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Quantum decoherence in a pragmatist view: Resolving the measurement problem

Abstract This paper aims to show how adoption of a pragmatist interpretation permits a satisfactory resolution of the quantum measurement problem. The classic measurement problem dissolves once one recognizes that it is not the function of the quantum state to describe or represent the behavior of a quantum system. The residual problem of when, and to what, to apply the Born Rule may then be resolved by judicious appeal to decoherence. This can give sense to talk of measurements of photons and other particles even though quantum field theory does not describe particles.

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1 Introduction

Attitudes to the quantum measurement problem vary widely. Optimists deny there is any problem, while pessimists maintain there is a serious problem that could be solved only by modifying quantum theory. An intermediate opinion is that while quantum theory does face a *prima facie* measurement problem, this problem is readily resolved by applying the unmodified theory to interactions that efficiently delocalize the phase of a system into its environment during a quantum measurement. Though widespread, this opinion remains controversial. Attempts to support it by argument have met objections from both optimists and pessimists intended to show why simply applying quantum theory to establish the rapid and effectively irreversible diagonalization of the reduced density operator of a system does not solve any problem posed by measurement in quantum theory.

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This paper aims to show how adoption of a pragmatist interpretation permits a satisfactory resolution of the quantum measurement problem. The classic measurement problem dissolves once one recognizes that it is not the function of the quantum state to describe or represent the behavior of a quantum system. The residual problem of when, and to what, to apply the Born Rule may then be resolved by judicious appeal to decoherence. This can give sense to talk of measurements of photons and other particles even though quantum field theory does not describe particles.

2 The classic measurement problem

The quantum measurement problem is to reconcile quantum theory with the fact that measurements have outcomes displaying patterns the theory is supposed to predict and (as far as possible) explain. The problem is most acute if one assumes that a system's quantum state gives a complete description of that system, for then the linearity of quantum theory implies that measurements typically fail to have outcomes, in manifest contradiction to experimental reports.

Discussions of measurement in quantum theory often begin with an idealized model discussed by von Neumann[1] in which a quantum state of a system S becomes correlated with that of a (quantum) apparatus system A. In a simple 2 qubit version of this model S acts as a c-NOT gate as follows:

$$\begin{aligned} |+\rangle_S \otimes |\Uparrow\rangle_A &\to |+\rangle_S \otimes |\Uparrow\rangle_A \\ |-\rangle_S \otimes |\Uparrow\rangle_A &\to |-\rangle_S \otimes |\Downarrow\rangle_A . \end{aligned} \quad (1)$$

By linearity, its action on a non-trivial superposed state ($|a|^2, |b|^2 \neq 0, 1$) of S is then

$$(a|+\rangle + b|-\rangle) \otimes |\Uparrow\rangle \to a(|+\rangle \otimes |\Uparrow\rangle) + b(|-\rangle \otimes |\Downarrow\rangle) \quad (2)$$

where the system subscripts have been omitted. According to the completeness assumption, equations (1) describe an interaction between an apparatus in some definite condition (say $\Uparrow$, with pointer pointing up) and a system with some definite property (symbolized either by $+$ or by $-$) that is undisturbed by the interaction, while the apparatus finally assumes a definite condition correlated to, and so recording, that property.

Applied to (2), however, the completeness assumption implies that after the interaction the system has neither property $+$ nor $-$, and the apparatus pointer points neither up nor down. If this were a faithful model of an actual quantum measurement, then that measurement would record no outcome for any non-trivial superposed state of S. Of course, the idealized model is wildly oversimplified, and one might have held out hope that a more realistic model of a quantum measurement could restore consistency with experimental observations. But a long history of failed attempts to solve the measurement problem by developing more realistic models of measurement as a linear interaction between quantum system and quantum apparatus has effectively removed that hope, as long as the completeness assumption remains in force.

Dirac[2] and Von Neumann[1] sought to preserve the completeness assumption by dropping linearity. They took measurement to "collapse" or reduce the quantum state stochastically onto an eigenstate of the measured observable. In the simple model this means replacing (2) by

$$(a\left|+\right\rangle + b\left|-\right\rangle) \otimes \left|\Uparrow\right\rangle \rightarrow \text{either } \left|+\right\rangle \otimes \left|\Uparrow\right\rangle, \text{ with probability } |a|^2 \qquad (3)$$
$$\text{or } \left|-\right\rangle \otimes \left|\Downarrow\right\rangle, \text{ with probability } |b|^2$$

This does reconcile quantum theory with the fact that measurements have outcomes. But it raises 'measurement' to the status of a primitive term in the principles of quantum theory, needed to mark the suspension of the normal continuous, linear dynamical evolution of the quantum state, and its temporary replacement by a nonlinear, stochastic evolution. This disqualifies quantum theory from giving any further account of the measurement process, leaving it quite unclear under what physical circumstances this process is supposed to occur. Moreover, many actual measurements do not leave the measured system in an eigenstate of the measured observable (Pauli[3] called these measurements of the second kind), and a measurement of a photon typically destroys or absorbs it.

Wigner[4, chapter 12] gave a classic restatement of the measurement problem. He took the problem to be that of reconciling the continuous, linear evolution of an unmeasured system's quantum state with its discontinuous, stochastic evolution on measurement—in the simple model, this means reconciling (2) with (3). Noting that (2) establishes a statistical correlation between results of possible observations on A and S, he concludes that while applying quantum theory to the measurement interaction (as does (2) in the simple model) does not (in general) show how measurement puts the measured system in a definite state, it does enable one to replace this task with the task of showing how observation of the apparatus puts *it* in a definite state.

> The problem of measurement on the object is thereby transformed into the problem of an observation on the apparatus. Clearly, further transfers can be made by introducing a second apparatus to ascertain the state of the first, and so on. However, the fundamental point remains unchanged and a full description of an observation must remain impossible since the quantum-mechanical equations of motion are causal and contain no statistical element, whereas the measurement does.[4, p.158]

A statistical element could be introduced into a quantum analysis of measurement by representing the initial state of a complex apparatus by a mixture of states from the eigenspace spanned by eigenvectors of the (massively degenerate) pointer position observable, all with the same eigenvalue. This could be regarded as the appropriate way of representing one's ignorance of the exact microstate of the apparatus. But this doesn't work, as Wigner shows:[1]

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[1] Von Neumann [1, pp.437-9] already in 1932 gave a similar demonstration of the failure of this "often proposed" attempt to reconcile the deterministic evolution of

It must be concluded that *measurements which leave the system object-plus-apparatus in one of the states with a definite position of the pointer cannot be described by the linear laws of quantum mechanics.* ([4, p.164] italics in the original)

This and other generalizations of the simple quantum model (2) of measurement establish the incompatibility between the linearity of quantum mechanical evolution and the occurrence of definite measurement outcomes only if the quantum state completely describes a system to which it is ascribed. Here and elsewhere in this article Wigner seems to accept this completeness assumption. But earlier indications that this cannot be his considered view are confirmed by his subsequent answer to the question "What is the state vector?" This makes it clear that he has abandoned the completeness assumption after initially seeming to accept it.

