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PRESS RELEASE

CONSTRUCTOR-BASED IRREVERSIBILITY: RECONCILING IRREVERSIBILITY WITH QUANTUM MECHANICS

A collaboration between INRiM and Oxford University proves, by defining irreversibility as the requirement that a task is possible, while its inverse is not, its compatibility with quantum mechanics time-reversal symmetric laws, in a quantum-homogenizer-based toy-model experimentally realized exploiting single-photon qubits.

Turin, February 23 2022 – A team of INRiM researchers, in collaboration with Oxford University, demonstrates in the study "***Emergence of Constructor-Based Irreversibility in Quantum Systems: Theory and Experiment***", published in ***Physical Review Letters*** **(American Physical Society)** (**doi.org/10.1103/PhysRevLett.128.080401**) the compatibility between irreversibility and quantum mechanics time-reversal symmetric laws.

The question about irreversibility has been tackled with different methods, from statistical mechanics methods to information-theoretic descriptions of logically irreversible tasks, as well as classical and quantum thermodynamics second laws. Anyway a tension always arises between the modelization of irreversible phenomena and the time-reversible quantum laws at the microscopic scale.

In this work, **irreversibility has been defined as the fact that a transformation T can be realized arbitrarily well by a cyclic machine, but the same does not hold for its inverse $T^{\sim}$**. A typical example of this irreversibility definition is given by *Joule's experiment*: a volume of water can be mechanically-only heated, but not cooled down. The concept of a cyclic machine performing a transformation was generalized by von Neumann to a *constructor*, i.e., a system able to perform a certain task on another system while remaining capable of repeating the procedure. Hence, a transformation is possible only if there exists a constructor able to realize it. In this study, this irreversibility, generalizing the one of Joule's experiment, is called *constructor-based irreversibility*.

To show the compatibility between this newly-defined irreversibility and the time-reversal-symmetric laws of quantum mechanics, the researchers study a qubit-based toy model centered on the quantum homogenizer (see Fig. 1), i.e., a machine composed of a set of N qubits each identically prepared in a specific state. Interacting with the N qubits of the

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homogenizer by means of subsequent partial SWAPs (quantum gates able to partially swap the states of two qubits), the state of a certain qubit Q can be adiabatically transformed into the homogenizer one, inducing at the same time a slight modification in the machine. If our T is the "pure-to-mixed" transformation, i.e., the one in which Q passes from a pure state to a maximally-mixed one, it can be shown that this quantum homogenizer satisfies the criteria to be considered a proper constructor, while the same does not happen for the one realizing $T^{\sim}$ ("mixed-to-pure" case). This means that, even though T is possible, its counterpart $T^{\sim}$ is not, hence we've recovered irreversibility even in a scenario modeled by time-reversible laws.

In order to quantitatively demonstrate this, **researchers performed an experiment exploiting high-precision single-photon qubits, generated by a low-noise prototype source emitting fiber-coupled single photons at 1550 nm (Fig. 2).**

The interaction between the qubit Q and a N=3 quantum homogenizer was obtained by cascading three 50:50 fiber beam splitters, whose outputs are detected by InGaAs/InP single-photon avalanche diodes. Finally, the detector's outputs are sent to a time-tagging coincidence module. With this setup, they first studied the performances of the quantum homogenizer for different intensities of the partial SWAP gate, and subsequently they evaluated, for both T and $T^{\sim}$, the accuracy of the machine in the task realization and its resilience to repeated usages. By doing this, researchers confirmed their theoretical predictions and numerical simulations, showing that, while the quantum homogenizer for T can qualify as a constructor, the one for $T^{\sim}$ deteriorates too fast, ultimately not being able to perform such a transformation.

This can be regarded as a **clear proof of the compatibility between *constructor-based irreversibility* and quantum theory time-reversible laws**, giving a new viewpoint on the emergence of thermodynamical irreversibility in a quantum mechanical framework.

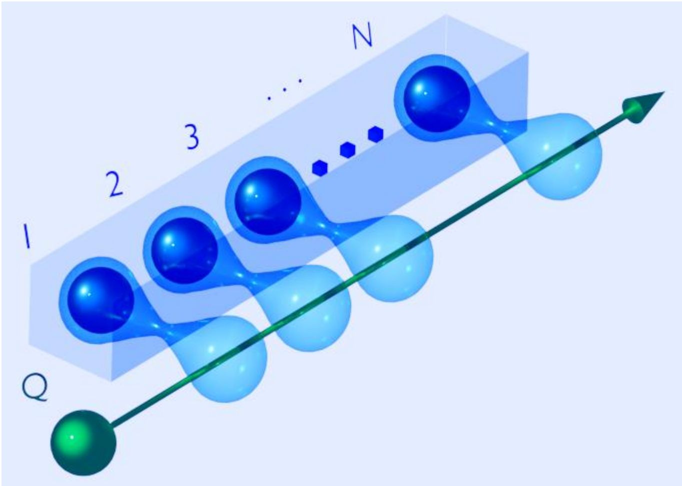

Fig.1: Interaction between the qubit Q and the N qubits of the quantum homogenizer, realized by means of the subsequent partial SWAPs indicated by the hourglasses.

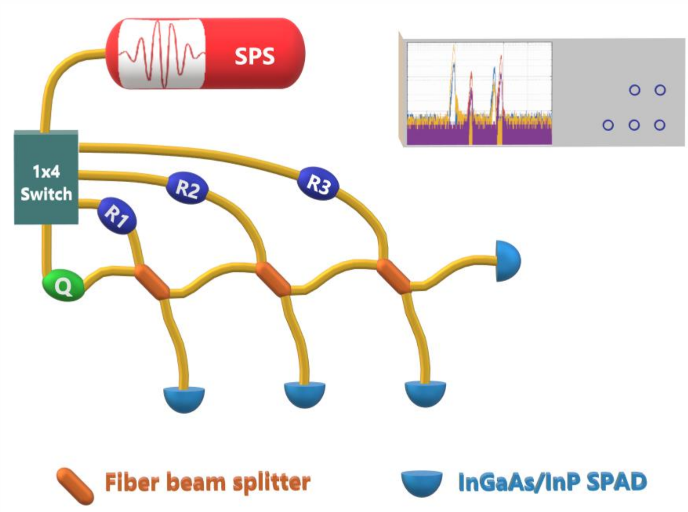

Fig.2: Experimental setup scheme. SPAD: single-photon avalanche diode.

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