

## SYSTEM AND METHOD FOR PARALLEL IMPLEMENTATION OF MULTI-QUBIT QUANTUM GATES

### CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application No. 62/873,009, filed July 11, 2019, which is hereby incorporated by reference in its entirety.

### BACKGROUND

[0002] Any unitary operation can be performed on a quantum computer equipped with a complete set of universal gates. A complete set of gates can be comprised of single qubit operations together with a two-qubit controlled-NOT (CNOT) gate. The CNOT gate has been demonstrated in several different physical systems including trapped neutral atoms, trapped ions, superconducting circuits, and linear optics.

[0003] Quantum information processing with neutral atoms offers many exciting opportunities. Neutral atoms can be trapped in flexible geometries and in large numbers using optical trapping techniques. Each individual atom can store a quantum bit of information in two hyperfine ground state levels  $|0\rangle$  and  $|1\rangle$ . Such a storage has the advantage of high coherence times, enabled by excellent isolation from the environment, near-perfect qubit initialization via optical pumping, individual optical readout of each qubit, and a straightforward manipulation of single qubits. Finally, strong and long-range interactions between atoms can be switched on by coupling to highly excited Rydberg states to operate multi-qubit entangling gates to enable universal quantum computation.

[0004] Protocols for entangling atoms using Rydberg interactions have been explored theoretically and experimentally over the last decade, but despite major advances, progress in this field has been limited by relatively low fidelities associated with ground-Rydberg state coherent control.

[0005] As described above, qubits encoded in hyperfine states of neutral atoms can be entangled using controlled-phase (*CZ*) or CNOT gates mediated by Rydberg state interactions. The standard Rydberg blockade *CZ* pulse sequence consists of a  $\pi$  pulse on the control qubit, a  $2\pi$  pulse on the target qubit, and a  $\pi$  pulse on the control qubit, with each pulse resonant between a ground hyperfine qubit state  $|1\rangle$  and a Rydberg level  $|r\rangle$ . If the control qubit enters the gate in state  $|1\rangle$ , then it is Rydberg excited and will sit in the Rydberg level during the  $2\pi$  pulse on the target qubit. Excitation and de-excitation of the target atom corresponds to a  $2\pi$  rotation of an effective spin  $\frac{1}{2}$  which therefore imparts a  $\pi$  phase shift to the wavefunction of the target atom. If the control atom blocks the target excitation, then the rotation does not occur and there is no phase shift of the target wavefunction. The result is a *CZ* controlled phase operation, in which the target atom's phase shift depends on the control atom's state. Together with arbitrary single-qubit gates, this entangling operation forms a universal quantum computing gate set. However, single-qubit addressing of multi-qubit quantum gates, as required to apply the local  $\pi$  and  $2\pi$  pulses on the control and target atoms, respectively, remains experimentally challenging.

[0006] Therefore, there is a continuing need for improved systems and methods for implementation of multi-qubit quantum gates.

## SUMMARY

[0007] In an example embodiment, the present disclosure provides a method of operating a quantum gate on a grouping of qubits, the method comprising selecting values for a set of parameters of at least a first and a second laser pulse, the parameters selected from a relative phase shift, a laser frequency, a laser intensity, and a pulse duration, and applying the at least first and second laser pulses to all qubits within a grouping of  $N$

qubits, where  $N$  is equal to two or more, thereby coupling a non-interacting quantum state  $|1\rangle$  to an interacting excited state  $|r\rangle$ , such that each qubit that begins in quantum state  $|1\rangle$  returns to the state  $|1\rangle$  upon completion of the at least first and second laser pulses, and such that qubits in the grouping are mutually blockaded.

[0008] In another example embodiment, the present disclosure provides a method of operating a quantum gate on a grouping of qubits, the method comprising selecting time-dependent values for a set of parameters of a laser pulse, the parameters selected from a laser phase, a laser frequency, a laser intensity, and a pulse duration, and applying the laser pulse to all qubits within a grouping of  $N$  qubits, where  $N$  is equal to three or more, thereby coupling a non-interacting quantum state  $|1\rangle$  to an interacting excited state  $|r\rangle$ , such that each qubit that begins in quantum state  $|1\rangle$  returns to the state  $|1\rangle$  upon completion of the laser pulse, and such that qubits in the grouping are mutually blockaded.

[0009] In yet another example embodiment, the present disclosure provides a device comprising a grouping of  $N$  qubits, where  $N$  is equal to two or more, and a coherent light source configured to, given selected values for a set of parameters of at least a first and a second laser pulse, the parameters selected from a relative phase shift, a laser frequency, a laser intensity, and a pulse duration: apply at least the first and second laser pulses to all qubits within the grouping of  $N$  qubits, thereby coupling a non-interacting quantum state  $|1\rangle$  to an interacting excited state  $|r\rangle$ , such that each qubit that begins in quantum state  $|1\rangle$  returns to the state  $|1\rangle$  upon completion of the at least first and second laser pulses, and such that qubits in the grouping are mutually blockaded.

[0010] In still another example embodiment, the present disclosure provides a device comprising a grouping of  $N$  qubits, where  $N$  is equal to three or more, and a coherent light source configured to, given selected time-dependent values for a set of parameters of a

laser pulse, the parameters selected from a laser phase, a laser frequency, a laser intensity, and a pulse duration: apply the laser pulse to all qubits within a grouping of  $N$  qubits, thereby coupling a non-interacting quantum state  $|1\rangle$  to an interacting excited state  $|r\rangle$ , such that each qubit that begins in quantum state  $|1\rangle$  returns to the state  $|1\rangle$  upon completion of the laser pulse, and such that qubits in the grouping are mutually blockaded.

[0011] The systems and methods described above have many advantages, such as obviating the need for high speed switching of lasers between different spatial locations, thereby enabling gate operations in large qubit arrays, as well as simultaneous operation of multiple gates on multiple separated atom groupings.

#### BRIEF DESCRIPTION OF THE FIGURES

[0012] Various objectives, features, and advantages of the disclosed subject matter can be more fully appreciated with reference to the following detailed description of the disclosed subject matter when considered in connection with the following drawings, in which like reference numerals identify like elements.

[0013] **FIG. 1A** is a schematic diagram representing relevant atomic levels employed in example embodiments of a system described herein.

[0014] **FIG. 1B** is a schematic diagram representing atoms arranged in pairs employed in example embodiments of the system described herein.

[0015] **FIG. 1C** is a plot of Rabi oscillations from  $|0\rangle$  to  $|1\rangle$  driven by Raman lasers employed in example embodiments of the system described herein.

[0016] **FIG. 1D** is a plot of Rabi oscillations from  $|1\rangle$  to  $|r\rangle$  driven by Rydberg lasers employed in example embodiments of the system described herein.

[0017] **FIG. 1E** is a plot of local phase shifts for an addressed target atom and a non-addressed neighbor atom employed in example embodiments of the system described herein.

[0018] **FIG. 2A** is a schematic diagram representing a pulse sequence employed in example embodiments of the system described herein.

[0019] **FIG. 2B** is a schematic diagram representing basis states employed in example embodiments of the system described herein.

[0020] **FIG. 2C** is a schematic diagram representing a two-level system employed in example embodiments of the system described herein.

[0021] **FIG. 2D** is a Bloch sphere representation of a pulse sequence on the two-level system shown in **FIG. 2C** employed in example embodiments of the system described herein.

[0022] **FIG. 2E** is a plot of the accumulated phase shown in **FIG. 2D** as a function of detuning employed in example embodiments of the system described herein.

[0023] **FIG. 2F** is a schematic diagram representing another two-level system employed in example embodiments of the system described herein.

[0024] **FIG. 2G** is a Bloch sphere representation of a pulse sequence on the two-level system shown in **FIG. 2F** employed in example embodiments of the system described herein.

[0025] **FIG. 2H** is a plot of the accumulated phase shown in **FIG. 2G** as a function of detuning employed in example embodiments of the system described herein.

[0026] **FIG. 2I** contains schematic diagrams representing relevant atomic levels of a 3-qubit gate employed in example embodiments of the system described herein.

[0027] **FIGS. 2J-O** contain Bloch sphere representations of a pulse sequence on the two-level systems shown in **FIG. 2I** employed in example embodiments of the system described herein.

[0028] **FIG. 3A** is a schematic diagram representing a quantum circuit employed in example embodiments of the system described herein.

[0029] **FIG. 3B** is a plot of measured populations of computational basis states employed in example embodiments of the system described herein.

[0030] **FIG. 3C** is a plot of parity oscillations as a function of accumulated phase employed in example embodiments of the system described herein.

