Heuristics and Tests of Quantum Gravity

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Heuristics of quantum gravity

For the attempt to create a gravitational quantum theory, there are several research programs, some of which became obsolete over time due to the higher heuristic power of other programs. J. Butterfield thus distinguishes three major research programs: [1]

The **program of particles** establishes as the basic entity the graviton, the quanta of the gravitational field. The graviton spreads in a Minkowski spacetime and is associated with the specific representation of the zero-mass Poincare group and the spin 0 or 2. But this program presents many conceptual dysfunctionalities.

The **program of superstructures**, an approach motivated by the success of the transition from the old non-renormalizable theory of weak interactions to the new renormalizable unification of the weak and electromagnetic forces found by Salam, Glashow and Weinberg. The idea was to add fields of matter from general relativity to eliminate the UV problem. Thus appeared the theory of supergravity which, after some minor successes, came to the conclusion that it does not solve the divergences, but its line of thinking is currently continued by the superstring theory, which is the dominant research program in quantum gravity. The program has not yet matured. From the point of view of the response offered to the conceptual aspects, the program of superstrings is similar in many respects with the program of particles.

The **program of canonical quantum gravity** began with the Wheeler-DeWitt theory. Later came the program of Ashtekar that uses the Wheeler-DeWitt equation, [2] with the help of a set of canonical variables that produce a simplification of the structure of the central constraint functions, and is still a very active program, with impressive developments in recent years.

All three programs are similar in that the main way they go beyond the common treatment of spacetime is by quantifying an amount that is a standard type of variable in classical physics.

There are three major problems in the conception of a theory of quantum gravity: both quantum theory and general relativity present significant conceptual problems in themselves, the disparate fundamental bases of the two theories generate major new problems when trying to combine them, and the contrast between the lack of a satisfactory theory of quantum gravity and successful ingredient theories raise questions about the nature and function of the philosophical discussion of quantum gravity.

[1] Jeremy Butterfield and Chris Isham, "Spacetime and the Philosophical Challenge of Quantum Gravity," in *Physics Meets Philosophy at the Panck Scale* (Cambridge University Press, 2001).

[2] Bryce S. DeWitt, "Quantum Theory of Gravity. I. The Canonical Theory," *Physical Review* 160, no. 5 (August 25, 1967): 160 (5): 1113–1148, https://doi.org/10.1103/PhysRev.160.1113.

According to Laudan, the preferred theory is the one that maximizes the empirical successes, while reducing the conceptual problems, and the research preferred tradition is the one that supports the most successful theories.

According to Péter Szegedi, the history of quantum mechanics interpretations fit very well with Lakatos' methodology of rival scientific research programmes, compared to Kuhn's methodology which does not allow the simultaneous existence of different rival paradigms.[3] [4] It turns out that the development of quantum mechanics itself is a development, an evolution of progressive problems, if it is progressive both theoretically and empirically. Interpretations of quantum mechanics can be arranged as a series of theories, resulting in theoretical progressivity, but empirical progressivity is difficult to evaluate. Thus, according to the criteria, the interpretive programs can be scientific, but they are degenerative, respectively they are characterized by stagnation. The evaluation may change in the future, being a long-term program: "Moreover, it occasionally happens that when a research pro gramme gets into a degenerating phase, a little revolution or a creative shift in its positive heuristic may push it forward again."[5]

There is a possibility that a degenerate program may be revived, or even considered successful if it provides useful results for other programs.[6]

Péter Szegedi distinguishes, in the case of various quantum interpretations, a hard core and a heuristic adapting to the problems that have arisen.[7] Thus, in Louis de Broglie's program, the synthesis of wave-particle images is the hard core, while the real forms of realization in order of appearance (positive heuristic) are the following: the principle of double solution, the theory of pilot waves, the hypothesis of non-linearity and the hidden thermodynamics. In the case of David Bohm, the hard core is the theory of hidden variables and the quantum potential, to which at one point he added the hypothesis of stochasticity. Vigier used the same hard core, but with an additional assumption of the hidden degrees of freedom hypothesis. There are other programs in the interpretations of quantum mechanics. In the Fényes-Nelson-de Peňa research program, stochasticity is not an additional hypothesis, but a hard core, where the positive heuristic forced the initial use of diffusion processes, then the Brownian motion and, finally,

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[3] Péter Szegedi, "Lakatos On Crucial Experiments And The History Of Interpretations Of Quantum Mechanics," in *Appraising Lakatos: Mathematics, Methodology and the Man*, ed. G. Kampis, L. : Kvasz, and M. Stöltzner (Kluwer Academic Publishers, 2002), 1–101.

