CAUSALITY, SYMMETRIES AND QUANTUM MECHANICS

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Abstract

It is argued that there is no evidence for causality as a metaphysical relation in quantum phenomena. The assumptions that there are no causal laws, but only probabilities for physical processes constrained by symmetries, leads naturally to quantum mechanics. In particular, an argument is made for why there are probability amplitudes that are complex numbers, which obey the Born rule for quantum probabilities. This argument generalizes the Feynman path integral formulation of quantum mechanics to include all possible terms in the action that are allowed by the symmetries, but only the lowest order terms are observable at the presently accessible energy scales, which is consistent with observation. The notion of relational reality is introduced in order to give physical meaning to probabilities. This appears to give rise to a new interpretation of quantum mechanics.

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1 Introduction

The world-view that the universe is governed by precise causal or dynamical laws, which was called the paradigm of laws [1], was due to Galileo, Descartes, Newton and others. It was argued, however, that the fundamental laws of physics are effective laws arising from symmetries [1]. This view has the advantage of naturally giving rise to the indeterminism of quantum phenomena. In the present paper, specific arguments towards obtaining quantum theory in the absence of causal laws using symmetries will be presented.

In section 2, the notion of causal laws will be critically examined in the context of wave-particle duality of quantum phenomena, from a historical point of view. A heuristic principle that eliminates metaphysical relations in physics that are not invariant under symmetries is formulated in section 3. This principle implies that causality as a metaphysical relation should be eliminated in a theory that has time-reversal symmetry. Then, in section 4, the EPR correlation, indeterminism of the outcomes of measurement, and the accepted view that there is no causal relation between space-like separated events are used to argue that there is also no metaphysical causal relation between time-like separated events. However, physical causality that is the ability to communicate information probabilistically distinguishes these two pairs of events. This distinction is made in section 5, and an argument, due to Weinberg, that the non-causality between space-like separated events is due to the Lorentz boost symmetries is presented. This reinforces the present view on the fundamental role of symmetries.

In sections 6 and 7, the physical causality is explained on the basis of two postulates, namely that there are no causal laws but that the probabilities of physical processes are invariant under a group of symmetries. The first postulate naturally leads, on using an algebraic theorem due to Horwitz and Albert, to probability amplitudes as complex numbers. The Born rule is then derived, in section 7, by considering a 'which way' experiment in which interference between probability amplitudes is lost. The second postulate then yields a generalization of Feynman path integral formulation in which the action includes all terms that are invariant under the symmetries; but only the lowest order terms that are in the standard model are observed in the experiments performed with presently accessible energy scales. The question of when a probability amplitude should be converted to probability, which is called a quantum 'measurement', is considered in section 8. The notion of relational reality that is jointly realized when two systems interact is introduced. This enables the predictions of probabilistic outcomes during 'measurements,' while preserving the universal validity of quantum mechanics. Also, this makes quantum mechanics both local and realistic; but the realism is relational instead of absolute, which enables the present view to be consistent with Bell's theorem. The present interpretation is shown to be intermediate between the Copenhagen and Everett interpretations, and some speculations are made, in the final section.

2 Causal Laws and Wave-Particle Duality

The first indications that the paradigm of laws may not be valid already appeared during Newton's study of light. Newton had formulated a highly successful set of laws for material particles, known today as Newton's laws of motion and gravitation. Contrary to Newton's famous statement, "hypotheses non fingo", the assumption that the material particles should obey these laws, or any laws, was a hypothesis. It was natural for Newton to then try to bring the behavior of light into this paradigm, which he has helped to create more than anyone else up to that time. So, he made the hypothesis that light consisted of material particles, called corpuscles. This was convenient for Newton because then these corpuscles are subject to the same laws of motion which he has already 'perfected'.

However, Newton's theory of light ran into problems almost immediately. It could not explain partial reflection, as Newton himself recognized. Why is that when a corpuscle encountered a slab of glass, it was sometimes transmitted and sometimes reflected? To explain this using the deterministic laws of motion of Newton, it was supposed at first that there are 'holes' and 'spots' in the glass, so that if the corpuscle encountered a hole it went through and if it struck a spot it was reflected. This was perhaps the first of the patchwork theories of physics that were proposed in order for physicists to remain within the paradigm of laws, which will be done all the way to the 21st century. But Newton himself realized that this theory does not work. This was because, as Feynman [2] has mentioned, Newton made his own lenses and mirrors by polishing glass. And he knew that the small scratches that he made with powder as he polished glass had no appreciable effect on the partial reflection of light.

Newton's hypotheses, in addition to not explaining partial reflection, could not explain also interference and diffraction, as is well known. Physicists tried to solve these problems by abandoning Newton's ontology of corpuscles, while keeping his basic assumption that light obeyed deterministic laws. They should have done the reverse! But I shall follow the historical route before discussing the logical alternative. Historically, physicists *replaced* Newton's corpuscles with a wave. What made this appealing to them was that Huygens had formulated a law for the propagation of a wave, called Huygens' principle, according to which every point on a wave front acted as a source of secondary wavelets whose interference was sufficient to reconstruct the subsequent wavefronts. This was the first dynamical or causal law to govern the propagation of a wave, as opposed to Newton's laws that governed the propagation of material particles. And using these laws and the new ontology that light *is* a wave it was easy to explain all phenomena of light known at that time, including partial reflection, interference and diffraction.

But today we know additional phenomena that would make Newton's ontology of light consisting of corpuscles appear to be fundamentally valid. For example, if we make the intensity of light falling on a photographic plate low enough we see spots appearing, which is interpreted as due to the corpuscles of light, or photons as they are now called, interacting with the plate. Newton could have saved his ontology for light by giving up his hypothesis that the corpuscles should obey causal deterministic laws. Suppose in the above example of the glass slab, 30% of the light is reflected and 70% is transmitted. Newton could have postulated that a corpuscle has a 30% *probability* of being reflected and detected in a detector and 70% probability of it being transmitted and detected in a different detector. But physicists were unwilling to give up causal deterministic laws until the twentieth century when observed physical phenomena made them question their cherished beliefs.

