Achronotopic Interpretation of Quantum Mechanics

Quantum objects and their measurement in emergent space-time scenarios

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Abstract

In conceptual debates involving the quantum gravity community, the literature discusses the so-called "emergence of space-time". However, which interpretation of quantum mechanics could be coherent with such claim? We show that a modification of the Copenhagen Interpretation of quantum mechanics is compatible with the claim that space-time is emergent for the macroscopic world of measurements. In other words, pure quantum states do not admit space-time properties until we measure them. We call this approach "Achronotopic" (ACT) Interpretation of quantum mechanics, which yields a simple and natural interpretation of the most puzzling aspects of quantum mechanics, such as particle-wave duality, wave function collapse, entanglement, and quantum superposition. Our interpretation yields the same results in all measurements as the Copenhagen Interpretation, but provides clues toward the sub-Planckian physics. In particular, it suggests the non-existence of quantum gravity in the conventional sense understood as the quantization of a classical theory.

Keywords: Quantum mechanics, spacetime emergence, measurement, quantum gravity

1 Introduction

Quantum mechanics (QM) is the theory that deals with the behavior of matter and its interactions with energy on the atomic and sub-atomic scales. This definition can be refined at will, but this won't eliminate the fact that it is one of the most problematic theories to interpret.[1] Paradigmatic is Feynman's take in *The Character of Physical Law*, according to which: "[...] nobody understands quantum mechanics" on the ground of ordinary concepts and, we add, standard ontology. The zoo of different interpretations of QM includes tens of different versions of the theory's conceptual underpinning and ontological implications, giving rise to competing schools and research programs in the foundations of physics. Examples include the pilot wave, the many worlds, the Diósi-Penrose [2], and the Ghirardi-Rimini-Weber (GRW) [3] interpretations that now populate this landscape in which one should also include Bohmian mechanics [4].[2] The current situation is even more complicated by the fact that research programs in fundamental physics and cosmology pursue the quest for a theory of quantum gravity (QG) without a univocal understanding of the ontology of quantum mechanics and without reaching a consensus about the approach that would lead us to show the emergent nature of spacetime.[3] Doubts concerning canonical quantization are well-known in the literature, and we reached at least consensus regarding the fact that whatever quantum gravity is or will be, it should bring with it a novel understanding and definition of ontology (i.e. what counts as physical reality), of the nature of spacetime (be it emergent or not), and even of our way of understanding "emergence".[4] Even if we are not dealing with nor endorsing any specific research program of quantum gravity, in what follows, we will pursue an important objective consisting in showing that a cogent approach to quantum gravity implies to drop the assumption that space-time is a property of all quantum states and one has rather to assume that delocalized states are not in spacetime. In other words, we show that *iff* spacetime is emergent, quantum systems can only acquire spatiotemporal properties by interacting with macroscopic systems, which are spatiotemporal. This move, in turn, will offer an interpretation of QM that is compatible with the major tenet of quantum gravity, i.e., the emergence of space-time, but it still leaves open the possibility that other research programs could enter the scene and dramatically change our understanding of GR and QM. To be more concrete, we will explore why and in which sense directions are to be understood as more fundamental than spatiotemporal properties and why the notion of classical time is to be dropped if one wants to recover a coherent view of quantum systems in both QM and QG. This is the reason why we termed our interpretation "Achronotopic (ACT) interpretation of quantum mechanics". In this context, we shall proceed as follows. In section 2 we will expose and discuss the axioms of QM and

[1] For a recent review see [1].

[2] For a sharp criticism of the dualism suggested by Bohmian mechanics and spontaneous collapse theories, see [5].

[3] Approaches to quantum gravity include Loop Quantum Gravity, Causal Dynamical Triangulation, Group Field Theory and many others, for a recent review on the state of the art and future perspectives, see [6]. We leave out of our discussion Rovelli's Relational Quantum Mechanics (RQM) [7], since it deserves a separate and deeper discussion. More recent details on the interpretation and surrounding debates can be found in [8].

