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Quantum Odyssey of Photons

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If only Ulysses had known that there is a fast shortcut to pass through an Odyssey. Taking advantage of quantum effects in nature allows for a quantum version of his classical random walk, providing intriguing differences like a tremendous speed-up. Since random walks are ubiquitous not only in classical history or economics, but also in fields like physics, chemistry and biology, there is an increasing interest to understand their quantum version and to explore whether quantum effects are already exploited by nature. For example, they are suspected to allow for the almost 100% efficiency of the energy transfer in photosynthesis, a performance that is not achievable classically. Furthermore, scientists do not only want to investigate, but also to benefit from quantum effects. For example many classical algorithms in computer science make use of random walks, where possible ways to solve a problem have to be chosen at random. Algorithms of that kind might get substantially speeded up by quantum versions of the random walk, testing all possible paths in parallel (Scheme 1). Alberto Peruzzo et al. report on their intriguing proof of principle experiment, a quantum walk of two indistinguishable photons in a pathway spanned by coupled optical guides and its perspectives.

Scheme 1. Caution: Pedestrians might cross themselves! Quantum walks, the quantum extension of classical random walks, had already been realized for different quantum particles. Now two walkers realized as photons were observed to pass through the same optical path network. For the first time, the two indistinguishable walkers were shown to interfere with each other.

To emphasize the characteristics of quantum walks it can be helpful to discuss their similarities and differences compared to classical random walks.[1] In a generic version of a random walk with discrete steps, every time a walker arrives at a crossroad, he has to choose the route to take. After several crossings and choices, made for example by flipping a coin [with heads (tails) leading to a step to the left (right)], he will have followed one out of many possible paths. For a quantum walker, in contrast, the result of each coin toss is a superposition of heads and tails. That is, the quantum coin takes both states simultaneously and therefore the walker follows all the possible paths simultaneously. As a consequence, strange phenomena arise. For example, if paths recombine again at subsequent crossings, the walker can meet himself, and due to interference increase his probability to be at this crossing or even disappear. One can comprehend this quantum weirdness by accepting the particle–wave dualism. Imagine a wave (walker) being split and recombined at a subsequent crossing. The shape of the resulting wave will strongly depend on the relative phase of the two incoming partial waves. If the two overlap in phase, that is the crests of the waves overlap, they constructively interfere and provide a larger (probability) amplitude. If the waves arrive with different phases, they might even completely cancel each other—so-called destructive interference, if each crest of one wave exactly meets one valley of the other one. Even though the characteristics of this walk are counterintuitive, at least for people not completely accustomed to quantum mechanics, the simplified picture one allows to derive why the term “random” would be misleading and is therefore omitted for the quantum version of the walk. The walker does not have to make a decision at crossings because he follows all paths simultaneously anyway. Since there is in principle no room for randomness and therefore no need for a coin toss, there is a different class of quantum walks, completely free of classical and quantum coins. Here, the evolution is not performed by discrete steps, but continuously, as in the one performed by Peruzzo et al., where photons are continuously leaking/tunnelling between several neighbouring optical pathways.

As a consequence of the absence of randomness each repetition of the quantum walk leads to the identical result (and even is reversible), at least as long as decoherence effects and measurements are absent. The walker can never lose the recollection of his initial state. Therefore, his final probability distribution to be found at a certain position does not average to a stationary distribution. In contrast, this is the case for every classical version, providing many different results when repeated with identical initial conditions. For example, the classical distribution of many repetitions of a one-dimensional walk is

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shaped like a (Gaussian) bell curve that spreads with the square root of the number of steps. On the contrary, the quantum version spreads linearly with the number of steps. However, the probability distribution for each individual walk remains identical. Indeed, the comparably faster spreading is the origin of the speed-up by the proposed quantum search algorithms that is boosted even further in higher-dimensional systems.[2]

Experimental quantum walks have been thoroughly investigated theoretically[1] and first attempts at implementation have been performed for the discrete and the continuous version. Systems that allow for realizing a quantum walk have to provide several crucial prerequisites. Among those are well-isolated walkers, the possibility to encode (coin- and) step operations at sufficient precision and to repeat them for a sufficient number of times. If disturbances from the environment destroy the coherences between the different paths, the walk becomes classical. In a simplified way one can see the coupling to disturbances as a leaking of information about the position of the walker into the environment from where it cannot be retrieved anymore. This is similar to a measurement that projects the former widespread superposition state of the walker, taking all paths simultaneously, on one single path or position, respectively. Therefore, on the one hand, decoherence has to be controlled, either by allowing for negligible impact or it even has to be engineered to provide the desired influences to mimic nature, for example the hot environment of photosynthesis.[3] On the other hand, the system has to be scalable to larger and higher dimensional path networks and an increased amount of correlated or even entangled walkers.[4]

