Consistent quantum theory as a realistic formulation
of quantum mechanics

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Abstract

The foundations of quantum mechanics have been plagued by controversy throughout the 85 year history of the field. It is argued that lack of clarity in the formulation of basic philosophical questions leads to unnecessary obscurity and controversy and an attempt is made to identify the main forks in the road that separate the most important interpretations of quantum theory. The consistent histories formulation, also known as “consistent quantum theory”, is described as one particular way (favored by the author) to answer the essential questions of interpretation. The theory is shown to be a realistic formulation of quantum mechanics, in contrast to the orthodox or Copenhagen formulation which will be referred to as an operationalist theory.
I. INTRODUCTION

A recent bibliography of the foundations of quantum mechanics, compiled in 2004, lists over 11,000 entries and the field shows no sign of dying down. This situation is unique, I would claim, in the history of modern physics, where a theory that is at the center of attention retains important controversial aspects for 85 years. It is legitimate to ask whether there is anything left to argue about or whether everything has been said, both correctly and incorrectly.

It is the view of the present author that much of the controversy arises from an incomplete or unclear formulation of basic philosophical assumptions. Once a set of assumptions has been accepted, detailed arguments and calculations, that in themselves are uncontroversial but complicated, can lead to surprising or controversial results. From this point of view it is usually the first page of any paper on the foundations of quantum mechanics that requires our scrutiny, since that is where the forks in the road take place, after which the rest is more or less conventional physics. The reason controversies do not normally last long in physics is that ordinarily there are no such early forks in the road: classical mechanics, thermodynamics, relativity, even textbook quantum mechanics in its calculational aspects, are accepted theories on whose basis physicists develop their experiments and theories. This is not the case for understanding the physical meaning of quantum mechanics, i.e. its relationship to reality, so experiments and theories that purport to answer questions of physical interpretation remain controversial.

The present paper makes one more attempt to understand the different philosophical forks in the road that arise in formulating and interpreting quantum mechanics and its relationship to the real world. Our aim is to clarify the important questions and the main answers that have been offered, rather than to present detailed arguments to justify those answers. One of the motivations for this effort is to present the author’s favorite interpretation, the consistent histories formulation, also known as consistent quantum theory (hereafter CQT) in this light and to argue that the theory charts a credible and convincing course through this thicket. It is also hoped that even those who are not totally convinced by that argument will nevertheless find the elementary analysis of the forks in the road instructive.
II. BASIC PHILOSOPHICAL ISSUES

A. Realism vs. Operationalism

The fundamental dichotomy in the different interpretations of quantum mechanics is between what one may call realist and operationalist formulations of the theory. A realist formulation represents quantum systems entirely in terms of properties or concepts intrinsic to these systems, i.e. in terms of what Bell has called the “beables” of the theory. An operationalist formulation, on the other hand, defines the theory in terms of macroscopic measurements and/or external observers. To be sure the terms “reality” and “realism” have a rich philosophical tradition with many subcategories and nuances which we shall strive to avoid. Here we are using the term as we would in referring to classical mechanics as a realist theory: we assume that there exists a “real world” out there, independent of anyone’s observations, and realist theories are defined to be representations of this world (not the actual world) with the property that they do not refer to observations or measurements as fundamental features. This definition implies no a priori assumption about the nature of this reality. In this class of theories measurements are merely one particular form of physical interaction, albeit an essential one for purposes of validating the theory. Operationalist theories take as fundamental those properties of quantum systems that can be measured or observed.

• The foremost example of an operationalist point of view is what we will call the “orthodox” or “textbook” version of quantum mechanics, also known as the “Copenhagen” interpretation, though there are differences of emphasis and viewpoint among the different versions. They can all, however, be characterized by the famous quote, attributed to Bohr: “No phenomenon is a phenomenon until it is an observed phenomenon.”

Let us briefly describe the main realist formulations of quantum mechanics:

• Hidden variable theories introduce unobserved (hidden) variables as beables to characterize a quantum system more fully than via the Schroedinger wavefunction. The best known example is the de Broglie-Bohm theory in which these variables are particle positions that are not observed in most experiments. The wavefunction itself guides the particles and it should also be considered a beable since it carries physical information, for example it describes the particle spin. In his first paper on the Bell inequalities, Bell showed that hidden
variables are always associated with nonlocality in quantum mechanics, not only in the de Broglie-Bohm theory but quite generally for any hidden variable theory whose predictions are consistent with quantum correlations.\\(^8\)

- The **many-worlds** interpretations, initiated by Everett, takes the wavefunction itself as the beable and states that in addition the the world we are aware of directly, there are many other similar (equally “real”) worlds which exist in parallel at the same space and time. Although this point of view removes randomness and action at a distance from the theory, its realism is so contrary to intuition and its language so obscure that many physicists remain unconvinced.