[0031] **FIG. 3D** is a schematic diagram representing a quantum circuit for a CNOT gate employed in example embodiments of the system described herein.

[0032] **FIG. 3E** is a plot of probabilities of four computational basis states employed in example embodiments of the system described herein.

[0033] **FIG. 3F** is a plot of a CNOT truth table employed in example embodiments of the system described herein.

[0034] **FIG. 4A** is a schematic diagram representing atoms arranged in triplets employed in example embodiments of the system described herein.

[0035] **FIG. 4B** is a schematic diagram representing a quantum circuit for a Toffoli gate employed in example embodiments of the system described herein.

[0036] **FIG. 4C** is a plot of probabilities of eight computational basis states employed in example embodiments of the system described herein.

[0037] **FIG. 4D** is a plot of a Toffoli truth table employed in example embodiments of the system described herein.

[0038] **FIG. 5A** is another schematic diagram representing relevant atomic levels employed in example embodiments of a system described herein.

[0039] **FIG. 5B** is a schematic diagram representing Raman-assisted optical pumping employed in example embodiments of the system described herein.

[0040] **FIGS. 5C-5I** are schematic diagrams representing quantum circuits employed in example embodiments of the system described herein.

[0041] **FIG. 6** is a plot of time variation of the Rydberg Rabi frequency and detuning employed in example embodiments of the system described herein.

[0042] **FIG. 7A** is a schematic diagram representing a quantum circuit for a controlled-phase gate employed in example embodiments of the system described herein.

[0043] **FIG. 7B** is a schematic diagram representing a pulse sequence employed in example embodiments of the system described herein.

[0044] **FIGS. 8A-B** are schematic diagrams representing measurement statistics for the CNOT and Toffoli truth tables employed in example embodiments of the system described herein.

[0045] **FIG. 9** is a schematic diagram representing a quantum circuit for a Toffoli gate employed in example embodiments of the system described herein.

[0046] **FIG. 10** is a plot of target probabilities for a Toffoli gate employed in example embodiments of the system described herein.

[0047] **FIG. 11A** is a schematic diagram representing another set of relevant atomic levels employed in example embodiments of a system described herein.

[0048] **FIG. 11B** is a schematic diagram representing atoms arranged in pairs in a contiguous chain of atoms employed in example embodiments of the system described herein.

## DETAILED DESCRIPTION

[0049] As used herein, the term “qubit” can refer to either a theoretical unit of information in a quantum computer, or a physical implementation of a unit of a quantum circuit. In either case, the term refers to a two-level quantum mechanical system having two basis states, usually denoted as  $|0\rangle$  and  $|1\rangle$ . Whereas a classical “bit,” a theoretical unit of information in a conventional computer, can exist in any one of the two states denoted “0” or “1”, a “qubit” can exist in any state that is a linear combination (superposition) of its two basis states. One example of a physical implementation of a quantum gate operated on two or more qubits comprises atoms (or ions) that can be excited into a Rydberg state (*i.e.*, a state with a very high value of the principal quantum number  $n$ ).

[0050] According to some embodiments, the present disclosure describes methods and systems for operating a quantum gate on a grouping of  $N$  qubits, where  $N$  is equal to two or more qubits. The methods and systems described herein are applicable to a variety of qubits, including atomic qubits, ionic qubits, and molecular qubits. In one example embodiment, a method for realizing multiqubit entangling gates between individual neutral atoms trapped in optical tweezers is introduced. Qubits are encoded in long-lived hyperfine states  $|0\rangle$  and  $|1\rangle$  that can be coherently manipulated individually or globally to perform single-qubit gates. A two-qubit gate, the controlled-phase gate, is implemented with a protocol consisting of two global laser pulses which drive nearby atoms within the Rydberg blockade regime. As described further below, this gate is benchmarked by preparing Bell states of two atoms with a fidelity  $\mathcal{F} \geq 95.0(2)\%$ , averaged across five pairs of atoms. After accounting for state preparation and measurement (SPAM) errors, the extracted entanglement operation fidelity is  $\mathcal{F}^c \geq 97.4(3)\%$ , an operation fidelity that is competitive with other leading platforms capable of simultaneous manipulation of ten

or more qubits. Additionally, an implementation of a three-qubit Toffoli gate is demonstrated further below, wherein two atoms simultaneously constrain a third atom through the Rydberg blockade, highlighting the potential use of Rydberg interactions for efficient multi-qubit operations.

**[0051]** In accordance with one or more embodiments, individual  $^{87}\text{Rb}$  atoms are trapped in optical tweezers and sorted by a real-time feedback procedure into groups of two or three, organized, for example, in a one-dimensional array. Qubits are encoded in the hyperfine ground states of these atoms, with  $|0\rangle = |5S_{1/2}, F=1, m_F=0\rangle$  and  $|1\rangle = |5S_{1/2}, F=2, m_F=0\rangle$ . All qubits are initialized in  $|0\rangle$  through a Raman-assisted optical pumping procedure described further below. Single-qubit coherent control is achieved through a combination of a global laser field that homogeneously drives all qubits, as well as local addressing lasers that apply AC Stark shifts on individual qubits. As shown in **FIGS. 1A-1B**, the global drive field **110** in a device **100** is generated by a 795 nm Raman laser, tuned near the  $5S_{1/2}$  to  $5P_{1/2}$  transition, as described further below. This laser is intensity modulated to produce sidebands which drive the qubits through a two-photon Raman transition with an effective Rabi frequency  $\Omega_{01} \approx 2\pi \times 250$  kHz shown in **FIG. 1C**. The local addressing beams **130** are generated by an acousto-optic deflector that splits a single 420 nm laser, tuned near the  $5S_{1/2}$  to  $6P_{3/2}$  transition, into several beams focused onto individual atoms **131**, resulting in a light shift  $\delta$  used for individual addressing. These two couplings,  $5S_{1/2}$  to  $5P_{1/2}$  and  $5S_{1/2}$  to  $6P_{3/2}$ , are described herein as global  $X(\theta) = \exp(-i\theta X/2)$  qubit rotations and local  $Z(\theta) = \exp(-i\theta Z/2)$  rotations, respectively. After each sequence, the individual qubit states are measured by pushing atoms in  $|1\rangle$  out of the traps with a resonant laser pulse, followed by a site-resolved fluorescence image of the remaining atoms, as described further below.

[0052] Multiqubit gates are operated by globally exciting atoms from the qubit state  $|1\rangle$  to the Rydberg state  $|r\rangle = |70S_{1/2}, m_J = -1/2\rangle$  by a bichromatic Rydberg laser **120** containing 420 nm and 1013 nm light. All atoms are homogeneously coupled from a non-interacting quantum state  $|1\rangle$  to an interacting excited state  $|r\rangle$  through a two-photon process with a detuning  $\Delta$  and an effective Rabi frequency  $\Omega \approx 2\pi \times 3.5$  MHz shown in **FIG 1D**. Within a given cluster of atoms **131** and **132**, the Rydberg interaction between nearest neighbors **131** and **132** is  $2\pi \times 24$  MHz  $\gg \Omega$ ; neighboring atoms **131** and **132**, therefore, evolve according to the Rydberg blockade such that qubits **131** and **132** in the grouping are mutually blockaded in that they cannot be simultaneously excited to the Rydberg state. The protocol described herein can be applied to other mutually blockaded qubits, such as mutually dipole blockaded qubits. As shown in **FIG. 1E**, local phase shifts as measured in a Ramsey sequence, averaged across the five atom pairs **131** and **132** shown in **FIG. 1B**, show high contrast oscillations **135** for the addressed target atom **131** and limited ( $<2\%$ ) crosstalk **140** for the neighboring nonaddressed atom **132**.

[0053] To entangle atoms in such arrays, a protocol is introduced herein for the two-qubit controlled-phase ( $CZ$ ) gate that relies only on global excitation of atoms within the Rydberg blockade regime. As shown in **FIG. 2B**, the desired unitary  $CZ$  gate maps the computational basis states as follows:

$$\begin{aligned}
 |00\rangle &\rightarrow |00\rangle, \\
 |01\rangle &\rightarrow |01\rangle e^{i\phi}, \\
 |10\rangle &\rightarrow |10\rangle e^{i\phi}, \\
 |11\rangle &\rightarrow |11\rangle e^{i(2\phi-\pi)}.
 \end{aligned} \tag{1}$$

[0054] This map is equivalent to the canonical form of the controlled-phase gate  $\mathcal{C}_\phi^{\otimes 2} = 2|00\rangle\langle 00| - \mathbb{1}$  up to a single-qubit phase  $\phi$ . As shown in **FIG. 2A**, two global Rydberg

laser pulses **210** of the same length or duration  $\tau$  and detuning  $\Delta$  that couple  $|1\rangle$  to  $|r\rangle$  are used to realize this gate, with the laser phase **220** of the second pulse **210** shifted by  $\xi$ .