...the state vector is only a shorthand expression of that part of our information concerning the past of the system which is relevant for predicting (as far as possible) the future behavior thereof. ... *the laws of quantum mechanics only furnish probability connections between results of subsequent observations carried out on a system.* ([4, p.166] italics in the original)

Here he advocates a very different view of the role of the quantum state, not as describing physical reality but as predicting our observations of it. This promises to dissolve the classical measurement problem. We'll soon see how far it is able to do so. But first note the rather artificial character of that problem. Dirac and Von Neumann notwithstanding, immediate repetition of an actual measurement of a quantum observable does not always, or even usually, give the same result: it may disturb or even destroy the measured system. When necessary, we apply linear quantum theory in studying how measurement affects a system. Quantum measurements must be carefully designed if they are to fufill their intended function. Their design involves application of the linear laws of quantum theory itself, not some primitive stochastic law like (3). The only useful function of Von Neumann's[1] postulation of stochastic collapse (his process 1) is to account for the possibility of definite outcomes of quantum measurements. But there is a need for something to play that role only if the quantum state completely describes the behavior of a quantum system.

3 How to dissolve it

If one accepts Wigner's[4] view of the quantum state one can try to reconcile (2) with (3) like this. (2) represents the evolution of information concerning the past of S and A. Observation of A adds new information: either that $\Uparrow$

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the quantum state with the statistical results of observations. This may have been the first of many demonstrations of "the insolubility of the quantum measurement problem" involving successive removal of idealizations of the simple model (2) of measurement: these now include, for example, [5],[6],[7],[8].

is true, or that $\Downarrow$ is true. On the basis of this new information, one should update the information represented by the right-hand side of (2) either to the information represented by $|+\rangle \otimes |\Uparrow\rangle$ or to the information represented by $|-\rangle \otimes |\Downarrow\rangle$. The right-hand side of (3) correctly represents the state of information of one who knows of the observation of A but is ignorant of its result, while the right-hand side of (2) correctly represents the information concerning the past of S and A prior to observation of A. (2) and (3) do not represent incompatible states of affairs, since no quantum state involved represents any state of affairs.

On this view, the function of a quantum state is not to represent the condition of a system to which it is ascribed, but to summarize information gleaned from prior observations that is relevant to predicting the probability of each possible outcome of any future observation. Wigner[4] claims to be reporting the orthodox view on measurement of the late 1920s: his view of the quantum state was held by Heisenberg[9], Peierls[10] and others and has a number of contemporary advocates.[2] The view promises to dissolve the classic measurement problem. If one denies that the evolution of a quantum state represents the changing physical condition of the system to which it is ascribed, it is no longer problematic that this state evolves in radically different ways according as the system is or is not measured. The quantum state does not track changes in the system, but in the available information relevant to predicting outcomes of future measurements on the system. This information changes discontinuously as more information becomes available, namely the results of relevant observations. In the Heisenberg picture, the quantum state changes *only* when this happens: in the Schrödinger picture, the state changes continuously, absent observational input. These are two different ways of keeping track of the information available to an agent who learns nothing new from observation, if that information is to continue reliably to predict statistics for outcomes of future measurements on the system.

By denying the completeness assumption, Wigner's view of the quantum state removes much of the sting of the measurement problem. On this view there is no inconsistency between the right hand side of (2) and an observation report of a definite (up or down) position of the apparatus's pointer after it has interacted with the system. But the view faces difficulties of its own. If the state vector is only a shorthand expression of the relevant part of *our* information, then the state vector should be updated whenever *one* of us learns of the result of a relevant observation, even though that new information remains unavailable to others.

Wigner was aware of this consequence of his view, even highlighting it in his "friend" paradox.[4, pp.179-81] If a friend updates "our" information on learning the outcome of a quantum measurement on a non-trivially superposed state conducted in an isolated laboratory, then anyone outside the laboratory should immediately adopt a new quantum state for the entire laboratory (including the "friend" as a physical object) that is in principle empirically distinguishable from the non-trivial superposition resulting from

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[2] Friederich[11] lists 12 recent papers developing versions of similar views in his second footnote.

the linear evolution of its prior quantum state. The decision to count the "friend" as one of us has empirical consequences.

To avoid the threat of solipsism, Wigner concluded that by becoming *consciously* aware of the outcome of a quantum measurement, someone could affect outcomes of future observations in a way that could not be brought about by any interaction with an unconscious physical system. This view now requires modification of quantum theory, and acknowledgment that Von Neumann's process 1 is a physical process that supersedes linear evolution just when the outcome of a quantum measurement is consciously registered. This is clearly not a satisfactory solution to the measurement problem. It involves not only modifying quantum theory, but replacing the unmodified theory with a vaguely formulated mixture of physics and psychology. Wigner's "friend" paradox is a *reductio ad absurdum* of the view that the state vector is only a shorthand expression of the relevant part of *our* information. But a natural variant of the view escapes the paradox and offers renewed hope of dissolving the measurement problem.

The key is to recognize that differently situated agents, with different information available to them, should ascribe different quantum states to one and the same system. This does not make the quantum state subjective. A system has an objective quantum state relative to the information accessible to an agent in each specific situation: but in so far as the accessible information depends on the physical situation of an (actual or potential) agent, so too does the quantum state for that agent-situation. This point has been explicitly recognized by some[10],[11],[12],[13],[14]. Brun *et al.*[15] show how much state assignments can differ on this view of a quantum state as a shorthand expression of that part of *a situated agent's* information which is relevant for predicting (as far as possible) the outcomes of measurements on a quantum system.[3]

On this latest view, a system is not *in* a quantum state, and does not *have* a (unique) quantum state.[13] Rather, it may be *assigned* a quantum state by an agent for the purposes of applying quantum theory, and the state to be assigned is a function of the (actual or hypothetical) physical (and *therefore* epistemic) situation of the one who assigns it. Relativizing a quantum state assignment to the information available to an agent helps to dissolve the measurement problem, but it does not yet answer an important question: How is an agent to update her quantum state on learning the result of a quantum measurement?

