Cosmic quantum measurement

by

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Abstract

Hardy’s theorem states that the hidden variables of any realistic theory of quantum measurement, whose predictions agree with ordinary quantum theory, must have a preferred Lorentz frame. This presents the conflict between special relativity and any realistic dynamics of quantum measurement in a severe form. The conflict is resolved using a ‘measurement field’, which provides a timelike function of spacetime points and a definition of simultaneity in the context of a curved spacetime. Locally this theory is consistent with special relativity, but globally, special relativity is not enough; the time dilation of general relativity and the standard cosmic time of the Robertson-Walker cosmologies are both essential. A simple but crude example is a relativistic quantum measurement dynamics based on the nonrelativistic measurement dynamics of Lüders.
1 Introduction

The theoretical ideas of Hardy [?], Bell [?], Wheeler [?] and Hawking and Seifert [?, ?], combined with the long-range entanglement experiments of Tittel, Gisin and collaborators [?, ?], lead to an elementary cosmological dynamics of quantum measurement that satisfies the principles of special and general relativity.

According to Bohr [?, ?], the result of a quantum measurement is influenced by the condition of the measuring apparatus. Dynamical theories of quantum measurement ascribe this influence to a dynamical process. Here the influence is due to interaction with a cosmic background field, the measurement field which plays the role of hidden variables in some other dynamical theories. By an extension of the Einstein, Podolsky and Rosen thought experiment [?], John Bell showed [?,?] that quantum theories which represent quantum measurement as a dynamical process are nonlocal. Hardy [?] showed the need for a preferred Lorentz frame. The measurement field provides the frame.

Generalized quantum measurement is a physical process by which the state of a quantum system influences the value of a classical variable. It includes any such process, for example laboratory measurements, but also other, very different, processes [?]. These include the cosmic rays that produced small but detectable dislocations in mineral crystals during the Jurassic era, and the quantum fluctuations in the early universe that may have caused today's anisotropies in the universe. It includes those quantum fluctuations that are amplified by chaotic dynamics to produce significant changes in classical dynamical variables. For such measurements, these are the dynamical variables of the measurer, although there is no measuring apparatus in the usual sense.

Assume, therefore, that quantum measurement is universal, that the measurement process is taking place throughout spacetime, with the possible exception of the neighbourhood of some spacetime singularities. Here I also assume that
quantum measurement dynamics includes a specific representation for the evolution of an individual quantum system: the evolution of an ensemble is not enough. And assume that there are no causal loops in spacetime.

This picture and the results that follow are based on the following five principles PR1-5 and two theorems PR6,7:

- **PR1. Kepler-Galileo** - Humans are not at the centre of the universe, in any sense.
- **PR2. Newton-Laplace** - Every physical process has a dynamical explanation.
- **PR3. Einstein** - Special relativity.
- **PR4. Einstein** - General relativity.
- **PR5. Cosmological** - On sufficiently large scales the universe is spatially isotropic and therefore uniform.

PR6. Hardy [?] - Measurement dynamics in flat spacetime and consistent with ordinary quantum theory needs a special Lorentz frame.

PR7. Hardy simultaneity - Measurement dynamics in curved spacetime needs a definition of simultaneity for events with spacelike separation.

I also assume that The principles PR1 and PR2 together are incompatible with ordinary quantum mechanics, in which quantum measurement is the preserve of humans, and does not require a dynamical explanation. Despite this, it is our most successful theory. A good reason for the recent revival of alternative realistic theories which are compatible with these principles is the greater control we have over quantum systems, which raises the possibility of distinguishing different quantum theories of measurement experimentally. Notice that the (weak) version of the Newton-Laplace principle PR2 does not require the dynamics to be deterministic.

Aharanov and Albert [?, ?, ?] pointed to the particular difficulties of reconciling special relativity and realistic quantum theories. According to Shimony [?], special relativity and quantum mechanics might live in ‘peaceful coexistence’, but Hardy’s theorem suggests a fundamental conflict between the expected results of quantum measurement and invariance under Lorentz transformations. The principal purpose of this paper is to resolve this apparent conflict between special relativity and the dynamics of quantum measurement.

There are now many alternative quantum theories that provide a nonrelativistic dynamics of quantum measurement. To my knowledge, there has been no alternative theory that resolves the major problem of reconciling special relativity and the dynamics of quantum measurement in general, or Hardy’s theorem PR6 in particular. Nor have I been able to formulate a consistent relativistic dynamical theory of quantum measurement that applies to our universe without including both general relativity and cosmology.
In order to make the paper more accessible, sections 2 to 4 include short reviews of the relevant quantum theory for general relativists and cosmologists, and some relevant general relativity and cosmology for quantum theorists.