- The **consistent (or decoherent) histories** approach to be described in more detail below is also a realist formulation.

- Finally, we mention **physical collapse** theories, that differ from the previous approaches in that they posit stochastic corrections to the Schroedinger equation that produce an actual collapse of the wavefunction at a sufficiently macroscopic level of description, which guarantees the realization of a definite measurement outcome. In such theories it is again the wavefunction that is the beable.

The distinction between realist and operationalist formulations of quantum mechanics has been described succinctly by Leggett, who states that the only realist theory he can accept is a physical collapse theory that would violate standard quantum mechanics, and barring experimental evidence for such a violation he would reluctantly accept the orthodox operationalist point of view. Indeed, Leggett states that in his opinion all of the other realist formulations amount to little more than “verbal window dressing”.

The difficulties of a realist formulation of quantum mechanics were apparent to the founders of the theory and it is a response to these difficulties that prompted the orthodox formulation in the first place, in a significant departure from classical physics. Early attempts to nevertheless find a realist formulation, spurred by Einstein, Schroedinger and de Broglie, to cite only the most prominent advocates, were dealt a severe blow by the famous EPR and Bell papers which demonstrated that classical realism was incompatible with quantum mechanics, short of introducing nonlocal features as was done in the de Broglie/Bohm theory. This result could of course be interpreted as simply a vindication of the operationalist point of view, which is indeed how Bohm responded. Nevertheless, over the years the quest for a realist formulation has not abated and it is the source of the
ongoing controversy.

A physical motivation for such a quest is that the dichotomy between classical and quantum phenomena, upon which the orthodox theory rests, becomes more and more difficult to sustain as a fundamental feature of the theory as experiments increasingly probe the interface between microscopic and macroscopic phenomena. An operationalist point of view made sense in the nineteen twenties and thirties, when experimental methods were relatively crude, but the increasing sophistication of techniques for probing this vast interface, particularly in the study of quantum information, makes the Einsteinian quest for a realist formulation of quantum mechanics even more compelling than it was seventy five years ago. In recent years therefore, attention has focussed on the phenomenon of decoherence to investigate the interaction of microscopic and macroscopic degrees of freedom with a common environment. It is decoherence that is supposed to link the two realms and help resolve some of the controversies. It may even be said that a new orthodoxy has arisen, in which decoherence plays a central role, but it is invoked by proponents of both the realist and the operationalist points of view, so by itself decoherence does not settle the matter.

B. The role of probability

Is probability an intrinsic and fundamental property of physical systems? If so, probability of what? The question arises primarily for realist formulations since for operationalist theories one is clearly dealing with the probability of various measurement results. There remains, however, a distinction between statistical interpretations that ascribe probability solely to ensembles of measurement results, and formulations in which probability is intrinsic and attaches to individual systems. Among the various realist formulations, the de Broglie/Bohm theory has an ignorance interpretation in terms of the uncontrollable initial values of the particle positions, so it has a statistical interpretation relative to the hidden variables, but since the uncertainty is unavoidable it has an intrinsic interpretation with respect to a single electron, for example. In the many-worlds interpretations probability is a rather subtle matter which is treated differently by different proponents, but it does not play as fundamental a role as in other formulations. In physical collapse theories probability is introduced microscopically as a stochastic correction to the Schroedinger equation, so it plays a fundamental role. We shall describe the status of probability in CQT below.
C. What is the relationship between classical mechanics and quantum mechanics?

In the original formulation of quantum mechanics and according to the orthodox view, classical mechanics was assumed as a separate theory valid in the macroscopic domain of observations and it was necessary to recognize a “split” or “cut” between the classical (macroscopic) and quantum (microscopic) domains. As remarked above, in the “new orthodoxy” decoherence is supposed to govern the interface between the microscopic and the macroscopic, but there remains a lively controversy\(^6\) over the precise role played by decoherence in the relationship between the classical and quantum theories and in the relationship between the realist and operationalist points of view.

Realist formulations generally start with a quantum world at the fundamental level and then argue that classical mechanics *emerges* as the limiting theory in the macroscopic limit. In particular this limit is called upon to account for “our experience”, which is classical in nature.