Dirac and Von Neuman took measurement of an observable to leave a system in an eigenstate of the corresponding operator with eigenvalue equal to the measured value. This gives a unique updating rule only following the measurement of an observable with non-degenerate eigenvalues whose eigenvectors span the system's Hilbert space. Lüders refined this to the following

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[3] Accepting the relativization of quantum state assignments to agent-situation also makes it easier to reconcile quantum theory with violations of Bell inequalities without any physical nonlocality and in conformity with fundamental Lorentz invariance (see [12], [13], [14], [16],[17]).

unique updating rule for a measurement of A that locates its value in Δ:

$$\rho \longrightarrow \rho' = \frac{P^A(\Delta)\rho P^A(\Delta)}{Tr[P^A(\Delta)\rho P^A(\Delta)]}, \tag{4}$$

where $P^A(\Delta)$ projects onto a subspace of vectors, each of which predicts that a measurement of observable A will (with probability 1) find a value in set Δ. A state updated in accordance with this rule will (with probability 1) yield the same outcome in an immediately repeated measurement of A, while leaving unchanged the relative probabilities for outcomes in a measurement of commuting observable B compatible with that outcome for A. Despite figuring prominently in some views of quantum theory, [18],[19],[20] Lüders' rule is clearly an incorrect way to update a quantum state after many actual measurements.[3],[21] The momentum of a neutron will change if it is measured by observing the track of a (previously stationary) recoil proton in a bubble chamber: measuring the position of a photon absorbs it at a localized detector. Pauli classified such measurements as of the second kind in order to *distinguish* them from measurements conforming to Von Neumann's process 1.

Actual measurements are more realistically modeled by POVMs[22], and the state following a POVM $\{E_i\}$ may be specified in terms of a set of measurement operators $\{M_i\}$ compatible with (but not defined by) it:

$$E_i = M_i^\dagger M_i \tag{5}$$

in which case the appropriate updating rule for a measurement with ith outcome is

$$\rho \longrightarrow \rho' = \frac{M_i \rho M_i^\dagger}{Tr[M_i \rho M_i^\dagger]} \tag{6}$$

There is no general rule for associating a particular measurement device with a POVM, nor for updating the quantum state of a system following a measurement by that device. One cannot specify either $\{E_i\}$ or $\{M_i\}$ theoretically without providing a quantum analysis of the interaction involved in the measurement. That analysis will depend on an application of the linear evolution of the combined state of system and detector (and detector of the detector...), which concludes either by applying classical physics to some device or with the claim that the "pointer position" or "click" of some detector was directly observable. The residual measurement problem is posed by the need to justify this concluding "objectification" step.

4 The residual measurement problem

With advances in technology and increased application of quantum theory to individual systems (e.g. in quantum optics and quantum computing), its has become increasingly important to design and characterize quantum measuring devices. Experimentally, tomography of quantum detectors has been

employed to determine what POVM characterizes a photon detector by "measuring the measuring device".[23] This involved comparing the detector response (in the form of a discrete number of "clicks", each intended to indicate detection of a single photon) with the probability of observed photon number predicted by applying the Born Rule to a pulse of incident laser light whose quantum state was taken to be approximately coherent. Increased complexity makes it harder and harder to model the operation of a detector quantum mechanically as a linear interaction between system and detector. Braginsky *et al.*[24] even said

> The Schrödinger equation cannot tell us the connection between the design of the measuring device and the nature of the measurement, because the Schrödinger equation neither describes nor governs the process of measurement. (p.38)

Their reason for saying this was that while the Schrödinger equation is reversible and deterministic, the reduction of the wave-function on measurement is irreversible and non-deterministic. But as Wigner already recognized, this does not prevent one from modeling the system/detector interaction by the linear evolution of their joint state: it merely requires one to accept that the measurement is not complete until the detector records a "click" in a way that (randomly) singles out one component of the resulting superposition.

This is the residual measurement problem: Given a superposed entangled state (such as that of quantum system and quantum detector), under what circumstances is it legitimate to infer that (at least) one of the entangled systems *has* some definite property, with probability given by the Born Rule? The completeness assumption implied that this is never a legitimate inference: but that assumption has now been rejected along with a representational view of the quantum state. The no-go theorems of Gleason[25], Bell[26], Kocken and Specker[27] (among others) imply that this is not always a legitimate inference. To resolve the residual measurement problem we need to formulate and defend a better answer. This can be done by applying the quantum theory of decoherence in the right way.

5 How to resolve it

In explaining how quantum decoherence helps solve the residual measurement problem, it will be useful to be able to refer to a simple model of decoherence introduced by Zurek[28] and further discussed in Cucchetti, Paz and Zurek[29]. Consider a single quantum system A interacting with a second "environment" system E. A is a single qubit, and its environment E is modeled by a collection of N qubits. One can think of each qubit as realized by a spin $\frac{1}{2}$ system, so that $|\Uparrow\rangle$ ($|\Downarrow\rangle$) represent z-spin up (down) eigenstates of the Pauli spin operator $\hat{\sigma}_z$ of A, while $|\uparrow\rangle_k$ ($|\downarrow\rangle_k$) represent z-spin up (down) eigenstates of $\hat{\sigma}_z^k$ for the the kth environment spin subsystem.

The individual Hamiltonians $\hat{H}^A$, $\hat{H}^E$ of A and E are assumed to be zero, while the interaction Hamiltonian $\hat{H}^{AE}$ has the form

$$\hat{H}^{AE} = \frac{1}{2}\hat{\sigma}_z \otimes \sum_{k=1}^{N} g_k \hat{\sigma}_z^k. \tag{7}$$

If A, E are assumed to be initially assigned pure, uncorrelated states

$$\psi_A = (a\,|\Uparrow\rangle + b\,|\Downarrow\rangle)\,, \tag{8}$$

$$\psi_E = \prod_{k=1}^{N} (\alpha_k\,|\uparrow\rangle_k + \beta_k\,|\downarrow\rangle_k) \tag{9}$$

then the initial state

$$\Psi(0) = \psi_A \otimes \psi_E \tag{10}$$

evolves according to the Schrödinger equation, becoming

$$\Psi(t) = (a\,|\Uparrow\rangle\,|\mathcal{E}_\Uparrow(t)\rangle + b\,|\Downarrow\rangle\,|\mathcal{E}_\Downarrow(t)\rangle) \tag{11}$$

at time t where

$$|\mathcal{E}_\Uparrow(t)\rangle = \prod_{k=1}^{N} \left(\alpha_k e^{ig_k t}\,|\uparrow\rangle_k + \beta_k e^{-ig_k t}\,|\downarrow\rangle_k\right) = |\mathcal{E}_\Downarrow(-t)\rangle\,. \tag{12}$$

The state of A, calculated by tracing over the Hilbert space of E, is therefore

$$\hat{\rho}_A(t) = |a|^2\,|\Uparrow\rangle\,\langle\Uparrow| + ab^* r(t)\,|\Uparrow\rangle\,\langle\Downarrow| + a^* b r^*(t)\,|\Downarrow\rangle\,\langle\Uparrow| + |b|^2\,|\Downarrow\rangle\,\langle\Downarrow|\,. \tag{13}$$

The coefficient $r(t) = \langle\mathcal{E}_\Uparrow(t)|\mathcal{E}_\Downarrow(t)\rangle$ appearing in the off-diagonal terms of $\hat{\rho}_A$ here is

$$r(t) = \prod_{k=1}^{N} \left[\cos 2g_k t + i\left(|\alpha_k|^2 - |\beta_k|^2\right)\sin 2g_k t\right]. \tag{14}$$

Cucchetti, Paz and Zurek[29] show that $|r(t)|$ tends to decrease rapidly with increasing N and very quickly approaches zero with increasing t. More precisely, while $|r(t)|^2$ fluctuates, its average magnitude at any time is proportional to 2^{-N}, and, for fairly generic values of the g_k, it decreases with time according to the Gaussian rule $|r(t)|^2 \propto e^{-\Gamma^2 t^2}$, where Γ depends on the distribution of the g_k as well as the initial state of E. This result is relatively insensitive to the initial state of E, which need not be assumed to have the product form (9), though if the environment is initially in an eigenstate of (7) $|r(t)| = 1$ so the state of A will suffer no decoherence. Since $r(t)$ is an almost periodic function of t for finite N, it will continue to return arbitrarily closely to 1 at various times: but for N corresponding to a macroscopic environment Zurek[28] estimated that the corresponding "recurrence" time exceeds the age of the universe.