The wave theory received a tremendous boost in the nineteenth century with the introduction of electric and magnetic fields by Faraday and Maxwell. These fields obeyed causal deterministic laws that were mathematically formulated by Maxwell. Moreover, light waves were recognized as special cases of this electromagnetic field, and Maxwell's laws justified Huygens' principle. The price paid now for staying within the paradigm of laws was only that the universe had to be regarded as a strange mixture of material particles and fields. Physicists lived with this dual ontology even when an inconsistency was found between the two sets of laws that governed material particles and fields. This inconsistency, first clearly recognized by Einstein, was that the symmetries of the laws of mechanics that governed material particles were not the same as the symmetries of the laws of the electromagnetic field. Einstein required that both symmetries should be the same, and asserted the primacy of fields over particles by requiring that the laws of mechanics should be modified so that they have the *same* Lorentz group of symmetries as the laws of the electromagnetic field. This was the first time in the history of physics that symmetries took priority over laws in the sense that the laws were modified to conform to the symmetries. Moreover, the existence of universal symmetries for all the laws of physics enabled the construction of a physical geometry having the same symmetries, namely the Minkowski space-time.

3 Role of Symmetries in Eliminating Metaphysical Relations

The Lorentz group of symmetries also eliminated the following three metaphysical relations that existed prior to Einstein's paper on relativity. 1) Newton's postulated "absolute space" (on the basis of his rotating bucket argument), or the "ether" in which light waves propagated, implied an absolute relation between two time- like separated events that have the same *absolute position* in this "absolute space". 2) Newtonian physics assumed that two events have the relation of *absolute simultaneity* if they occur at the same "absolute time". 3) Newtonian physics allowed for causal relations to exist between absolutely simultaneous events. For Newton's gravitational interaction, these were the only causal relations. But since these three relations are not Lorentz invariant (relation (1) is not even Galilei invariant), and therefore not an objective property of the world, they were discarded. The overthrow of (3), which Newton himself regarded as unnatural, meant that, since any pair of space-like events is simultaneous in an appropriately chosen inertial frame, and all inertial frames are related by the Lorentz group of symmetries, the resulting acausality needed to be extended to all space-like separated events.

In order to eliminate such metaphysical relations in general, I now formulate a heuristic principle, called M: *A necessary and sufficient condition for a relation to be admissible as an ontological relation in a physical theory is that it should be invariant under all the symmetries of the theory.* Here the term 'relation' is understood in the usual sense of this term between two physical concepts or objects, in general. The above three relations, specifically, are between events in space- time **S**. Any relation in **S** is defined mathematically as a subset of $\mathbf{S} \times \mathbf{S}$. On the basis of M, the metaphysical relation (1) of absolute position, and hence absolute space, was not admissible even in Newtonian physics because this relation is not invariant under the Galilei boosts that are symmetries of this theory. But the other two metaphysical relations mentioned above were invariant under the Galilei group of symmetries and therefore excluded only because the Galilei group was superseded by the Lorentz group of symmetries as a result of the work of Lorentz, Poincare and Einstein.

However, there still remained the following metaphysical relation: 4) The causal relation between two events that are time- like separated. But this relation is asymmetric in time because while an earlier event a may influence a later event b, it is not possible for the later event to influence the earlier event. Even in a deterministic theory like classical electrodynamics, time asymmetric causality is introduced by the choice of retarded Green's functions. This is unlike Newton's causal relation between simultaneous events, which is a symmetric relation because of Newton's third law of motion, and invariant under the Galilei group of symmetries. The physical theories we have today are invariant under time reversal symmetry T, apart from weak interaction which is irrelevant to the problem at hand because causality is posited today even in the absence of weak interaction. Moreover, all theories of physics today, including weak interactions, have CPT symmetry. Hence, the principle M, and time reversal symmetry in the absence of weak interactions or CPT symmetry in the presence of weak interactions imply that the metaphysical relation (4) of causality should be discarded. Alternatively, if causality is to be kept then CPT symmetry or T symmetry in the absence of weak interactions should be discarded. But while people would agree that the later event b cannot influence the earlier event a, they would not accept the reverse even though the intervening space-time region between a and b has the same structure for both relations!

4 Indeterminism and the EPR Paradox

Eliminating causality means that a given event is not uniquely determined by the 'earlier' events. Then there must be indeterminism in our physical theory. But historically, physicists seriously entertained indeterminism only after the wave-particle duality was forced upon them. The work of Planck and Einstein showed that it was necessary to associate particles with the electromagnetic field, vindicating the ontology of Newton. But at the same time, the field included the wave aspect. This wave-particle duality was recognized as characteristic of all particles by De Broglie, and Schrödinger introduced the wave function that obeyed Schrödinger's equation to represent the wave properties. The relation between the wave and the particle was given in probabilistic terms by Born: The probability density of observing a particle at $\mathbf{x}$ is $|\psi(\mathbf{x})|^2$, where ψ is the wave function of the particle representing its state. More generally, the probability of observing this particle in a state ϕ is $| < \psi|\phi > |^2$. Originally, this Born rule was associated with an assumed indeterministic change from the state ψ to ϕ. Subsequently, two different deterministic descriptions of quantum phenomena were given by Bohm [5] (also called the causal interpretation of quantum mechanics) and Everett [6]. But for these descriptions to be empirically relevant, they need to give the experimentally well confirmed Born rule. In the latter two descriptions, however, probabilities are introduced ad hoc, which amount to bringing the indeterminism of quantum mechanics through the back door.

I shall now show that, owing to this indeterminism, the correlation between two entangled states, between which there is no causal relation, is metaphysically similar to the correlation between two states that are related by Schrödinger evolution. Consider two spin-half particles 1 and 2, which interacted some time ago but no longer interacting, and whose spin states are now EPR correlated:

$$\psi = \frac{1}{\sqrt{2}}(\psi_\uparrow(1)\psi_\downarrow(2) - \psi_\downarrow(1)\psi_\uparrow(2)) \tag{1}$$

where $\psi_\uparrow(1)$ is the spin-up state of particle 1 and $\psi_\downarrow(2)$ is the spin-down state of particle 2 etc. The state (1) is spherically symmetric because its total spin is zero; therefore the 'spin-up' and 'spin-down' basis states may be with respect to any direction in space. As is also well known, it is not possible to communicate using the entanglement between the two particles in (1) because they are non interacting. Suppose Alice and Bob make measurements on particles 1 and 2, respectively, and try to use their outcomes to communicate. If Alice observes 1 to have spin- up (spin-down) along the $z-$direction, she can predict with certainty that 2 has spin-down (spin-up). Therefore, Bob by measuring the spin along the $z-$direction for 2 can verify the outcome of Alice's measurement, provided Alice has informed Bob beforehand that she will measure spin in the $z-$direction. But it is impossible for Alice to send a signal this way because of the *indeterminacy* of the outcome of her own measurement. Suppose now that Alice and Bob have decided beforehand that if Alice measures spin along the $z-$direction ($x-$direction) the signal she sends to Bob is 'yes' ('no'). But it is impossible for Bob to know which observable Alice has actually measured because of the *indeterminacy* of the outcome of his own measurement. Thus the indeterminacy of quantum mechanics prevents Alice communicating with Bob using the entanglement in (1).