D. What is the physical interpretation of the wavefunction? Does it collapse? Is there a “measurement problem”?

This set of questions is at the heart of the controversies over the proper interpretation of quantum mechanics. In the orthodox formulation the wavefunction of a microscopic system is a means to predict the results of macroscopic measurements via the well-known Born probability formula. It thus does not describe any intrinsic properties of the microscopic system which are forever out of reach. The wavefunction merely carries the *information* necessary to calculate the probabilities of measurement results and it is the latter that represent reality. This interpretation in terms of information seems to only make sense from an operationalist perspective, since otherwise one would ask “information about what?”\(^6\), a question that is easily answered in the operationalist theories. However, since the wavefunction evolves deterministically according to the Schroedinger equation, the question arises even from an operationalist perspective, as to how it *collapses* to yield specific measurement results. This question is known as the *measurement problem*. Decoherence describes the interaction among the microscopic system, its environment and the measurement apparatus, but while unanimity has not been reached on this question, many authors believe that deco-
herence does not fully resolve the measurement problem (also known as “the Schroedinger cat paradox”) and that an additional assumption is needed in order to account for the observed phenomena\textsuperscript{6}. The controversy over the effectiveness of decoherence in eliminating the measurement problem was highlighted by Bell’s\textsuperscript{11} discussion of the shift between “and” and “or”, and between probabilities and actualities in describing the decohered density matrix of a measured quantum system. A strict operationalist point of view should not attach any reality to this density matrix. Instead it treats the density matrix as the information necessary to answer the “real” question, “what will the reading on the measuring instrument be?”. As mentioned above, however, in the new orthodoxy the boundary between operationalism and realism becomes blurred\textsuperscript{6}. The different realist interpretations distinguish themselves by the way they respond to the question of collapse: they either deny that the wave function collapses at all (as most of them do), or explicitly insert a physical collapse mechanism into the fundamental theory. We shall return to wave function collapse in Subsec. III.E below.

III. CONSISTENT QUANTUM THEORY

We now wish to describe the histories formulation of quantum mechanics, in the form known as consistent quantum theory (CQT), as one particular way to chart a course through the roadmap of choices for answering the basic questions of interpretation. Our discussion will be primarily discursive, with a minimum of formalism. The interested reader is invited to consult References \textsuperscript{4} and \textsuperscript{5} for a more detailed exposition of the basic theory.

One of the motivations for the development of the histories formulation, pursued in particular by Gell-Mann and Hartle\textsuperscript{12}, was to continue the program of Everett to provide a quantum mechanical basis for cosmology, an area where observers and measurements are not naturally defined. Worthy as this goal is, it is rather more ambitious than the formulation of non-relativistic quantum mechanics for arbitrary closed systems, which is the focus of the present discussion. We shall not be concerned with the larger cosmological questions, but we note that some discussions and criticisms of the histories formulation (e.g. by Dowker and Kent\textsuperscript{13}) do not distinguish adequately between the two sets of goals.
A. General formulation

We consider an arbitrary closed quantum system and represent it by its “properties” referred to as “histories”, defined in terms of projectors onto subspaces of the system Hilbert space. Although the theory is fully time-reversal invariant, its predictive content is generally expressed as determining the probability or weight of any meaningful history, which involves properties of the system for \( t > t_0 \), given that the system starts out in a particular state (or has a particular property) at \( t = t_0 \). In order to clarify the above statements we shall consider a few simple examples, but it should already be clear that at this most basic level no reference is made to observers or measurements.

B. A single spin-\( \frac{1}{2} \) particle

As described earlier\(^4\), the significance of the theory can be illustrated by considering the simplest possible quantum system, a spin-\( \frac{1}{2} \) and its two-dimensional Hilbert space. A “property” is then defined as the projection operator

\[
[w^+] \equiv |w^+\rangle \langle w^+|,
\]

onto the eigenstate \(|w^+\rangle\) of the spin component \( S_w \) with eigenvalue \( +\frac{1}{2} \). If we choose the initial state of the system to be \(|z^+\rangle\), then the representation of this state in the basis \( \{|w^+\rangle, |w^-\rangle\} \)

\[
|z^+\rangle = c_{z,w}^+ |w^+\rangle + c_{z,w}^- |w^-\rangle,
\]

