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Accessibility
Discrete single-photon quantum walks with tunable decoherence

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Quantum walks have a host of applications, ranging from quantum computing to the simulation of biological systems. We present an intrinsically stable, deterministic implementation of discrete quantum walks with single photons in space. The number of optical elements required scales linearly with the number of steps. We measure walks with up to 6 steps and explore the quantum-to-classical transition by introducing tunable decoherence. Finally, we also investigate the effect of absorbing boundaries and show that decoherence significantly affects the probability of absorption.

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posed linear-optical version of the Galton board based on beamsplitters and phaseshifter [12, 27]. A similar, polarization-encoded setup has been proposed for cube polarizing beamsplitters [28]. Figure 1(a) shows a schematic of the experiment.

Pairs of single photons were created via type-II spontaneous parametric down-conversion in a PPKTP crystal. This crystal was pumped by a 5 mW diode laser centered at 410 nm and emitted orthogonally polarized photon pairs with a wavelength of 820 nm and a FWHM bandwidth of 0.6 nm. The pairs were separated at a polarization beamsplitter; one photon from each pair served as a trigger, while the second photon was launched into the QW. At an average heralded photon rate of ~20000 s⁻¹, the mean longitudinal distance between two photons was about 250000 times longer than the setup length of ~60 cm. The probability of randomly creating more than one photon pair simultaneously was ~9 · 10⁻⁵, i.e., only one photon was in the setup at any given time.

Quantum coin states were encoded in the polarization |H⟩ and |V⟩ of the input photon. Throughout our experiment, the initial coin state was set to left-circular polarization, \( |L⟩=|H⟩+i|V⟩ \), using a quarter- and a half-wave plate, leading to symmetric probability distributions. For the results presented here, the remaining coin operators \( C \) were Hadamards, realised with half-wave plates set to 22.5°. We can, however, prepare arbitrary pure input states as well as arbitrary coin operators for each step with suitable wave plate settings.

The lattice sites of the QW were represented by longitudinal spatial modes. The shift operator \( S \) acting on these modes was implemented by a 27 mm long, birefringent calcite beam-displacer. The displacers had a clear aperture of 20×10 mm² and were mounted on manual, tip-tilt rotation stages with a resolution of 217 µrad/5° turn. The optical axis of each calcite prism was cut so that vertically polarized light was directly transmitted and horizontal light underwent a 2.7 mm lateral displacement into a neighboring mode. Lattice sites were, typical for discrete walks on a line, labeled so that there were odd sites at odd time steps and even sites at even times.

The first two steps of the QW are shown in detail in Fig. 1(b). The spatial modes after step 1 were recombined interferometrically in step 2. A series of steps then formed an interferometric network, Fig. 1(c). We aligned this network iteratively, to a single interferometer per step. For example, the second beam displacer was aligned to maximize the interference visibility of the interferometer in Fig. 1(b): the state \( |D⟩ \) was input in mode 0 and the beam displacer rotated to maximize the overlap of the output mode 0 with \( |D⟩ \). The third displacer was then aligned to the second and so on. We reached interference visibilities of typically ~ 99.8% per step.

The photons emerging in the \( N+1 \) spatial modes at the output of an \( N \)-step QW were coupled into an optical fiber and subsequently detected by a single-photon avalanche photodiode, in coincidence with the trigger photon. We measured the probability distributions sequentially, translating the fiber coupler between the individual modes using a manual translation stage.

The measured probability distributions for detecting the photon at a given site, for 1 to 6 steps, are shown in Fig. 2(b). The experimental data are in excellent agreement with theory, with an average \( L_1 \)-norm distance, \( d = \frac{1}{2} \sum_i |p_i^{exp} - p_i^{th}| \), of 0.031 for the coherent and 0.017 for the decohered walks. The quality of our data degrades somewhat for a higher number of steps, largely due to nonplanar optical surfaces, which caused small relative phase shifts between the multiple interferometers. The decohered walk is insensitive to phase errors and therefore better agrees with theory.

