The Consistent Histories Interpretation of Quantum Mechanics

Abstract

The consistent histories reformulation and interpretation of quantum mechanics is presented as a replacement for the measurement interpretation. An evaluation of this interpretation as a successor to the measurement interpretation, rather than as a fundamental theory, mitigates the outstanding objections brought against this interpretation.

The consistent histories (CH) reformulation and interpretation of quantum mechanics (QM) was developed by Robert Griffiths, given a formal logical systematization by Roland Omnès, and under the label 'decoherent histories', was independently developed by Murray Gell-Mann and James Hartle and extended to quantum cosmology. It is presented as a replacement for 'the measurement interpretation', loosely identified with the Copenhagen interpretation. Many physicists have recognized this formulation as a serious candidate for a revised interpretation, yet raised serious criticisms about its acceptability. Philosophers of science have generally ignored it. The basic contention of the present article is that the CH interpretation should be judged as a successor to the measurement interpretation, rather than as a fundamental theory. An outline of the CH formulation and a reconstruction of the measurement interpretation, which cannot be identified with standard versions of the Copenhagen interpretation, supplies a basis for treating the leading criticisms brought against this interpretation.

1 The Griffiths formulation of Consistent Histories

The Griffiths formulation of Consistent Histories broke with the orthodox interpretation by treating closed systems, by not assigning measurement a foundational role, and by insisting that quantum mechanics supply an account of all basic processes including measurements.[1] There are three basic features. First, there is the specification of a closed system at particular times by a series of events. An event is the specification of the properties of a system through a projection operator for the Hilbert sub-space representing the property. Second, there is a stochastic dynamics. Though Griffiths relied on Schrödinger dynamics, he treated it as going from event to event, rather than as a foundation for unitary evolution of a system prior to measurement and collapse. The events could be stages in a uniform evolution, measurements, interaction with the environment, or a virtual interaction. At this stage there is no distinction between real and virtual processes. A history is a time- ordered sequence of events. It is represented by projectors on a tensor product of the Hilbert spaces of the events. Third, a consistency condition is imposed on histories, or families of histories. Only those that may be assigned probabilities are given a physical interpretation.

The developers of the CH interpretation are insistent on presenting this as a replacement for 'the measurement interpretation'. Why does this need replacement? For Griffiths (2002a, Preface) and Omnès (1994, chap. 2) the basic reason is that a measurement-based interpretation does not accord with what a fundamental theory should be. It subordinates the mathematical formalism to the language of experimental physics. A fundamental theory should supply a basis for interpreting experiments. Omnès puts this in stronger terms. "By an *interpretation* we shall mean a translation of the empirical language describing the experiments and the phenomena in a way involving only the formal concepts of the theory."[2] Also, any form of a measurement interpretation presupposes an outside observer making measurements. Quantum cosmology, which treats the cosmos as a quantum system, does not admit of an outside observer.

A comparison with classical physics clarifies the status accorded quantum histories. In classical statistical mechanics the state of a system is represented by a point in phase space and the evolution of the system, or its history, by the trajectory of this point. The phase space may be coarse-grained by dividing it into a set of cells of arbitrary size that are mutually exclusive and jointly exhaustive. The projectors B_i for these cells satisfy eq. (1).

$$\sum_i B_i = 1 \qquad B_i^\dagger = B_i \qquad B_i B_j = \delta_{ij} B_j \tag{1}$$

A cell will be assigned a value 1 only if the phase point representing the system is in the cell. This assignment of 0 and 1 values supports a Boolean algebra. To represent a history, construct a tensor product of copies of the phase space and let them represent the system at times $t_0, t_1, \ldots, t_n$. Then the product of the projectors for these time slices represents the history. The relation to classical probabilities can be given an intuitive expression. The tensor product of the successive phase spaces has a volume with an a priori probability of 1. Each history is like a worm hole through this volume. It's a priori probability is the ratio of the volume of the worm hole to the total volume. The probability of two histories is additive provided the worm holes don't overlap. In the limit the total volume is the sum of a set of worm holes that are mutually exclusive and jointly exhaustive.

Quantum mechanics uses Hilbert space, rather than phase space and represents properties by sub-spaces. The correlate to dividing phase space into cells is a decomposition of the identity, dividing Hilbert space into mutually exclusive and jointly exhaustive subspaces whose projectors also satisfy eq. (1). Each history generates a subspace wormhole through the tensor product of Hilbert spaces. The a priori probability of a particular history is the ratio of the volume of its wormhole to the total volume. A history might have incompatible quantities at different stages, e.g. of σ_x at t_1 and σ_y at t_2, but has only projectors for compatible properties at each time slice. Corresponding to the intuitive idea of a wormhole volume the *weight operator* for a history is

$$K(Y) = E_1 T(t_1, t_2) E_2 T(t_2, t_3) \cdots T(t_{n-1}, t_n) E_n, \tag{2}$$

where E stands for an event or its orthogonal projection operator, $T(t_1, t_2)$ is the operator for the evolution of the system from t_l to t_2. Eq. (2) can be simplified by using the Heisenberg projection operators

$$\hat{E}_j = T(t_r, t_j) E_j T(t_j, t_r) \tag{3}$$

leading to

$$\hat{K}(Y) = \hat{E}_1 \hat{E}_2 \cdots \hat{E}_n. \tag{4}$$

Then the weight of a history may be defined in terms of an inner product

$$W(Y) = \langle K(Y), K(Y') \rangle = \langle \hat{K}, \hat{K}' \rangle \rangle. \tag{5}$$

The significance of this equation, defined on the vector space of operators, may be seen by the phase-space comparison used earlier. Classical weights used to assign probabilities are additive functions on the sample space. If E and F are two disjoint collections of phase-space histories, then $W(E \bigcup F) = W(E) + W(F)$. Quantum weights should also satisfy this requirement, since they yield classical probabilities and must be non-negative.

As Griffiths (2002a, 121-124) shows, Eq. (5) achieves this. Quantum histories behave like classical histories to the degree that mutual interference is negligible. This is the key idea behind the varying formulations of a consistency condition. If two histories are sufficiently orthogonal, $\langle K(Y), K(Y')\rangle \approx 0$, then their weights are additive and can be interpreted as relative probabilities. This idea of mutual compatibility may be extended to a *family* of histories. Such a family is represented by a consistent Boolean algebra of history projectors. This may be extended from a family of projectors, $\mathfrak{F}$ to a refinement, $\mathfrak{G}$, that contains every projector in $\mathfrak{F}$.

This consistency requirement concerns pairs of histories that may be assigned probabilities. Essentially, it is the requirement that interference between two histories be negligible. Interference and superposition are not eliminated. They are essential features of the formulation. This consideration introduces the basic unit for interpretative consistency, a *framework*, a single Boolean algebra of commuting projectors based upon a particular decomposition of the identity[3]. A framework supplies the basis for quantum reasoning in CH. Almost all the objections to the CH interpretation are countered by showing they violate the single framework rule, or by a straightforward extension, the single family rule. This notion, accordingly, requires critical analysis.