The inability to communicate signals faster than the speed of light c, and the ability to communicate signals with speed less or equal to c is called Einstein causality. We saw above that since quantum mechanics allows for entanglement, the indeterminism in the outcome of measurements is essential to preserve Einstein causality. People often wonder why non relativistic quantum mechanics should preserve Einstein causality, which was obtained from relativistic physics. However, the above argument that Alice cannot communicate with Bob through entanglement without interaction applies to any two degrees of freedom that are entangled. Alice's and Bob's measurements need not be space-like separated events; Bob could make his measurement to the future of Alice. And the two entangled degrees of freedom need not be separated in space like the two particles above; they could be right on top of each other. To prove this, it is sufficient to note that the evolution of the reduced density matrix ρ_2 of particle 2 is governed entirely by the Hamiltonian of particle 2 because there is no interaction between particles 1 and 2. Therefore, whatever measurement Alice makes on particle 1 would affect ρ_1 but not ρ_2. Hence, the outcomes of Bob's measurements on particle 2 that are determined by ρ_2 are unaffected by Alice's measurements.

Thus Alice's inability to send a signal from event a to event b by means of entanglement between two non- interacting systems is independent of whether a and b are space-like, time-like or null separated. However, Alice may send a signal using the time-evolution of the wave function when a and b are time-like or null separated. For example, Alice and Bob may agree beforehand to measure a particular component of spin, say S_z, and that if Alice sends a spin-up (spin-down) particle to Bob then Alice means yes (no). Suppose Alice wishes to send the signal 'yes'. She then measures a spin component on the wave function ψ of a spin-half particle at time 0 in the neighborhood of a. If the outcome is spin-up she does nothing, but if the outcome is spin-down she rotates it to make it spin-up or she keeps measuring other spin-half particles until she gets one in the spin-up state. Then she sends $\psi(0) = \psi_\uparrow$ to Bob. During the subsequent time evolution, there is rotational symmetry. Therefore, due to conservation of angular momentum, at time t, $\psi(t)$ will have spin up. Bob then measures S_z in the neighborhood of b that is in the future of a. He finds it be in the state $\psi_\uparrow$ with 100% proabability, and feels elated because Alice has said 'yes'.

However, if Alice had not communicated to Bob beforehand which spin-component she will measure, Bob cannot determine the signal she had sent. This is because the outcome of Bob's measurement of the spin-component in a general direction is indeterminate. Alice then would have to send a large number of particles in the state $\psi(0)$ at time $t = 0$ to Bob so that Bob may statistically determine by means of his own measurements the signal that she sent. Even this would not be possible if Alice is not allowed to get around the indeterminacy of her measurements and put her particle(s) in the state $\psi(0) = \psi_\uparrow$ as in the first case of trying to communicate via entanglement mentioned above. Hence *the metaphysical connection, due to entanglement, between* $\psi_\uparrow$ *and* $\psi_\downarrow$ *is similar to the metaphysical connection, due to Schrödinger evolution, between* $\psi(0)$ *and* $\psi(t)$*, because of the indeterminacy in the outcomes of measurements* of Alice and Bob. But, as seen above, there is nevertheless an important distinction between the two connections or correlations, which is called physical causality in the next section.

5 Physical and Metaphysical Causalities

It is necessary to distinguish between two types of "causality" at this point. By metaphysical or deterministic causality will be meant the relation between occurrences α and β that exists if the occurrence α always produces, determines or necessitates the occurrence β. But the ability to communicate information, albeit probabilistically, is here called physical causality. More precisely, physical or probabilistic causality is the relation between the occurrence α and occurrences $\beta_1, \beta_2, \beta_3, ...$ that holds if given the occurrence of α we can predict the probabilities of $\beta_1, \beta_2, \beta_3, ...$ In the examples in section 4, if Alice and Bob do not measure the same component of spin, say by prior agreement, then Alice's measurement, call it α, does not necessitate the result β of Bob's measurement, whether or not these two measurements are separated by a space-like, time-like or null intervals. So, there is no metaphysical causality in all these cases. However, Alice can influence the *probability* of the outcome of Bob's measurements if Bob makes his measurements to the future of Alice, as in the example in the previous section in which she sends him polarized particles, but not when the two sets of measurements are space-like separated. This is an example of physical causality. In this section it will be argued that symmetries are responsible for some common statements involving physical causality.

One such statement is Einstein causality according to which there can be *physical causality* between time-like or null separated events but not between space-like separated events. As mentioned above, this is realized only probabilistically in quantum phenomena. But Einstein himself was deeply attached to metaphysical causality, as shown from his following statement [7]:

"... I should not want to be forced into abandoning strict causality without defending it more strongly than I have so far. I find the idea quite intolerable that an electron exposed to radiation should choose of its own free will, not only its moment to jump off, but also its direction. In that case I would rather be a cobbler, or even an employee in a gaming-house, than a physicist."

It is ironical that Einstein who overthrew three of the four metaphysical relations mentioned in section 3, could never give up the fourth metaphysical relation of causality.

The only way to experimentally test physical causality is by means of a large number of trials of the form $(\alpha, \beta_1), (\alpha, \beta_2), (\alpha, \beta_3), ...$ The relative frequency of each distinct pair in this experiment, as the number of trials tend to infinity, is the probability of occurrence of this pair. However, in a given trial, say (α, β_3), we may ask, as Einstein does implicitly in the above statement, why is it that α was followed by β_3 and not β_1, β_2 or $\beta_4, ..$? This absence of metaphysical causality, due to the indeterminism in quantum phenomena, should make us reexamine the meaning and validity of physical causality as well. Suppose Alice sends a large number of spin-half particles in state α, say the spin-up state, to Bob. By doing experiments of the above form with a large number of trials, Bob determines to a very high probability the state α. This is possible in this instance because of conservation of angular momentum that ensures that all the particles are in the same spin state when they reach Bob. But this conservation of angular momentum is due to rotational symmetry.

In general, conservation laws are due to symmetries. And if the state is not an eigenstate of the conserved quantity then the conservation is realized only statistically, i.e. the expectation value of the conserved quantity is preserved in time. The equality of the expectation values of the conserved quantity at two different times is therefore like physical causality, because of the probabilistic manner in which they are both determined, and does not imply metaphysical causality. But the symmetries are not probabilistic as far as we know. This suggests that symmetries may be more basic than dynamical laws that may actually be effective laws arising from symmetries.

