Popper's Propensity Interpretation and Heisenberg's Potentia Interpretation — A comparative assessment

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1.0 INTRODUCTION

Every textbook on quantum mechanics emphasizes the difference between classical and quantum mechanical statistical description. Classically, probabilities add. For example, if P1 and P2 are the probabilities for two events E1 and E2—say the head or tail in a coin toss—the probability for *either* event to occur is

$$P\ (E1 \text{ or } E2) = P1 + P2 \qquad [1]$$

Quantum mechanically, there is a key difference. Consider the quantum mechanical equivalent of coin-tossing, namely letting an electron (or photon) "go through" a two-slit screen, with two detectors placed close to the screen on the other side. One and only one of the detectors will always fire. The top (bottom) detector firing would be the quantum mechanical equivalent of heads (tails). Quantum theory gives the probability for either of these localized detection events to occur as

$$P1 = a_1^2$$

$$P2 = a_2^2$$

where a_1 and a_2 are complex-valued coefficients, also called "probability amplitudes".

According to quantum theory, given the probabilities for individual events, the probability for *either one* of the two events to occur is *not* P1 + P2, but rather

$$\begin{aligned} P\ (E1 \text{ or } E2) &= (a_1 + a_2)^2 \\ &= (a_1)^2 + (a_2)^2 + a_1\, a_2^* + a_1^*\, a_2 \\ &= P1 + P2 + a_1\, a_2^* + a_1^*\, a_2 \end{aligned}$$

In other words, classically, probabilities add; quantum mechanically, the probability *amplitudes* add, leading to the presence of the extra product terms in the quantum case. What this means is that in quantum theory, even though always only one of the various outcomes is obtained in any given observation, some aspect of the *non*-occurring events, represented by the corresponding complex-valued quantum amplitudes, plays a role in determining the overall probabilities. Indeed, the observed quantum interference effects are correctly captured by the quantum statistical description only because of the presence of these product terms. Therefore, in a realistic construal of quantum theory, if we treat the superposed Ψ function as representing the real state of an individual quantum system, these quantum amplitudes need to be given an ontological status.

Thus, an important part of understanding the physical reality described by quantum theory involves understanding the physical situation represented by these complex-valued quantum amplitudes when treated as being real. Consider the standard two-slit experiment, with two detectors placed close to the two slits. Because only *one* of the detectors *always* fires, it is routinely taken that a photon (or electron), when detected, is always present at one of the two possible localized regions in the usual classical, absolute sense. The observed electron or photon is furthermore taken to be in the corresponding eigenstate at the point of detection.

How about when it passes through the two-slit screen, prior to detection? If it is a localized entity, then it must go through one or the other slit, it would seem. But the observed quantum statistics governing the behavior of an ensemble of such localized entities (usually called the interference effect) can be predicted correctly only if we use the superposed state, which features product terms involving the quantum amplitudes. It is in this sense that the quantum amplitudes indicate the objective presence of the undetected photon at both slits, simultaneously. Since only one detector always fires, we must conclude that this presence at both slits indicated by the quantum amplitudes *cannot be in the usual, classical sense*. The unobserved quantum entity is present at both slits in a non-classical sense, and causes a classical detection event at only *one* of the slits.

The problem quantum theory poses to causality at the level of single events can now be seen. In the most general case, what is considered the state of the system (superposition) cannot be linked to the observations; and the state at which the system is at the point of observation (eigenstate) could not have caused the observation, since it does not belong to the system *prior* to the observation. The mainline approach assumes that the state of superposition changes into an eigenstate at the point of measurement. The problem of accounting for this change is called the 'measurement problem'.