[4] While there is no consensus over suitable approach(es) to quantum gravity, the philosophical community endorses Butterfield's relational definition of emergence as "behaviour that is novel and robust relative to some comparison class", see [9]; [10].

explain the rationale behind the choice of dropping spacetime from the fundamental ontology of the theory.[5] In section 3, we offer a discussion of topical examples from the theory (wave-particle duality, one and double-slit experiments, entanglement, and Schrödinger's cat) for which our interpretation offers a clear explanation. Section 4 offers a novel perspective on the Schrödinger equation and associated ontology. We then conclude in Section 5 with a discussion of our results and the research lines that our approach opens in the fields of quantum gravity and cosmology.

2 ACT framework and the axioms of QM

Our interpretation of QM keeps the following fundamental axioms:

- The quantum states $|\psi\rangle$ of a system form a Hilbert space $\mathcal{H}$.
- The eigenvalues of the Hermitian operators in $\mathcal{H}$ represent measurements.
- A measurement projects a system into a definite eigenstate probabilistically.
- The Born rule for transition probabilities is $|\langle\phi|\psi\rangle|^2$. This rule naturally applies to eigenstates of operators.

Since our assumption of interest is that spacetime is emergent, we do not expect at this stage to pre-determine space-time (Galilean or Lorentzian) as the natural realm for QM; therefore, we postpone the discussion of the rule for unitary evolution. While we might speculate on how space-time could emerge through, e.g., a correlation of quantum states, such details are unnecessary for our present purpose. However, the domain in which we perform measurements and most of our apparatuses possess spatio-temporal structure. Thus, the operators always correspond (sometimes implicitly) to space-time measurements. Ultimately, we endow quantum states with space-time attributes through and because of measurements.[6]

If quantum measurements are represented by operators, the Heisenberg uncertainty principle follows from a condition equivalent to the Liouville incompressibility of phase space, namely given our incomplete knowledge of the initial conditions, we cannot gain information during (Hamiltonian) evolution. Thus, QM has a fundamental phase space information uncertainty measured by $\hbar$. Heisenberg attributed this to a very specific ontology and epistemology, according to which there is no unique accessible reality, but levels or domains of reality, more precisely "Bereiche der Wirklichkheit" that remain unaccessible or disclosed to us depending on the stage of human history and culture. In this context, we do not need to enter the discussion of the ontology grounding Heisenberg's uncertainty principle. We are satisfied by concluding that the formal proof of the uncertainty principle for operators shows that non-commutation expresses such an information limit and that this universally holds in the systems

[5] Similar reflections can be found along the lines of [11] and [12] that pointed to the consideration of imaginary proto-time evolution in quantum cosmology, and to quantum regimes in which time is not defined, respectively.

[6] Interestingly, in [13], a reading of QM basic postulates identifies the quantum jump with the notion of physical event in such a way that the temporal localization of a set of physical quantities happens without any necessary relation with the measurement processes and apparatus. Temporal localizations of physical quantities is all "there is" and the common notion of object is dropped from the theory. Our view differs from this proposal, since for ACT quantum objects are neither waves, nor particles and reside outside of space-time. Furthermore, we do not assume temporal localizations of physical quantities as the ontological subject matter of interest.

observed so far, thereby making of this invariant principle an unavoidable quantum censorship. Indeed, we want to point out that a pure quantum state often has a direction (momentum and energy or spin) while not localized in space or time[7]. In mathematical language, this points to the idea that at the more fundamental level, the underlying world is projective, in contrast to an emergent affine space-time. A measurement thus localizes such projective world in the sense of connecting it into our space-time. For this reason, Heisenberg's uncertainty principle enforces what the CI describes as the collapsing wave function, which conserves information.[8]

