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Two-qudit logical transformations on atomic-field modes with orbital angular momentum

Elizaveta Bashmakova*, Evgenii Vashukevich, Tatiana Golubeva, Yuri Golubev

St. Petersburg State University, St. Petersburg, Russia
*E-mail: bashmakova.elizaveta@mail.ru

Abstract

In this work, we propose a method for implementing multipartite interaction based on a quantum nondemolition interaction protocol between multimode light with orbital angular momentum and an ensemble of cold atoms. We have demonstrated an original method of logical encoding atomic-field subsystems by the parity of the orbital angular momentum, which makes it possible to introduce a logical basis that belongs to the space of two-qubit states. We have shown that, the resulting two-qubit transformation is equivalent to the SWAP transformation operation under the certain physical conditions.

Today there has been significant interest to high-dimensional ($d-$dimensional) quantum systems (qudits) due to the possibility of increasing the information capacity of the channel – the amount of information that can be encoded in one physical carrier. That turns out to be very useful in the problems of quantum communication and quantum information processing [1]. Nevertheless, there are still blind spots in the problem of efficient manipulation of multidimensional quantum states.

The orbital angular momentum (OAM) is one of the exciting resource for constructing a qudit since the OAM can take any integer values, which allows us to work in the Hilbert space of high dimension [2]. A significant factor is also that Laguerre–Gaussian modes with OAM show high stability and a relatively high decoherence time when propagating in a turbulent atmosphere [3].

To achieve the universality of quantum computation, it is necessary to be able to implement a universal set of quantum logical operations. Moreover, in order to create quantum gates, we need to find the appropriate physical system for the gates' realization, and the ability to organize efficient interaction between quantum objects. In this work, the multimode light with orbital angular momentum (OAM) and atomic ensemble are considered as a physical systems, and quantum nondemolition (QND) interaction [4] is applied.

In this work, we have studied in detail the mechanism of interaction between multimode light with orbital angular momentum and an atomic ensemble in the dipole approximation. First, we described a model for the interaction of an ensemble of cold atoms with a non-resonant field, which is a superposition of modes with certain angular momentum in the presence of a control field (see Fig. 1). And then we analyzed the interaction Hamiltonian in this model, which contains all the information about the evolution of the field and atomic variables. Moreover, one of our aims was to search for the certain physical conditions under which the interaction is reduced to the mechanism of quantum nondemolition interaction.

We have shown that phase-sensitive excitation transfer from the even field modes to odd medium modes and vice versa can be achieved selecting a control field whose OAM is equal to ± 1. In other words, in our system we classify all quantum states into states with either even or odd OAM values. This structure of the atomic-field subsystems allowed us to use the parity modes for the original encoding of logical states. Therefore, we have deeply studied states with OAM in the framework of quantum nondemolition interaction in terms of discrete variables. We analyzed the quantum nondemolition interaction of multidimensional atomic-field systems. In this work, we present the results of the simplest example, the qubit consideration.

In our analysis, the logical states "0" and "1" encode as a superposition of atomic-field states when excitations are distributed among the subsystems of different parity. Generally, the nondemolition interaction of atomic-field systems does not belong to the computational basis of qubits, since the excitation bunching effect can take place. However, we managed to find a logical basis that belongs to the two-qubit space.

We have demonstrated that the implemented type of logical operation on atomic-field qubits depends on the effective interaction constant, therefore, determined by the interaction geometry. We obtained that when the value of the interaction constant is equal to 2, the considered logical operation is equivalent to the SWAP transformation operation. Then, it can be provide an entangling two-qubit gate $\sqrt{SWAP}$ by manipulating the interaction time. Then we want to apply the developed apparatus of multimode QND interaction to $d-$dimensional systems.

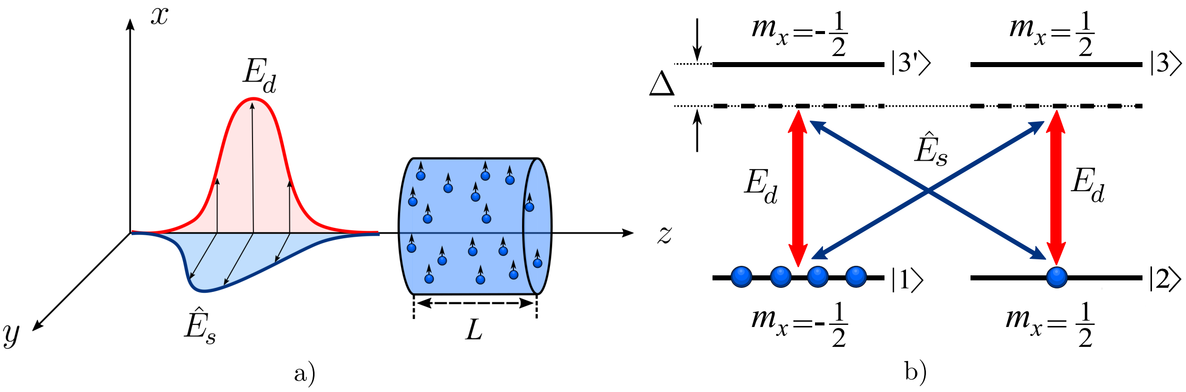

Figure 1: The schematic draw of the system under consideration: a) a cell with a cloud of four-level atoms represented as a cylinder with a length of L along the z axis interacts with a strong driving field $\vec{E}_d$ and a weak signal field $\hat{E}_s$; b) the energy levels diagram of an ensemble of atoms interacting with quantum signal field $\hat{E}_s$ and driving $\vec{E}_d$ fields in a quantum nondemolition interaction. The frequencies of the fields are detuned from the frequencies of the atomic transitions, respectively, by Δ. For the quantization axis along x the value m_x is total angular momentum quantum number.

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