2.0 HEISENBERG'S POTENTIA INTERPRETATION

Heisenberg in his later years proposed an answer to the measurement problem that has become more or less the standard way of talking about quantum reality. He introduced the language of *potentia*, following Aristotle, to describe the nature of the objective reality represented by the superposed state. Since the quantum amplitudes squared give the probabilities for the photon to go through either slit, and since probabilities are measures of possibilities of outcomes, we can say that the quantum amplitudes in some sense represent the objective reality of the very possibilities of the electron or photon being at either slit. The possibility for being present at a location is of course different from being actually present at that location. The former is potential, the latter is actual. Thus, the electron or photon in the state of superposition can be said to be potentially present at both slits when not observed, and actually present (i.e. in an eigenstate) at only one of the slits when observed.

The idea of possibilities *qua* possibilities constituting the state of physical reality raises several difficulties. First, if quantum reality is the nature of the possible, the fact that we see the observable world as the world of factuality would only be a fact of *our* knowledge. In this case, the predictions of quantum theory would have to pertain not to what is happening out in the world, but to our knowledge of what is happening out there. Heisenberg took this view:

> The conception of the objective reality of the elementary particles has thus evaporated in a curious way, not into the fog of some new, obscure, or not yet understood reality concept, but into the transparent clarity of a mathematics that represents no longer the behavior of the elementary particles [themselves] *but rather our knowledge of this behavior*. [1958a, p. 100, italics mine]

Note the date of this writing. It is as late as 1958. Heisenberg concluded that quantum theory requires the use of two different languages, involving the vocabulary of possibilities and the vocabulary of actualities, as we shift our conceptual gaze from the world of atomic objects, as captured by the theory and to our knowledge as given by the observations.

> Quite generally there is no way of describing what happens between two consecutive observations. It is of course tempting to say that the electron must have been somewhere between the two observations and that therefore the electron must have described some kind of path or orbit even if it may be impossible to know which path. This would be a reasonable argument in classical physics. But in quantum theory it would be a misuse of language which cannot be justified. [Heisenberg, 1958b, p. 48]

In two observations involving two successive position measurements, we can only say that we gained knowledge of the electron in two different observations that corresponded with two of its possibilities. If these are two position measurements, so be it. But we cannot combine two such observations of the positions, and speak of the electron as moving from one position to another, either in a continuous trajectory, or by way of a ‘quantum jump’. This is because the observations represent *our knowledge* of the positions of the electron, not the positions of the electrons in and of themselves. Once we deal with our knowledge, discrete shifts are the order of the day.

> When old adage `Natura non facit saltus' is used as a basis of a criticism of quantum theory, we can reply that certainly our knowledge can change suddenly, and that this fact justifies the use of the term `quantum jump'. [Heisenberg, 1958b]

Heisenberg himself left “it open for the moment whether it [the language of possibilities] is a statement about the way in which we should talk about atomic events or a statement about the events themselves, i.e. whether it refers to epistemology or to ontology.” [1958a, p. 48] Nevertheless, by introducing a complete disjunction between nature as it is (a realm of possibilities), and nature as observed by is (the world of actualities), Heisenberg paved the way for the modern, so-called “standard interpretation” in which the change from one to the other is taken to be a change in the ontology itself, the wave function "collapsing" at the point of measurement. As noted earlier, this has, in turn, introduced the famed measurement problem, accounting for the physical basis for the occurrence of this collapse.

The famous EPR argument pointed out that if indeed a collapse physically occurs, it must involve a non-local (i. e. superluminal) process that is quite different from the local interaction of the observed system with the experimental arrangement. In so far as the Schrödinger equation itself does not predict this collapse, the non-local mechanism, deemed necessary in order to ontologically complete quantum mechanics, leaves quantum mechanics incomplete. The explanation for the mechanism of the non-local collapse would have to come from outside of quantum mechanics, either through ad-hoc assumptions added to quantum theory, or from another theory in physics.