There are two aspects to consider: the relation between a framework and quantum reasoning, and whether the framework rule is an *ad hoc* imposition. The first point is developed in different ways by Omnès and Griffiths. Omnès develops what he calls consistent (or sensible) logics. The logic is standard; the way it is applied is not. A consistent logic applies to a framework and by extension to families of histories. If two families differ in any detail, then they have different logics (Omnès 1992, p. 155). A specific logic that is consistent may become inconsistent by changing the framework, e.g., using a larger radius (*ibid*, p. 174). In the standard philosophical application of logic to theories, one first develops a logic system, or syntax, and then applies it. The content to which it is applied does not alter the logic. Omnès reverses this order by picking out a framework and then developing a specific logic to fit it. I am not claiming that Omnès's logic is incorrect. The logic he develops is standard logic. His methodology, however, can occasion misunderstanding.

Griffiths focuses on frameworks and develops the logic of frameworks by considering simple examples and using them as a springboard to general rules The distinctive features of this reasoning confined to a framework can be seen by contrast with more familiar reasoning. Consider a system that may be characterized by two or more complete sets of compatible properties. The Hilbert space representing the system may be decomposed into different sets of subspaces corresponding to the different sets of compatible properties. To simplify the issue take σ_x^+ and σ_z^+ as the properties. Can one attach a significance or assign a probability to 'σ_x^+ AND σ_z^+'? In CH propositions are represented by projectors of Hilbert subspaces. The representation of σ_x requires a two-dimensional subspace with states $\mid X^+\rangle$ and $\mid X^-\rangle$, projectors $X^\pm = \mid X^\pm\rangle\langle X^\pm \mid$, and the identity, $I = X^+ + X^-$. One cannot represent 'σ_x^+ AND σ_z^+' in any of the allowed subspaces. Accordingly it is dismissed as 'meaningless'.

Adrian Kent has repeatedly criticized this[4]. Consider two histories with the same initial and final states and intermediate states σ_x and σ_z, respectively. In each history one can infer the intermediate state with probability 1. A simple conjunction of two true propositions yields 'σ_x AND σ_z. Griiffiths and Hartle contend, and Kent concedes, that there is no formal contradiction since the intermediate states are in separate histories. Kent finds this defense arbitrary and counter-intuitive. Our concepts of logical contradiction are established prior to and independent of their application of quantum histories. Physicists have also criticized CH on the grounds that: a straightforward extension leads to inconsistent property assignments (d'Espagnat 1995, chap. 11); it is rendered inconsistent by well-established quantum no-go theorems (Goldstein 1994); and it cannot support a realistic interpretation (Bassi and Ghirardi 1999).

For our purposes, we will distinguish internal criticisms, that CH involves inconsistencies, from external criticisms, concerning meaning and truth Griffiths's detailed refutations of internal criticisms all hinge on showing that strict adherence to the single framework rule avoids inconsistencies[5]. I believe that Griffiths has demonstrated that his formulation is internally consistent. Two examples of how the single framework rule functions supply a basis for treating the external objections.

Superposition of states is at the heart of the measurement problem. Critics who reject a projection postulate, or wave-function collapse,as an *ad hoc* solution inquire how the superposition of states that the mathematical formalism yields becomes the mixture that the interpretation of experimental results requires. Griffiths attempted to isolate the problem of superposition by considering the analogous situation in one spatial dimension (Griffiths 2002b, p. 20)

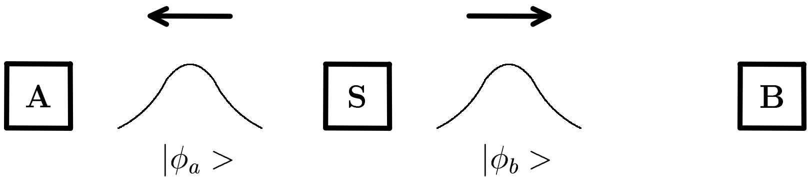

Figure 2: One Particle Superposition

The wave function for the particle (*one* particle not two!) is given by a linear superposition

$$|\psi(t)\rangle = (|\phi_a(t)\rangle + |\phi_b(t)\rangle)/\sqrt{2} \tag{6}$$

of two wave packets moving outwards from a central source S towards two detectors A and B, with A closer to S than B. In the wave collapse treatment if A detects the particle then the b part of the wave packet instantly vanishes. If A does not detect the particle, then the a part of the wave packet vanishes. Both alternatives, literally interpreted, illustrate, in Einstein's terms, spooky action at a distance. Does this objection also apply to CH?

Equation (6) is a superposition that does not allow a position specification. Different histories may be set up depending on the questions asked. I will follow, but simplify, Griffiths's treatment and ignore relativistic considerations. We divide the time into a series of intervals, t_i, and introduce a decomposition of the identity,

$$I_j = \sum_{\lambda_j} P^{\lambda_j},$$

where the projectors, P^{λ_j}, project onto non-overlapping intervals of the x-axis chosen so that they are much larger than the wave packets, but much smaller than the macroscopic paths.

This allows for a family, $\mathfrak{F}$, with support consisting of

$$\mathfrak{F}: \quad \psi(t_0) \odot \psi(t_1) \odot \left(\begin{array}{c} P_2^{a_2} \odot P_2^{a_3} \odot \cdots , \\ \\ P_2^{b_2} \odot P_2^{b_3} \odot \cdots , \end{array} \right), \tag{7}$$

where $\odot$ is a symbol for a tensor product of Hilbert spaces corresponding to projectors at different times. What eq. (7) means is that the particle is in a non-local superposition from t_0 to t_1. After t_1 it follows either the coarse-grained a trajectory or the coarse-grained b trajectory. The formalism does not treat the question of **how** the superposition became a mixture. This simple example indicates the general procedure for handling measurements (*Ibid.*, Ch. 34). Both the measured system and the apparatus are treated as part of a single closed system. This excludes an outside observer making measurements. However, it is presumed that measurements yield definite results rather than macroscopic quantum superpositions (MQS, or Schrödinger-cat states). Griffiths's treatment of the measurement problem relies on two general principles: 1) *A quantum mechanical description of a measurement with particular outcomes must employ a framework in which these outcomes are represented.* 2) *The framework used to describe the measuring process must include the measured properties at a time before the measurement took place.* This implements the requirement that a pointer reading in the apparatus after the measurement records the property value characterizing a system before the measurement.

The distinctive features and associated difficulties of this framework reasoning are illustrated by Griffiths's reworking of Wheeler's (1983) delayed choice experiment. Both Wheeler and Griffiths (1998) consider a highly idealized Mach-Zehender interferometer.

