

# Relational Quantum Gravity V: Discussion

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## ABSTRACT

Quantum theory is famous for a number of conceptual paradoxes which have lead many physicists to think that interpretation in terms of visualizable mechanistic processes is not possible. Relational quantum gravity challenges this viewpoint, by developing a model from first principles in which Hilbert space is seen to make statements concerning measurements in a model in which the fundamental objects are particles, and in which all measurements are relative, in the sense that they involve comparison between matter and matter and such that the quantification of a relationship between matter and a background spacetime is meaningless at the fundamental level of the theory. A consistent mathematical model incorporating qed and general relativity was constructed from this interpretation. I review conceptual aspects of the model, and discuss the resolution of the important conceptual paradoxes of quantum mechanics.

**Key Words:** Foundations of quantum mechanics; Quantum gravity; Quantum electrodynamics; Philosophy of science.

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## 1 Introduction

### 1.1 Background

Relational quantum gravity (RQG I) reviewed the orthodox interpretation of quantum mechanics, finding that natural constructs of language are responsible for the formal structure of Hilbert space. The fundamental building blocks of matter are particles, but spacetime is not fundamental. The apparent wave or field structure underlying physics is not an expression of a material actuality, but rather of the possibility of finding a particle at a given position, where position is a measurement result, not an *a priori* concept. This interpretation is orthodox and is based on Heisenberg's original discussion of uncertainty *'If one wants to be clear about what is meant by "position of an object", for example of an electron..., then one has to specify definite experiments by which the "position of an electron" can be measured; otherwise this term has no meaning at all'* (1927). Uncertainty arises not only from the unknown initial condition of the electron, but also because the specific configuration of particles comprising the apparatus is always unknown. Heisenberg's argument was criticised by Bohr because it did not show

why the Schrödinger equation is obeyed, but it has since been demonstrated that a Schrödinger follows from conservation of probability via Stone's theorem (e.g. RQG I).

In this view ultimate reality is not modelled by either the classical picture of particles in spacetime, nor by the more modern notion of quantum fields defined on spacetime, but is rather described mathematically by graphs in which a lines represent the timelines of particles, and vertices represent interactions, the paper on which a graph is drawn having no meaning. The aim here is to discuss the conceptual aspects of this model, with particular reference to the famous paradoxes of quantum mechanics and issues concerning the unification of quantum theory with general relativity.

### *1.2 Quantum Particles and the Plenum*

The classical notion of a particle places a point-like object at a particular position in a background space. A classical particle always has a position in space, whether or not its position is known. This is not the notion described in quantum mechanics. For a quantum particle, a numerical value of position only exists when a measurement of position is carried out or when the interactions of the particle with other matter are such as to define a numerical value of position which may or may not be known. Photons do not have a measurable position at all. We can (within the limitations of quantum uncertainty) talk of the position of an electron when it creates or annihilates a photon, but not the position of the photon itself. This is entirely in keeping with the fundamental precepts of Cartesian relationism, according to which the position of an object only exists by dint of contact (interaction) with other objects.

The absence of a position observable for photons and the lack of positive definite norm for photon states have lead many physicists to reject the idea that photons are particles. Relational quantum gravity takes a different view of "particle". Particles are sizeless objects. A position observable is only required in so far as position can be measured. Positive definite norm is only required to give probabilities for those measurements which can actually be performed, and is satisfied since there is no observable polarization between longitudinal and timelike photon states.

In typical field theoretic treatments of quantum electrodynamics, Feynman diagrams have meaning only as aids to calculation. In contrast, in relational quantum gravity, Feynman diagrams describe possible configurations of small sections of a material plenum consisting of interactions between physical electrons and physical photons (the model can be extended to include additional particles, but for simplicity I consider only these two). Lines represent particles and vertices represent interactions. The whole represents the material plenum. The diagrams we use to calculate probabilities for events (e.g., scattering) represent possibilities for small sections of the plenum. We cannot say what combination of particle interactions takes place between measurements and we form the sum of possible diagrams, where sum means quantum logical OR.

Mathematically Feynman diagrams are graphs. Only the relationships between lines and vertices are important. The paper on which a graph is drawn has no meaning. Spacetime does not appear at a fundamental level in a Feynman diagram. It is an emergent quantity, describing an organisational principle resulting from the calculations of probabilities for observed results. Stable configurations (with probability equal to 1) in

Feynman diagrams lead to the structures of matter we observe (I do not here consider strong interactions). Distance scales defined from these diagrams depend on the exchange of photons between charged particles, the same elemental physical process as is used to define distance by the radar method. Although the precise mechanism according to which distance emerges classically in the general case remains obscure, the fact of its emergence in classical electromagnetism is shown by the derivation of Maxwell's equations and the Lorentz force law (RQG II).