A second problem with Heisenberg's potentia *qua* potentia approach is that his idea of quantum reality as being the very nature of possibilities, without any further layer underlying the actual state of affairs, is not easily understood in terms of our everyday intuitions. After all, in everyday thinking, our discourse about possibilities supervenes on the idea of the existence of an underlying realm of actualities. The very talk about possibilities and hence probabilities, classically speaking, is meaningful only if there is an underlying world of definite situations. Schrödinger expressed this objection quite clearly:

> Probability surely has as its substance a statement as to whether something *is* or *is not* the case—an uncertain statement, to be sure. But nevertheless it has meaning only if one is indeed convinced that the something in question definitely either is or is not the case. A probabilistic assertion presupposes the full reality of its subject. But the quantum mechanics people sometimes act as if probabilistic statements were to be applied *just* to events whose reality is vague. The conception of a world that really exists is based on there being a far-reaching common experience on many individuals, in fact all individuals who come into the same or a similar situation with respect to the object concerned.
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> [Letter from Schrödinger to Einstein, 18 November 1950, in Prizibam (1967); emphasis in the original]

Can the notion of probability be made meaningful when we speak of single events by associating a *definite* situation underlying the notion of potentia? Popper devised his "propensities" interpretation explicitly to respond affirmatively to this question. While the idea of "propensities" is quite similar to Heisenberg's potentia qua potentia, Popper showed how we can think of "propensities" to supervene on an underlying world of objects. However, it will be argued here that Popper's notion of propensities ends up being a metaphysical concept for being too classical.

3.0 POPPER'S PROPENSITY INTERPRETATION

Popper gives the example of the pin ball machine to explain his idea of "propensities." When we release a ball in the machine, the ball will take one trajectory depending on which way all the relevant forces vectorially add. But we cannot determine this in real practice, so we can talk of probabilities for the ball to go this way or that way depending on what we do. Now, Popper says, suppose *after* a player releases the ball, we place a wedge or block in the machine. He says that now the probabilities for the ball's behavior will change. Classically, what is the difference between the two situations? Just one new block has been added to the machine configuration. Yet this changes the probabilities for the observable behavior of the pin ball. He says that we can understand this without any expensive deviation from our usual notion of the deterministic world, by introducing the notion of propensities.

> "The situation [of the two slits] is similar to the one in a well-known game of change (pin board, or bagatelle table): little balls roll down a board hitting pins and moving on either to the right or to the left at each pin. If one ball rolls down, there will be many pins which it never touches. They do not influence the ball. But they influence the propensities inherent in the experimental arrangement: the propensities would change if these pins were shifted or removed. And upon frequent repetition of the experiment, the statistical results would change with the changed propensities.
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> . . . [W]e take any other arrangement which might enable us to find out through which of the two slits the particle passes . . . . Any such arrangement will change the experiment; and calculating the experiment will show us that the change does away with the fringes. . . . We interpret this to mean that the propensities—which depend on the arrangement—have changed. We do not even need to ask whether the change is due to an interference with the electron (as in the case of the light beam guarding the slits) or only interfering with the possibilities, that is, the propensities themselves (as in the case of shutting one slit): all we need to know for all these cases is that the wave equation which allows us to determine the propensities entails the Heisenberg scatter relations and that these limit the possible predictions." (Popper, 1982)

Propensity means simply that, while objects have the propensity to cause events, it may not always be possible to trace the causality in any given interaction. Nevertheless, events do happen. Probabilistic descriptions, by their very nature, miss underlying causality, and hence individual predictions, but propensities enable us to understand how the objects interact differently under physically different conditions to cause the individual events.

Popper's idea of propensities is somewhat similar to the idea of "dispositions" which is used to understand secondary properties, such as color, which are at the level of our perception and hence constitute our subjective knowledge about the object. Quantum mechanical properties have been likened by Priest (1989) to secondary properties, because they can be predicated to quantum systems only in the context of what is actually in the laboratory. Thus, similar to dispositions of objects to produce secondary properties, we can think of propensities of objects to underlie the probabilities governing observable outcomes. Just as by changing the surface properties of an object we can change its disposition to reflect certain frequencies of light (and hence it's perceived color), the propensities change when we change the macroscopic object configurations. The photon or the electron becomes the "pin ball" and the changes in the experimental arrangement we make correspond to introducing or eliminating some wedges from the path of the pinball. The underlying propensities characterizing the new objective situation in turn change the probabilities of outcomes that *we* will observe. There is no need to think of the electrons or photons as disobeying causality, in order to understand statistical quantum theory.