Some aspects of quantum walks have been realized in a nuclear magnetic resonance experiment[5] using the internal degrees of freedom of molecules to span the coin and position space. An implementation based on neutral atoms in an optical lattice[6] has resulted in an experiment[7] where the lattice sites in a standing wave of light span the positions of the walker/atom and two electronic states depict the two coin states. A state-dependent optical force provides the conditional steps. Other proposals considered an array of microtraps illuminated by a set of microlenses,[8] Bose–Einstein condensates,[9] and atoms in cavities.[10] A scheme for trapped ions was proposed[11] and realized recently.[12] While coin states and steps are operated similar to the atoms in the optical lattice, the position is encoded in the motional degree of freedom of the walker ion(s), oscillating in a quantized trapping potential. Photons have been walking already as well, on the one hand as classical light in an optical resonator,[13] on the other, as single photons revolving in a loop of a split optical fibre.[14] Classical light was used to mimic single photons travelling and interfering in a lattice of optical waveguides.[15] It is important to note that single-photon and many-photon walks of classical light are described by the identical probability distribution. Thus, finally measuring the light intensity is equivalent to performing a series of mutually not-interfering single-photon walks, from which the spatial probability distribution can be derived. A single photon's walk can still be characterized by measuring the light intensity emitted from each individual path. Now, the authors of ref. [15] around Yaron Silberberg combined forces in an international collaboration with Jeremy O'Brian's group and others and extended their approach.

They still perform a quantum walk with light. However, on the one hand, they succeed to use a single photon as a walker and therefore extend their previous work on mimicking photons by classical light. Additionally, for the first time, they investigate the effects caused by two indistinguishable walkers. They provide two time-correlated photons via optical parametric down-conversion in a nonlinear crystal. This creates a pair of correlated photons at half the energy and frequency of the injected one. The photons are coupled into two waveguides and perform their walk by spreading into a path-network of 21 waveguides. The propagation of photons in this waveguide lattice is essentially a continuous quantum walk with the photons tunneling continuously between neighbouring guides.

Unambiguous differences in the characteristics of the outcome of the quantum walk now occur due to the interference between the two indistinguishable walkers. As described above, the new physics of two indistinguishable, interfering photons cannot be revealed via a measurement of the intensity of the light. However, it can be revealed by measuring two-photon correlation functions. That is, measuring the probability for detecting two correlated (simultaneous) events in two single-photon detectors behind different pairs of waveguides. For comparison, a single photon's walk will always result in a single detection event. For two indistinguishable photons walking and interfering, the authors, for example, report on correlation measurements revealing a bunching of photons, that is, both tend to travel to one side or the other side of the array. Most convincing is the comparison between the experimental (and theoretical) results of correlated and uncorrelated photon pairs. The authors regain the distinguishability between their two photons by adding a controlled, temporal delay for one of the photons. For a temporal delay leaving one photon behind by more than the coherence length, the non-classical correlations vanish.

The huge potential of their approach as well as the related challenges become obvious when we take a closer look at their system of choice. Former waveguide lattices suffered from their difference in the refractive index being too small to realize large angles of total reflection, necessary for fast changes of their course. This was unfavourable, because, on the one hand, sufficient spatial separation between the individual waveguides has to provide initially efficient coupling into the path network as well as finally efficient separation of the passed photons into separate detectors. On the other hand, in between, the waveguides must approach each other closely enough to allow for sufficient tunneling rates. The authors now fabricated their waveguide lattice within a different material, silicon oxynitride, mitigating the difficulties described above and allowing for sufficiently fast adaptation of the mutual distances between waveguides, as shown in Figure 1. The high level of engineering and control of their waveguide lattices enable the study of a wide range of different parameters and initial conditions. For example, further decreasing the waveguide separation might allow one to access effects beyond nearest-neighbour coupling, towards multimode inter-