Section 2 describes Bell's theorem and Hardy's theorem. Section 3 presents an alternative proof of Hardy's theorem based on a combination of two classically connected Bell experiments. Their spacetime configuration is similar to that of the no-simultaneity thought experiment of Einstein's original work on special relativity. It goes on to sketch a proof the Hardy simultaneity theorem, which is an extension of his original theorem, but for curved spacetime, and to state the Hawking-Seifert theorem on timelike functions in some general curved spacetimes.

Section 4 uses general relativistic time dilation to demonstrate that for two clocks at different heights on the Earth or at different locations in the universe, local proper times do not provide a global definition of simultaneity. Two reasons for a cosmological theory of quantum measurement are given in section 5, and section 6 introduces the measurement field, which provides the simultaneity needed for such a theory, and for the resolution of the conflict between quantum measurement and relativity.

Section 7 sketches a simple example of relativistic measurement dynamics based on the measurement field, which leaves much room for improvement, and the final section 8 includes a brief discussion of the relation between this dynamics and some other alternative quantum theories.

### 2 Hardy’s theorem

Hardy’s theorem PR6 [?] goes further than Bell’s theorem on nonlocality of quantum measurement. From this theorem it follows that any dynamical theory of measurement, in which the results of the measurements agree with those of ordinary quantum theory, must have a preferred Lorentz frame. The theorem does not determine this frame.

Bell’s theorem shows that measurement dynamics is nonlocal if the results of measurements follow the rules of ordinary quantum theory [?, ?]. Bell demonstrated his theorem by a thought experiment illustrated in figure 1, in which two entangled particles, each with spin nonzero, and with total spin zero, are produced from a source S. A component of spin perpendicular to the direction of motion of each particle is measured, one at A, and the other at B, where typically ASB is a straight line, with S at its centre. The alignment of the spin measuring apparatus at A or B is the preparation event, or input, A1 or B1, and the measurement and recording of the spin component is the measurement event, or output, A2 or B2. Both the events A1,A2 at A have spacelike separation from both the events B1,B2 at B. In the illustrated example the particles are photons, and a line at 45 deg represents a photon at the velocity of light.
Figure 1: Spacetime diagram of Bell’s experiment. Thin diagonal lines at 45° represent the velocity of light. At both A1 and B1, the angle is the setting of the angle of spin or polarization measurement, which is an input event, and at A2 and B2, +/- represents the recording of the spin or polarization, an output event.

Bell’s theorem then states that for any realistic dynamics of quantum measurement, if the results agree with ordinary quantum theory, either the input at A1 affects the output at B2 or the input at B1 affects the output at A2, or both. There must be nonlocal space-like causality.

Such an experiment was carried out by Aspect and his collaborators [?, ?], although there remains at least one loophole to be closed because, despite the considerable care that was taken, it is not clear that the events fully satisfied the spacelike separation condition. [?, ?].

Hardy demonstrates his theorem through a thought experiment involving two matter interferometers, one for electrons and one for positrons, with an intersection between them that allows annihilation of the particles to produce gamma rays. In its original form, this experiment is likely to remain a thought experiment. Improved versions which depend on similar principles and are experimentally feasible are given in [?, ?]. A different derivation based on classical
links between two Bell experiments is given in [?] and section 3.

3 Simultaneity

In classical special relativity with flat spacetimes there is no unique simultaneity for events with spacelike separation. This was demonstrated by Einstein in the famous classical thought experiment, which we describe for later convenience. In Einstein’s experiment, illustrated in figure 2,

![Spacetime diagram of Einstein’s simultaneity experiment. The straight lines ASB and A’S’B’ represent a source and two receivers at rest in their respective frames.](image)

one part consists of a source S which emits a flash of light, and two receivers A and B, equidistant from S in the same straight line, where A,S and B are at
rest in a frame L. It is received simultaneously at A and B with respect to this frame. The other part of the experiment consists of an identical trio A’S’B’, in the same straight line as ASB, which are at rest in a different frame L’, moving with respect to L in the direction AOB, where S and S’ are nearly coincident at the time $t_0$ when both of them flash. The light from S’ is received simultaneously at A’ and B’ with respect to L’, and this is clearly not simultaneous with respect to L. Hence relativity.

