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Time and the Quantum Measurement Problem

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Abstract: The quantum measurement problem resolves according to the twofold nature of time. Whereas the continuous evolution of the wave function reflects the fundamental nature of time as continuous presence, the collapse of the wave function indicates the subsidiary aspect of time as the projection of instantaneity from the ongoing present. Each instant irreversibly emerges from the reversible temporal continuum implicit in the smoothly propagating wave function. The basis of this emergence is periodic conflict between quantum systems, the definitive resolution of which requires the momentary reduction of each system from the potentially infinite dimensions of configuration space to the three dimensions of classical space at an instant.

Keywords: Wave function; projection postulate; instantiation; complementarity

1. Introduction

Not so long ago, writes Michael Albert [1], science sought a complete account of nature. Then quantum mechanics came along and imposed unprecedented restriction on what is knowable. Citing the impossibility of clearly delineating (1) observer from observed and (2) what is describable in classical terms from what is not, Niels Bohr banished the classical scientific ideal of unambiguous knowledge. Albert characterizes Bohr's claim as "weird, glib, scary, oppressive, intolerant," a "dark fog" that only in the last few decades has begun to lift.

Albert's reaction to Bohr reveals a misconception of quantum mechanics as merely a mathematical account of the evolution of a quantum system coupled with an interpretation of that account. Faced with a theory encapsulated in mathematics, our only concern is how we choose to swallow it.

The key element missing from this picture is experimentation and the link to reality. Bohr understood that experimentation not only generates a specific result but defines quantum mechanics as against classical mechanics. Quantum experiments are complicated by the quantum jump, the discontinuity between the prediction of the formalism and the actual outcome. Whereas in classical mechanics the observer measures what is already there, in quantum mechanics the act of measurement incorporates the measuring device into the wave function governing the system under investigation. As a result the measuring device and the measured system are melded into an irreducible *individual* impervious to further analysis [2]. What is measured is not simply a quantum system but the *measurement* of that system. The loss of a sharp divide between the subject and the object of investigation precludes any possibility of the classical ideal of objectivity.

Only by ignoring the indivisibility of subject and object inherent to all quantum experiments can we conclude that classical objectivity still applies. Albert implicitly embraces a view of science as pure thought, a dialectic of mathematics and interpretation with no mooring in the fundamental lesson of quantum measurement.

Bohr intended his principle of complementarity to provide a framework within which theorists could investigate quantum systems despite the absence of classical objectivity. The irony in the proliferation of alternative interpretations of quantum theory is that the solution to the measurement problem - the riddle at the heart of quantum mechanics - follows precisely from the complementarity of time.

2. Complementarity

Quantum mechanics took incipient form with Planck's discovery that the oscillations of charged particles, contra classical assumption, are restricted to frequencies corresponding to multiples of a fundamental constant. Planck's constant is the minimal amount of action allowed by nature. Any measurable action must either correspond to that constant or comprise a multiple of it. From this unexpected and purely contingent fact, Bohr concluded that electrons orbit their atomic nuclei at specific " quantized" frequencies and not continuously across frequencies. Though Bohr in this way accounted for atomic stability, his "quantum of action" posed a serious problem for physics as traditionally practiced [2].

To identify the properties of a physical system and predict its behavior, classical physics utilizes the Hamiltonian, a function of two parameters from which the future state of the isolated system can be determined. One parameter keeps track of the system's space-time coordinates while the other applies the conservation of energy and momentum to attain accurate prediction. The conjugate parameters of position-momentum and time-energy, well known in quantum theory, apply also to classical mechanics. Even in the classical framework, determining position precludes determining momentum, and arriving at the precise time of an event precludes determining its energy. These values cannot be obtained simultaneously but require successive measurements. This is not a problem for classical physics, however, because the time of the second measurement can be " rewound" via calculation to the time of the first measurement as if they had been simultaneous [2].

The quantum of action destroys all that. Because a measurement of a microphysical system involves a discontinuous jump in whatever property of the system is under investigation, we cannot simply rewind the second measurement to match the first in time. If we discover the system's position at a given instant, its momentum and energy are lost and with them the causal description upon which to base a prediction. Likewise, if we have the exact values of momentum and energy, we cannot determine the system's space-time coordinates and therefore, again, cannot make a reliable prediction.