**[0055]** The gate can be understood by considering the behavior of the four computational basis states. The  $|00\rangle$  state is uncoupled by the laser field, and, therefore, does not evolve. The dynamics of  $|01\rangle$  (and  $|10\rangle$ ) are given by the coupling of the single atom on the  $|1\rangle \leftrightarrow |r\rangle$  transition, forming a two-level system with Rabi frequency  $\Omega$  and detuning  $\Delta$ , as shown in **FIG. 2C**. The  $|11\rangle$  state evolves within the Rydberg blockade regime as a two-level system due to the collective coupling from  $|11\rangle \leftrightarrow |W\rangle = (1/\sqrt{2})(|1r\rangle + |r1\rangle)$ , with enhanced Rabi frequency  $\sqrt{2}\Omega$  and the same detuning  $\Delta$ , as shown in **FIG.**

**2F**. For a chosen detuning  $\Delta$ , and a laser intensity selected such that the Rabi frequency of the laser pulses is  $\Omega$ , the pulse length or duration  $\tau$  is, optionally, selected such that the first laser pulse **210** completes a full cycle **230** of a detuned Rabi oscillation for the  $|11\rangle$  system, as shown in **FIG. 2G**, that is,  $\tau = 2\pi/\sqrt{\Delta^2 + K\Omega^2}$ , where ( $N=K=2$ )  $K$  is the number of qubits in the grouping of  $N$  qubits that are mutually blockaded. The same pulse **210** drives an incomplete Rabi oscillation **240** on the  $|01\rangle$  system, as shown in **FIG.**

**2D**. A subsequent relative phase shift  $220 \Omega \rightarrow \Omega e^{i\xi}$  rotates the orientation of the drive field around the  $Z$  axis by an angle  $\xi$  such that a second pulse **210** of length  $\tau$  completes the oscillation **250** and returns the state to  $|01\rangle$ , while driving a second complete detuned oscillation **235** on the  $|11\rangle$  configuration. By the end of the second laser pulse **210**, both  $|01\rangle$  and  $|11\rangle$  return to their initial positions on the Bloch sphere but with accumulated dynamical phases  $\phi_{01}$  and  $\phi_{11}$ , which depend on the geometric surface area of the Bloch sphere enclosed by the  $\Delta$ -dependent trajectories. As shown in **FIG. 2H**, for a specific choice of laser detuning ( $\Delta \approx 0.377 \Omega$ ),  $2\phi_{01} - \pi = \phi_{11}$ , realizing the  $CZ$  gate, with the laser frequency, the pulse duration, and the phase shift selected based on the conditional phase

angle  $\theta$  of the controlled phase gate. Remarkably, this gate protocol is faster (total time  $2\tau \approx 2.732\pi/\Omega$ ) than the traditional approach of sequential local pulses (total time  $4\pi/\Omega$ ), and offers the additional advantage of requiring only global coupling of both qubits.

[0056] Parallel operation of the  $CZ$  gate is demonstrated on five separate pairs of atoms by using the  $CZ$  gate to create Bell states of the form  $|\Phi^+\rangle = (1/\sqrt{2})(|00\rangle + |11\rangle)$  using the quantum circuit shown in **FIG. 3A**. All atomic qubits are initialized in  $|0\rangle$ , then a global  $X(\pi/2)$  Raman pulse is applied to prepare each atom in  $|-\rangle_y = (1/\sqrt{2})(|0\rangle - i|1\rangle)$ . The  $CZ$  gate protocol, consisting of the two Rydberg laser pulses, is then applied over a total time of  $0.4\ \mu\text{s}$ , during which time the optical tweezers are turned off to avoid antitrapping of the Rydberg state. The pulse sequence realizes map (1) discussed above and shown in **FIG. 2B**, along with an additional phase rotation on each qubit due to the light shift of the Rydberg lasers on the hyperfine qubit states. The  $CZ$  gate implementation is embedded in a spin echo sequence to cancel the effect of the light shift, and an additional short light shift is added to eliminate the single-particle phase  $\phi$ , as described further below. Altogether, this realizes a unitary that combines the canonical  $\mathcal{C}_2$  gate with a global  $X(\pi)$  gate as shown in **FIGS. 3A** and **3D**. A final  $X(\pi/4)$  rotation produces the Bell state  $|\Phi^+\rangle$ , as shown in **FIG. 3A** and described further below.

[0057] The experimentally produced state  $\rho$  is characterized by evaluating its fidelity with respect to the target Bell state  $\mathcal{F} = \langle \Phi^+ | \rho | \Phi^+ \rangle$ . The fidelity is the sum of two terms, the first of which is the Bell state populations, given by the probability of observing  $|00\rangle$  or  $|11\rangle$ , as shown in **FIG. 3B**. Raw measurements associating  $|0\rangle$  with atom presence and  $|1\rangle$  with atom absence yield  $97.6(2)\%$  in the target states. Separate measurements of leakage out of the qubit subspace indicate a small contribution to these probabilities; subtracting this contribution, the measured population is  $\geq 95.8(3)\%$ . The second term is

the coherence between  $|00\rangle$  and  $|11\rangle$ , measured by applying a global  $Z(\theta)$  rotation followed by a global  $X(\pi/2)$  rotation, shown in **FIG. 3A**, and observing parity oscillations, shown in **FIG. 3C**. The parity oscillation with respect to accumulated phase  $\theta$  has a measured amplitude of 94.2(4)%. The raw measurement outcomes result in a fidelity of  $\mathcal{F}^{raw} \geq 95.9(2)\%$ . When evaluating the contributions to the fidelity, the atom population left in the Rydberg state is accounted for after the operation and after accounting for background losses. Both of these losses correspond to leakage out of the qubit subspace, and can lead to overestimation of the  $|1\rangle$  population and Bell state fidelities in the raw measurements. Using separate measurements of atoms in both hyperfine qubit states, a conservative upper bound on these leakage errors is determined and subtracted, as described further below. The resulting lower bound on the Bell state fidelity is  $\mathcal{F} \geq 95.0(2)\%$ .

[0058] The measured Bell state fidelity includes errors in state preparation and measurement (SPAM), as well as errors in the two-qubit entangling gate. To characterize the entangling gate specifically, the error contributions from SPAM are evaluated (1.2(1)% per atom), and a SPAM-corrected fidelity  $\mathcal{F}^c \geq 97.4(3)\%$  is computed, as described further below. The majority of the remaining error is due to finite atomic temperature and laser scattering during Rydberg dynamics, as described further below. The native  $\mathcal{C}\mathcal{Z}$  gate is separately characterized by converting it to a controlled-NOT (CNOT) gate with the addition of local hyperfine qubit rotations, as shown in **FIG. 3D**. As shown in **FIG. 3E**, the four computational basis states are prepared with average fidelity of 96.8(2)%. The action of the CNOT gate is measured on each computational basis state to obtain its truth table fidelity to be  $\mathcal{F}_{\text{CNOT}} \geq 94.1(2)\%$ , and  $\mathcal{F}_{\text{CNOT}}^c \geq 96.5(3)\%$ , corrected for SPAM errors, as shown in **FIG. 3F**, and described further below.

[0059] Furthermore, control of multiple atomic qubits is extended to implement the three-qubit controlled-controlled-phase ( $CCZ$ ) gate. This logic operation can be decomposed into five two-qubit gates. Instead, this multiple-control gate is realized directly by preparing three atoms in the nearest-neighbor blockade regime, such that both outer atoms constrain the behavior of the middle atom. The complicated three-atom dynamics makes it challenging to analytically construct global laser pulses that realize a  $CCZ$  gate in this configuration. Therefore, numerical optimization is used to construct a global amplitude and frequency modulated laser pulse which approximately implements the  $CCZ$  gate, as described further below. The laser pulse is optimized through the remote dressed chopped random basis (RedCRAB) optimal control algorithm.