with \(|c_{z,w}^+|^2 + |c_{z,w}^-|^2 = 1\), leads, via the Born probability rule to the conditional probabilities

\[
\text{Prob}(w^+ | z^+) = |c_{z,w}^+|^2, \quad (3a)
\]

\[
\text{Prob}(w^- | z^+) = |c_{z,w}^-|^2, \quad (3b)
\]

where for the moment the symbol “\( \text{Prob} \)” is a formal weight associated with any property. If one now considers some other property \([v^+]\), then one has

\[
\text{Prob}(v^+ | z^+) = |c_{z,v}^+|^2, \quad (4a)
\]

\[
\text{Prob}(v^- | z^+) = |c_{z,v}^-|^2. \quad (4b)
\]
These definitions can be extended to sequences of properties at different times \( t_1, t_2, ..., t_n \), which we will refer to as “histories”, denoted \( C(\alpha) = [\alpha_1(t_1)] \times [\alpha_2(t_2)] \times ... \times [\alpha_n(t_n)] \).

Let us now ask under what circumstances we can interpret the symbol “Prob” as a classical (Boolean) probability. It is clear from the simple example of Eqs. (3) and (4) above, that such an interpretation can be applied either to the basis \( \{|w^+\rangle, |w^-\rangle\} \) or to the basis \( \{|v^+\rangle, |v^-\rangle\} \), but not to both at the same time, since there is in general no larger sample space \( \{|w^+\rangle, |w^-\rangle, |v^+\rangle, |v^-\rangle\} \) in which Eqs. (3) and (4) make sense simultaneously as probabilities if the vectors \( w \) and \( v \) are in different directions. We thus conclude that the the symbol “Prob” can only be interpreted as a physical probability with its usual classical (Boolean) meaning if it refers to a single orthonormal basis.

More generally, we associate each history \( C(\alpha^{(i)}) \) with a set of other histories \( \{C(\alpha^{(1)}), C(\alpha^{(2)}), ..., C(\alpha^{(N)})\} \), called a “family”. The weight \( \text{Prob}[C(\alpha^{(i)})] \) only has the classical meaning of a probability if the family to which history \( C(\alpha^{(i)}) \) belongs satisfies consistency conditions, which are generalizations of the conditions defining an orthonormal basis discussed above. Such a family will be referred to as a consistent framework or simply framework for short and the consistency conditions are summarized by saying that the framework represents an “exhaustive set of exclusive alternatives (ESEA)”. Only histories belonging to some consistent framework have physical meaning and for those histories the weight “Prob” can be interpreted as a classical probability. All quantum mechanical statements are relative to the particular framework to which a history belongs and different frameworks are in general incompatible, i.e. they may not be combined. This syntactical or logical rule, known as the single framework rule is fundamental to the consistent histories theory. Moreover, the existence of multiple incompatible frameworks is the distinctive property that characterizes quantum, as opposed to classical, systems. The incompatibility of frameworks and the single framework rule are the precise statement of Bohr’s concept of complementarity, which is here defined precisely, without explicit reference to measurements or observers.

Griffiths\(^{16}\) has summarized the theory by the phrase “Liberty, Equality, Incompatibility”, to emphasize the multiplicity of frameworks and the fact that there is in general no “preferred” or “correct” framework and thus no “framework selection problem”, contrary to what has been claimed\(^{13}\). Multiple incompatible frameworks are an intrinsic and distinctive feature of quantum systems. We shall, however, introduce the notion of physically relevant
histories and frameworks, namely those that have a possibility of being experimentally studied, since this restriction with respect to the formal definition of histories and frameworks is relevant for understanding the relationship of CQT to the orthodox formulation of quantum mechanics and to the classical limit.

C. A single spin-$\frac{1}{2}$ coupled to a Stern-Gerlach apparatus

In order to verify the predictions of the theory we shall couple the spin to a Stern-Gerlach apparatus which can point in any direction and can thus measure an arbitrary component of spin, for a system prepared in the $|z^+\rangle$ state at $t = t_0$. Once one has picked a particular direction $w$, say, it can be shown (see Sec.17.3 of Ref.5) that the predictions of Eq.(3) above, involving the values of the $w$-component of the spin at $t = t_1$, say, are confirmed by the pointer positions of the apparatus, assuming the measurement is carried out at $t = t_2$, with $t_0 < t_1 < t_2$. The physical interaction between the microscopic spin system and the macroscopic (classical) apparatus, as well as its environment, ensures the consistency of the two histories in the $w$-framework, in which the properties $[w^+]$ and $[w^-]$ become entangled with the measurement apparatus via the phenomenon of decoherence. The foregoing description reproduces the orthodox interpretation for a measured spin system.

