Probing Quantum Correlations with a Temporal Superposition

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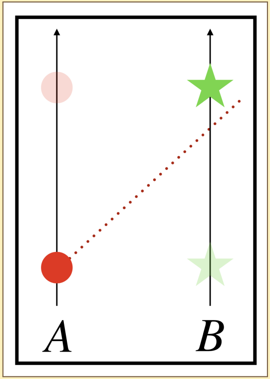
Indefinite Causal Order

Quantum gravity (uniting general relativity and quantum mechanics) may lead to an indefiniteness in causal structure[1,2].



- Taking this seriously allows for situations where it cannot be determined if operation A came before operation B or vice-versa.
- Both situations could occur in superposition $\implies$ the order is indefinite.
- Detection? Use a particle detector!
- **We use a quantum controlled switch so that 2 UDW detectors interact with the field in a coherent superposition of "A before B" and "B before A".**

[1] O. Oreshkov, F. Costa, and Č. Brukner, Nat. Commun. 3, 1092 (2012)

[2] G. Chiribella, G. M. D'Ariano, P. Perinotti, and B. Valiron, Phys. Rev. A 88, 022318 (2013)

Quantum Fields on Curved Spacetimes and Entanglement Harvesting

- Quantum fields on curved spacetimes: treats both the quantum field and gravitational effects with equal physical significance
  - Provides clues into what can be expected from a "true" theory of quantum gravity.
- The UDW[3,4] detector model (local two level quantum system) provides an operational approach to probing properties of quantum fields and structure of spacetime.
  - Field entanglement can be swapped to **initially separable** detectors[5,6] ("**entanglement harvesting**"[7]).
  - The resulting entanglement is sensitive to the properties of the field and underlying spacetime.

[3] W. G. Unruh, Phys. Rev. D, vol. 14, pp. 870–892, 1976

[4] B. S. DeWitt, Cambridge University Press, 1979

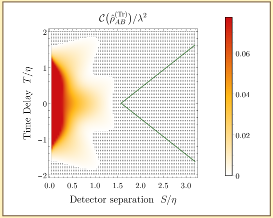
[5] A. Valentini, Phys. Lett. A, 153:321 (1991)

[6] B. Reznik, Found. Phys., 33:167 (2003)

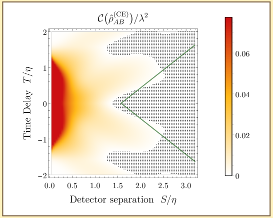
[7] G. Salton, R. B. Mann, and N. C. Menicucci, New J. Phys., 17:035001(2015).

Result: Entanglement Enhancement

Pointlike detectors couple to the field with **compact switching**: $\chi(t) = \cos\left(2(t - T_i)/\eta\right),\ |t - T_i| \leq \pi\eta/2$ where $T_i = \pm T/2$ (depending on the output of the the control).



Probablistic mixture
(Definite Causal Order)



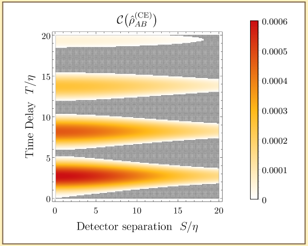
Coherent superposition
(Indefinite Causal Order)

The green lines mark spacelike separation (to the right).

- **Entanglement harvesting (EH) is now possible in regions of spacelike separation.**
- Also: significant enhancement in regions where EH is possible.

Result: Entanglement Despite a No-Go Theorem

Gaussian smeared detectors couple to the field with **instantaneous switching**: $\chi(t) = \eta\delta(t - T_i)$ where $T_i = \pm T/2$ (depending on the output of the the control).



Coherent superposition (Indefinite Causal Order)

- A no-go theorem forbids entanglement harvesting using instantaneous switching[8,9].
- In our setup, detectors are on **only once** in each branch of the superposition
- **But we still see entanglement harvesting!**
- The interaction is complex enough to avoid the no-go theorem.

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[8] P Simidzija and E. Martín-Martínez Phys. Rev. D 96, 065008 (2017)

[9] P Simidzija and E. Martín-MartínezPhys. Rev. D, 97:125002 (2018)