Context, spacetime loops and the interpretation of quantum mechanics

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Abstract
Three postulates are discussed: first that well-defined properties cannot be
assigned to an isolated system, second that quantum unitary evolution is
atemporal, and third that some physical processes are never reversed. It
is argued that these give useful insight into quantum behaviour. The first
postulate emphasizes the fundamental role in physics of interactions and
correlations, as opposed to internal properties of systems. Statements about
physical interactions can only be framed in a context of further interactions.
This undermines the possibility of objectivity in physics. However, quantum
mechanics retains objectivity through the combination of the second and third
postulates. A rule is given for determining the circumstances in which physical
evolution is non-unitary. This rule appeals to the absence of spacetime loops
in the future evolution of a set of interacting systems. A single universe
undergoing non-unitary evolution is a viable interpretation.

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1. Introduction

It is well established that the physical world is quantum mechanical. This is established
not only by carefully controlled experiments designed to demonstrate basic phenomena such
as interference of de Broglie waves, and Bell-EPR correlations, but also by the success of
theoretical developments, such as Dirac's deduction of the existence of anti-matter, and more
complex insights such as quantum field theory and the predicted existence of further particles
such as the Z boson, which were subsequently detected experimentally. Despite this, there
remains a fundamental difficulty: there is no consensus on the clearest way to set out the basic
physical content of the theory of quantum mechanics. That is to say, we understand how to
use the theory for all practical purposes, but this is done by making free use of loosely defined
words such as 'measurement'. If pressed to state exactly what physical process constitutes

a measurement, physicists experience varying degrees of satisfaction with their own answer, but no one's answer has commanded the sort of near-universal agreement which we normally expect in science. This proves, in my opinion, that we have not yet understood this subject properly.

I believe it is likely that a thorough resolution of this difficulty will only be possible once a more general theory has been developed, such as one unifying quantum mechanics and general relativity. It may also be that the whole reductionist approach, though a useful method for simple systems, is limited in scope, and not capable of treating some phenomena in sufficiently complex systems. Even so, we should seek a reductionist description if one is available, on the principle of not introducing unnecessary hypotheses.

In this paper I will set out a symmetry principle which is not commonly taught or emphasized in physics but which, I will argue, should be given a more prominent position. It is obeyed by quantum mechanics and not by classical physics, and gives a useful insight into the former. I will also comment on reversible behaviour. I will argue from the combination of these ideas for a specific physical interpretation of quantum theory. That is, I will set out a way to link the abstract mathematical apparatus of the theory to statements about physical phenomena. In particular, I provide a rule for determining the circumstances under which a 'quantum event' occurs, where a quantum event is a non-unitary evolution roughly equivalent to a 'collapse of the wavefunction'. The discussion is like the Copenhagen Interpretation (CI) of quantum mechanics [1–3], but seeks to avoid unsatisfactory elements of the latter, especially its use of concepts such as 'measurement' or 'classical apparatus' without a satisfactory definition. My approach also has an element reminiscent of the 'transactional interpretation' of Cramer [4–6], namely the idea that some aspects of physical behaviour are atemporal, and correlations are established by a combination of local interactions and a specific type of influence from the future.

The symmetry principle, which I call the principle of 'contextuality', is the assertion that physical entities cannot have physical properties in and of themselves. Interactions and correlations between entities are more fundamental, and properties such as mass, velocity, etc arise by a type of symmetry breaking. Basic theories of kinematics and dynamics must respect this symmetry and this may be regarded as a partial explanation for some of the basic features of quantum mechanics. Correlations can be regarded as invariants of the associated transformation.

The idea that relationships and correlations are the only proper subjects of physics is suggested by Everett's 'relative state' formulation of quantum mechanics [7], it was briefly discussed by Zurek [8] and has been stressed more recently by Rovelli [9], Mermin [10] and others [11]; see also [12]. However, there is a further ingredient to experimentally observed behaviour that is not satisfactorily treated in these works, in my opinion. This is the everyday observation that the universe evolves in a non-unitary way. Quantum theory correctly predicts the type and degree of correlation to be expected between systems, but physical systems express these correlations by randomly adopting physical configurations drawn from an appropriate set: for example, alive or dead, in the case of Schrödinger's cat [13]. Therefore, although I agree the 'relational' symmetry is important to understand the quantum formalism, I claim it is broken in the actual dynamics. I introduce the word 'contextual' because I will be concerned with dynamics involving groups of three systems, not two.

In the following I aim to elucidate this symmetry-breaking behaviour, not by extending quantum theory, but by providing a rule for determining the circumstances under which it occurs. The rule involves an appeal to processes that are not reversed, cf [14, 15], but does not assume such processes are not treatable by standard quantum theory. Instead, it is asserted that unitary evolution is essentially atemporal, and quantum processes are sensitive to the absence

of loops (to be defined) in their future. One can then consistently claim that physical evolution consists of a sequence of non-unitary transformations or 'quantum events', with probabilities given by the standard formalism, and preferred basis related to the idea of contextuality.

Although I will draw links between this 'quantum event postulate' and the other ideas presented here, it is nevertheless a mere assertion, and this may be a weakness of the present account. A mechanism would greatly clarify matters, if one exists, such as the transactional idea [4], the Ghirardi–Rimini–Weber or other stochastic mechanism [16–18] or a gravitational effect [19, 20]. The present discussion leans towards the former (transactional) account, which is an interpretation not an extension of quantum theory, without committing itself to any particular view. That is, the approach presented here does not require any fundamental new dynamics, but it can be formulated so as to be consistent with some types of new dynamics (see section 8). Generalizations of quantum dynamics, such as nonlinear terms in Schrödinger's equation, can have the result of implying that some physical processes are computationally very efficient, for example collapsing the complexity class NP to P. This would be very surprising and when it happens it may merely indicate that the attempted generalization is wrong. Here I take the view that progress in formulating dynamical equations will require mathematical tools able to handle a dynamical spacetime (i.e. quantum gravity), but interpretive discussions such as the present one can help in placing constraints on and identifying desirable features of such a theory.

I will present the postulate on quantum events in a form where no new dynamics are assumed. It has been argued by Marchildon that Cramer's transactional interpretation makes correct predictions, but retains one of the problems of CI, namely the difficulty of making a 'quantum-classical' type of distinction [6]. The quantum event postulate provides the required distinction. Another approach to quantum mechanics which does not change the dynamical equations is the 'consistent histories' or 'decoherent histories' formalism of Griffiths, Omnès, Gell-Mann and Hartle; see for example [21–23] and references therein. Brief comments on the relationship between those ideas and the ones presented here are given in section 5.3.1. The mathematical notion of a set of 'consistent histories' appears to be able to describe a wide range of physical behaviour, and has to be carefully interpreted. The degree to which interpretive statements need to be added to the formalism is a matter of continuing debate [24, 25]. For example, it is argued in [21, 25, 26] that there exist a large number of consistent sets of histories, only a small proportion of which correspond to the type of quasi-classical behaviour we observe in the world. Therefore, a further set selection criterion, beyond consistency, is needed. The ideas presented here do not require a 'consistent histories' formulation, but in that formulation they would provide a further set selection criterion.

Sections 2 and 3 introduce the general flavour of the ideas. In the former I sketch the overall pattern of behaviour observed in experiments sensitive to quantum phenomena, and comment on different mathematical approaches to time evolution. The observations about reversible evolution open the way to an appeal to atemporal behaviour which is used in the arguments later in the paper.

