Theses of the Dissertation

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Constructive Decoherence in Quantum Systems

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Overview

Quantum information processing promises several advancements over traditional, classical devices. The secure transmission of information via quantum states is already commercially available. However, the predicted speedup over classical computers have not been realized yet with sufficiently high computational steps and data sizes, where it would matter. Additionally, it has been shown that the transmission of data can be made equivalently secure without the application of quantum systems. The storage of information in a quantum system differs essentially from the classic approach. The information can be only approximately copied, and in general a single quantum system's state can not be completely determined. Transferring the information between parts of a quantum computer is possible, and can be performed by quantum state teleportation. In the classical computer the signal levels assigned to the logical values zero and one undergo frequent thresholding. This error correction process is the key of preserving the integrity of information while millions of logic gates interact with each other. Due to the inherent nature of quantum states a similar thresholding process is not applicable to quantum information processing units. From that viewpoint the quantum computer is more related to analogue computers than the digital ones.

The main reason behind the lack of large-scale quantum algorithm realizations is decoherence. The coupling between a quantum system and its environment defines a state set of the system, and the interaction drives an originally pure quantum state into the mixture of these states. However, the quantum algorithms are more efficient than their classical counterparts only if the state of the system is in a superposition and interference effects are present. Several methods have been developed for lessening or avoiding the undesired decoherence effects. One kind of error correction protocols is the analogue of the classical bit-flip error correction methods. A linear subspace of the Hilbert spaces is chosen as the error-free set of states, and if the system's state leaves that subspace then the event is detected by a measurement. Based on the measurement results a unitary transformation corrects the bit flip and the system is being brought back into the error-free subspace. A well-chosen subspace is orthogonal to the errors caused by the interaction with the environment. A different method is the application of decoherence-free subspaces for quantum computation. The key is encoding the quantum information in those subspaces that do not undergo decoherence, for example the relevant state transitions are prohibited in the first order. Besides decoherence, the errors caused by inexact quantum operations is also relevant. These errors are not easily detectable or correctable, due to leaving the quantum state in a perfectly valid, slightly perturbed form. By successive application of quantum gates these errors add up, just like in the analogue computer. Therefore it is important to develop high-precision information processing units, working well independently of environmental conditions. For circumventing that problem one approach is the introduction of a quantum computer model without quantum gate, where the quantum state is adiabatically altered by application of slowly changing external fields. Similarly, implementing quantum gates by adiabatic processes, for example by stimulated Raman adiabatic passage (STIRAP) robust gate operations is feasible. In general, solving the problems in the way of large-scale experimental realization of quantum information processing is not an easy task. Subject of research is developing new methods for preserving the quantum properties of qubits and manipulating their state, and finding such physical systems where the effects of decoherence can be avoided to large extent, and still many quantum bits can be realized and manipulated.

Objectives

The research documented in the dissertation aimed at learning more about decoherence effects, and showing applications where the relaxation processes behind those effects are not only destructive of nature, rather provide some gains or at least their negative effects can be avoided. Our objective is to show that the combination of incoherent and coherent interactions allow

- the suppression of negative effects caused be incoherent transition channels,
- appearance of quantum interference when increasing the magnitude

of the incoherent interactions,

- applications where the quantum properties of the state are preserved and the relaxation effects are used constructively.

Methods

The dissertation starts with the introduction of open quantum systems. They can be modeled by a Hilbert space of direct product form. The subject of interest is one, usually the smaller part of the system, the larger part is considered to be the environment of the other subsystem. The assumption about the size of the environment, and the additional condition of lack of memory in the environment allows to perform the Born-Markov approximation, and that greatly simplifies the equations of motion of the smaller subsystem. Then the time evolution can be described by a master equation in Lindblad form. The Lindblad operators show which transition channels are responsible for relaxation in the system. The relaxation-less part of the time evolution is governed by the Hamiltonian, and if the dissipation processes are negligible the time-evolution equations simplify to a Schrödinger equation. The relaxation processes usually cause decoherence, e.g. if the system initially is in a superposition of pure states the relaxation has the effect of transferring the state into a mixture of pure states, and the originally present interference effects attributed to quantum properties of the system are destroyed. Quantum trajectory methods are equivalent to the master equation in describing the time-evolution of the system. We have used the quantum jump method in Markov approximation. By using that method the time-evolution of individual quantum trajectories receive a physical meaning. A quantum jump occurs when the environment acts as a measuring device on the subsystem under investigation, and the back-action of the measurement is seen as a jump in the state of the quantum trajectory. The equations of motion describing an open quantum system are usually not analytically solvable if the interaction with external forces or the environment is time-dependent, and in these cases numeric methods have to be applied. In the presented work we dealt with small quantum systems, and the direct Runge-Kutta integration of the master equation was feasible. The more scalable quantum trajectory method has been used not for performance reasons, rather to show some insight in the evolution of single atoms and to allow calculation of time-correlation functions for a single trajectory.

