Optimization of a Rydberg-atom based quantum CZ gate

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Rydberg atoms present a prospective tool for quantum technologies. In particular, one of the most promising realizations of a scalable quantum computer is based on single Rydberg atoms trapped in optical lattices. Such system theoretically satisfies all of the DiVincenzo criteria and hence makes Rydberg-atom based quantum computing a very prospective approach.

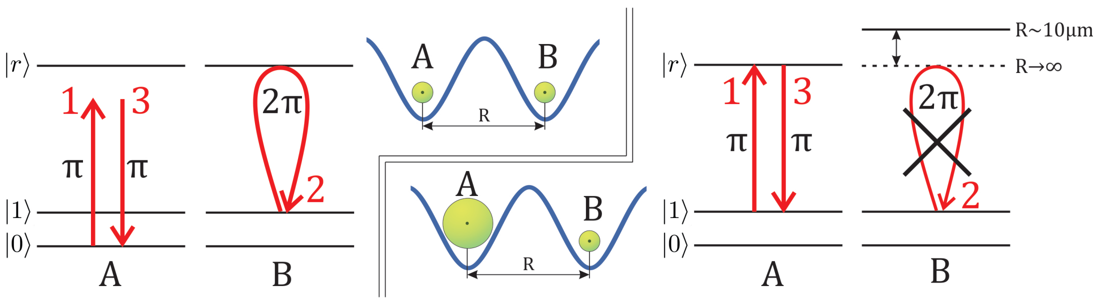
Despite it appears to be relatively simple to perform single-qubit operations with atomic qubits, high-fidelity two-qubit operations still remain a challenge. Current experimental results on Rydberg two-qubit gates demonstrate relatively low fidelity, which is not yet sufficient for large-scale quantum computations [**?**].

Our study focuses on the possible way to overcome these difficulties by considering different approaches to Rydberg-based two-qubit operations as well as to quantum computing itself. The ultimate goal is to develop a neural algorithm, which finds the optimum protocol for implementing one- and two-qubit operations with atomic qubits in a real-life optical lattice, which may contain defects. The algorithm's aim is to minimize the operation error by choosing between several gate protocols and adjusting certain experimental parameters. Such a hybrid approach may allow one to implement high-fidelity two qubit operations and create a platform for scalable quantum computations.

This work is a first step towards creating such an algorithm. On this stage, we consider several protocols for the Rydberg implementation of the C_Z-gate in order to account for the errors arising in the concrete experimental conditions imposed by the setup located at the Moscow State University. The setup allows us to consider 2- and 3-dimensional lattice geometries and methods of atomic manipulation.

CZ gate protocols considered

The idea behind controllable gates protocols considered in our work is the strong dipole-dipole interaction between two rubidium atoms excited in low-lying Rydberg states, which could be turned on and off using laser pulses. The first gate protocol under consideration is based on the concept of dipole blockade [2]: while it is easy to excite one atom into a Rydberg state, if the interaction between two atomic qubits is strong enough, the Rydberg excitation process becomes off-resonant for the second atom. It is then possible to obtain a conitional phase shift for the two-qubit system using a special sequence of laser pulses. The main feature of this protocol is that the dipole blockade occurs even if the distance R between the atoms is not preciesly controlled. This also lessens the requirements on the atomic temperature, but requires strong interatomic interactions, which may not be achievable for certain lattice geometries.



$$\{|00\rangle, |01\rangle, |10\rangle, |11\rangle\} \text{ , } \hat{U} = \mathrm{diag}(1, -1, -1, -1)$$

Figure 1: Dipole blockade phase gate

Unlike the blockade protocol, the "interaction" gate protocol includes both atoms being excited into Rydberg states. Under certain circumstances, such a two-atom system will obtain a phase shift linear

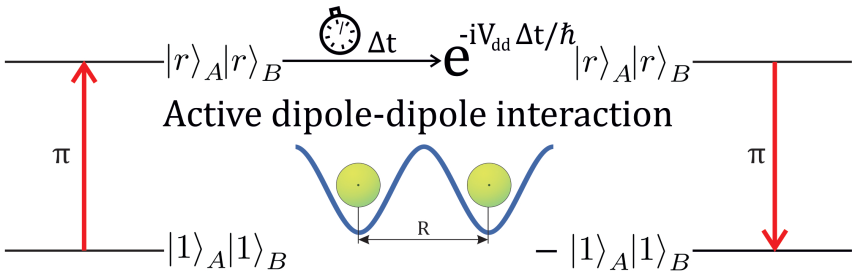


Figure 2: Interaction phase gate

with time and proportional to the interaction strength. By controlling the interaction time, it is possible to generate a desirable phase shift.This key advantage of this approach is that the operations could be performed with much more distanced atoms. It is also relatively simple to adopt this gate protocol to be used with the qubits at different separations. On the other hand, this procedure is more sensible to position variations, which strengthens the requirements on atomic temperature. Moreover, the active dipole-dipole interaction causes interatomic dipole forces, which act as an additional decoherence source.

Errors and optimization

The main error sources are spontaneous emission (from qubit and Rydberg states), laser noises, atomic motion, AC Stark effect, spatial crosstalk, Doppler-induced pulse area errors, etc. The errors could be divided in two groups: the intrinsic system's ones imposed by the Hamiltonian and the errors due to experimental imperfections. We account for both of the error types and find optimum operation modes for the considered gate protocols based on the comparison of their fidelities under certain experimental conditions.

References

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