Section 3 discusses the principle of relativity, in order to use it to illustrate the role of a symmetry principle in furthering our understanding of a physical theory. It introduces the general idea of the need for a certain subtle type of economy in physical theories, namely that a basic theory should not imply, even indirectly, that physical entities can have unmeaningful characteristics, such as absolute velocity. Section 3.1 then introduces the general idea that it is questionable whether properties ought to be attributed to isolated physical entities, and it illustrates how this is handled in quantum theory. Section 4 introduces the three postulates which underpin the main argument. Section 5 is the main part of the paper; it applies these ideas to the interpretation of quantum mechanics, and introduces the rule for quantum events.

Section 6 presents a rough sketch of a way of thinking about the rule, in the spirit of the 'transactional' mechanism. A brief comment on the second law of thermodynamics is made in section 7, and then section 8 discusses the issue of possible falsification of these ideas, and 9 concludes.

2. Quantum-mechanical behaviour

Experimental observations, such as Young's slits experiment with a low-flux source, invite us to relinquish the classical vision of a spacetime which simply exists and has the worldlines of all the particles of the universe in it. Instead, physical reality consists of a richer behaviour which is harder to describe, because things really 'happen', in the following sense. In a reversible evolution, time is merely a parameter, and whether it goes forward or backward is of no fundamental significance: the future causes the past in just the same way as the past causes the future, in the sense that a given situation at a time t_f defines what the situation must have been at earlier times t_i. The classical vision of worldlines laid out in spacetime in what amounts to a sort of 'permanent present' is consistent with this. However, nature is not like that. There is genuine freedom for novelty in the universe. Some events which might have happened do not happen, (e.g. the death of a cat) and others which might not have happened, do (e.g. the cat survived). The initial and final situations do not uniquely prescribe one another. The universe lurches stepwise into the future like a wobbly child picking her way across a stream on stepping stones.

In my opinion, part of the difficulty of understanding these things lies with the fact that the language of state vectors and Schrödinger's equation, while very useful for formulating calculations, is frankly misleading when it comes to getting a good physical sense of what is going on. It has two problems. First, it focusses too strongly on the idea of a 'state' of a system, whereas we need to make interactions between systems the central idea. Second, the notion of gradual evolution through time, described by a differential equation, while it can be pressed into use with sufficient interpretive statements accompanying it, is not the natural language to describe the real world.

To illustrate the second point, consider classical mechanics. This can be mathematically treated both by a differential equation describing gradual evolution through time, and also by a path integral (least action) method. The predictions are the same and in the classical case there is no difficulty in making a close comparison between the two physical pictures suggested by the mathematical equations. However, in the quantum case, I will argue, the path integral method gives a better physical picture than the time-dependent differential equation method. This is because it forces one to consider a physical problem from the point of view of final as well as initial conditions, and it presents a global view of the worldline. The formulation presents the final condition as a *fait accompli*, and asks for its probability. The global view of the worldline emphasizes that time acts simply as a parameter during reversible evolution, and there is no way to pick its direction without further information.

In the following, I will regard the paths entering into a path integral as (highly structured) links between different points in spacetime, but physical evolution is non-unitary. Processes in the present are sensitive to the absence of a loop (of a type to be defined) in their future light cones. We avoid causal-loop paradoxes or contradictions by ensuring that the physical predictions are those of standard quantum theory.

3. The principle of relativity

It is useful to clarify what *type* of explanation is to be put forward here. I will not be proposing any new equation, but rather offering a new perspective on familiar phenomena.

A useful comparison can be made with the type of explanation provided by Einstein's special theory of relativity [27]. At the time Einstein put forward his ideas, it was already known that objects in motion relative to a given reference frame should be contracted and evolve more slowly, etc, which is why the Lorentz contraction and the Lorentz transformation have been named after Lorentz rather than Einstein. Indeed, if one assumes that Maxwell's electromagnetic equations are correct, then the special theory of relativity makes no new predictions for electromagnetic phenomena (which include the dimensions of everyday objects, the mechanism of everyday clocks, and so on). However, Einstein's theory provides a profound and very useful insight, because it shows that the Lorentz transformation arises in a simple and general way from a few reasonable assumptions about nature. This both clarifies what the Lorentz transformation means (i.e. it is a statement about space and time and not about electromagnetism *per se*), and it allows one to expect and require not just electromagnetic theory but any theory of the natural world to be Lorentz covariant.

Einstein singled out two principles: relativity, and the principle that the speed of light in vacuum is independent of the motion of the source[1]. He then insisted that these two, which appear at first to be contradictory, are in fact mutually consistent, as long as one lets go of the mistaken idea that simultaneity is absolute.

Any interpretation of quantum theory which does not involve an extension to the formalism must make an argument of this broad type, in that the difficulty is in reconciling things which appear to be contradictory, and to do this one must let go of some mistaken preconception. The apparently contradictory things in quantum mechanics are the unitary equations of motion and the observed non-unitary physical behaviour. In a 'many-worlds' type of interpretation [28], one tries to reconcile these by letting go of the notion of a single universe, or of an observer-independent set of physical events. However, it is not clear that this succeeds, because one needs irreversible behaviour to cause a 'split', which is begging the question (*petitio principii*). Rovelli's 'relational' interpretation has some similarities with 'many-worlds', and suffers, in my opinion, from a similar problem. In [9], the preliminary discussion appeals to 'a specific measurement outcome' and 'the standard account of measurement'. Admittedly the full discussion is more thorough, but it still has to use terminology such as 'a quantum event' involving 'discrete changes of the relative state, when information is updated' [29].

I will advocate that one should retain a single universe with observer-independent physical events, but allow a more subtle relationship between the present and the future than is the case in classical physics.

The idea of contextuality, to be discussed below, is similar to the relativity principle. To bring out the similarity it is useful to state the principle of relativity in the form

> **Principle of Relativity of Kinematics**: *The laws of nature should take a form such that only relative uniform motion, not absolute uniform motion, can be meaningfully defined.*

The related statement, 'the Laws of Nature must take the same mathematical form in all inertial reference frames,' can be regarded as following from the former. I have called this the 'principle of relativity of Kinematics' rather than simply the 'principle of relativity' since I will be discussing a broader type of relativity principle below.

The principle of relativity of kinematics takes a logically satisfying intuition about the way physical systems can be expected to behave, and proposes it as a law of nature. In particular, it claims that a statement intended to describe or quantify uniform motion can only be framed in terms of the relative motion of one body with respect to another. From this

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[1] One does not have to refer to light, it is sufficient to claim that there is a finite maximum speed for signals.

it follows that the mathematical expression of the laws of physics should not imply that a further, absolute, type of uniform motion is detectable, or has physical consequences of any sort. I propose to take this idea further, and claim that not just uniform motion, but every aspect of physical reality can only be defined in a relative way, in the following sense. First, there are no properties of any physical entity in and of itself; rather, 'properties' are a useful way to summarize collections of interactions between entities. These interactions, and the correlations between entities which they produce, are the fundamental elements of physical reality. Furthermore, these 'fundamental elements' (i.e. the interactions and/or correlations) cannot be defined in an absolute way, but rather they can be specified only relative to other sets of interactions and correlations, which I will call their *context*. However, some aspects of the context are permanent, and this allows objective events to occur. I will clarify the meaning of these statements after I have given some further argument in support of this general approach.

