Anderson localization of entangled photons in an integrated quantum walk

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First predicted for quantum particles in the presence of a disordered potential, Anderson localization is a ubiquitous effect, observed also in classical systems, arising from the destructive interference of waves propagating in static disordered media. Here we report the observation of this phenomenon for pairs of polarization-entangled photons in a discrete quantum walk affected by position-dependent disorder. By exploiting polarization entanglement of photons to simulate different quantum statistics, we experimentally investigate the interplay between the Anderson localization mechanism and the bosonic/fermionic symmetry of the wavefunction. The disordered lattice is realized by an integrated array of interferometers fabricated in glass by femtosecond laser writing. A novel technique is used to introduce a controlled phase shift into each unit mesh of the network. This approach yields great potential for quantum simulation and for implementing a computational power beyond the one of a classical computer in the ‘hard-to-simulate’ scenario.

One-dimensional quantum walks

A one-dimensional QW is an extension of the classical random walk, where the walker goes back and forth along a line and the direction at each step depends on the result of a fair coin flip. At the quantum level, interference and superposition phenomena lead to a non-classical behaviour of the walker, giving rise to new interesting effects that can be harnessed to exponentially speed up search algorithms and to realize universal quantum computation. QWs have also been proposed to analyse energy transport in biological systems. Different experimental implementations of single-particle QWs have been demonstrated with trapped atoms, ions, energy levels in NMR schemes, photons in waveguide structures, in bulk optics, and in a fibre loop configuration. Very recently, QWs of two identical photons have been demonstrated, but only in ordered structures.

A physical realization of a one-dimensional discrete QW can be provided by photons passing through a cascade of balanced beam-splitters arranged in a network of Mach–Zehnder interferometers, as represented conceptually in Fig. 1. Each beamsplitter simultaneously implements the quantum coin operation (that is, the choice of direction in which the particle will move) and the step operator, which shifts the walker in the direction fixed by the quantum coin state. The time evolution is simulated stroboscopically. Accordingly, every output of a beamsplitter of the network corresponds to a given point in the space–time of the QW, with the
The application of a phase shifter.

Different colours indicate different phase shifts and violet waveguides represent the accessible paths for photons injected from inputs A and B.

Integrated circuits for photonic QWs

The above approach would be extremely hard to implement with bulk optics, mainly because of size and very challenging stability issues. However, in the last few years integrated photonics has proven to be a highly promising experimental platform for quantum information science. Integrated waveguide circuits have been used recently for quantum applications, to realize two-qubit gates, quantum algorithms, QWs on a chip, and quantum interferometry experiments. In particular, femtosecond laser waveguide writing is emerging as a powerful technology for realizing such circuits. This technology exploits the nonlinear absorption of femtosecond pulses, focused below the surface of a transparent dielectric substrate, to obtain a permanent and localized refractive index increase. Translation of the sample under the laser beam along the desired path enables the fabrication of optical waveguide circuits with arbitrary three-dimensional design. Circuits with different designs can thus be fabricated with unequalled rapidity and versatility, and without the costs of lithographic masks. Furthermore, femtosecond laser-written waveguides are known to support the propagation of polarization-entangled states. To study disorder-induced effects, such as Anderson localization, for polarization-entangled photons, an important step forward is required in the currently available experimental platforms, namely to conjugate in the same setup polarization-independent elements, interferometric structures and a proven capability to implement a controlled phase shift in different points of the QW circuit.

In our experiment the setup of Fig. 1 was realized by integrated waveguide circuits fabricated by femtosecond laser writing, according to the layout depicted in Fig. 2. Beamsplitter elements were replaced by directional couplers. The discrete m-axis indicates the different sites of the QW, while the discrete n-axis identifies the different time steps. To obtain a totally polarization-independent behaviour, the three-dimensional geometry detailed in ref. 19 was adopted. The controlled phase shifts were implemented by deforming one of the S-bent waveguides at the output of each directional coupler (green or red segments in Fig. 2b), to stretch the optical path. The phase shift \([-\pi, \pi]\) in each Mach–Zehnder cell was implemented by lengthening the optical path either in the green segment to introduce a \([0, \pi]\) phase shift in different points of the QW circuit.

