Rydberg physics: an atomic approach to Quantum Computing

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Rydberg atoms, which are atoms in highly excited states of the principal quantum number n, have been studied for more than a century [1,2]. And over the past two decades, Rydberg atom physics, particularly at ultracold temperatures [3-8], has contributed to a string of exciting discoveries, owing to their "exaggerated" properties. The large separation between the highly excited valence electron and the atomic core and the consequent loose binding leads to huge electric polarizabilities and strong long-range dipole-dipole and Van-der-Waals (vdW) interactions with the surrounding atoms. Since vdW interactions between atoms depend on their polarizability (which in the case of almost hydrogen-like Rydberg atoms scales as n^7), one can show that vdW forces scale as n^{11}. The use of Rydberg atoms with n in the 50–100 range can thus enhance the interaction energy by 17 to 20 orders of magnitude [9].

In a frozen gas, these interactions make Rydberg atoms possible candidates for quantum information processing [10-14]. One promising approach is based on the concept of a dipole blockade [15], i.e., the inhibition of multiple Rydberg excitations in a confined volume due to interaction-induced energy shifts. This can be employed for scalable quantum logic gates.

The task of designing a quantum computer is equivalent to finding a physical realization of quantum gates between a set of qubits, where a qubit refers to a two-level system. At the heart of quantum computation is the entanglement of many of these two-state systems, which form the register of the quantum computer. The requirements for creating and maintaining such a highly entangled state seem to be almost contradictory: the qubits must be strongly coupled to one another and to an external field to produce the conditional-logic operations for quantum computation, yet coupling to other external influences must be minimized because it leads to decoherence.

A new system for implementing quantum logic gates was proposed in 1999 [16]: trapped neutral atoms made to interact via laser-induced coherent electric dipole-dipole interactions. Such a system has two advantages: decoherence is suppressed because neutrals couple weakly to the environment, and operations can be performed in parallel on a large ensemble of trapped atoms, thus offering avenues for scaling to many qubits.

Two-qubit operations involve conditioning the state of one atom on the state of the other. For example, a C-NOT (controlled NOT) gate can be implemented using the mechanism of Rydberg blockade, as shown in Figure 1 below.

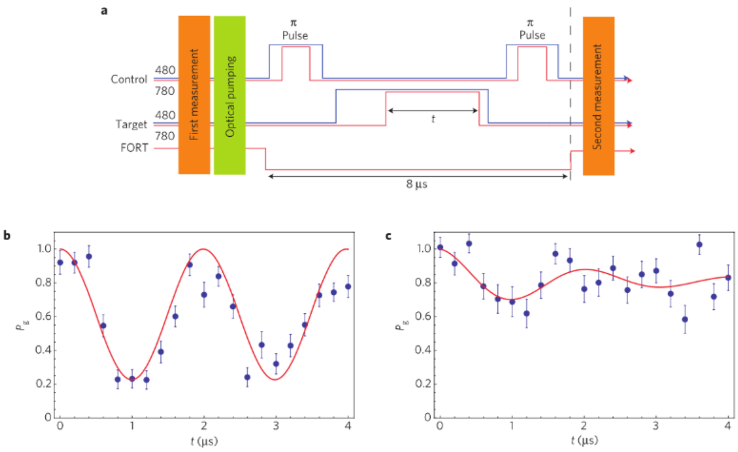

Figure 1: Rydberg blockade experiment between control and target atoms. a, Experimental sequence. b, Rabi oscillations on site 2 when no π pulses are applied to site 1. c, Blockaded oscillations on site 2 when the π pulses are applied to site 1. [17]

Two atoms, one labelled 'control' and the other 'target', are placed in proximity with each other. The ground state $|1\rangle$ and Rydberg state $|r\rangle$ of each atom forms a two-level system that is coupled by laser beams with Rabi frequency Ω. Application of a 2π pulse ($\Omega t = 2\pi$ with t being the pulse duration) on the target atom results in excitation and de-excitation of the target atom giving a phase shift of π on the quantum state, $|1\rangle_T \rightarrow -|1\rangle_T$. If the control atom is excited to the Rydberg state before application of the 2π pulse, the dipole–dipole interaction $|r\rangle_C \leftrightarrow |r\rangle_T$ shifts the Rydberg level by an amount B that detunes the excitation of the target atom so that it is blocked and $|1\rangle_T \rightarrow |1\rangle_T$. Thus, the excitation dynamics and phase of the target atom depend on the state of the control atom. Combining this Rydberg-blockade-mediated controlled-phase operation with π/2 single-atom rotations between states $|0\rangle_T$ and $|1\rangle_T$ of the target will implement the CNOT gate between two atoms [17].

It has been shown by detailed analysis of the atomic structure of the heavy alkalis that this pulse sequence is in principle capable of creating entanglement with fidelity $F > 0.998$ [18]. Many other gate protocols using Rydberg atoms have been proposed [19].

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