3.1. Isolated systems are ill-defined

Suppose there only exists, in the whole of reality, one simple particle. What statements can be made about such a particle? None (except the assumed fact of its existence). Obviously there is no way to define its location and speed, since the notion of absolute motion is ill-defined (i.e. meaningless), and there is nothing with respect to which it can have a relative motion or position. Similarly, only relative mass and charge and so on is meaningful.

It may be objected that if the whole of physical reality were to consist of a single simple particle, one could not reason about it in any case. However, in the real universe there can exist an approximation to the above situation, namely a simple particle which is isolated from all other things for a long time. To the extent to which such a particle is in fact isolated, and remains so, we should therefore expect the laws of nature to describe it in such a way that all its properties are undefined. Classical physical theories could not do this, because their starting point is the concept of entities with well-defined properties. However, quantum mechanics does offer a mathematically consistent way to handle such a possibility.

The way in which the properties of an isolated particle are not well defined in quantum mechanics is not merely a matter of quantum uncertainty, a spread in the wavefunction. It is that one cannot assign a quantum state to such a particle. When we make statements such as 'a particle is prepared in the state $|\phi\rangle$' what we mean is that the particle undergoes an interaction with another system (typically large and complicated such as an absorbing barrier) such that the particle and the other system are entangled, and the evolution to be described concerns only one part of this entangled state. However, if the part of the entangled state which was ignored is later caused to interfere with the part which was under discussion, then the whole discussion was invalid because the premise (particle prepared in $|\phi\rangle$) is false. For an isolated particle, there is always the possibility that it will in future couple to systems with which it is currently entangled, so that it is impossible to make well-defined statements about its quantum state without reference to such other systems.

A simple example of a physical property that is undefined, and indeed meaningless, is the spin state of a spin-half particle that is one of a pair of particles in a maximally entangled state such as the singlet:

$$(|\uparrow\rangle \otimes |\downarrow\rangle - |\downarrow\rangle \otimes |\uparrow\rangle)/\sqrt{2}. \tag{1}$$

Einstein, Podolsky and Rosen gave an argument to suggest that an 'element of reality' should be associated with the spin state of either particle individually, but the fact that such a quantum system can give rise to correlations which do not satisfy the Bell inequality shows either that this assumption is false, or that each spin 'element of reality' is sensitive to distant apparatus

settings [2, 30, 31]. I maintain the former, i.e. the term 'spin state' simply cannot be applied to each individual particle in a singlet (except to say it is part of the singlet). Locality and the concept of a 'state' are discussed further in section 5.3.1.

The analysis offered by quantum mechanics, which we write down using a mathematical notation such as (1), offers a precise way to express the notion that, in appropriately prepared circumstances, the assignment of a value of a property, in this example the direction of spin angular momentum, to an individual entity (one of the particles), can be meaningless, even though there are other circumstances where such an assignment can be made.

The notation in the Schrödinger picture, equation (1), is unfortunate in that it forces us to write what might appear to be individual states for the two particles, suggesting to some that the spin of either particle is 'partly up' and 'partly down'. This is merely a limitation of notation, however, or a case of over-interpreting mathematical symbols. One must simply refrain from trying to speak as if properties can be assigned to individual systems[2]. The fact that the spin is not 'partly up' and 'partly down' is underlined by the fact that there is no way one can legitimately choose the 'up' and 'down' directions instead of some other pair of directions, because of the well-known rotational symmetry of the singlet state, e.g.

$$\tfrac{1}{\sqrt{2}}(|\downarrow\uparrow\rangle - |\uparrow\downarrow\rangle) = \tfrac{1}{\sqrt{2}}(|\rightarrow\leftarrow\rangle - |\leftarrow\rightarrow\rangle)),$$

where $|\leftarrow\rangle = (|\downarrow\rangle + |\uparrow\rangle)/\sqrt{2}$, $|\rightarrow\rangle = (|\downarrow\rangle - |\uparrow\rangle)/\sqrt{2}$, and I use the shorthand $|m_1 m_2\rangle \equiv |m_1\rangle \otimes |m_2\rangle$. In the language of quantum-mechanical interpretation discussions, we say there is no 'preferred basis'.

Another instructive way to present this rotational symmetry is as follows. Suppose we first rotate just one of the particles. Then in order to restore the ket to its initial form, one can rotate either of the particles: either reverse the rotation of the 1st particle, or apply the same rotation to the second. Therefore, a given transformation of the composite system can be accomplished by rotating either one of the constituent particles. A similar symmetry applies to all the Bell states [32]. It is obvious that such behaviour is not possible for a pair of classical arrows, and it implies that it cannot be correct to discuss the composite system as if the two constituent particles contributed individual spin properties. I am labouring this point because it is particularly striking when one recalls that the two particles can be space-like separated. It may also bear on the computational power of quantum computers. I have argued elsewhere that the advantage available to quantum computing, compared with classical computing, arises from exploiting precisely this feature, namely that quantum systems can express and manipulate a physical representation of the correlations between logical entities, without the need to completely represent the logical entities themselves [33].

The feature of quantum mechanics which allows it to provide this type of description is, of course, entanglement. Entanglement is the means by which the laws of nature are consistent with the requirement that mutual influences and correlations are more fundamental than properties of isolated entities.

Why is it the case, then, that assigning properties to entities (the cup is blue, the ball is heavy, etc) is so thoroughly built in to almost all our reasoning about the physical world? This is because such statements are made within a context, namely the actual history and future of the world, and properties are emergent phenomena. That is, physical behaviour tends towards a situation where associating specific properties with individual entities is valid. I will clarify this in the following sections.

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[2] We will discuss later the circumstances under which such language can be allowed because the context makes it unambiguous.

4. Contextuality, atemporal evolution and irreversible processes

I will now state the physical principles that I wish to put forward, and whose implications are the main subject of this paper.

> **Postulate 1** (Contextuality). *The laws of nature should take a form such that well-defined properties cannot be assigned to an isolated system. Only interactions between systems are meaningful, and these can only be described through their influence on subsequent interactions of the systems in question with the rest of the world.*

> **Postulate 2** (Atemporal evolution). *Quantum unitary evolution is atemporal.*

> **Postulate 3** (Irreversibility). *There are in nature processes that are not reversed.*

To many physicists, the first and third of these assertions may be unremarkable, even obvious. However, it is remarkable that, in conjunction with the basic equation of motion (furnishing the propagator for unitary evolution, for example by a path integral) they suffice to allow a physical interpretation of quantum theory. What is meant by the second postulate, on atemporal evolution, will be explained in the following. I have included it in this list in order to highlight it, and to bring out the tension between this postulate and the third (irreversibility).

The irreversibility postulate refers to 'processes that are not reversed'. The discussion will not involve an irreversible component to the fundamental equations of motion, such as in dynamical wavefunction collapse theories [16–20]. For a process to be called 'non-reversed' here, it is sufficient if the equations of motion are reversible but the motion is such that it never gets reversed in practice. For example, it could involve a particle emitted to very large distances, or it could be very complex.

Even supposing that the equations of motion are reversible, it is clear that many physical processes are in actual practice not reversed on any time scale to which we are able to assign meaning (e.g. the lifetime of galaxies, the proton decay time). Furthermore, it might be strictly impossible to reverse a very complicated process such as an avalanche, because any apparatus intended to reverse the motion of all the particles would itself be large and complicated, and could not be sufficiently isolated. For example, its gravitational influence on the rest of the world would be especially hard to avoid or reverse.