It is often stated that Einstein causality is incorporated in quantum field theory by the requirement that field operators at events that are space-like separated are independent in the sense that they must commute if they are Bosonic fields and anti-commute if they are Fermionic fields. I.e. if $\phi_m(x)$ are the components of the various fields in the theory, where x stands for the space-time coordinate $(\mathbf{x}, t)$, then

$$[\phi_m(x), \phi_n(y)]_\pm = 0 \tag{2}$$

whenever x and y are space-like separated. The $\pm$ in (2) refers to anti-commutator if the fields are Fermionic and commutator if the fields are Bosonic.

However, (2) does not require Einstein causality and may be introduced in order that a local quantum field theory is Lorentz invariant [8]. To see this, consider the time evolution operator U for quantum states in the interaction picture of a canonically quantized field theory that is generated by the interaction Hamiltonian $H_I(t)$. Since $H_I(t)$ represents the interaction energy, and the locality assumption requires that this energy is the sum of energies in all the different regions of space,

$$H_I(t) = \int d^3x \mathcal{H}(x),$$

where $\mathcal{H}(x)$ is the interaction Hamiltonian density. It follows that

$$U = T\exp(-\frac{i}{\hbar}\int H_I(t)dt) = 1+\sum_{n=1}^{\infty}\frac{1}{n!}(-\frac{i}{\hbar})^n\int d^4x_1d^4x_2....d^4x_n\, T\{\mathcal{H}(x_1)\mathcal{H}(x_2)....\mathcal{H}(x_n)\}$$

where T denotes the time ordering operation meaning that it orders the operators from left to right in the monotonically decreasing order of the values of their argument t. This ordering is independent of the chosen Lorentz frame if every pair $\mathcal{H}(x_r), \mathcal{H}(x_s)$ commute whenever x_r, x_s are space-like separated. This is guaranteed by the independence of fields at space-like separated events given by (2). Thus 'Einstein causality' in a local quantum field theory may be regarded as due to the Lorentz group of symmetries. This is analogous to how the same symmetries discarded the metaphysical relations (2) and (3) of Newtonian absolute simultaneity and causality between simultaneous events during the creation of special relativity, as mentioned in section 3.

6 Objective Probabilities and Probability Amplitudes

The metaphysical causality, mentioned above, was associated with the metaphysical necessity of causal dynamical laws [1]. Therefore, since this metaphysical causality was discarded above, it is no longer necessary to assume the metaphysical necessity that is responsible for causal laws. An advantage of discarding metaphysical causality is that the indeterminism of quantum phenomena may then be deduced, instead of postulating it *a priori*. This solves the statistical aspect of the measurement problem, mentioned in Einstein's statement quoted in section 5. The only causality which now remains is the physical causality that is determined by the operator U, and which is realized only probabilistically.

The above arguments suggest, however, that symmetries are more fundamental than physical causality. I shall therefore, from now on, assume A) *there are no causal dynamical laws.* This implies that physical processes cannot be deterministic, because there is nothing compelling a physical system to evolve in a definite manner. It follows that we can only assign probabilities for physical processes, which is consistent with the experimentally observed intrinsic indeterminism of quantum phenomena, as mentioned above. I shall assume also that B) *the probabilities of physical processes are invariant under a group of symmetries.*

According to classical physics, a particle goes from an event a to an event b along a definite path that is determined by the laws of classical physics. If we discard causal dynamical laws, in accordance with assumption (A), then the particle need not take a definite path and all paths between a and b are equally probable. If we give up only determinism which is associated with metaphysical causality, then it is possible for the probabilities for the paths to be different, e.g. the classical path may have probability greater than all the other paths. But this would be a causal law that is probabilistic. I am taking assumption (A), however, to imply a maximal violation of the classical causal dynamical law, which is why all paths are given equal probability. Physically, this means that if we observe precisely whether the particle takes an *arbitrary* path between a and b then it would take this path with 100% probability; this makes all paths between a and b have the same probability[15]. This condition will be discussed more later. More generally, the paths may be in the configuration space of a more complicated physical system. The preference for configuration space instead of, say, the momentum space of the system is because the observation of the path by an apparatus needs to be realized by an interaction between the apparatus and the system, and all interactions are local at presently accessible energy scales. In order for such an observation to be like any other physical process, reality needs to be defined relationally as the outcome of interactions, which will be done in section 8. For simplicity and ease of visualization, I shall continue to treat the possible paths of the system as space-time paths of a particle.

If we suppose naively that the probability of the particle to go from a to b, denoted $P(b,a)$, is the sum of the probabilities of the possible individual paths then, since there are an infinite number of equally probable paths, the probability of each path is zero. We may try to mathematically implement this equal probability rule by defining on this set of paths a measure and a probability density that is positive and constant. Then if the volume of this set of paths with respect to this measure is infinite, the integral of this probability density would also be infinite and cannot equal $P(b,a) \leq 1$. Restricting the volume of the infinite dimensional manifold of paths to be finite would be artificial and would amount to introducing a law. Therefore, there must be cancellation between different paths in order to obtain a sensible result for $P(b,a)$. This may be achieved by introducing the *probability amplitude* for each path such that the set $\mathcal{A}$ of probability amplitudes is a group under the operation of addition. If we require that the probability amplitudes should first be added before forming the probability from this sum, then adding these amplitudes would give the required cancellation. Also, the probability of a system going from a to c through b should be the product of its probabilities to go from a to b and b to c. This suggests that it should be possible to multiply probability amplitudes. Then $\mathcal{A}$ should form an algebra. To obtain a probability that is a non-negative number from the probability amplitude, one may introduce a norm, denoted by $||$, on $\mathcal{A}$. The above mentioned multiplicative property of probabilities suggests that $|\psi\phi| = |\psi||\phi|$, for probability amplitudes ψ and ϕ. A theorem by Hurwitz [13], generalized by Albert [14], states that $\mathcal{A}$ should then be the reals, complex numbers, quaternions or octonions [16].

Octonions may be excluded as candidates for probability amplitudes due to the non associativity under multiplication, if addition is also taken into account. Consider the case of an electron that can either go through two screens with a single slit in each or go around both screens to reach the point where it is detected. If we use octonions as probability amplitudes, then the probability of detection is determined by the norm $|(\psi_1\psi_2)\psi_3+\phi|$ or $|\psi_1(\psi_2\psi_3)+\phi|$ where the octonions $(\psi_1\psi_2)\psi_3$ or $\psi_1(\psi_2\psi_3)$ are the amplitudes to go through the two slits and the octonian ϕ is the amplitude to go around the two slits. But the above two norms are unequal in general. For a fixed set of amplitudes, one could try to remove this ambiguity by choosing a particular order of multiplication, e.g. $((\psi_1\psi_2)\psi_3)$... which violates time reversal symmetry. Also, if we divide a path into segments, then it is not possible to see how one could define a product of amplitudes associated with the segments that would be independent of the choice of this division.