[4] Imre Lakatos, *The Methodology of Scientific Research Programmes: Volume 1: Philosophical Papers* (Cambridge University Press, 1980), 33–34.

[5] Lakatos, 51.

[6] H. Zandvoort, Paul Weingartner, and Methology and Philosophy of Science International Congress of Logic, *Intrinsic Success and Extrinsic Success of Research Programs, in 7th International Congress of Logic, Methodology and Philosophy of Science: Salzburg, July 11th-16th, 1983 Vol. 4, Vol. 4,* (Salzburg: Huttegger, 1983), 289–92.

[7] Szegedi, "Lakatos On Crucial Experiments And The History Of Interpretations Of Quantum Mechanics."

stochastic electrodynamics. The positive heuristics of these programs are different, but generally they use the relativistic approach, the principle of determinism or causality and the principle of the unity of nature. In orthodox interpretation, according to Cushing, the hard core consists of the canonical commutation relations and Hamiltonian equations of motion, and the positive heuristic applies to the classical forms of Hamiltonians for specific systems, the principle of correspondence and the principle of observables; as an auxiliary hypothesis, the operator-observer report was used. Lakatos says about this program:

> "In the new, post-1925 quantum theory the 'anarchist' position became dominant and modern quantum physics, in its 'Copenhagen interpretation', became one of the main standard bearers of philosophical obscurantism. In the new theory Bohr's notorious 'complementarity principle' enthroned [weak] inconsistency as a basic ultimate feature of nature, and merged subjectivist positivism and antilogical dialectic and even ordinary language philosophy into one unholy alliance. After 1925 Bohr and his associates introduced a new and unprecedented lowering of critical standards for scientific theories. This led to a defeat of reason within modern physics and to an anarchist cult of incomprehensible chaos." [8]

Lakatos' crucial experiments in quantum mechanics begin with a Gedanken experiment, the Einstein-Podolsky-Rosen experiment. [9] Commentators distinguish (at least) five hypotheses here: the principle of realism, the validity of quantum mechanical formalism, the hypothesis of completeness, the principle of separability, and the validity of classical logic. According to the EPR argument, one of the five assumptions is false. The next step was taken by Bohm, who reformulated the Gedanken experiment with spins, [10] but without seeming yet another crucial experiment as it was not stated that different theories offer different measurement results.

The work of John Bell has given hope that experimental testing of interpretations is possible, [11] emphasizing that there must be differences between quantum mechanical and hidden predictions. He assumed that in a real experiment we could measure probabilities. Bell's inequality was even closer to the real conditions of an easy-to-manage experiment.

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[8] Lakatos, *The Methodology of Scientific Research Programmes*, 59–60.

[9] A. Einstein, B. Podolsky, and N. Rosen, "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?," *Physical Review* 47, no. 10 (May 15, 1935): 770–80, https://doi.org/10.1103/PhysRev.47.777.

[10] David Bohm, *Quantum Theory*, Revised ed. edition (New York: Dover Publications, 1989).

[11] J. S. Bell, "On the Einstein Podolsky Rosen Paradox," *Physics Physique Fizika* 1, no. 3 (November 1, 1964): 447, https://doi.org/10.1103/PhysicsPhysiqueFizika.1.195.

The tests of quantum gravity

The primordial test of any quantum theory of gravity is the reproduction of the successes of general relativity. This involves reconstructing the local geometry from the non-local observables. In addition, quantum gravity should probabilistically predict the large-scale topology of the Universe, which may soon be measurable, [12] and phenomena at the Planck scale. [13]

There is already a prediction that relates to quantum gravity: the existence and spectrum of Hawking radiation of the black hole, a "semi-classical" prediction resulting from quantum field theory on a fixed curved background, and subsequently confirmed theoretically. [14] It is assumed that a theory of gravity that will not reproduce this prediction is wrong.