Once we insist on a context to statements about physical behaviour, there immediately arises the possibility of ambiguity. For example, relative motion is a well-defined concept because the relative motion between one body and another can be specified without the need to bring in a possible relative motion of the second body with respect to a third. However, if a statement about relative motion is only meaningful within a context, then a third body might be important after all, because the context could depend on it. This is exactly what is investigated in well-known paradoxical experiments that have been long discussed in quantum mechanics, such as 'delayed-choice' experiments, the 'quantum eraser' and 'Wigner's friend' [2, 4, 34]. We will avoid ambiguity about physical behaviour by using postulates 2 and 3. This will be discussed in section 5 below. I will also argue that these three postulates are intimately linked.

By requiring that physical systems cannot be regarded as isolated entities, the contextuality postulate places a constraint on the form of other laws of nature. In common with what is found in general when physical behaviour is subject to a constraint at a fundamental level, we may guess that physical behaviour will be found in practice to fill the constraint, i.e. satisfy it but only just. Therefore, I predict that physical systems will show a tendency to maximize the degree to which they can be regarded as separate entities with individual properties.

This means they will minimize entanglement. This prediction is not unavoidably implied by postulate 1, however, therefore I will propose it as part of a further postulate below (section 5.2). The point is that the further 'quantum event' postulate is not altogether independent of 1–3, but rather is suggested by them.

5. Application to quantum theory

5.1. No properties for isolated systems

Standard quantum mechanics obeys the contextuality postulate at the most basic level of single isolated entities because quantum entanglement implies that no statements can be made about the properties of completely isolated systems.

For example, consider the projection onto some chosen direction (taken as the z axis) of the spin σ of a given electron. We know that the possible eigenvalues of the spin component σ_z are $\pm\hbar/2$. However an electron, in and of itself, cannot be said to have a value of σ_z since its spin state might always be entangled with something—possibly the last atom it scattered off, or else if it never scattered off anything then a distant positron (if the electron came from pair production), or a proton and anti-neutrino (if it was a product of beta decay), or some quantum fields (if it came from the big bang). We will discuss in the following section the circumstances in which a 'quantum event' can result in a well-defined σ_z, but such an event depends on the interaction of the electron with other things.

It is reasonable to assume that all properties, including mass and charge and the total spin of particles, are generated by quantum effects, in which case the argument also applies to these properties. When we say an electron has a well-defined mass, which we regard as an intrinsic property, this is because it has acquired a well-defined mass by virtue of past events, involving interactions with other systems. Different mass states were entangled with decay products in the early history of the universe (just as an atom undergoing spontaneous emission is entangled with the emitted photon), when evolution between mass states of the fundamental entities (strings or whatever) took place. However these decays are not going to be reversed in the future, and in this circumstance (see the following section) one of the mass states was adopted randomly. One of the mass eigenvalues is $\sim 9.10939 \times 10^{-31}$ kg, and entities of this mass (and various other properties which come about in analogous ways) we call electrons. We can talk about 'properties' because we have implicitly assumed this history.

5.2. Quantum events

The interpretation problem, or measurement problem, in quantum mechanics is essentially the problem of wavefunction collapse. It is illustrated by the Schrödinger cat experiment: we want to know whether and how the 'both and' character of a superposition can be resolved into the 'either or' character of a set of possible outcomes. CI handles this by a statement that the whole theoretical formalism is there to describe possible behaviours of 'classical' systems, but it fails to explain how these classical systems are identified, or why they are not quantum systems. In the approach taken by Feynman in his famous lectures on physics [35, 36], the problem is there but hidden. In this approach, one identifies the final situation whose probability is desired to be calculated (just as in a path integral calculation), and one goes ahead and calculates it. It is not discussed how the physical system 'knows' to adopt just one of the possible outcomes and not all of them in superposition. The discussion of Cramer [4] makes the same omission. Cramer appeals to the notion of a 'quantum event' and discusses how it may insightfully be understood as an atemporal 'transaction' between emitter

and absorber. However, he omits to say how one identifies when a 'quantum event' occurs, as opposed to a unitary evolution in which several absorbers become entangled. This point has also been raised by Marchildon [6].

I agree with Cramer that a 'quantum event' is best understood to take place over an extended region in spacetime, not at a spacetime point. This idea is implied in CI, but not clearly spelled out. The minimum formal apparatus we need in order to interpret the theory is a statement to identify when a 'quantum event' occurs. I will now provide such a statement. The rest of the paper is a discussion of its meaning and application.

Quantum event postulate (No-loop)

Strong version. *A 'quantum event' or 'transaction' is undertaken whenever there is no loop in the future whereby the relative phase of two parts of an entanglement could influence further events. The preferred basis is that in which separability is maximized.*

Weak version. *A 'quantum event' or 'transaction' is undertaken whenever there is no loop smaller than A_{max} in the future whereby the relative phase of two parts of an entanglement could influence further events. The preferred basis is that in which separability is maximized.*

In this postulate, the term 'quantum event' refers to a non-unitary evolution from the present to the future, in which one of a set of possible outcomes is realized. It corresponds roughly to the notion of 'measurement' in CI. The preferred basis defines from which orthonormal set the outcome is to be drawn (randomly with probability equal to the modulus square of the quantum amplitude). The absence of a loop recalls the well-known idea of (the presence of) 'which path' (*welcher weg*) information, also known as a *record*. Under purely unitary dynamics, a system W carrying *welcher weg* information would be entangled with the system S whose path information it carries. The postulate applies when S is itself composite, and asserts, essentially, that if the future dynamics does not erase the *welcher weg* information, and the latter can discriminate between separable and inseparable states of S (see below), then an event occurs, i.e. a non-unitary evolution is completed in a finite region of spacetime. Separability here refers to the absence of non-local correlations, i.e. it is a property of the physical behaviour in spacetime, not the abstract analysis of vectors in Hilbert space. The spacetime area A_{max} is a non-trivial quantity whose definition will be discussed in the following, as will the identification of the preferred basis.

I have employed Cramer's term 'transaction' in order to make it clear that the 'quantum event' is extended over spacetime. The postulate is independent of whether or not a microscopic machinery of 'offer wave' and 'confirmation wave' is assumed, but I sketch in section 6 how such a machinery might be constructed. The statement about preferred basis advances the hypothesis that systems in practice tend to become separable, within the constraints set by the equations of motion and the boundary conditions.

I will discuss the strong version of the postulate, and comment on the weak version afterwards. I will use 2-state systems to illustrate the physics, and refer to them as 'spin-half particles'. The two states in question do not have to be spin states, they could for example refer to left and right motion, or ground and excited states of some system. However the 2-state systems in question are small and simple. I will use standard quantum mechanics in the Schrödinger picture to treat the evolution mathematically, and I will show how the quantum event (no-loop) postulate is suggested by or connected to postulates 1–3. The discussion will treat a 'toy' or simplest possible case, followed by some comments on the extension to more general cases.
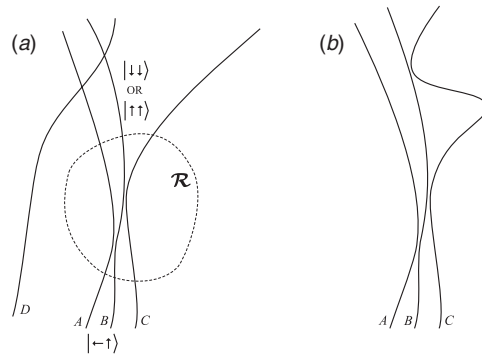
Figure 1. Spacetime diagrams. (*a*) Particles A, B, C interact and become entangled. A and B subsequently interact with other systems D, but not with C or any system influenced by C (but see section 5.3). The resulting evolution is non-unitary, placing A and B in one of $|\downarrow\downarrow\rangle$ or $|\uparrow\uparrow\rangle$ (before their further possible interactions with D). (*b*) Particles A, B, C interact and become entangled, and then C subsequently becomes disentangled with the others. This evolution is unitary and part of some larger event.

