Dynamics and measurement in coherent and open quantum information networks

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Final Report

I. Dynamical properties of quantum walks

Recurrence properties of quantum walks

We implemented controlled measurements in a discrete-time quantum walk based on time-multiplexing. This was achieved by adding a deterministic outcoupling of the optical signal to include measurements constrained to specific positions resulting in the projection of the walker's state on the remaining ones. With this platform and coherent input light, we experimentally simulate measurement-induced single-particle quantum dynamics. We demonstrated the difference between dynamics with only a single measurement at the final step and those including measurements during the evolution. To this aim, we study recurrence as a figure of merit, that is, the return probability to the walker's starting position, which is measured in the two cases. We track the development of the return probability over 36 time steps and observe the onset of both recurrent and transient evolution as an effect of the different measurement schemes, a signature which only emerges for quantum systems. Our simulation of the observed one-particle conditional quantum dynamics does not require a genuine quantum particle but is demonstrated with coherent light.

The dimensionality of the internal coin space of discrete-time quantum walks has a strong impact on the complexity and richness of the dynamics of quantum walkers. While two-dimensional coin operators are sufficient to define a certain range of dynamics on complex graphs, higher-dimensional coins are necessary to unleash the full potential of discrete-time quantum walks. In this work, we present an experimental realization of a discrete-time quantum walk on a line graph that, instead of two-dimensional, exhibits a four-dimensional coin space. Making use of the extra degree of freedom we observe multiple ballistic propagation speeds specific to higher-dimensional coin operators. By implementing a scalable technique, we demonstrate quantum walks on circles of various sizes, as well as on an example of a Husimi cactus graph. The quantum walks are realized via time-multiplexing in a Michelson interferometer loop architecture, employing as the coin degrees of freedom the polarization and the traveling direction of the pulses in the loop. Our theoretical analysis shows that the platform supports implementations of quantum walks with arbitrary 4×4 unitary coin operations, and usual quantum walks on a line with various periodic and twisted boundary conditions.

One of the unique features of discrete-time quantum walks is called trapping, meaning the inability of the quantum walker to completely escape from its initial position, although the system is translationally invariant. The effect is dependent on the dimension and the explicit form of the local coin. A four-state discrete-time quantum walk on a square lattice is defined by its unitary coin operator, acting on the four-dimensional coin Hilbert space. The well-known example of the Grover coin leads to a partial trapping, i.e., there exists some escaping initial state for which the probability of staying at the initial position vanishes. On the other hand, some other coins are known to exhibit strong trapping, where such an escaping state does not exist. We present a systematic study of coins leading to trapping, explicitly construct all such coins for discrete-time quantum walks on the two-dimensional square lattice, and classify them according to the structure of the operator and the manifestation of the trapping effect.

Dynamical evolution of systems with sparse Hamiltonians can always be recognized as continuous-time quantum walks (CTQWs) on graphs. We analyzed the short-time asymptotics of CTQWs. It was shown in recent studies that for the classical diffusion process the short-time asymptotics of the transition probabilities follows power laws whose exponents are given by the usual combinatorial distances of the nodes. Inspired by this result, we perform a similar analysis for CTQWs in both closed and open systems, including time-dependent couplings. For time-reversal symmetric coherent quantum evolutions, the short-time asymptotics of the transition probabilities is completely determined by the topology of the underlying graph analogously to the classical case, but with a doubled power-law exponent.

Anderson localization in quantum walks

We considered two particles hopping on a chain with a contact interaction between them. At strong interaction, there is a molecular bound state separated by a direct gap from a continuous band of atomic states. Introducing weak disorder in the interaction, the molecular state becomes Anderson-localized. At stronger disorder, part of the molecular band delocalizes and dissociates due to its hybridization to the atomic band. We characterize these different regimes by computing the density of states, the inverse participation ratio, the level-spacing statistics, and the survival probability of an initially localized state. The atomic band is best described as that of a rough billiard for a single particle on a square lattice that shows signatures of quantum chaos. In addition to typical "chaotic states," we find states that are localized along only one direction. These "separatrix states" are more localized than chaotic states, and similar in this respect to scarred states, but their existence is due to the separatrix isoenergy line in the interaction-free dispersion relation, rather than to unstable periodic orbits.