From the point of view of CQT, however, it is reasonable to ask about the predictions in Eq.(4), involving the values of the $v$-framework properties $[v^+]$ and $[v^-]$ at $t = t_1$, which were just as “real” in the general formulation of the theory in Subsec. B above in which no measurement at $t = t_2$ was assumed. The answer is that due to the physical interaction occurring at $t_2$ among the measurement apparatus (which is set in the $w$-direction), the spin system and the environment, this $v$-framework is no longer consistent. In the language of Ref.12 we can say that in the coupled system the $v$ properties no longer “decohere”, so the apparatus has performed a type of “framework selection”, in agreement with the orthodox theory which makes no reference to multiple frameworks. If, however, one abandons the operationalist point of view implicit in the above discussion, for example by retaining the possibility of pointing the Stern-Gerlach magnet in any direction, then the more general (realist) point of view of CQT becomes valuable in avoiding paradoxes and in clarifying the essential features of quantum phenomena. One can summarize the above discussion by saying that the orthodox theory is recovered as a special case of CQT for the simple case of
observed quantum systems.

D. A simple macroscopic system

We now consider a system of atoms forming a macroscopic sphere which can oscillate about some equilibrium position and allow this sphere to interact with its environment. Starting from the microscopic (quantum) description in terms of interacting atoms, we can proceed to coarse-grain the original histories and as described by Gell-Mann and Hartle\textsuperscript{12} and by Omnès\textsuperscript{14} we end up with a \textit{quasiclassical framework}, in which the histories are essentially the classical orbits of the sphere in the phase space of collective coordinates appropriate to the semi-classical limit. Apart from small and controllable quantum noise the ensuing probabilities are consistent with classical determinism, applied to histories as opposed to wavefunctions. Here again, as emphasized by Gell-Mann and Hartle\textsuperscript{12} it is the physical phenomenon of \textit{decoherence} that ensures quasiclassical behavior on the scale of macroscopic phenomena. It is also due to decoherence that the other frameworks of the microscopic description have become \textit{physically irrelevant} when examined on the macroscopic scale because their histories correspond to no measurable properties. Here again we can summarize this discussion by the statement that in CQT classical mechanics \textit{emerges} from quantum mechanics in the macroscopic limit.

E. An arbitrary quantum system coupled to measurement instruments

In many situations the scenario for an arbitrary quantum system is analogous to the one for the single spin coupled to a Stern-Gerlach magnet, namely the apparatus picks out particular frameworks that reveal specific properties or histories of the microscopic system and renders the other frameworks either inconsistent (meaningless) or physically irrelevant by the effects of decoherence. As amply demonstrated in the book by Griffiths\textsuperscript{5}, on the other hand, in cases where there exist \textit{different options} for the measurement instruments, it is important to keep the possibility of choosing different frameworks open and to enforce the \textit{single framework rule} in the process, in order to avoid the well-known paradoxes.

As an example let us consider the problem of Schroedinger’s cat, since it has been designated by Leggett\textsuperscript{10} as exemplifying the quantum mechanical \textit{measurement problem} in its
starkest form. One way to highlight the issue is to note that even in the presence of decoherence the wavefunction of the coupled source + cat + environment system still contains a live cat term and a dead cat term, whereas common sense (macrorealism) says that it is either/or. The operationalist answer is that the wavefunction is only a formal means for calculating the relevant quantities, namely the probabilities of macroscopic outcomes, but any realist interpretation must deal with this question of “and vs. or”\textsuperscript{11}. It is interesting to note that although Bohr felt it necessary to respond to the EPR paper\textsuperscript{15} there does not seem to be a similar response to Schroedinger’s cat paper. One must assume that he saw no problem from his operationalist perspective.

From the point of view of CQT the answer is in some sense embarrassingly simple: the theory deals only with distinct alternatives ("or") in both the microscopic and the macroscopic domains. The beables in CQT are histories, not wavefunctions and these do not superpose or entangle: they are exclusive alternatives. Superpositions and entanglements are properties of wavefunctions, which are not “real". In CQT superpositions are handled by the existence of incompatible frameworks whose histories contain projectors onto the superposed states. For example, the $x$-framework in the simple case of Subsec. B above, consists of the $[x^+]$ and $[x^-]$ histories, and superpositions of $|x^+\rangle$ and $|x^-\rangle$, say, are not represented by any combination of $x$-framework histories, but rather by the $[z^+]$ and $[z^-]$ histories in the (incompatible) $z$-framework.