For the Planck energy scale several tests have been proposed based on two ideas: that we can detect very small deviations of the exact symmetries, and that we can integrate over long distances or times to observe very small collective effects. These proposals remain extremely speculative, but they are plausible. [15] Some of these ideas can be found in Giovanni Amelino-Camelia, *Are we at the dawn of quantum-gravity phenomenology*: [16]

- Violations of the principle of equivalence. [17] Accuracy tests of the equivalence principle could be developed by atomic and neutron interferometry.
- Violations of CPT (charge, parity, and time) invariance, [18] for example by forming virtual black holes. The current experimental limits approach the observation level of these

[12] Neil Cornish, David Spergel, and Glenn Starkman, "Circles in the Sky: Finding Topology with the Microwave Background Radiation," *Classical and Quantum Gravity* 15, no. 9 (September 1, 1998): 15, 2657, https://doi.org/10.1088/0264-9381/15/9/013.

[13] Richard Easther et al., "Inflation as a Probe of Short Distance Physics," *Physical Review D* 64, no. 10 (October 16, 2001): 103502, https://doi.org/10.1103/PhysRevD.64.103502.

[14] Fay Dowker et al., "Pair Creation of Dilaton Black Holes," *Physical Review D* 49, no. 6 (March 15, 1994): 2909, https://doi.org/10.1103/PhysRevD.49.2909.

[15] S. Carlip, "Quantum Gravity: A Progress Report," *Reports on Progress in Physics* 64, no. 8 (August 1, 2001): 885–942, https://doi.org/10.1088/0034-4885/64/8/301.

[16] Giovanni Amelino-Camelia, "Are We at the Dawn of Quantum-Gravity Phenomenology?," *ArXiv:Gr-Qc/9910089*, October 25, 1999, http://arxiv.org/abs/gr-qc/9910089.

[17] G. Z. Adunas, E. Rodriguez-Milla, and D. V. Ahluwalia, "Probing Quantum Aspects of Gravity," *Physics Letters B* 485, no. 1–3 (July 2000): 215, https://doi.org/10.1016/S0370-2693(00)00697-3.

[18] Alan Kostelecky and Rob Potting, "Expectation Values, Lorentz Invariance, and CPT in the Open Bosonic String," *Physics Letters B* 381, no. 1–3 (July 1996): 89, https://doi.org/10.1016/0370-2693(96)00589-8.

effects. [19] Violations of other global symmetries, such as CP, can also occur, with consequences that can be observed on the Planck scale. [20]

- Distortions of dispersion relationships for light and neutrinos over long distances, resulting in a frequency-dependent light speed. [21] It can be observed by observing the gamma rays, the current experimental limits are close to the observation level. If the effect depends on polarization, gravity-induced birefringence tests may be within observation limits. [22]
- Interferometers for detecting gravitational waves could observe quantum fluctuations testable in space geometry, [23] an idea still controversial.
- Quantum gravity near Planck mass affects renormalization group fluxes and low energy coupling constants in large unified theories, [24] but this effect is rather a disadvantage making other possible tests more difficult.
- Use of powerful lasers for (indirect) observation of Unruh radiation, the counterpart of Hawking radiation for an acceleration particle. [25] This may be at least a test of theoretical quantum field predictions from quantum gravity.
- An indirect test from analogues of condensed matter with black holes, which should emit phonons through "Hawking radiation" from sonic horizons. [26] Tests may be possible in

[19] R. Adler et al., "Test of CPT Symmetry and Quantum Mechanics with Experimental Data from CPLEAR," *Physics Letters B* 364, no. 4 (December 1995): 239, https://doi.org/10.1016/0370-2693(95)01416-0.

[20] Renata Kallosh et al., "Gravity and Global Symmetries," *Physical Review D* 52, no. 2 (July 15, 1995): 912, https://doi.org/10.1103/PhysRevD.52.912.

[21] Jorge Alfaro, Hugo A. Morales-Tecotl, and Luis F. Urrutia, "Quantum Gravity Corrections to Neutrino Propagation," *Physical Review Letters* 84, no. 11 (March 13, 2000): 2318, https://doi.org/10.1103/PhysRevLett.84.2318.

[22] Reinaldo J. Gleiser and Carlos N. Kozameh, "Astrophysical Limits on Quantum Gravity Motivated Birefringence," *Physical Review D* 64, no. 8 (September 2001): 083007, https://doi.org/10.1103/PhysRevD.64.083007.

[23] Y. Jack Ng and H. van Dam, "Measuring the Foaminess of Space-Time with Gravity-Wave Interferometers," *Foundations of Physics* 30, no. 5 (2000): 795, https://doi.org/10.1023/A:1003745212871.