Thus far, Popper's propensities have the same objective significance as Heisenberg's potentia. However, unlike Heisenberg who had to contend with a *change* from potentia to actualities at the point of an observation, Popper sees only the change in probabilities as having empirical basis. Physics concerns itself only with what we can observe. We can only change the configurations of macroscopic objects, as in deciding to close or open both slits, or in choosing to place the photographic plate near to or far from the two-slit screen. These different experimental choices correspondingly lead to different probabilities for observable outcomes. The notion of propensities helps us to understand how probabilities concerning outcomes that we observe can objectively change when we simply make changes in the macroscopic configurations with which the quantum pinball interacts, without the need for propensities themselves being the base ontology. Thus, there is no sudden change from potential to actual. There are only changes in experimental setups and corresponding outcomes.

By avoiding the notion that propensities constitute the ground of reality by themselves, and by introducing it only as a buffer concept to understand how the probabilities concerning the interaction of underlying objects can change, Popper avoids any causal role for measurement, and thus the need for a collapse postulate.

At the same time, he can claim to recover a quantum ontology that need not in any way necessitate the abandonment of causality. Electrons or photons are real particles, and the uncertainty relations are nothing but scatter relations concerning the observable behavior of an ensemble of such particles. Quantum theory, evidently, does not describe the motions of particles themselves.

By reducing the amount of work propensities have to do, Popper certainly improves upon Heisenberg's direct interpretation of possibilities qua possibilities as constituting the quantum ontology. However, by limiting the empirical consequences of quantum theory to only the observable probabilistic statements concerning detector statistics, Popper falls short of explaining how exactly quantum theory has managed to capture the notion of propensities. As Hitchcock notes, "calling this property a 'propensity' of a certain strength does little to indicate just what this property is" (quoted in Hajek 2003).Specifically, how does the Schrödinger equation capture the evolution of probabilities for outcomes of interactions between the quantum entity and macroscopic experimental arrangements in which the latter are freely chosen by the experimenters? In the absence of such an explanation –Popper doesn't provide one—propensities remain a metaphysical concept. As Hajek (*ibid*) comments:

> "It is *prima facie* unclear whether single-case propensity theories obey the probability calculus or not. To be sure, one can *stipulate* that they do so, perhaps using that stipulation as part of the implicit definition of propensities. Still, it remains to be shown that there really are such things -- stipulating what a witch is does not suffice to show that witches exist. Indeed, to claim, as Popper does, that an experimental arrangement has a tendency to produce a given limiting relative frequency of a particular outcome, presupposes a kind of stability or uniformity in the workings of that arrangement (for the limit would not exist in a suitably *unstable* arrangement). But this is the sort of 'uniformity of nature' presupposition that Hume argued could not be known either *a priori*, or empirically."

I believe Popper's approach is too classical. The propensities are dispositions of objects to cause events and they are no different in the world described by classical physics than in quantum theory. For Popper, what is different between classical and quantum mechanical description does not consist in the nature of the description of the world itself, but merely in the shift from appealing to propensities instead of underlying causes or deterministic laws for explanation. In this sense, Popper is too classical. A realist interpretation of quantum theory must provide an ontology that is different from classical theories, since it is the failure of classical theories that necessitated the introduction of the quantum postulate in the first place.