According to Bohr, the space-time and causality descriptions - united in classical physics - are "complementary but exclusive" in quantum analysis [2]. We may still apply the space-time (position-instant) and causality (momentum-energy) modes of analysis but never both at once. Though position and instant are associated with "particle" while momentum and energy correspond to "wave," we can no longer assume these classical terms refer to an underlying reality. Until a measurement takes place, the quantum system is neither particle nor wave, though we may represent it by a *wave function*, a mathematical device that enables computation of likely values of properties should the system be measured. Rather than confirm the pre-existence of definite properties, the measurement triggers a jump from the true and unknowable state of the system to a "phenomenon" that comes across as either particle or wave depending on whether the measurement is intended to provide space-time coordination or an account of causality.

Suppose we measure a quantum system for position. The result is a particle with a specific location. Then we measure the same system for momentum, yielding a wave that causally connects one instant to the next. The problem is that "particle" and "wave" are mutually exclusive. The system cannot be both. We must accept that these classical concepts can be used only to describe the results of our interactions with the system, not the system in itself.

Bohr's principle of the complementarity of opposites allows scientific investigation to proceed despite the absence of a simple one-to-one correspondence between concepts and reality [2]. The point is not to explain the world as it truly is but simply to find a workable framework for continued research. Bohr evaded not only the status of the underlying quantum reality but the question of how a classical world of the senses somehow emerges from the innately mysterious domain of the wave function.

As the solution of the Schrödinger equation for a given set of boundary conditions, the wave function determines the values of all variable properties of a quantum system. Rather than a single value for a given property, however, the wave function describes the evolution of a set of *potential* values in superposition. To get from the world of wave mechanics (or, equivalently, Heisenberg's matrix mechanics) to the classical world of the senses requires "collapse" of the wave function, that is, the reduction of a superposition of potential values of a given property to a single value.

As Albert points out [3], if the Schrödinger equation is applied to measurements, the superposition of values characterizing the quantum system should also characterize the measuring device, which would then display a superposition of all possible outcomes of a given measurement instead of one *actual* outcome. This is known as the measurement problem.

Bohr got around the measurement problem simply by assuming a classical level of existence in the form of a measuring device. Rather than try to derive a classical world from the wave function, he *postulated* a classical world and explained how to use classical concepts to interpret the results of quantum measurements. For Bohr the measurement problem had no more meaning than the status of Schrödinger's cat. As we can plainly see, the superposition of potential properties in no way characterizes the classical world, whether an indicator on a measuring device pointing every direction at once or a cat both dead and alive.

Yet quantum mechanics, not the classical predecessor, is the fundamental description of nature. Only because of the smallness of the quantum of action is the world of the senses seemingly devoid of the organizing presence signified by the wave function. What justification, beyond merely utilitarian, allows Bohr to brush aside the measurement problem? The answer lies in the nature of time.

3. Instantiation and Translation

To tell us something about the world, a physical theory must accord with experimentation, the results of which must be experienced. Since experience is temporal, the result of an experiment must be available at a moment in time.

"Measurement" in quantum theory is a stand-in for "event." The meaning of the experiment is that something *happens*. In other words, a definite event takes place at a definite instant. We can justifiably assume the reality of measurement and a measuring device - and by extension a classical world - because the succession of events we call "time" is real. The question of quantum measurement is not so much a problem in itself as an opportunity to resolve the problem of time.

So long as a quantum system is isolated, its wave function propagates without interruption and therefore expresses time as continuous presence. The emergent aspect of time as a fleeting instant is revealed in wave function collapse upon environmental interaction, including the specialized form of interaction known as measurement. Macroscopic objects like cats and measuring devices repeatedly undergo wave function collapse presumably on the basis of the mutual interaction of their components. In effect, the large-scale system repeatedly "measures" itself innumerable times per second, derailing it in each instance from continuous time to discontinuous time. Whereas continuous time, as an ongoing or "rolling" present, need not entail a specific and definite value of a variable property, within the confines of a distinct instant each property by necessity takes a single value. The classical world is built upon the extremely rapid succession of *instantiations* of fundamental time. Excluding exotic states such as Bose-Einstein condensate, only at the microphysical level can the pace of succession relax. At the ideal limit of the perfectly isolated quantum system, instantiation is withheld indefinitely and the wave function evolves without interruption.

Implicit in the Schrödinger equation is the primary nature of time as ongoing and reversible presence. By contrast, the projection postulate of Dirac and von Neumann follows from the secondary nature of time as the successive projection of instantaneity from the underlying ceaseless present. According to the projection or "collapse" postulate, measurement is the key factor that distinguishes the domain of the wave function from the classical world. The problem with this view, according to Albert [3], is that measurement resists precise definition. The problem disappears, however, with the recognition that "measurement" in quantum theory is merely a placeholder for the instantaneous event, which is not only precisely definable but constitutes the application of precision to time. The relation of instant to ongoing presence is the same as that of figure to ground.