First, we have investigated the connection between decoherence and quantum interference, in the system of strongly driven, collisionally perturbed Rb atoms. The atoms formed a small pressure molasses where by varying the pressure and the density of the atom cloud the collision rate was experimentally controllable. The internal state of the atoms was exposed by measuring the resonance fluorescence spectrum. It has been experimentally observed that by increasing the collision rate over the Rabi frequency an unexpectedly sharp dip appeared in the spectrum. For deeper understanding of that phenomenon a simple model has been applied for describing the system, and the resonance fluorescence spectrum has been calculated analytically by application of the quantum regression theorem. By introducing dressed states of the atom the effects of detuning and the coherent excitation has been described in a rotating frame. Then the quantum jump method has been used to observe the time evolution of individual quantum trajectories, allowing a different perspective than the description with density operators. The quantum jumps could be attributed to collisions between atoms, and between collisions the time-evolution was a simple Rabi-oscillation. By increasing the collision rate time-correlations emerged in the phases of individual quantum trajectories, phase stabilization occurred between the dressed state levels. These correlations could be directly attributed to the occurrence of the narrow dip in the spectrum, the width of the dip and the length of correlations were strongly dependent. Finally we discuss the quantum interference effects that result from the phase stabilization, and show that the dip in the spectrum can be attributed to them.

In the second section the stimulated Raman adiabatic passage (STIRAP) method has been applied to a six-level Λ system. The decoherence effects are suppressed by evolving the system in a dark state throughout the whole process. Dark states are characterized by not emitting or absorbing photons during time evolution. Of course these states do not have infinite lifetime, but if that is much longer than the time to perform the STIRAP process the additional decoherence channels can be discarded from the model. The subspace of dark states can be altered by modifying the properties of the coherent excitation. By slow modification of these properties it is possible to achieve an adiabatic limit where the state of the system follows the instantaneous dark state adiabatically, and within a good approximation it does not participate in photon emission or absorption processes. It is important to check how precisely is that approximation fulfilled during time evolution, and to what level do incoherent processes change the final state. A well-known property of the STIRAP method is that it successfully avoids the negative effects of decoherence. In our work the numeric integration of the Schrödinger equation has been used to determine the amount of population present in the bright states of the system. These are the states in which decoherence effects can occur. If the population in the bright states remains low throughout the whole process then these effects are guaranteed to be small. We have also calculated the final state analytically in the adiabatic limit. A numeric proof has been provided for being able to reach any prescribed final state adiabatically.

In the third section relaxation effects have been used in combination with coherent excitation for preparing prescribed mixed or pure states in the dark state subspace of a four-level Λ system. In the system considered the three base states interact with coherent laser pulses of different polarization, and participate in Raman transitions through the single excited state. The time-evolution of the system has been described by a master equation. Two cases have been considered, one which assumes that all transitions occur between the four levels, and one where we allow transitions to external levels by photon emission, and compensate for the population loss by a pumping process in the excited state. For both cases the asymptotic states of the system have been determined, together with the input-output relations. The asymptotic states are necessarily in the dark state subspace of the system, which is of dimension two in the system considered. By properly chosen polarization and relative phase of the applied laser pulses it has been possible to reach any two-component mixture of pure ground states with good approximation. The optimal pulse sequence parameters have been obtained numerically by the conjugate gradient method, and the obtained optimal pulses have been tested by fourth order Runge-Kutta integration of the master equation.

Theses

1. The anomalous Mollow spectrum of coherently driven, collisionally perturbed Rb atoms has been analyzed. I have shown that modeling the collisional interaction by stochastic interaction, and increasing the stochastic noise the calculated resonance fluorescence spectrum matches the previous experimental observations. By investigating the background of that process I have shown the means by which frequent incoherent interactions are causing long-time phase correlation in the

system. I have proven that these long-time phase correlations are responsible for the narrow dip in the spectrum [1, 2].