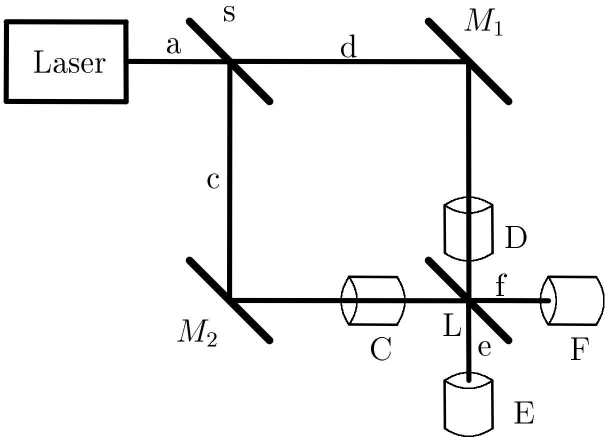

Figure 1: A Mach-Zehender Interferometer

The classical description in terms of the interference of light waves may be extended to an idealized situation where the intensity of the laser is reduced so low that only one photon goes through at a time. Here S and L are beam- splitters, M_1 and M_2 are perfect mirrors, and C, D, E, and F are detectors. If D registers, one infers path d; if C registers, then the path is c. If C and D are removed, then the detectors E and F can be used to determine whether the photon is in a superposition of states. Wheeler's delayed choice was based on the idealization that detectors C and D could be removed after the photon had passed through S. It is now possible to implement such delayed choice experiments, though not in the simplistic fashion depicted.

To see the resulting paradox assume that detectors C and D are removed and that the first beam splitter leads to the superposition, which can be symbolized in abbreviated notation as

$$\mid a\rangle \mapsto \mid s\rangle \; = \; (\mid c\rangle + \mid d\rangle)/\sqrt{2}, \tag{8}$$

where $\mid a\rangle$, $\mid c\rangle$, and $\mid d\rangle$ are wave packets at the entrance and in the indicated arms. Assume that the second beam splitter L leads to a unitary transformation

$$| c\rangle \mapsto | u\rangle \ = \ (| e\rangle + \ | f\rangle)/\sqrt{2}, \quad | d\rangle \mapsto | v\rangle \ = \ (- \ | e\rangle + \ | f\rangle)/\sqrt{2}, \tag{9}$$

with the net result that

$$| a\rangle \mapsto | s\rangle \mapsto | f\rangle. \tag{10}$$

Equations (8) and (10) bring out the paradox. If the detectors, C and D were in place, then the photon would have been detected by either C or D. If it is detected by C, then it must have been in the c arm. If the detectors are removed and the F detector registers, then it is reasonable to assume that the photon passed through the interferometer in the superposition of states given by eq. (8). The detectors were removed while the photon was already in the interferometer. It seems reasonable to ask what state the photon was in before the detectors were removed. The intuitive answer seems to be that the photon had some foreknowledge of whether the detectors would be removed and adjusted its state accordingly. This assumption of the future influencing the past is highly implausible.

Griffiths treats this paradox by considering different families of possible histories. Using C and D for the ready state of detectors, considered as quantum systems, and C* and D* for triggered states then one consistent family for the combined photon-detector system is

$$|a\rangle|CD\rangle \longrightarrow \begin{pmatrix} |c\rangle|CD\rangle \longrightarrow |C^{*}D\rangle \\ |d\rangle|CD\rangle \longrightarrow |CD^{*}\rangle \end{pmatrix} \tag{11}$$

Here $|a\rangle|CD\rangle$ represents a tensor product of the Hilbert spaces of the photon and the detector. Eq. (11) represents a situation in which the photon enters the interferometer and then proceeds either along the c arm, triggering C^{*} or along the d arm, triggering D^{*}. These paths and outcomes are mutually exclusive.

For the superposition alternative, treated in eqs. (8)–(10), there is a different consistent family of histories,

$$|a\rangle|EF\rangle \longrightarrow |s\rangle|EF\rangle \longrightarrow \begin{pmatrix} |e\rangle|EF\rangle \longrightarrow |E^{*}F\rangle \\ |f\rangle|EF\rangle \longrightarrow |EF^{*}\rangle \end{pmatrix} \tag{12}$$

Eq. (12) represents superposition inside the interferometer and exclusive alternatives after the photon leaves the interferometer. In accord with eq. (10) the upper history in eq. (12) has a probability of 0 and F^{*} is triggered.

Suppose that we replace the situation represented in eq. (12) by one in which the photon is in either the c or d arms. There is no superposition within the interferometer, but there is when the photon leaves the interferometer. This can be represented by another consistent family of histories,

$$|a\rangle|EF\rangle \longrightarrow \begin{pmatrix} |c\rangle|EF\rangle \longrightarrow |u\rangle|EF\rangle \longrightarrow |U\rangle \\ |d\rangle|EF\rangle \longrightarrow |v\rangle|EF\rangle \longrightarrow |V\rangle \end{pmatrix}, \tag{13}$$

where

$$|U\rangle \;=\; (|E^{*}F\rangle \,+\, |EF^{*}\rangle)/\sqrt{2},$$

$$|V\rangle \;=\; (-|E^{*}F\rangle \,+\, |EF^{*}\rangle)/\sqrt{2}.$$

Both $|U\rangle$ and $|F\rangle$ are MQS states. The formalism allows for such states. However, they are not observed and do not represent measurement outcomes. This delayed choice example represents the way traditional quantum paradoxes are dissolved in CH. Reasoning is confined to a framework. Truth is framework-relative. The framework is selected by the questions the physicist imposes on nature. Within a particular framework, there is no contradiction. One is dealing with consistent histories. The traditional paradoxes all involve combining elements drawn from incompatible histories.

CH is internally consistent. Yet the external questions remain concerning meaning, truth, and *ad hoc* rules. In CH meaning and truth are framework relevant. Kent and others find the classification of propositions as meaningful and meaningless arbitrary. Inference and conjunction are general notions that logically precede a histories formulation. If two intermediate states can both be inferred, then their conjunction should be meaningful, regadless of which histories they are in. Similarly with regard to truth claims. Thus, Some critics wonder where the photon *really* was before the detectors were removed. This criticism is implemented by interpreting a set of projectors as representing the properties a system *possesses* at a time and arguing that a given initial state may lead to inconsistent property assignments. (See d'Espagnat 1995, chap. 11). In a similar vein Bub (1997, 236) expressed the objection that if there are two quasiclassical histories for Schrödinger's cat, then one still does not know if the cat is *really* alive or dead. Bassi and Ghiradi, (1999) argue that the attribution of properties to a system is true if and only if the system actually possess the properties. This should not depend on membership in a family. This is extended to probabilities. From an ontological perspective probabilities of properties must refer to objective and intrinsic properties of physical systems. According to Bassi and Ghirardi "There is no other reasonable alternative." These critics are all relying on the traditional notion of truth as a correspondence between propositions and reality. Then an answer to the question, 'Where was the photon before the detectors were removed?', is either true or false even though we are unable to determine which. The answer that truth is relative to a framework seems to reduce truth to internal consistency. Finally, it seems that the measurement problem is solved by ducking the controverted issue. How does a superposition become a mixture?

We will separate these questions, which chiefly concern semantics, from the ontological questions, which will be relegated to the Gell-Mann–Hartle formulation. The questions of meaning, truth, and arbitrariness admit of a correspondence principle justification. The measurement interpretation gives essentially the same answers and justifies them by an informal semantic analysis. If the CH is to replace the measurement interpretation, then something of a correspondence principle approach should apply. This is a very limited justification of the CH formulation as a first step beyond the measurement interpretation, not as a fundamental theory. Hence, a detour through the measurement interpretation and the roles of informal semantics and the correspondence principle.