In order to get at the nature of non-classical reality described by quantum amplitudes, perhaps we have to introduce some correspondingly non-classical notions about the observed world. In the reminder of this paper, I shall make one suggestion. Both Heisenberg and Popper each bring an important idea to the project of understanding the physical meaning of quantum probability amplitudes in progression. Heisenberg proposed that understanding quantum reality requires shifting from the language of actualities to the language of possibilities. Popper showed that in considering the realm of possibilities, we need not altogether abandon the idea of an underlying world of objects and causality thereof, even if such objects are classical. Perhaps, though, the basic idea of potentia/propensities can be tied to a more non-classical conception of the quantum object.

In this regard, we will do well to note that both Heisenberg and Popper are responding to the question of how the occurrence of specific individual events can be reconciled with quantum mechanical probabilistic descriptions. In the next two sections I point out that quantum theory justifies separating the physical meaning of quantum amplitudes (which are related to the state underlying and causing the individual observation events) from the probabilities (which concern an ensemble of observation events). I show that in pre-quantum physics, we use the term "probability" to refer to both observable events and underlying ontological states. I trace the reasons why this is possible in classical statistical description, and show how these reasons fail in quantum theory. Thus, I propose that in quantum theory we must reserve the words statistics or probability for only the occurrence of observable events, and altogether renounce the notion of probabilities when talking about quantum ontological states.

This argument suggests the idea that in order to physically visualize the object represented by quantum amplitudes and hence quantum superposition, we would have to go outside the scope of the current statistical interpretation. In the concluding section, I discuss how some other features of the quantum formalism too lend support to this approach.

4.0 CLASSICAL PROBABILITIES

Classical probabilistic descriptions do not imply that nature itself is acausal. Rather, classical probabilities are compatible with the assumption that nature itself is causal and deterministic. Let us consider, for example, the case of classical coin tossing. By tossing a coin a large number of times, we can empirically compute the relative frequency of occurrence of the two possible toss results, i.e. Tails (T) or Heads (H).

Let us say in one trial, we get the result sequence H T T H H H T T H T T T.

We can think of the occurrence of a *corresponding* sequence of states in nature that causes these events. Let us call these 'heads-producing' and 'tails-producing' states, S_T and S_H respectively.

In classical statistics, if an H or T result has occurred in the laboratory, one *assumes* that the corresponding S_T OR S_H state has occurred in nature and caused the observed result in each individual case. The sequence in which the S_T and S_H states occur and the sequence of toss results are assumed to bear a 1-1 correspondence.

Under this assumption, classical probabilistic description and causality in nature become compatible. Each distinct observational event is caused by an underlying, correspondingly *unique* state in nature. Only because we are unable to specify in practice the state occurring in nature at the point of an actual toss (which would be a function of any number of physical parameters including the angle at which the coin is perched on the fingers, the force with which we click it, the force of the wind at the instant of tossing, the gravitational pull of all other bodies on the coin and so on ad infinitum), we are obliged to resort to a probability description. We take a survey of relevant, different, distinct outcomes possible (say, N) and simply compute the probability for any of the individual events to occur is 1/N. This computation contains two premises: (i) only *one* of these N-possible outcomes will occur in any single observation, and (ii) nature does not in any way prefer one outcome over the other, *ceteris paribus*.

This is the usual frequency interpretation of classical probability. Note the distinction I have made between observation events and ontological states. In standard literature this distinction is not often made, since the assumption of causality allows the term "probability" to refer inter-changeably to either the toss results (H or T) to the *observation event* (S_T OR S_H).

5.0 QUANTUM PROBABILITIES

In quantum statistical description, however, the idea that different states underlie different possible distinct observational outcomes is simply not true. Consider the equivalent of the simple coin tossing in quantum theory, namely the standard two-slit experiment in which a beam of identically prepared electrons(or photons approaches a two-slit screen, one by one. Born's rule assigns equal probability for each electron to be detected at the top or bottom slit. Yet, a *single* superposed state will underlie both of these two distinct outcomes.