Today, we witness a lively debate surrounding the interpretation of the wave function collapse, including contributions from both the physics and philosophy community. The latter tried to develop metaphysical positions giving rise to notions, such as quantum indeterminacy, grounding and so forth, applied to specific interpretation of QM, such as GRW and Everettian Quantum Mechanics.[9] In our framework, the notion of quantum indeterminacy can be dropped, because the eigenstate-eigenvalue link associated to such a notion [18] does not appear in our version as it does in other interpretations. Moreover, in the context of the ACT framework, even epistemic indeterminacy is not taken into account, partly due to the assumption of the above-mentioned axioms, partly due to the fact that we aim at showing that an interpretation consistent with spacetime emergence is, at least for the time being, functional to a research program of QG that wants to determine the quantum discrete structure of spacetime or the collective behaviour of spacetime atoms in analogy with BECs. In what follows, we therefore want to clarify the subtle differences between our interpretation and the CI through simple examples, thereby showing that a different take on the wave function collapse is possible and can be coherently conjugated with the idea of emergent spacetime. We assume a working knowledge of QM and CI. In particular, we do not need to repeat standard calculations since our interpretation leaves them intact. *The critical new insight we want to include in building our interpretation is that space-time enters only through measurements within an existing space-time frame.* We take it as an empirical fact that such a space-time framework exists in our physical realm where we place our experiments. And this brute fact is undeniable.

3 Interpreting QM in view of QG scenarios

3.1 Wave-particle duality

In CI, an incoming plane wave represents a moving particle. When the particle enters a detector, the wave function "collapses" and becomes a particle. The paradox at the heart of this basic example is that the delocalized wave function in *space-time* collapses instantly through an acausal process in space-time.

In our view, the collapse is just an illusion. The particle is in a momentum state $|p\rangle$. When the particle enters the detector, we measure it with the probability of $\propto |\langle p|x\rangle|^2 = \left|e^{ipx/\hbar}\right|^2 = \text{const}$. Thus, there is no wave function collapse: the $|p\rangle$ state

[7] While we do not explicitly use it in our considerations, the fact that a pure state can have a direction would be compatible with holographic ideas of space-time emergence.

[8] On a related note, this can imply that holography is likely to be related to the emergence of space-time.

[9] For recent work, see [14];[15];[16]; [17]. For a different account, see [18].

is in a Hilbert space separate from our space-time, it signifies something that lives in a sort of Platonic world of Forms, and the "wave" strictly emerges in the detector.

We rather interpret the quantum-mechanical wave function as a statistical object: if we had a source producing particles in state $|\psi\rangle$ and we put detectors at all points in our space-time frame, we would measure probabilities of $\left|\langle\psi|x\rangle^2\right| = |\psi(x)|^2$. But a crucial difference from the CI is that the wave amplitude only emerges when and if we measure it at points x. Otherwise, a particle resides in a separate Hilbert space, again it is in a sort of Platonic hyperuranium.[10] This means that space-time is not a quantum number/property of $|\psi\rangle$.

If we formally expand such a state into space-time states, we formally combine many measurements into a statistical object. Once a particular measurement localizes the state, the statistical object, i.e. the wave function disappears. Hence, what is left to us is just the non-physical "collapse of the wave function". Therefore, according to the ACT interpretation, quantum objects are neither waves, nor particles: they reside outside of space-time, interact with space-time through measurements, and those measurements decorate the quantum objects with wave or particle properties when the measurement takes place.

3.2 The one-slit experiment

The one-slit experiment is foundational in quantum mechanics. Traditionally, it assumes a particle generator, say, on the left side of the apparatus, a single slit in the middle, and a particle detector on the right side.

According to the ACT interpretation, a particle in a true (Platonic) $|p\rangle$ state has no space-time properties. Therefore, it is a slight abuse of notation and concept to start with the statement that "a particle in state $|p\rangle$ occupies the left side of the experimental apparatus". The fact that we start the experiment at a particular time and generate the particle stream in space corresponds to a rudimentary measurement. Initially, the particle is not in a perfect Platonic $|p\rangle$ state. Rather, the experiment starts with the particle in a slightly perturbed $|p, \mathrm{left}, \mathrm{t}_0\rangle$ state. We assume that this state is sufficiently close to a perfect $|p\rangle$ state that can neglect the difference in any calculation.

A pure $|p\rangle$ state has a direction. Therefore, we can talk about directions parallel and perpendicular to the direction of $|p\rangle$.