There is an alternative proof [?] of Hardy’s theorem, which depends on two Bell experiments in a similar spacetime configuration to Einstein’s simultaneity experiment, and labelled similarly in figure 3. This is the double Bell experiment. The two Bell experiments are independent at the quantum level, but they are

Figure 3: Spacetime diagram of the double Bell experiment, with photons in optical fibres. The meaning of the symbols corresponds to their meaning in the first two figures. On the scale of this figure, the photons remain at rest while in the delay coils. CL are classical links, by which an output from each experiment determines an input to the other.

linked classically so that the output A2 controls the input A1’, which is in its future lightcone, and the output B2’ controls the input B1. According to Bell’s theorem, there are nonlocal interactions NI, such as the setting of the angle at
A1 affecting the measurement at B2, or the setting of the angle at B1' affecting the measurement at A2'. If both of these are present, then there is a causal loop
\[
A2' \xleftarrow{\text{CL}} A1 \xrightarrow{\text{NI}} B2 \xleftarrow{\text{CL}} B1' \xrightarrow{\text{NI}} A2'
\] (1)

The assumption that there are no causal loops in spacetime or the equivalent assumption that there is no backward causality, then leads to the exclusion of one of the nonlocal interactions, which makes the dynamics dependent on the Lorentz frame, and so leads to Hardy’s theorem. Details are in the letter [28].

As it stands, Hardy’s theorem makes no statement about simultaneity, but this also can be derived using the double Bell experiment. Thus a configuration similar to that used by Einstein to show that classical special relativity has no universal simultaneity, can be used to show that quantum measurement requires universal simultaneity, which is the Hardy simultaneity theorem PR7 of the introduction.

In flat spacetimes, a preferred Lorentz frame or a standard of rest defines a universal time and simultaneity between distant events. For curved spacetimes, only a local Lorentz frame or standard of rest has meaning, and even if there is a standard of rest for every point, this does not necessarily provide a definition of simultaneity. The examples of the next section show that in the presence of gravitational fields, the local times defined by local preferred Lorentz frames are not necessarily consistent with a universal simultaneity defined throughout a region. For curved spacetimes, simultaneity is a stronger condition. For flat spacetimes they are equivalent.

It is therefore important to extend Hardy’s theorem by showing that universal quantum measurement dynamics requires universal simultaneity.

It is not feasible to set up the double Bell experiment so that the curvature of spacetime has a significant and relevant effect, but the thought experiment is needed to study the effect of the curvature on the dynamics of quantum measurement. Just as for flat spacetime, the condition that there is no backward causality or equivalently that there is no causal loop requires that there is a time ordering for an event at A with respect to an event at B, which is spatially separated from the event at A. Unfortunately this time ordering depends on the hidden variables or background field, which are not accessible to current experiments. Universal quantum measurement therefore requires a universal time ordering for events with spacelike separation, which is equivalent to a universal simultaneity. This is the Hardy simultaneity theorem, which applies to curved spacetime. It is an extension of the original Hardy theorem and is based on the assumption that the events occur at spacetime points. Some latitude is allowed when they take a finite time or occupy a finite region of space.

Hawking[?] and Seifert[?] proved that in all universes in the neighbourhood of which there is no backward causality, there are timelike functions, spacelike
foliations of spacetime and corresponding definitions of simultaneity [?]. It is interesting to note that ‘no backward causality’ is the same condition as that used in [?] to prove that measurement dynamics needs a local Lorentz frame, and is used here to show that it needs simultaneity. Hardy showed that special frames are needed. However, the example of section 4 illustrates that the existence of a special frame at every point of a curved spacetime does not imply that there is a consistent definition of simultaneity.

4 Not proper time

The most obvious choice of a time to define simultaneity is the proper time of local matter, but this is inconsistent, because, as in Einstein’s experiment, the local matter can have different frames. In the neighbourhood of the Earth, we could use the Earth as a standard of rest, but this also is inconsistent, because in gravitational fields it leads to ‘simultaneity’ between events that have timelike separation.

As an example take two small clocks at rest with respect to the surface of the Earth, one vertically at a height $h$ above the other, where $h$ is small compared with the radius of the Earth. They could be at the top and bottom of a tall building, or one on a table in a laboratory, and one on the floor beneath it. Suppose they are synchronized at time $t = 0$ in the rest frame at this time. At later times, the general relativistic time dilation due to their gravitational potential difference is much greater than the special relativistic time dilation due to their different velocities around the Earth’s centre. The clocks will show a time difference $\Delta t$ after time $t$, where

$$\frac{\Delta t}{t} = \frac{gh}{c^2}$$

(2)

and $g$ is the acceleration due to the Earth’s field near its surface.

