself is a smeared mass density, with the smearing function \( \sigma \) having characteristic scale \( r_C \).

Considering the cytoplasm as homogeneous

We thus cannot apply Eqn. (11) directly, taking \( m_i \) as the actual masses for the relevant particles, for superpositions arising in an otherwise homogeneous fluid. A more relevant approximation would be to take

\[ m_i' = m_i - \rho V, \]  

(18)

where \( m_i \) is the actual particle mass, \( \rho \) the average smeared density of the fluid, and \( V \) the volume of fluid notionally displaced by the particle. More precisely, we could take \( \rho V = k_i m \), where \( k_i \) is the (not necessarily integer) average number of fluid particles absent in a volume of \( r_C^3 \) when that volume contains a particle of type \( i \) and \( m \) is the mass of each fluid particle.

This is significant because the densities of the relevant particles in BDF’s analysis and of the cytosol and other components of the cytoplasm are likely not dissimilar. It is hard to be precise, because the details depend on the properties of the relevant particles when suspended in the cytosol environment, which itself is complex. I have found it hard to locate data even for aqueous suspensions. The best I can offer are very crude estimates, which nonetheless illustrate the problem and the need for closer analysis.
For example, the density of metallic sodium, 968 kgm$^{-3}$, is very close to that of water, 997 kgm$^{-3}$. While data on the effective density of Na$^+$ ions in water solution is harder to find, one crude estimate is given by comparing the estimated effective radius of Na$^+$ in water 9 (218 pm), by that of Na atoms (227 pm). If (which is admittedly not clearly justified by the cited data) we could approximate the effective density of Na$^+$ in water by $(227/219)^3 \times 968 \approx 1078$ kgm$^{-3}$, we would get an effective $m'_i$ for sodium ions in water of approximately 0.08 $m_i$, thus multiplying the estimated collapse rate by < $10^{-2}$.

To get a crude estimate for the $\alpha$-subunits and GMP molecules, we could compare the typical density of proteins, $\approx 1200 - 1400$ kgm$^{-3}$, with either the density of water or, presumably better, the density of the rod cytosol or cytoplasm (perhaps 1100 kgm$^{-3}$). This gives an effective $m'_i \approx 0.3 m_i$, multiplying the estimated collapse rate in the rod by $\approx 10^{-1}$ in this case.

Allowing for these factors gives a collapse rate estimate in the rod of

$$6 \times \sum_{i=1}^{3} (m'_i)^2 n_i^2 N_i \approx 2 \times 10^{10} - 5 \times 10^{10}.$$  (19)

This would imply bounds in the range

$$\lambda \approx 2 \times 10^{-8} - 5 \times 10^{-8}.$$  (20)
Figures 1 and 2 give schematic illustrations of superposition states illustrating the relevance of relative densities. Here the red dots represent idealized ions and the blue dots idealized fluid molecules. In the first state, the ions are concentrated at the edge of the volume; in the second, they have diffused throughout the fluid. In our simplified model, the ions have the same mass and volume as the fluid molecules and diffuse so that the molecule positions are identical (although different molecule types occupy some positions) in the two components. An approximation which considers only the ion positions would suggest that the two states are significantly distinct, and hence that the mass-dependent CSL model should predict the superposition will collapse. However, when all the particles are taken into account, the two states have identical mass distributions. Hence the mass-dependent CSL model predicts no collapse.

![FIG. 1: Ions concentrated on left](image1)

![FIG. 2: Ions diffused](image2)

Allowing for cytoplasmic inhomogeneity

Even these last estimates, however, are based on an invalid model. Cytosol and cytoplasm are not at all homogeneous on the relevant scales. To calculate the difference in smeared mass density distributions between a superposition component in which some number of proteins have or have not diffused around the cell, for example, one thus has to consider all the proteins and other components that may have been relocated in the course of the diffusion. To then apply (11), one needs to know – or at least plausibly estimate – all the relevant separations and displacements of all these proteins (including but not only those actively involved in photo-detection), and all the ions and other solutes. Without a very detailed understanding of rod cell biology and biochemistry at very small scales, it is hard to know how to begin making a plausible estimate. I do not know whether sufficiently detailed and complete information is presently available or obtainable. It is thus impossible to say for sure, but to me the most plausible guess is that an accurate estimate would produce significantly higher collapse rate bounds than those of Eqn. (20).