[24] L. J. Hall and U. Sarid, "Gravitational Smearing of Minimal Supersymmetric Unification Predictions," *Physical Review Letters* 70, no. 18 (May 3, 1993): 2673, https://doi.org/10.1103/PhysRevLett.70.2673.

[25] Pisin Chen and Toshi Tajima, "Testing Unruh Radiation with Ultraintense Lasers," *Physical Review Letters* 83, no. 2 (July 12, 1999): 256, https://doi.org/10.1103/PhysRevLett.83.256.

[26] Matt Visser, "Acoustic Black Holes," *ArXiv:Gr-Qc/9901047*, January 15, 1999, http://arxiv.org/abs/gr-qc/9901047.

> the future in Bose-Einstein condensates,[27] superfluid helium 3[28] and "slow light" in dielectrics.[29]

These experiments will not differentiate between specific models of quantum gravity, as current models cannot yet make sufficiently clear predictions, but phenomena can be tested on the Planck scale affected by quantum gravity. Lately, physicists have focused on the idea of experimental tests for a certain class of quantum gravity models, "gravity on the TeV scale" or "world of branes",[30] which postulate additional "large" dimensions, of one millimeter.

The problem of how the measurement affects the ontological state of the observed system is called the *measurement problem*. Measurement in quantum mechanics is viewed in different ways in various interpretations. In classical mechanics, a simple point system is fully described by the particle's position and momentum. In quantum mechanics, a system is described by its quantum state, by the probabilities of possible positions and momentums. The predicted values of the measurements are described by a probability distribution or an "average" (or "expectation") of the measurement operator based on the quantum state of the prepared system. The measurement process is often considered random and indeterministic in some interpretations, while in other interpretations indeterminism is fundamental and irreducible.

There are several possible ways to mathematically describe the measurement process (both the probability distribution and the collapsed wave function). The most convenient description depends on the spectrum (ie the set of eigenvalues) of the observable.

The most obvious feature in quantum gravity is the lack of data (there are no phenomena that can be identified unequivocally as a result of an interaction between general relativity and quantum theory). This is because the quantum gravity scale (Planck length) is extremely small, as is Planck energy and Planck time. It turns out that the only physical regime in which the effects of quantum gravity could be studied directly is in the immediate post-Big Bang era, in addition to the problems related to the interaction of spin-2 gravitons with a conserved energy-momentum tensor. It follows that different quantum gravity theories could be empirically verified only at very high energies.

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[27] L. J. Garay et al., "Sonic Analog of Gravitational Black Holes in Bose-Einstein Condensates," *Physical Review Letters* 85, no. 22 (November 27, 2000): 4643, https://doi.org/10.1103/PhysRevLett.85.4643.

[28] G. E. Volovik, "Field Theory in Superfluid 3He: What Are the Lessons for Particle Physics, Gravity and High-Temperature Superconductivity?," *Proceedings of the National Academy of Sciences* 96, no. 11 (May 25, 1999): 6042, https://doi.org/10.1073/pnas.96.11.6042.

[29] U. Leonhardt and P. Piwnicki, "Relativistic Effects of Light in Moving Media with Extremely Low Group Velocity," *Physical Review Letters* 84, no. 5 (January 31, 2000): 822, https://doi.org/10.1103/PhysRevLett.84.822.

[30] Lisa Randall and Raman Sundrum, "A Large Mass Hierarchy from a Small Extra Dimension," *Physical Review Letters* 83, no. 17 (October 25, 1999): 3370, https://doi.org/10.1103/PhysRevLett.83.3370.

For physics, this means that it is very difficult to build a fully satisfactory theory. From a philosophical point of view, the difficulty is due to the conceptual problems of space, time and matter, but also due to the theoretical construction, since there is no agreement on the types of data that a quantum theory of gravity would obtain. In this situation, J. Butterfield states that the theoretical construction becomes much more strongly influenced by theoretical considerations, based on the different first-hand opinions on how the theory should look, based in part on the philosophical bias of the researcher and on the mathematical techniques considered. successful. Thus, a research program tends to construct abstract theoretical schemes compatible with a preconceived conceptual framework and internally coherent in a mathematical sense, resulting in a "sub-determination of data theory". Moreover, the program tends to produce schemes based on a wide range of philosophical motivations, which could be presumed to be unconscious projections of the individual researcher's psychic, and could be rejected as such.