2 Bohrian Semantics

The Copenhagen interpretation has been given so many formulations that there is a serious problem of interpreting the interpretation. It has regularly been accused of inconsistency in: introducing a special type of process to accommodate measurements; mixing classical and quantum physics; relying on arbitrary assumptions; and relying on an outside observer not subject to the laws of QM. We will make a sharp distinction between the Copenhagen interpretation and Bohrian semantics[6]. The development of Bohrian semantics preceded the formulation of QM and stemmed from Bohr's struggles to overcome the contradictions that plagued the final stages of the Bohr-Sommerfeld theory.

1a. **Electromagnetic radiation is continuously distributed in space.** The high precision optical instruments used in measurements depend on interference, which depends on the physical reality of wavelengths.

1b. **Electromagnetic radiation is not continuously distributed in space.** This is most clearly shown in the analysis of X-rays as needle radiation and in Compton's interpretation of his eponymous effect as a localized collision between a photon and an electron.

2a. **Electromagnetic radiation propagates in wave fronts.** This is an immediate consequence of Maxwell's equations.

2b. **Electromagnetic radiation travels in trajectories.** Again, theory and observation support his. The theory is Einstein's account of directed radiation. The observations concern X-rays traveling from a point source to a point target.

3a. **Photons function as discrete individual units.** The key assumption used to explain the three effects treated in Einstein's original paper is that an individual photon is either absorbed as a unit or not absorbed at all. Subsequent experiments supported this.

3b. **Photons cannot be counted as discrete units** Physicists backed into this by fudging Boltzmann statistics. It became explicit in Bose- Einstein statistics.

These and further contradictions concerning electronic orbits, were not contradictions derived from a theory. The B-S theory had become a thing of rags and patches. These contradictions were encountered in attempts to give a coherent framework for interpreting experimental results. We will distinguish the language of phenomena from the language of theories. Bohr's resolution of these problems included a reformation of the language of phenomena. In resolving this crisis, Bohr introduced something of a Gestalt shift, from analyzing the apparently contradictory *properties* attributed to objects and systems to analyzing the *concepts* used. As Bohr saw it, the difficulties were rooted in "...an essential failure of the pictures in space and time on which the description of natural phenomena has hitherto been based."[7]. Bohr reinterpreted the role of the language used to give space-time descriptions of sub-microscopic objects and properties.

The description of experiments and the reporting of results must meet the conditions of unambiguous communication of information. This requires ordinary language supplemented by the terms and usages developed through the progress of physics. Thus, the meanings of the crucial terms 'particle' and 'wave' were set by their use in classical physics. Each of these terms is at the center of a cluster of concepts that play an inferential role in the interpretation of experiments. From tracks on photographic plates experimenters infer that a particle originated at a point, traveled in a trajectory, collided with another particle, penetrated an atom, and displaced an inner electron. Waves do not travel in trajectories. They propagate in wave fronts, interfere with each other, are diffracted or absorbed. A straightforward extension of these concepts to different contexts generated contradictions.

Bohr's new guidelines, complementarity, resolved these contradiction by restricting the meaningful use of classical concepts to contexts where these concepts could be related to real or ideal measurements. Concepts proper to one measurement context could not be meaningfully extended to a complementary measurement context. Bohr treated the mathematical formalism as a tool and regarded these analyses of idealized experiments as the chief means of establishing the consistency of the language of quantum physics[8]. This explains the chiaroscuro nature of his analyses featuring detailed representations of grossly unrealistic experiments: diaphragms rigidly clamped to wooden tables, clocks with the primitive mechanism showing, a scale supported by a dime-store spring. These are belligerently classical tools used to illustrate the limits of applicability of classical concepts in atomic and particle experiments. Bohr thought he achieved an overall consistency only after 1937. Subsequently he introduced an idiosyncratic use of ‘phenomenon’ as a unit of explanation. The object studied, together with the apparatus needed to study it constitute a phenomenon, an epistemologically irreducible unit. Idealized thought experiments supplied the basic tool for testing consistency.

Bohr’s use of ‘phenomenon’ corresponds to Griffiths’s use of ‘framework’ as the unit specifying the limits of meaningful expressions. The parallel between Bohrian phenomena and CH frameworks is illustrated by Wheeler’s treatment of the delayed choice experiment. Wheeler explained the situation by adapting Bohr’s idiosyncratic use of ‘phenomenon’: “No elementary phenomenon is a phenomenon until it is a registered (observed) phenomenon.” The only phenomena to be explained are those with known outcomes. If interference is actually observed, then there was a superposition of paths. If C detects a photon, then there was no superposition. Each situation is treated as an epistemologically irreducible unit. Bohr was clear and consistent on the significance of his semantics. Physicists following his rules are not describing electrons or photons as they exist objectively. The realization that it is not possible to give objective space-time descriptions of atoms, electrons, and photons launched his novel semantics. One is using classical terms in experimental contexts in a way that accords with the limits of meaningful usage. The best we can do in describing these objects as they exist independent of our experiments is to rely on complementary accounts. When he adopted a motto for his crest of arms it was “*Contraria sunt Complementaria*”. Though contraries cannot both be true; they can both be false.

2.1 A Measurement Interpretation

The CH interpretation has been promoted as a replacement for *the measurement interpretation*. Though often loosely identified with the Copenhagen interpretation, we distinguish the two by their treatment of the measurement problem, roughly how a superposition of states becomes a mixture in a measurement situation. Orthodox Copenhagen physics appeals to a collapse postulate, or a reduction of the wave packet. Bohr's experimental analyses never appeal to any such reduction. For him measurement supplies a foundation for the formalism, not a problem to be explained through the formalism. Measurement interpretation were developed as extensions of the key features of Bohrian semantics. It is possible to make a distinction between a sharp and a loose measurement interpretation. In a strict measurement interpretation, initiated by Paul Dirac and developed by Julian Schwinger, an analysis of idealized measurements generates the mathematical formalism[9]. In a loose measurement interpretation a consistency between the language used in experimental results and mathematical formulations supplies a basis for developing and interpreting QM. I am only familiar with five books that develop QM on this basis: Heisenberg (1930), Pauli (1947[original 1930]), Kramers (1957), Landau and Lifshitz (1965 [1956]), and Gottfried (1966). A measurement *interpretation* changes the status of the traditional measurement *problem*. In treating measurement Gottfried (p. 180), following Pauli and Schwinger, concludes that an experimental arrangement is a measuring device if and only if it functions in a context where a pure state and a mixture are experimentally indistinguishable. This is not determined by the formalism, but by the requirement that proper measurements yield results. Hence, it is reasonable to rely on experimental expertise to determine when this switch from a superposition to a mixture is justified and to treat the formalism as a functional tool, rather than a deductive theory. The difficulty many have with this was most clearly expressed by John Bell (1990). He claimed that Gottfried's solution may work for all practical purposes (FAPP) but is logically incoherent. It replaces $\psi_1 \psi_1^* \; and \; \psi_2 \psi_2^* \; and \; \ldots,$ by $\psi_1 \psi_1^* \; or \; \psi_2 \psi_2^* \; or \; \ldots.$

Both the measurement interpretation and the CH formulation have the same theoretical gap. The question of how a superposition becomes a mixture is not only unanswered. It is not recognized as a properly formulated question. Rather than ask how measurements get results, both adapt the formalism to the acceptance of measurement results. This allows for a supplemental explanation, such as the decoherence proper to an experimental setup. This theoretical gap is not a serious obstacle, when one is treating the mathematical formalism as an inference mechanism leading from measurement results to the prediction of results of actual or possible measurements.