Consider two spin-half particles A and B which interact with one another. Referring to 'spin-half particles' is logically consistent because the total spin of the physical entities under discussion, and some other basic characteristics, will be well defined by past processes. In order to keep the problem simple, it will be assumed that the particles are not identical, and their motional states are small wavepackets which can be approximately treated as classical particles moving along classical trajectories. This is consistent when the interactions of the particles with the rest of the universe have resulted in well-defined motional states, and the further evolution under discussion does not entangle their motional degrees of freedom.

In view of the postulate (contextuality) that physical statements must not imply that isolated particles have absolutely defined properties, one must be careful not to use the word 'state' inappropriately. Therefore when referring to the mathematical apparatus of vectors in Hilbert space, I will use the word 'ket' rather than 'state vector' or 'state'. Also the phrase 'in the context $\mathcal{R}$' will be used as a shorthand for the phrase 'in the context of interactions outside spacetime region $\mathcal{R}$'.

Suppose that, in some spacetime region $\mathcal{R}$, the spins of the particles are initially (i.e. where the world lines enter $\mathcal{R}$) described by the ket $|\leftarrow\rangle \otimes |\downarrow\rangle$ (we will examine at the end how this can come about). Suppose first that they evolve under an interaction between them, such as $\sigma_x \otimes \sigma_x$, but they do not interact with anything else. In this case, by postulate (contextuality), there are no physical predictions to make. This is because we need at least three entities: two to have an interaction, and a third to be influenced by the result. This places the interactions at a more basic level than the entities interacting[3].

Next consider the case that A and B begin in $|\leftarrow\rangle \otimes |\downarrow\rangle$ and subsequently interact with each other and a third particle C so as to evolve into a tri-partite fully entangled ket such as $|\psi_3(\phi)\rangle \equiv (|\downarrow\downarrow\downarrow\rangle + e^{i\phi}|\uparrow\uparrow\uparrow\rangle)/\sqrt{2}$. We consider two cases for the further evolution of the particles. In case (a), A and B do not ever interact further with C, or with any system influenced by C (figure 1(*a*)). In case (b), A and B interact again with C so as to disentangle the latter, to produce the final ket $|\psi_2(\varphi)\rangle \equiv (|\downarrow\downarrow\rangle + e^{i\varphi}|\uparrow\uparrow\rangle) \otimes |\uparrow\rangle/\sqrt{2}$ (figure 1(*b*)).

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[3] The related idea in Cramer's analysis is that a fundamental irreducible event involves the emitter, the absorber, and the field. For example, if a 2-level atom emitted a photon, then the transactional interpretation only allows a discussion of the outcome when another atom is available to absorb the photon.

In case (b), the phase φ is observable. That is, it can influence events in the future. In case (a), the phase ϕ is unobservable because in order for it to influence further events, an interference or a correlation must be brought about, but, by construction, this does not happen, because we said A and B do not again interact with C or any system influenced by C.

By postulate (no-loop), in case (a) a quantum event takes place, whereas in case (b) one does not—instead, the unitary evolution is part of some larger event.

When a quantum event occurs (i.e. case (a)), the preferred basis is identified as follows. According to the contextuality postulate, we want to discuss the interaction between A and B in terms of its influence on future interactions. In view of the fact that A and B are not further influenced by C, this can be done without reference to C. Therefore, we can get the complete information we need after using a mathematical device to discard all information associated with C. This device is the standard (and arguably unique [37]) procedure of averaging over the possible influences C might have on some further system. In mathematical terms, it is the partial trace [2, 37] of the density matrix, $\rho^{AB} = \text{Tr}_C[\rho^{ABC}]$. After this averaging, we obtain for the ket of A and B a probabilistic statement which can be expressed by means of the density matrix:

$$\rho^{AB} = (|\downarrow\downarrow\rangle\langle\downarrow\downarrow| + |\uparrow\uparrow\rangle\langle\uparrow\uparrow|)/2. \tag{2}$$

This density matrix can be written in terms of any set of basis states. For example, expressed in the basis $\{|\rightarrow\rangle, |\leftarrow\rangle\}$ it is

$$\rho^{AB} = \tfrac{1}{4}((|\rightarrow\rightarrow\rangle + |\leftarrow\leftarrow\rangle)(\langle\rightarrow\rightarrow| + \langle\leftarrow\leftarrow|) + (|\rightarrow\leftarrow\rangle + |\leftarrow\rightarrow\rangle)(\langle\rightarrow\leftarrow| + \langle\leftarrow\rightarrow|)). \tag{3}$$

It is well established that the density matrix contains all the information about the relevant systems (A and B) needed to discuss their future in terms of observables and expectation values, as long as they are not entangled with something else. It does not, in and of itself, define a preferred basis: it can be decomposed (expressed as a sum of pure density matrices) in infinitely many ways. However, the property of separability can distinguish one basis from another, for a density matrix of a composite system. By postulate, we now pick the basis in which the terms in the decomposition are separable, i.e. in this case $\{|\uparrow\uparrow\rangle, |\downarrow\downarrow\rangle\}$ rather than the Bell basis. The quantum event evolves A and B to one of these final states, where now the word 'state' is well defined, it refers to the initial condition of the next quantum event involving the spins of these particles.

Although the term 'quantum event' suggests an abrupt process, I have already emphasized that it is best understood to be extended in spacetime, and one can further remark that it is not necessary to be precise about when it begins and ends. It is sufficient to take the final condition of one event to be the initial condition of the next.

There is an important distinction to note here, between different uses of the density matrix. In a physical process involving entanglement whose presence can be observed, such as case (b) above, one has an inseparable joint ket describing two or more systems. In this case one can use the partial trace as a mathematical tool to study the composite system, and indeed this is commonly done in quantum information theory and is a useful tool. Such a reduced density matrix is different from the one we used in case (a) however, where it was a device to help identify the preferred basis when a quantum event occurs. In equation (2) the mixture represents the 'ignorance' of the universe, before the event, of which outcome will occur, and this is also our ignorance, after the event but before we learn the outcome. In case (a) the density matrix gives complete information on what can be said about the outcome before the event. In case (b) any reduced density matrix one may care to calculate (describing part of a composite entangled system) gives incomplete information. This distinction is not drawn in [10].

It is now possible to specify more precisely what was meant by our opening statement that 'the spins of the particles are initially described by the ket $|\leftarrow\rangle \otimes |\downarrow\rangle$'. This means that the spins had previously interacted with other systems such that the result was a quantum event in which this was one of the terms in the preferred basis (that which maximized separability), and in the event the physical configuration adopted was the one described by this ket. Furthermore, it was legitimate to talk of 'particles of spin half', because this is a shorthand for a history in which the particles earlier (e.g. in the big bang) interacted with other systems in such a way as to make their total spin well defined.