We investigated numerically and theoretically the effect of spatial disorder on two-dimensional split-step discrete-time quantum walks with two internal "coin" states. Spatial disorder can lead to Anderson localization, inhibiting the spread of quantum walks, putting them at a disadvantage against their diffusively spreading classical counterparts. We find that spatial disorder of the most general type, i.e., position-dependent Haar random coin operators, does not lead to Anderson localization but to a diffusive spread instead. This is a delocalization, which happens because disorder places the quantum walk to a critical point between different anomalous Floquet-Anderson insulating topological phases. We base this explanation on the relationship of this general quantum walk to a simpler case more studied in the literature and for which disorder-induced delocalization of a topological origin has been observed. We review topological delocalization for the simpler quantum walk, using time evolution of the wave functions and level spacing statistics. We apply scattering theory to two-dimensional quantum walks and thus calculate the topological invariants of disordered quantum walks, substantiating the topological interpretation of the delocalization and finding signatures of the delocalization in the finite-size scaling of transmission. We show criticality of the Haar random quantum walk by calculating the critical exponent η in three different ways and find $\eta \approx 0.52$ as in the integer quantum Hall effect. Our results showcase how theoretical ideas and numerical tools from solid-state physics can help us understand spatially random quantum walks.

II. General open quantum dynamics and measurement in networks

We generalized the so-called de Finetti theorem. The essence of this theorem is that it implies that in the ground and finite-temperature states of Hamiltonians on complete graphs small subsystems cannot be very entangled with each other (due to the monogamy of entanglement), moreover, their reduced density matrices have asymptotically a form of a convex combination of iid-states. The theorem originally applied to quantum spin systems on complete graphs, which we generalized also to fermionic systems. It is generally believed that such theorems should also hold for other graphs with large coordination number, we will try to address this question next year.

We studied the bilinear-biquadratic Hamiltonian on the complete graph, determined its ground states in the full parameter space, and obtained the phase diagram. In the different parts of the space phase diagram the structure of correlations were very different corresponding to the symmetry group representations defining the ground-state subspace.

The concept of universal gravity-related irreversibility began in quantum cosmology. The ultimate reason for universal irreversibility is thought to come from black holes close to the Planck scale. Quantum state reductions, unrelated to gravity or relativity but related to measurement devices, are completely different instances of irreversibilities. However, an intricate relationship between Newton gravity and quantized matter might result in fundamental and spontaneous quantum state reduction—in the non-relativistic Schrödinger–Newton context. The above two concepts of fundamental irreversibility emerged and evolved with few or even no interactions. The purpose here is to draw a parallel between the two approaches first, and to ask rather than answer the question: can both the Planckian and the Schrödinger–Newton indeterminacies/irreversibilities be two faces of the same universe.

With the simplest proof ever, we justify the significance of quantum-gravity in non-relativistic quantum mechanics together with the related theories and experiments. Since the de Broglie wave length is inverse proportional to the mass, it would descend towards and below the Planck scale 10−33 cm for large masses even at slow non-relativistic motion. The tricky relationship between gravity and quantum mechanics —well-known in the relativistic case—shows up in non-relativistic motion of massive objects. Hence the gravity-related modification of their Schrüdinger equation is mandatory. We also recall the option of an autonomous Newtonian quantum-gravity, a theory parametrized by hbar and G. On cancellation of c from the Newtonian limit of Planck scale metric fluctuations is given a new hint.