For the probabilities of different paths between a pair of events to be equal, in accordance with assumption (A), it is reasonable for the norms of the corresponding probability amplitudes to be equal. If $\mathcal{A}$ is taken to be the field of real numbers then these amplitudes can only differ in sign, and the sum of these infinite number of amplitudes would not give a sensible result. It is perfectly possible *a priori* to have a physical theory that uses only real numbers, e.g. classical physics. But such a theory would not satisfy assumption (A), above, if we allow for infinite number of ways in which a system may go from a configuration a to a configuration b with equal probabilities. The probability amplitude should therefore be taken to be a complex number or quaternion. Adler [16] has found it not possible to construct a path integral using quaternions. We therefore take $\mathcal{A}$ to be the field of complex numbers, because the present approach leads naturally to a path integral, as will be seen explicitly in the next section.

7 Origin of the Born Rule and Quantum Dynamics

The question arises as to how the probability $P(b,a)$ may be obtained from the sum of probability amplitudes, denoted $K(b,a)$. To answer this, consider the double slit experiment and, for simplicity, suppose that there are just two paths, γ_1 and γ_2 for a particle to go from an event a at the source to an event b at the screen through slit 1 and slit 2, respectively. Then $K(b,a) = \psi_1 + \psi_2$ where ψ_1 and ψ_2 are the complex probability amplitudes for the paths γ_1 and γ_2, respectively. Let $\tilde{P}(\psi)$ denote the probability of the probability amplitude ψ.

Now if we observe through which slit the particle went through then the probability is the sum of the probabilities of going through either slit. This is a consequence of the relational reality which will be introduced in the next section according to which the interaction of the particle with another system determines the state of each of them relative to the other. Interaction, by definition, changes the phase of the probability amplitude. Since a device that interacts with the particle to determine whether it took path γ_1 is also quantum mechanical, the phase of ψ_1 is uncertain[1]. I shall suppose that this interaction is such that the phase of ψ_1 is completely uncertain. Averaging over this uncertain phase should give the sum of the probabilities for the two paths:

$$\frac{1}{2\pi}\int_0^{2\pi} d\theta_1\ \tilde{P}(\psi_1 + \psi_2) = \tilde{P}(\psi_1) + \tilde{P}(\psi_2) \tag{3}$$

where $\tilde{P}(\psi_1)$ and $\tilde{P}(\psi_2)$ are the probabilities for the paths γ_1 and γ_2, and $\theta_1 = \arg\psi_1$, $\theta_2 = \arg\psi_2$. This averaging may be physically visualized by means of an ensemble of particles that pass through the double slit and strike the screen as follows. The particles acquire all possible relative phases for ψ_1 and ψ_2 with equal probabilities. Each relative phase gives a corresponding probability distribution for detecting the particle on the screen. Then (3) is the average of this probability distributions.

[1]The usual description of decoherence regards it as occurring due to the entanglement of the system with states of the environment that are orthogonal due to the influence of the system. But it has been shown that [17], equivalently, decoherence may be regarded as due to an uncertain phase difference θ between interfering probability amplitudes due to the influence of the quantum environment. Specifically, if the average $< e^{i\theta} >= 0$, then there is decoherence.

Since θ_1 in the left hand side of (3) is integrated over, $\tilde{P}(\psi_1)$ in the right hand side is independent of θ_1. Hence, $\tilde{P}(\psi)$ is a function of $|\psi|$ only. Since $\tilde{P}(\psi)$ is a non-negative function, it is reasonable to suppose that $\tilde{P}(\psi) = |\psi|^n$, where n is a non-negative integer. Suppose also that $\tilde{P}(\psi_1) = \tilde{P}(\psi_2)$, which is the case if γ_1 and γ_2 are the only paths available to the particle. Then, $|\psi_1| = |\psi_2| = a$, say, so that $|\psi_1 + \psi_2| = 2a|\cos(\theta/2)|$, where $\theta = \theta_1 - \theta_2$. Therefore, (3) reads

$$\frac{2^n}{2\pi}\int_0^{\pi} d\theta |\cos^n \theta| = 1. \tag{4}$$

Now for any non-negative integer m,

$$\int_0^{\pi} d\theta |\cos^{2m+1}\theta| = 2\int_0^{\pi/2} d\theta \cos^{2m+1}\theta = \frac{2^{2m+1}(m!)^2}{(2m+1)!}$$

Since this is a rational number, (4) cannot be satisfied by odd n. Therefore, $n = 2m$. Now,

$$\int_0^{\pi} d\theta \cos^{2m}\theta = \frac{(2m)!}{2^{2m}(m!)^2}\pi$$

Hence, (4) reads

$$\frac{(2m)!}{2(m!)^2} = 1 \tag{5}$$

This is satisfied for $m = 1$. But for $m > 1$, it is easily shown that $\frac{(2m)!}{2(m!)^2} > 1$ and therefore (5) is not satisfied. Also, for $n = 0$ clearly (4) is not satisfied. Hence, *(3) is satisfied with* $\tilde{P}(\psi) = |\psi|^n$ *if and only if* $n = 2$, i.e.

$$\tilde{P}(\psi) = |\psi|^2 \tag{6}$$

Hence, $P(b, a) = |K(b, a)|^2$, which gives the Born rule. This of course is in agreement with the observed interference pattern that results if we do not observe which slit the particle went through.

Since all paths are equally probable, in accordance with assumption (A), it follows that the probability amplitude assigned to an arbitrary path γ joining a and b should be $N\exp[i\mathcal{S}(\gamma)]$, where N is independent of γ and $\mathcal{S}$ is real. Hence,

$$K(b, a) = \sum_{\gamma} N \exp[i\mathcal{S}(\gamma)], \tag{7}$$

Assumption (B) then implies that the probability $|K(b,a)|^2$ is invariant under the symmetry group. A sufficient condition for this is that $\mathcal{S}$ is invariant under the symmetry group. The highly successful Feynman path integral formulation of quantum mechanics assumes (7) with $\mathcal{S}(\gamma) = S_\gamma/\hbar$, where S_γ is the classical action for the path γ. Under this assumption it is easy to understand why the classical limit corresponds to the particle taking the trajectory for which S is an extremum: In the classical limit $S_\gamma >> \hbar$ for all possible trajectories, but the amplitudes for trajectories far away from the classical or extremal trajectory cancel out each other, while those in the neighborhood of the extremal trajectory add constructively.

