“Time” replaced by quantum correlations: experimental visualization

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Today scientists describe the universe in terms of two basic partial theories – the general theory of relativity and quantum mechanics.

The general theory of relativity describes the force of gravity and the large-scale structure of the universe, that is, the structure on scales from only a few miles to as large as a million million million miles, the size of the observable universe.

Quantum mechanics, on the other hand, deals with phenomena on extremely small scales, such as a millionth of a millionth of an inch. Unfortunately, however, these two theories are known to be inconsistent with each other – they cannot both be correct.

One of the major endeavours in physics today is the search for a new theory that will incorporate them both – a quantum theory of gravity.
There are a number of proposed quantum gravity theories. Currently, there is still no complete and consistent quantum theory of gravity, and the candidate models still need to overcome major formal and conceptual problems. They also face the common problem that there is no way to put quantum gravity predictions to experimental tests.

### Introduction

If space and time are not fundamental, then what is? Theoretical physicists are exploring several possible answers.

#### One clue

Quantum effects in the gravitational field of a black hole cause it to radiate energy as if it were hot, implying a deep connection between quantum theory, gravity, and thermodynamics — the science of heat.

#### 1. Gravity as thermodynamics

The equations of gravity can actually be derived from thermodynamics, without reference to space-time curvature.

This suggests that gravity on a macroscopic scale is just an average of the behaviour of some still-unknown ‘atoms’ of space-time.

#### 2. Loop quantum gravity

The Universe is a network of intersecting quantum threads, each of which carries quantum information about the size and shape of nearby space.

Imagine drawing a closed surface anywhere in the network. Its volume is determined by the intersections it encloses; its area by the number of threads that pierce it.
3. Causal sets
The building blocks of space-time are point-like "events" that form an ever-expanding network linked by causality.

4. Causal dynamical triangulations
Computer simulations approximate the fundamental quantum reality as tiny polygonal shapes, which obey quantum rules as they spontaneously self-assemble into larger patches of space-time.

5. Holography
A three-dimensional (3D) universe contains black holes and strings governed solely by gravity, whereas its 2D boundary contains ordinary particles governed solely by standard quantum-field theory.

An earlier event can affect a later one, but not vice versa.
Are principles of the quantum mechanics and general relativity correct or should be modified?

What happens in singularities of general relativity?

How to give description of nature at all scales?

What is Time?

**Wheeler-De Witt equation** (1967) - canonical quantization of the general relativity

\[ \mathcal{H}_{tot} |\Psi\rangle = 0 \]

...the Time disappears and the Quantum Cosmos doesn’t evolve...

*It clashes with our everyday experience of an evolving world....*
THE PROBLEM OF TIME IN QUANTUM GRAVITY

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The problem of time in quantum gravity

Classical parameter…
…for a fully consistent theory we need a quantum description!

How to define time?

Time – “what is shown on a clock”

How to define clock?

Clock – an quantum system

Degree of freedom

Time
Time is a quantum degree of freedom, evolution emerges via correlations (entanglement) between this quantum degree of freedom and the rest of the system. It exists only for internal observer. Any external observer outside sees a static, unchanging universe, just as the Wheeler-DeWitt equation predicts...
The PaW Formalism

Model of the isolated Universe

"super-observer" mode
The staticity of the global system

"observer" mode
The flow of time consists in the entanglement between the quantum degree of freedom of time and the rest and recover from the conditional measurements

The PaW formalism

• Time represents a dynamical degree of freedom connected to some quantum system (Experiment 1)

• Time degree of freedom as an abstract purification space (Experiment 2)
The polarization of both photons evolves in the birefringent quartz plates as:

$$|V\rangle \rightarrow |V\rangle \cos \delta + i |H\rangle \sin \delta.$$ 

$\delta$ : material’s optical thickness
Quantum state reconstruction (quantum tomography) - set of projective measurements (16)
realized with polarization filters consisting of a sequence of quarter- and half-wave plates and a
polarization prism which transmits vertical polarization (V).

\[ |\Psi\rangle = \frac{1}{\sqrt{2}} \left( |H\rangle_c |V\rangle_r - |V\rangle_c |H\rangle_r \right) \]

Two-photon polarization state \( \rightarrow \) four-dimensional Hilbert space

How to reconstruct the state of the Universe?

\[ K_4 \equiv (K_2)_1 \otimes (K_2)_2 = \begin{pmatrix} A & E & F & G \\ E^* & B & I & K \\ F^* & I^* & C & L \\ G^* & K^* & L^* & D \end{pmatrix} \rightarrow \rho = |\Psi\rangle \langle \Psi| \]

\[ A = \langle a_1^* a_2^* a_1 a_2 \rangle = |c_1|^2, \quad B = \langle a_1^* b_2^* a_1 b_2 \rangle = |c_2|^2, \]

\[ C = \langle b_1^* a_2^* b_1 a_2 \rangle = |c_3|^2, \quad D = \langle b_1^* b_2^* b_1 b_2 \rangle = |c_4|^2 \]

\[ E = \langle a_1^* a_2^* a_1 b_2 \rangle = c_1^* c_2, \quad F = \langle a_1^* a_2^* b_1 a_2 \rangle = c_1^* c_3, \quad G = \langle a_1^* a_2^* b_1 b_2 \rangle c_1^* c_4, \]

\[ I = \langle a_1^* b_2^* b_1 a_2 \rangle = c_2^* c_3, \quad K = \langle a_1^* b_2^* b_1 b_2 \rangle = c_2^* c_4, \quad L = \langle b_1^* a_2^* b_1 b_2 \rangle = c_3^* c_4 \]

\[ \rho_{\text{out}}: \text{final state after its evolution through the plates} \]

\[ \text{Fidelity} = \left( \text{Tr} \sqrt[1/2]{\rho_{\text{teor}}^{1/2}\rho_{\text{exp}}^{1/2}\rho_{\text{teor}}^{1/2}} \right)^2 \]
Approach 1: observer mode

