The Foundational Questions

as viewed from quantum geometrodynamics

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Main approaches to quantum gravity

No question about quantum gravity is more difficult than the question, "What is the question?" (John Wheeler 1984)

- Quantum general relativity
  - Covariant approaches (perturbation theory, path integrals, . . .)
  - Canonical approaches (geometrodynamics, connection dynamics, loop dynamics, . . .)
- String theory
- Other approaches
  (Quantization of topology, causal sets . . .)

Topic here: quantum geometrodynamics

What is quantum geometrodynamics?

Central equations of canonical quantum gravity are constraints:

$$\boxed{\hat{H}\Psi = 0}$$

Oldest approach: Quantum geometrodynamics
(Wheeler–DeWitt equation):

- Apart from non-gravitational fields, Ψ depends only on the threedimensional metric, but is invariant under coordinate transformations
- no external time parameter is present
- Wheeler–DeWitt equation has the structure of a wave (Klein–Gordon type) equation and thereby defines an intrinsic time
- very conservative approach because this equation gives the correct Einstein equations in the semiclassical limit and should thus be valid at least away from the Planck scale

The foundational questions

- Are there reasons to believe that standard quantum mechanics is insufficient?
  Not from the point of view of the formalism of quantum geometrodynamics, which so far does not seem to lead to any inconsistencies
- Can we apply quantum mechanics to the entire universe?
  Yes, we can; it is even most natural to do so (“quantum cosmology”)

B. S. DeWitt 1967:

Everett’s view of the world is a very natural one to adopt in the quantum theory of gravity, where one is accustomed to speak without embarassment of the ‘wave function of the universe.’ It is possible that Everett’s view is not only natural but essential.

- What is quantum physics fundamentally about?

  About reality!

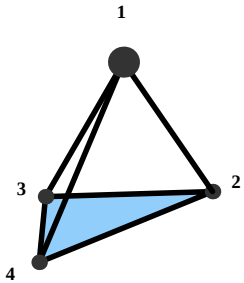
- Can one define probabilities (in an eternally inflating spacetime)?

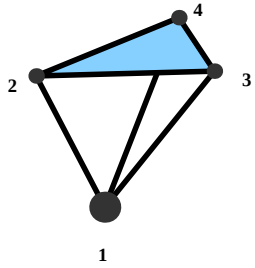
  The Wheeler–DeWitt equation is fundamentally timeless and cannot accommodate probabilities in a natural way; this can only be done in the semiclassical (“Born–Oppenheimer”) limit where an approximate time parameter emerges. In this limit, decoherence plays a crucial role.

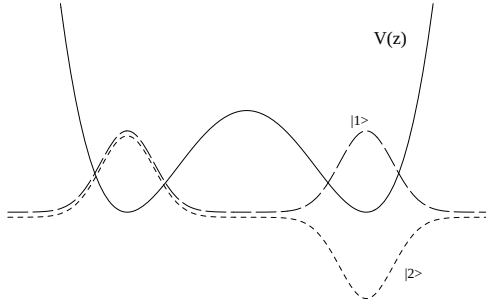
  In theories of inflation (which make sense only in the semiclassical limit), the Born rule may have to be replaced by another rule for observational probabilities in cosmology; Don Page argues in arXiv:0903.4888v2 [hep-th] that there are many such rules

Time from Symmetry Breaking

Analogy from molecular physics: emergence of chirality







dynamical origin: decoherence due to scattering with light or air molecules

quantum cosmology: decoherence between $\exp(\mathrm{i}S_0/\hbar)$- and $\exp(-\mathrm{i}S_0/\hbar)$-part of wave function through interaction with multipoles

one example for decoherence factor:

$\exp\left(-\frac{\pi m H_0^2 a^3}{128\hbar}\right) \sim \exp\left(-10^{43}\right)$ (C. K. 1992)

- On what side of the borderline between science and philosophy are parallel universes?

  On the side of science

- Why did our universe begin in a low-entropy state?

  Fundamental asymmetry with respect to “intrinsic time”:

$$\hat{H}\Psi = \left(\frac{\partial^2}{\partial \alpha^2} + \sum_i \left[-\frac{\partial^2}{\partial x_i^2} + \underbrace{V_i(\alpha, x_i)}_{\to 0 \text{ for } \alpha \to -\infty} \right] \right) \Psi = 0$$

  Is compatible with a simple boundary condition:

$$\Psi \overset{\alpha \to -\infty}{\longrightarrow} \psi_0(\alpha) \prod_i \psi_i(x_i)$$

  Entropy increases with increasing α, since entanglement with other degrees of freedom increases
  $\longrightarrow$ defines time direction

Is the expansion of the Universe a tautology?

- Is there any hope of experimentally testing quantum gravity?

  Yes; perhaps through quantum gravitational corrections: the next order in the Born–Oppenheimer approximation gives

$$\hat{H}^{\mathrm{m}} \rightarrow \hat{H}^{\mathrm{m}} + \frac{1}{m_{\mathrm{P}}^2}\,(\text{various terms})$$

  (C. K. and T. P. Singh (1991); A. O. Barvinsky and C. K. (1998))

  Can these correction terms be observed e.g. by the Planck satellite?

  general reference: C.K., *Quantum Gravity* (Oxford 2007)