[0060] The  $CCZ$  gate is implemented in parallel on four triplets of atomic qubits using the same lasers as for two-qubit gates described above, as shown in **FIG. 4A**. The three atoms **410**, **420**, and **430** in each triplet are arranged such that nearest neighbors (**410**, **420**, and **420**, **430**) are blockaded by the strong  $2\pi \times 24$  MHz interaction, as in the two-qubit implementation. The edge atoms **410**, and **430** interact with each other weakly ( $2\pi \times 0.4$  MHz). As with the two-qubit gate, the  $CCZ$  gate is embedded in a spin echo sequence to cancel light shifts, such that the gate implements  $CCZ$  along with a global  $X(\pi)$  rotation. The performance of this three-qubit gate is characterized by converting it into a Toffoli gate by applying a local Hadamard on the middle atom **420** before and after the  $CCZ$  gate (along with edge  $X(\pi)$  pulses, to simplify implementation, as shown in **FIG. 4B** and described further below). Eight computational basis states are prepared with average fidelity of 95.3(3)%, as shown in **FIG. 4C**. The Toffoli gate is applied to each computational basis state to measure the truth table fidelity  $\mathcal{F}_{\text{Toff}} \geq 83.7(3)\%$ , and  $\mathcal{F}_{\text{Toff}}^c \geq 87.0(4)\%$ , corrected for SPAM errors, as shown in **FIG. 4D**, and described further below. Additionally, “limited tomography” was performed, consisting of truth table

measurements in a rotated basis, to verify the phases of the Toffoli unitary in a more experimentally accessible manner than full process tomography. The limited tomography fidelity is  $\mathcal{F}_{\text{LT}}^c \geq 86.2(6)\%$ , as described further below.

[0061] These results can be directly improved and extended along several directions. The fidelity of Rydberg coupling is primarily limited by finite atomic temperature and off-resonant laser scattering, which can be addressed by sideband cooling of atoms within optical tweezers and by higher power lasers. The background atomic loss and state preparation can be improved using higher quality vacuum systems and more sophisticated state preparation techniques. Finally, atomic qubit readout can be improved using recently demonstrated nondestructive readout protocols to give stronger constraints on the atomic populations.

[0062] While parallel gate implementation on spatially separated clusters of atoms was performed herein, the same approach can be extended to nonlocal coupling within contiguous atom arrays using local addressing with an additional off-resonant laser system. Specifically, subsets of the array could be simultaneously illuminated to create light shifts that bring them into resonance with a global resonant Rydberg excitation laser, as described further below. Furthermore, with more atoms arranged in the blockade volume, the controlled-phase gate demonstrated here can be extended to higher multiqubit gates with global coupling, as described further below. The dipolar interaction between  $S$  and  $P$  Rydberg states could also be used to achieve improved gate connectivity between qubits. A combination of the present results with recently demonstrated trapping and rearrangement of individual neutral atoms in two-dimensional (2D) and three-dimensional (3D) arrays will be well-suited for the implementation of deep quantum circuits or variational quantum optimization with hundreds of qubits. In addition, such a

platform could be utilized to explore efficient methods for error correction and fault-tolerant operation to eventually enable scalable quantum processing.

#### Raman Laser

[0063] Transitions between qubit states are driven using a 795 nm Raman laser that is  $2\pi \times 100$  GHz red-detuned from the  $5S_{1/2}$  to  $5P_{1/2}$  transition. The laser is coupled into a fiber-based Mach-Zehnder intensity modulator (Jenoptik AM785) that is DC biased around minimum transmission. The modulator is driven at half the qubit frequency ( $\omega_{01} = 2\pi \times 6.83$  GHz), resulting in sidebands at  $\pm 2\pi \times 3.42$  GHz, while the carrier and higher order sidebands are strongly suppressed. This approach is passively stable on the timescale of one day without any active feedback, in contrast with other approaches to generate sidebands through phase modulation and then separate suppression of the carrier mode with free-space optical cavities or interferometers.

[0064] The Raman laser is aligned along the array of atoms (co-aligned with the 8.5 G bias magnetic field) and is  $\sigma^+$  polarized, such that the two sidebands coherently drive  $\pi$  transitions between the  $F = 1$  and  $F = 2$  ground state manifolds with a Rabi frequency of  $\Omega = 2\pi \times 250$  kHz, as shown in **FIG. 5A**. The Raman drive light induces a differential light shift of  $2\pi \times 20$  kHz on the qubit transition; the drive frequency of the intensity modulator is adjusted to correct for this light shift when a Raman pulse is applied.

#### Optical Pumping into $|0\rangle$

[0065] Atoms are optically pumped into  $|0\rangle = |5S_{1/2}, F=1, m_F = 0\rangle$  using a Raman-assisted pumping scheme with an 8.5 G magnetic field. As shown in **FIG. 5B**, coarse pumping of atoms into all  $m_F$  states within the  $|5S_{1/2}, F=1\rangle$  manifold begins by shining

resonant light on the  $|5S_{1/2}, F=2\rangle$  to  $|5P_{3/2}, F=2\rangle$  transition. A Raman  $\pi$  pulse is then applied at a detuning that drives population from  $|F=1, m_F=-1\rangle$  to  $|F=2, m_F=-1\rangle$ . A second pulse drives population from  $|F=1, m_F=+1\rangle$  to  $|F=2, m_F=+1\rangle$ . The process then repeats by again coarse pumping any population that was transferred to  $F=2$  back into the  $F=1$  manifold. The net effect of one cycle is to transfer a portion of the population in  $|F=1, m_F=\pm 1\rangle$  into  $|F=1, m_F=0\rangle$ . This cycle is typically repeated 70 times over a duration of 300  $\mu$ s to achieve a  $|0\rangle$  preparation fidelity of 99.3(1)%.

#### Rydberg Laser System

[0066] Atoms are coupled from  $|1\rangle = |5S_{1/2}, F=2, m_F=0\rangle$  to  $|r\rangle = |70S_{1/2}, m_J = -1/2\rangle$  through a two-color laser system at 420 nm and 1013 nm. The lasers are polarized to drive  $\sigma^-$  and  $\sigma^+$  transitions, respectively, through an intermediate state  $|6P_{3/2}\rangle$ . In previous implementations using  $|5S_{1/2}, F=2, m_F=-2\rangle$  as the ground state level, selection rules ensured that only a single intermediate sublevel within  $|6P_{3/2}\rangle$  and only a single Rydberg state could be coupled. Additionally, the combined two-photon transition was magnetically insensitive.

[0067] Coupling from  $|1\rangle = |5S_{1/2}, F=2, m_F=0\rangle$  to Rydberg states, as described herein, adds a few complications. Firstly, multiple intermediate states are coupled and both  $|70S_{1/2}, m_J = \pm 1/2\rangle$  sublevels within the Rydberg manifold can be reached. This requires working at a higher magnetic field to spectrally separate the  $m_J = \pm 1/2$  Rydberg levels. In the embodiments described herein, a magnetic field of 8.5 G produces a splitting between  $m_J = \pm 1/2$  of  $2\pi \times 23.8$  MHz. The matrix element is also reduced in the coupling from  $|1\rangle$  to  $|r\rangle$  while the laser scattering rate stays the same; additionally, the transition is now magnetically sensitive. Nonetheless, this scheme benefits from high-quality qubit states

$|0\rangle$  and  $|1\rangle$  within the ground state manifold that can be easily coupled with a Raman laser system and that preserve coherence in optical tweezers. Note that the sensitivity to electric fields is unchanged in this scheme, but drifting or fluctuating electric fields can be bounded such that the Rydberg resonance varies by less than 50 kHz.

[0068] One additional complication in this implementation is coupling to another Rydberg state  $|\bar{r}\rangle$ . However, this coupling merely gives rise to an AC Stark shift that can be taken into account by appropriate renormalization of the detuning  $\Delta$ .

#### Constructing Quantum Circuits from Native Single-Qubit Gates

[0069] All pulse sequences described above are decomposed into pre-calibrated single-qubit gates (and, where indicated above, global multi-qubit gates). The two single-qubit gates are  $X(\pi/4)$ , implemented globally on all qubits simultaneously, and  $Z(\pi)$ , implemented by a light shift from a laser focused onto a single atom. In practice, the local  $Z(\pi)$  gates are applied to one atom from each cluster at the same time (*i.e.*, the left atom of each cluster or the middle of each cluster).

#### Initializing Computational Basis States

[0070] For two qubits, all four computational basis states are initialized using global  $X(\pi/2)$  pulses (consisting of two sequential  $X(\pi/4)$  gates) and local  $Z(\pi)$  gates on the left atom only (top qubit in each circuit)). The  $|00\rangle$  state requires no pulses to prepare, and the  $|11\rangle$  state requires only a global  $X(\pi)$  gate. The state  $|01\rangle$  is prepared as shown in **FIG. 5C**, and the state  $|10\rangle$  is prepared as shown in **FIG. 5D**.

