New research synthesizes different aspects of causality in quantum field theory

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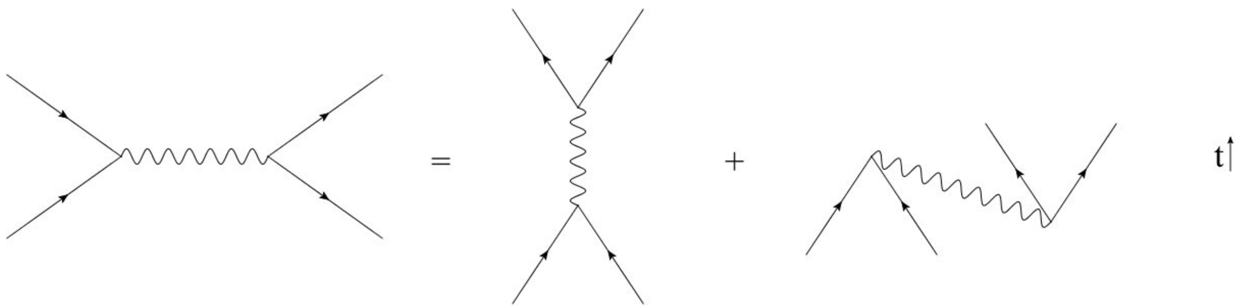

The simple Feynman diagram on the left is decomposed into two time-ordered diagrams. In one of the time orderings, the final particles emerge before the initial particles have been annihilated. Credit: Donoghue & Menezes.

In current quantum field theory, causality is typically defined by the vanishing of field commutators for spacelike separations. Two researchers at the University of Massachusetts and Universidade Federal Rural in Rio de Janeiro have recently carried out a study discussing and synthesizing some of the key aspects of causality in quantum field theory. Their paper, published in Physical Review Letters, is the result of their investigation of a theory of quantum gravity commonly referred to as "quadratic gravity."

"Like the ingredients of the standard model, quadratic gravity is a renormalizable quantum field theory, but it has some peculiar properties," John Donoghue, one of the researchers who carried out the study, told Phys.org. "The small violation of causality is the most important of these and our goal was to understand this better. In the process, we realized that some of the insights are of more general interest and we decided to write our understanding as a Physical Review Letter, to share these insights more widely."

The paper written by Donoghue and his colleague Gabriel Menezes synthesizes many different aspects of causality that have been part of quantum field theory for several decades now. The realization that there can be microscopic violations of causality in certain theories dates back to the 1960s, specifically to the work of physicists T.D. Lee and G.C. Wick. In their study, however, Donoghue and Menezes also drew inspiration from a more recent study carried out by Donal O'Connell, Benjamin Grinstein and Mark B. Wise.

So far, most theoretical discussions about causality, specifically the "arrow of time," have asserted that the laws of physics do not have any preference for the flow of time. However, this particular assumption is not applicable to quantum physics, where a direction for causal effects is present.

"The various factors of *i* in the quantization procedures are related to the direction of causal action, which leads to the 'arrow of causality' in quantum physics," Donoghue explained. "This connection is not discussed very often."

Donoghue and Menezes were intrigued by the fact that the macroscopic feeling of causality, which is also applicable to classical physics, is due to the underlying structure of quantum theory. In their recent paper, they thus examined this particular aspect of causality further, in order to gather insight about its meaning and implications.

"The idea that there can be dueling arrows of causality within the same theory is even more obscure," Donoghue said. "However, it happens in a very simple setting where the Lagrangian for the theory has more powers of derivatives than usual. This is what happens in quadratic gravity, but it could also happen in other theories too."

Even though the direction of causal influence is a convention associated with the choice of a description of the measurement of time, its existence is a necessary requirement based on the laws of quantum physics. In this context, Donoghue and Menezes observed that the arrow of causality can be potentially violated by having conflicting conventions.

"Perhaps the most important implication of our study is that we collected evidence of causal uncertainty due to spacetime fluctuations that can arise in a quantum theory of gravity," Menezes said. "This would provide us with a deep intuitive understanding of the origins of causality."

About a decade ago, O'Connell, Grinstein and Wise carried out a study that was partially based on a series of lectures by Sidney Coleman. They specifically suggested that in a wavepacket description of a scattering process with mixed causal arrows, one can verify that the decay products can be detected earlier than would be expected from the time of production and the associated probability of detection decreases exponentially backwards in time. In their study, Donoghue and Menezes examined this idea further.

"An implication of our study is that while the ideas put forward by O'Connell and his colleagues, as well as other research teams, could in principle be observed, there is no conflict with experiments in the case of gravity as the phenomenon occurs at energies of order of the Planck scale, which is 15 orders of magnitude greater than the energy range accessible to the LHC," Menezes said.

The recent study by Donoghue and Menezes offers a general and valuable discussion of causality and the arrow of causality, specifically focusing on how a given theory may have both forward and backward arrows. This discussion touches on the topic of time reversal in field theory, so it could inform a variety of physics studies. It could also help to clarify the quantum theory of quadratic gravity, which still has many unanswered questions.

Overall, Donoghue and Menezes suggest that mixed conventions in individual physics theories could in fact be possible and that future studies should explore this topic further. The researchers are now working on a project aimed at fully exploring the phenomenon of causality uncertainty due to quantum fluctuations of the gravitational field.

"There are some other technical considerations that we need to address concerning this description of quantum gravity as a renormalizable quantum field theory," Menezes said. "One of them concerns the stability of quadratic gravity in curved backgrounds, which has already been studied by other authors. Hopefully these will also be part of this future work. In any case, the most intriguing investigation we hope to conduct will be the study of the effect of the causal uncertainty in the early Universe."

More information: John F. Donoghue et al. Arrow of Causality and Quantum Gravity, *Physical Review Letters* (2019). DOI: 10.1103/PhysRevLett.123.171601

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