Our scheme has several advantages: first, the interferometric network is inherently stable. The transversal mode-match is fulfilled because two beams emerging from one displacer will always be parallel, independent of small deviations in the optical alignment. The stability and alignment procedure of the QW grid are facilitated by the fact that the \( N \) interferometers between steps \( N \) and \( (N+1) \) are formed between only 2 optical components. Our setup—even though it is interferometric—does therefore not require active phase locking. Secondly, our system scales well, with the number of optical components increasing as \( 2^N \) (as opposed to \( (N^2+N)/2 \) in [12, 27]), and exhibits low optical loss of ~1% per step.
The remaining obstacle to scalability are nonideal optical components, a problem that can be alleviated with careful manufacturing or the use of shorter displacers.

A unique feature of this setup is that tunable decoherence can be introduced by intentional misalignment of QW steps, Fig. 1c). Setting a non-zero relative angle between neighboring beam displacers leads to both a temporal delay and a transversal mode mismatch between interfering wave packets. Because the coincidence time window was much longer than the temporal shift we essentially integrated over the timing information, which corresponds to dephasing, cf. Eq. 2. Similarly, we traced the spatial mode information by coupling the photons into a multi-mode fiber—as opposed to the single-mode fiber used for the coherent walks shown in Fig. 2a). In practice, this reduced the interference contrast in all interferometers in the respective step. The QW was fully decohered \([q=1\text{ in Eq. } 2]\) when the interference visibility in each individual step reduced to 0, which occurred at a relative angle of 10.5° in our experiment. Figure 2c) shows the experimental results given by our system at full decoherence for steps 1 to 6. The probabilities—as expected for a classical random walk—follow a binomial distribution around the origin.

A distinguishing feature of an ideal QW is the speed at which the walker traverses the line. In particular, the standard deviation of the QW is proportional to the number of steps and not, as for the classical walk, its square root. This has been exploited to design quantum-walk–based search algorithms that exhibit a Grover-like quadratic speedup. The measured standard deviations for both our quantum and fully decohered walks are shown in Fig. 2c). The results show very good agreement with theory: the fully decohered walk spreads diffusively, while the quantum walk spreads ballistically.

Tunable decoherence enabled us to investigate the quantum-to-classical transition for a 5-step walk. By applying Eq. 2 to a two-step walk, see Fig. 1b), we calculated the interference visibility in output mode 0 after the second beam-displacer as a function of the decoherence parameter \(q\). We then adjusted the relative angle, Fig. 1c), between beam displacers to a target visibility. Figure 3 shows the resulting probability distributions, compared to theory, Eq. 2. Note the interesting nonlinear dependences of the probability distributions on \(q\).

Finally, we demonstrate another qualitative difference between classical and quantum walks, by incorporating absorbing boundaries. While a classical walker is eventu-
FIG. 4: Transmission probability of quantum (black circles) and classical (red triangles) walkers with an absorber located at position $-1$ and initial coin state $|L\rangle$. The transmission was obtained as the ratio of the number of transmitted photons measured with absorbers in place to the number measured without them. Error bars are smaller than symbol size. The insets show the fifth step walk with an absorber at position $-1$ (red columns) compared to the original walk (blue columns) for the quantum (QW) and classical case (CW).

ally absorbed in the presence of an absorbing boundary, a quantum walker escapes with probability $1 - 2/\pi$ \cite{21,22}. A difference between the two exit probabilities first occurs after 5 steps, making it experimentally accessible with our current setup and providing a novel way of characterizing the degree of coherence in the walk. Absorbing boundaries were implemented using beam blocks in every spatial mode $-1$. Figure 4 shows the measured single-photon transmission probabilities in the quantum and fully decohered (classical) cases.

The most compelling features of our scheme are the ability to add tunable decoherence to a QW and the fact that every individual lattice site is fully accessible at any given time step. Future work could be to implement random or position-dependent coin operators to study walks on random environments \cite{29}, inhomogeneous walks \cite{30} and topological insulators \cite{31}. We could also add another walker on a separate line, using the existing setup with a vertical offset between input beams, or on the same line, with two or more photons launched in the same (or neighboring) spatial modes. This would allow exploration of entangled QW’s \cite{32}, as high-quality polarization-entangled photons can be routinely produced at high rates \cite{33}. Finally, the setup can be used to prepare photon-number and path-entangled states across a large number of modes \cite{34}.

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