Random density matrices play an important role in simulations of open quantum mechanical systems. In this note it is shown that the asymptotic spectral distribution, location and distribution of the largest eigenvalue of a large class of random density matrices coincide with that of Wishart-type random matrices using proper scaling. As an application, the asymptotics of the entropy production rate is considered and shown to be logarithmic. These results are generalizations of those of Nechita, and Sommers and Życzkowski.

Numerical simulations are very useful for testing and validating theories, especially in quantum mechanics where experiments are costly and hard to prepare. These computational methods make it possible to prepare aimed experiments in various cases. In this paper we present a stepwise adaptive-timestep version of the Quantum Jump (Monte Carlo wave-function) algorithm. Our method has proved to remain robust even for problems where the integrating implementation of the Quantum Jump method is numerically problematic. The only specific parameter of our algorithm is the single a priori parameter of the Quantum Jump method, the maximal allowed total jump probability per timestep. We study the convergence of ensembles of trajectories to the solution of the full master equation as a function of this parameter. This study is expected to pertain to any possible implementation of the Quantum Jump method.

We propose and analyze, focusing on non-adiabatic effects, a technique of manipulating quantum spin systems based on local 'cutting' and 'stitching' of the Heisenberg exchange coupling between the spins. This first operation is cutting of a bond separating a single spin from a linear chain, or of two neighboring bonds for a ring-shaped array of spins. We show that the disconnected spin can be in the ground state with a high-fidelity even after a non-adiabatic process. Next, we consider inverse operation of stitching these bonds to increase the system size. We show that the optimal control algorithm can be found by using common numerical procedures with a simple two-parametric control function able to produce a high-fidelity cutting and stitching. These results can be applied for manipulating ensembles of quantum dots, considered as prospective elements for quantum information technologies, and for design of machines based on quantum thermodynamics.

We consider transformation from a closed to an open spin chain and vice versa produced by changing single link strength in a pair of neighboring spins. We show that in the non-adiabatic time domain fidelity of such a process can be increased by proper choosing of the control function for spin–spin exchange coupling. We obtain this function for an antiferromagnetic quantum Ising chain and present heuristic reasons restricting possible time- dependences of Hamiltonians applied for a high-fidelity control.

We imposed the Newtonian criteria of inertial frames on the c.o.m.trajectories of massive objects undergoing spontaneous collapse of their wave function. The corresponding modification of the so far used stochastic Schrödinger equation eliminates the Brownian motion of the c.o.m., and restores the exact inertial motion for free masses. For the collapse of Schrödinger cat states the Born rule is satisfied invariably. The proposed machinery comes from the radical assumption that, in the vicinity of the spontaneously localized mass, the stochastic fluctuations of the c.o.m.—inevitable in the collapse process—would drag the physical inertial frame with themselves. The perspective of a general theory is presented where the spontaneous-collapse-caused breakdown of local energy-momentum conservation could be remedied by altering the metric, resulting in collapse-induced curvature of the space-time.

Roger Penrose proposed that a spatial quantum superposition collapses as a back-reaction from spacetime, which is curved in different ways by each branch of the superposition. In this sense, one speaks of gravity-related wave function collapse. He also provided a heuristic formula to compute the decay time of the superposition—similar to that suggested earlier by Lajos Diósi, hence the name Diósi–Penrose model. The collapse depends on the effective size of the mass density of particles in the superposition, and is random: this randomness shows up as a diffusion of the particles' motion, resulting, if charged, in the emission of radiation. Here, we compute the radiation emission rate, which is faint but detectable. We then report the results of a dedicated experiment at the Gran Sasso underground laboratory to measure this radiation emission rate. Our result sets a lower bound on the effective size of the mass density of nuclei, which is about three orders of magnitude larger than previous bounds. This rules out the natural parameter-free version of the Diósi–Penrose model.