Figure 1 | Concept scheme of cascaded beamsplitters to implement photonic QWs. Disorder is introduced by phase shifters placed at each beamsplitter’s output port, before entering the next one.

Figure 2 | Integrated circuit for disordered QW. a, Scheme of the network of directional couplers implementing an eight-step one-dimensional QW with static disorder. Different colours indicate different phase shifts and violet waveguides represent the accessible paths for photons injected from inputs A and B. b, Controlled deformation of either of the two S-bent waveguides at the output of each directional coupler extends the optical path and is equivalent to the application of a phase shifter. c, The deformation is given by a nonlinear coordinate transformation, which is a function of deformation coefficient \(d\) (Supplementary Section SIV). The graph shows the undeformed S-bend (solid line), together with a deformed one (dashed). d, Schematic of the Mach–Zehnder structure, representing the unit cell of the directional couplers network, fabricated for calibrating the phase shift induced by the deformation. e, Phase shift induced by the deformation: theoretical curve calculated from the nominal geometric deformation (solid line), and experimental measurements (diamonds).
phase shift, or in the red segment to span the complementary range \([-\pi,0]\). In this way, small deformations, always of the same kind (lengthening of the path), are capable of providing the full range of phase shifts. Figure 2c shows both an undeformed and a deformed S-bend.

To test our technique and calibrate the achieved phase shift as a function of the imposed deformation \(d\) (see Supplementary Section SVI for a detailed definition) several Mach–Zehnder interferometers were fabricated with the design of Fig. 2d, reproducing exactly the unit cell of the QW network. Each interferometer had one S-bend (the one coloured in the figure) deformed with a different value of \(d\). Laser light at a wavelength of \(\lambda = 806\) nm was injected into the interferometers, and the induced phase shift was then retrieved from the measured light distribution at the output. Figure 2e reports the experimentally measured phase shifts as a function of the deformation parameter \(d\). The experimental points are in good agreement with the phase shift predicted by evaluating numerically the geometric lengthening \(\Delta l\) of the deformed S-bend, \(\phi_{\text{theo}} = \frac{\pi}{2}n\Delta l\). The designed phase shift is actually achieved with an accuracy of about \(\lambda/30\).

### Experimental one- and two-photon Anderson localization

We implemented a lattice with static disorder by imposing the same phase shift to the Mach–Zehnder cells corresponding to a fixed site of the QW line as in Fig. 2a (\(\phi_{\text{theo}} = \phi_{m} + \phi_{d}\)). QW circuits composed of four, six and eight steps, affected by static disorder, were realized in a way that the four-step phase pattern was embedded within the six-step phase pattern and, in turn, this was embedded within the eight-step one. A set of four-, six- and eight-step QW circuits implementing an ordered structure was also realized (that is, with perfectly symmetric Mach–Zehnder cells), to enable comparison to the corresponding disordered one.

We first measured the single particle distributions so as to demonstrate the polarization insensitivity of the integrated QWs. We repeated this measurement by injecting single photon states with different polarizations and compared the obtained results with the expected ones by calculating the associated similarity function (that is, with the generalization of the classical fidelity between two distributions \(D\) and \(D'\) defined as \(S = \langle \sum_{j,k} \sqrt{D_{jk}D'_{jk}} \rangle / \sum_{j,k} D_{jk} \sum_{j,k} D'_{jk} \rangle\). The obtained mean values are reported in Table 1 for the ordered QW circuits and for QWs with static disorder. These high values and low deviations highlight once more the fabrication control and polarization insensitivity of our integrated devices.