[0071] For three qubits, the eight computational basis states are again initialized using  $X(\pi/2)$  pulses and local  $Z(\pi)$  pulses that can be applied to any of the three atoms.  $|000\rangle$

and  $|111\rangle$  can again be prepared with either no operation or with a global  $X(\pi)$  gate, respectively. Other states have one atom in  $|1\rangle$  and other two in  $|0\rangle$  or *vice versa*. How both configurations are prepared is illustrated herein by showing two examples. First,  $|100\rangle$  is prepared as shown in **FIG. 5E**. Second, preparation of  $|110\rangle$  requires instead local addressing on the rightmost atom, as shown in **FIG. 5F**.

#### Local $X(\pi/2)$ for CNOT Gate

[0072] To convert the  $\mathcal{C}_2$  gate to the CNOT gate, a local  $X(\pi/2)$  is applied to the target atom before and after the gate, implemented as shown in **FIG. 5G**. The circuit shown in **FIG. 5G** applies a local  $X(\pi/2)$  on the right atom; while it additionally applies a  $Z(\pi)$  gate on the left atom, this circuit is only applied in a context in which the left atom is in a computational basis state  $|0\rangle$  or  $|1\rangle$ , in which case the  $Z(\pi)$  gate only introduces a global phase and therefore plays no role. In general, applying additional  $Z(\pi)$  gates could be used to cancel the effect on the left atom, but this was not necessary for the implementations described herein.

#### Local Hadamard for Toffoli Implementation

[0073] To convert the  $CCZ$  gate to a Toffoli gate, a local rotation is applied on the target (middle) qubit before and after the  $CCZ$  pulse. The simplest method to accomplish this given this native gate set is to apply a global  $X(\pi/4)$ , followed by a local  $Z(\pi)$  on the middle qubit, and then a global  $X(3\pi/4)$ , as shown in **FIG. 5H**.

[0074] On each edge qubit, the net effect is simply an  $X(\pi)$  gate. On the middle qubit, this sequence constitutes a Hadamard gate (defined along a different axis than the typical definition), where

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & i \\ -i & -1 \end{pmatrix} \quad (2)$$

### Design of Two-Qubit CZ Gate

[0075] This section provides a detailed theoretical discussion of the two-qubit gate realized herein. The desired unitary operation maps the computational basis states as follows:

$$\begin{aligned} |00\rangle &\rightarrow |00\rangle, \\ |01\rangle &\rightarrow |01\rangle \\ |10\rangle &\rightarrow |10\rangle \\ |11\rangle &\rightarrow |11\rangle e^{i\pi}. \end{aligned} \quad (3)$$

[0076] Up to a global gauge choice (*i.e.*, a global rotation of the qubits), this is equivalent to the following gate:

$$\begin{aligned} |00\rangle &\rightarrow |00\rangle, \\ |01\rangle &\rightarrow |01\rangle e^{i\phi_1} \\ |10\rangle &\rightarrow |10\rangle e^{i\phi_1} \\ |11\rangle &\rightarrow |11\rangle e^{i(2\phi_1+\pi)}. \end{aligned} \quad (4)$$

where  $\phi_1$  is arbitrary.

[0077] To realize such a gate, both atoms are driven globally and homogeneously with a laser that couples state  $|1\rangle$  to the Rydberg state  $|r\rangle$ . This can be achieved via a single laser field or by a two-photon process. The Hamiltonian governing the dynamics of a pair of atoms is given by

$$H = \sum_{i=1}^2 \frac{1}{2} (\mathcal{Q}|1\rangle_i \langle r| + \mathcal{Q}^* |r\rangle_i \langle 1|) - \Delta |r\rangle_i \langle r| + V |r\rangle_1 \langle r| \otimes |r\rangle_2 \langle r|$$

where  $\Delta$  is the detuning of the excitation laser from the transition frequency between states  $|1\rangle$  and  $|r\rangle$ , and  $\Omega$  is the corresponding Rabi frequency. The interaction strength between two atoms in Rydberg states is given by  $V$ . In the following analysis, it is first assumed that  $V \gg |\Omega|, |\Delta|$ , which can be realized by trapping the atoms sufficiently close to each other. This so-called Rydberg blockade regime simplifies the following description, but is not required for the realization of the gate.

[0078] The dynamics of the system decouple into a few simple sectors:

- (i) The state  $|00\rangle$  does not evolve.
- (ii) If one of the atoms is in  $|0\rangle$ , only the other system evolves. The dynamics are thus equivalent to that of a two-level system (TLS) with states  $|1\rangle = |a_1\rangle$  and  $|r\rangle = |b_1\rangle$  and Hamiltonian

$$H_1 = \frac{1}{2}(\Omega|a_1\rangle\langle b_1| + \Omega^*|b_1\rangle\langle a_1|) - \Delta|b_1\rangle\langle b_1|.$$

- (iii) If both atoms are initially in state  $|1\rangle$ , then the dynamics are again equivalent to that of an effective single TLS, formed by the states  $|11\rangle = |a_2\rangle$  and  $\frac{1}{\sqrt{2}}(|r, 1\rangle + |1, r\rangle) = |b_2\rangle$ , with Hamiltonian

$$H_2 = \frac{\sqrt{2}}{2}(\Omega|a_2\rangle\langle b_2| + \Omega^*|b_2\rangle\langle a_2|) - \Delta|b_2\rangle\langle b_2|.$$

This assumes a perfect Rydberg blockade, equivalent to  $V \rightarrow \infty$ . Note, however, that this assumption simplifies the analysis, but is not necessary to realize the gate described herein.

[0079] The controlled-phase gate can be constructed from two identical pulses of the Rydberg laser field, with equal duration  $\tau$  and detuning  $\Delta$ , along with a phase jump (*i.e.*, relative phase shift) by  $\zeta$  in between. Each pulse changes the state of the atoms according

to the unitary  $U = \exp(-iH\tau)$ . The change of the laser phase between pulses,  $\Omega \rightarrow \Omega e^{i\xi}$ , effectively corresponds to driving the system around a different axis on the Bloch sphere.

[0080] Consider how the four computational basis states evolve under the action of  $\mathcal{U}$ , which describes the effect of both laser pulses combined. First, note that  $\mathcal{U}|00\rangle = |00\rangle$ .

Thus, the unitary  $\mathcal{U}$  maps the state  $|00\rangle$  as expected for the CZ gate.

[0081] Next, consider the evolution of state  $|11\rangle$ , wherein all qubits in the grouping begin in the quantum state  $|1\rangle$ . The length or duration of each pulse  $\tau$  is, optionally, chosen such that a system prepared in state  $|11\rangle$  undergoes a complete, detuned Rabi oscillation and returns to the state  $|11\rangle$  already after the first laser pulse; that is  $U|11\rangle = e^{i\phi_2/2}|11\rangle$ . The return to the state  $|11\rangle$  is ensured by the choice of  $\tau$  as

$$\tau = 2\pi / \sqrt{\Delta^2 + 2\Omega^2} \quad (5)$$

The second laser pulse also leads to a complete, detuned Rabi cycle about a different axis, such that all qubits in the grouping return to the quantum state  $|1\rangle$  upon completion of each of the first and the second laser pulses, with the second laser pulse resulting in the same accumulated phase. In total,  $U|11\rangle = e^{i\phi_2}|11\rangle$ . The dynamical phase accumulated by this process is given by  $\phi_2 = 2\pi \times 2\Delta / \sqrt{\Delta^2 + 2\Omega^2}$ .