We analyze the difference between ex ante and ex post equilibria in classical games played with the assistance of a nonlocal (quantum or no-signaling) resource. In physics, the playing of these games is known as performing bipartite Bell-type experiments. By analyzing the Clauser-Horn-Shimony-Holt game, we find a constructive procedure to find two-person Bayesian games with a nonlocal (i.e., no-signaling, and, in many cases, quantum) advantage. Most games of this kind known from the literature can be constructed along this principle, and share the property that their relevant ex ante equilibria are ex post equilibria as well. We introduce here a different type of game, based on the Bell theorem by Vértesi and Bene, which does not have the latter property: The ex ante and ex post equilibria differ.

We propose a simple scheme to reduce readout errors in experiments on quantum systems with finite number of measurement outcomes. Our method relies on performing classical post-processing which is preceded by Quantum Detector Tomography, i.e., the reconstruction of a Positive-Operator Valued Measure (POVM) describing the given quantum measurement device. If the measurement device is affected only by an invertible classical noise, it is possible to correct the outcome statistics of future experiments performed on the same device. To support the practical applicability of this scheme for near-term quantum devices, we characterize measurements implemented in IBM's and Rigetti's quantum processors.

We proposed and analyzed a nonunitary variant of the continuous time Grover search algorithm based on frequent Zeno-type measurements. We showed that the algorithm scales similarly to the pure quantum version by deriving tight analytical lower bounds on its efficiency for arbitrary database sizes and measurement parameters. We also studied the behavior of the algorithm subject to noise, and find that under certain oracle and operational errors our measurement-based algorithm outperforms the standard algorithm, showing robustness against these noises. Our analysis is based on deriving a non-Hermitian effective description of the algorithm, which yields a deeper insight into components responsible for the quantum and the classical operation of the protocol.

The ability to evaluate the outcomes of quantum annealers is essential for such devices to be used in complex computational tasks. We introduce a statistical test of the quality of Ising-based annealers' output based on the data only, assessing the ground state's probability of being sampled. A higher probability value implies that at least the lower part of the spectrum is a part of the sample. Assuming a plausible model of the univariate energy distribution of the sample, we express the ground-state energy and temperature as a function of cumulants up to the third order. Using the annealer samples, we evaluate this multiple times using Bootstrap resampling, resulting in an estimated histogram of ground-state energies and deduce the desired parameter on this basis. The approach provides an easily implementable method for the primary validation of Ising-based annealers' output. We demonstrate its behavior through experiments made with actual samples originating from quantum annealer devices.

Pairwise coupled networks of quantum systems

Modern quantum technologies in the fields of quantum computing, quantum simulation, and quantum metrology require the creation and control of large ensembles of entangled particles. In ultracold ensembles of neutral atoms, nonclassical states have been generated with mutual entanglement among thousands of particles. The entanglement generation relies on the fundamental particle-exchange symmetry in ensembles of identical particles, which lacks the standard notion of entanglement between clearly definable subsystems. Here, we present the generation of entanglement between two spatially separated clouds by splitting an ensemble of ultracold identical particles prepared in a twin Fock state. Because the clouds can be addressed individually, our experiments open a path to exploit the available entangled states of indistinguishable particles for quantum information applications.

We studied entanglement in coupled networks of quantums ystems, in particular, we considered several spin chains coupled together at a joint junction, and calculated the entanglement between some of the chains and the rest of the system. It turned out that changing a one-dimensional geometry to such a network has a huge large effect on the entanglement properties.

We generalized the Toeplitz-matrix techniques previously developed by us in the last few years to construct spin and fermion chain models for which the Rényi and von Neumann entanglement entropy diverges sublogarithmically with the subsystem size. This is the first translation-invariant state presented in the literature that has these type of entanglement entropy asymptotics.

The quantum approximate optimization algorithm (QAOA) is considered to be one of the most promising approaches towards using near-term quantum computers for practical application. In its original form, the algorithm applies two different Hamiltonians, called the mixer and the cost Hamiltonian, in alternation with the goal being to approach the ground state of the cost Hamiltonian. Recently, it has been suggested that one might use such a set-up as a parametric quantum circuit with possibly some other goal than reaching ground states. From this perspective, a recent work [S. Lloyd, arXiv:1812.11075] argued that for one-dimensional local cost Hamiltonians, composed of nearest neighbor ZZ terms, this set-up is quantum computationally universal, i.e., all unitaries can be reached up to arbitrary precision. In the present paper, we give the complete proof of this statement and the precise conditions under which such a one-dimensional QAOA might be considered universal.

Bipartite entangled quantum states with a positive partial transpose (PPT), i.e., PPT entangled states, are usually considered very weakly entangled. Since no pure entanglement can be distilled from them, they are also called bound entangled. In this paper, we present two classes of $(2d\times 2d)$-dimensional PPT entangled states for any $d\geq 2$ which outperform all separable states in metrology significantly. We present strong evidence that our states provide the maximal metrological gain achievable by PPT states for a given system size. When the dimension d goes to infinity, the metrological gain of these states becomes maximal and equals the metrological gain of a pair of maximally entangled qubits. Thus, we argue that our states could be called "PPT singlets."

We derived several inequalities related to the Robertson-Schrödinger uncertainty relation. In all these inequalities, we considered a decomposition of the density matrix into a mixture of states, and use the fact that the Robertson-Schrödinger uncertainty relation is valid for all these components. By considering a convex roof of the bound, we obtained an alternative derivation of the relation in Fröwis et al. [Phys. Rev. A 92, 012102 (2015)], and we can also list a number of conditions that are needed to saturate the relation. We also derived further uncertainty relations that provide lower bounds on the metrological usefulness of bipartite quantum states based on the variances of the canonical position and momentum operators for two-mode continuous variable systems. We could show that the violation of well-known entanglement conditions in these systems discussed in Duan et al. [Phys. Rev. Lett. 84, 2722 (2000)] and Simon [Phys. Rev. Lett. 84, 2726 (2000)] implies that the state is more useful metrologically than certain relevant subsets of separable states.

Understanding the structure of nonlocal correlations is important in many fields ranging from fundamental questions of physics to device-independent cryptography. We presented a protocol that can convert extremal two-party–two-input nonlocal no-signaling boxes of any type into any other extremal two-party–two-input nonlocal no-signaling box perfectly. Our results are exact, and even though the number of required boxes cannot be determined in advance, their expected number is finite. Our protocol is adaptive and demonstrates for the first time the usefulness of using no-signaling boxes in different causal orders by the parties.

Distance to uncontrollability is a crucial concept in classical control theory. Here, we introduce quantum distance to uncontrollability as a measure of how close a universal quantum system is to a nonuniversal one. This allows us to provide a quantitative version of the quantum speed limit, decomposing the bound into geometric and dynamical components. We consider several physical examples including globally controlled solid state qubits, scrambling of quantum information, and a cross-Kerr system, showing that the quantum distance to uncontrollability provides a precise meaning to spectral crowding, weak interactions, and other bottlenecks to universality. We suggest that this measure should be taken into consideration in the design of quantum technology.

Measurement and preparation of quantum states

We have proposed two quantum state engineering schemes containing only a few beam splitters and two or three homodyne measurements for the preparation of nonclassical states based on coherent-state superpositions in traveling optical fields. In spite of their simplicity, we have found that the schemes are capable of generating a large variety of nonclassical states including amplitude squeezed states, binomial states, squeezed cat states, and various photon number superpositions. We have demonstrated this by calculating the parameters of the setups to achieve the maximal fidelity of the generated state with respect to the desired one for several states. We have found that the achievable fidelities are high, while the parameters required to achieve them are experimentally feasible. Moreover, the same figures of merit can be achieved with several different choices of parameters of the input states. Meanwhile, the success probabilities are also found to be relatively high.

We showed that multipartite quantum states that have a positive partial transpose with respect to all bipartitions of the particles can outperform separable states in linear interferometers. We introduce a powerful iterative method to find such states. We present some examples for multipartite states and examine the scaling of the precision with the particle number. Some bipartite examples are also shown that possess an entanglement very robust to noise. We also discuss the relation of metrological usefulness to Bell inequality violation. We find that quantum states that do not violate any Bell inequality can outperform separable states metrologically. We present such states with a positive partial transpose, as well as with a nonpositive partial transpose.

We have proposed a quantum state engineering scheme based on the interference of two separately prepared squeezed coherent states for the conditional generation of various types of nonclassical states. Our approach unifies the benefits of simple conditional preparation and general quantum engineering schemes. It contains a single measurement thereby maintaining a proper success probability. Furthermore, it supports a broad variety of target states via parameter optimization. It can thus provide high-fidelity experimental access to many states which have relevant applications in quantum optics and quantum information science, and which cannot be efficiently generated otherwise.

We propose an experimental quantum state engineering scheme for the high-fidelity conditional generation of various nonclassical states of practical relevance in traveling optical fields. It contains a single measurement, thereby achieving a high success probability. The generated state is encoded in the optimal choice of the physically controllable parameters of the arrangement.

III. Dynamics conditioned on measurements

Conditional, iterative dynamics of qubits and complex chaos

We considered the task of deciding whether an unknown qubit state falls in a prescribed neighborhood of a reference state. We assume that several copies of the unknown state are given and apply a unitary operation pairwise on them combined with a postselection scheme conditioned on the measurement result obtained on one of the qubits of the pair. The resulting transformation is a deterministic, nonlinear, chaotic map in the Hilbert space. We derive a class of these transformations capable of orthogonalizing nonorthogonal qubit states after a few iterations. These nonlinear maps orthogonalize states which correspond to the two different convergence regions of the nonlinear map. Based on the analysis of the border (the so-called Julia set) between the two regions of convergence, we showed that it is always possible to find a map capable of deciding whether an unknown state is within a neighborhood of fixed radius around a desired quantum state.

We considered a special iterated quantum protocol with measurement-induced nonlinearity for qubits, where all pure initial states on the Bloch sphere can be considered chaotic. The dynamics is ergodic with no attractive fixed cycles. We show that initial noise radically changes this behavior. The completely mixed state is an attractive fixed point of the dynamics induced by the protocol. Our numerical simulations strongly indicate that initially mixed states all converge to the completely mixed state.

We determined that such protocols may exhibit sensitive, quasi-chaotic evolution not only for pure initial states but also for mixed states, i.e., the complex dynamical behavior is not destroyed by small initial uncertainty. We showed that the appearance of sensitive, complex dynamics associated with a fractal structure in the parameter space of the system has the character of a phase transition. The purity of the initial state plays the role of the control parameter, and the dimension of the fractal structure is independent of the purity value after passing the phase transition point. The critical purity coincides with the purity of a repelling fixed point of the dynamics, and we show that all the pre-images of states from the close neighborhood of pure chaotic initial states have purity larger than this.

We experimentally realized a nonlinear quantum protocol for single-photon qubits with linear optical elements and appropriate measurements. Quantum nonlinearity is induced by postselecting the polarization qubit based on a measurement result obtained for the spatial degree of freedom of the single photon which plays the role of a second qubit. Initially, both qubits are prepared in the same quantum state and an appropriate two-qubit unitary transformation entangles them before the measurement of the spatial part.

For single-qubit systems, there is a one to one correspondence of the pure-state quantum dynamics to the iterated dynamics of quadratic rational maps with one complex variable. The initial states not converging to stable cycles form a closed set on the Bloch sphere, corresponding to the Julia set of the quadratic rational map. This set, describing the chaotic regime of the dynamics, may have a fractal structure. We investigate here the problem of starting the dynamics of a single-qubit protocol from an initially noisy quantum state, described by a density matrix. The initial noise either diminishes during

the evolution, resulting in the purification of the quantum state, or it gets amplified by the process, resulting in the completely mixed state. We carry out a systematic analysis and present strong evidence that the fractal structure of the border points between different convergence regions remains a fractal for noisy initial states, up to a certain critical purity value. The dimension of the fractal, estimated by box counting, remains constant and drops suddenly at the critical purity. This is analogous to a phase transition. An alternative way to examine the nature of this transition point is to follow the pre-images of points from the neighborhood of the pure-state fractal. We find that these pre-images always fall on borders between convergence regions. They never have purity smaller than the critical purity, which coincides with the purity of an unstable fixed point to which branches of the backwards iterated fractal points converge, verifying the transition point.
We experimentally realize a nonlinear quantum protocol for single-photon qubits with linear optical elements. Quantum nonlinearity is induced by postselecting the polarization qubit based on a measurement result obtained for the spatial degree of freedom of the single photon which plays the role of a second qubit. Initially, both qubits are prepared in the same quantum state and an appropriate two-qubit unitary transformation entangles them before the measurement of the spatial part. We analyze the result by quantum state tomography of the polarization degree of freedom. We then demonstrate the usefulness of the protocol for quantum state discrimination by iteratively applying it to either of two slightly different quantum states which rapidly converge to different orthogonal states by the iterative dynamics.

Iterated quantum protocols with measurement-based selection lead to deterministic chaos for the evolving pure state representing an ensemble of qubits. Deterministic chaos for the pure quantum state may lead to ergodic evolution in the sense that initial states from any small area on the Bloch sphere will cover the whole sphere after a finite number of iterations. We realize two steps of an ergodic protocol in a photonic experiment, where initial qubit states are encoded in the polarization and path degrees of freedom of down-converted photons stemming from a parametric process. We numerically analyze the effect of noise on the time evolution and show that the protocol, described by a Lattès map, remains quasi-ergodic for any initial state if the initial noise is small. Tomographic reconstruction of the quantum states throughout the evolution is consistent with simulations and thus demonstrates ergodicity of the quantum dynamics.

Topological invariants

Central to the AdS/CFT correspondence is a precise relationship between the curvature of an anti–de Sitter (AdS) space-time and the central charge of the dual conformal field theory (CFT) on its boundary. Our work shows that such a relationship can also be established for tensor network models of AdS/CFT based on regular bulk geometries, leading to an analytical form of the maximal central charges exhibited by the boundary states. We identify a class of tensors based on Majorana dimer states that saturate these bounds in the large curvature limit, while also realizing perfect and block-perfect holographic quantum error correcting codes. Furthermore, the renormalization group description of the resulting model is shown to be analogous to the strong disorder renormalization group, thus giving an example of an exact quantum error correcting code that gives rise to a well-understood critical system. These systems exhibit a large range of fractional central charges, tunable by the choice of bulk tiling. Our approach thus provides a precise physical interpretation of tensor network models on regular hyperbolic geometries and establishes quantitative connections to a wide range of existing models.

The study of critical quantum many-body systems through conformal field theory (CFT) is one of the pillars of modern quantum physics. Certain CFTs are also understood to be dual to higher-dimensional theories of gravity via the anti-de Sitter/conformal field theory (AdS/CFT) correspondence. To reproduce various features of AdS/CFT, a large number of discrete models based on tensor networks have been proposed. Some recent models, most notably including toy models of holographic quantum error correction, are constructed on regular time-slice discretizations of AdS. In this work, we show that the symmetries of these models are well suited for approximating CFT states, as their geometry enforces a discrete subgroup of conformal symmetries. Based on these symmetries, we introduce the notion of a quasiperiodic conformal field theory (qCFT), a critical theory less restrictive than a full CFT and with characteristic multi-scale quasiperiodicity. We discuss holographic code states and their renormalization group flow as specific implementations of a qCFT with fractional central charges and argue that their behavior generalizes to a large class of existing and future models. Beyond approximating CFT properties, we show that these can be best understood as belonging to a paradigm of discrete holography.

Photonic experiments

Detectors inherently capable of resolving photon numbers have undergone a significant development recently, and this is expected to affect multiplexed periodic single-photon sources where such detectors can find their applications. We analyze various spatially and time-multiplexed periodic single-photon source arrangements with photon-number-resolving detectors, partly to identify the cases when they outperform those with threshold detectors. We develop a full statistical description of these arrangements in order to optimize such systems with respect to maximal single-photon probability, taking into account all relevant loss mechanisms. The model is suitable for the description of all spatial and time multiplexing schemes. Our detailed analysis of symmetric spatial multiplexing identifies a particular range of loss parameters in which the use of the new type of detectors leads to an improvement. Photon number resolution opens an additional possibility for optimizing the system in that the heralding strategy can be defined in terms of actual detected photon numbers. Our results show that this kind of optimization opens an additional parameter range of improved efficiency. Moreover, this higher efficiency can be achieved by using less multiplexed units, i.e., smaller system size as compared to threshold-detector schemes.

We reviewed the method of quantizers and dequantizers to construct an invertible map of the density operators onto functions including probability distributions and discuss in detail examples of qubit and qutrit states. The biphoton states existing in the process of parametric down-conversion are studied in the probability representation of quantum mechanics.

We devised an approach to characterizing the intricate interplay between classical and quantum interference of two-photon states in a network, which comprises multiple time-bin modes. By controlling the phases of delocalized single photons, we manipulate the global mode structure, resulting in distinct two-photon interference phenomena for time-bin resolved (local) and time-bucket (global) coincidence detection. This coherent control over the photons' mode structure allows for synthesizing two-photon interference patterns, where local measurements yield standard Hong-Ou-Mandel dips while the global two-photon visibility is governed by the overlap of the delocalized single-photon states. Thus, our experiment introduces a method for engineering distributed quantum interferences in networks.

We developed a statistical theory describing the operation of multiplexed single-photon sources equipped with photon-number-resolving detectors that includes the potential use of different input mean photon numbers in each of the multiplexed units. This theory accounts for all relevant loss mechanisms and allows for the maximization of the single-photon probabilities under realistic conditions by optimizing the different input mean photon numbers unit-wise and the detection strategy that can be defined in terms of actual detected photon numbers. We applied this description to analyze periodic single-photon sources based on asymmetric spatial multiplexing realized with general asymmetric routers. We showed that optimizing the different input mean photon numbers results in maximal single-photon probabilities higher than those achieved by using optimal identical input mean photon numbers in this setup. We identified the parameter ranges of the system for which the enhancement in the single-photon probability for the various detection strategies is relevant. An additional advantage of the unit-wise optimization of the input mean photon numbers is that it can result in the decrease of the optimal system size needed to maximize the single-photon probability. We found that the highest single-photon probability that our scheme can achieve in principle when realized with state-of-the-art bulk optical elements is 0.935. This is the highest one to our knowledge that has been reported thus far in the literature for experimentally realizable single-photon sources.

We propose two novel types of spatially multiplexed single-photon sources based on incomplete binary-tree multiplexers. The incomplete multiplexers are extensions of complete binary-tree multiplexers, and they contain incomplete branches either at the input or at the output of them. We analyze and optimize these systems realized with general asymmetric routers and photon-number-resolving detectors by applying a general statistical theory introduced previously that includes all relevant loss mechanisms. We show that the use of any of the two proposed multiplexing systems can lead to higher single-photon probabilities than that achieved with complete binary-tree multiplexers. Single-photon sources based on output-extended incomplete binary-tree multiplexers outperform those based on input-extended ones in the considered parameter ranges, and they can in principle yield single-photon probabilities higher than 0.93 when they are realized by state-of-the-art bulk optical elements. We show that the application of the incomplete binary-tree approach can significantly improve the performance of the multiplexed single-photon sources for suboptimal system sizes that is a typical situation in current experiments.