The cat paradox is thus resolved by saying that to the extent that there is no observable interference between the live and dead cats, there is no physically relevant framework in which such interference occurs with nonzero probability in any history. Only the so-called “cat framework”, with separate probabilities associated with live and dead cats, respectively, is relevant. Were there a possibility of observing such macroscopic (or quasimacroscopic) superpositions, then CQT would declare that the system is displaying true quantum behavior, since it has more than one physically relevant framework. The existence and observability of macroscopic quantum superpositions is an interesting physical question, but not one that should present a problem of principle for a well-formulated theory. It appears that the implication of Leggett\textsuperscript{10} that CQT is incapable of dealing with macroscopic quantum superpositions corresponds to a misunderstanding of the theory on his part.
F. How does one prepare the initial state?

It was stated in Subsec. A above that the statements of CQT are generally expressed in the form of determining the probability of a consistent history for a system whose initial condition at $t = t_0$ is specified and this specification can be either via a pure state $|\psi_0\rangle$ or via a mixed state with density matrix $\rho_0$. The question arises as to how one might in practice prepare such initial states with certainty. As far as the author knows there is no general answer to this question, but to the extent that the initial state can be thought of as the final state of some “physically relevant” history, then a way to obtain the state is to prepare the system so that this history is a possibility in some consistent framework. One then focuses on that particular outcome, rejecting all the other possible histories, and considers that outcome as the initial condition of a new history (see Chap. 18 of Ref.5 and Theorem 5 in Sec. 8.10 of Ref.14).

From a fundamental point of view this just displaces the problem to determining the initial state of the first history but in practice such manipulations, when properly carried out, can bring one closer to the desired state. It should be recognized quite generally that since the predictions of CQT are always conditioned on some assumed state (generally the initial state $|\psi_0\rangle$), these predictions will only be as reliable as is the assertion that this state has been correctly characterized. In this sense CQT is not fundamentally different from classical mechanics, where the predictions are also conditioned on knowledge of an initial (or final) state.

IV. SUMMARY OF CQT: QUESTIONS AND ANSWERS

We shall summarize the preceding discussion in the form of a list of questions and answers.

Q1: How is CQT defined?
A1: Consistent quantum theory (CQT) represents a closed quantum system by a set of properties at different times, called histories. These are defined by projectors on the system Hilbert space. To each history $C$ is associated a weight denoted $\text{Prob}(C)$, which is interpretable as a classical probability, provided the history $C$ belongs to a consistent family or framework. Such a framework is a set of histories that satisfy consistency conditions of
(i) completeness and (ii) orthogonality, which are generalizations of the conditions defining an orthonormal basis in terms of which any vector in Hilbert space can be expanded. All predictions of CQT can be phrased as determining the probability of a consistent history, i.e. the probability of a set of properties for \( t > 0 \), given that the system starts out in a particular state at time \( t = 0 \). The distinctive feature of a quantum system is the existence of a multiplicity of incompatible frameworks that are necessary for a complete description of the system. Quantum calculations and arguments are relative to the particular framework in which they are carried out and histories or arguments referring to different frameworks may not be combined in any meaningful quantum description. This is the single framework rule.

Q2: Is CQT a realist theory?
A2: The main thesis of the present paper is that CQT is a realist theory in the same sense as classical mechanics can be said to be realist, according to our definition. CQT represents a physical system in terms of properties and concepts intrinsic to that system, with no reference to external observers or measurements in the basic definitions.

Q3: How does CQT account for our experience?
A3: Since probability is an intrinsic feature of the theory, quantum mechanics cannot tell us “what happens”, but only what the odds are that this or that will happen. A fundamental premise of CQT is that only one history “occurs”, with \( \text{Prob}(C) \) determining the probability that the history \( C \) will in fact occur: the different histories in any consistent framework are defined to be exclusive alternatives. All of the mystery and “weirdness” of quantum phenomena is encapsulated by the inevitable presence of incompatible frameworks, i.e. of overlapping layers of reality that are the price that must be paid in this formulation to achieve a realist theory.