Zurek[30] called the unitary evolution (2) a *premeasurement*, and stressed that no actual measurement can be said to have taken place until A interacts with its environment. This interaction may be represented by (7) in an extension of this simple model. The result is this generalization of (11)

$$\Psi(t) = (a\,|+\rangle\,|\Uparrow\rangle\,|\mathcal{E}_{\Uparrow}(t)\rangle + b\,|-\rangle\,|\Downarrow\rangle\,|\mathcal{E}_{\Downarrow}(t)\rangle)\,, \qquad (15)$$

where $|\mathcal{E}_{\Uparrow}(t)\rangle\,,|\mathcal{E}_{\Downarrow}(t)\rangle$ are given by (12). Zurek[28] defends a slight generalization of this model to an n-dimensional Hilbert space $\mathcal{H}_S$ and $n+1$ dimensional Hilbert space $\mathcal{H}_A$ as an idealized model of *measurement* on two grounds.

First, the form (15) preserves the correlation between component states of S,A under the influence of the environmental interaction (7), and thereby singles out a "pointer basis" $|\Uparrow\rangle\,,|\Downarrow\rangle$ of states in $\mathcal{H}_A$ that correlate with preferred states $|+\rangle\,,|-\rangle$ of S. This is important, since the right-hand side of (2), representing the state after the premeasurement, may be expressed as an entangled superposition in a continuous infinity of other orthogonal bases of $\mathcal{H}_A$. But none of *these* correlations will be preserved under (7). This defines the interaction as a measurement of an observable Q on S corresponding to a self-adjoint operator $\hat{Q}$ of which $|+\rangle\,,|-\rangle$ are eigenvectors. Second, as $|\mathcal{E}_{\Uparrow}(t)\rangle\,,|\mathcal{E}_{\Downarrow}(t)\rangle$ quickly become (and remain indefinitely) very nearly orthogonal, the reduced state ρ_{SA} similarly stably becomes very nearly diagonal in the $\{|+\rangle\,,|-\rangle\} \times \{|\Uparrow\rangle\,,|\Downarrow\rangle\}$ basis of $\mathcal{H}_S \otimes \mathcal{H}_A$. Zurek apparently believes this endows claims about both the value of Q and the value of the "pointer position" P (corresponding to operator $\hat{P}$ on $\mathcal{H}_A$ with eigenvectors $|\Uparrow\rangle\,,|\Downarrow\rangle$) with enough significance to justify application of the Born Rule, warranting one confidently to expect these values rapidly and stably to become both definite and correlated.

The idealizations involved in this simple model are so severe that it can reasonably be applied to few if any actual cases in which physicists take themselves to measure the value of a magnitude on a quantum system. It covers only measurements of the first kind: it assumes the quantum states of A and E are initially pure, so that the initial quantum states of S and A are unentangled and both are unentangled with the state of E: it further assumes the initial state of A is $|\Uparrow\rangle_A$: it neglects any effects of the individual Hamiltonians of S,A,E on the evolution of the total state: and it assumes that the environment does not interact with S directly, or with A during the interaction between S and A. But if the model is generalized to relax these idealizations, it is not clear that it retains the features that Zurek took to ground its defense as a model of *measurement*.

According to Zurek[30]

> In the idealized case, the preferred basis was distinguished by its ability to retain perfect correlations with the system in spite of decoherence. This remark will serve as a guide in other situations. It will lead to a criterion—the predictability sieve—used to identify preferred states in less idealized circumstances. (p.734)

However, his applications of the predictability sieve in less idealized circumstances typically concern only *two* systems: while these are often labeled A and E, a third system S plays no role. So he effectively abandons his first

line of defense that his idealized model is of *measurement*. But by doing so he suggests a more flexible analysis of the role of decoherence in measurement.

The idea is to drop any requirement that refers to the post-measurement condition of the measured system itself, and concentrate only on securing the direct applicability of the Born Rule to significant claims about the "pointer position" of a system thought to have interacted with it. As we saw, the subsequent state of the system depends on details of the measurement interaction that are irrelevant to justifying application of the Born Rule to claims about the outcome recorded by a detector. One can think of the measured system as effectively absorbed into an environment $E = E' \oplus S$ that also includes degrees of freedom of a physical apparatus independent of its "pointer" degree of freedom. The "pointer position" P is then represented by an operator $\hat{P}$ in a Hilbert space $\mathcal{H}_A$ spanned by a preferred basis of its eigenstates, the "pointer states". The total state is then represented in $\mathcal{H}_A \otimes \mathcal{H}_E$.

So consider an interaction between a system S and an "apparatus" $A \oplus E'$ with initial states $|\psi_i\rangle_S , |\psi_{0j}\rangle$ respectively, where

$$|\psi_{0j}\rangle = |\varphi_0\rangle_A \otimes |\varphi_j\rangle_{E'} . \tag{16}$$

Here $|\varphi_0\rangle_A$ represents the "ready to measure" state of the "pointer" subsystem, and $|\varphi_j\rangle_{E'}$ is some basis vector in an environment-system Hilbert space E' that also represents degrees of freedom of the physical apparatus. To serve as a measurement, the interaction should set up a correlation between the initial state of the system and the value of a "pointer position" magnitude P on the apparatus. In the absence of interaction with the environment, such an interaction may be thought of as follows (for some normalized $|\chi_{ijk}\rangle_S$, $|\chi_{ijk}\rangle_{E'}$)

$$|\varphi_0\rangle_A \otimes |\psi_i\rangle_S \otimes |\varphi_j\rangle_{E'} \longrightarrow |\varphi_i\rangle_A \otimes \sum_k \alpha_{ijk}(|\chi_{ijk}\rangle_S \otimes |\chi_{ijk}\rangle_{E'}) : \tag{17}$$

and so, by linearity,

$$|\varphi_0\rangle_A \otimes \sum_i c_i |\psi_i\rangle_S \otimes |\varphi_j\rangle_{E'} \longrightarrow \sum_i c_i(|\varphi_i\rangle_A \otimes \sum_k \alpha_{ijk}(|\chi_{ijk}\rangle_S \otimes |\chi_{ijk}\rangle_{E'})). \tag{18}$$

But suppose interaction between A and E' rapidly renders environmental states corresponding to distinct values of i effectively orthogonal $({}_{E'}\langle\chi_{i'jk}|\chi_{ijk}\rangle_{E'} \to 0$ for $i' \neq i)$. Then the reduced state ρ_A will stably approach diagonal form in the $|\varphi_i\rangle_A$ basis. A more realistic model would take the initial "apparatus" state to be a mixture of states of the form (16), with variable j. The reduced state ρ_A will stably approach diagonal form in the $|\varphi_i\rangle_A$ basis in this model also. While this remains a very crude model of measurement, I think it will help to indicate the role of decoherence in establishing the applicability of the Born Rule to the results of measurements, as represented by significant claims about the value of a magnitude ("the pointer position") on a system that serves as an apparatus.