As a second step we carried out the investigation of two-particle QWs. By adopting the experimental apparatus described in detail in

![Figure 3](image-url)
Supplementary Section SV, polarization-entangled photon pairs, generated via spontaneous parametric downconversion, were simultaneously injected into arms A and B of the four-, six- and eight-step QW circuits. As anticipated in the introduction and illustrated in ref. 14, different quantum statistics of two test particles can be simulated through the polarization entanglement of a biphonon state (for the sake of completeness full details on this theoretical construction are reported in Supplementary Section SIII). In particular, by setting the phase $\phi$ of the state $|\Psi(\phi)\rangle = \frac{1}{\sqrt{2}} [ |\psi_1; H\rangle |\psi_2; V\rangle + e^{i\phi} |\psi_2; H\rangle |\psi_1; V\rangle ]$ to $\phi = 0$ or $\phi = \pi$, bosonic or fermionic QWs were obtained, respectively.

The graphs in Fig. 3 show, for different numbers of steps, the experimental measured symmetric joint probabilities $p_{(j,k)}^{(\text{sym})}$ of detecting one particle in the output port $j$ and the other in the output port $k$ independently from their polarization, when a bosonic ($|\Psi^{(+)}\rangle = |\Psi(0)\rangle$) or a fermionic ($|\Psi^{-}\rangle = |\Psi(\pi)\rangle$) two-particle input state is injected into the device. The different panels compare the ordered and disordered cases for input states with symmetric and antisymmetric wavefunctions. The case of single photons is also retrieved by tracing out the position of one of the particles of the entangled pair obtaining the distributions $p_{(j,k)}^{(\text{sym})} = \sum_{k} p_{(j,k)}^{(\text{sym})}$, which do not depend upon the symmetry of the input state (see Supplementary Section SII for details). Whereas in the case of an ordered system the walkers spread ballistically with increasing number of steps, particle propagation is progressively quenched in the case of static disorder; Anderson localization implies that the wave packets remain localized around the central sites. This is indeed what we observe, leading to a difference between the ordered and disordered case that is most evident for the eight-step QW (compare Fig. 3g,h with Fig. 3p,q). In addition, qualitatively different correlation patterns are observed for input states with bosonic or fermionic symmetry, showing a marked influence of the quantum statistics on the localization of the particle pair. The agreement of the experimental data with theoretical predictions, again quantified by the similarities, is reported in Table 2. One may note that in the ordered case $S$ is slightly worse for the eight-step QW. This discrepancy, due to some unavoidable uncertainty in beamsplitter realization, is milder in the disordered case. Here, as expected, additional phase shift to the ‘intentionally chosen’ random one will have less effect due to localization.

### Table 2 | Similarities between the experimental distributions of Fig. 3 and the expected ones.

| Steps  | Bosons | Fermions | Single |
|--------|--------|----------|--------|
| Ordered | 0.948 ± 0.003 | 0.923 ± 0.003 | 0.997 ± 0.001 |
| 4      | 0.943 ± 0.003 | 0.866 ± 0.003 | 0.997 ± 0.001 |
| 6      | 0.768 ± 0.006 | 0.780 ± 0.007 | 0.957 ± 0.004 |
| 8      | 0.934 ± 0.003 | 0.904 ± 0.004 | 0.993 ± 0.001 |
| Static disorder | 0.905 ± 0.007 | 0.914 ± 0.004 | 0.986 ± 0.002 |
| 4      | 0.830 ± 0.004 | 0.802 ± 0.004 | 0.954 ± 0.002 |
| 6      | 0.004 0.986 | 0.001 0.997 | 0.004 0.991 |
| 8      | 0.007 0.957 | 0.004 0.957 | 0.002 0.986 |

Uncertainties arise from the Poisson distribution of counting statistics.