Earlier we have called for a distinction between empirical probabilities concerning observable events and ontological probabilities concerning underlying physical states. We have seen that classically, a theory that states probabilities of possible outcomes can also be treated as a theory that gives the probabilities of corresponding underlying physical states, due to the fact that we can assume a one-to-one correspondence between distinct possible outcomes and corresponding distinct, underlying physical states.

But, fact that in quantum theory the same physical state (i.e. the superposed state) underlies all different possible outcomes means we cannot maintain this facile parity between empirically probabilities and ontological probabilities.

In other words, our foregoing discussion suggests the conclusion that quantum theory is empirically a probability theory, but ontologically not a probability theory. It follows then that the predictions of current *statistical* quantum theory cannot be causally explained using the superposed state, and vice versa: the ontological superposed state must be causally related to events other than predicted via Born's rule.

This conclusion is corroborated by another feature of the quantum formalism.

A superposed state Ψ, expressed as a superposition of possible eigenstates, say, $\sum_{i=1}^{N} \alpha_i \psi_i$ *always* satisfies the condition, $\Psi = \sum_{i=1}^{N} \alpha_i^2 = 1$.

Since the coefficients α_i^2 add up to unity, Born interpreted the coefficients as the probabilities for the various eigenstates to appear in observation outcomes. Under this interpretation, all possible observations are related to eigenstates, and the probabilities for these observations add up to unity. It follows that there is no room within the statistical interpretation for an observation corresponding to the superposed state itself to occur, corroborating our earlier conclusion: the predictions of current statistical quantum theory cannot be causally explained using the superposed state, and vice versa.

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We are now faced with a conundrum. On the one hand, the superposed state does yield the statistical predictions only because the quantum amplitudes corresponding to all possible events produce interference terms. This suggests that in a realistic interpretation of quantum theory, the superposed state and hence its constituent quantum amplitudes must be treated as objectively real. Both Heisenberg and Popper, we have seen, moved to precisely give a conception of the physical reality corresponding to the superposed state in terms of "potentia" and "propensities" respectively. Yet, the statistical interpretation is so designed, via Born's rule, as to preclude the possibility for relating the superposed state causally to the single events predicted by Born's rule. The conclusion follows that the notions of potentia or propensities, by themselves, are insufficient to give an ontological and thereby a causal interpretation of quantum theory, unless the individual observations themselves are conceived differently in a manner that they are relatable to the superposed state. In other words, the observations themselves may have to reconceived, in ordinary thinking, in a different manner, in order to link the superposed state causally to the individual events.

This is a radically new conclusion. Indeed, the majority of physicists universally regard quantum theory as providing a non-classical view of the microscopic world, but assume that at the level of observations, the classical worldview must prevail. In this, they follow Bohr, who explicitly asserted:

> "The task of science is both to extend the range of our experience and to reduce it to order, and this task presents various aspects, inseparably connected with each other. Only by experience itself do we come to recognize those laws which grant us a comprehensive view of the diversity of phenomena. As our knowledge becomes wider, we must always be prepared, therefore, to expect alterations in the points of view best suited for the ordering of our experience. In this connection we must remember, above all, that, as a matter of course, all new experience makes its appearance within the

> frame of our customary points of view and forms of perception." [Bohr, 1934, p.1]

In comparison, Einstein was willing to entertain the much more radical idea that the way we relate to observations and our corresponding idea about causality at the level of ordinary thinking itself may have to undergo radical revisions in order to get at the reality underlying quantum theory.

> "[W]hen we speak of one event being the *cause* of another, [o]ur concept here is confined to one happening within one time-section. It is dissected from the whole process. Our present rough way of applying the causal principle is quite superficial. We are like a child who judges a poem by rhyme and knows nothing of the rhythmic pattern. Or we are like a juvenile learner at the piano, just relating one note to that which immediately precedes or follows. To an extent this may be very well when one is dealing with very simple and primitive compositions; but it will not do for the interpretation of a Bach Fugue. Quantum physics has presented us with very complex processes and to meet them we must further enlarge and refine our concept of causality. [Einstein in Planck, 1931, p. 203-4]

Here, Einstein who is invariably portrayed as having remained too classical compared to Bohr, comes out to be much more radical. However, Einstein also held that the statistical interpretation is the only one possible of the present quantum theory. This led him to look for an alternative theory to bring home a causal explanation of the single events.