The separation between ‘simultaneous’ events as given by the two clocks becomes timelike after a time $t$ for which a signal from one to the other takes a time $\Delta t$, where

$$\Delta t = \frac{h}{c},$$

so that $t = \frac{c}{g} \approx 1$ year,

(3)

which is independent of $h$. The greater height leads to greater time shifts because of the greater gravitational potential difference, but the time taken for light to travel between the bodies increases in proportion. The fact that $t = c/g$ is so close to the time taken for the Earth to orbit the Sun is a well-known coincidence.

One could try to define simultaneity by using some kind of average over local times, but it is not at all clear over what scale the average should be taken: the
scale of the apparatus? of the Earth? of the Solar System? the galaxy? or the universe? An answer to this question is suggested in section 6.

There is the same problem if we try to use the rest frame of a field to define simultaneity. Suppose that we follow Hardy’s example (see also [?, ?]) of the universal background radiation. This provides a local standard of rest. We could use any kind of clock in this standard of rest to define the local ‘time’. But then there is a gravitational time shift between the clocks in a gravitational potential well, and outside it. So again, using these measures of local time, ‘simultaneous’ events can have a timelike separation, which is not allowed. The same applies to the universal background neutrino fields, or any other background field, of zero or any other rest mass.

Also, as pointed out by Hardy, there is no clear dynamical process whereby the quantum measurement of individual systems can be made to depend on the background radiation.

Section 6 shows that the Hawking-Seifert theorem leads to a possible resolution of this problem of simultaneity.

5 Cosmology

Wheeler [?] considered the possibility that entanglement and localization might occur on cosmological scales. We have no observational evidence that entanglement survives over such distances, but the Hardy simultaneity theorem and the experiments of Tittel, Gisin et al [?] provide two strong arguments for the importance of cosmology to quantum measurement.

According to the Hardy simultaneity theorem, quantum measurement needs simultaneity between distant events. There is already a cosmological definition of simultaneity for the standard models like the Robertson-Walker metric for isotropic spacetime. Cosmic standard time provides a time function, dividing (or foliating) spacetime into three-dimensional spacelike surfaces of constant cosmic standard time, which are maximally symmetric subspaces of the whole of the spacetime [?]. Any timelike function provides a definition of simultaneity, in which events with the same functional value are simultaneous. However, on scales smaller than the cosmological, the spacetime of the universe in our epoch is not isotropic, which leads to the problems of defining simultaneity given in the previous section.

The second follows from the experiments that demonstrate entanglement over a given distance, which is currently greatest for the Tittel et al. experiment. A system AB consisting of two parts A and B is in an entangled pure state when AB is in a pure state, but neither A nor B separately is in a pure state. Suppose that the systems A and B are distant from one another. Then spacelike separated measurements of A and of B lead to the nonlocality and simultaneity
problems of dynamical theories of measurement. The experiment of Tittel and his collaborators (?) shows directly that there can be entanglement over 10km, so simultaneity must be defined over regions of this size. Assuming that generalized measurement is universal, and that the Earth is typical regarding measurement, following the Kepler-Galilean principle PR1, entanglement and its destruction by measurement over distances of 10km is present always and everywhere. Now fill spacetime with overlapping regions of linear dimension 10km in space and 10km/c in time.

For every overlap region the definitions of simultaneity must be consistent, so by iteration they must be consistent throughout spacetime, or at least where and when generalized measurement takes place. We have no means of checking whether this includes the neighbourhood of singularities in spacetime or very strong gravitational fields, including the very early universe, the late stages of a closed universe, or in the neighbourhood of a black hole, but the rest of spacetime needs a definition of simultaneity, with a corresponding timelike function and spacelike foliation.

6 Measurement field

Experimenters in any field of physics who work in a nearly flat spacetime, and find that the results of their experiments depend on the Lorentz frame of the apparatus, do not immediately conclude that special relativity is wrong. They look for some previously unsuspected background influence that depends on the environment and which determines a special frame. This influence comes from a background physical system which interacts with the system being studied. No one has found a convincing example for which this procedure fails. Environment is used in a broad sense, and may include fields that penetrate the system.