### 1.3 Paper Structure

Section 2 reviews the main aspects of relational quantum gravity, with particular reference to the measurement problem (section 2.2), the emergence of coordinates (section 2.3), and the notion of space-time as an organisational principle (section 2.4). Section 3 reviews the famous paradoxes of quantum mechanics and shows how they may be resolved in this interpretation. Section 4 considers the issues arising in unification due to the Page-Geilker experiment and the Eppley-Hannah thought experiment, and describes how pre-expansion as an ametric phase presents an alternative to inflation as resolution of the horizon problem. Conclusions are given in Section 4.7.

## 2 Relational Quantum Gravity

### 2.1 Overview

In relational quantum gravity it is shown that quantum interference effects do not arise from classical interference between waves, but from the mathematical structure of Hilbert space under the requirement of conservation of probability. The principle of superposition is simply logical disjunction in a formal language describing hypothetical measurement results in the subjunctive mood, and constructed to give probabilistic results for actual measurements. The Schrödinger equation was shown from the requirements of the probability interpretation, and is an abstract device which does not determine the motion of a mechanistic or material wave, and does not depend on the physical metric.

The formulation uses a representation of finite dimensional Hilbert space in which kets are smooth wave functions. A continuum of position states was defined using linear combinations of basis states. Differential operators were defined and a form of covariance is obeyed, described as *quantum covariance*. RQG II showed that this permits a formulation of relativistic quantum mechanics which is suitable for the construction of particle theoretic qed under the Feynman-Stückelberg interpretation. In finite dimensional Hilbert space, fields are operator valued functions, not distributions. Thus, products between fields are defined. Under the identification of addition between kets with logical OR, fields do not describe the actuality of a material medium on spacetime, but the possibility for creation and annihilation of particles anywhere, dependent on the matter distribution. Feynman diagrams then have a direct physical interpretation as possibilities for configurations of matter. Loop diagrams contain improper integrals and do not produce divergences provided that the correct order of taking limits is respected.

Maxwell's equations and the Lorentz force law were derived in the classical correspondence, showing that bare mass and charge are equal to their physical values. The Landau pole can be avoided by introducing a physical cut-off in the form of a minimal proper time between discrete particle interactions (the perturbation expansion is asymptotic, not exact).

Since kets refer to measurement results, Hilbert space is necessarily defined at the time and position of measurement. Kets are therefore defined at a point, just as spacetime vectors are defined at a point on a curved manifold. A generalization of the notion of a connection is required in order to define the inner product when the initial state is remote from the final state, but whereas a connection on a manifold is defined between nearby tangent spaces, states in quantum theory between the initial and the final state have no direct physical meaning. In RQG III, the teleconnection defined the inner product for remote initial and final states. It was shown that the teleconnection is equivalent to the Levi-Civita connection in the limit when the initial and final states are close.

The physical metric is not required for the probabilistic determination of the Schrödinger equation from Stone's theorem. Transforms used in the solution of Schrödinger's equation are integrals over states in a Hilbert space defined at particular position, not integrals over space. RQG III introduced the metric from the physical process of photon exchange, and showed that the introduction of a small interval of proper time between the interactions of an electron has physical import equivalent to curvature in accordance with Einstein's field equation.

Under the teleconnection one finds different predictions for cosmological spectral shift when light is treated as a quantum motion than would be the case for the classical transmission of light treated as a mechanistic wave on a smooth Lorentzian manifold. Cosmological parameters were calculated in RQG IV. Good agreement was found between predictions and supernova redshifts for a closed Friedmann Cosmology with no cosmological constant and expanding at half the rate of the standard model. Previously unmodelled components of cosmological redshift account for the anomalous Pioneer blueshift and for the flattening of galaxy rotation curves. For orbiting bodies the unmodelled component simulates a MONDian law with a value for the critical MOND acceleration in agreement with observation. Distant lenses have a quarter of the mass required by standard general relativity, resolving observational issues for both CDM and MOND. Missing mass can be accounted by a massive neutrino. CDM is not required.

Direct evidence of an unmodelled component in radial velocity of local stars was found from a straightforward statistical test on a population of 20 608 local stars with accurate parallax and known radial velocities. The test rejected the null hypothesis, *there is no systematic error in spectrographic determinations of heliocentric radial velocity*, with 99.99999% confidence. Further direct evidence is expected from observations of galaxies in the early universe by new telescopes, and comparison between direct and spectrographic measurements of heliocentric radial velocity by Gaia.

## 2.2 The Measurement Problem

The inherent conflict between determinist wave motion and probabilistic collapse has come to be known as the measurement problem. It has been suggested that probabilities

in the results of measurement might arise from unknowns within the microscopic structure of a measurement apparatus and that the underlying physical processes in measurement are also governed by a wave equation, but there is no way to reconcile the linear process of wave evolution with the non-linear outcome of measurement.