Bohrian semantics and the measurement interpretation can supply a *correspondence principle*(CP) basis for an initial interpretation of the CH formulation. However, a preliminary clarification is necessary. Today any invocation of the CP generally refers to the backwards CP. QM reduces to classical physics in the limits of large quantum numbers and $\hbar \longrightarrow 0$. During the formative period the forward CP was a heuristic guide for guessing formulas of the to-be-constructed quantum mechanics using classical physics and the old Bohr-Sommerfeld theory as springboards[10]. A CP approach to the new QM was operative on three levels. It served as a guide for quantum formulations. Classical Hamiltonians and Lagrangians supply formulas for setting up a quantum Hamiltonians and Lagrangians. The final achievement of the forward CP is the basic relation Dirac established between classical Poisson brackets and quantum commutators, $\{p, q\} = \imath\hbar[p, q]$. The problems that admitted only of patchwork solutions in the B-S program supplied a source of problems for judging the new theory. Finally, classical physics supplied an initial basis for interpreting the new QM.

The measurement interpretation so conceived includes the distinctive features previously labeled 'external problems' for the CH. Meaning and truth are framework relevant. In a measurement situation a superposition may be replaced by a mixture without any explicit justification. In a measurement interpretation these are not arbitrary impositions, or *ad hoc* rules. They are justified by Bohrian semantics. This justification is intelligible only in a perspective focusing on language, not theories, as the basic explanatory unit. I will indicate how this justification functions for meaning and truth and then their relation to the CH formulation.

Bohrian semantics does not involve any theoretical account of meaning and truth. It assumes that the meaning of such terms as 'trajectory' or ''interfere' is set by their usage in classical physics. The problem is restricting their usage in quantum contexts. To relate Bohr's idiosyncratic use of 'phenomenon' to more familiar terms we may say that a complete specification of an experimental situation supplies the minimal language game in which these disputed terms may properly be used. Thus, the term 'trajectory' cannot be meaningfully extended to the experimental situation in which the interferometer, previously considered, manifests interference. The situation with no interference is not a part of the two-slit experiment. It is a separate experiment. There is no meaningful use of 'trajectory' in this context. The acceptance of experimental reports as true entails the implicit acceptance of a nested collection of truth claims concerning the normal functioning of the apparatus and the presuppositions of routine experimental inferences.

The measurement interpretation does not rely on a theory of truth. As Bohr and Heisenberg repeatedly insisted, its conceptual basis is ordinary language as extended through classical physics to quantum contexts. What we will consider, accordingly, is how the notion of truth, implicit in ordinary language usage, is extended to classical and quantum physics[11] The point of departure is Donald Davidson's truth semantics. His gradual abandonment of an extensional theory of 'true' led to a critical rethinking of the interrelation of truth, language, interpretation, and ontology, summarized in the concluding Essay of his (2001, Essay 14). Philosophers have been traditionally concerned with three different types of knowledge: of my own mind; of the world; and of other minds. The varied attempts to reduce some of these forms to the one taken as basic have all proved abortive. Davidson's method of interrelating them hinges on his notion of radical interpretation. My attempt to interpret the speech of another person relies on the functional assumption that she has a basic coherence in her intentions, beliefs, and utterances. Interpreting her speech on the most basic level involves assuming that she holds an utterance true and intends to be understood. The source of the concept, 'true' is interpersonal communication. I also assume that by and large she responds to the same features of the world that I do. Without this sharing in common stimuli, or public objects, thought and speech have no real content. The three different types of knowledge are related by triangulation. I can draw a baseline between my mind and another mind only if we can both line up the same aspects of reality. Knowledge of other minds and knowledge of the world are mutually dependent. "Communication, and the knowledge of other minds that it presupposes, is the basis of our concept of objectivity, our recognition of a distinction between false and true beliefs". (*Ibid.*, 217). Discourse may involve false beliefs, factual errors, deliberate deception. Nevertheless, the designation of some practice as anomalous is only meaningful against a background of established practices that set the norms. Thus, normal discourse presupposes the acceptance of a vast, amorphous collection of claims as true.

Instead of a theory of truth we begin with the notion of 'true' implicit in language usage. This is taken as a semantic primitive. In most contexts asserting a proposition is equivalent FAPP to quoting the proposition and predicating 'true' of it, though the latter is more formal. 'True', when used in the minimal sense, does not have ontological import beyond the framework in which it functions. Consider the ontological progression:

This shirt is yellow. (S1)

This cloth has the property of being yellow. (S2)

Color is a property of extended material objects. (S3)

Someone asserting (S1) need not hold, or even consider (S3). (S1) is an observation report, not an ontological claim. Accepting it as true is compatible with holding a different explanation of color, or having no explanation at all. Acceptance of the shirt as a public object is not an ontological claim. (S2) has an in-between status, depending on whether the use of 'property' is simply a rephrasing of (S1), or an ontological claim. (S1) can be considered an objective claim, when objectivity is based on intersubjective agreement concerning public objects. (S3) reflects an Aristotelian categorization of substance and properties. A rejection of (S3) need not entail a rejection of (S1). This loose collection of shared beliefs is not a theory of what the world is independent of our knowledge of it. It is an articulation of what it means to be an agent in a lived world.

The report of experimental results presupposes the acceptance of a vast, but not so amorphous, collection of claims as true. The instruments must be calibrated to assure that they give true readings. Handbooks and databases must be checked to assure that the values used for resistance, conductivity, specific heat, and other quantities are the true values. In a typical particle experiment one must assume that the collaborating scientists are telling the truth as they know it. Any one of these implicit truth claims may be called in question, if there is specific reason for doubt. However, one cannot simultaneously call them all in question without paralyzing the experimental process. This promiscuous experimental acceptance of facts and values as true contrasts with the chaste reserve concerning the truth of theoretical claims. The reporting of experimental results fits into this semantic network. Consider the ontological progression:

The electron went through the upper slit in the diaphragm. (E1)
The electron traveled in a trajectory from source to slit to the target. (E2)
The electron is an object with a sharp spatial location. (E3)

Here (E1) is an immediate inference in the familiar experimental context with only one slit open. (E2) is an immediate extrapolation, a classical description of an electron's trajectory in a context supporting this classical account. (E3), however, extrapolates beyond the experimental context and attempts to state a property an electron possesses objectively. It is incompatible with QM and wave-particle duality. Someone asserting (E1) need not hold, or even consider, (E3) It is semantically misleading to treat the presuppositions of discourse as similar to the axioms of a theory.

