The impact of gravity on quantum evolution

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Fundamental Frontiers of Quantum Science and Technology

Introduction

- According to General Relativity (GR), gravity is merely an aspect of the geometry of space and time:

$$\Delta\Phi = 4\pi G\,\rho \qquad \text{(Newton)}$$

$$R_{ab} - \tfrac{1}{2}Rg_{ab} = \frac{8\pi G}{c^4}\,T_{ab} \qquad \text{(Einstein)}$$

- The physical link between gravity and geometry is Einstein's Principle of Equivalence.
- That principle concerns contingent properties of the physical world that may well either fail to hold in the quantum domain, or simply become meaningless.
- Clarification of that point is expected to provide essential clues and physical intuition into the *Problem of Quantum Gravity*.

Equivalence Principle

- **Universality of Free Fall (UFF):** The space-time trajectory of a test-particle only depends on its initial position and velocity but not on its other physical or chemical attributes.
- **Local Lorentz Invariance (LLI):** The outcome of any local experiment is independent of the instantaneous orientation and velocity of the equipment (laboratory).
- **Universality of Clock Rates and Gravitational Redshift (UCR/UGR):** The rates of any two physical clocks agree if taken along the same worldline. If taken along different worldlines and intercompared with electromagnetic signals, they differ by the standard ($\alpha = 0$) redshift formula

$$\frac{\nu_2 - \nu_1}{\nu_1} = (1 + \alpha) \frac{\Phi(\vec{x}_2) - \Phi(\vec{x}_1)}{c^2}$$

Experimental Status of EP

- **Universality of Free Fall** is tested by measuring the Eötvös factor for two different materials A and B. Typical modern results are:

$$\eta(A, B) = 2 \cdot \frac{|a(A) - a(B)|}{a(A) + a(B)} < 10^{-13}$$

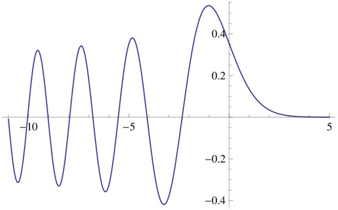
- **Local Lorentz Invariance** is tested by, e.g., modern versions of the Michelson-Morley experiment (isotropy of two-way speed of light). Typical modern results are:

$$\frac{\Delta c}{c} < 10^{-16}$$

- **Universality of Gravitational Redshift.** Still best test to date is 1976 comparison of two maser clocks, one of which boosted to an altitude of $10\,000\,\mathrm{km}$ by a Scout rocket:

$$\alpha < 7 \times 10^{-5}$$

Quantum Tests of EP

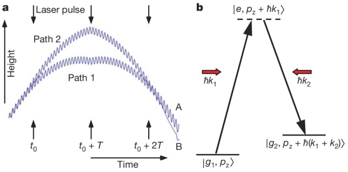


plot of Airy function

$$T_{\mathrm{ret}} = 2 \cdot \left[\frac{m_i}{m_g}\right]^{\frac{1}{2}} \cdot \left[\frac{2h}{g}\right]^{\frac{1}{2}}$$

$$\kappa = \left[\frac{2m_i\, m_g\, g}{\hbar^2}\right]^{\frac{1}{3}}$$

$$E_n = \left[\frac{m_g^2 g^2 \hbar^2}{2m_i}\right]^{\frac{1}{3}} \cdot (-z_n)$$



Müller-Peters-Chu 2010

$\alpha < 7 \times 10^{-9}$???

$$\Delta\Phi = (1+\eta)(1+\alpha)\kappa T^2 g$$

Activities at ZARM (Bremen)

- **QUANTUS** (Quantengase unter Schwerelosigkeit) Aim: Pathfinder for space-based EP tests Method: Begun 2004, 2007 first BEC under microgravity conditions (87Rb-based).
- **MICROSCOPE** (Micro Satellite à trainée compensée pour l'Observation du Principe d'Equivalence) Scheduled 2014, duration 1 year. Aim: Test UFF up to 10^{-15} level. Method: Sensitive capacitive acceleration, drag-free satellites.
- **PRIMUS** (Präzisionsinterferometrie mit Materiewellen unter Schwerelosigkeit). Aim: Pathfinder experiment for atom interferometric measurements at extended free evolution times in a microgravity environment Method: BEC matter-wave source

Self-Gravity of Matter Waves: The Schrödinger-Newton Equation

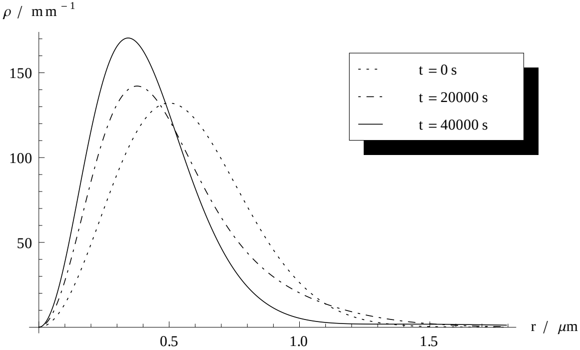
$$i\hbar\frac{\partial\Psi}{\partial t} = \left(-\frac{\hbar^2}{2m}\Delta + m\Phi\right)\Psi$$
$$\Delta\Phi = 4\pi G m\,|\Psi|^2$$

- A stable ground state exists, which is of energy

$$E_0 = -0.163\,\frac{G^2 m^5}{\hbar^2} = -0.163\cdot mc^2\cdot\left(\frac{m}{m_P}\right)^4$$

- For $m < m_P = 10^{19}\,\mathrm{u}$ this is well bounded away from black hole formation and the Newtonian approximation can be trusted.

The time-dependent SN-Equation



Time evolution of rotationally symmetric Gauß packet of initial width 500 nm. Collapse sets in for masses $m \gtrsim 4 \times 10^9\,\mathrm{u}$, but collapse times are still very long indeed.

Conclusion

- Future tests of basic principles of space-time theory and gravitation will depend crucially on further development in quantum technology.
- The scientific gain could be enormous. It is reasonable to expect insights beyond that of mere quantum-matter dynamics in *external* gravitational fields. As an intermediate step towards Quantum Gravity we need to probe the gravitational self-interaction of quantum systems. Can gravity inhibit the superposition principle?
- Ultimately this should promote our physical intuition of what it means (physically) to have a quantum theory of the gravitational field, i.e. spacetime. That is most badly needed!

THANKS!

Did you know?

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A fundamental threat to quantum cryptography: gravitational attacks

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Abstract. An attack on the "Bennett-Brassard 84" (BB84) quantum key-exchange protocol in which Eve exploits the action of gravitation to infer information about the quantum-mechanical state of the qubit exchanged between Alice and Bob, is described. It is demonstrated that the known laws of physics do not allow to describe the attack. Without making assumptions that are not based on broad consensus, the laws of quantum gravity, unknown up to now, would be needed even for an approximate treatment. Therefore, it is currently not possible to predict with any confidence if information gained in this attack will allow to break BB84. Contrary to previous belief, a proof of the perfect security of BB84 cannot be based on the assumption that the known laws of physics are strictly correct, yet. A speculative parameterization that characterizes the time-evolution operator of quantum gravity for the gravitational attack is presented. It allows to evaluate the results of gravitational attacks on BB84 quantitatively. It is proposed to perform state-of-the-art gravitational attacks, both for a complete security assurance of BB84 and as an unconventional search for experimental effects of quantum gravity.