From the Born rule we learn that deriving the probable values of a given quantum property in the event of its measurement requires squaring the amplitude of the wave function of the quantum system. Already implicit in the Born rule, instantaneity is made explicit with the projection postulate. The lightning-like projection from a cloud of superposed values to a single definite value not only takes place at a precise instant but *defines* the instant. The precision of the instant eliminates the problem of where to place the "Heisenberg cut" between wave mechanics and the classical world. Nature does the job for us by placing the cut at each successive instantiation of a single potential value of a quantum property to the exclusion of competing values also encoded in the wave function.

Complementarity emerged from Bohr's observation that the space-time coordination of a quantum system and the causal description on the basis of the conservation of energy and momentum cannot be established *at the same time*. This is, of course, exactly as we would expect if time is ongoing presence repeatedly projected as instantaneity. Since time cannot come across as both continuous and discontinuous at once, measurements intended to bring out the position of a particle at an instant cannot be expected to reveal momentum or energy, given that these properties are continuous over space-time. This is why light, when measured for position, resolves as a particle at an instant despite the fact that measuring its energy resolves it as a wave. A particle is an expression of the wave function at a *particular* moment. A wave, on the other hand, expresses the wave function over a succession of moments, causally binding them in accord with the conservation laws. Whereas a particle *instantiates* a wave function, a classical wave *translates* the continuity of the wave function into the domain of space-time. Each instantiation follows directly from wave mechanics and therefore stands apart from both previous and subsequent instantiations. *Over* time as opposed to *in* time, the classical wave - and the field that mediates its transmission - threads together otherwise causally unconnected instantiations.

Translation follows by necessity from a rapid succession of instantiations in the context of the continuous present underlying the wave function. Whereas a particle with definite properties instantiates from the wave function, translation faithfully preserves wave continuity from one domain to the other. This is why measurements of energy and momentum require noninvasive interaction. So, for instance, instead of causing the electron to collide with another object, simply allowing it to glide through a crystal "spreads out" its wave function, yielding a definite wavelength from which to compute momentum [4]. By contrast, invasive interaction yields only a particle at an instant. What we call measurements of position or time are simply human-designed variants of the invasive interactions going on at all times in all matter-rich regions of the universe.

Neither vibration (energy) nor wavelength (momentum) can be measured in the confines of a single instant. On the other hand, a particle cannot have a definite position except at a definite time. Yet causality requires both aspects of time, not only unique instants that distinguish cause from effect but the underlying continuity that causally binds the second instant to the first.

The duality of time grounds Bohr's claim that classical concepts like particle and wave cannot describe the ongoing reality of the quantum system but instead must be used in alternation to describe the results of measurements. To get beyond Bohr - that is, to explain the reality of quantum systems - we must treat the wave function as a real object. Yet the wave function exists in configuration space, the dimensions of which correspond to the number of particles in a given system. Since the wave function computes the possible positions of each particle of a system in three-dimensional space, the total number of dimensions in configuration space is three times the number of particles in the system. For a system of 100 particles, the wave function inhabits a "space" of 300 dimensions. How can our three-dimensional world and its contents co-exist with a world of potentially infinite dimensions? The challenge, as Alyssa Ney points out, is to explain how there can be a world of macroscopic objects if the wave function is real [1].

Suppose a photon is hurtling toward the moon. As a macroscopic object, the moon is continually departing from a quantum state into a definite object on the basis of the interaction or mutual "measurement" of its constituent atoms. The isolated photon, by contrast, remains in its quantum state, a superposition of potential values of properties determined by its wave function. As it nears an atom on the surface of the moon, its wave function is thrown into conflict with that of the atom. Whereas the continued momentum of the photon is included in its wave function, the atom disagrees. The result of the conflict is the *momentary* collapse of configuration space into classical space.

Though not every interaction generates a particle at a space-time location, invasive interaction - such as the collision of atoms or their exchange of energy via photon - entails not only that the potential properties of each system come into conflict but specifically that the conflict cannot be decisively resolved without reduction of configuration space into classical space at an instant. The collapse of the wave function is simply nature's method of bookkeeping.

Wave function realism requires time realism. In the configuration space woven by wave computation, a quantum system is temporally continuous. When the possible states of different systems come into conflict, the collapse of configuration space into classical space indicates the decoupling of each system from continuous time as each system manifests definite values of properties in a definite if fleeting instant. Regardless of how many dimensions a system occupies in configuration space, upon instantaneous discontinuity the system collapses to precisely three. Only the irreversible event enables definitive resolution of clashing probabilities encoded in each wave function. Though the transition from wave mechanics to classical mechanics can be expressed in terms of space, the defining factor is time. Configuration space expresses the fundamental reality of time-presence while classical space expresses the emergent reality of time-passage.