Relational quantum gravity can be classed as an information theoretic interpretation. Information theoretic interpretations have their roots in the original discussions between Bohr, Heisenberg, and others, which led to the Copenhagen interpretation, but they discard the notion of complementarity. The wave function is not conceived as describing a fundamental property of matter, but rather it describes what we can say about measurement. “*What we observe is not nature itself, but nature exposed to our method of questioning*” (Heisenberg, 1958) or “*correlations without correlata*” (Mermin, 1998). The wave function is not real but is simply a way of calculating the probability for the outcome of an experiment. Information theoretic interpretations invert the measurement problem. Collapse is simply the change in a probability once the outcome of a measurement is known, but wave evolution requires explanation.

The problem with information theoretic interpretations is that they fall short of being complete interpretations of nature. If the wave function describes what we can know about reality, not reality itself, then we are lacking a description of the underlying physics. We must explain why the laws of quantum mechanics yield correct probabilities and the reason that why evolution obeys the laws of wave mechanics. In relational quantum gravity states are *constructed* so as to yield probabilities. Wave evolution then follows from the probability interpretation via Stone’s theorem, and is determined by the mathematical requirements of probabilities irrespective of physical mechanism. It shows that quantum theory describes correlations rather than correlata, but it does not show that correlata do not exist. Rather, the laws of quantum theory reflect Kant’s transcendental idealism, and Plato’s allegory of the cave, according to which an ultimate reality exists but is not perceived directly by us, and may have a very different fundamental character from that which we do perceive.

### 2.3 Coordinates

RQGI used measurement of position as the fundamental physical process on which to base Hilbert space. As pointed out by Descartes, and acknowledged by Newton, there is no measurement of absolute space. We can only measure relative positions of matter with respect to other matter. Newton required absolute space in order to formulate mechanics, because without it, at the time at which he was writing, there was no other way to define a mathematical framework in which to express physical law. We may now understand that Hilbert space provides a mathematical model of hypothetical measurement of a reality in which only relative position appears as a physical quantity.

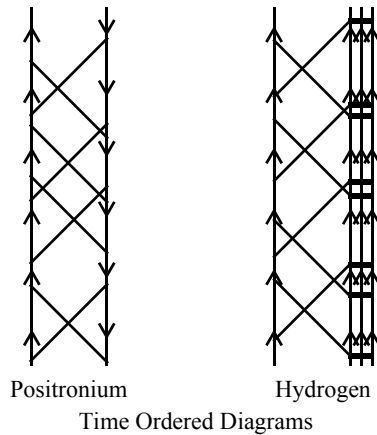
In special relativity the coordinate system is defined from physical processes dependent on the speed of light, or more strictly on the maximal speed of information transfer. In practice, the maximal speed of information transfer is the same as the speed of light, but experiment cannot entirely eliminate the possibility that the photon has a very small mass and that light travels slightly slower than the maximal speed. It can be argued that a maximal speed of information is a physical necessity. Either there is a maximal speed

or there is not. If there were not, instantaneous transmission would be possible, at least in a limiting case. It would then be possible to define absolute synchronicity and absolute space. Special relativity would not hold, and we would find a universe obeying different properties from those we observe. We can conclude that the reason the speed of light is an absolute constant is that coordinates depend for their definition on the speed of light. It then remains true in general relativity that locally Minkowski coordinates are physically more fundamental than general coordinates, because they are directly defined from physical processes while other coordinates are constructed mathematically.

#### 2.4 Space-time; an Organisational Principle?

It is possible to conjecture that the three dimensional structure of spacetime emerges naturally from photon exchange in large conglomeration of matter, but precise mechanisms by which this might occur have not been demonstrated. The existence of 4-coordinates is established empirically whenever a measurement of position is performed (measurement is used here in a broad sense, and includes the visual determination of the relative positions of objects in our immediate environment). Coordinates are taken as a fundamental postulate, but they only have meaning as measurable quantities, requiring a relationship between matter and reference matter which only exists when there are sufficient interactions that position can be determined. Quantum mechanics applies in situations when relative positions are meaningless because of the absence of interactions from which they can be determined.

It was seen in RQG III that an absolute space-time structure exists and is given by Penrose coordinates. However, there is no empirical determination of Penrose coordinates but we may consider whether spacetime as described in Penrose coordinates has its own existence as a fundamental structure of the universe, or whether it is an organisational principle which emerges from sufficiently large configurations of particles and interactions. Although it is not possible to prove that Penrose coordinates are not fundamental, we may observe that if they have their own prior existence the universe appears to be, in some sense over-defined. That is to say, it is clear that physical spacetime is defined from coordinates which are determined locally from physical measurement procedures, and that Penrose coordinates are defined in terms of locally defined quantities. Another definition of Penrose coordinates, in which they have some absolute physical meaning, is then superfluous.



**Figure 1:** These notional diagrams restore time ordering between the interactions, showing photon exchange as a two way process. Such a diagram is at best an approximation to the truth. There is no fixed time interval between emission and absorption, and we can only describe the radius of the orbit of an electron with a probability amplitude, not a numerical value.