But if we admit the possibility that our observations have to be reconceived in ordinary thinking in a manner more suitable for quantum theory, it may be the case that there are *two* different ways of linking the superposed state, and its evolution as per the Schrödinger equation, to the two different ways of conceiving the observations in ordinary thinking (see Figure 1). In one, the superposed state, used as an instrument via Born's rule, may connect statistically to the observations interpreted in terms of the classically definite states of measuring devices. This will be a pragmatically successful theory without the possibility for interpreting the superposed state ontologically. In the other, the superposed state treated ontologically may be connectible individually to the same laboratory events re-interpreted in the quantum compatible manner— and hence causally. This might be another pragmatic use of the Schrödinger equation that is realistic. Perhaps these two are complementary. If so, the paradoxes that statistical quantum theory has currently generated at the ontological level may owe their existence to the fact that we are attempting to ontologically interpret the wave function within the statistical interpretation. The aim of the paper has been to raise doubts about the fundamental validity of this approach.

6.0 CONCLUSION

In the task of making clear the physical meaning of quantum probability amplitudes, Heisenberg made an early proposal that has become more or less the standard way of thinking about quantum reality. The quantum amplitudes represent the objective reality of *potentia*, i.e. the very possibilities of the electron or photon to be at either slit. In this paper, we pointed out at least two difficulties with this approach:

(i) The notion of potentia ('possibilities' qua possibilities) deprives quantum theory of the ontology of objects; yet, the very notion of the possibility for an electron to be at the top slit supervenes on the notion of there being an electron as an actual object.

(ii) Since what we observe are not possibilities for location but an actual location, we have been faced with the measurement problem, which is in principle not solvable within quantum theory.

We then compared Heisenberg's potentia interpretation with Popper's *propensity* interpretation. The two concepts are very similar, yet Popper shows how the idea of propensities can be reconciled with the existence of objects, in fact classical particles, within quantum theory. Popper's attempt is an improvement in the sense it avoids the two above-mentioned difficulties of Heisenberg's interpretation. Yet, it has its own difficulties: (i) it renders propensities an entirely metaphysical concept that works as an explanatory device, but falls short of providing us a realist interpretation of the quantum amplitudes; (ii) it is too classical.

We then offered an analysis of the notion of probability in quantum theory that differs essentially from the notion of probability in classical, pre-quantum physics. It has been pointed out that in quantum theory we cannot use the term "probability" to refer to both observable events and underlying ontological states, as one can do in pre-quantum physics. In particular, this is because one and the same superposed state can underlie more than one distinct outcome in the same experiment. Indeed, the current paradoxes that we face within quantum theory may owe their existence to the fact that we are attempting to ontologically interpret the wave function within the statistical interpretation. I concluded that perhaps we must search for an ontological and causal interpretation of the superposed psi function independent of the observations predicted by the current statistical interpretation.

In this context, Heisenberg's and Popper's approaches contain valuable insights. Heisenberg recognized that we have to shift from the language of the definite to the language of possible to really understand the ontology of quantum theory. Popper showed that such a shift need not necessarily undermine the ontology of objects so essential to physics; one that Einstein rightly demanded should be brought back at the quantum level. Elsewhere, I have explored a way to avoid the paradoxes of the statistical interpretation and move toward a causal interpretation of single events outside the scope of the statistical interpretation (Gomatam 1999, 2005). This ongoing effort can be seen as effectively integrating the insights of Popper and Heisenberg as well as going past them. For I strive for an object ontology for quantum theory, one that replaces the metaphysical idea of propensities with the notion of relational physical properties that change from being potential to actual at the point of an observation.

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