Similarly, the need for a consistent definition of simultaneity for measurement does not contradict special relativity. But it requires a physical system that defines simultaneity and interacts with the measured system. Suppose that this physical system is a measurement field $\mu(x)$, where $x = (x^0, x^1, x^2, x^3)$ are the time and space coordinates of a spacetime point. Make the following further assumptions:
MU1. For the purposes of the present paper, $\mu(x)$ is a real classical scalar field. Later it will have to be quantized, it may have imaginary components and may not be scalar.

MU2. There was an epoch in the early universe with a cosmic time $t$.

MU3. In this early epoch $\mu$ was a monotonically increasing function of $t$.

MU4. In local inertial frames and in epochs like ours, $\mu(x)$ satisfies the zero-mass Klein-Gordon equation, or wave equation ($c = 1$):

$$\left( \frac{\partial^2}{\partial t^2} - \nabla^2 \right) \mu(x) = 0. \quad (4)$$

From the boundary condition in the early universe, the solution of the Klein-Gordon equation has a component of zero wavenumber. In quantum theory, these solutions are usually ignored.

For an early homogeneous universe, $\mu(x)$ has no space dependence. It is a time-like function, and the surfaces $S_0[\mu(x) = \mu_0]$ form a spacelike foliation of this part of spacetime. A critical question for measurement dynamics is whether this is true for all spacetime. I have been unable to prove it or find a counterexample, but there are physical arguments suggesting that in our universe, sufficiently far from singularities like black holes, the field $\mu(x)$ is a timelike function.

Locally in inertial frames and globally in flat spacetime, if $\mu$ is independent of the space coordinates $x_1, x_2, x_3$, then it is a linear function of $x^0 = t$,

$$\mu = at + t_0.$$  

$\mu(x)$ is a timelike function in some early epochs, so consider a spacelike surface $S[\mu(x) = \mu_0]$ at such an epoch. From the form of the Green function of the Klein-Gordon equation, the solution at any later spacetime point $x'$ is a weighted mean over the values and derivatives of $\mu$ on the intersection of the backward light cone of $x'$ and the surface $S$. If $x'$ is not near a region of large spacetime singularity, for example if it is on or in the Earth or the Sun, the local curvature of spacetime is small, and on scales small compared with the radius of the universe, the light cone will approximate a light cone for flat space, with the exception of strong focussing by gravitational lenses, which are rare. The weighted mean will then be the mean over a large spherical shell.

According to the cosmological principle, the universe is isotropic, and therefore homogeneous on sufficiently large scales, so this mean will approximate the mean for an isotropic universe. So for such $x'$, the Green function can be used to propagate the solution forward in time, as a small perturbation of the solution for an isotropic universe. For such a universe, $\mu$ is a timelike function, which provides the definition of simultaneity needed for quantum measurement.
The required cosmological principle says that on sufficiently large scales, averages over spherical shells are uniform. This is a stronger than the usual cosmological principle, that, usually by implication, refers to averages over solid spheres or similar regions.

7 A simple relativistic measurement dynamics

A nonrelativistic stochastic measurement dynamics, which is consistent with the Kepler-Galileo and Newton-Laplace principles, was proposed long ago by Lüders [?].

The mathematics comes from the Copenhagen school, particularly von Neumann and Heisenberg, but the physics is consistent with measurement as a nonrelativistic dynamical process, not with the Copenhagen interpretation. Heisenberg gave a descriptive account in [?]. Gisin used Lüders dynamics as a starting point for the quantum state diffusion approach to measurement [?].

Because the measurements in this nonrelativistic theory are localized in spacetime, it can be assumed that they have a definite time order. Consider just one measurement of a dynamical variable of the quantum system with corresponding nondegenerate Hermitean operator $G$ with eigenstates $|g\rangle$. Before the measurement, the quantum system is in the initial state $|i\rangle$ and afterwards it is in a final state $|f\rangle$, which is one of the eigenstates $|g\rangle$. The measurement dynamics is stochastic, and the probability that the system will finish in state $|g\rangle$ is

$$\Pr(|f\rangle = |g\rangle) = \langle i | g \rangle^2.$$ (5)

In general the classical system also changes its state, from some initial configuration to a final configuration corresponding to the measurement of the value $g$ whose probability (5) depends on $|i\rangle$. This is the influence of the initial quantum state of the quantum system on the final state of the classical system, that characterizes generalized quantum measurement.