### 2.5 Primitive Structures of Matter

It does not follow from the use of the radar method of determining distance that radar is the fundamental definition of distance. In relational quantum gravity, the fundamental structure of matter is a plenum consisting of arrangements of interacting particles. The equivalence of two way photon exchange with the electromagnetic force was shown by the derivation of Maxwell's equations and the Lorentz force law from the minimal interaction between electrons and photons. Distance can then be seen as an emergent quantity arising from the structure of the plenum. Within our immediate environment, the stable structures of matter are bound by the interchange of photons (figure 1). Systems of larger numbers of particles contain greater structure. For large structures the uncertainties in position are small compared to the scale of the structure. Radar provides a direct measurement of distance because it uses the same physical process, two way photon exchange, as is seen in time ordered diagrams for stable configurations of matter. Thus, we may understand the radar method as a measure of the binding between the particles constituting a stable configuration of matter.

## 3 Quantum Paradox

### 3.1 Schrödinger's Cat

Schrödinger put a cat in a box with a capsule of cyanide, triggered to break and kill the cat with a 50% chance by a quantum process. A physicist looking at the box does not know whether the quantum process has broken the capsule or not, so he describes it with a quantum state, that is to say a wave function in which the process has part broken the cyanide capsule, and part not. If the wave function collapses when the observation takes place, then, prior to opening the box, he should describe the cat with a quantum state as well, in which the cat is part alive, and part dead. This is not an issue in relational quantum gravity because the quantum state is not a description of reality. The reality is that Schrödinger's cat is definitely either alive or dead. The state encodes probability and merely means that there is a 50% chance that the cat will be found alive when the box is opened.

### 3.2 The Delayed Choice Quantum Eraser

In a Young's slit experiment, electrons are detected as particles and the cumulative effect from many electrons is an interference pattern. This raises questions like "*Which slit did the electron come through?*" and "*If it came through a particular slit, how can there be interference in a wave pattern from both slits?*". It is possible in principle to test which slit an electron comes through, for example by placing a laser just behind the two slits, so that a photon scatters off the electron just after it passes through them. The electron now behaves like a particle as it comes through the slits. It is always seen to come through one or other slit. But the interference fringes disappear. The measurement to decide which slit the electron came through has changed the overall result.

Because light travels faster than electrons, in principle, the electron can pass through the slits before the decision is made, whether to switch on the laser or leave it off. If we leave the laser off, the electron apparently passes through the slits as a wave. If we switch it on, we find that the electron has passed through one or other slit, as a particle. We can apparently decide what type of behaviour the electron had at the slits after it has passed through them. Of course, this simplified version of the experiment is not viable in practice. However, a delayed choice quantum eraser experiment has been performed (Kim et al, 2000), and shows that we actually can determine behaviour at the slits *after* the particle passes through them.

If spacetime is an emergent quantity, it can only be used to describe the behaviour of matter when sufficient contact relationships (interactions) exist in the process under study. We can only say which slit a particle comes through if the particle has sufficient contact relationships with other matter to define position with respect to the slits. An electron passing through the slits does not interact with the environment, and does not participate in the structure of spacetime created by other matter in the environment. It is therefore impossible to say which slit the electron passes through. The spacial relationship of a particle passing through the slits is not determined at the time at which it passes through the slits, but only later, when the final form of its spacial relationships becomes established through interactions with matter.

### 3.3 *The Einstein Podolsky Rosen Paradox (EPR)*

We observe interference fringes which can be calculated from waves, but there is no direct observation of the wave function or of the infinite speed implicit in collapse. In order to highlight what they saw as a very deep conflict between relativity and quantum mechanics, Einstein, Rosen and Podolsky (1935) imagined that a quantum mechanical process generates two particles flying in opposite directions with equal momenta. The momenta of the particles is not known, so the rules of quantum mechanics dictate that it is governed by a wave function. The two particles become separated. Alice measures the momentum of one particle, and Bob measures the momentum of the second particle, at a distance remote from Alice. According to conservation of momentum, at the precise time at which Alice does her measurement, the outcome of Bob's measurement is determined. So, the quantum state of a particle can be instantaneously changed by the remote action of an observer, in apparent conflict with relativity which prevents the instantaneous transmission of an effect. Einstein, Rosen and Podolsky concluded that "No reasonable definition of reality could be expected to permit this".

### 3.4 *Bell's Inequality*

John Bell (1964) adapted the EPR experiment to a form which is easier to test experimentally and demonstrated Bell's inequality, by which the experimental predictions of quantum theory can be quantitatively tested against theories of local hidden variables. He proposed using a process which emits two particles with equal and opposite spin. Initially spin is not aligned, but it can be measured in any axis. When spin is measured, it aligns with the axis chosen for the measurement. This implies that the other particle must

be aligned on the same axis, with opposite spin. It appears that the fact of a spin measurement on one particle not only affects the result of measurement spin of the other, but actually determines the axis on which the spin of the second particle is aligned. Bell's inequality shows that quantum theory and local hidden variables theories predict different correlations between the results of measurements on different axes, and enables us to experimentally determine which is correct.

