Experimental superposition of time directions

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Differently from our day-to-day experience, the laws of Nature suggest that time is not an asymmetric quantity, which always flows from past to future. Indeed, the description of the evolution of quantum systems remains valid also when flipping the sign of the time coordinate. This leads to the conclusion that quantum systems could offer the possibility to study and implement processes displaying a superposition of time directions. It is noteworthy that this type of process, due to its generality, would not be describable through the process matrix formalism, introduced to represent indefinite causal order operations. An example of operation that remains valid both in the "forward" and "backward" time direction are unitary evolutions, whose "backward version" amounts to their transpose.

In our experiment, using the theoretical tools introduced in [1], we implement a quantum supermap (the so-called "quantum time flip") transforming a given channel, acting on a target system, into the superposition of its forward and backward forms. In detail, we encode the quantum state undergoing a time evolution in the polarization of a single photon, while the time direction is encoded in its path degree of freedom (control system). We show that polarization operations with waveplates naturally implement different time directions for forwards and backwards propagation directions, given the correct Stokes-parameter convention. Hence, we realize the quantum time flip deterministically by sending single photons through the waveplates in a superpositon of the two propagation directions.

We then witness the indefinitess in the time direction of our implemented process through a computational game, in which the use of the quantum time flip is demonstrated to guarantee an advantage over any other strategy, even those that exploit indefinite causal order. 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 directions (see Fig. 1).

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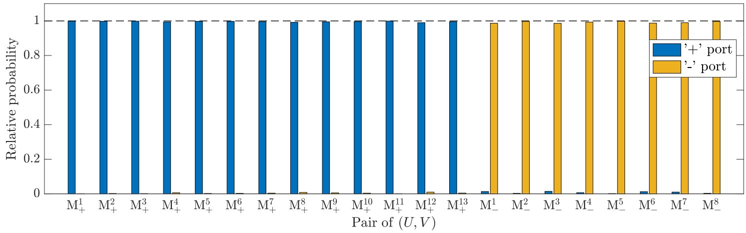

Fig. 1: Observed winning frequencies. The implemented computational game consists in classifying pairs of unitaries to two classes, $\mathscr{M}_+$ and $\mathscr{M}_-$. The first contains pairs (U,V), such that $UV^T = U^T V$, while unitary pairs belonging to the latter satisfy the condition $UV^T = -U^T V$. The figure shows the observed relative frequency of answers $f_\pm^{\mathrm{rel}}$ in the quantum flip game for all the pairs of unitaries in the sets $\mathscr{M}_+$ and $\mathscr{M}_-$. For the gates in the set $\mathscr{M}_+$ ($\mathscr{M}_-$) the game is won when the player outputs the answer '+' ('−'). The observed average winning frequency is 0.9945.

This result paves the way for future studies of processes with an indefinite time order, which promise to expand both the theoretical and experimental toolkit and open up new avenues for quantum information processing.

References

[1] G. Chiribella, Z. Liu, Communications Physics 5, 190 (2022).