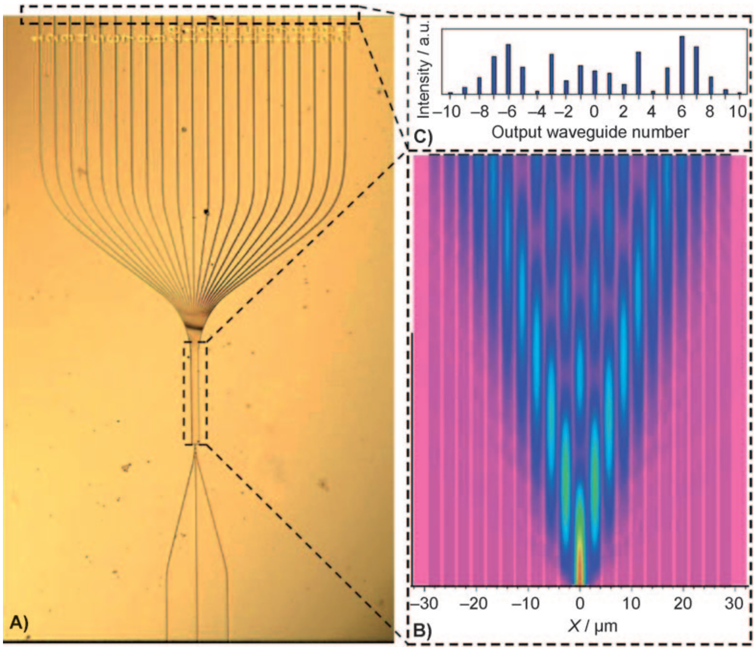

Figure 1. A continuously coupled waveguide array for realizing continuous quantum walks of one or two photons. A) An top view of a 21-waveguide array showing the three input waveguides, initially separated by 250 μm, bending into the 700 μm-long coupling (tunneling) region. All 21 outputs bend out to 125 μm spacing. For their experiments, the authors couple two photons into two different input waveguides. The required small bending radii allow to separate the different regions sufficiently fast. B) Simulation of the intensity of laser light and therefore of single photons propagating in the array. C) Output pattern of laser light propagating through the waveguide array, featuring the predicted interference pattern. To evaluate the differences in the output for two interfering photons walking simultaneously, correlation measurements between pairs of output waveguides are required. Reprinted with permission from the American Association for the Advancement of Science.

ference. For their current experiments they chose the propagation parameters within each guide as the coupling coefficient between neighbouring guides to be equal. Varying the parameters for each guide separately might provide the possibility to engineer the envisioned pathway of the walk for a distinct purpose. If the distance between waveguides is not constant but varies randomly, different, nonclassical behaviour can be investigated. For example in large disordered walks, the walk (transmission) can be exponentially suppressed. This suppression does not occur in classical random walks and can be described by the effect of Anderson localisation, the absence of diffusion of waves and particles, respectively. This phenomenon finds its origin in the destructive interference between multiple-scattering paths that can completely halt the waves inside the disordered medium. Arranging the waveguides in a spatially nonperiodic (random) fashion leads to the accumulation of random phases resulting in destructive interferences. Furthermore, the authors describe that their waveguides could be easily extended into three-dimensional lattices. The propagation of more complex quantum states could be investigated using two or even more entangled walkers. Intriguing interactions are predicted for state-of-the-art entangled walkers. Dependent on the symmetry of their entangled state (symmetric or anti-symmetric) a Bosonic (attractive) or Fermionic (repulsive) interaction is predicted.[6]

Besides all these beautiful perspectives, one also has to see the challenges still to be mastered. Scalability is probably the largest technical challenge of this research field. As for the approaches in other systems, there remain many issues. How does an increase of the system's size increase the required effort? The overall coupling efficiency through the waveguide lattice given by the authors amounts to 10%. One might think that the amount of coincidence events will therefore drop with the amount of walkers N as 0.1^N. The approach still relies on post-selecting the events of interest. Increasing the amount of waveguides will further reduce the count rate per channel. To consider pairs of entangled photons, it should be debated how to increase the very small fraction of entangled photons out of the currently used correlated photons. Despite these open questions, there is no doubt that the described system of coupled waveguides is a promising candidate to accept the related challenges.

Quantum walks could substantially speed up algorithms used for quantum systems. Even though the concept is promising, one should not forget to mention that it is already quite optimistic to hope for a universal quantum computer (involving or not involving quantum walks) within the next decade. However, long before the first quantum computer is realized in whatever (hybrid) system, quantum walks can also lead to new insight into the behavior of mesoscopic systems that mark the border between the classical and the quantum mechanical world.

Keywords: interference · photons · quantum algorithm · quantum particles · quantum walk

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