Bell test experiments had been carried out a number of times and it had been found that Bell's inequality is violated; the predictions of quantum mechanics supported. This left the possibility that the wave functions for both particles collapsed at the time of the decision of which axes to use, and that as this took place before the experiment, nothing need to travel faster than the speed of light. Alain Aspect et al. (1982) in Paris set up the experiment in such a way that the decision on which axes were used to measure spin was made by a pseudorandom generator, after the particles were emitted. They still found that Bell's inequality was violated. Improved versions of the experiment have since confirmed the result (e.g., Salart et al., 2008; Tittel et al. 1998a, 1998b; Weihs et al., 1998). The decision on which direction to measure spin of one particle affects the measurement of the other, even though a message from the point of decision to the second particle would have to travel faster than the speed of light.

In spite of this result, no information travels from the results of one measurement to the other. At the time when Bob measures the spin of the second particle, there is no way he can say that his result is affected by Alice's measurement of the first, because he does not yet know Alice's result. Alice and Bob's results must be brought together before a correlation can be found establishing that Bell's inequality is violated. The question, however, remains. If nothing travels faster than light, how can the correlation come about?

### 3.5 *Emergence of Spacetime*

The notion of separation can only be said to hold when the particles exist in spacetime, that is to say after the required interactions of the particles with other matter have taken place for the emergence of spacetime. This has not happened at the time of Alice and Bob's measurements in the Bell tests, but it has happened when Alice and Bob get together and determine the correlation. In relational quantum gravity, the resolution of Bell's theorem is not that we must reject realism, locality or causality, but rather we must recognize that spacetime is an emergent concept.

The notion of separation can only be said to hold when spacetime exists, that is to say *after* the required physical processes have taken place for the emergence of spacetime. This has not happened at the time of Alice and Bob's measurements in the Bell tests, but it has happened when Alice and Bob get together and determine the correlation. There can be no exchange of photons between the immediate environments of Alice and Bob at the time of their measurements, because this would require that photons travel faster than the speed of light. Therefore, while Alice and Bob each observe spacetime structure in their immediate environment, the structure connecting those two regions is not yet complete. At the time when Alice and Bob bring their measurement results together, there will have been many more billions of interactions exchanging photons, and a single

spacetime structure containing the regions of spacetime in which Alice and Bob carry out their measurements is then completed.

We cannot say that the outcome of one measurement has effected the other, because this presupposes the existence of spacetime, and puts the logical cart before the horse. We can only discuss the relative orientation of Alice & Bob's measurements in the context of a spacetime structure which contains both. We can only talk of spacetime after two way photon exchange has taken place in such a way that spacetime structure has emerged, not at the time the measurements take place.

### 3.6 *Locality and Causality*

As stated by Bell, the implication of Bell's theorem is that, if quantum mechanics is correct, we must sacrifice at least one locality, causality, and realism. Physics makes no sense if we sacrifice realism. It seems we must have a problem with either locality, causality, or both. In relational quantum gravity we do not have to sacrifice either locality or causality, but we do have to be careful about how we state them. We have to dismiss naive statements based on an assumption of background spacetime. Bell's theorem does not lead us to reject locality or causality, but rather to reject the notion of a fundamental spacetime.

**Definition: Locality.** A particle is in contact with another when it interacts with it. A particle can be considered to be in a neighbourhood of another if, in principle, a photon can be emitted by one particle and absorbed by another, and then a photon emitted by the second and absorbed by the first within a small proper time period.

This relationist definition reflects the locality condition in qed, and allows that entangled particles in Bell's theorem are separated, in accordance with our intuitive ideas.

**Definition: Causality.** There is a causal relation between two measurements if the outcome of one measurement alters the probability of the outcome the other.

By this definition there is no causal relationship between the measurements of the entangled particles in Bell's theorem. The measurement of one particle does not alter the probabilities for the results of measurement of the other. Only when the two experimenters get together and compare results do they find a correlation. This can only be done at a later time, showing that the correlation is causally related to the measurements, but not that the measurements are causally related to each other.

Causality in physics is usually taken to mean that there is some kind of a logical relationship according to which the past determines, or at least affects, the future. This view is taken from our daily experience and from our perception of time as a flow in which we remember the past but do not know the future. However, it is not reflected in time reversibility, which is a feature of fundamental physical law, and nor is it reflected in the Stückelberg-Feynman interpretation that anti-matter is matter evolving backwards in time. The arrow of time which we perceive from past to future is an expression of the law of entropy. Increasing entropy is shown in statistical mechanics from time symmetric laws, together with an asymmetric boundary condition. Ultimately the arrow of time is determined from the low entropy state of the universe at the big bang.