[0082] Finally, consider the evolution of the states  $|01\rangle$  and  $|10\rangle$ . In each case, this evolution is also described by a detuned Rabi oscillation. However, due to the mismatch between the effective Rabi frequencies in  $H_1$  and  $H_2$ , the state  $|10\rangle$  ( $|01\rangle$ ) does not return to itself after the time  $\tau$  but a superposition state is created:  $U|10\rangle = \cos(\alpha)|10\rangle + \sin(\beta)e^{i\gamma}|r0\rangle$ , and  $U|01\rangle = \cos(\alpha)|01\rangle + \sin(\beta)e^{i\gamma}|0r\rangle$ . The real coefficients  $\alpha$ ,  $\beta$ , and  $\gamma$ , are determined by the choice of  $\Omega$ ,  $\Delta$ , and  $\tau$ . By a proper choice of the phase jump (*i.e.*, relative phase shift) between the first and the second laser pulse,  $\xi$ , one can always

guarantee that the system returns to the state  $|10\rangle$  ( $|01\rangle$ ) after the second laser pulse. The phase jump can be calculated as

$$e^{-i\xi} = \frac{-\sqrt{y^2+1}\cos\left(\frac{1}{2}s\sqrt{y^2+1}\right)+iysin\left(\frac{1}{2}s\sqrt{y^2+1}\right)}{\sqrt{y^2+1}\cos\left(\frac{1}{2}s\sqrt{y^2+1}\right)+iysin\left(\frac{1}{2}s\sqrt{y^2+1}\right)} \quad (6)$$

where  $y = \Delta/\Omega$  and  $s = \Omega\tau$ . With this choice of the phase,  $U|10\rangle = e^{-i\phi_1}|10\rangle$  and  $U|01\rangle = e^{-i\phi_1}|01\rangle$ , and each qubit that begins in quantum state  $|1\rangle$  returns to the state  $|1\rangle$  upon completion of the first and second laser pulses. The acquired dynamical phase can be calculated using straightforward algebra, and is a function of  $\Delta/\Omega$ ,  $\tau\Omega$ , and  $\xi$ . As  $\tau$  is fixed in Equation (5), and  $\xi$  is fixed in Equation (6),  $\phi_1$  is actually solely determined by the dimensionless quantity  $\Delta/\Omega$ . Note that  $\phi_2$  is also only a function of  $\Delta/\Omega$ . However, the functional dependence is different, and a choice can be found for  $\Delta/\Omega$  such that  $e^{i\phi_2} = e^{i(2\phi_1+\pi)}$ , as shown in **FIG. 2H**. With these selected values for the set of parameters of the first and second laser pulses, the parameters selected from the relative phase shift, the laser frequency, the laser intensity, and the pulse duration, the gate given in map (4) is exactly obtained, which is equivalent to the controlled-phase gate map (3) (up to trivial single qubit rotations). The corresponding numerical values of the relevant parameters are:

$$\Delta/\Omega = 0.377371 \quad (7)$$

$$\xi = 3.90242 \quad (8)$$

$$\Omega\tau = 4.29268 \quad (9)$$

where  $\xi$  has units of radians.

[0083] Note that, as described further below, this construction can be generalized to multi-qubit controlled-phase gates in fully blockaded systems with more than two atoms.

## Accounting for Imperfect Blockade

[0084] The above analysis is based on the perfect blockade mechanism. Finite blockade interactions (and other imperfections, such as coupling to other Rydberg states) can be accounted for, and lead only to an effective renormalization of the parameters given in Equations (7-9). To see this, note that a finite value of  $V$  only affects the dynamics if the system is initially in the state  $|11\rangle$ . Instead of being restricted to the two states  $|a_2\rangle = |11\rangle$  and  $|b_2\rangle = (|1r\rangle + |r1\rangle)$ , a third state  $|c_2\rangle = |rr\rangle$  has to be considered, and  $H_2$  is replaced by

$$H_2 = \frac{\sqrt{2}}{2} (\Omega |a_2\rangle \langle b_2| + \Omega |b_2\rangle \langle c_2| + \Omega^* |c_2\rangle \langle b_2| + \Omega^* |b_2\rangle \langle a_2|) - \Delta |b_2\rangle \langle b_2| + (V - 2\Delta) |c_2\rangle \langle c_2|. \quad (10)$$

For  $V \gg |\Delta|, |\Omega|$ , the effect for finite blockade simply reduces to the two-level system  $\{|a_2\rangle, |b_2\rangle\}$  where  $\Delta$  is renormalized by an amount  $\Omega^2/(2V)$ . Even for small  $V > 0$  and a given  $\Delta, \Omega$  and  $\tau$  can always be chosen such that the system initialized in the state  $|a_2\rangle$  returns to the state  $|a_2\rangle$  after the first pulse. Thus, finite blockade simply replaces the complete Rabi oscillation in the fully blockaded regime by a slightly more complicated, but still closed path in a two-dimensional Hilbert space. The analysis of the dynamics of the other computational basis states is unaffected by the finite value of  $V$ . It is thus straightforward to ensure that a system initially in the state  $|10\rangle$  returns to  $|10\rangle$  for each choice of  $V$  and  $\Delta$ . This enables one to use  $\Delta$  as a control knob for the relative dynamical phases acquired by  $|11\rangle$  and  $|10\rangle$ , and thus realize a  $CZ$  gate for all values of  $V$ . Three example solutions are listed in Table 1.

Table 1.

| Example 1                  | Example 2                   | Example 3                   |
|----------------------------|-----------------------------|-----------------------------|
| $V/\Omega = 2.7685$        | $V/\Omega = 4.31092$        | $V/\Omega = 7.28278$        |
| $\Delta/\Omega = 0.539911$ | $\Delta/\Omega = -0.320228$ | $\Delta/\Omega = -0.342217$ |
| $\zeta = -2.21031$         | $\zeta = 2.52094$           | $\zeta = 2.46328$           |

#### Experimental Calibration of CZ Gate

[0085] The CZ gate requires two laser pulses with a relative phase shift between them. The detuning of the two pulses  $\Delta$  is determined relative to the experimentally calibrated Rydberg resonance by numerical calculations. The pulse time and the phase jump between pulses both require experimental calibration due to perturbations in timing and phase associated with an acousto-optic-modulator (AOM)-based control system. The pulse time  $\tau$  is calibrated first by preparing both atoms in the qubit pair in  $|1\rangle$  and driving at detuning  $\Delta$  to the Rydberg state. Detuned Rabi oscillations to the symmetrically excited state  $|W\rangle = \frac{1}{\sqrt{2}}(|1r\rangle + |r1\rangle)$  are observed, and the pulse time at which the population returns fully to  $|11\rangle$  is extracted.

[0086] After fixing  $\tau$ , only single isolated atoms are prepared in  $|1\rangle$  and two pulses of length  $\tau$  are driven with a variable relative phase. The relative phase  $\zeta$  is fixed by identifying the phase for which the single atom returns fully to  $|1\rangle$  by the end of the sequence.

[0087] Finally, a calibration is described herein of the global phase shift necessary to convert the CZ gate (with single-particle phase  $\phi$ ) into the canonical form:

$$\mathcal{C}_Z^{\otimes 2} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}. \quad (11)$$

[0088] This phase correction is implemented by applying the global 420 nm laser for a fixed time in the absence of the 1013 nm Rydberg light; this avoids any resonant Rydberg excitation and instead only adds a phase shift. To calibrate the phase correction, the Bell state sequence is applied, in which an attempt is made to prepare the Bell state  $|\Phi^+\rangle$  and then an additional  $X(\pi/2)$  rotation is applied to both qubits. If the phase correction is optimal, then the state  $|\Psi^+\rangle$  should be prepared, which can be measured in populations. The global phase correction is varied to maximize the measured populations in  $|\Psi^+\rangle$  at the end of this sequence.

#### Preparation of Bell State Using $\mathcal{C}\mathcal{P}$ Gate and $\pi/4$ Pulse

[0089] The global implementation of the  $\mathcal{C}\mathcal{P}$  gate described herein enables the preparation of Bell states with no local addressing. The protocol is most naturally understood by describing the two-qubit system in the Bell basis:

$$|\Psi^\pm\rangle = \frac{1}{\sqrt{2}}(|01\rangle \pm |10\rangle) \quad (12)$$

$$|\Phi^\pm\rangle = \frac{1}{\sqrt{2}}(|00\rangle \pm |11\rangle) \quad (13)$$

The system is prepared in  $|11\rangle$ , and after a global  $X(\pi/2)$  pulse, the following state is prepared:

$$|\psi_1\rangle = \frac{1}{2}(|00\rangle - i|01\rangle - i|10\rangle - |11\rangle) \quad (14)$$

The controlled phase gate creates the state

$$|\psi_2\rangle = \mathcal{C}\mathcal{P}|\psi_1\rangle = \frac{1}{2}(|00\rangle - i|01\rangle - i|10\rangle - |11\rangle) \quad (15)$$

$$= \frac{1}{\sqrt{2}}(|\Phi^+\rangle + i|\Psi^+\rangle) \quad (16)$$

The states  $|\Phi^+\rangle$  and  $|\Psi^+\rangle$  are both within the triplet manifold of the two qubits and are coupled resonantly by a global drive field to form an effective two-level system with

twice the single-particle Rabi frequency. A  $\pi/2$  pulse within this effective two-level system corresponds to a  $\pi/4$  pulse at the single-particle Rabi frequency, and maps:

$$|\psi_2\rangle = \frac{1}{\sqrt{2}}(|\Phi^+\rangle + i|\Psi^+\rangle) \rightarrow |\psi_3\rangle = |\Phi^+\rangle \quad (17)$$

Implementation of the *CCZ* Gate

[0090] One can generalize the above two-qubit gate to a 3-qubit gate controlled-controlled-phase gate with a mapping given by

$$\begin{aligned} |000\rangle &\rightarrow |000\rangle \\ |001\rangle &\rightarrow |001\rangle e^{i\phi_1} \\ |010\rangle &\rightarrow |010\rangle e^{i\phi_1} \\ |100\rangle &\rightarrow |100\rangle e^{i\phi_1} \\ |011\rangle &\rightarrow |011\rangle e^{2i\phi_1} \\ |101\rangle &\rightarrow |101\rangle e^{2i\phi_1} \\ |110\rangle &\rightarrow |110\rangle e^{2i\phi_1} \\ |111\rangle &\rightarrow |111\rangle e^{i(3\phi_1+\pi)} \end{aligned} \quad (18)$$

which is equivalent to a controlled-controlled-phase gate (up to global single qubit rotations).