It is important to determine if quantum gravity effects are measurable below the Planck limits, possibly resulting from a non-perturbative effect. But the very existence of such effects, and the phenomena they predict, are themselves probably strongly dependent on theory. It follows that the subject of quantum gravity presents to the philosopher a wide and varied range of approaches, provided that in quantum gravity there are not sufficiently well defined theories, not even well established.

From the dimensional analyzes it would appear that quantum gravity requires experimentally high energies, of the Planck energy level. This would require a particle accelerator larger than our galaxy, so direct quantum gravity tests seem impossible according to these calculations. It turns out that high precision laboratory tests in the weak field will be the only possibility to make quantum gravity a testable / falsifiable physical theory. This would be possible in macroscopic systems that still adhere to the laws of quantum theory - those described by macroscopic wave functions. These would allow, for example, the measurement of quantum gravitational excitation energies. [31] Johan Hansson and Stephane Francois suggest the possibility of testing quantum gravity theories using macroscopic quantum systems; superfluid helium, Bose-Einstein gas condensates and "macroscopic" molecules still subject to quantum mechanics, and neutron stars. The effects of quantum gravity, defined here as observable gravitational interactions between quantum objects, should be observed using existing technology, allowing for low energy falsifiability in the weak field regime. [32]

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[31] Johan Hansson, "Aspects of Nonrelativistic Quantum Gravity," *ArXiv:0910.4289 [Astro-Ph, Physics:Gr-Qc, Physics:Hep-Ph, Physics:Quant-Ph]*, October 22, 2009, 707 (2009), http://arxiv.org/abs/0910.4289.

[32] Johan Hansson and Stephane Francois, "Testing Quantum Gravity," *International Journal of Modern Physics D* 26, no. 12 (October 2017): 1743003, https://doi.org/10.1142/S0218271817430039.

Roberto Balbinot and Alessandro Fabbri, in *Amplifying the Hawking Signal in BECs*,[33] propose simple models of Bose-Einstein condensates to study the analogue effects of pair creation, namely, the Hawking effect of acoustic black holes and the Casimir dynamic effect. The idea is to reproduce in a context of condensed matter some quantum effects predicted by quantum field theory in curved space, including the thermal emission of black holes predicted by Hawking in 1974.[34] The authors of this experiment conclude that they have obtained some results that could be useful in future experimental research.

THe formalism is based on the Lagrangian form which regulates the dynamics of the point particles with mass and charge and the electromagnetic field in a static, spherically symmetrical gravitational field described by the phenomenological gravitational potentials T, H, e. This theory was used to interpret the results of the experimental tests of the strong equivalence principle.[35]

The *xg formalism* introduced by W.-T. Ni[36] initially offered us a framework for the analysis of electrodynamic physics in a gravitational background field, then expanded to cover other sectors of the standard model.

The *Kostelecky formalism*, developed by Colladay and Kostelecky, is used to deal with the possibility of spontaneous breakdown of Lorentz symmetry in the context of string theory.[37]

A formalism based on the forms of the equations of motion has the advantage of directly addressing some natural requirements.

[33] Roberto Balbinot and Alessandro Fabbri, "Amplifying the Hawking Signal in BECs," *Advances in High Energy Physics* 2014 (2014): 1–8, https://doi.org/10.1155/2014/713574.

[34] S. W. Hawking, "Particle Creation by Black Holes," *Communications in Mathematical Physics* 43, no. 3 (August 1, 1975): 199–220, https://doi.org/10.1007/BF02345020.

[35] J. E. Horvath et al., "Einstein Equivalence Principle and Theories of Gravitation: A Gravitationally Modified Standard Model," *Physical Review D* 38, no. 6 (September 15, 1988): 1754, https://doi.org/10.1103/PhysRevD.38.1754.

[36] W.-T. Ni, "Equivalence Principles and Electromagnetism," *Physical Review Letters* 38 (February 1, 1977): 301, https://doi.org/10.1103/PhysRevLett.38.301.

[37] Don Colladay and Alan Kostelecky, "Lorentz-Violating Extension of the Standard Model," *Physical Review D* 58, no. 11 (October 26, 1998): 6760, https://doi.org/10.1103/PhysRevD.58.116002.

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