5.3. Discussion

The toy example, figure 1(a), considered a case where the third particle, C, never influenced A and B again in any way at all. This was to keep the discussion as simple as possible. More generally, the same conclusions would hold if any further influence (direct or indirect) of C on A and B is not such as to make the phase ϕ observable. In practice, this could come about by a number of ways. The simplest is where C propagates to infinity, but this is arguably unphysical. More usually, it would be because C interacted with further particles and initiated a non-reversed process such as an avalanche in the $\{|\downarrow\rangle, |\uparrow\rangle\}$ basis, e.g. the propagator $|\uparrow\rangle_C|\Uparrow\rangle_D \rightarrow |\uparrow\rangle_C|\Uparrow\rangle_D, |\downarrow\rangle_C|\Uparrow\rangle_D \rightarrow |\downarrow\rangle_C|\Downarrow\rangle_D$, where D is a large system of many particles. The literature on the 'environment-induced decoherence' is a study of this type of process; see for example [38] and references therein. Decoherence, in which the off-diagonal elements of a density matrix are zero although the related populations are not, does not on its own solve the interpretation problem, but it allows one to discover circumstances in which a relative phase is going to be unobservable in the future because the required loop in spacetime involves a reversal of complex behaviour. One then needs to assume that such a process is indeed not going to be reversed (irreversibility postulate), and then apply the quantum event (no-loop) postulate (or make some other statement).

As an example of a slightly more complicated process in which the phase ϕ in $\psi_3(\phi)$ is observable, consider the following. First recall the identity

$$\frac{|\downarrow\downarrow\downarrow\rangle + e^{i\phi}|\uparrow\uparrow\uparrow\rangle}{\sqrt{2}} = \frac{|\phi_+\rangle_{AB}|\leftarrow\rangle_C + |\phi_-\rangle_{AB}|\rightarrow\rangle_C}{\sqrt{2}}, \tag{4}$$

where $|\phi_\pm\rangle = (|\downarrow\downarrow\rangle \pm e^{i\phi}|\uparrow\uparrow\rangle)/\sqrt{2}$. We introduce some further particles, and consider the following further evolution of the joint system:

$$|\psi_3\rangle_{ABC}|\downarrow\downarrow\downarrow\downarrow\rangle \longrightarrow (|\phi_+\rangle_{AB}|\leftarrow\rangle_C|\downarrow\downarrow\downarrow\downarrow\rangle + |\phi_-\rangle_{AB}|\rightarrow\rangle_C|\uparrow\uparrow\uparrow\uparrow\rangle)/\sqrt{2}. \tag{5}$$

In traditional language, (5) could be the start of a measurement of C in the $\{|\leftarrow\rangle, |\rightarrow\rangle\}$ basis. The eventual measurement outcome could be found to have perfect correlation with the result of a measurement of A, B in the Bell basis, leading to the conclusion that A, B were properly described by $|\phi_+\rangle$ or $|\phi_-\rangle$, not $|\uparrow\uparrow\rangle$ or $|\downarrow\downarrow\rangle$, after their interaction with C. Scenarios such as this have been long discussed, and I do not want to rehearse that discussion here. The central point is that all such observations involve a loop in spacetime: in this example, the loop includes the 'classical' transmission of the measurement outcome from one place to another, in order to allow the correlation to be revealed. Such a loop is precisely the one referred to in the quantum event postulate. The quantum event, or, if you prefer, collapse of the wavefunction, or transaction, occurs precisely in those circumstances where no future process will probe the presence of an entanglement.

If there is a spacetime loop, then usually it is not the only possible future: the unitary evolution includes other paths which do not form a loop. This simply means that more than one

type of quantum event is available. Each possible event (i.e. each case having a no-loop future) has a well-defined quantum amplitude, and is picked with the corresponding probability. This agrees with the standard predictions which one could arrive at, for example, via CI, but we have replaced the notion of 'measurement' by its underlying ingredients: non-erased *welcher weg* information, and evolution towards separable states.

It is dangerous to use the word 'never' in physics, but we have done so (implicitly) twice: in the postulate on irreversibility and again in the postulate on quantum events (the absence of loops in the future). There are two ways to avoid an appeal to the infinite future here. First, if it is possible to identify a non-reversed process in a finite time, that would be sufficient for the strong version of the event postulate. Second, one can imagine that quantization of spacetime, such as in loop quantum gravity, might make the interference phase undefined for finite but very large or complicated loops in spacetime: this would be sufficient for the weaker version of the event postulate. The loop area bound $A_{\max}$ would be a complicated function of the behaviour of all the systems involved in a large entanglement.

In practice, it is easy to identify processes which we can be close to certain will never be reversed. The traditional 'measurements' such as absorption of a photon by a barrier are among these.

This concludes the resolution of the measurement/interpretation problem in quantum theory. In the Schrödinger cat paradox, we conclude that the cat really is either alive or dead, not both, and outcomes of 'measurements' are well defined as either one outcome or another, because they are associated with non-reversed entanglement[4].

One may say that the postulates 1–3 'work together' in the following sense. The contextuality postulate on its own does not allow an unambiguous interpretation of quantum theory, because it implies that physical behaviour depends on context. One is left with a universe apparently unable to have any objective physical behaviour. It seems to require therefore the irreversibility postulate, as a minimal statement that something objective can happen in the universe. In order to satisfy both postulates, quantum theory involves a combination of atemporal behaviour, where time is merely a parameter, and temporal behaviour (the irreversible quantum events). The temporal behaviour occurs whenever it is consistent with the topology of the atemporal worldlines. The overall result is that while the contextuality postulate constrains physical behaviour so as to prevent assignment of properties to isolated systems, systems behave in practice in such a way that properties can be assigned to them as much as possible.

5.3.1. Quantum states, locality. We already showed that the concept of a 'state' is inappropriate to degrees of freedom of a given system which are entangled with other systems. We now discuss a more general limitation to the notion of a 'state' in quantum mechanics.

When we refer to a physical 'system' we are taking the step of referring, for purposes of discussion, to some set of objects such as the particles in some spatial region, following the principle that this is useful because of reductionism. In referring to a 'state' of a system, we are making a similar notional separation, but now with regard to time instead of space. By the 'state' of a system, we mean generally whatever information is enough to specify the outcome of any interaction with any other system, such that the only further information

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[4] There is no need for any conscious observer in these discussions. The interpretation correctly predicts the outcome of the Schrödinger cat experiment, *viz.* the objective reality of a cat *either* alive *or* dead. If we happen not to be aware of which eventuality has come about, then we can choose to represent our best knowledge in terms of classical probabilities for the outcomes. If we become aware of which eventuality has happened, then of course the probabilities we assign must change, in the same way they will change when a classical die is thrown under a cup, and we lift the cup.

needed is the state of the other system and the type of interaction. If two different preparation processes bring two similar systems to a situation such that, if they were subject to the same future interactions with third parties then the same outcomes would occur, then we say the two systems were prepared in the same state. This is an important idea because the information needed to specify a state can be finite, and need not involve the details of the past history or future evolution of the system. In fact, the concept of a 'state' in classical physics serves to identify just those aspects of a system which can be assigned to a specific time.