[0091] The dynamics of the three atoms involved are described by the Hamiltonian

$$\begin{aligned} H = \sum_{i=1}^3 \left( \frac{\Omega}{2} (|1\rangle_i \langle r| + |r\rangle_i \langle 1|) - \Delta |r\rangle_i \langle r| \right) &+ V_{1,2} |r\rangle_1 \langle r| \otimes |r\rangle_2 \langle r| + V_{2,3} |r\rangle_2 \langle r| \otimes |r\rangle_3 \langle r| \\ &+ V_{1,3} |r\rangle_1 \langle r| \otimes |r\rangle_3 \langle r| \end{aligned}$$

[0092] Consider an arrangement of the three atoms such that they are all within the blockade radius, that is, all qubits in the grouping are mutually blockaded such that effectively no two atoms can be simultaneously excited to the Rydberg state, meaning that  $V_{ij} \gg |\Omega| \gg |\Delta|$ . Then, the only difference from the discussion above of the 2-qubit

controlled-phase gate is that now there is an additional two-level system that has to be considered, with states  $|111\rangle = |e\rangle$  and  $\frac{1}{\sqrt{3}}(|11r\rangle + |1r1\rangle + |r11\rangle) = |f\rangle$ , and

Hamiltonian

$$H_3 = \frac{\sqrt{3}\Omega}{2}(|e\rangle\langle f| + |f\rangle\langle e|) - \Delta|f\rangle\langle f|.$$

[0093] A sequence of pulses interspersed with jumps (*i.e.*, relative phase changes) of the laser driving phase is used to realize a doubly-controlled-phase gate, as described by

$$[0094] \quad \mathcal{U} = \prod_{l=1}^p \exp(-i\xi_l) \exp(-iH\tau). \quad (19)$$

[0095] This pulse sequence is a generalization of the above two-qubit pulse sequence, with  $p$  cycles (of equal length, Rabi frequency, and detuning), interspersed with  $p-1$  relative changes of the laser phase ( $\xi_p = 0$  without loss of generality). The controlled-controlled-phase gate can be realized with  $p = 6$  pulses and a palindromic (e.g., symmetric) sequence of pulses, where  $\xi_l = \xi_{p-l}$ .

[0096] As used herein, the term “palindromic,” when referring to a sequence (a train) of ordered pulses, means that the sequence remains the same when reversed in order. An example of a palindromic sequence of laser pulses is a “symmetrical” sequence, *i.e.*, a sequence of laser pulses that starts at time  $t = t_0$  and terminates at time  $t = t_1$ , characterized in that the plot of the amplitude of laser light as a function of time  $A = A(t)$  has a reflection symmetry about the line  $t = \frac{1}{2}(t_1 - t_0)$ .

[0097] The pulse length or duration is again, optionally, chosen ( $N=K=3$ ) to be

$$\tau = 2\pi / \sqrt{\Delta^2 + 3\Omega^2}, \quad (20)$$

such that  $\exp(-iH\tau)|111\rangle = \exp(i\phi_3/6)|111\rangle$ . This choice of  $\tau$  ensures that the fastest effective two-level system completes a detuned Rabi oscillation upon completion of each of the 6 pulses. The three parameters quantifying the phase jumps (*i.e.*, relative phase

changes)  $\xi_1$ ,  $\xi_2$ , and  $\xi_3$  are determined such that a system initialized in one of the three basis states returns to the same state (up to a dynamical phase) after the 6 pulses. That is,  $\mathcal{U}|001\rangle = \exp(i\phi_1)|001\rangle$ ,  $\mathcal{U}|011\rangle = \exp(i\phi_2)|011\rangle$ . The other states satisfy corresponding equations by symmetry, and the state  $|000\rangle$  trivially does not evolve. In addition to the above conditions, the dynamical phases acquired in these dynamics satisfy  $\exp(i2\phi_1) = \exp(i\phi_2)$  and  $\exp(i3\phi_1) = \exp(i\phi_3 + \pi)$ . The four independent free parameters  $\Delta/\Omega$ ,  $\xi_1$ ,  $\xi_2$ , and  $\xi_3$  are numerically determined from these 4 equations. A specific solution is given by

$$\Delta/\Omega = -0.229479 \quad (21)$$

$$\xi_1 = 0.5869771 = \xi_5 \quad (22)$$

$$\xi_2 = 4.5323846 = \xi_4 \quad (23)$$

$$\xi_3 = 6.2250881 \quad (24)$$

[0098] The three two-level systems, denoted **A**, **B**, and **C**, are shown in **FIG. 2I**. The first pulse is shown in **FIGS. 2J-O** as **A10**, **B10**, and **C10**. In **FIGS. 2J-O**, the notation **X##** is used — the letter indicates the two-level system **A**, **B**, or **C**, the first number indicates the pulse number **1-6**, and the second number indicates the phase shift number **1-5**. As illustrated in Bloch sphere **C10**, the first pulse **C10** leads to a complete, detuned Rabi cycle at an enhanced Rabi frequency of  $\sqrt{3}\Omega$  and detuning  $\Delta$  shown in **FIG. 2I**, system **C**. As shown in Bloch spheres **A10** and **B10**, the first pulse **A10** and **B10** leads to an incomplete Rabi cycle for the two-level systems **A** and **B**, with the same detuning  $\Delta$ , Rabi frequency  $\Omega$  for the two-level system **A**, and enhanced Rabi frequency  $\sqrt{2}\Omega$  for the two-level system **B**, as shown in **FIG. 2I**, systems **A** and **B**, respectively. The first phase shift, ( $\xi_1=0.5869771$  rad $\approx 33^\circ$ ) is shown as **A11** and **B11** in Bloch spheres **A11** and **B11**, respectively. As shown in Bloch sphere **C11**, the two-level system **C** is in its ground state and therefore is unchanged by the phase shift, remaining at the south pole **C11** of the

Bloch sphere during this phase shift. The second pulse **C21** again leads to a complete, detuned Rabi cycle, as shown in Bloch sphere **C21**, and incomplete Rabi cycles **A21** and **B21**, as shown in Bloch spheres **A21** and **B21**, respectively. The second phase shift, ( $\xi_2=2\pi-4.5323846 \text{ rad} \approx -100^\circ$ ) is shown as **A22** and **B22** in Bloch spheres **A22**, and **B22**, respectively. As shown in Bloch sphere **C22**, the two-level system **C** is in its ground state and therefore is again unchanged by the phase shift, remaining at the south pole **C22** of the Bloch sphere during this phase shift. The third pulse **C32** again leads to a complete, detuned Rabi cycle, as shown in Bloch sphere **C32**, and incomplete Rabi cycles **A32** and **B32**, as shown in Bloch spheres **A32** and **B32**, respectively. The third phase shift, ( $\xi_3=2\pi-6.2250881 \text{ rad} \approx -3.3^\circ$ ) is shown as **A33** and **B33** in Bloch spheres **A33**, and **B33**, respectively. As shown in Bloch sphere **C33**, the two-level system **C** is in its ground state and therefore is again unchanged by the phase shift, remaining at the south pole **C33** of the Bloch sphere during this phase shift. The fourth pulse **C43** again leads to a complete, detuned Rabi cycle, as shown in Bloch sphere **C43**, and incomplete Rabi cycles **A43** and **B43**, as shown in Bloch spheres **A43** and **B43**, respectively. The fourth phase shift, ( $\xi_4=\xi_2=2\pi-4.5323846 \text{ rad} \approx -100^\circ$ ) is shown as **A44** and **B44** in Bloch spheres **A44**, and **B44**, respectively. As shown in Bloch sphere **C44**, the two-level system **C** is in its ground state and therefore is again unchanged by the phase shift, remaining at the south pole **C44** of the Bloch sphere during this phase shift. The fifth pulse **C54** again leads to a complete, detuned Rabi cycle, as shown in Bloch sphere **C54**, and incomplete Rabi cycles **A54** and **B54**, as shown in Bloch spheres **A54** and **B54**, respectively. The fifth phase shift, ( $\xi_5=\xi_1=0.5869771 \text{ rad} \approx 33^\circ$ ) is shown as **A55** and **B55** in Bloch spheres **A55**, and **B55**, respectively. As shown in Bloch sphere **C55**, the two-level system **C** is in its ground state and therefore is again unchanged by the phase shift, remaining at the south pole **C55** of the Bloch sphere during this phase shift. The sixth pulse **A65** and **B65**

returns the **A** and **B** two-level systems to their initial positions, as shown in Bloch sphere **A65** and **B65**, respectively, and completes a final detuned Rabi cycle **C65**, as shown in Bloch sphere **C65**.