2. I have proposed an efficient, precise method for calculating resonance fluorescence, absorption and emission spectra solely based on quantum trajectory simulations of the atomic system emitting the observed photons. The method is especially well applicable for small quantum systems having long characteristic time, and high stochastic noise amplitude [1, 5].

3. I have shown that in a system, where coherent and incoherent interactions are both present, it is possible to reach any prescribed superposition of the three excited atomic states with high precision, in a robust manner. The applied method is resistant to small changes in the pulse shape or amplitude of the applied coherent excitations. The relative amplitude and phase of the pulses both influence the population in the final state [3].

4. I have determined a sufficient condition for the adiabaticity of the state preparation method developed for six-level Λ systems. The condition depends on the amplitude of the applied laser pulses, their timing and displacement. If fulfilled, the whole state preparation process is nearly adiabatic [3].

5. I have determined the asymptotic states and the relations between

initial and final states in a 4-level Λ system interacting with coherent laser pulses, taking into account the decoherence effects. I have shown that the relaxation drives the system into a two-dimensional subspace of the ground state space, and it can be adjusted freely by suitably choosing the relative amplitudes and phases of the lasers [4].

6. In a system with an externally adjustable multidimensional dark state subspace I developed a state preparation method. The method utilizes successive pulses that change the orientation of the dark state subspace. The method has been applied in a 4-level Λ system. Both in the case of no transitions into external states, and in the case when the population scattered into various external states is compensated by incoherent repumping of the excited state, I have shown that with few steps wide range of mixed and pure states can be prepared precisely [4].

Conclusions

We have shown that simultaneous presence of coherent and incoherent interactions can lead to quantum interference, and the incoherent processes are capable more than only to contribute to loss of quantum mechanical features. The incoherent processes when applied together with coherent interactions still do allow adiabatic population transfer to succeed, and can actively participate in robust state preparation. The state preparation methods outlined in the dissertation are general, they can be applied not only to atomic systems interacting with laser light, but to many other systems with similar Hamiltonian and incoherent interaction channels.

In the field of quantum informatics, independent of what kind of quantum computer realization we look at, the effects of decoherence show up during state preparation, information storage and when performing quantum operations. The effects of decoherence are destructive from the viewpoint of quantum algorithms, and various methods have been developed to overcome the difficulties, for example storing the quantum state in a decoherence-free subspace, or the quantum error correction that is capable of detecting the event of leaving a prescribed subspace by measurement, and performing corrective actions. For realizing these schemes in practice the better understanding of incoherent processes, and their constructive application could be helpful.

Related publications

[1] A. Karpati, P. Adam, W. Gawlik, B. Łobodziński, and J. Janszky, *Quantum-trajectory approach to stochastically induced quantum-interference effects in coherently driven two-level atoms*, Phys. Rev. A **66**, 023821 (2002).

[2] A. Karpati, P. Adam, W. Gawlik, B. Łobodziński, and J. Janszky, *Quantum-trajectory approach to stochastically induced quantum-interference*, Prog. Phys. **51**, 179 (2003).

[3] A. Karpati and Z. Kis, *Adiabatic creation of coherent superposition states via multiple intermediate states*, J. Phys. B **36**, 905 (2003).

[4] A. Karpati, Z. Kis, and P. Adam, *Engineering mixed states in a degenerate four-state system*, Phys. Rev. Lett. **93**, 193003 (2004).

[5] A. Karpati, P. Adam, and J. Janszky, *A method for calculating two-time correlation functions in the quantum trajectory approach*, J. Opt. B **6**, S79 (2004).

Other publications

[6] P. Adam, A. Karpati, J. Janszky, S. Szabo, and E. Lugosi, *Relations between input and output states of integrated optical systems*, Laser Phys. **1**, 127 (2000).

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[8] S. Szabo, P. Adam, and A. Karpati, *Phase optimized light in complex optical systems*, Prog. Phys. **49**, 1109 (2001).

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[12] A. Karpati, P. Adam, Z. Kis, and J. Janszky, *Stochastic unraveling of the time-evolution operator of open quantum systems*, Eur. Phys. Lett. **75**, 209 (2006).