The residual quantum measurement problem was to answer the question: Given a superposed entangled state, under what circumstances is it legitimate to infer that (at least) one of the entangled systems *has* some definite

property, with probability given by the Born Rule? When this question was posed in the previous section, it may have appeared that the relevant entangled state is that of a quantum system and quantum detector(s) following their interaction. Now we see the importance of acknowledging the role of an environment that makes quantum system plus quantum detector(s) itself an open system.[4] In terms of the simplified model, environmental interactions transfer the relevant entanglement from $S + A$ to $A + E$. Their effect is then to delocalize the phase of A into E so that the reduced state of A rapidly and stably becomes very nearly diagonal in the "pointer basis".

According to the pragmatist interpretation I outline in [14], *this is exactly what is required to license application of the Born Rule to claims about the position of A's pointer.* The Born Rule may be applied only to claims with a well-defined meaning. The significance of a claim depends on the context, as specified by the nature and extent of decoherence. When there is extensive and robust decoherence in the "pointer basis", a claim about the pointer position is richly significant, since it supports dynamic and measurement inferences: in this context, repeated measurements of the pointer position do give the same result if repeated quickly enough, and one can consistently take such results to confirm that the pointer position evolves continuously, whether or not it is measured. The Born Rule is not limited in its application to measurement outcomes (however these may be characterized). But the claims to which it may justifiably be applied do include some that we endow with the additional significance of reporting the outcome of some measurement, whether in a laboratory experiment or elsewhere (e.g. in the context of measurement-based quantum computation).

Quantum theory cannot account for the fact that claims about the values of magnitudes have truth-values or that measurements have outcomes for the simple reason that its application *presupposes* that they do—or more specifically that the set of significant claims of the form $\mathbf{Q} \in \mathbf{\Delta}$ concerning a system to which the Born Rule is applicable contains a Boolean algebra of events over which a Boolean homomorphism defines a (classical) truth-value assignment. But it is not at all surprising that a measurement has some outcome. Quantum theory is empirically based on observations of measurement outcomes: and application of the Born Rule to a corresponding claim leads one to assign some definite (though sometimes small) credence to whatever outcome is observed. Since the application of the Born Rule is not limited to the outcomes of measurements, it is equally unsurprising that the world can be truly described by many other claims—enough to constitute a rich description in non-quantum terms.

Quantum decoherence through environmental delocalization of phase has often been take to explain the appearance of a classical realm, though both the meaning and truth of this claim remain controversial. One could take the claim to be that classical physics is reducible to quantum theory, or (in a different usage) that quantum theory reduces to classical physics in some

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[4] In fact the relevant environment includes subsystems of the detector(s) corresponding to degrees of freedom other than those associated with the "pointer observables" whose positions are intended to record an outcome of the measurement.

appropriate limit (e.g. as $\hbar \to 0$). The concepts of reduction involved here cry out for further clarification. But the pragmatist interpretation of quantum theory outlined in [14] encourages no such reductionist claim, since on this interpretation one does not use quantum states to describe a "quantum world" within which a (quasi)classical realm may emerge. An agent is well-advised to use quantum states as a guide in assessing the content and credibility of various claims about physical systems, and sometimes is justified in wholly believing some such claims. But the truth of those claims does not then rest on that of any underlying *quantum* truths about these or any other systems. If that is what Bohr meant by his reported remark "There is no quantum world" then he was correct.[31]

Nevertheless, an agent applying quantum theory may be warranted in making claims that would also be warranted within classical physics, and these claims may be justified by suitable application of the quantum theory of environmental decoherence. Hornberger, Sipe and Arndt[32] applied the quantum theory of environmental decoherence to show why one would be warranted in expecting the visibility of the interference pattern to decrease in the experiment of Hackermüller *et al.*[33] as they increased the laser heating of the fullerene molecules that passed through their interferometer until the pattern accorded with classical physics. The theory of quantum Brownian motion[34] already provides a simplified model of how claims about the classical trajectory of a quantum particle bound in a harmonic potential may be warranted as a result of environmental decoherence. A more sophisticated application of the quantum theory of decoherence would be expected to provide an even stronger warrant for claims about the fixed locations of the fullerenes deposited on the silicon surface in the experiment of Juffman *et al.*[35]—claims that would also be a consequence of applying classical physics to their initial locations on the surface.

There are cases in which quantum theory itself seems to imply a claim about the value of a magnitude. Ehrenfest's theorem is even adduced as a case in which a law of classical mechanics (Newton's second law of motion) follows from a law of quantum mechanics in suitable circumstances. For a single particle subject to a potential $\Phi(\mathbf{r}, t)$ the following is an easy consequence of the Schrödinger equation:

$$\frac{d}{dt}\langle \mathbf{p} \rangle = -\langle \nabla \Phi \rangle \qquad (19)$$

This closely resembles Newton's second law in the form $d\mathbf{p}/dt = -\nabla\Phi$. But what it actually says is rather different: that the rate of change of the *expectation value* of momentum equals minus *the expectation value* of the gradient of the potential. A claim about the expectation value of a magnitude is not a claim about the actual value of that magnitude. According to the pragmatist interpretation outlined in [14] its function is not to describe values of magnitudes but rather to guide an agent's *expectation* as to their values. Indeed, the terminology of "expectation values" nicely captures this function. Mathematically, an expected value is the mean of a random variable in a probability distribution—in this case calculated by application of the Born Rule to a quantum state. But how can such applications be justified

in the case of (19) when the magnitudes on either side of the equation are represented by non-commuting operators that have no joint distribution in any quantum state?

