Matteo Cardi

Third Year PhD Report

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Research Activity (under the supervision of Pierantonio Zanghì and Paolo Solinas)

Unruh effect:
During my third year, I worked together with P. Zanghì and P. Solinas on the Unruh effect.
Within the framework of quantum field theory, an observer undergoing linear acceleration in a Minkowski vacuum state will detect a thermal spectrum at a temperature T_U—called the Unruh temperature—proportional to their proper acceleration. The direct empirical observation of this phenomenon presents formidable technical challenges, which has motivated a substantial research effort to identify viable alternative measurement strategies. A particularly promising candidate is the detection of an analogue Unruh effect in circular trajectories. It is noteworthy that, unlike linear acceleration, circular motion does not generate a proper Unruh temperature but instead gives rise to an energy-dependent effective temperature. Our recent research in this domain has involved a detailed analysis of the parameter regimes under which this effective temperature becomes constant in the energy variable, thereby providing a close approximation to a proper thermal state. Specifically, we investigated electron spin depolarization in storage rings as a potential experimental signature for this effect.

Quantum Information:
As a side project, together with Paolo Solinas and Dario Melegari, we studied the violation of macrorealism. Macrorealism is defined by a set of assumptions that are satisfied by all classical systems but can be violated by quantum systems. The primary method for investigating macrorealism is through Leggett-Garg inequalities (LGIs), which are Bell-like inequalities that provide sufficient conditions for its violation.
We analysed a quantum non-demolition measurement (QNDM) protocol recently proposed by P. Solinas, which provides a necessary and sufficient condition for macrorealism violation. By storing the information in a quantum detector, it has been possible to construct a quasi-probability distribution whose negative regions unequivocally identify the quantum behaviour of the system. We performed the simulations in real-case situations, taking into account the statistical and environmental noise. Our analysis shows that the protocol can always identify the quantum features, also requiring fewer resources than the standard LGIs, making it a viable alternative to identify the macrorealism violation.

Courses

- AdS-CFT correspondence (A. Moretti).
- Black Hole thermodynamics (S. Giusto) (programmed for September)
- Foundations of Quantum Mechanics and applications (programmed around the end of September)
- Fisica delle strutture cosmiche (programmed around the end of September)

Teaching activities

- Tutor of the theoretical group during high school's stages (27 Jan - 6 Feb 2025)

Conferences

- The Time Machine Factory [unspeakable, speakable] on Time Travel, Turin, 22-25 September 2024, attended
- Quantum Computing@INFN, Padova, 29-31 October 2024, attended
- QMP 25 - Quantum Information, Entanglement and Causality, Milano, 8-9 May 2025, attended
- Quantum 2025, Turin, 18-24 May 2025, poster session
- International Conference on Quantum Energy, Padova, 3-6 June 2025, attended
- 5th Annual Conference on Time in Quantum Theory, Genova, 17-20 June 2025, poster session
- 15th Annual Conference on relativistic Quantum Information (North), Napoli, 23-27 June 2025, poster session

Publications

- *On the Measurement of the Unruh Effect Through Extended Quantum Thermometers*, Authors: P. Solinas, M. Cardi, P. Zanghì

Abstract: The Unruh effect, predicting a thermal reservoir for accelerating systems, calls for a more refined understanding of measurement processes involving quantum systems as thermometers. Conventional models fail to account for the inherent spatial extent of the thermometer, neglecting the complexities associated with accelerated extended quantum systems. Our work builds upon the seminal work of Bell, Hughes, and Leinaas. We propose a refined thermometer model incorporating a spin-1/2 particle where the spin acts as a temperature indicator. This refined model demonstrates the ability to effectively measure the temperature under specific, realistic conditions, providing a unique value that essentially averages the local Unruh temperatures throughout the extended quantum system acting as the thermometer.

- *Quantum simulations of macrorealism violation via the quantum nondemolition measurement protocol*, Authors: D. Melegari, M. Cardi, P. Solinas

Abstract: The Leggett-Garg inequalities have been proposed to identify the quantum behavior of a system; specifically, the violation of macrorealism. They are usually implemented by performing two sequential measurements on quantum systems, calculating the correlators of such measurements and then combining them arriving at Leggett-Garg inequalities. However, this approach only provides sufficient conditions for the violation of macrorealism. Recently, an alternative approach was proposed that uses nondemolition measurements and gives both a necessary and sufficient condition for the violation of macrorealism. By storing the information in a quantum detector, it is possible to construct a quasiprobability distribution whose negative regions unequivocally identify the quantum behavior of the system. Here, we perform a detailed comparison between these two approaches. The use of the IBM quantum simulators allows us to evaluate the performance in real-case situations and to include both the statistical and environmental noise. We find that the nondemolition approach is not only able to always identify the quantum features, but it requires fewer resources than the standard Leggett-Garg inequalities. In addition, while the efficiency of the latter is strongly affected by the presence of the noise, the nondemolition approach results incredibly robust and its efficiency remains unchanged by the noise. These results make the nondemolition approach a viable alternative to the Leggett-Garg inequalities to identify the violation of macrorealism.