In quantum physics it has been common to refer to the system ket as a 'state vector', or simply a 'state', on the grounds that it is sufficient to allow the calculation of any experimental outcomes in which we may take an interest. Thus, if a ket $|\psi(t_i)\rangle$ describes a system (which could be large and complicated, such as a 'measuring apparatus') at some initial time t_i, then, should a human calculator wish to know the probability of a quantum event outcome $|\phi(t_f)\rangle$, he or she can calculate $|\langle\phi(t_f)|U(t_f, t_i)|\psi(t_i)\rangle|^2$, where $U(t_f, t_i)$ is the propagator. However, it does not follow that $|\psi(t)\rangle$, at any given time t, completely captures what can be said about the system, because it does not in itself contain the information that an event is taking place with $|\phi(t_f)\rangle$ in the final preferred basis. That is, the quantum system cannot 'know', from the information in $|\psi(t)\rangle$ at any given time t alone, what sort of non-unitary evolution it is participating in. Therefore to call $|\psi(t)\rangle$ a 'state' is a misnomer.

Sufficient information (to allow the non-unitary evolution to be specified) is contained in the unitary evolution of $|\psi(t)\rangle$ extended over time, through the topology. According to the quantum event postulate, the non-unitary evolution is the one actually undertaken by the system, but the set of paths extended over spacetime (i.e. the unitary evolution) is what determines the possible outcomes (in the strong sense of picking the actual preferred basis) and their probabilities. Therefore, the classical notion of an instantaneous 'state' has to be abandoned (it will emerge as a good approximation in circumstances corresponding to classical-like evolution). The closest equivalent to a 'state' at time $t \geqslant t_i$ is perhaps offered by the set of pairs:

$$\mathcal{S} = \{(|\phi_n(t)\rangle, |\langle\phi_n(t_f)|U(t_f, t_i)|\psi(t_i)\rangle|^2), n = 1, 2, \ldots\}, \tag{6}$$

where $|\phi_n(t_f)\rangle, n = 1, 2, \ldots$ is the preferred basis selected by U, $|\phi_n(t)\rangle = U^\dagger(t_f, t)|\phi_n(t_f)\rangle$, and $t \leqslant t_f$. Each pair $(|\phi\rangle, P)$ in the set consists of a ket and its probability.

In summary, an event outcome (for example, A and B in $|\downarrow\downarrow\rangle$ or $|\uparrow\uparrow\rangle$) is established both by the interactions between particles and by their context, i.e. future interactions with other systems. The unitary future says 'these are the kinds of quantum event outcome which may occur' (because their relative phases are going to be inconsequential in any case), and the unitary evolution from the past allows the probabilities to be obtained. This information is combined in the non-unitary quantum event. This is similar to CI, but we have replaced the appeal to 'measurement' or 'classical' systems by postulates 2 and 3: an appeal to the atemporal character of unitary behaviour, and yet an arrow of time revealed by the structure, and especially the topology, of that behaviour. Atemporal behaviour was hinted at in classic paradoxes such as the 'delayed choice', but here we extend it right into the workings of the 'classical' device.

Our interpretation therefore requires the idea of atemporality, and this naturally leads to the consideration of non-locality. It is well known that the combination of objective reality and Einstein locality is compromised in quantum theory: this is essentially what the Bell argument and related experiments demonstrate. Most authors conclude that locality is compromised, but some, notably Rovelli [9] and perhaps Mermin [10], propose the opposite conclusion. It is certain that locality should not be lightly jettisoned. It is deeply ingrained in physics, most notably in general relativity.

I share the general unease with the phrase 'collapse of the wavefunction'. In a CI-like interpretation, one can save locality by blurring objectivity a little. For, during the unitary part of a quantum event, the relevant system is described equally well by two kets: that evolved forwards from the past, and that evolved backwards from the future. We already presented this fact in equation (6). In the example of figure 1(a), given the future context, the initial condition of A and B could be one of $|\downarrow\rangle \otimes |\downarrow\rangle$ or $|\uparrow\rangle \otimes |\downarrow\rangle$, instead of $|\leftarrow\rangle \otimes |\downarrow\rangle$ as we said before. If A and B adopt one of these, their subsequent interaction will put them in one of $|\downarrow\downarrow\rangle$ or $|\uparrow\uparrow\rangle$. Therefore, the probabilistic aspect of a quantum event does not have to be located across a space-like interval in the final conditions, it can equally be located at a point in the initial conditions. More generally, because quantum events are extended not in an arbitrary way, but along the worldlines, a local (but atemporal) interpretation of the way correlations come about is always available.

The above has some elements in common with the 'consistent histories' or 'decoherent histories' formulation or interpretation of quantum mechanics. In common are the idea that the fundamental objects of the theory are extended in time, and the assertion by postulate that the theory associates physical reality with just those sets of possibilities in which classical sum rules for probabilities are obeyed. However, that condition is not very restrictive, and in particular it would not on its own allow one to prefer one basis over another in equations (2), (3). The present treatment makes (by postulate) a stronger statement, by preferring separable outcomes over inseparable ones, where both are consistent with the classical sum rules. This stronger condition might suffice to settle the set-selection questions raised in [21, 25, 26]. Discussions of consistent histories are sometimes ambiguous about whether there exists a single evolving world with a definite past [21, 22]. In the present discussion it is assumed that there is a single evolving world and by examining individual (extended) quantum events we can deduce what aspects of the past are definite.

6. Microscopic mechanism to detect spacetime loops

One can adopt the 'no-loop' quantum event postulate simply as a statement without putting forward a mechanism, but if one could find a mechanism then it would clarify matters. In this section, I sketch a speculative account of how one might think about the presence or absence of spacetime loops in the future being probed by particles in the present. The sketch is inspired by Cramer's transactional interpretation. Something like this is needed to complete it.

Let us adopt Cramer's language of offer wave (OW, retarded) and confirmation wave (CW, advanced), and consider two simple scenarios in one dimension (figure 2). An emitter a emits an OW propagating left and right towards two absorbers b and c. In case (a), the absorbers and subsequent OW/CW worldlines and absorbers are so placed that there is no spacetime loop (of a type relevant to the event postulate). In (b) there is a spacetime loop.

We adopt the language of a sequence of events for purposes of discussion, but of course we are referring to a single atemporal event. We will refer to the initial offer wave emitted by a as a 'first-order' OW.

Upon receiving a first-order OW, each absorber b, c emits a further OW (retarded, propagating forwards in time), but of a higher order (second-order) type, describing entanglement between itself and other absorbers. Second-order OWs can only be absorbed in groups of more than one. In case (a) there is no absorber for the higher-order wave, in case (b) there is. In case (a), upon receiving no CW for the second-order OW, b and c proceed to emit a first-order CW back towards the emitter a, and the transaction proceeds as in Cramer's description. In case (b), one of the further absorbers, e, receives two second-order OWs from b and c. It emits a third-order OW into the future, but receives no CW for that. Then it returns
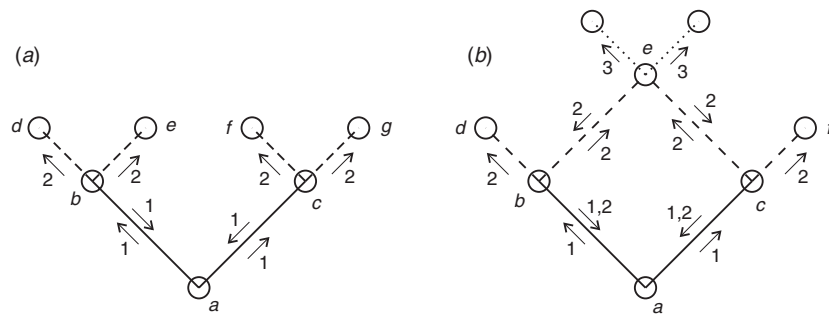
Figure 2. Spacetime diagrams, showing a sketch of a transactional-type mechanism for detecting spacetime loops and thus deciding what type(s) of event can happen. An emitter a emits offer waves (OW) to absorbers b and c, which in turn emit second-order OWs. (*a*) No absorber receives two second-order OWs, so no second-order CWs return to b and c, and these emit only first-order CWs to a. (*b*) An absorber e receives two second-order OWs. It generates a third-order OW and second-order CWs to b and c. The second-order OWs are not fully absorbed, so b and c pass both first- and second-order CWs to a.

