Measuring a dynamical topological order parameter in quantum walks

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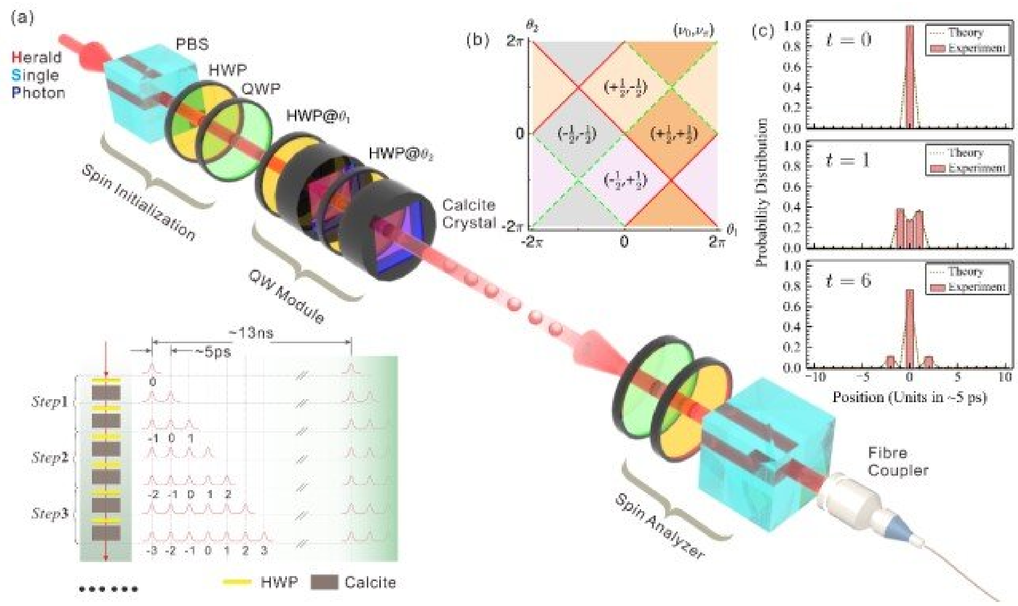

Figure 1 | Sketch of the experimental setup. (a) Implementation of the time-multiplexing split-step quantum walk. A heralded single photon with a central wave length 780 nm generated from beam-like spontaneous parametric down conversion is adopted as the walker. The anticorrelation parameter measured in experiment reads 0.031 ± 0.001. Its polarization state is prepared by a spin initialization module composed of PBS-HWP-QWP in sequence at the beginning, and is measured by a spin analyzer composed out of QWP-HWP-PBS in sequence at the end of the quantum walk. A full step of the split-step quantum walk is composed out of two HWPs with their optical axes oriented at $\theta_1$and θ_2, respectively, for implementing coin tossing, and two calcite crystals, with their optical axies cut colinearly and orientated horizontally, for implementing spin-orbit coupling. The final arrival time of the photon is measured by a home-made up-conversion single photon detector. We diagram in the inset of **(a)** the split-step quantum walk in the conventional time frame. For accessing the two shifted non-equivalent time frames, we change the rotation angle of the first HWP and add an extra HWP at the end, for each complete step. The walker's position space is composed of the time bins (defining the arriving time of single photon) with pulse interval 5 ps (determined by the length of calcite crystal). The maximum repetition ratio is 76 MHz corresponding to 13 ns in time. Here we use ten quantum walk modules in total for split-step quantum walk and one extra quantum walk module for adiabatically preparing some special initial states. **(b)** shows the complete topological phase diagram hidden in split-step discrete time quantum walk. In **(c)**, we present the probability distributions at time $t = 0, t = 1,$ and $t = 6$ in the first configuration, i.e., quench from a ground state of Hamiltonian in trivial phase ($\theta_2 = \pi$) ending in one non-trivial phase ($\theta_1 = \frac{8\pi}{9}$ and $\theta_2 =- \frac{\pi}{3}$). The total coincidence counts between the idle photon and the up-conversion signal is above 200 Hz at last, and for each basis we set the integral time as 200 seconds. PBS, polarized beam splitter; HWP, half wave plate; QWP, quarter wave plate.