Localization properties of bosonic and fermionic pairs

Different figures of merit have been adopted in the literature to provide a quantitative estimate of the localization properties, such as localization length $l$ or variance of the single-particle distribution $X_M^2$. The latter proved to be particularly useful for comparing the effects of different kinds of disorder$^{46}$. However, when a pair of particles is concerned, different parameters may be adopted. The state of a system composed of two indistinguishable particles walking on a line can be described by two coordinates: their mean position $x_M = (j + k)/2$ (j and k label different sites) and their relative distance $R = j - k$. It turns out to be very convenient to measure the spread of the collective wavefunction through the variance of both quantities. Figure 4a,b,d,e shows the variance of $x_M$ and $R$, calculated from the probability distributions $p_{(j,k)}^{(\text{sym})}$ of Fig. 3 as a function of the number of steps. Although in the case of an ordered QW the two quantities grow quadratically with the number of steps $n$, due to the ballistic spread of the wavefunction$^{14}$, they become only slightly dependent on $n$ in the case of static disorder, indicating that the system tends towards localization.
disorder, show that the tendency to localization is generally visible considering discrete time QWs with random configurations of static dynamical localization. Numerical simulations, performed by considering discrete time QWs with random configurations of static disorder, show that the tendency to localization is generally visible (see, for instance, ref. 48 for a similar analysis in the context of dynamical localization). Numerical simulations, performed by considering discrete time QWs with random configurations of static disorder, show that the tendency to localization is generally visible (see, for instance, ref. 48 for a similar analysis in the context of dynamical localization).

even with a relatively small number of steps. A fully localized state is predicted for \( n \approx 100 \), currently out of reach for any technological platform. Anyway, the difference observed in our experiment between ordered and disordered QWs confirms that the onset of Anderson localization can already be observed after a small number of steps.

Figure 4c,f compares, in the same graphs, data for the bosonic and fermionic symmetry of the input state. Interestingly, it can be observed that the ‘centre of mass’ \( x_M \) of two fermions undergoes stronger localization, in the same disordered potential, if compared to two bosons (Fig. 4c); the opposite is observed for the relative distance \( R \). The latter feature can also be appreciated from Fig. 5, which reports the measured distribution of the absolute value of this quantity (that is, \( |R| \)) in the eight-step QW case. Again, one can observe how the distribution of \( |R| \) spreads more in the ordered QW (Fig. 5a,b) than in the statically disordered one (Fig. 5c,d), where the stronger contributions for small values of \( |R| \) indicate the localization trend. More notably, when an antisymmetric two-particle state is injected, the probability associated with \( |R| = 0 \) drops (Fig. 5d) because of the Pauli exclusion principle. This explains why, in the presence of Anderson localization, a less pronounced contraction of the final two-particle distribution is observed in the case of the fermionic symmetry of the input state.

A deeper comprehension of these different localization properties of fermionic states with respect to bosonic ones can be achieved by calculating the general expressions of the variance of \( x_M \) and \( R \).
for bosonic and fermionic input states. As discussed explicitly in Supplementary Section SIII these can be expressed as
\[
\text{Var}^{\pm}(x_A) = \left[ \Delta_A^2 + \Delta_B^2 \pm \Delta_{AB}^2 / 2 \right]
\]

the \( \pm \) sign being associated with the simulation of bosonic (\(|\Psi^+\rangle\)) or fermionic (\(|\Psi^-\rangle\)) statistics. In these equations, \( x_A \) and \( x_B \) are, respectively, the mean position and the position spread one would obtain if only one particle was injected into the setup from the input port \( Q = A, B \), while \( \Delta_{AB}^2 \) is a non-negative term arising from two-particle interference. We notice that, independently of the specific properties of the single-particle contribution terms, the two functionals respond quite differently at the particle statistics. As a consequence of the positivity of the interference term \( \Delta_{AB}^2 \) one has, for the variance of the mean position,
\[
\text{Var}^{+}(x_A) \geq \text{Var}^{+}(x_B)
\]

Hence, the centre of mass of two fermions is better localized than that of two bosons. In contrast, for the relative distance \( R \), in agreement with what one would expect from the Pauli principle, one has
\[
\text{Var}^{-}(R) \geq \text{Var}^{+}(R)
\]

which is smaller in the bosonic case than in the fermionic case, reflecting their bunching/antibunching tendency.