The quantum theory of decoherence can help answer this question. If the particle in question is subject to the right kind of environmental interaction (e.g. weakly coupled to an oscillator bath, as in the case of quantum Brownian motion[34]) its reduced quantum state will rapidly and robustly become approximately diagonal in a basis of coherent states. This will justify application of the Born Rule both to claims about its position $\mathbf{r}$ (and functions such as $\Phi(\mathbf{r})$) and to claims about its momentum $\mathbf{p}$. When the Wigner function of this quantum state is non-negative everywhere it is even possible to represent these as deriving from a corresponding joint probability distribution, though such representation is merely a technical convenience. Any agent applying quantum theory is then warranted in believing both that the particle has some reasonably well defined position and momentum and that these will almost certainly evolve continuously in accordance with Newton's second law. If the agent is warranted in ascribing a *particular* narrow Gaussian wave-function as the initial quantum state, then the warrant extends to confident belief in claims restricting the particle's position and momentum to values close to the peak of that evolving Gaussian.

Among many similar examples in which the quantum theory of decoherence justifies replacing quantum expectation values by corresponding claims about non-quantum magnitudes is this important claim:

> When a constant voltage V is applied across a Josephson junction, an alternating current I with frequency $2(e/h)V$ flows across the junction.

Each of the voltage V and the current I here results from identification of a non-quantum magnitude with an expectation value in a quantum analysis that associates "macroscopic wave-functions" with the superconductor on either side of the junction. In any experimental realization of this AC Josephson effect, it is environmental decoherence acting on these wave-functions that justifies application of the Born Rule, though no simple model of such decoherence may be available.

6 Measuring photons

Measurement of photons has always been difficult to reconcile with the Dirac-Von Neumann account of measurement.[36] This process can be accommodated within the more general POVM framework by associating it with measurement operators such as $\{M_n\}$ ($n = 0, 1, ...$), each element of which projects a Fock state of the quantized electromagnetic field onto the vacuum state:

$$M_n = |0\rangle \langle n| . \tag{20}$$

But notice that these do not yield any subsequent state of the photon, but the "zero-photon" state of the electromagnetic field—in other words, the measurement destroys the measured photon. A more general treatment of

measurement of the quantized electromagnetic field may be given in terms of measurement operators that modify its state in ways that do not correspond naturally to measurements of photons, such as the coherent state measurement operators

$$M_\alpha = 1/\sqrt{\pi} \, |\alpha\rangle \, \langle\alpha| . \tag{21}$$

Nevertheless, many experiments in quantum optics are taken to involve measurements on single photons, and the Born Rule is applied to claims about their properties, including even their positions. How can this be justified?

Sinha *et al.*[37] set out to test an important implication of the Born Rule: In the interference pattern resulting from more than two paths, the interference terms are the sum of the interference terms in the patterns resulting from these paths taken two at a time. They matched observed interference patterns against an instance of this implication in a variety of experiments involving the interference of light at up to three slits. One of these involved single photons, detected in coincidence with a second "herald" photon from an entangled pair by two avalanche photodiodes. The experimental interference pattern is generated by moving a multimode optical fiber uniformly across a plane intercepting light from the slits and counting the relative number of photons detected in each small region.

One can understand this experiment as a test of the Born Rule only if that rule is applicable to the experimental data. Perhaps the simplest way to apply it would be to claims of the form:

(X) The position of the photon lies between x and $x + \Delta x$

Here Δx represents a small interval of positions in a direction perpendicular to the slits and the optical axis, and the claim concerns the position in the tracking plane where a photon enters the fiber. But there are reasons to question the significance of a claim of this form here. There is no well-behaved position operator in relativistic quantum theories, and it is difficult if not impossible to understand a relativistic quantum field theory as *describing* localized particles.[38],[39],[40] Any talk of photons acquires whatever theoretical significance it has from applications of the quantum theory of the electromagnetic field. In cavity quantum electrodynamics, for example, it is often convenient to use the term 'photon' when considering quantized energy states of the field in the cavity.

Photon talk also acquires practical significance in quantum optics experiments like that of Sinha *et al.* In the course of their review of several such experiments, Zeilinger *et al.*[41] say

...the quantum state is simply a tool to calculate probabilities. Probabilities of the photon being somewhere? No, we should be even more cautious and only talk about probabilities of a photon detector firing if it is placed somewhere. One might be tempted, as was Einstein, to consider the photon being localized at some place with us just not knowing that place. But, whenever we talk about a particle, or more specifically a photon, we should only mean that which a 'click in the detector' refers to.

Indeed, Sinha *et al.* take the Born Rule to specify the probability (density) *to find* or *detect* a particle at position r, not for a particle to *be* at r. But of course such appeals to experimental practice do not answer the interpretative question as to exactly when and why an agent applying quantum theory is entitled to claim that a particle has been detected at position r. In the pragmatist interpretation outlined in [14] the quantum theory of decoherence can help answer this question.

In the present situation, no significant decoherence occurs before the quantized electromagnetic field interacts through the photoelectric effect with electrons in the avalanche photodiodes. Such interaction directly endows a claim about a system with a rich empirical significance only at the photodiodes themselves. But it may be taken thereby indirectly to render significant some claim about photon position at the interception plane across which the multimode optical fiber is tracked. For the "backtracking" inference from a warranted claim about the value of a magnitude at the photodiode to some claim about photon position in the interception plane may seem justified here by the assumption that the multimode fiber provided the only available channel through which the field could propagate. This suggests that such an inference could legitimize application of the Born Rule to claims of the form (X) concerning the position of photons in the interception plane. But that is not quite right.

The photodiode is designed to produce a substantial (milliampere) electron current when light injects even a single electron into the depleted region by the photoelectric effect. In practical terms, the subsequent amplification process in the photodiode is highly irreversible, but it is not this irreversibility but rather the associated decoherence that ensures that some claim about a magnitude on a system within the diode directly acquires substantial empirical significance. This is not, however, a claim about the position of a photon.

Neither I nor the authors of Sinha *et al.* have presented any quantum model of decoherence at the avalanche photodiode in the experiment described. But it is not necessary to advance such a model to be sure that almost immediately after any electron is freed by the photoelectric effect a claim about *some* system within the diode will acquire substantial empirical significance through interactions with the system's environment. Exactly what this system is and what magnitude figures in the claim is immaterial to the operation of the photodiode. So in practice the effective nature and location of the 'detector click' cannot be specified more precisely than somewhere within the photodiode's "window" of sensitivity. The spatial window is comparable to the 65 micron core of the multimode fiber whose aperture probes the interference: the temporal window is of the order of nanoseconds. But the practical impossibility of verifying, or even unambiguously specifying, any more precise claim about a system at the photodiode here is not what determines the limits of empirical significance of such magnitude claims and whether this justifies applying the Born Rule to them.

Electrons ejected from a metal surface by the photoelectric effect have a definite energy, as experiments reveal. Similarly, it is generally assumed that when an electron is ejected into the depletion region of a photodiode it has

a definite energy, equal to the difference between the energy of the photon involved and the electron's binding energy. This goes along with the idea that the electron was ejected from a definite energy level—an assumption that implicitly depends on a model of decoherence for the crystalline structure of the semiconductor. So a claim of the form

(Y) The kinetic energy of an ejected electron is $E > 0$

owes its substantial empirical significance to energy decoherence affecting systems within the photodiode. One may take this as a claim about an event corresponding to detection of the photon—to what Zeilinger *et al.* call a click in the detector—even prior to the electron avalanche it induces. On the interpretation sketched in [14], it is claims such as this that indirectly justify application of the Born Rule to claims about photon position in the interception plane.