Although it is difficult for us, as human beings with limited mental abilities, to think in terms of laws which lie outside our immediate experience, of a universe in which the future can affect the past, it is not impossible to do so, and there is no scientific reason to think that, at a fundamental level, causality is a logical relation from past to future. Both the Aspect experiment and the delayed choice quantum eraser furnish direct evidence that a future event, the decision on which observation is performed, can have influence over a past event, the production of the photon pair, or the configuration of matter at the passage of the particle through the slits.

## 4 Unification Issues

### 4.1 The Cosmological Constant

The cosmological constant does not appear in the calculation for curvature due to a single gravitating particle. This is not sufficient to show that the cosmological constant is zero, but it does show that there is no known mechanism by which it can be non-zero. Such a mechanism may be possible. For example, in a universe with less than critical mass for closure, one might invoke a principle to introduce a cosmological constant to ensure a finite universe. However, such arguments generally hold little sway in physics.

An unjustified term in an equation should be considered as a “fiddle factor”. It is best regarded as meaning that the theory behind the equation is likely to contain an unknown fault, rather than that the term necessarily models reality. We have seen that observational evidence using the teleconnection supports a universe with no cosmological constant.

### 4.2 Non-Quantisability of Einstein's Field Equation

It is tempting to try to define a curvature observable as a Hermitian operator with eigenvalues given by

$$G^{ab}(x)|y\rangle = 8\pi GT^{ab}(x)|y\rangle \quad (4.2.1)$$

but this is incorrect. Quantum theory is defined using plane wave motions on a Penrose diagram. The factor  $k$  is only invoked to determine the redshift between the initial and final states.  $k$ , and hence also  $G^{ab}$ , is a parameter, not an operator on Hilbert space.  $G^{ab}$  cannot be modelled as an observable in quantum mechanics because it cannot be determined from a single experiment. It takes a succession of measurements of position to determine curvature.  $G^{ab}$  specifies a relationship between Hilbert spaces defined at different times, and has no meaning regarding the measurement of a state at given time.

After replacing stress energy with an observable operator, we may consider the equation

$$G^{ab} = 8\pi G\langle T^{ab}\rangle \quad (4.2.2)$$

This can only be true in approximation, because  $k$  and  $G^{ab}$  depend on the actual, but intrinsically unknown, distribution of matter, not on the quantum state which only describes our knowledge of the distribution. Since we cannot know the exact matter distribution, we cannot know the precise values of  $k$  and  $G^{ab}$  at all points of a Penrose

diagram. Because  $k$  and  $G^{ab}$  are parameters, not operators on Hilbert space, uncertainty in their values is modelled not by standard quantum theory but by classical probability theory. Because the actual distribution of particles is intrinsically unknown, we cannot write down an exact equation for  $k$  or  $G^{ab}$ . We can calculate the probability for where a particle will be found, and in principle we can calculate probability densities for  $k$  and  $G^{ab}$ . In practice the calculation is academic; variations in the gravitational field due to quantum fluctuations are tiny compared to the resolution of gravitational measurement.

#### 4.3 The Page-Geilker Experiment

Page and Geilker (1981) placed a massive body inside a box, with a mechanism to control its position at A or B depending on the result of a quantum process with a fifty-fifty outcome. They argued that if the classical gravitational field depends on its quantum wave function, then its gravitational attraction should point toward some intermediate ‘average’ location. This was not observed, so they conclude that measurement of the gravitational field is equivalent to measurement of position. But this means that there is an instantaneous collapse, and hence an instantaneous change takes place in the manifold exceeding the speed of light. Page and Geilker described this as “Indirect Evidence for Quantum Gravity”, but the argument is not conclusive because in information theoretic interpretations, such as relational quantum gravity, the wave function describes what is known of the matter distribution, not the actual matter distribution. The actual matter distribution has the massive body at either A or B; it only becomes known where the mass is when a measurement is performed. This does not necessitate any change to the manifold at the time when a measurement is performed.

#### 4.4 The Eppley-Hannah Thought Experiment

In a famous thought experiment, Eppley and Hannah (1977) proposed that gravitational waves are used to determine the position of a particle initially in a state of poor localization and precise momentum. They argued that, if gravitational waves behave classically then, in principle, waves of indefinitely high frequency and indefinitely low intensity can be used. If the measurement causes collapse, then position is determined to an accuracy dictated by frequency, while the change in momentum is determined by intensity and will be small. Provided that momentum is conserved, then the uncertainty principle will be violated. If, on the other hand, measurement does not cause collapse, then there exists a direct observation of the (poorly localised) wave function. In this case instantaneous collapse could be observed in principle by performing a standard measurement of position, and the speed of light would be exceeded. They concluded that the gravitational field cannot be classical without violating accepted principles of physics, and must therefore satisfy the principles of quantum mechanics.