The stochastic evolution of classical and quantum systems consists of continuous evolution of each according to their own deterministic dynamics, with sudden stochastic jumps which correspond to the measurements that take place at times determined by the classical system, in which the quantum and classical systems influence each other. In this theory, the classical system can influence the quantum system through time-dependent Hamiltonians whose current value depends on the state of a classical system. But the quantum system can only influence a classical system through a measurement.

In the corresponding relativistic theory, the jumps do not occur at constant time, but at constant values of $\mu$. In this way the measurement field affects the dynamics of quantum measurement, there are no causal loops, and relativistic principles are preserved, at least formally.
This picture of measurement is unsatisfactory in several ways. In particular, the
timing of the jumps is not normally determined by the classical system alone.
In the modern theory of continuous laboratory measurements, originating with
Davies [?], developed by many authors [?, ?, ?] and now used widely in quantum
optics, the timing of the jumps is determined also by the state of the quantum
system. Further, the Lüders picture assumes that there are distinctly classical
and distinctly quantal degrees of freedom, with a ‘shifty split’ between them
[?]. This split is convenient for conventional quantum theory, but there is no
evidence that the world is divided in this way into purely classical and purely
quantum domains.

Modern nonrelativistic dynamical theories of measurement have neither of these
problems, but the theory of the measurement field has not yet been extended
to relativistic versions of these theories.

8 Discussion and conclusions

It may seem surprising that tachyons have played no role [?]. There is a rea-
son for this. The usual theory of tachyons has no preferred frame [?]. This is
normally considered an advantage, but without the preferred frame, interaction
with normal matter leads to causal loops. Hence the difficulty of giving a phys-
ical interpretation to such interaction. Here the preferred frame is a necessity,
through a a nonlocal interaction with the measurement field, and without using
tachyons.

There are many versions of nonrelativistic measurement dynamics without the
faults of the Lüders theory discussed in section 7. All of them are nonlocal,
following Bell’s theorem. The first was the pilot wave theory of de Broglie and
Bohm, in which there are both waves and particles, and measurement dynamics
is the result of the effect of the quantum waves on the classical particles [?, ?].
Since then there have been dynamical theories based on waves alone, in which
the Schrödinger equation is modified by a weak stochastic process of localization,
leading to the ‘collapse’ of the quantum wave. Particles are just very localized
waves [?]. The nonlocal processes depend on simultaneous changes that take
place at spacelike separated points, where the simultaneity is determined by the
universal time variable t.

The theory presented here assumed that events like the orientation of a polarizer
or the recording of a spin take place at spacetime points. In fact preparation and
recording occupy finite regions of space and take a finite time. This complicates
the theory, but quantum state diffusion models of nonrelativistic measurement
show that this complication leads to no fundamentally new problems. [?].

To each of the nonrelativistic dynamical theories there corresponds a relativistic
theory in which the definition of simultaneity is provided by the measurement
field variable µ, just as in the case of Lüder’s dynamics. But none of these
relativistic theories represents a complete solution to the problem of relativistic measurement dynamics. There are still many unsolved problems.

If there is two-way interaction between matter and the measurement field, then superluminal signals might be possible. Then conclusions based on their non-existence would no longer hold [?]. Their existence leads to no contradiction, because there is a consistent and universal timelike function which defines past and future. In some respects the measurement field plays the role of an ether, yet there is no conflict with the principle of special relativity.

Section 6 introduced the measurement field, with the familiar Klein-Gordon dynamics. But the dynamics of the interaction between the measurement field and the matter fields is not familiar: it introduces the nonlocality of measurement. Relativistic theories of measurement dynamics cannot be considered in isolation from the rest of quantum physics. The nonlocality of the interaction is not consistent with the usual local interactions. For typical quantum systems studied in laboratory experiments, the nonlocal interactions have been too weak for their effects to be be seen so far. But even now there is a fundamental problem in reconciling the nonlocal dynamics of measurement with the usual local dynamics of quantum fields.

It might be that the introduction of nonlocal dynamics could solve some of the outstanding problems of a ‘theory of everything’ but there is little evidence for this as yet. It is unacceptable to have a dynamical theory of measurement that is incompatible with the theory of quantum fields or strings, just as it is unacceptable to have a theory of gravity that has no universally accepted quantization, even though so far neither the details of measurement dynamics nor quantum gravity are accessible to experiment. This paper shows that the large-scale curvature of spacetime is relevant to the problems of quantum measurement. But quantum measurement may or may not be connected to the problem of quantizing gravity, as has been suggested [?].

Much remains to be done.

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