In contrast to the emergence and passage of each distinct moment of classical time, continuous presence has neither past nor future and is therefore fully reversible. The time-reversibility of classical mechanics only approximates the true time-reversibility of wave mechanics. What seems past, given our classical bias, ought to remain present in the context of wave mechanics. This is indeed the case.

In the double slit experiment, a photon must negotiate a barrier with two slits before arriving at a photographic plate. Only when interacting with a detector at one of the slits is the photon revealed as a particle. In the absence of contact with a detector, light comes across as wave, not particle, and passes through both slits rather than only one. In this case we might say the wave is revealed by the wave interference pattern that appears on the photographic plate, but this is not exactly right since the interference pattern does not appear all at once but is built up one point at a time as each photon reaches the plate. Each moment of contact constitutes an interaction that yields a particle. Only over time do these points on the plate add up to a wave interference pattern and only because *no* contact previously occurred at the slits. Hence the past state of the photon remains present until interaction triggers instantiation.

This point is more dramatically illustrated by the delayed choice variant of the double slit experiment. In this case the choice of whether or not to detect a photon is delayed until after it has passed the slits [5]. Because the photon in its default state occupies continuous presence, it has no history distinct from its present. Thus its passage through the slits is still present when the decision is later made to detect which slit it went through. The photon can be retraced to its arrival at the slits because its entire path remains present. By contrast, once a mark appears on a screen, it cannot later be made to disappear. Only indefinite presence, as exemplified by the continuous wave function, is time-reversible. The precise instant generated via interaction, on the other hand, is both irreversible and fleeting.

The curious time of the wave function is further revealed in the case of nonlocal entanglement. As Schrödinger observed [1], entanglement reflects the history of interacting systems. By interacting, two photons become entangled such that if one of them is measured for the value of a property, the other will reveal a correlated value no matter how far apart the photons travel. According to the authors of a recent paper in *Physical Review Letters* [6], "the non-locality of quantum mechanics, as manifested by entanglement, does not apply only to particles with spatial separation, but also with temporal separation." Megidish and colleagues demonstrated this principle by "generating and fully characterizing an entangled pair of photons that never coexisted." They began by entangling a pair of photons, 1 and 2, and measuring the polarization of 1 *before* entangling another pair, photons 3 and 4, after which they entangled photon 2 with photon 3. When they measured photon 4, its polarization was correlated to the outcome of the measurement of photon 1.

This effect is best explained according to fundamental time as ongoing presence. Due to entanglement the measurement result of photon 1 remains present to photon 2. Once photon 2 is entangled with 3 - which is already entangled with 4 - the result of measuring photon 1 is still present when photon 4 is measured. At no point is the ongoing present derailed and "lost to history." Instead of supposing, according to the concept of retrocausality, that the current measurement of photon 4 retroactively influences the previous measurement of photon 1, we simply recognize that the presence of the wave state is ongoing.

4. The Copenhagen Misinterpretation

The ideas lumped together under the term "Copenhagen interpretation" go well beyond Bohr's pragmatic principles and include, crucially, von Neumann's attempt to resolve the measurement problem according to observation-induced collapse of the wave function. Whereas Bohr merely stated that our knowledge, as represented by the wave function, undergoes a jump at the moment of measurement, von Neumann proposed a metaphysical claim on the basis of the interaction of physical object and conscious subject.

In contrast to Bohr, who regarded the measuring device as a classical object, von Neumann treated the measuring device as a quantum mechanical object. Far from triggering the collapse of the wave function of the quantum system under investigation, the measuring device therefore becomes a second component, along with the quantum system, of a newly expanded wave function [7]. Collapsing the wave function of the combined system-device thus requires a third object, such as the eye of the observer. But this only entangles the eye with the combined system-device, necessitating a fourth object, perhaps the brain of the observer. Yet neural processing of the visual image can only entangle the brain with the combined system-device-eye. To break the chain of local entanglements, von Neumann posited an "abstract ego" of the observer that definitively collapses the wave function, thereby producing a single result of measurement in place of a superposition of results [8]. Because the Schrödinger equation implies that physical objects entangle upon interaction, a mental object is required to break the chain of entanglements. The classical world therefore depends on the interaction of psychic and physical elements.

Perhaps to avoid such a metaphysical commitment, Bohr never spoke of wave function collapse and never invoked the Copenhagen interpretation with respect to his beliefs [9]. Yet Bohr's epistemic approach, despite following from purely pragmatic considerations, paved the way to von Neumann's analysis and ultimately Wigner's claim of a causal role for consciousness in the emergence of definite values of physical properties, i.e., a classical world [7].