Sketch of the experimental setup Credit: by Xiao-Ye Xu, Qin-Qin Wang, Markus Heyl, Jan Carl Budich, Wei-Wei Pan, Zhe Chen, Munsif Jan, Kai Sun, Jin-Shi Xu, Yong-Jian Han, Chuan-Feng Li, Guang-Can Guo

Nonequilibrium dynamical processes are central in many quantum technological contexts. However, it has remained a key challenge to identify concepts for their characterization and classification, as the resulting quantum states purposely defy a description in terms of equilibrium statistical physics in order to realize states not accessible by conventional means. Scientists have now achieved a characterization in terms of a dynamical topological order parameter for quantum walks, which represent a paradigmatic class of nonequilibrium processes.

Coherence in quantum dynamics is at the heart of fascinating phenomena beyond the realm of classical physics, such as quantum interference effects, entanglement production and geometric phases.

Quantum processes of inherent dynamical nature defy a description in terms of an equilibrium statistical physics ensemble. Up to now, to identify general principles behind the underlying unitary quantum dynamics which preserve quantum coherence remains a key challenge.

Quantum walks provide a powerful and flexible platform to experimentally realize and probe coherent quantum time evolution far from thermal equilibrium. As opposed to classical random walks, quantum walks are characterized by quantum superpositions of amplitudes rather than classical probability distributions. This genuine quantum character has already been harnessed in various fields of physics, ranging from the design of efficient algorithms in quantum information processing, observation of correlated dynamics and Anderson localization, to the realization of exotic physical phenomena in the context topological phases.

While the topological order can be retrieved in the real space, accessing the full complex amplitude information characterizing the coherent superposition remains as one of the key challenges in quantum walk experiments.

In a new paper published in *Light Science & Application*, scientists from the CAS Key Laboratory of Quantum Information and international collaborators reported on the direct observation of a dynamical topological order parameter (DTOP) that provides a dynamical characterization of quantum walks.

