Detectors in superposition: probing the causal and geometric structure of spacetime in relativistic quantum field theory

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Abstract. We extend the standard treatment of the Unruh-deWitt detector model to include the detector travelling in quantum-controlled superpositions of trajectories. As it interacts with the background quantum field, the detector gains access to nonlocal correlation functions which reveal novel information about the global structure of the spacetime, including the causal relations between localised spacetime regions and curvature.

Keywords: QFT, correlations, causal structure

UdW detectors are widely used as probes of the foundational properties of relativistic quantum fields, entanglement between distinct field regions, and the geometry of spacetime. Nevertheless, all studies to date have explored regimes where the detector's motion is classical - that is, detectors traversing classical trajectories in spacetime.

In our recent preprints [1-2], we develop a framework describing a UdW detector travelling in an arbitrary superposition of trajectories. Our main result is the discovery that a detector in such a quantum superposition of paths can gain information about the quantum field that is otherwise inaccessible to a single system. Specifically, we found that the final state of the detector includes non-local

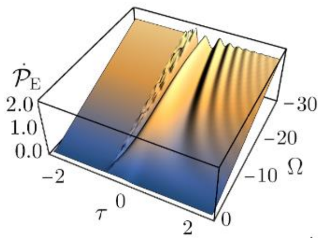

Figure 1 Time-dependent transition rate of a detector in superposition of spatially translated accelerated trajectories [1]

field correlations between the different trajectories that produces interference effects in the detector's excitation probability and transition rate. These interference effects are traced back to the different causal relations between the superposed trajectories, demonstrating that the detector model is directly relevant to the study of causality in relativistic quantum theory.

The utility of our approach allows for its application to relativistic settings (e.g. uniformly accelerated trajectories [1]) and curved spacetimes (e.g. expanding spacetimes [2]), which are of fundamental importance in the study of quantum field theory, cosmology, and quantum gravity. For example, questions concerning the causal structure of spacetime may be explored by superposing the temporal order of the detector's interaction with a quantum field. Finally, our approach can be extended to explore causal structures in non-classical spacetimes, where the quantum causal relations between the field regions probed by the detector originate from a quantum-controlled superposition of different spacetime metrics. Such an extension enables the study of the properties of non-classical spacetime backgrounds, which is an important open question in theoretical physics.

References/Preprint Links

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