The slit corresponds to a measurement of x in the perpendicular direction to $|p\rangle$. Thus, on the right side of the apparatus, the state will generate a perpendicular uncertainty in p due to the Heisenberg principle. A narrower slit results in more uncertainty. The smeared particle distribution in the detector plane will match that uncertainty. As emphasized earlier, the wave function-like amplitude only appears at the detector, where $|\langle p|x\rangle|^2$ is measured. For the sake of simplicity, we disregarded time, although the detector performs a time measurement as well. Disregarding time

[10] This analogy with Plato's hyperuranium needs some clarification. We do not literally claim that the $|p\rangle$ state in a Hilbert space is in a separate world, but we want to stress that without measurement the state is in an epistemically inaccessible (but not indeterminate!) region, since the theory cannot tell us more about spatio-temporal properties of the system. This view is compatible with quantum gravity scenarios.

corresponds to a statistical average over a large enough time interval approaching the results of an ideal experiment lasting for an infinite time.

According to the CI, a plane wave propagated through the slit, scattered, and finally collapsed in the detector. According to the ACT framework, there is no spontaneous collapse of the wave function: the state resides in a Hilbert space and interacts with space-time only at two measurement locations.

3.3 The double-slit experiment

When there are two slits, the measurement in the perpendicular direction causes a range of p directions, as in the case of the one-slit experiment. The two slits constrain x to a lesser degree, and two sets of $|p\rangle$'s are allowed by the Heisenberg uncertainty principle.

The detector measures the state in space(-time). Two different directions of p can produce a hit for a particular position. The transition amplitude is $(\langle p_1| + \langle p_2|)\,|x\rangle$, where p_1 and p_2 represent the two possible directions connecting to x. Squaring the amplitude will produce interference. Still, according to our interpretation, no waves propagate in space(-time). Only the final measurement of the $|x\rangle$ projection induces a wave-like property.

An additional detector near the slit to observe "which slit the particle travels through" will spoil the interference. However, observing the slits corresponds to an additional perpendicular $|x\rangle$ measurement that eliminates one of the paths — the uncertainty in x decreases. Therefore, the uncertainty in p increases. At the detector, the amplitude will be $\langle p_i|x\rangle$ for one of $i = 1, 2$, i.e., there is no interference.

States in the slit experiments are pinned to space-time twice: once partially (perpendicular only) at the slit(s) and once at the detector. Outside these two contacts, the state lives in a Hilbert space beyond space-time. We arrive at the important conclusion, which is certainly more radical than other interpretations, namely, at the ontological level, there are neither "in-between" nor wave functions since we make no measurements in-between.

3.4 Entanglement

The source of all the entanglement puzzles is the assumption that the entangled particles (or quantum systems) are in space-time. If we drop this assumption, there is no need for a causal path between the two measurements: they connect into space-time only by measuring one state. When we measure the spin state of one particle, we pin it to space-time, determining the correlation of the spin state of the other particle at once. When we measure the other spin, we pin the other particle to space-time. It is just after a measurement that causality will eventually apply to the pair of correlated states in space-time.[11] However, entanglement is broken as soon as the measurements connect the particles to different space-time points. Entanglement is thus fundamentally nonlocal since in space-time endowed with a causal structure, there cannot be

[11] Correlation is not causation, but it is clear that once we connect correlated states to space-time, we go far beyond what the theory describes and make a subreption by attributing causal structure to entangled states.

entanglement. Thus, conceptually, there is no paradox, even if the philosophical implications of entanglement are enormous and regard the emergent nature of spacetime, as well as the fact that quantum correlations and entangled states disclose to us a world for which local realism is just an illusion.[12] Furthermore, the philosophical bias behind the fundamental misunderstanding of entanglement consists in applying old metaphysical pairs, such as substance/accident, to particles/states, as if states pertain to particles as things in themselves. In this sense, Feynman's words could not be more appropriate in explaining why QM is puzzling.

3.5 Schrödinger's cat

At this point, we deal with one of the most famous examples in the form of an ideal experiment used to highlight (in an inappropriate way) quantum superposition. It should be clear from the above that a cat, a macroscopic object, is part of our space-time. Each of its cells measures space and time independently of random events that may or may not occur. These measurements project the cat into definite states in space-time. Therefore, the cat does not exist as a pure wave function and thus cannot be in a mixed state. The cat is dead or alive, regardless of the opening of the box or the addition of Wigner's friend [22].[13] Both in the case of quantum superposition and in the interpretation of quantum correlations the puzzles and apparent contradictions of QM come from interpreting delocalized initial states as local before connecting them to space-time in a measurement.