**QW with dynamic disorder**

So far, we have discussed the case of static, time-independent disorder. However, different types of disorder, in which a time dependence is also considered, affect the evolution of the entangled pair wavefunction differently. As our technology is capable of implementing arbitrary phase maps in the QWs, we studied two more cases, namely two six-steps QWs with different dynamic disorder configurations (for more details see Supplementary Section SI). In the first, we applied the same (random) phase shift to the beamsplitters belonging to the same time step of the walk \( (\varphi_{m,n} = \varphi_m, \forall m) \); a fully space-correlated randomness may simulate the dephasing effect of a time-varying external environment on a spatially ordered structure. In the second case we applied a completely uncorrelated map of phase shifts \( \varphi_{m,n} \) to the beamsplitter network; this simulates external decoherence effects on spatially disordered lattices.

Experimental single- and two-photon output distributions are summarized in Fig. 6 for the bosonic and fermionic cases separately. Comparing Fig. 6a,b to the output distributions of the ordered case (Fig. 3d,e) it is clear that the effect of space-correlated randomness is to destroy the ballistic spread and force the system towards a diffusive behaviour. On the other hand, comparing Fig. 6c,d to the output distributions of the static case (Fig. 3m,n), we observe that the onset of dynamic disorder actually quenches the Anderson localization effects, and the distribution is far less localized. As a matter of fact, simulations with a high number of steps and different random phase maps show that the limit distribution is, for both types of disorder, a binomial centred in the middle of the spatial axis, with width growing with the square root of the number of steps. This means that, in both cases, the system evolution converges to a diffusion process, equivalent to a purely classical random walk. However, the early evolution qualitatively differs in the two cases, as appears clearly by comparing Fig. 6a,b and Fig. 6c,d.

Let us note that the experiments presented in this work were performed on a single phase map realization of each disorder. Although there are still features that are linked to the particular choice of the (randomly picked) phase maps, the number of beamsplitters is large enough to observe the differences between ballistic, diffusive and localized regimes.

**Discussion**

We have reported on the experimental realization of a quantum simulator based on discrete quantum walks of entangled particles in integrated photonic circuits. By properly engineering the phase shifts at the output ports of the beamsplitters and by changing the number of QW steps, we were able to follow in real time the evolution towards Anderson localization. The symmetry of the total wavefunction (Fermi- or Bose-like) clearly affects the localization properties. The quantum simulation we performed will help to ascertain the efficiency of quantum algorithms with entangled particles on realistic QWs. The capability of our technology to implement arbitrary phase maps in QWs will enable the experimental quantum simulation of the quantum dynamics of multiparticle correlated systems and its ramifications towards the implementation of realistic universal quantum computation with QWs. We envisage the development of an integrated photonic system that implements arbitrary phase and reflectivity maps, enabling the realization of any kind of unitary transformation within the optical network. This will pave the way towards genuine hard-to-simulate, scalable quantum linear optical circuits.

**Methods**

**Fabrication of the photonic circuits.** For the fabrication of the integrated photonic circuits used in these experiments, pulses with 220 nJ energy, \( \sim 100 \) fs duration and 1 MHz repetition rate from a Yb:KYW cavity dumped oscillator were focused by a \( \times 50, 0.6 \text{ NA} \) microscope objective. The substrate was Corning EAGLE2000 borosilicate glass. The translation speed of the sample for inscribing the waveguides was fixed at 40 mm s\(^{-1}\). Waveguides were fabricated 170 \( \mu \text{m} \) below the sample surface. The low birefringence (\( \sim 7 \times 10^{-5} \)) of this kind of waveguide has proven to allow the propagation of polarization-encoded qubits preserving coherence and entanglement.

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Author contributions
L.S., F.D.N., F.S., P.M., A.C. and R.R. conceived the experimental approach for simulation of the Anderson localization. A.C., R.O. and R.R. fabricated the integrated devices and performed the characterization with classical light. L.S., F.D.N., F.S. and P.M. carried out the quantum experiments. V.G. and R.F. contributed to the theoretical analysis on how statistics influences localization. All authors discussed the experimental implementation and results and contributed to writing the paper.

Additional information
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Competing financial interests
The authors declare no competing financial interests.