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Magdalena Zych

Quantum Systems Under Gravitational Time Dilation

Doctoral Thesis accepted by
University of Vienna, Vienna, Austria

Springer

Author
Magdalena Zych
Centre for Engineered Quantum Systems,
School of Mathematics and Physics
The University of Queensland
Brisbane, QLD
Australia

Supervisor
Prof. Časlav Brukner
Institute for Quantum Optics and Quantum
Information, University of Vienna
Vienna
Austria

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Supervisor's Foreword

Time in physics is unambiguously operationally defined as "what a clock shows". Accordingly, time is defined through other quantities, such as spin precession in a magnetic field, which can serve as a reference clock. The status of time varies in different theories in physics. In Newtonian physics and non-relativistic quantum mechanics, time flows at the same rate for all clocks. According to general relativity, however, clocks tick slower when they are closer to a massive body and faster if they are placed further away from the massive body. This time dilation effect results in a so-called "twin paradox": if one twin moves out to live at a higher altitude, they will age faster than the other twin, who remains on the ground. This effect was verified with remarkable accuracy in general relativistic experiments, but never in conjunction with genuine quantum effects such as quantum superposition or entanglement.

In her work, Magdalena Zych considers a single clock that is brought into a quantum superposition of two locations—one closer and one further away from a massive body. The single quantum clock then takes the role of both "twins" from the classical paradox. *What is the time as shown by the clock?* Taking this problem as a starting point, the author proposes several original and ingenious ways to probe the notion of time at the interplay between quantum theory and general relativity. This topic is in the focus of the research conducted at the University of Vienna and the Institute for Quantum Optics and Quantum Information (IQOQI).

The author investigates a matter and an optical interferometer where time dilation induced by different gravitational potentials in the two arms of the interferometer lead to a decrease in visibility of the quantum interference patterns. The innovative aspect of this experiment as compared to typical atom interferometer setups lies in the clock that is used. While standard setups induce a phase shift explainable with Newtonian gravity, Zych's experimental proposal employs an internal time-evolving degree of freedom to work as a clock. In consequence, relativistic time of the clock becomes a "which-path" witness. As a result of Bohr's complementarity principle, a loss in the visibility of the interference pattern occurs.

The origin of this loss lies in the entanglement between the internal states of the clock and its spatial position.

Zych then argues that the entanglement induced by the time dilation affects the coherence of spatial superpositions of generic composite systems, for which the revival time of coherence increases with the size of the system. For macroscopic systems, this effectively leads to a new decoherence mechanism. In this way, the author demonstrates that gravity plays a certain role in the transition from the quantum world to the classical world.

The formalism developed by Magdalena Zych for composite quantum systems in gravity relies on the metric nature of gravity, and in particular on the Einstein Equivalence Principle (EEP). The weak version of the principle states the equivalence between rest, inertial and gravitational mass-energies. However, in quantum mechanics, even non-relativistic, quantized internal energies contribute to the total mass-energies. In her work, the author proposes a "quantum weak EEP" to state the equivalence between the rest, inertial and gravitational internal energy *operators* and explores ways to test it in experiment.

Finally, the author considers a situation where the temporal order between a set of events A is entangled with the temporal order between a set of events B. Here, the order of events is defined operationally with respect to physical "clocks". Zych goes on to show that combined quantum and general relativistic effects allow a violation of a Bell-like inequality for temporal order. An experimental violation of the inequality would question the mere possibility of defining temporal order prior to and independent of measurement.

Readers geared towards theory will delight in the stringent, precise and detailed way in which Magdalena Zych lays out her arguments. But also experimentalists will appreciate the analysis as the author never leaves the ground of operationally justified concepts and understands well experimental constraints.

Ever since in 2012, the Nobel Prize in Physics was awarded to Serge Haroche and David J. Wineland for their independent development of revolutionary experimental methods for the control of individual quantum systems, the development of quantum technologies has seen a drastic rise. We have good reason to believe that soon, we will be able to enter the joined regime of quantum and relativistic physics, breaking new ground in the study of the notion of time. When we arrive at that waypoint, Magdalena Zych's thesis will have been among the most important first steps in the right direction.

Vienna, Austria
December 2016

Prof. Časlav Brukner

Abstract

The regime where quantum mechanics and general relativity jointly apply is not yet completely understood and remains beyond reach of our experimental capabilities. Therefore, there is a fundamental interest in finding feasible experiments that could probe the interplay between quantum and general relativistic phenomena.

This thesis explores how time dilation affects internal dynamics of quantum particles—topic largely overlooked in theoretical research. Crucially, such particles can be seen as ideal "clocks"—and the thesis thus focuses on new quantum effects from proper time in interference experiments with "clocks". The framework developed to that purpose also reveals that new experimental paradigm is necessary to tests the very validity of the metric picture of gravity at the interplay with quantum mechanics. In contrast to the present understanding, its validity in quantum theory does not follow from its validity in the classical limit, and relevant for the difference is the quantisation of the internal states of test particles—and not of their position. The operational approach to "clocks" is finally extended to a scenario where a large mass in a quantum superposition state influences the causal relations between the "clocks". The resulting causal structure is non-classical: temporal order between a pair of time-like events can become entangled with the order between another pair of time-like events. This permits for a violation of Bell-like inequality formulated here for temporal order. On the one hand this shows quantitatively how temporal relations can exhibit quantum features. On the other—that such scenarios can be described within standard quantum theory and general relativity and no inconsistencies arise.

New physical effects of time dilation in quantum mechanics derived in this work can be within reach of the near future interference experiments with "clocks" implemented in electrons, atoms, also photons. The operational approach to proper time at the interplay with quantum theory might further lead to a new framework describing non-perturbative effects of quantum gravity.

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