3.6 The Schrödinger equation, path integrals and unitary evolution

We are now in a position to express the unitary evolution and its rule for QM systems. The realm of QM is a Hilbert space of possible states $|\psi\rangle$. We associate the dual space with measurements in the following way: let us introduce the projector P representing a *primitive measurement*, a simple yes and no question: is the system's state $|\phi\rangle$?

$$P_\phi = |\phi\rangle \langle\phi| \,. \tag{1}$$

The measurement will influence the system, and the answer is yes with probability $p = |P_\phi |\psi\rangle|^2$, and no with probability $1-p$. From the formal mathematical standpoint, it's a projector because subsequent applications of P_ϕ to ψ will not change the result. The classic quantum operators representing measurement operators are the sum of

[12] Note here that one could endorse a perspectivalist view and further elaborate on the fact that what is "real" in a portion of the world endowed of a certain four-dimensional structure can be seen as an "llusion" when seen from the perspective of another portion of the world possessing different structure. This means that the true picture can be obtained only by means of a higher standpoint explaining how dilemmas in physics, e.g. local vs non-local interactions, can be overcome. For the debate on perspectivism in science and models, see [19]; [20]; [21].

[13] Wigner's Friend is a meta-observer who calculates the superposition states of an observer performing an experiment. Does the state collapse when the observer performs the measurement or when the meta-observer learns the result? In our interpretation, it is the former.

primitive measurements weighted by the results of such measurements:

$$A = \sum \lambda_i |\phi_i\rangle \langle\phi_i| , \tag{2}$$

where usually the states $|\phi_i\rangle$ span the Hilbert space. Note the distinction of expanding a state in a set of other states as a linear combination, and a measurement that determines the coefficients of these expansions. The former is a mathematical trick using the properties of Hilbert spaces; the latter is a statistical ensemble of measurements. Neither corresponds to one measurement that will result in one definite value and put the system into a definite state. Once we define operators representing (composite) measurements, one can derive the Heisenberg uncertainty relation in the usual way.[14]

Furthermore, since all measurements are made in space-time, the most fundamental states are $|x\rangle$, $|t\rangle$, and $|x,t\rangle = |x\rangle \otimes |t\rangle$. In a definite momentum state, $\langle p|x\rangle = e^{ixp/\hbar}$ and in a definite energy state $\langle E|t\rangle = e^{-iEt/\hbar}$. From the first formula, using $\psi(x) = \langle\psi|x\rangle$, follows the Schrödinger representation of the momentum operator $\hat{p} = -i\hbar d/dx$. From the second formula, defining $\psi(t) = \langle\psi|t\rangle$, implies the Schrödinger equation as outlined next:

A state with definite energy satisfies the following differential equation:

$$\frac{d\langle E|t\rangle}{dt} = -\frac{i}{\hbar} E \langle E|t\rangle . \tag{3}$$

Therefore, any state that is a linear combination of $|E_i\rangle$ states also satisfies this equation. On the other hand, if we can build a Hamilton operator from primitive energy measurements as described above:

$$H = \sum E_i |E_i\rangle \langle E_i| , \tag{4}$$

which guarantees that the energy states are eigenstates of this operator. Comparing it with the right-hand side of Eq. 3, the Schrödinger equation follows.

The above outline is, however, incomplete since we did not explicitly follow contraction, i.e., measurement, with the full space-time projectors.[15]

Note that the above argument yields the Schrödinger equation in the Schrödinger picture, i.e. the states are fully expanded over space-time states. The Heisenberg picture in CI assumes a time-dependent Hilbert space $|\psi(t)\rangle$, which in our interpretation corresponds to a partial contraction over the $|t\rangle$ states, but not the $|x\rangle$ states.

If a pure quantum system is in a state ψ and we have access to a Hamilton operator H (usually constructed from classical theory; we adhere to Dirac's canonical quantization), then

$$i\hbar \frac{\langle\psi|t\rangle}{dt} = \langle H\psi|t\rangle \tag{5}$$

The equation is the usual one and follows from canonical quantization. The difference in interpretation is subtle: we claim that H assumes time measurements and relates

[14] Does the Hilbert space contain states that are orthogonal to space-time states? It is possible, but we will never know: we only have access to measurements through our own space-time.