As mentioned earlier, quantum mechanics maximally violates the laws of classical physics because the classical laws constrain the particle to move along the classical trajectory for which the classical action is an extremum, whereas quantum mechanics gives equal probability to all possible trajectories. But if the action in (7) is confined to be the classical action, as in ordinary quantum mechanics, then this would constitute a law, albeit probabilistic. Therefore, in accordance with the principles (A) and (B) above, I require a maximal violation of the laws of quantum mechanics as formulated by Feynman by postulating the following hypothesis: S_γ *contains all terms that are invariant under the symmetries.* For this hypothesis to be in agreement with observation, it is of course necessary that the resulting quantum theory should be approximately in agreement with quantum mechanics that uses only the classical action for all the experiments that we have performed so far.

In order to do this, we need to replace S_γ by an action S made from all the fields which are obtained from representations of the symmetry group. The development of effective field theories [18] have enabled the inclusion into S all the terms that are allowed by the symmetries that can be formed from the fields in the standard model. Only the lowest order terms are conventionally renormalizable, in the sense that they require a finite number of counter terms to cancel the ultraviolet divergences, which may thus be included into a finite number of coupling constants. This makes the standard model unique apart from the values of the coupling constants which need to be determined by experiments. While the somewhat unique determination of the standard model by the requirement of invariance under symmetries and renormalizability may be an indication of the fundamental role played by the symmetries, the principles (A) and (B) would require that we include in S all the terms that are allowed by symmetries. It turns out that including every term that is consistent with the symmetries in S, as shown by Weinberg [8], provides counter terms to cancel all the ultraviolet divergences in the Feynman diagrams. It is the lowest order terms that we directly observe at presently accessible energies, which gives the illusion that the action contains only a finite number of terms, as assumed in the paradigm of laws. If we go to high enough energies, we should be able to see the other terms, and measure the associated coupling constants, according to this hypothesis. The standard model, which was originally formulated with a finite number of terms in the Lagrangian that are invariant under the symmetries, defines an effective field theory, which is sufficient to make all the observable predictions at the energy scales at which we now do experiments, according to the present view.

Also, from the above path integral, Schrödinger's equation for the fields and its non relativisitic limit for particles may be obtained in a well known manner. This may be turned around, and one may start with Schrödinger's formulation and obtain the path integral. If one asks for the probability for observing the system taking any path between the initial and final states, the answer turns out to be unity, and the system then acquires the phase associated with this path that is predicted by Feynman [15]. This result shows the consistency of Schrödinger's or the equivalent Heisenberg formulation of quantum mechanics with the above assumption that all paths have equal probability and the result that the phases of the probability amplitudes associated with the paths at low energies are the Feynman phases.

In the present view, the action is more fundamental than the 'laws' derived by extremizing the action, which has important physical consequences. It implies that a given field that obeys an effective law cannot be regarded as complete unless this law can be obtained from an action principle, which may require introducing other fields. For example, the electromagnetic field strength $F_{\mu\nu}$ obeys the Maxwell's equations and the Lorentz force classically. But to obtain these laws from an action principle, we need to introduce the potential A_μ. And the action that is a function of A_μ then gives rise to new effects, such as the Aharonov-Bohm effect [9]. While the Aharonov-Bohm effect may be expressed non locally in terms of the field strength $F_{\mu\nu}$, its generalizations to non-Abelian gauge fields cannot be expressed in terms of only the Yang-Mills field strength $F^i_{\mu\nu}$ even non-locally, and requires the potential A^i_μ.

The present approach explains the physical causality discussed in section 5 in a lawless manner. The probability for any physical process is obtained from (7), where all possible histories are given equal probability weights. Therefore, when Alice's and Bob's measurements are time-like separated, the determination of the probabilities of the outcomes of Bob's measurements by Alice's measurement is due to the constraint of the probability amplitudes by the symmetries, and not because of any causal dynamical law.

8 The Physical Meaning of Probabilities and the Quantum Measurement Problem

The probability amplitudes were obtained in the previous section on the basis that there are no causal laws. The 'probabilities' that are obtained from the probability amplitudes are the probabilities of 'real' events. This raises the question of what reality means. So far no objective criterion has been provided for when the probability amplitudes should be converted to probabilities, which is the quantum measurement problem in the present language of probability amplitudes (as opposed to wave functions) [10].

The notion of reality that has been commonly used is the view that 'existence' is an absolute property or predicate that any conceivable object does or does not possess. If it has this property or predicate then it is said to exist, otherwise it is said not to exist, and this is independent of its interactions with other objects. I shall call this the notion of absolute reality.

But from an operational point of view, absolute reality is meaningless. Consider the statement that there is only one object in the universe. Whether this object exists or does not exist cannot be operationally distinguished and seems to be a meaningless question. However, the existence of two objects may be given meaning through the interaction between them. This leads to the notion of *relational reality* or interactive reality, namely that two objects exist in relation to each other if they interact. According to this view, the state or wave function in which an object 'exists' is meaningless if it is not interacting with another object. It was mentioned in section 4 that, although entanglement between two objects represents correlations, it is not possible to communicate by means of this entanglement unless the objects interact; thus interaction between two objects is necessary for one object to know the (relative) existence of the other.

Another motivation for introducing relational reality comes from the criterion of reality formulated sometime ago [11]. According to this if two objects interact in such a way so as to satisfy the action-reaction principle, then both objects exist. This criterion was then used as a sufficient condition for establishing the reality of objects in particular cases. But the relational reality introduced above is symmetrical with respect to the two objects, and may provide a deep reason why the action-reaction principle is *always* satisfied in nature, or this may conversely be regarded as indication of relational reality. Indeed, I shall use the action-reaction principle here as a necessary and sufficient condition for reality. As a particular application, according to the De Broglie-Bohm hypothesis, the wave guides the particle to move along a particular trajectory, but the particle itself does not react back on the wave [5]. According to the above symmetric criterion of reality therefore we cannot regard the particle being in this trajectory as real.