Henry Stapp [8] characterizes Heisenberg's matrix mechanics - forerunner to Schrödinger's wave mechanics - as a game of "20 questions." To conduct a quantum experiment is to pose a "yes or no" question to nature. "Before nature delivers any information about any system," writes Stapp, "a specific question must be posed." To claim that a tangible event occurs only when conscious beings intentionally probe nature is to imprison wave function collapse in subjectivity. Yet Heisenberg himself flatly stated that quantum theory "does not introduce the mind of the physicist as a part of the atomic event" and that mentality enters the picture only due to the necessity for classical concepts in the interpretation of experimental results [10]. If a purely physical interaction can generate a conflict necessitating a definitive outcome in classical space at an instant, then collapsing the wave function need not involve consciousness. We bypass von Neumann's Cartesian cul-de-sac simply by recognizing nature as its own interrogator.

Whereas von Neumann inflated Bohr's epistemic approach into a full blown dualistic metaphysics, applying Bohr's principle of complementarity to the nature of time yields an ontological interpretation without psycho-physical complication.

In summary, the quantum of action generates indivisible wholeness of quantum object and measuring device, thereby destroying classical objectivity and necessitating the complementary use of classical concepts in the interpretation of experimental results. For Bohr this is where the story ends. Restoring realism, however, in no way requires the introduction of consciousness as a *deus ex machina* or, worse still, the rejection of Bohr's analysis altogether in favor of an alternative formulation of quantum theory.

Instead we simply recognize wave mechanics and classical mechanics as artifacts of the complementarity of continuous (wave function) time and discontinuous (collapse) time.

5. Conclusion

At the core of Bohr's vision of quantum mechanics is the recognition that a classical world must be assumed from the outset. Without the reality of a sensorial world, human experience cannot provide a reliable guide in the acquisition of knowledge. Given its foundation in empirical investigation, science itself cannot exist without the assumption of classicality.

Yet classical mechanics only approximates the fundamental reality as described by quantum mechanics. Contrary to our intuitive sense of things, the leap from the world of the wave function to that of the senses requires the inconceivably rapid succession of instantiations of wave computation. This means that natural interactions, not just measurements, routinely generate wave collapse. "Nature herself," as Penrose says, "is continually enacting [wave function collapse] without any deliberate intentions on the part of an experimenter or any intervention by a conscious observer" [11]. Unless invasive interactions in general - and not just quantum measurements - yield a particle at a place and time, there are no building blocks upon which a classical world can stand.

The only counter to this argument is Everettian idealism, that is, the denial of an objective classical world and the adoption of an eternally branching universal wave function as the true reality concealed by sensorial experience. Whereas Everett's world is serenely mathematical, the actual world - the one built up from the rapid succession of instantiations of quantum systems - is a pandemonium of microphysical collisions and energy transfers. The dispute boils down to the purity of idealism versus the messiness of realism. Take your pick.

Unlike Bohr, Heisenberg attempted to get past the complementary application of classical concepts and uncover the quantum system in and of itself. To this end he proposed that potentiality is an objective property of nature and that the wave function quantifies Aristotle's notion of unformed matter as *potentia* [10]. If potentiality and "actual events" enjoy equal ontological status, the act of measurement merely transforms one objective state into another. As Kastner, Kauffman and Epperson point out, this approach explains several quantum phenomena which are anomalous from the perspective of classical physics [12]. However, the authors resolve one question at the expense of creating another: why should there be two fundamentally different objective states? The answer follows from the nature of time. On the one hand, definite values of variable properties require a succession of definite instants. On the other hand, without an indefinite temporal substrate - in the context of which are indefinite values of quantum properties - there could be no precise instants in the first place as there would be nothing from which to instantiate.

The Schrödinger equation fails to predict the collapse of the wave function upon interaction because its purview is limited to one aspect of time, the fundamental ongoing aspect, and leaves out the subsidiary transient aspect. Time is not only presence but passage, and a theory that leaves out the second part cannot account for the world of experience and experimentation. Though Alberto Cordero [13] attempts to provide the mathematical basis of a complete quantum theory by adding a nonlinear term to the Schrödinger equation that represents the departure from the smooth progression of the wave function, like the prior effort by Ghirardi, Rimini and Weber [14], Cordero's equation falls short due to the fact that departures from continuous linear time are purely contingent and therefore resist mathematical modeling. Indeed, the complete absence of mathematics - that is, of "timeless" equations - in Bohr's principle of complementarity may just be the basis of its enduring value.

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