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Cold-atom test of gravitational quantum interference

Observation of the quantum equivalence principle for matter-waves
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Recommended with a Commentary by Carlo Beenakker, Instituut-Lorentz, Leiden University

"The happiest thought of my life" is how Einstein referred to his 1907 insight that, since objects in free-fall don't feel their own weight, acceleration and gravity are locally indistinguishable. This equivalence principle, at the basis of the general theory of relativity, is formulated in terms of classical mechanics. A quantum mechanical formulation asserts that a uniform gravitational field can be removed from the Schrödinger equation by a coordinate transformation to an accelerated reference frame. The transformed wave function picks up a phase factor $e^{i\Lambda}$, which is however not locally detectable. The characteristic cubic time dependence $\Lambda \propto t^3$ of this "gauge phase" has now been measured in a nonlocal interferometric experiment.

The theoretical argument goes as follows [see Einstein's equivalence principle in quantum mechanics revisited by Nauenberg (2016)]. Start from the Schrödinger equation for a particle of inertial mass m in a uniform force field F,

$$i\hbar\frac{\partial}{\partial t}\psi(x,t) = -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}\psi(x,t) - Fx\psi(x,t), \tag{1}$$

and transform to a reference frame with acceleration $g = F/m$. The transformed coordinate x' is time dependent, $x' = x - \frac{1}{2}gt^2$. The transformed wave function $\psi'(x',t) = e^{i\Lambda(x,t)}\psi(x,t)$ satisfies the free equation

$$i\hbar\frac{\partial}{\partial t}\psi'(x',t) = -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x'^2}\psi'(x',t) \tag{2}$$

if we choose

$$\Lambda(x,t) = (mg/\hbar)\int x'dt = (mg/\hbar)(xt - \tfrac{1}{6}gt^3). \tag{3}$$

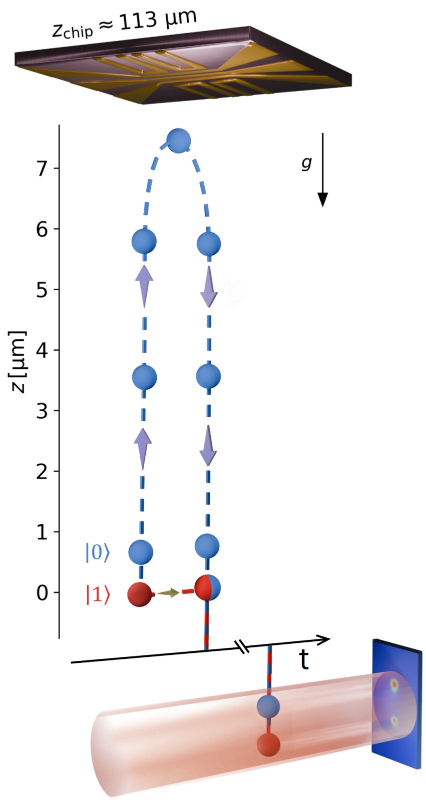
This applies to any force field, what is special about the gravitational force is that F/m is mass independent — on the assumption that the inertial mass equals the gravitational mass. There is thus a single "free-fall" reference frame in which the effect of a gravitational field on a quantum state is reduced to a phase factor.

An early experiment to measure Λ focused on the x-dependent contribution, linear in t. A neutron interferometer had two arms of the same length at different height Δx in the Earth's gravitational field. The phase difference $(mg/\hbar)t\Delta x$ showed up as an oscillating neutron count when the interferometer was rotated [Observation of gravitationally induced quantum interference, by Colella, Overhauser, and Werner (1975)].

To measure the t^3 contribution to Λ requires the interference of a beam in free fall with a beam that is stationary relative to the Earth. A thought experiment along these lines was described in On the testability of the equivalence principle as a gauge principle detecting the gravitational t^3 phase by Marletto and Vedral (2020). Dobkowski *et al.* have now realized it in the laboratory.

The figure illustrates their cold-atom interferometer in which one wave packet is held stationary in the laboratory frame, while the other is launched (using magnetic gradient pulses), rising and falling ballistically (constant acceleration g). After a time t the launching pulse is reversed so that the freely falling wave packet matches up in momentum and position with the stationary wave packet, enabling recombination and measurement of the accumulated phase difference. Their result confirms (within experimental uncertainty) the expected t^3 scaling of the phase difference.

This experiment, and its earlier variations, demonstrates that a gravitational force coherently changes the phase difference of a quantum superposition. This is one of the hallmarks of a quantum mechanical force, the other being its ability to produce entanglement — which is still under investigation.



Schematic of the atom wave interferometer of Dobkowski *et al.*: The stationary wave packet of ^{87}Rb atoms is held against gravity using magnetic gradients produced by currents in microfabricated wires on an atom chip. The ballistic wave packet reaches a height of about 7.5 μm (seven times the wave packet size).