Q4: What is the relationship between CQT and the orthodox theory? What is the role of measurements in CQT?
A4: CQT applies to any closed quantum system. For the special case of a microscopic system coupled to a classical measurement apparatus CQT reduces to the orthodox (Copenhagen) formulation, which is an operationalist theory that considers measurement results
as fundamental in the very definition of the theory. Bohr’s principle of complementarity is the reflection of the single framework rule when applied to this special case.

Q5: What is the status of classical mechanics in CQT?
A5: From the point of view of CQT classical mechanics emerges as the limit of quantum mechanics when applied to macroscopic systems, via a process of coarse graining that takes into account the physical phenomenon of decoherence. The quasiclassical histories that survive this process are excellent approximations to classical orbits and the frameworks of the microscopic theory that do not involve quasiclassical histories are rendered physically irrelevant by the phenomenon of decoherence.

Q6: What is the advantage of using CQT?
A6: Apart from the intrinsic benefit of permitting a consistent realist formulation of quantum mechanics, CQT is particularly useful in situations where various classically incompatible measurement instruments are available to probe a system, as usually occurs in discussions of the standard quantum paradoxes. The single framework rule then provides a useful guide to consistent reasoning to avoid confusion.

Q7: What is the role of the wavefunction and wavefunction collapse in CQT?
A7: In CQT the wavefunction does not in general represent physical reality; it is rather a tool for calculating the probabilities of histories via a generalized Born rule. The wavefunction thus plays a role similar in CQT to its role in the orthodox operationalist formulation of quantum mechanics. In contrast, other realist formulations, for example the many-worlds approach, assign physical reality to the wavefunction, a feature which leads to various problems of interpretation.

Q8: Does CQT resolve the quantum measurement problem?
A8: The quantum measurement problem arises in many realist interpretations of the wavefunction since different macroscopic properties, i.e. measurement results, necessarily remain present in the wavefunction or the associated density matrix of a measured quantum system as superpositions corresponding to different instrument readings. This feature conflicts with our experience and with common sense, since macroscopic experiments yield a unique
answer, so the system wavefunction must somehow collapse. CQT has an operationalist interpretation of the wavefunction so the problem does not arise. Measurement results are represented by histories, for which a unique answer is guaranteed within a framework. To the extent that only one framework is physically relevant for measured quantum systems there is thus no measurement problem. If the possibility exists of a practical detection of a macroscopic quantum superposition then more than one framework becomes physically relevant and the choice of measurement (involving either the superposition or the individual macroscopic states) dictates which framework will yield relevant results. Rather than being a problem, this feature of CQT provides an understanding of the real physical situation.

Q9: Is CQT a local theory?
A9: CQT describes nonlocal states and nonlocal histories of quantum systems, but the theory (as well as quantum mechanics itself) does not allow for nonlocal influences from one localized state to another sufficiently distant localized state, i.e. CQT respects the EPR condition of separability\(^{20}\).

Q10: Is there a framework selection problem?
A10: The existence of multiple physically relevant but incompatible frameworks is the distinctive feature that characterizes a general quantum system. No single framework fully exhausts the properties of such a system. There is thus no need or even possibility of selecting the “right” framework in general. Two important exceptions to this general rule are (i) most measured quantum systems, if a particular choice of initial state and macroscopic measurement have been made, and (ii) most purely macroscopic systems that are describable by classical mechanics. In those cases physical couplings to the environment cause decoherence of many histories of the uncoupled system, with the result that only one framework (or one class of equivalent frameworks) becomes physically relevant. In that sense, nature has selected the appropriate framework. This explains why both the orthodox theory and classical mechanics, to which CQT reduces in the appropriate limits, do not speak of multiple incompatible frameworks. Thus the relevant question is not “which framework is selected?” but rather “are incompatible frameworks necessary to represent all the available information about the system?”. In general the answer is yes, but for cases (i) and (ii) above, a single framework (or class of compatible frameworks) may be sufficient.
On the other hand even in those cases one may wish to test the assumed initial condition, say, and then a different framework could be relevant.

Q11: In what sense are the predictions of CQT true?  
A11: For a general quantum system with its multiple incompatible frameworks it can be shown\(^5\) that no universal *truth functional* can be consistently defined. Any truth functional must be attached to one and only one framework, i.e. it too satisfies a single framework rule. It is only in the special cases considered in Q10 above, where only one framework becomes physically relevant, that one can introduce a truth functional for the system, which then has the intuitively expected properties.