a second-order CW to b and c, which pass it on to a. The second-order transaction with e is not guaranteed to happen: the conserved quantities (energy, momentum, etc) might be passed on to d or f, so b and c also return first-order CWs to a, of smaller amplitude than in case (a). a then forms either a first-order transaction with one of b and c, or a second-order transaction with e. The latter case involves an entanglement between b and c, of the form

$$(|g\rangle_b|e\rangle_c + e^{i\phi}|e\rangle_b|g\rangle_c)/\sqrt{2}, \tag{7}$$

where $|g\rangle$, $|e\rangle$ are ground and excited states.

To keep things simple, here I assumed there were no further possible transactions in the future. If there were, then both cases would be more involved: one would need to allow for the possibility of entanglement involving all of d, e, f, g for example, and therefore these would all emit third-order OWs. I repeat that this account is only a sketch and could be disregarded without impact on the rest of the discussion.

7. Second law of thermodynamics

The statement I have called the postulate of irreversibility is closely linked to, though not identical with, the second law of thermodynamics. The latter is a stronger statement, as is clear from the Carathéodory version: *In the neighbourhood of any equilibrium state of a system there are states which are inaccessible by an adiathermal process.* [39]. However, the present discussion suggests that the second law should be regarded from a new perspective.

The second law of thermodynamics and the concept of entropy are commonly regarded as useful devices rather than insights into the basic fabric of the world. That is to say, the usual perspective is that the basic equations of motion are reversible, but given that one would rather not keep track of all the microscopic details of particle motion, it is useful to study the average behaviour of large-scale quantities such as entropy. The concept of entropy is then an idealization which applies in the thermodynamic limit, but is not needed to describe the underlying motions of the constituent particles of any real system.

However, according to the quantum event postulate, microscopic evolution is a subtle mixture of reversible and irreversible components. The irreversible part involves the system

'forgetting' an alternative outcome, and the relative phase which would otherwise be retained. Therefore, entropy is a basic ingredient in any fundamental physical theory, and not merely a calculational device.

8. Falsification, outlook

In this section, I will discuss ways in which the ideas presented here could be falsified if they are in fact wrong, and I will outline avenues for further investigation.

Interpretations of quantum theory which agree with the standard predictions cannot be distinguished by experimental tests within the realm of applicability of the theory. However, they can offer guidance in formulating generalizations or extensions of known physics. The most obvious area of study in which this might be relevant is in efforts to unify quantum theory and general relativity, such as string theory, twistor theory and loop quantum gravity.

The contextuality principle may be regarded as a type of symmetry principle, stating that any fundamental physical theory must not implicitly provide more information about isolated systems than is allowed by the principle. I believe that standard quantum theory is in agreement with it, and indeed this appears to be a deep aspect of quantum theory that any future theory will share.

The quantum event (no-loop) postulate might appear to be making a circular argument. However, it is not. It claims, roughly speaking, that the moon is in one place as long as no one will ever check to see if it is in two places. This is the strong statement. The weak statement is, roughly, that the moon is in one place as long as no one could ever check to see if it is in two places. It also adds the hypothesis that natural processes tend towards separable states (other things being equal).

The combination of the ideas in this paper emphasizes spatial degrees of freedom, since these are required for the definition of separability, and only the results of interactions between spatially separable systems determine the physical reality. The interpretation thus places space, and spacetime, at a more profound level in the description of things than Hilbert space. That is, the notions of Hilbert space and operators should be regarded as useful tools, but the fundamental equations are best formulated directly in terms of motion in spacetime, such as for example in Feynman's spacetime approach to quantum mechanics [36]. If the more general forms of quantum theory which (we hope) will be discovered in the future do not have this feature then the ideas would be undermined.

On the other hand, positive evidence for the correctness of this approach would be furnished if it and a quantum gravity theory were mutually supportive. For example, it might clarify which aspects of a highly complex theory represent identifiable elements of physical reality, and which are part of the mathematical background. If quantum effects in the structure of spacetime provided the A_{max} invoked in the weak statement of the quantum event (no-loop) postulate, that is, a limit to the definition of phase in quantum interferences of large systems, then this would lend (modest) support to the postulate. Quantization of spacetime might also permit a natural way to identify, or place boundaries around, the start and finish of quantum events.

Like consistent/decoherent histories, Cramer's transactional description has in common with the ideas put forward here that it emphasizes spacetime above Hilbert space, cf [21, 40]. It is, I have argued, in need of completion, but it is valuable because it is mathematically precise, and the sketched suggestion for completing it given in section 6 does not do justice to that. If this sketch could be replaced by a thorough analysis, it would provide one way to make a more detailed statement of the no-loop postulate. Conversely, if this were not possible, it would tend to undermine the postulate.

If there is a further dynamical collapse mechanism to be discovered, the present discussion suggests that it would involve or promote a resistance to non-separable physical configurations, and would have an atemporal element.

The discussion drew on the concepts both of entanglement and of irreversibility. This suggests that there may exist a unifying theoretical structure which brings together these two concepts more thoroughly. For example, one might link the maximization of separability of a given pair of systems with the maximization of entropy in the rest of the universe. A weakness of the discussion provided here is the lack of information on how one is to calculate separability in cases more complicated than the simple example treated. This is a hard problem and is currently undergoing extensive study in the quantum information community [37].

9. Conclusion

The combination of ideas in this paper may be called a 'contextual, temporal' interpretation of quantum mechanics. According to our treatment, *it is possible to have objective physical events if and only if some processes are non-reversed*. The tension between reversibility and irreversibility is the same as the tension between contextuality and objectivity.

In summary, the principle of contextuality states that isolated entities cannot have well-defined properties in and of themselves, and a basic theory ought not to imply that they can. It provides a symmetry principle which, if correct, will be respected by basic theories in physics. Quantum mechanics is a formalism in which this principle finds mathematical expression through the concept of entanglement. Because interactions and correlations are more fundamental than the entities interacting and correlated, physical entities have to be considered in groups of at least three in order to allow statements about what transpires: two to have an interaction, and a third to be influenced by the result.

When placed in the context of the actual evolution of the universe, systems can acquire properties through a symmetry-breaking process. Physical reality constitutes a sequence of random non-unitary evolutions between physical configurations. The configurations and their probabilities are determined by a mathematical apparatus describing quantum amplitudes and unitary evolution along all paths. The quantum amplitudes contain more information than finds physical expression. When the paths form closed loops (in the sense of no 'which-path' information), the relative phases of the amplitudes can influence events, when they do not, the relative phases cannot. The physical behaviour is so constituted as to express this in as economic a way as possible. That is, the random quantum events evolve systems to new configurations drawn from a set whose quantum amplitudes have relative phase that will never be physically relevant. This is possible because non-reversed processes, that is, paths which never form closed loops, occur.

Acknowledgments

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