Taken literally, the claim (X) has no empirical content in this experiment since it cannot be grounded either in the quantum theory of light or in experimental practice. To justify application of the Born Rule the claim must therefore be reformulated or reinterpreted. So consider the following reformulation, which, as we have seen, accords well with how many physicists express themselves.

(X′) The position of the photon is detected between x and $x + \Delta x$

The content of (X′) is quite unclear as it stands. But one can now use an inferentialist account of content to clarify it. The key is to link the content of (X′) to that of (Y) by taking it as an essential part of the content of (X′) that it follow by a justified (though not deductively valid) inference from (Y). This is not to equate the contents of (X′) and (Y)—these claims certainly don't mean the same thing. But (X′) owes its substantial empirical significance to this close inferential relation to (Y), and that is what justifies application of the Born Rule—not to (X) but to (X′). Here and elsewhere, the empirical significance of a magnitude claim about a system (in this case, the claim (X′)) hinges on what actually happens *later*. Moreover, the pivotal later event may involve a distinct system (the ejected electron, in this case).

7 Measurement and Quantum Fields

We saw that measurement of photons is just a special case of measurement of the state of the quantized electromagnetic field. This is only one of many relativistic quantum fields that figure in contemporary physics. That electromagnetism has well understood manifestations as a classical field even at low energies makes it a useful example to introduce a discussion of the special issues quantum field theories raise for the measurement problem.

Traditionally, the outcome of a quantum measurement was taken as a record of the value of an observable on the measured system. But the POVM framework allows an understanding of the measurement process as giving probabilistic information about the quantum state of the measured system that may take a more general form, not necessarily focused on a specific observable. Measurements represented by the measurement operators (20) and

(21) yield different probabilistic information about the state of a quantized electromagnetic field while (in general) altering that state: only for the first of these can measurement serve to record the value of an observable. The information provided by a general quantum measurement is useful not because it tells one what value some observable had on the measured system, nor because it tells one what value some observable has acquired as a result of the measurement, but because it guides expectations concerning the possible results of future measurements either on the original state or on the state after this initial measurement.

Freed from the need to think of measurement as a process directed toward recording the value of some magnitude on a system, an analysis of measurement on quantum field systems should address two separate questions: 1) How can a measurement of a quantum field lead to an outcome? 2) What makes a claim about a quantum field magnitude significant?

Deléglise *et al.*[42] report studies of many non-classical states of the electromagnetic field in a cavity. The field is probed by Rydberg atoms passed through the cavity whose energy states become entangled with the state of the cavity and are subsequently observed. Such an atom functions as a quantum "probe", and the outcome of the field measurement is objectified by observing the state of atomic excitation. That observation is performed by ionizing the atom and detecting the emitted electron, a process that is selective since different energy states are ionized in different electric field strengths in the detector. Unlike many measurements on the field, observation of the atom is thought of as a (destructive) measurement of an observable—its energy. Prior to this measurement, the atom's state was (typically) entangled, but only with that of the cavity field, so a claim about its energy lacked significance. But after detection of its ionized electron a claim about the state of the detector acquires a rich significance through environmental decoherence of the detector's state. It is only at this stage that an objective outcome of the cavity field state measurement emerges. This involves no significant claim about a quantum field magnitude, and no significant claim about the value of any magnitude on the atom—not even about its energy. A measurement of the quantum field leads to an outcome only through decoherence in the atom detector. What is measured is not a quantum field magnitude.

This illustrates an important generic feature of measurements on a quantum field system that goes a long way toward answering question (1). The outcome of such a measurement is recorded not in a claim about the value of a magnitude on that quantum field, but in a claim about the value of a magnitude in a detector, even when that outcome is called the result of a measurement of the field. The state of the field becomes entangled with that of some subsystem of the detector, which is then decohered by interaction with its environment. It is this decoherence that gives rise to an outcome of the measurement—not by "collapsing the state" (instead, the system-detector entanglement is extended to the environment) but by rendering significant a claim about the value of a magnitude on the detector. The detector is designed so that the truth of this claim may be readily checked and/or recorded by directly examining it.

While the result of the measurement is often expressed in language that apparently commits its author to the existence and properties of physical systems associated with a quantum field (as in the example of single photon detection) such talk should be seen as inferentially grounded in claims about properties of some distinct probe or detector system involved in the measurement. This "inferential buck-passing" is not a feature that distinguishes measurement of quantum fields from measurement of other quantum systems, as was illustrated by the measurement of the energy of the Rydberg atoms used to probe the cavity field. In no such case does the objectification of the measurement outcome require the attribution of the measured property to the measured system itself, either before or after the measurement.

It is in answering question (2) that a distinctive feature of quantum fields appears. Along with quantum mechanics and other variants of quantum theory, quantum field theories share a common framework of quantum states and probabilities, whose joint function is to advise an agent applying the theory on the content and credibility of magnitude claims. The Born Rule is applicable directly only to canonical magnitude claims—those of the form σ **has** $\mathbf{Q} \in \mathbf{\Delta}$, for Δ a Borel set of real numbers, where Q is a magnitude corresponding to self-adjoint operator $\hat{Q}$ on a Hilbert space (or in some algebra of operators, in a more abstract form of quantum theory). In a quantum field theory, such magnitudes include components of fields such as the electric field $\mathbf{E}(\mathbf{r})$ and magnitudes corresponding to the fermion number density $\hat{\psi}^{\dagger}(\mathbf{r})\hat{\psi}(\mathbf{r})$, but not to the fermion field $\hat{\psi}(\mathbf{r})$ itself. Fully to specify the content of a canonical claim one must say what the system σ is.

Call this system σ the *target* of an application of quantum theory. While targets will vary from application to application, most if not all systems figuring in canonical claims may be naturally grouped into two kinds: fields and particles. Besides advising on the content of a predicate $\mathbf{Q} \in \mathbf{\Delta}$, a quantum state must also advise a user on the content of the singular or general term σ that picks out the target system (or systems) to which the predicate is applied.

Quantum mechanics is targeted on systems of particles—individually or collectively. This is true of Dirac's relativistic theory of electrons as well as non-relativistic quantum mechanics as applied to condensed matter, molecules, atoms or atomic constituents at low energies. While quantum field theory is superficially (and mathematically) a theory of fields, it is not targeted on physical *quantum* field systems. The canonical claims on which the quantum state of a quantum field theory directly offers advice may concern either *classical* fields or particles, depending on the circumstances in which the theory is applied. Consider first the case of the quantized electromagnetic field.