V. CONCLUSION

The orthodox (operationalist) formulation quantum mechanics has served many generations of students and researchers and it provides a useful description of observed quantum systems. If, however, one wishes to probe in more detail the physics of such observations, or alternatively if one inquires about the intrinsic properties of microscopic systems, then one requires a realistic formulation. There exists no straightforward formulation of quantum mechanics that conforms entirely to our (classical) intuition: any realistic formulations must pay some price. Hidden variable theories pay the physical price of introducing unobservable beables and of contradicting the spirit, if not the letter, of relativity. Many-worlds theories pay the philosophical price of modifying language and requiring a reorientation of intuition that is difficult for most to accept. Physical collapse theories pay the smallest conceptual price, but since they contradict both quantum mechanics and relativity, until experimental evidence in favor of such a point of view is obtained it cannot be considered a credible resolution of the issues. That leaves CQT, which the present paper argues to be the most satisfactory realistic interpretation, in that the price to be paid is a reorientation of our classical intuition about the nature of microscopic (quantum) reality and a change in the language used to describe that reality. Once such a “syntactical” reorientation is accepted the theory proceeds in a completely logical and consistent manner.
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1 A. Cabello, “Bibliographic guide to the foundations of quantum mechanics and quantum information”, quant-ph/0012089 (2004).

2 Basic references in the field can be found in J.A. Wheeler and W. J. Zurek, Quantum Theory and Measurement (Princeton University Press, Princeton, NJ, 1983), or in D. Home, Conceptual foundations of Quantum Physics. An Overview from Modern Perspectives (Plenum, New York, 1997), or in Refs. 4-6 below, as well, of course, as in Reference 1.

3 J.S. Bell, Speakable and Unspeakable in Quantum Mechanics (Cambridge University Press, Cambridge, U.K., 2004, Second Edition).

4 P.C. Hohenberg, “Colloquium: An Introduction to Consistent Quantum Theory”, Rev. Mod. Phys. 82, 2835-2844 (2010).

5 R. B. Griffiths Consistent Quantum Theory (Cambridge University Press, Cambridge, U.K., 2002).

6 See for example M. Schlosshauer, “Decoherence, the measurement problem and interpretations of quantum mechanics”, Rev. Mod. Phys. 76, 1267-2004 (2004).

7 Besides the four classes of realist interpretations listed here there are a number of others, with designations such as modal, relational, or transactional, as well as variations on these, but the ones we have singled out have attracted the most attention [see, e.g., Refs. 18 and 19].

8 In subsequent work Bell emphasized that hidden variables were a consequence, rather than a premise of his arguments and that quantum mechanics was inconsistent with his version of locality, without further assumptions. The minimum assumptions necessary to prove Bell inequalities remain a subject of controversy to this day, but for our purposes this issue can be circumvented since there is no disagreement on the claim in Bell’s original paper referred to above [see e.g. Refs. 4 and 16].

9 S.L. Adler and A. Bassi, “Is Quantum Theory Exact?”, Science 325, 275-276, (2009).

10 A.J. Leggett, “The Quantum Measurement Problem”, Science 307, 871-872 (2005).
11 J.S. Bell, “Against Measurement”, reprinted in Ref. 3.

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15 N. Bohr, “Can Quantum-Mechanical Description of Reality be Considered Complete?”, Phys. Rev. 48, 696-702 (1935).

16 R. B. Griffiths, “EPR, Bell and Quantum Locality”, quant-ph/1007.4282.v1 (2010).

17 An exception to this statement concerns a particular framework, called the unitary framework, that contains as its only nontrivial history projectors onto the total wavefunction of the system evolved in time according to the Schroedinger equation, but this framework rarely provides verifiable predictions [see Refs. 4 and 5].

18 See Interpretations of quantum mechanics, http://en.wikipedia.org/wiki/Interpretations_of_quantum_mechanics.

19 See Minority interpretations of quantum mechanics, http://en.wikipedia.org/wiki/Minority_interpretations_of_quantum_mechanics.

20 Although Bell and his followers [e.g. Ref. 3, p.143 and Ref. 21] have argued that locality alone is inconsistent with quantum mechanics, their definition of locality involves an assumption, referred to as “classical realism” in Ref. 4, which violates the single-framework rule. CQT is thus a counterexample to the claim that any local theory must violate quantum mechanics, but the disagreement rests entirely on the definition of locality [see also Ref. 16].

21 T. Norsen, Bell Locality and the Nonlocal Character of Nature, Foundations of Physics Letters, 19, pp 633-655 (2006).