[15] This, in turn, similarly to the case of CI, does not explain the correspondence principle, i.e., the miracle of obtaining quantum Hamiltonians from classical ones. More about it in the next section.

two measurements infinitesimally close to each other. Again, time is a property of our framework, not the original quantum state $|\psi\rangle$. In this sense, unitary evolution follows from integration. The Schrödinger equation, indeed, is equivalent to the path integral formalism. Once a space-time framework is defined, the path integral corresponds to a series of space-time measurements $\langle\psi|x,t\rangle$.

4 Discussion and conclusion

Classical and relativistic mechanics describe motion in the same rigid space-time, serving as a QM measurement grid. The Hamiltonian drives motion in classical mechanics, and the corresponding Hamiltonian operator does the same for a quantum state. However, dynamics belong entirely to the space-time framework and are not inherent to quantum mechanics. Our interpretation thus sheds new light on the correspondence principle: dynamics of classical and quantum mechanics are similar since both play out in the same emergent space-time. Therefore QM, regardless of internal details, mostly inherits the dynamics of classical mechanics. Another important point follows from our interpretation and regards quantum gravity. Perhaps surprisingly, ACT implies that quantum gravity does not exist in the conventional sense. General Relativity (GR) is the theory *of* the emergent space-time, not a theory that plays out *in* space-time.[16] According to the above, space-time is a fundamental property of our (macroscopic) measurement grid, but not of pure quantum states. Thus, quantum theory in curved space-time makes a lot of sense. It is analogous to the case of classical mechanics in curved space-time. On the other hand, if space-time is emergent, its theory, i.e. GR, is emergent as well. However, the notions of emergence is here too vague. What GR had taught us in the last century is that it makes spacetime determinable: there are fixed properties of spacetime metric, but there are also properties and gravitational phenomena that 'emerge' from the theory, e.g. Kerr BH, gravitational waves and so forth. Near the Planck scale, such emergence is likely to break down, along with it, the fundamental assumption of a local Minkowskian space-time grid. However, this consideration is not enough to assume that current QG research programs will be successful. We rather conclude that gravity does not admit a traditional quantization, if any. A close analogy would be quantizing Euler's equations: a quantum fluid arises from the interactions of many quantum objects. Using statistical physics and a deep understanding of the interacting objects, we can generalize the classic Euler's equation by adding a quantum potential [23]. That procedure is approximate and different from the standard (canonical or path integral) quantizations. Perhaps an emergent quantization akin to the quantum potential for Euler's equation would be a more fruitful approach. Implicitly assuming that GR is a fundamental theory and quantization is a technical problem might have limited the construction of quantum gravity for over a century. Nevertheless, things could also be different: what if GR discloses the possibility of unexpected solutions removing singularities in black holes? After more than a

[16] It must be noticed that GR is an incomplete theory in a peculiar sense, because we do not master the theory, many of the solutions, i.e. phenomena it implies, are unknown to us. However, since we can find new solutions of Einstein Field Equations, this is also a determinable theory, which also make physical phenomena determinable in space-time and makes space-time itself determinable, e.g. in the case of gravitational waves.

century from Einstein's GR, we still have a poor understanding of the implications of the theory, i.e. our understanding of GR is incomplete in a deeper sense, and it comes as no surprise that QG represents a tantalizing effort of the scientific community.[17]

Let us now consider other possibilities to expand the discussion. We started from the experimental fact that our macroscopic world admits space-time. If our world is ultimately a quantum system, how did space-time emerge in the first place? Without a peak 'under the hood', it is impossible to know a priori, yet one could perhaps try to define a super-path integral, integrating through all states from the initial to final states. Of course, without time, the meaning of such an integral is somewhat dubious. But if some quantum states are more correlated, one could connect 'nearby' states, whereas nearby means more correlated. If an approximate Born-chain of states dominates, we could introduce a parameter along the chain, call it "time", and reformulate the integral as a conventional path integral. It is clear that once we can define localization in terms of quantum states, a simple structure might emerge.