The above relational reality removes some of the paradoxes associated with the quantum measurement problem. For example, the Schrödinger cat may be inside a box in the alive state $|\psi_a>$ relative to the interactions it undergoes with itself and the box. But an observer outside the box, who so far has not interacted with the cat, could in principle observe the cat in the state $|\psi_c>= \frac{1}{\sqrt{2}}(|\psi_a> + |\psi_d>)$ with probability 1, where $|\psi_d>$ is the state of the dead cat, *provided* there is an interaction between her or her apparatus and the cat such that $|\psi_c>$ is an eigenstate of the interaction Hamiltonian H_I. There would be no contradiction between the two states of the cat, namely $|\psi_a>$ and $|\psi_c>$ because these are states that the cat has relative to the interactions it undergoes with two different systems. But in practice, there is no interaction for which the cat would have the state $|\psi_c>$, because if there were one, then $<\psi_a|H_I|\psi_d>\neq 0$, which is not possible because of the large number of degrees of freedom of the cat. Therefore, it is not possible to give relational reality to the superposition $|\psi_c>$. Also, the outside observer is interacting with the cat through the gravitational field and via the box with which they both interact; so they form a single interactional reality. For example, she could verify in principle that the cat is alive by interacting with its time dependent gravitational field outside the box as it moves inside the box, without opening the box. Hence, when she opens the box, she will see the cat in the alive state. In general, the relational reality of the cat is that it is alive or dead.

But for microsystems, it is easy to produce examples like the one above. For example, consider a double slit experiment with electrons. The state of each electron when it passes the double slilt screen is $\frac{1}{\sqrt{2}}(|\psi_1> + |\psi_2>)$ relative to the screen because of its interaction with the screen. Suppose that near one slit a neutron is introduced which is in a spin-up state $|\uparrow>$, with respect to the $z-$axis of a Cartesian coordinate system, which is verified by a separate interaction of an apparatus with the neutron. If the neutron does not interact with the electron, then due to conservation of angular momentum which in turn is due to rotational symmetry, the neutron may subsequently observed by means of a suitable interaction to be in the same state with probability 1. The arrangement is such that whenever the neutron interacts with the electron, it undergoes a spin flip, i.e. its state is $|\downarrow>$ relative to the electron, while the state of electron relative to the neutron is then $|\psi_1>$. But an external observer may observe the combined system of the neutron and electron in the state

$$|\psi>=\frac{1}{\sqrt{2}}(|\psi_1>|\downarrow>+|\psi_2>|\uparrow>)$$

with probability 1, relative to an interaction that she or her apparatus has for which $|\psi>$ is an eigenstate of H_I. On the other hand, the neutron and the electron 'observe' each other, whenever they interact, in the state $|\psi_1>|\downarrow>$ with probability 1/2. Of course, neither particle can express what they 'observe,' unlike human beings. But this statement is not empty because it may be verified by observing the state of the neutron to be $|\downarrow>$ in half of an ensemble of such experiments.

The third example that I shall consider is the protective observation of the extended wave function of a single particle [12]. The key to the protective observation is that the combined system of the particle being observed and the particle that does the probing is in an *unentangled* state $\psi\phi$, where ψ and ϕ are the wave functions of the two particles, respectively. This is achieved by having ψ originally in an eigenstate of the Hamiltonian and making the interaction between the two particles adiabatic and weak so that $\psi\phi$ continues to evolve as an approximate eigenstate of the Hamiltonian, according to the adiabatic theorem. For example, ψ may be the ground state of a proton inside a box and ϕ may be the localized wave packet of an electron slowly moving in the box. By sending several such electrons, from the behavior of the corresponding states ϕ, it is possible in principle to reconstruct ψ, even though this is the extended wave function of a single particle. The usual non adiabatic strong measurements, however, would enable the reconstruction of an extended ψ only statistically by putting sequentially many protons inside the box in the state ψ, and observing each of them with electrons. This is because in the usual measurements there will be an entanglement between the two systems, which prevents us from saying which state the proton is in. If we try to find this by means of a subsequent measurement on the electron, the entangled wave function of the combined system appears to undergo a sudden unpredictable change, which brings up the measurement problem in the language of wave functions.

There is now the following paradox: Suppose we observe ψ protectively (adiabatically) and conclude that it is real or ontological. And then we do the usual measurement, which leads to the "collapse" of this wave function to a localized state ψ'. For the new measurement, ψ is only used epistemologically to predict the probability of the new state ψ' by means of the Born rule. So, what happened to the reality of ψ? This paradox is resolved if we give up the notion of absolute reality, and accept that both ψ and ψ' are real only in relation to the interaction that they undergo with the systems they interact with. The sudden change from ψ to ψ' is not paradoxical if we do not assign absolute reality to either wave function, but instead assign relational reality to them, which requires that such a change should take place because the interaction that determines this relational reality has changed.

In all three examples, above, in the assigment of relational reality to one of two interacting systems, the following condition is satisfied, which will be called R: *Two systems interact with each other in such a way that their states remain unentangled, and the interaction satisfies the action-reaction principle.* This suggests using the condition R as necessary and sufficient criterion for the relational reality of states or wave functions, in general. I shall therefore assume this to be the case, and postulate that the quantum probabilities of the previous section apply to states that satisfy the condition R.

The influence of each state on the other provides information about the former via the interaction, when R is satisfied. To illustrate this, consider the commonly encountered situation in which the Hamiltonian for two systems S_1 and S_2 is $H = H_1 + H_2 + H_{12}$. The subscripts 1 and 2 designate operators that act on the Hilbert spaces of S_1 and S_2, respectively, and H_{12} is the interaction Hamiltonian. Suppose now that $H_{12} = g(t)A_1A_2$, where $g(t)$ is a c-number coupling constant that represents the turning on and off of the interaction. In the impulse approximation, $g(t)$ is very large for a short period of time so that the free Hamiltonian is negligible compared to the interaction Hamiltonian during this period. Then, if the combined system $S_1 + S_2$ was initially in the unentangled state $\psi_1\psi_2$, where ψ_1 is an eigenstate of A_1 with eigenvalue a, S_1+S_2 will continue to be unentangled during the interaction. But the response of S_2 to the interaction, which may be determined by subsequent observations (interactions), will depend on the eigenvalue a of A_1. This is the usual von Neumann measurement specialized to the case in which S_1 was already in an eigenstate of the observable A_1 at the beginning of the interaction. On the other hand, more generally, if ψ_1 were not an eigenstate of A_1 then the state of $S_1 + S_2$ that is obtained by solving Schrödinger's equation is an entangled state ψ_{12} due to the interaction. According to the present view, ψ_{12} should be regarded as the probability amplitude from which the probabilities for the various states in this superposition that satisfy condition R, such as the above $\psi_1\psi_2$, may be obtained. The only way to give relational reality to ψ_{12} is to let it interact with another system with state ϕ such that $\psi_{12}\phi$ satisfies condition R which makes ψ_{12} real with respect to ϕ.