- Plate A provides time evolution of the state
- Plate B introduces a “time” delay

The Clock photon polarization has a dial with only two values:

|H⟩, clicked D1, corresponding to time $t = t_1$
|V⟩ clicked D2, corresponding to time $t = t_2$

$t_2 - t_1 = \pi/2\omega$

To obtain a more interesting clock a $\tau$ dependence is introduced by varying time delays to the clock photon (plates of variable thickness B)

In this way he obtains a sequence of time-dependent values for the conditional probability

$p(t_1) = P_{3|1}$
$p(t_2) = P_{3|2}$
The super-observed mode is employed to prove that the global state is static respect to abstract coordinate time.

\[ |\Psi^-\rangle_{\text{teor}} = \frac{1}{\sqrt{2}} (|H_1V_2\rangle - |V_1H_2\rangle) \]

The fact that the fidelity is constant and close to one (up to experimental imperfections) at different coordinate times proves that the global entangled state is static.
Approach 2: Theory

- Wheeler-DeWitt equation

consider a Hilbert space: \[ \mathcal{H} := \mathcal{H}_T \otimes \mathcal{H}_S \]

Constraint operator of the model:

\[ \hat{J} := \hbar \Omega \otimes 1_S + 1_T \otimes \hat{H}_S \]

Global state of system plus clock:

\[ |\Psi\rangle = \int dt |t\rangle_T \otimes |\psi(t)\rangle_S \]

- Wheeler-DeWitt equation

Conditional state at time t

\[ i\hbar \frac{\partial}{\partial t} |\psi(t)\rangle_S = \hat{H}_S |\psi(t)\rangle_S \]

- Schrödinger equation
Approach 2: Theory

$\mathcal{H}_T \otimes \mathcal{H}_S$ expand space

X, Y – Hilbert space of the system,

$\psi(t)$

$\mathcal{H}_S$ – Hilbert space of the clock system

“Super-observer” mode – time-independent state

Observer mode – evolution is reconstructed through the two-time measurements
Experimental setup: observer mode

SPS - narrow-band attenuated He-Ne laser
System - photon’s polarization
Clock - photon’s position/time of arrival
Clock must be in superposition of all relevant times - > “flow of time” - birefringent quartz plates

\[ P(b=-1 | a=1) \]
\[ P(b=1 | a=-1) \]
\[ P(b=1 | a=1) \]
\[ P(b=-1 | a=1) \]
Experimental conditions

**SPS** - narrow-band attenuated He-Ne laser

**System** - photon’s polarization

**Clock** - photon’s position/time of arrival

Clock must be in superposition of all relevant times - >

“flow of time” - birefringent quartz plates
Experimental setup: super-observer mode

Experimental conditions

SPS - narrow-band attenuated He-Ne laser
System - photon’s polarization
Clock - photon’s position/time of arrival
Clock must be in superposition of all relevant times → "flow of time" - birefringent quartz plates

Control that global system is time independent (control the coherence length)
LGI is analog of spatial Bell’s inequality, but involves correlations of measurements on a system at different times.

For the two-state system an observable $Q(t)$ takes values $\pm 1$

two-time correlation functions:

$$C_{ij} = \sum_{Q_i, Q_j=\pm 1} Q_i Q_j P_{ij}(Q_i, Q_j)$$

$$K^3_{\text{max}} = \frac{3}{2} \text{ at } t\omega=\frac{\pi}{6}$$

$$K_3 \equiv C_{12} + C_{23} - C_{13} \leq 1$$
**Leggett-Garg inequality and PaW mechanism**

**We should measure values:**

\[ C(t_1, t_2), C(t_1, t_3), C(t_2, t_3), \]

\[ \Delta t_{12} = \Delta t_{23} = \Delta t_{13} / 2 \quad \Rightarrow \quad U = U' \]

<table>
<thead>
<tr>
<th>( \delta )</th>
<th>Theory</th>
<th>Experiment</th>
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<tbody>
<tr>
<td>0.2</td>
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<tr>
<td>0.7</td>
<td>1.282</td>
<td>1.238±0.012</td>
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✓ The experimental illustration of two different approaches of Page and Wootters mechanism of quantum description of time had been done

✓ The PaW mechanism gives conventional quantum mechanic description of evolution in observer mode though the conditional probabilities and at the same time operates with a global, time independent state in super-observer mode.

✓ We have shown that Page and Wootters experiment with quantum time from the "internal" observer point of view clearly demonstrates a violation of the classical limits imposed by the Leggett-Garg inequality

References: