Experimental tools for quantum networking operations with single photons and single ions

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Abstract

One promising approach for future quantum networks is the combination of strings of trapped ions as quantum-information processors with entangled photon pairs produced by spontaneous parametric down conversion (SPDC) to establish quantum communication links between distant processing units.

This work reports on experiments using a hybrid quantum-optics set-up, comprising two separate linear ion traps and a resonant SPDC photon-pair source. It demonstrates the controlled interaction of single entangled photon pairs with a single trapped $^{40}\mathrm{Ca}^+$ ion. Preparing the ion as polarization selective absorber in the main polarization bases allows for the reconstruction of the biphoton quantum state, manifesting the photon entanglement in the absorption process.

Beyond that, the thesis documents the implementation of additional experimental tools enabling quantum state transfer experiments from photons to single ions. A dedicated narrow-bandwidth laser system is set up, laser sequences are developed for state discrimination and state rotations of ion qubits, and for the creation and characterization of coherent superposition states, of particular importance for state-transfer schemes. Finally, detection efficiencies of single Raman photons emitted by an ion are characterized with a well controlled single-photon source, and absorption probabilities of single photons are determined with a calibrated laser beam, providing precise values to assess efficiencies for different transfer scenarios.

Zusammenfassung

Ein mögliches System für zukünftige Quantennetzwerke ist die Verknüpfung gefangener Ionen als Quanteninformationsprozessoren mit durch SPDC (Spontaneous Parametric Down Conversion) erzeugten verschränkten Photonenpaaren zum Aufbau von Quantenkommunikationskanälen.

Diese Dissertation behandelt Experimente an einem hybriden Quantenoptikaufbau, bestehend aus zwei separaten linearen Ionenfallen und einer SPDC-Photonenpaarquelle. Sie zeigt die kontrollierte Wechselwirkung einzelner verschränkter Photonenpaare mit einem einzelnen $^{40}\mathrm{Ca}^{+}$ Ion. Durch Präparation des Ions als polarisationsselektiven Absorber in den drei Hauptpolarisationsbasen, wird der Zwei-Photonen-Quantenzustand rekonstruiert und somit über den Absorptionsprozess die Verschränkung der Photonenpaare nachgewiesen.

Überdies dokumentiert die Arbeit die Einrichtung zusätzlicher Methoden, welche den Zustandstransfer von Photonen auf einzelne Ionen ermöglichen. Ein schmalbandiges Lasersystem wird aufgebaut, Lasersequenzen für Zustandsbestimmung und Zustandsrotationen von Ionen-Qubits und zur Erzeugung und Charakterisierung kohärenter Superpositionszustände werden entwickelt. Ferner werden mit Hilfe einer Einzelphotonenquelle Nachweiseffizienzen für einzelne, von einem Ion erzeugte, Raman-Photonen gemessen und Absorptionseffizienzen einzelner Photonen mit einer kalibrierten Laserquelle charakterisiert. Die ermittelten Werte bilden eine solide Grundlage zur Abschätzung von Erfolgswahrscheinlichkeiten geplanter Transferschemata.

Resumen

Un enfoque prometedor para futuras redes cuánticas es la combinación de iones atrapados con pares de fotones entrelazados que se generan por el proceso SPDC (Spontaneous Parametric Down Conversion). Los iones atrapados se utilizarán como procesadores de información cuántica. Los pares de fotones permitirán el establecimiento de enlaces de comunicación cuántica entre unidades de procesamiento distantes.

En el transcurso de este trabajo, que se situa en el marco de la óptica cuántica, se han combinado dos implementaciones experimentales independientes para la realización de un experimento híbrido. Las dos partes del experimento corresponden con dos trampas de iones lineales separadas y con una fuente de pares de fotones resonantes creados por SPDC. En este experimento se demuestra la interacción controlada de pares de fotones individuales entrelazados con un ión atrapado individual de $^{40}\mathrm{Ca}^{+}$. La preparación del ión como absorbente selectivo de polarización en las bases de polarización principales permite la reconstrucción del estado cuántico de los pares de fotones, manifestando así su entrelazamiento a través del proceso de absorción.

Además, en la tesis presente se documenta la implementación de herramientas experimentales adicionales que permitirán experimentos de transferencia de estados cuánticos de fotones a iones individuales. Así mismo, se describe el montaje de un sistema láser acondicionado con ancho de banda estrecho. Adicionalmente, se desarrollan secuencias de láser para la discriminación y la rotación de estados de qubits de iones y, para la creación y caracterización de estados de superposición coherente, especialmente importantes para varios esquemas de transferencia de estado. Por último, se caracterizan las eficiencias de detección de fotones individuales Raman emitidos por un ión con una fuente de fotones individuales bien controlada, así como también se determinan las probabilidades de absorción de fotones individuales con una fuente láser calibrada. Los valores precisos obtenidos servirán para la evaluación de la eficiencia de diferentes esquemas de transferencia.

Contents

Introduction

Since its foundation and first practical implementation in the first half of the 20th century, classical computation theory became soon one of the most important developments from that time. Until now its main technical application, i.e. the classical computer, has a huge influence both on science and on everyday life. Besides the fact that a completely new branch of communication technologies arose from it, culminating in the realization of a permanent worldwide network of computers, the exponentially growing amount of available computing power at any point of the planet also led to entirely new research areas as for example the study of complex systems known from Biology or the highly computationally intensive field of global climate research. Due to the miniaturization process of the devices that comes with the increase in computational speed, the hardware used in classical computers for the implementation of logic gates and memories will soon be at the quantum limit, when the classical regime does not hold anymore and quantum mechanical effects gain influence on the systems.

At the end of the 20th century people started to think about how to use fundamental quantum-mechanical phenomena to process information [1, 2]. Initially, these visions were still far away from any implementation because this would have required the isolation and control of single quantum systems. Nevertheless, such systems became available with the first trapping and cooling of a single atomic ion [3] and with the control over individual photons in cavity QED [4]. Soon, a complete new combined experimental and theoretical research area called *quantum information* started to evolve. Analogous to its classical counterpart it is nowadays subdivided into *quantum computation* and *quantum communication*.

Different to the developed classical digital communication technologies, basic quantum communication does not necessarily require a quantum computer to establish a communication link. As a consequence, both fields of quantum computation and quantum communication have since the beginning evolved independently. In the recent years, big progress has been made in both research areas, resulting in the experimental demonstration of first quantum processors and even already commercial applications for quantum key distribution over quantum communication links, to secure classical communication channels. Although both areas are still at the beginning, future limitations become already present. To provide the scalability of quantum processors for the execution of complex quantum algorithms, many individual processing units must be linked via quantum communication channels which allow for an exchange of quantum information between them. On the other hand, the long-distance quantum communication channels demonstrated so far are typically implemented with photonic carriers of quantum information, suffering from photon losses just as classical optical communication channels. Long-distance quantum communication will be possible if the channel is sub-divided in several short-distance links with quantum processors at the breaking points, allowing for the implementation of so-called *quantum-repeater* schemes. The strong need for interfaces between quantum processing units and communication channels and the efficient link between distant processing units gave rise to a third important research field in the context of quantum information. This is the research area of *quantum networks*.

The motivation for this thesis is to establish the last missing experimental tools in an existing experimental set-up which is intended for a general study of different quantum-network scenarios with ion-trap quantum processors. In the following, this introduction will give a very short overview over the state-of-the-art in the mentioned three principal research branches of quantum information to provide the necessary context.

Quantum information processing

Several quantum algorithms were proposed that promise to be much more efficient than their classical counterparts for the solution of certain classical problems. The most prominent examples are one by Grover [5] for the search of data bases, and Shor's algorithm for the factorization of large numbers [6]. The great potential in quantum information processing comes from the fact that its fundamental information unit called *qubit* does not only allow two discrete logic states 0 and 1 but also arbitrary superpositions of these, which means that several possible input states can be computed in a single operation (*quantum parallelism*). Arbitrary quantum logic gates are then usually composed from a universal set of two- or multi-qubit entanglement operations and single-qubit manipulations [7, 8, 9]. Apart from the prospect of a device for universal quantum-information processing tasks that would outperform any classical computer when solving classical problems, great hope lies in the development of a so-called quantum simulator, a special purpose quantum computer. This could be, for example, a quantum mechanical many-body system whose dynamics are engineered such that they mimic the dynamics of other quantum-mechanical many body systems, enabling the study of all sorts of phase transitions. As the simulation of these strongly coupled many-body systems is far beyond the possibilities of today's computing capabilities, striking results and important theoretical insights are expected from large-scale quantum simulators. Prominent physical phenomena to study are for example magnetism and superconductivity.

There exists a huge variety of different physical systems which are promising candidates for the realization of a quantum processor. Just to name a few, the investigated candidates range from very small quantum-optical systems as single atoms [10] and ions [11] to solid-state or molecular systems using nuclear spins [12, 13], superconducting Josephson junctions [14], and quantum dots [15]. Also, purely photonic schemes exist to carry out quantum-logic operations [16].

To date, one of the most developed devices is based on strings of laser-cooled atomic ions confined in Paul traps. The potential of these systems lies in very high fidelities for multi-qubit operations [17, 18] and practically unity efficiency for the measurement of qubit states [19]. Depending on the ion species that is used and on the electronic states that are chosen for the implementation of a qubit, long coherence times are achievable [20, 21], allowing the storage of quantum information, which is an essential requirement when operating in a quantum network structure. First quantum algorithms as the Deutsch-Jozscha algorithm [22], quantum teleportation [23, 24], quantum error correction [25, 26], and the operation of a universal quantum processor [27] were already experimentally demonstrated. Also, the quantum Fourier transform, which plays a key role in the implementation of Shor's factoring algorithm, has been successfully implemented [28, 9]. Ion-trap quantum processors are also perfectly suited for the field of quantum simulation. A large number of simulations covering a broad field in physics has been experimentally demonstrated so far. Plenty of examples are available in [29] and references therein.

Quantum communication

While quantum computers may threaten the security of today's communication by the efficient factorization of large prime numbers, there exist communication protocols using flying qubits (e.g. single photons or entangled photon pairs) for the transmission of a classical encryption key, which are absolutely tap-proof [30]. This technology of quantum cryptography relies on the existence of entanglement in a quantum system and/or on the fact that a quantum-mechanical measurement always projects the system into the eigenstate corresponding to the measurement result.

Apart from this first practical application of quantum communication, the reliable transmission of quantum information is one fundamental ingredient for the realization of quantum networks by the interconnection of several qubits or small quantum processors. Using photons as carriers of quantum information seems to be the most practical approach as they have suitable properties in terms of coherence and propagation. Nevertheless, due to photon loss, the transmission of quantum information is nowadays limited to distances of about one hundred kilometers. To be able to still work with high efficiency over such lossy quantum channels, the general strategy is to use photons only to distribute entanglement between the two ends of a communication channel and to use this entanglement then as a resource for the transmission of quantum information with a teleportation scheme, as proposed in [31]. Entangled photon-pair sources based on spontaneous parametric down conversion (SPDC) play a very prominent role in the field of quantum communication, as they provide a robust way of creating entangled photons at high rates. When placed in the middle of a quantum channel and sending each photon of a pair to opposite ends to carry out a teleportation scheme, this configuration makes it in principle possible to double the maximal length of the channel. Enabling even higher communication distances requires already a quantum-network structure which offers the possibility for the temporal storage of entanglement in quantum memories or processors at the ends of several short-distance channels. By local operations in these intermediate nodes, the entanglement can then be extended to the outermost ends of a long-distance communication channel consisting of several subsequent short-distance links by using a quantum-repeater scheme, as proposed in [32].

The field of quantum cryptography is nowadays already so far evolved that commercial solutions for quantum key distribution (to secure classical communication channels) are available by a growing number of companies. Experiments in quantum communication using entangled photon pairs have demonstrated the teleportation of quantum states over the distance of 55 m by using a 2 km long optical fiber link [33]. Teleportation over distances of up to 143 km was demonstrated by transmitting the photons over free space [34]. The successful operation of a quantum repeater has not been documented yet.

Quantum networks

The research area in quantum information comprising the biggest experimental challenges is the field of quantum networks [35]. The main task here is to develop efficient interfaces to transfer quantum information between the nodes of a network that are established with quantum processors, and the quantum channels that we just discussed. To realize a quantum channel with teleportation protocols, distant entanglement between two nodes of the network is required as a resource. One can distinguish two classes of entanglement schemes. The first class relies on the entanglement of each node with an *emitted* photon [36]. Letting the photons from two distant nodes interfere on a beam splitter and performing a coincidence measurement enables then the projection of the two emitters into an entangled state. This was proposed for two-photon interference [37, 38, 39] as well as for single-photon interference [40]. The second class of entanglement schemes is not based on the entanglement transfer via photon emission but via photon *absorption*. The idea is to generate an entangled photon pair independently of the state of the two nodes (this is conveniently achieved with SPDC) and to let the distant nodes absorb the two photons in such a way, that their entanglement gets transferred [41]. Once that distant entanglement is established, this will not only allow the exchange of quantum information between two distant quantum processors but also enable the execution of remote quantum gates between distant network sites. This procedure will facilitate to implement algorithms that require higher numbers of qubits than contained in a single processing unit without the need to scale up the individual processors.

Concerning the network interfaces, different strategies are pursued to efficiently couple single atomic qubits to photons. The most efficient approach is to place single atoms or ions inside an optical cavity [42, 43, 44]. Systems without optical cavities usually make use of sophisticated high numerical-aperture objectives [45, 46]. Recent progress in the production of good quality high numerical-aperture aspheric lenses significantly simplifies this approach [47]. Another possibility is to place the atoms close to mirrors, covering a significant portion of the whole solid angle [48, 49]. As photons are conveniently transmitted over optical fibers, it seems natural to develop interfaces that directly couple the mode of a fiber with a single atom. This is achieved by simply bringing the atoms very close to a fiber end [50, 51] or by placing an atom in between two facing ends of optical fibers with specially engineered surfaces, forming a cavity [52, 53]. Another approach uses the evanescent coupling between atoms and a tapered fiber [54] in the vicinity of the fiber surface.

The successful operation of a quantum network, especially the execution of deterministic remote quantum information processing between macroscopically separated matter qubits has not fully been demonstrated yet. But in the few worldwide existing experimental set-ups that would theoretically offer the possibility for such a demonstration, important preliminary steps have already been achieved: Atom-photon entanglement via the emission of single photons [55, 43, 44], distant entanglement between two atomic systems using projective measurements after two-photon interference [56, 57] and single-photon interference [58], and the generation of distant entanglement via direct photon transmission [59]. Finally, proof-of-principle experiments for the teleportation between distant matter qubits were performed [60, 61].

All of the mentioned experiments have in common that they make use of a single species of quantum system, i.e. single atoms or ions. But in the context of quantum networks it is most likely that the unique properties from different quantum systems have to be combined to develop efficient network infrastructures. In the recent years this gave rise to another research field, called *hybrid quantum systems*, which is aiming at the interconnection of different quantum systems. The variety of investigated combinations is too large to provide a representative list here. The most prominent candidate system is certainly the combination of SPDC photon-pair sources (as the most adequate system for quantum communication) with quantum processors based on trapped ions (as the most developed system for quantum information processing). Additionally, systems aiming at the interconversion of photons from the visible (resonant with the employed atomic species) to the well established telecommunication bands [62, 63] and vice versa [64] will make it possible to use the already existing infrastructure for classical optical communication and will play a key role in the further development of quantum networks.

This work

The presented thesis project was carried out on an experimental set-up which is intended to study general principles of operation of a small-scale quantum network. Its main components are two separate linear ion traps, high numerical-aperture optics for efficient atom-photon coupling, and an entangled photon-pair source which is operated on resonance with an optical transition in the utilized ion species. This thesis contributes the ability for coherent manipulations and state detection of qubits in both ion traps. Specifically, it documents the setup of a laser system which allows for the required coherent control of single ions in the experiment (Chapters 4–6), paving the way for entanglement transfer from photon pairs to ionic qubits. Concerning the operation of a hybrid quantum system, the thesis presents experiments which show for the first time the heralded interaction of single *entangled* SPDC photons with a single trapped ion (Chapter 3). The same chapter documents further experiments at the single-photon level that were performed for a detailed characterization of the maximally achievable coupling efficiencies between single photons and single ions with the set-up. Chapters 1 and 2 introduce the general theoretical concepts and set-up for the ion-trap apparatus and the photon-pair source.

It should be emphasized, however, that joining the laboratory in Spain after the general experimental set-up had been just finished gave me the great opportunity to participate in a series of demanding experiments right from the beginning. These results are not detailed here but have been reported in earlier theses [65, 66, 67, 68] and in publications: In an experiment with atomic single-photon sources we observed the pulsed interference of single Raman-scattered photons emitted by a single ion in each trap [69]. A second experiment was carried out to investigate the polarization correlation between successively emitted fluorescence photons on a short-lived atomic transition [70]. With the hybrid set-up of the SPDC photon-pair source and a single ion trap we first demonstrated the basic interaction between the two systems by essentially doing spectroscopy of an atomic transition with the down-conversion photons [71]. In the following mile-stone experiment we showed the heralded interaction of single down-conversion photons with a single trapped ion [72].

Further remarks

A major burden and, at the same time, opportunity of this thesis project was the fact that the lab was moved from Spain to Germany at about half time. I was the main person to transfer the know-how of the ion-trap experiment and was therefore heavily involved in the coordination and execution of the move. The rebuilding of the apparatus in Saarbrücken, while delaying notably the progress of the work, also enabled the renovation of important parts of the set-up with the help of a new team of PhD students who joined the efforts and, in the course of the reconstruction, learned operating the lab.