The normal practice of experimental physics routinely accepts as true assertions about particle trajectories e. g., in analyzing cloud-chamber photographs or solar neutrinos. Cartwright (1983, 172) notes a similar point in her analysis of the Stanford linear accelerator. A descriptive account of bursts of electrons passing through drift tubes and accelerating gaps yields the observed outcome, high-energy highly collimated electrons. A Schrödinger equation account yields a vast multiplicity of superpositions and no measurable outcome at all. These are all framework-dependent assertions. Descriptive accounts of electron diffraction experiments do not presuppose or support any claims about electron trajectories. Bohrian semantics and the measurement interpretation are essentially epistemological interpretations of QM resting on a foundation of public objects, not ontological theories.

Griffiths did not rely on a measurement interpretation or a correspondence principle approach in developing the CH formulation. However, he did rely on the lessons learned through the development of QM. He did intend to develop a foundationasl theory.However, the testing ground for the new formulation was the development of a consistent approach to the collection of problems and paradoxes that separated interpretations of QM, e.g., the single-slit, double-slit experiment, the EPR paradox, Hardy's paradox, and the measurement problem. If the CH formulation is interpreted as a correspondence principle extension of the measurement interpretation, then one can appeal to Bohrian semantics as an initial answer to the external objections previously considered. A framework, the Hilbert-space representation of a Bohrian 'phenomenon', supplies the basic unit for meaningful expressions and truth claims. The retrodiction of photon paths has the same epistemological status as claims

E1-E3. This is an epistemology grounded in the public objects of experimental-theoretical discourse. It does not rely on any assumptions about reality as it exists independent of our knowledge. In this setting such questions are rejected as not properly formulated. This is a very limited piggyback epistemological justification of the CH interpretation. If this were the only justification, then the CH formulation would simply be a cumbersome reformulation of the measurement interpretation. The founders of CH clearly intend more than a reformulated measurement interpretation. Bell famously criticized the limitations of a measurement interpretation:

> But it is interesting to speculate on the possibility that a future theory will not be intrinsically ambiguous and approximate. Such a theory could not be fundamentally about 'measurements', for that would again imply incompleteness of the system and unanalyzed interventions from outside. Rather it should again become possible to say of a system not that such and such may be observed to be so but that such and such be so. The theory would not be about 'observables' but about *'beables'*. (Bell 1987, p. 41)

In a joint article Griffiths and Omnès responded to this criticism: "The beables in consistent-histories quantum theory are a collection of mutually exclusive histories to which probabilities may be assigned by the dynamic laws of quantum mechanics (Schrödinger's equation) (Griffiths and Omnè 1999, p. 30). A measurement situation picks out one history as physically significant. Apart from such measurement-based selection, one must consider what significance is to be accorded a collection of mutually exclusive histories.

3 Beyond the Correspondence Principle

When we go beyond CPCH then there is no classical anchor to secure probability values for particular histories. This raises two questions. How is such a generalization properly formulated? What significance can be attached to the totality of histories proper to a system? Since Dowker and Kent (1995,1996) provided the most carefully developed answer to these questions we begin with their analysis.

Consider a system whose initial density matrix, ρ_i is given along with the normal complement of Hilbert-space observables. Events are specified by sets, σ_j of orthogonal Hermitian projectors, $P^{(i)}$ characterizing projective decompositions of the identity at definite times. Thus,

$$\sigma_j(t_i) \;=\; \{{P_I}^{(i)} : i \;=\; 1, 2, \ldots, n_j\}_{t_j}$$

defines a set of projectors obeying eq. (1) at time t_i. Consider a list of sets and time sequences. The histories given by choosing one projection from each set in all possible ways are an exhaustive and exclusive set of alternatives, $\mathcal{S}$. They impose the Gell-Mann–Hartle medium decoherent consistency conditions, restrict their considerations to exactly countable sets, consider consistent extensions of $\mathcal{S}$, $\mathcal{S}'$ and then ask how many consistent sets a finite Hilbert space supports. The answer is a very large number. This prompts two interrelated questions. How is one set picked out as the physically relevant set? What sort of reality can be attributed to the collection of sets?

The first question admits of an easy answer in an experimental context. A physicist chooses the history capable of answering the questions she asks. Dowker and Kent are primarily concerned with the Gell-Mann–Hartle extension of CH to the universe considered as a quantum system. There are no outside observers. The only allowed observers are internal to the system, evolved Information Gathering and Utilizing Systems (IGUSes). Suppose I identify myself with an IGUS and pick out my own immediate experiences as the 'actual facts' (Omnès's term) selecting a particular history as the physically relevant set. Would this suffice?

Apart from the complex problem of establishing a theory of experience, Dowker and Kent raise a formidable objection. Consider a history of the universe as a system leading up to the present. Following both Gell-Mann–Hartle and Kent-Dowker, assume that my experiences are of a quasiclassical realm, a sequence of histories sufficiently coarse-grained to approximately reproduce the large-scale deterministic laws of classical physics. What extensions of this history preserve quasiclassicality? Dowker and Kent argue that $\mathcal{S}'$ admits of a very large number of extensions, with only a minute fraction preserving quasiclassicality. To say that a member of this small fraction is selected on the grounds that I will continue to experience a quasiclassical universe requires, but lacks, a theory of experience. Without the perseverance of quasiclassicality we do not have a universe that can be approximately described by the deterministic laws of classical physics. Dowker and Kent see this as a major flaw. They conclude that a general formulation of CH is seriously incomplete without such a selection principle and that the theory, as presently formulated, is incapable of supplying such a principle.

None of the developers of CH considers this objection a sufficient basis for either rejecting the CH formulation or considering it radically incomplete. (See Gell-Mann and Hartle 1996, Griffiths 1998, Omnès 1999, pp. 175, 288). Kent (2000, 8) answers that: "Even on the assumption that we will continue to observe quasiclassical physics, no known interpretation of the formalism allows us to derive the predictions of classical mechanics and Copenhagen quantum theory." Instead of attempting to analyze any particular response, I will consider the more general issue. Assigning probabilities and making predictions depends on the selection of a history. The formalism supplies no basis for such a selection. Does this imply a serious incompleteness of the theory?

An answer to this question hinges on what one expects from a physical theory. Here there are two opposing perspectives. Adapting Laura Ruetsche's (2002) terminology, we may label them *Formalistic Imperialists* and *Dialectical Emergentists*. The clash between them is most clearly visible in contrasting evaluations of the standard model of particle physics. For a Formalistic Imperialist a theory must be mathematically precise and the mathematical formalism should have a consistency independent of its physical interpretation. Two distinct groups are in the forefront of this movement. The first group includes the developers of algebraic quantum field theory[12]. They reject the standard model of particle physics, in spite of its unprecedented success, because it does not meet their requirements for a properly formulated theory. The second group includes philosophers of science whose theories about the interpretation of theories supply a basis for evaluating current theories. Both syntactic and semantic reconstructions of theories take the mathematical formulation of a theory as the foundation for an interpretation. This entails the requirement that the mathematical formalism have a consistency independent of its physical interpretation. The standard model of particle physics, along with quantum electrodynamics and standard quantum field theory, does not meet this requirement.[13].