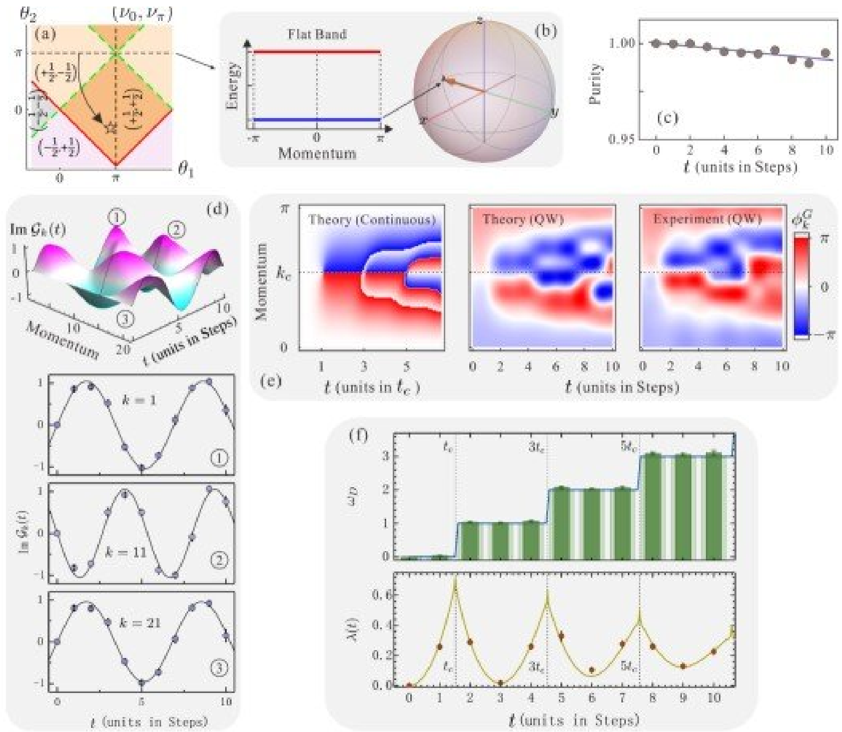

Figure 2 | Experimental measurement of DTOP for observing DQPT. (a) shows the quenching strategy in phase diagram: starting from a ground state of Hamiltonian with flat band ($\theta_2 = \pi$) in trivial phase and ending in one non-trivial phase (pentagram with $\theta_1 = 8\pi/9$ and $\theta_2 = -\pi/3$). The energy band (theoretical) and the initial state (black point for theoretical expectation and arrow for experiment) are presented in (b). We fit the experimental data in rank 2 for revealing the decoherence, and the purity for each step is given in (c) (errors are smaller than the point size). In (d), we show how to extract the dynamical phase with the full knowledge of the wave-function for each step. The imaginary part of the Loschmidt amplitude is presented in the top, with three cases $k = 1,\ 11,\ 21$ showing in the bottom. We read out its amplitude and period by fitting the measured results (circle points) to a trigonometric function. Density plot of the associated PGP $\phi_k^G(t)$ is given in (e), from left to right: theoretically consideration in momentum space (continuous time evolution), theoretically simulation of the QW (discrete time evolution) and our experimental results. The exact critical time is calculated from the continuous time evolution which reads $t_c = 1.513$ and predicts the first occurrence of DQPT. Experimentally measured DTOP is presented in (f) by the opaque bars (blue line is the theoretical prediction numerically calculated in momentum space (continuously) and transparent bars are predictions from the simulation of quantum walk. Vertical dashed lines gives the critical times for each occurrence of DQPT. In the bottom, we present the rate function $\lambda(t)$ with the red line (obtained in continuous simulation) and the experimental measured values with points. Each non-analyticities predicts the occurrence of DQPT. Errors are estimated using numerical Monte Carlo simulations with considering the counting noise.

Experimental measurement of DTOP for observing DQPT Credit: by Xiao-Ye Xu, Qin-Qin Wang, Markus Heyl, Jan Carl Budich, Wei-Wei Pan, Zhe Chen, Munsif Jan, Kai Sun, Jin-Shi Xu, Yong-Jian Han, Chuan-Feng Li, Guang-Can Guo

To this end, they realized a split-step quantum walk in a photonic system using the framework of time multiplexing. Using a previously developed technique, they achieved full state tomography of the time-evolved quantum state for up to 10 complete time steps. Importantly, this provided the full complex amplitude information of the quantum walk state.

"This is essential for our central goal of a dynamical classification of the quantum walk using the DTOP, since the DTOP measures the phase winding number $\omega_D(t)$ in momentum-space, namely of the so called Pancharatnam geometric phase (PGP)".

From the experimental results, they found that dynamical transitions between topologically distinct classes of quantum walks can be uniquely distinguished by the observed time-dependent behavior of $\omega_D(t)$.

"For a quench between two systems with the same topological character, we find $\omega_D(t)=0$ for all time steps; instead, for a quench between two topologically different systems, $\omega_D(t)$ also starts at $\omega_D(t=0)=0$, but monotonously changes its value at certain critical times," they added.

Generalizing these observations, they further established a unique relation between the behavior of $\omega_D(t)$ and the change over a parameter quench in the topological properties of an effective Floquet

Hamiltonian that stroboscopically describes the quantum walk.

The scientists conclude: "In this way, we provide a nonequilibrium perspective onto quantum walks, which can be understood as a starting point towards approaching time-dependent processes from an inherently dynamical angle that goes beyond the notion of equilibrium statistical physics. With this and the mapping onto quenches in an equivalent quantum many-body system, our experiment offers a versatile platform to study coherent nonequilibrium dynamics of many paradigmatic models such as the Su-Schrieffer-Heeger model, the p-wave Kitaev chain, or the transverse field Ising model in the future."

More information: Xiao-Ye Xu et al, Measuring a dynamical topological order parameter in quantum walks, *Light: Science & Applications* (2020). DOI: 10.1038/s41377-019-0237-8

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