Kiefer[43],[44] analyzes the interaction of a quantized electromagnetic field with a quantized scalar matter field ("scalar quantum electrodynamics"). He describes circumstances in which this interaction has the effect of decohering the quantum state of the electromagnetic field (in a Schrödinger functional representation) so that the reduced state (after tracing over the matter field Hilbert space) rapidly becomes diagonal in a basis of WKB

states that approximate a state of the classical electromagnetic field—with quite well-defined electric field and magnetic vector potential.

Anglin and Zurek[45] give a model in which the state of a quantized electromagnetic field is decohered by a set of harmonic oscillators representing a homogenous, linear, dielectric medium. In this model the reduced state of the field quickly becomes approximately diagonal in a basis of coherent states. This shows how, in suitable circumstances, environmental decoherence can select a basis of preferred states that closely approximate a classical electromagnetic field. According to [14] this is exactly what is required to endow a claim about the strength of the electric or magnetic field at a point with the significance required to justify application of the Born Rule to assign a probability to that claim. While their model incorporates a number of idealizations that do not hold for an electromagnetic field in a medium such as the atmosphere, they argue that this result is robust enough to hold also for electromagnetic radiation at wavelengths down to the ultraviolet propagating through the air. Moreover the dynamics of the decohered states will conform closely to classical electromagnetic theory. In a situation in which an agent is warranted in ascribing a particular coherent initial quantum state to the quantized electromagnetic field, the Born Rule will entitle him to expect the electric and magnetic fields to evolve in a way consistent with classical electromagnetic theory.

Anglin and Zurek also discuss the status of photons and other "particles" in the light of their model. Referring to the coherent states that provide a stable, overcomplete basis for the decohered reduced state of a quantum field as pointer states, they conclude

> Each pointer state of a quantum field is surrounded, in Hilbert space, by a quantum halo — a set of states which are negligibly decohered from the pointer state over whatever time period is of interest. When the environmental noise is weak enough that it does not significantly degrade the pointer states themselves, this quantum halo is large enough to contain at least a few particles, excited above the background classical field configuration represented by the pointer state. We have thus recovered the familiar field-theoretic dichotomy between background classical fields and N-particle excitations. The relative immunity of the particle excitations to decoherence, in comparison with the strong decoherence of superpositions of distinct pointer states, explains the coexistence of effective classical electrodynamics and coherent propagation of photons. The n-particle excitations are not localized by our homogeneous environment. All localization occurs in the space of coherent state amplitudes, and not in position space.[45, p.7334]

This sheds further light on the extent to which application of the quantum theory of the electromagnetic field endows talk of photons with empirical content. Even experimenters in quantum optics violate the injunction: "whenever we talk about a particle, or more specifically a photon, we should only mean that which a 'click in the detector' refers to". They do so whenever they speak of *propagation* of photons—through an optical fiber, the

atmosphere, or empty space. A *classical* electromagnetic field corresponding to a coherent state *can* significantly be said to propagate. When the coherent state is surrounded by a quantum halo—a space of "nearby" quantum states—it is tempting to say these states describe photons propagating with the classical field to which the coherent state corresponds, even though no quantum state describes any physical system. But such talk can mislead. One must remember that not every state in the quantum halo of a coherent state can be thought to contain any definite number of photons: the halo contains superpositions and mixtures corresponding to different "photon numbers", that are not decohered by the environment. Moreover, in an experiment such as that of Ursin *et al.*[46] if one speaks of creating a pair of entangled photons a,b one of which (a) traveled to one detector while the other (b) traveled to another distant detector, this must either be understood as merely a metaphorical gloss on claims about propagating classical fields, non-linear sources and "detector clicks", or (consistent with an inferentialist account of what gives a claim meaning) allowed to stand on its own *provided* the inferences it is taken to support are carefully circumscribed.

In quantum theory one models target systems by assigning quantum states to systems and applying the Born Rule. Models in quantum mechanics (relativistic as well as non-relativistic) can be taken to assign quantum states to the target systems themselves, be they electrons, atoms or other particles.[5] So the general practice of applying a significant predicate $\mathbf{Q} \in \mathbf{\Delta}$ to electrons, atoms and other particles needs no defense in quantum mechanics. But a model of a quantum field theory such as quantum electrodynamics assigns quantum states not to electrons or other target systems, but to an abstract quantum field system (such as interacting quantized electromagnetic and charged lepton fields): model systems can no longer be identified with target systems. So the attribution of location, momentum, spin, etc. to electrons, atoms and other particles does require justification in an application of a quantum field theory model. It is clear that this cannot take the same form as that just given for photon talk in the context of the quantum theory of electromagnetism. We ascribe energy, momentum, spin, etc. to elementary particles when applying the quantum field theories of the Standard Model and think of them as located in a particle accelerator or in one of the associated detectors used to test the Model. But unlike the electromagnetic field, neither the fermionic nor the massive bosonic fields of the Standard Model have manifestations as classical fields.

Anglin and Zurek discuss this issue in their conclusion, where they argue that the key difference between an application of a quantum field theory where classical field-like behavior becomes manifest and an application where classical particle-like behavior becomes manifest is the different character of environmental coupling present in the two cases. Specifically, while the electromagnetic field typically couples to its environment through a linear coupling, the electron field (say) typically couples to its environment *bi*linearly. They suggest (but do not give a comparable analysis to prove) that such a

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[5]   But this is not necessary. Quantum models often represent quantum states e.g. of abstract harmonic oscillator or spin systems in an appropriate Hilbert space model in order to abstract from messy details of actual target systems.

coupling will select a basis of n-particle states, rather than coherent states, as those that remain stable under environmental interactions. According to the interpretation outlined in [14] this is exactly what is required to endow at least some claims about the values of magnitudes on the particles present in such a state with the significance required to justify application of the Born Rule to assign a probability to those claims.

This cannot be the whole story. Consider the suggestion that the significance of claims attributing classical field values requires a linear coupling to a decohering environment to select a basis of coherent states of a quantized field, while a bilinear coupling selects out n-particle states. This may help explain the difference between how we talk about certain gases as collections of particles at ordinary temperatures but as coherent fields in BECs at extremely low temperatures. But it seems unlikely that decoherence can ground familiar claims about most of the extremely short-lived "elementary particles" detected in high energy accelerators, whether bosons or fermions. Perhaps claims apparently ascribing properties to these "particles" could be rephrased as (non-descriptive) claims about states of their associated quantum fields, just as talk of N photons in a cavity is often rephrased as talk of an N-photon state. Alternatively, claims about properties of "elementary particles" could derive their significance from their inferential relations to significant descriptive claims about outcomes of measurements on their associated quantum fields, along the lines of claims about positions of photons.

8 Conclusion

One can reconcile the observed outcomes of measurements with quantum theory by recognizing the non-descriptive role of the quantum state. Decoherence grounds the significance of claims about these outcomes and their probabilities. But quantum theory assumes and cannot account for the fact that measurements have outcomes (still less the *particular* outcome we observe) since it is not the role of a quantum state to represent a measurement outcome.

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