In the development of atomic and particle physics, theoretical breakthroughs emerge from and are tested through the ongoing dialog between theoreticians and experimenters. Theories emerge through processes of incorporation of theoretical hypotheses, adjustments, and compromises. The principal ingredients that led to the development of the standard model were: quantum physics; special relativity; group theory, especially Lie groups and Lie algebras (but not *-algebras); extension of symmetry principles to internal symmetries; the extension of gauge invariance from global to local gauges; the renormalization group, and spontaneous symmetry breaking. The constraints included considerations of analyticity, unitarity, covariance, and fitting Feynman diagrams. There was a sustained collective effort to fuse these into a viable synthesis. The standard model is a collection of disjoint parts weakly unified by a particle ontology. Its formulators generally relegate the development of properly formulated theories that meet *a priori* constraints to the status of a mopping up operation. Formalistic imperialists regard the standard model as an ugly collection of rules, rather than a proper theory.

Murray Gell-Mann provides the paradigm of dialectical emergence, with his development of the Eightfold way and the prediction of the Ω^- meson, the introduction of Lie groups and the quark hypothesis, and his major role in the shaping of the standard model. When he teamed up with James Hartle to study quantum cosmology they independently developed a consistent history formalism as a transformation of Feynman's sum-over-histories formulation and Everett's many-histories interpretation of QM (See Gell-Mann and Hartle 1990, 428-430). Consider their formulation of the task they set themselves:

> In a universe governed at a fundamental level by quantum-mechanical laws,

> characterized by indeterminacy and distributed probabilities, what is the origin of the phenomenological, deterministic laws that approximately govern the quasiclassical domain of everyday experience? What features of classical laws can be traced to their underlying quantum-mechanical origin?

In this context 'foundational' is ambiguous. In philosophical discussions it generally refers to a theory about ultimate entities, or at least the most basic entities known. Gell-Mann and Hartle suggest heterotic superstring theory as a candidate for this role. QM is not a theory about entities. The assumption is that the laws of QM are basic. The non-classical characteristic features of QM systems, indeterminacy, distributed probabilities, and interference, must be taken as characterizing the quantum realm (their later substitution for 'domain'). The distinctive features characterizing classical physics, large scale deterministic laws, should be considered phenomenological manifestations of the underlying classical reality. How can one use a formulation of QM plus various types of coarse grainings to reproduce these phenomenological manifestations? This is the goal of the G-H project. To evaluate this as a theoretical advance we should compare it with the standard model, rather than with *a priori* criteria for fundamental theories. A fundamental particle theory should explain the different coupling constants. The standard model does not deduce these. It accepts values determined from adjustments of experimental values. It is not the fundamental theory. Yet, it is a significant theoretical advance. Similarly, if the G-H project can show how a CH formulation of QM can supply a basis for explaining the appearance of large-scale deterministic laws, then it represents a significant theoretical advance, even if it cannot supply a deductive account of the perseverance of a quasiclassical order. Accordingly, we should consider the

G-H project as a theoretical advance, rather than a fundamental theory.

The universe is the ultimate closed system. Now it is characterized by formidable complexity, of which we have only a very fragmentary knowledge. The assumptions behind the big bang hypothesis confer plausibility on the further assumption that in the instant of its origin the universe was a simple unified quantum system. If we sidestep the problem of a state function and boundary conditions characterizing the earliest stages[14], we may skip to stages later than the Planck era, where space-time was effectively decoupled. Then the problem of quantum gravity may be avoided. The universe branched into subsystems. Even when the background perspective recedes over the horizon, a methodological residue remains, the treatment of closed, rather than open systems. To present the basic idea in the simplest form, consider a closed system characterized by a single scalar field, $\phi(x)$. The dynamic evolution of the system through a sequence of spacelike surfaces is generated by a Hamiltonian labeled by the time at each surface. This Hamiltonian is a function of $\phi(\mathbf{x},t)$ and the conjugate momentum, $\pi(\mathbf{x},t)$. On a spacelike surface these obey the commutation relations, $[\phi(\mathbf{x},t),\pi(\mathbf{x}',t)] = \imath\delta(\mathbf{x},\mathbf{x}')$ (with $\hbar, c = 1$). Various field quantities (aka observables) can be generated by ϕ and π. To simplify we consider only non-fuzzy 'yes-no' observables. These can be represented by projection operators, $P(t)$. In the Heisenberg representation, $P(t) = e^{\imath Ht}\, P(t_0)\, e^{-\imath Ht}$.

A sum over histories formulation of QM allows different histories. Using the index, k, to distinguish histories and the subscript, α to distinguish observables, an exhaustive set of 'yes-no' observables at one time is given by the set of projection operators, $\{{P^k}_{\alpha_k}(t_k)\}$. Since these are exhaustive and mutually exclusive,

$$\begin{aligned} {P^k}_{\alpha_k}(t_k)\,{P^k}_{{\alpha'}_k}(t_k) &= \delta_{\alpha_k {\alpha'}_k}\,{P^k}_{\alpha_k}(t) \\ \sum_{\alpha_k} {P^k}_{\alpha_k}(t_k) &= 1 \end{aligned} \tag{14}$$

A particular history can be represented by a chain of projection operators,

$$C_\alpha \;=\; P^n_{\alpha_n}(t_n)\cdots P^1_{\alpha_1}(t_1) \tag{15}$$

This is essentially the same as the Griffiths's formulation. The novel factor introduced here is a coarse graining of histories.

Coarse graining begins by selecting only certain times and by collecting chains into classes. The decoherence functional is defined as

$$D(\alpha', \alpha) \;=\; \mathrm{Tr}[C'_\alpha\,\rho\,C^\dagger_\alpha], \tag{16}$$

where ρ is the density matrix representing the initial conditions. In this context 'decoherence' has a special meaning. It refers to a complex functional defined over pairs of chains of historical projectors. The basic idea is the one we have already seen. Two coarse grained histories decohere if there is negligible interference between them. Only decoherent histories can be assigned probabilities. Different decoherence conditions can be set. (Gell-Mann and Hartle, 1995) We will consider two.

$$Weak: \quad Re\,Tr[C'_\alpha\,\rho\,C^\dagger_\alpha] \;= \delta(\alpha'\alpha)P(\alpha) \tag{17}$$

$$Medium: \quad Tr[C'_\alpha\,\rho\,C^\dagger_\alpha] \;= \delta(\alpha'\alpha)P(\alpha) \tag{18}$$

Weak decoherence is the necessary condition for assigning probabilities to histories. When it obtains the probability of a history, abbreviated as α is $P(\alpha) = D(\alpha\alpha)$. Medium decoherence relates to the possibility of generalized records. Here is the gist of the argument.

Consider a pure initial state, $|\psi\rangle$ with $\rho = |\psi\rangle\langle\psi|$. Alternative histories obeying exact medium decoherence can be resolved into branches that are orthogonal, $|\psi\rangle = \sum_\alpha C_\alpha|\psi\rangle$. Only when this condition is met are the corresponding projectors unique. If the projectors did not form a complete set, as in weak decoherence, then the past is not fixed. Other decompositions are possible. This relates to the more familiar notion of records when the wave function is split into two parts, one representing a system and the other representing the environment, $R_\alpha(t)$. These could not count as environmental records of the state of a system if the past could be changed by selecting a different decomposition. Thus, medium decoherence, or a stricter condition such as strong decoherence, is a necessary condition for the emergence of a quasiclassical order.