Another possibility is that there is always a 'time', but we might not be able to observe it as if there were a censorship dictated by a specific mechanism. One realization of this idea depends on measurement, the other on some dynamical mechanism. A simple example of the first instance is a classical gas at room temperature. Let us suppose we can observe and take pictures of the gas particles in a region with our measurement apparatus. The order of magnitude speed of the gas particles is $10^3 m/s$. Thus, if we take 1000 pictures in 1000 seconds, we cannot relate the images to each other. If this is our universe, we would conclude that there is no time. We might not discern any movement if we take the same 1000 pictures in 10^{-9} seconds. We would conclude that the gas is static. Thus, again, we would observe no time. If we take our pictures at a speed that matches the movement of the particles and the accuracy of our observations, then we could observe the classical paths of individual particles and assign position and time to each of them. We could call the above phenomenon of not being able to observe time a *time impedance mismatch*. The concept extends to a *spacetime impedance mismatch* by analogy. We can then interpret the constant $\hbar$ as a quantitative measure of such a mismatch. If the pace of our measurements is sufficiently different from the dynamics of the quantum world, our measurements cannot discern the correlations that imply time and causality. Quantum mechanics could be too fast compared to the speed limit enforced by the emergent space-time. Interestingly, the opposite is true for cosmology, where our measurements are too fast and limited by the human life span compared to the evolution of the universe.

What kind of experiments could we do to test our interpretation? Those that explicitly connect the CI concept of the collapsing wave function to pinning the quantum state onto space-time. In the case of the standard EPR entanglement, we suggest that the implicit contracting with $|x, t\rangle$ along with measuring the spin, has a role in CI wave function collapse. An experiment leaving x and t ambiguous (similar to the double-slit experiment) would not cause the wave function to collapse entirely in the CI sense.

[17] For instance, one could find a scenario in which atemporality is the dynamical mechanism responsible for the transition from a regime with a real-valued time variable to a new one featuring an imaginary time that naturally prevents infalling bodies in the BH event horizon to reach the singularity, see [24].

If there is no wave function, or more precisely, if it emerges only at the moment of measurement, why is wave mechanics so successful? According to the ACT interpretation, wave mechanics is a *Gedanken* experiment where one *imagines* measuring the quantum state in each space-time point. The resulting $\psi(x) = \langle\psi|x\rangle$ represents delocalized states in our localized space-time grid. This representation correctly predicts the probability $|\psi(x)|^2$. But taking the CI at face value, the first measurement collapses the wave function. Therefore, we cannot ever realize $\psi(x)$, only statistically, measuring many copies of the same state.

On the contrary, delocalized in the ACT framework means no attachment to space-time except for direction. Indeed, a wave determines a direction (via the energy-momentum vector) in space-time. A universe filled with an actual plane wave is 'Everything Everywhere All the Time'. Nevertheless, *Gedanken* measurements miss that the state does not reside in space-time. Hence the assumption of the wave function collapse or the sci-fi movie alternative of the many world interpretation. If the latter is correct, there is at least one universe where the ACT is standard. Why not make that our universe?

To conclude, we have formulated an interpretation of QM that is slightly different from the gold standard of CI. Our central assumption is dropping a ubiquitous and often implicit assumption: space-time is a property of all quantum states. On the contrary, we posit that space-time properties of pure quantum systems typically emerge through interaction with our macroscopic world that is necessarily spatio-temporal. In particular, delocalized states are not in space-time. This opens the path for a deeper interpretation (philosophical in nature), regarding the atemporal character of the interactions at Planck scale and stimulates further investigation on the mathematical foundations of QM at the intersection with QI theory. Finally, the reader will notice that our interpretation is more conservative than the CI: it does not assume that the quantum states live in our emergent space-time, although they exhibit directional properties. Space-time manifests strictly through measurements that pin quantum states and this assumption together with other philosophical takes dropping classical metaphysics eliminates paradoxes of the standard and alternative interpretations.

