Experimental superposition of time directions

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Quantum systems do not experience time as an asymmetric quantity, i.e. flowing in a fixed direction, from past to future. This is reflected in the laws of Nature, which remain valid also when flipping the sign of the time coordinate.
This implies that, if it was possible to interact with physical systems both in the forward and backward time direction, we could implement a coherent superpositions of time directions. This would be of great interest, first, due to the generality of such a process, which could not be described even through process matrices, the formalism of indefinite causal order (e.g. quantum switch [1]). Secondly, time direction superposition has been demonstrated to bring an informational-theoretic advantage in specific computational tasks.
However, to experimentally investigate the possibility of realizing a process with indefinite time direction, it is first necessary to clarify the operational meaning of a time direction change. This topic was recently addressed in [2], by introducing an "input/output" inversion supermap, sending a general quantum channel C into its backward version $C_{bwd} = C^*$. At this point, valid operations (i.e. completely positive trace preserving) that remain valid under such transformation are defined bidirectional, i.e. accessible in both time directions. An example is constituted by unitaries, where $U_{bwd} = U^T$.
In this work [3], we experimentally implement an instance of an indefinite time direction process, the so-called "quantum time flip", defined as $C \rightarrow C\,|\psi\rangle_T|0\rangle_C + C^*|\psi\rangle_T|1\rangle_C$ where the subscript C(T) indicates a control (target) system.
In our experiment, we exploit the polarization of a single photon state as our target qubit and its path as the control. Then, we adopt an interferometric structure (see Fig. 1), such that, when the control is in the state $|0\rangle$ ($|1\rangle$) the operation applied to the target will be UV^T (U^TV), with U and V being arbitrary unitary operations. Then, when the control is in the state $|+\rangle$ or $|-\rangle$ we have a coherent superposition.
We then witness the indefinitess in the time direction of our implemented process through a game, in which the use of the quantum time flip beats any other strategy. This game amounts to guessing if two unitaries U and V belong to the set S_- or S_+, having access to them only for one shot, with $S_- = \{U, V: UV^T = -U^TV\}$ and $S_+ = \{U, V: UV^T = U^TV\}$. For this game, the highest winning probability for fixed-time direction strategies amounts to 0.92. In our case, the experimental success rate was 0.9945, which certifies that our apparatus is implementing a process indefinite in the time direction.

Figures

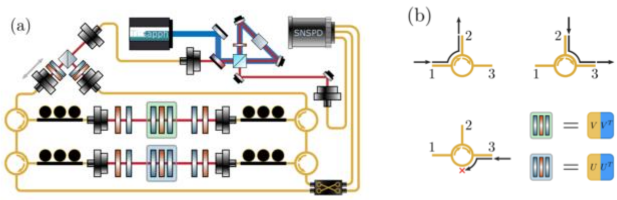

Figure 1: Experimental apparatus for the coherent superposition of two time directions on a photonic platform (a). The green and blue optical apparatuses implement any arbitrary unitary U when photons travel in one direction and its transpose U^T in the opposite one (b).

References

[1] G. Rubino et al., Sci. Adv., vol. 3 Issue 3 (2017).
[2] G. Chiribella et al., Comm. Phys. Vol. 5, Issue 190 (2022).
[3] T. Strömberg et al., arXiv:2211.01283 (2022), preprint.