It is far from a sufficient condition. The order represented in classical physics presupposes deterministic laws obtaining over vast stretches of time and space. The GH program must show that it has the resources required to produce a quasiclassical order in which there are very high approximations to such large scale deterministic laws. At the present time the operative issue is the possibility of deducing such quasi-deterministic laws. The deduction of detailed laws from first principles is much too complex. Zurek, Feynman and Vernon, Caldeira and Leggett, and others initiated the process by considering simplified linear models. The GH program puts these efforts into a cosmological framework and develops methods for going beyond linear models. The standard implementation of a linear model represents the environment, or a thermal bath, by a collection of simple harmonic oscillators. In an appropriate model the action can be split into two parts: a distinguished observable, q^i, and the other variables, Q_i, the ignored variables that are summed over.

The G-H program extends this to non-linear models, at least in a programmatic way. I will indicate the methods and the conclusions. As a first step we introduce new variables for the average and difference of the arguments used in the decoherence function:

$$\begin{aligned} X(t) &= 1/2(x'(t) + x(t)) \\ \xi(t) &= x'(t) - x(t) \\ D(\alpha', \alpha) &= f(X, \xi) \end{aligned} \tag{19}$$

The rhs of eq. (19) is small except when $\xi(t) \approx 0$. This means that the histories with the largest probabilities are those whose average values are correlated with classical equations of motion. Classical behavior requires sufficient coarse graining and interaction for decoherence, but sufficient inertia to resist the deviations from predictability that the coarse graining and interactions provide. This is effectively handled by an analog of the classical equation of motion. In the simple linear models, and in the first step beyond these, it is possible to separate a distinguished variable, and the other variables that are summed over. In such cases, the analog of the equation of motion has a term corresponding to the classical equation of motion, and a further series of terms corresponding to interference, noise and dissipation. The factors that produce decoherence also produce noise and dissipation. This is handled, in the case of particular models, by tradeoffs between these conflicting requirements. The goal is to produce an optimum characteristic scale for the emergence of classical action. In more realistic cases, where this isolation of a distinguished variable is not possible, they develop a coarse graining with respect to hydrodynamic variables, such as average values of energy, momentum, and other conserved, or approximately conserved, quantities. A considerable amount of coarse graining is needed to approximate classical deterministic laws. Further complications, such as the branching of a system into subsystems, present complications not yet explored in a detailed way. Nevertheless the authors argue that they could be handled by further extensions of the methods just outlined. This represents a distinct advance in theoretical cosmology, even though much more work is needed, e.g., closing in on the conditions for the perseverance of quasiclassicality.

With this background we can attempt an appraisal of the ontological significance to be accorded consistent histories. Copenhagen QM is arguably the most successful interpretation in the history of physics in its empirical precision, and in the very wide range of phenomena treated. Yet, Copenhagen physics is grounded in the classical realm, the 'real for us'. The measurement formulation, which CH attempts to replace, treats the mathematical formalism of QM as an inferential tool for interrelating the results of actual and possible measurements. Interpretations of QM bundled under the banner, 'Taking Quantum Mechanics seriously', assume that the mathematical formalism of QM somehow represents features that characterize reality at a basic level, superposition, interference, distributed probability, and entanglement. There is an obvious analogy to Kant's 'phenomenon/noumenon' distinction. The CH formulation incorporates all the established features of the measurement interpretation and transposes them into a perspective where the formalism is regarded as a means of representing the properties characterizing basic reality, rather than an inference mechanism. It does not yet have the status of a fundamental theory. The CH formulation is, in my opinion, the only presently viable candidate to replace the Copenhagen interpretation.

Acceptance of this evaluation puts the problematic of realism in a totally different perspective. The 'really real' is the mesh of events unified through histories. At this level, the distinction between real and virtual processes has no purchase. What physical significance can be accorded virtual processes? If the CH formulation is regarded as a revision of the Feynman formulation[15], then one may consider the most detailed empirically successful application of this formulation, the treatment of the Lamb effect. To get precise results one must include all the pertinent virtual transitions of the electron to higher states and all the virtual processes proper to the perturbation level considered. To adapt d'Espagnat's apt term, these processes have a veiled reality. They are basic to reality. We can view them only through the veil of the QM formalism. This supports the evaluation that the present formulations of the Consistent Histories formalism should be interpreted as the first step beyond a measurement interpretation, not as a foundational theory.

Notes

[1] This is based on Griffiths (1984, 1996, 1997, 2002a, 2002b) and on Griffiths's helpful comments on an earlier draft of this material.

[2] Omnès 1994, p. 93, 1992, p.340. A less technical summary is given in his 1999. I am focusing primarily on Griffiths on the assumption that the philosophical systematization Omnès gives may be an obstacle to acceptance by philosophers.

[3] This idea of a distinctive form of quantum reasoning was developed by Omnès 1994 Chaps. 9, 12, and in Griffiths 1999, 2002a, Chap. 10.

[4] The Dowker-Kent criticism of the Gell-Mann–Hartle formulation will be considered later. Kent's (1996) criticism was answered by Griffiths and Hartle (1997), which was answered by Kent (1998). Here we are slighting the differences between contrary and contradictory inferences.

[5] See Griffiths 1997, and 2001b, chaps. 20-25 for a detailed treatment of quantum paradoxes.

[6] The differences between the Copenhagen interpretation and Bohr's interpretation of QM are clarified in Gomatam 2007.

[7] This was from a talk given in August 1925 before Bohr was familiar with Heisenberg's new formulation of QM. A more detailed analysis of this crisis may be found in MacKinnon 1982, chap. 5

[8] "The physical content of quantum mechanics is exhausted by its power to formulate statistical laws governing observations obtained under conditions specified in plain language". (Bohr 1958, p. 12)

[9] Schwinger's 1970 is the final version of earlier versions in unpublished notes. Schwinger's extension of this measurement interpretation to quantum field theory is summarized in MacKinnon(2007)

[10] Bohr's original development of the CP is summarized in Jammer (1966), pp. 109-117 and Petruccioli (1993), pp. 78-110. Born, Heisenberg, and Jordan claimed that their new matrix mechanics could be regarded as an exact formulation of Bohr's correspondence considerations. (See Darrigol(1992), 273-242.

[11] This will be treated in much more detail in a forthcoming book.

[12] Appraisals of the present state of AQFT are given in Haag 1992, Buchholz 1998, Buchholz and Haag 1999

[13] See Halvorson and Muger 2006, and Fraser 2006

[14] This is treated in Hartle (2002a, 2002b)

[15] Griffiths did not develop CH on this basis. However, Gell-Mann and Hartle explicitly develop CH as an extension of Feynman's sum-over-histories formulation . Gell-Mann claimed that Feynman explicitly endorsed this reformulation. See his letter reproduced in Goldstein 1999

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