The validity of this thought experiment has been challenged, for example by Mattingly (2006) who calculates that Eppley and Hannah’s experimental apparatus cannot be built from any feasible materials, and would be so massive as to be included within its own Schwarzschild radius. Other issues also cast doubt on Eppley & Hannah’s conclusion. The experiment assumes the scattering of a gravitational wave will take place

by analogy with the scattering of an electromagnetic wave, but this assumption preempts the conclusion. A classical gravitational wave is a solution of Einstein's field equation, and refers to perturbations to the structure of spacetime, not to a classical wave on spacetime, so that the assumption that scattering takes place by analogy with electromagnetic radiation does not appear justified. The detection of the position of a particle due to a perturbation in the gravitational field may be no different in principle from the detection of the position of the massive body in the experiment of Page and Geilker.

In order to formulate the treatment of quantum wave functions under the teleconnection it was necessary to postulate an unobservable universal time parameter  $\tau$ , as well as a precise value for the expansion parameter  $a(\tau)$ . The expansion parameter is also unobservable, at least in local experiments described by quantum mechanics. This is also true of curvature - to determine the curvature in a region of space we require several measurements at separate points of spacetime. As there is a collapse with each measurement, we may conclude that curvature is not an observable operator in quantum theory, and that Einstein's field equation should not be quantized.

#### 4.5 Pre-expansion as an Ametric Phase

The description of a particle by the state  $|x\rangle$  implies that the particle's position has been measured relative to an apparatus. The description of matter using states in Hilbert space requires at least that position can be measured in principle. But in the initial phase after the big bang measurement of position is impossible in principle, and it is not possible to abstract Hilbert space from properties of measurement. Since Hilbert space no longer applies, some other mathematical structure is required to describe evolution from the big bang. Research will be required to identify the precise properties of such a structure, which would describe particle interactions without using the concept of spacetime in any form. Spin networks appear to have some of the requisite properties. Here I merely a few general remarks regarding behaviour near the big bang.

In a discrete manifold it is not possible to divide the early universe into indefinitely small regions which did not communicate. At an initial singularity all particles are at the same place, and relative position has no meaning. Rather than rapid inflation from a small size, there was an initial phase during which we cannot talk of spatial dimension or size and when horizons did not exist. There is a minimum interaction time and several interactions are required to establish a distance between elementary particles. It might have taken thousands, or many thousands, of discrete intervals of proper time to establish the properties of a Riemannian manifold. Prior to that the image is one of perfect chaos, in which any photon may interact with any charged particle, so that the entire is causally connected. Because positions cannot be distinguished during the ametric phase, this phase can only lead to an isotropic initial condition for normal expansion.

It does not appear necessary to postulate that all the matter initially contained in the universe participates in the creation of spacetime. Indeed, if some matter remains disconnected from the observable universe it could account for the observed matter/antimatter imbalance without the need to postulate an exotic and unobserved process in particle physics, viz. the decay of the proton.

There must be a first time at which sufficient interactions had taken place that relative position between particles became possible. A lower bound for the duration of the initial period can be estimated by applying a Doppler shift to one interval of discrete time as appropriate to the high energies of particles near the big bang. Typical quoted energies for particles near the big bang are in the order of a factor  $10^{30}$  greater than rest mass. In this case the discrete interval of proper time  $10^{-65}$ s for an electron is redshifted to  $10^{-35}$ s, within range of the time scales normally postulated for the end of inflation and the beginning of normal expansion.

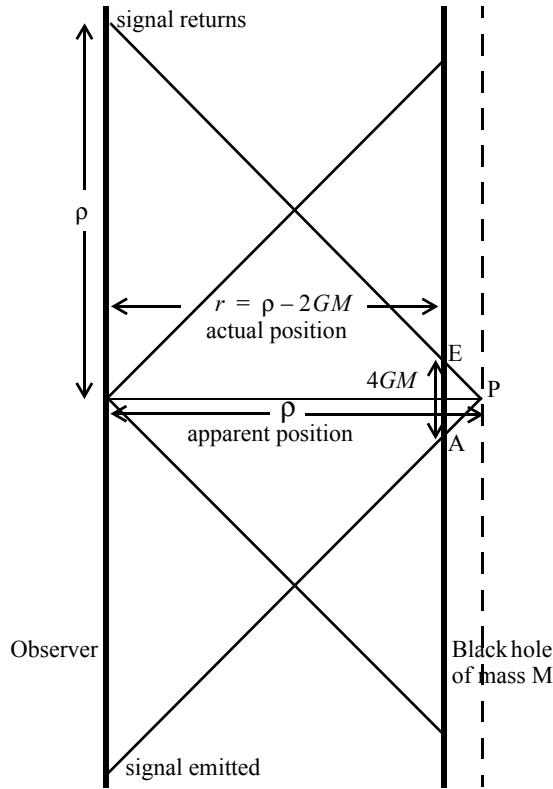
#### 4.6 Black holes

General relativity is known to be valid on large scales and describes matter fields, not pointlike particles. However, on small scales we observe that matter consists of pointlike particles (up to quantum effects). The treatment of (RQGIII, section 4.2) placed an elementary particle in a position eigenstate at  $r = 0$ , in a continuous manifold and found that the event horizon of the Schwarzschild geometry was also at the point,  $r = 0$ . Although  $r$  is related to the Schwarzschild radial coordinate  $\rho$  by  $\rho = r + 2Gm$ , the region  $\rho < 2Gm$  does not map to these coordinates (the manifold with  $r$  as radial coordinate is not a chart on the maximally extended Schwarzschild geometry, because  $r = 0$  is a single point).