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References

[1] Snoke, D.W.: Interpreting Quantum Mechanics: Modern Foundations. Cambridge University Press, Cambridge (2024)

[2] Bahrami, M., Smirne, A., Bassi, A.: Role of gravity in the collapse of a wave function: A probe into the diósi-penrose model. Physical Review A **90**(6), 062105 (2014)

[3] Ghirardi, G.C., Rimini, A., Weber, T.: Unified dynamics for microscopic and macroscopic systems. Physical review D **34**(2), 470 (1986)

[4] Bohm, D.: A suggested interpretation of the quantum theory in terms of "hidden" variables. i. Physical review **85**(2), 166 (1952)

[5] Belot, G.: Quantum states for primitive ontologists: A case study. European Journal for Philosophy of Science **2**(1), 67–83 (2012) https://doi.org/10.1007/s13194-011-0024-8

[6] Kiefer, C.: Quantum gravity - an unfinished revolution. (2023)

[7] Rovelli, C.: Relational quantum mechanics. International journal of theoretical physics **35**, 1637–1678 (1996)

[8] Laudisa, F., Rovelli, C.: Relational Quantum Mechanics. In: Zalta, E.N., Nodelman, U. (eds.) The Stanford Encyclopedia of Philosophy, Summer 2024 edn. Metaphysics Research Lab, Stanford University, Stanford (2024)

[9] Butterfield, J.: Emergence, reduction and supervenience: A varied landscape. Foundations of Physics **41**(6), 920–959 (2011) https://doi.org/10.1007/s10701-011-9549-0

[10] Fletcher, S.C.: Similarity structure and emergent properties. Philosophy of Science **87**(2), 281–301 (2020) https://doi.org/10.1086/707563

[11] Hartle, J.B., Hawking, S.W.: Wave function of the universe. Phys. Rev. D **28**, 2960–2975 (1983) https://doi.org/10.1103/PhysRevD.28.2960

[12] Rovelli, C.: Quantum mechanics without time: A model. Phys. Rev. D **42**, 2638–2646 (1990) https://doi.org/10.1103/PhysRevD.42.2638

[13] Licata, I., Chiatti, L.: Event-based quantum mechanics: A context for the emergence of classical information. Symmetry **11**(2) (2019) https://doi.org/10.3390/

sym11020181

[14] Oldofredi, A.: Unexpected quantum indeterminacy. European Journal for Philosophy of Science **14**(1), 1–30 (2024) https://doi.org/10.1007/s13194-024-00574-9

[15] Wilson, A.: Fundamentality and levels in everettian quantum mechanics. In: Allori, V. (ed.) Quantum Mechanics and Fundamentality: Naturalizing Quantum Theory Between Scientific Realism and Ontological Indeterminacy. Springer, Cham (2022)

[16] Torza, A.: Derivative metaphysical indeterminacy and quantum physics. In: Allori, V. (ed.) Quantum Mechanics and Fundamentality: Naturalizing Quantum Theory Between Scientific Realism and Ontological Indeterminacy, pp. 337–350. Springer, Cham (2022)

[17] Calosi, C., Wilson, J.: Quantum indeterminacy and the double-slit experiment. Philosophical Studies **178**(10), 3291–3317 (2021) https://doi.org/10.1007/s11098-021-01602-7

[18] Glick, D.: Quantum mechanics without indeterminacy. In: Allori, V. (ed.) Quantum Mechanics and Fundamentality: Naturalizing Quantum Theory Between Scientific Realism and Ontological Indeterminacy. Springer, Cham (2022)

[19] Giere, R.N.: Scientific Perspectivism. University of Chicago Press, Chicago (2006). https://doi.org/10.7208/9780226292144 . https://doi.org/10.7208/9780226292144

[20] Massimi, M.: Perspectival Realism. Oxford University Press, Oxford (2022)

[21] Fraassen, B.C.V.: Scientific Representation: Paradoxes of Perspective. Oxford University Press UK, Oxford, GB (2008)

[22] Wigner, E.P.: Remarks on the mind-body question. In: Philosophical Reflections and Syntheses, pp. 247–260. Springer, Berlin, Heidelberg (1995)

[23] Eingorn, M.V., Rusov, V.D.: Emergent quantum euler equation and Bose–Einstein condensates. Found. Phys. **44**(2), 183–191 (2014)

[24] Capozziello, S., Bianchi, S.D., Battista, E.: Avoiding singularities in Lorentzian-Euclidean black holes: the role of atemporality. accepted in Physical Review D on 24 April 2024 (2024)