We may now take the opposite limit in which $g(t)$ is small and varies slowly or adiabatically, so that the interaction Hamiltonian may be regarded as a perturbation of the free Hamiltonian. Also, suppose that ψ_1 is a non degenerate eigenstate of H_1 and $g(t)$ does not contain any frequency component that connects ψ_1 and the nearest eigenstate. This is the case of protective measurement [12] in which the combined system remains in the unentangled state; but the response of ψ_2 depends on $< \psi_1|A_1|\psi_1 >$, which generalizes the eigenvalue of A_1. The third example is the weak measurement of Aharonov (see for example [19]) in which H_{12} is so weak that it causes only a small entanglement to the initial or preselected unentangled state of the two systems. One then makes a postselection of a particular state ψ_1 of system S_1. This puts the combined system in an unentangled state. From the state of system S_2, compared to its initial state, the 'weak value' $A_{1w} =< \psi_1|A_1|\phi_1 > / < \psi_1|\phi_1 >$ is obtained, where ϕ_1 is the preselected state of S_1. The preselection of ϕ_1 and the postselection of ψ_1 mean that each of these states has relational reality with respect to another system that interacts with it satisfying condition R at the times of preselection and postselection, respectively. Hence, the information obtained about these states, ϕ_1 and ψ_1, from A_{1w} is consistent with the relational reality assigned to these states.

In practice, we obtain the information about the state ψ_1 through its interaction with ψ_2 by choosing S_2 to be macroscopic or from a subsequent interaction of S_2 with a macroscopic system. But this is only because we are macroscopic beings, and it does not imply any necessary asymmetry between the two interacting systems, objectively speaking. The above relational reality condition R is explicitly symmetric. For example, in the Stern-Gerlach experiment with neutrons, a given neutron is in the spin-up or spin-down state relative to the inhomogeneous magnetic field of the magnet, and the magnet relative to the neutron is then in one of two possible states that have opposite momenta during their interaction. This is because each of these unentangled states of the combined system satisfies R, and the above objective probabilities require that only one of these possibilities are realized. The magnet may be microscopic or macroscopic. If it is microscopic, then it becomes necessary *for us* to verify the response of the magnet by means of its interaction with a macroscopic system.

The nonentanglement stipulated in condition R may be satisfied only approximately in practice. But if one views reality as fluid and not concrete then this is not a problem. The notion of stark, concrete, absolute reality that we use in our daily lives, according to which something *is* or *is not*, may be useful for our survival, for example, if we encounter a tiger in a jungle. For this reason, our brains may have acquired the notion of absolute reality during evolution by natural selection. This may be due to the stability of certain unentangled states in our brains due to the nature of the interactions between them. But an objective examination of the interactions between microsystems suggests that absolute reality is not valid. The symmetrical relational reality being postulated here, instead, does *not* lead to solipsism because each of us is interacting by means of the gravitational and electromagnetic fields with all the other objects, which are therefore real to us, and we are to them. But the state in which we observe another system depends on the nature of our interaction with it.

9 Discussion and Speculation

According to the present view, an arbitrary state of any isolated object represents only the potentialities for the relational reality that it may have if and when it interacts with another object. An 'event' for which quantum mechanics assigns a probability of occurrence is the interaction of a pair of states of two systems that satisfy condition R. Since the interactions are local (due to the fundamental interactions of gravity and gauge fields being local), the two states must be localized in order for them to remain unentangled as required by R. This explains why the world of events that we observe appears to be classical even though quantum mechanics is universally valid, in the present approach. It also appears to explain the origin through these events of the space-time description, which is different from the Hilbert space description of quantum mechanics.

The interpretation of quantum mechanics which emerges from the above analysis is intermediate between the Copenhagen and the Everett interpretations. It may be reached from the Everett interpretation by replacing the notion of absolute reality in this interpretation, which makes all the worlds that are nearly orthogonal because of decoherence to be real, by relational reality that makes only one of these Everett worlds to have relational reality. The reason for the latter conclusion is that there is no interaction that connects two Everett worlds, as in the case of the alive and dead states of the cat mentioned above, i.e. a superposition of the states of two Everett worlds cannot interact with another object so that condition R is satisfied. Therefore, a superposition of two Everett worlds cannot have reality with respect to another object. Furthermore, the *objective probabilities*, introduced in sections 6 and 7, give a probabilistic prediction for the realization of one of these Everett worlds at each instant of time. On the other hand, the Everett picture is deterministic and therefore cannot contain objective probabilities; hence probabilities may be introduced only by coarse-graining, i.e. through ignorance of the precise initial conditions, as in classical statistical mechanics where also there are no objective probabilities. It is not clear how the empirically successful Born rule that uses the geometry of Hilbert space could be obtained from coarse-graining. But in the present interpretation, these probabilities emerge naturally and objectively from the denial of fundamental causal laws, and the requirement of invariance under symmetries, as shown in sections 6 and 7.

The present interpretation may also be reached from the Copenhagen interpretation if in addition to the denial of absolute reality in the latter interpretation, we introduce relational reality. This removes the anthropomorphic concepts from the Copenhagen interpretation, such as the need for a 'classical' measuring apparatus with a human observing it, or introducing 'measurement' by a human or at least a macroscopic system as a special interaction. As Niels Bohr said, we need to specify the entire experimental arrangement before assigning reality to any part of it. But this is necessary only because relational reality is determined by all the interactions in the entire experimental arrangement. It is not necessary for the specified experimental arrangement to contain a macroscopic subsystem. The present interpretation therefore abolishes the notion of 'measurement' as a special interaction, and provides an objective, but relational, description of this process assuming the universal validity of quantum mechanics.

If absolute reality is replaced by relational reality then it would seem that any universe that is made of interacting parts and is mathematically consistent may have relational reality. I shall call the collection of such hypothetical universes the *polyverse*. This speculation, because it is based on the notion of reality being purely relational, provides an answer to the old philosophical question of why there is something and not nothing. Each universe contained in the polyverse has no reality as a whole because none is interacting with any other. However, parts of each universe have relational reality due to their mutual interaction. Incidentally, this implies that the wave function of the universe as a whole has no reality, but it is meaningful to assign a wave function to any part of the universe in relation to another part with which it is interacting. Although none of the other universes in the polyverse has reality to us, the polyverse nevertheless has a physical consequence in explaining why the symmetries and coupling constants of our universe are such that they allow life to evolve, without assuming that our universe was a special creation to allow this [1]. In other words, the polyverse provides a physical basis for an anthropic principle. If we assume, on the other hand, that the polyverse consists of just one universe, then the only alternative to the special creation hypothesis is to try to discover a principle that explains the symmetry groups and values of the coupling constants in our universe.

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