The argument describes a pointlike particle at  $r = 0$ , surrounded by the exterior region of a Schwarzschild geometry. For a pointlike particle, it makes no physical sense to extend the coordinate system interior to the particle. The extension exists mathematically, but has no physical meaning. By considering a classical body, such as the earth, as a composition of these pointlike particles, and by replacing the pointlike structure with a density, we restore the field equations, as an excellent large scale approximation.

We can model a black hole, neglecting the effect of the exclusion principle, by placing large numbers of elementary pointlike particles at  $r = 0$ . We will then have a large mass,  $M$ , at  $r = 0$  surrounded by the exterior region of a Schwarzschild geometry. There is again no physical meaning to the interior region. A curious feature is that  $r = 0$  cannot be enclosed in a surface of arbitrarily small surface area. However, this is not inconsistent and is no more counter intuitive than, for example, that in a closed homogeneous isotropic universe a circle of sufficiently large radius will have zero circumference. Since the surface and the point are disjoint, the properties of the one don't have an immediate bearing on the other. If the argument were valid, it would show a discontinuity of the metric at  $r = 0$ , not that  $r = 0$  cannot be a point. However in relational quantum gravity this argument has no meaning, because the very notion of a surface breaks down on small distance scales. The manifold is not conceived as some kind of metaphysical entity generalising the properties of Newton's absolute space, but rather as a collection of potential measurement results, arising from the *operational* definition of time and space coordinates.

In practice black holes are believed to be formed from the collapse of neutron stars. Neutrons are Fermions. In their seminal paper of 1939, Oppenheimer and Volkoff say "*A discussion of the probable effect of deviations from the Fermi equation of state suggests that actual stellar matter after the exhaustion of thermonuclear sources of energy will, if massive enough, contract indefinitely, although more*



**Figure 2:** A black hole is modeled in Penrose coordinates as a large point-like gravitating mass,  $M$ . The geometry surrounding the hole can be understood as equivalent to an inherent time delay of  $4GM$  in reflection of photons by particles in the hole.

*and more slowly, never reaching true equilibrium*". The Pauli exclusion principle prohibits placing more than one fermion at  $r = 0$ , so the probable structure of a real black hole is as described by Oppenheimer and Volkoff. Rotation will also slow down the collapse.

Hawking radiation is not possible, since this depends on the classical structure of spacetime in the vicinity of the event horizon. Nonetheless a black hole can be expected to radiate, figure 2, in which a photon is reflected from an elementary particle after a delay  $2GM$ , as described in RQG III. Wave functions for particles are plane waves in this diagram and can be emitted to infinity provided that there is sufficient energy in the initial state. There is always sufficient energy to emit zero mass particles, which can have arbitrarily low energies at infinity. Matter in the hole will have high energy from gravitational collapse, and in addition, as the hole becomes more compact and particles approach  $r = 0$ , wave functions have components with ever increasing energies. For a hole of 1 000 000 solar masses, the energy required of an electron to escape to infinity is 952 kg, eleven orders of magnitude less than the maximal energy  $p_{\max} = 4.08 \times 10^{14}$  kg corresponding to the lattice spacing. We may conclude that localisation of matter near  $r = 0$  creates energy states from which electrons can be radiated to infinity.

## 4.7 Conclusion

In this series of papers I have developed quantum mechanics from first principles, showing that the structure of Hilbert space is derived, like other structures in mathematics, from *natural* structures in language used to discuss reality, and that the Schrödinger equation is required by conservation of probability. It is shown that this leads to a formulation of particle qed avoiding divergences and other inconsistencies, and in which Feynman diagrams provide a direct description of the underlying structures of matter. The formulation leads naturally to general relativity in the classical correspondence, up to a difference in predictions concerning cosmological redshift, and resolves the well known conceptual problems of quantum theory.

There is no other satisfactory interpretation of quantum theory or consistent formulation of quantum mechanics and general relativity but here it is shown from first principles that this formulation is required by the probabilistic structure of quantum theory, secondly the range of observational problems known as a “crisis in cosmology”, and third the direct empirical evidence for the prediction of an unmodelled component in spectral shift found from the study of the local velocity distribution. Further evidence can be expected from new telescopes and from Gaia, but in the author’s view there can be very little doubt that this is the correct formulation and interpretation of our most fundamental theories of physics at the present time.

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