Figures 3 and 4 give schematic illustrations of superposition states illustrating the relevance of inhomogeneities. Here the red dots represent protein molecules relevant to visual perception and the blue dots other protein molecules.
in the cytoplasm. In the first state, the red molecules are concentrated at the edge of the volume; in the second, they have diffused throughout the cytoplasm. An approximation which considers only the red molecule positions suggests that the two states are significantly distinct, and that the separations relevant to the two red molecule states are large. In this model, the molecule positions are different in the two components. Thus, when all the particles are taken into account, the two states still have distinct mass distributions. However, if the red and blue protein molecules have identical masses and densities, the relevant separations are those between dots of either colour in the two component states. These are much smaller than the typical differences between red molecule positions in the two states or the typical separations between red molecule positions in the second state.

**FIG. 3: Red protein molecules concentrated on left**

**FIG. 4: Red protein molecules diffused**

**Limits of human perception**

Since BDF’s work, evidence has been presented [10] suggesting that humans are able to detect single photons. The evidence is not as yet compelling: results are reported for three individuals, and their responses were statistically significant but not perfectly reliable.

If it could be shown that humans can reliably detect single photons, BDF’s collapse rate bounds, and others similarly derived, would be increased by a further factor of 6. Given the uncertainty in interpreting the evidence, I do not include this additional factor here. It is worth keeping in mind, though, given that it would increase the bounds by close to a further order of magnitude.

**CONCLUSIONS**

Dynamical collapse models in general, and mass-dependent continuous spontaneous localization models in particular, are well motivated and experimentally testable alternatives to quantum mechanics. It is an intriguing question
whether these models can be excluded with foreseeable technology, or even are already excluded by existing experimental and observational data. Lower bounds on the model collapse rates can only ultimately be justified by assuming that collapses take place within human perception times, so that the models predict that humans should perceive one component of a superposition.

BDF’s pioneering work gives a basis for deriving such bounds. However, their assumptions and approximations are questionable enough that it seems unwise to rely on the bounds they suggest. Further work is needed to decide whether mass-dependent continuous spontaneous localization models remain viable (for some parameter choices) or are already effectively excluded.

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References

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[1] Eugene P Wigner. Remarks on the mind-body question. In Philosophical Reflections and Syntheses, pages 247–260. Springer, 1995.
[2] Lajos Diosi. A universal master equation for the gravitational violation of quantum mechanics. Physics Letters A, 120(8):377–381, 1987.
[3] Roger Penrose. On gravity’s role in quantum state reduction. General Relativity and Gravitation, 28(5):581–600, 1996.
[4] Gian Carlo Ghirardi, Alberto Rimini, and Tullio Weber. Unified dynamics for microscopic and macroscopic systems. Physical Review D, 34(2):470, 1986.
[5] Gian Carlo Ghirardi, Philip Pearle, and Alberto Rimini. Markov processes in Hilbert space and continuous spontaneous localization of systems of identical particles. Physical Review A, 42(1):78, 1990.
[6] Angelo Bassi, D-A Deckert, and Luca Ferialdi. Breaking quantum linearity: Constraints from human perception and cosmological implications. EPL (Europhysics Letters), 92(5):50006, 2010.
[7] Stephen L Adler. Lower and upper bounds on CSL parameters from latent image formation andigm heating. Journal of Physics A: Mathematical and Theoretical, 40(12):2935, 2007.
[8] Simon Saunders, Jonathan Barrett, Adrian Kent, and David Wallace. Many worlds?: Everett, Quantum Theory, & Reality. Oxford University Press, 2010.
[9] Zhong-Hua Yang. The size and structure of selected hydrated ions and implications for ion channel selectivity. RSC Advances, 5(2):1213–1219, 2015.
[10] Jonathan N Tinsley, Maxim I Molotsov, Robert Prevedel, David Wartmann, Jofre Espigulé-Pons, Mattias Lauwers, and Alipasha Vaziri. Direct detection of a single photon by humans. Nature Communications, 7:12172, 2016.