[0099] Another version of this gate can be constructed if the atoms are arranged such that  $V_{1,2}, V_{2,3} \gg |\Omega|, |\Delta|$ , and  $V_{1,3} \ll |\Omega|, |\Delta|$ . The same palindromic (e.g., symmetric) 6-pulse ansatz described by Eq. (19) is used, now with the pulse length or duration  $\tau$  optionally chosen ( $K=2$ ) as

$$\tau = 2\pi/\sqrt{\Delta^2 + 2\Omega^2}, \quad (25)$$

and parameters

$$\Delta/\Omega = 0.0422037 \quad (26)$$

$$\zeta_1 = -1.20646 = \zeta_5 \quad (27)$$

$$\zeta_2 = 5.18936 = \zeta_4 \quad (28)$$

$$\zeta_3 = 5.30347 \quad (29)$$

This set of parameters gives approximately the desired 3-qubit gate, with an error in the populations that is less than  $\mathcal{O}(10^{-2})$  and an error in the phase that is less than  $\mathcal{O}(10^{-5})$ .

[0100] As discussed above, this controlled-controlled-phase (*CCZ*) gate is implemented in the regime in which nearest neighbors are constrained by the Rydberg blockade, but next-nearest neighbors have only weak interactions, that is  $V_{1,2}, V_{2,3} \gg |\Omega|, |\Delta|$ , and  $V_{1,3} \ll |\Omega|, |\Delta|$ . In light of this, the *CCZ* gate that is to be implemented is motivated by the fact that both edge atoms can simultaneously blockade the middle (target) atom. In particular, the following scheme is considered to implement *CCZ* that involves local excitation to Rydberg states:

**[0101]**

1. Apply a  $\pi$  pulse on both edge atoms, transferring all of their population in  $|1\rangle$  to  $|r\rangle$ .
2. Apply a  $2\pi$  pulse on the center atom, exciting from  $|1\rangle$  to  $|r\rangle$  and back to  $|1\rangle$ , accumulating a  $\pi$  phase shift only if neither edge atom is blockading this central atom and the atom is in  $|1\rangle$ .
3. Apply another  $\pi$  pulse on the edge atoms to return any population from  $|r\rangle$  to  $|1\rangle$ .

Such a protocol realizes the following unitary:

$$CCZ = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \end{pmatrix} \quad (30)$$

This unitary is equivalent to the canonical controlled-controlled-phase gate, denoted

$\mathcal{CCZ} = \mathbb{1} - 2|111\rangle\langle 111|$  up to local rotations, as shown in **FIG. 5I**.

**[0102]** In the absence of local excitation to Rydberg states, global Rydberg coupling can still approximately realize this unitary. Since different input configurations evolve according to dynamics of few-level systems with different coupling frequencies, it is challenging to design a single analytic global pulse to control all input configurations properly. For example, the  $|001\rangle$  state couples to  $|00r\rangle$  as a two-level system with Rabi frequency  $\Omega$ . The  $|011\rangle$  state couples to  $\frac{1}{\sqrt{2}}(|r11\rangle + |0r1\rangle)$  with Rabi frequency  $\sqrt{2}\Omega$ . The  $|111\rangle$  state couples both to  $|1r1\rangle$  with Rabi frequency  $\Omega$ , and also couples to  $\frac{1}{\sqrt{2}}(|r11\rangle + |11r\rangle)$  with Rabi frequency  $\sqrt{2}\Omega$  (which then couples to  $|r1r\rangle$ ). The systems

are further complicated by the finite next-nearest neighbor interaction between edge atoms.

[0103] To find a global pulse that works on all input configurations, in one embodiment, the RedCRAB optimal control algorithm was used to optimize the amplitude and frequency profile for the coupling field, and thereby selecting the laser intensity, the laser frequency, pulse duration, and laser phase. The optimized pulse, shown in **FIG. 6**, has a duration of 1.2  $\mu\text{s}$  and achieves a desired numerically simulated gate fidelity of 97.6%.

[0104] Additional implementations with colder atoms could achieve higher gate fidelities by designing gate timings to intentionally cancel the effect of the unwanted phase accumulation between next-nearest neighbors. Alternatively, few-qubit gates could be implemented with all atoms in the fully blockaded regime by bringing atoms closer together or by exciting to higher Rydberg states.

#### Spin Echo Procedure for *CZ* and *CCZ*

[0105] The implementation of the controlled-phase gate in the enclosed region shown in **FIG. 7A** is shown in more explicit detail on the right hand side of the equal sign. The direct implementation of the  $\mathcal{C}_2$  gate (region I) includes an extra phase shift on both qubits. This is corrected by a hyperfine qubit  $X(\pi)$  echo pulse (II), followed by the appropriate phase shifts (III and IV). The Rydberg pulse that implements the *CZ* or the *CCZ* gate includes both a 1013 nm laser field and a 420 nm laser field, the latter of which adds a differential light shift to the qubit levels of  $\sim 2\pi \times 3$  MHz. To correct for the phase accumulated due to this light shift, after the *CZ* gate, a qubit  $X(\pi)$  rotation is applied on all atoms, and then the same 420 nm pulse used for the *CZ* gate is applied, but this time in the absence of 1013 nm light. The single particle phase  $\phi$ , shown in map (1) above, that

is inherent in the design of the  $CZ$  protocol is separately corrected by an additional short pulse of the 420 nm laser. The full detailed pulse sequence is shown in **FIG. 7B**. The full pulse sequence for preparing Bell states begins with both atoms in  $|0\rangle$  and a global  $X(\pi/2)$  pulse (produced by two  $\pi/4$  pulses) to put both atoms in  $|-\rangle_y$ . Then, while the 1013 nm laser is on, the 420 nm laser is applied in two pulses (with a relative phase between the pulses) to enact the  $CZ$  gate, along with global phase shifts coming from the light shift of the 420 nm laser. A global  $X(\pi)$  pulse flips the qubit states, at which point the same 420 nm pulses are applied, but now in the absence of 1013 nm light. This negates the effect of light shifts in the first portion of the  $CZ$  gate implementation. Then, an additional short pulse of the 420 nm laser adds an additional phase correction to turn the  $CZ$  gate into the canonical  $\mathcal{C}\mathcal{Z}$  gate. A subsequent global  $X(\pi/4)$  pulse prepares the two atoms in the Bell state  $|\Phi^+\rangle$ . A final 420 nm laser pulse can be used to add dynamical phase to this Bell state, which can be detected by a subsequent global  $X(\pi/2)$  for measuring parity oscillations. Finally, atoms in  $|1\rangle$  are pushed out to detect populations.

#### State Readout Through Atom Loss

[0106] The primary technique used herein for state readout is to apply a resonant laser pulse that heats atoms in  $|1\rangle$  (in  $F = 2$ , more generally) out of the tweezers, after which a fluorescence image of remaining atoms in  $|0\rangle$  is taken. This method correctly identifies atoms in  $|0\rangle$ , but can mistake atoms that were lost through background loss processes or by residual Rydberg excitation for atoms in  $|1\rangle$ , leading to an overestimation of the population in  $|1\rangle$ . For any measurements involving Rydberg excitation, measurement statistics were collected both with and without the pushout pulse, which provides an

upper bound on how much leakage out of the qubit subspace occurred, and therefore also gives a lower bound on the true population in  $|1\rangle$ .

[0107] This procedure is illustrated in the context of the two-qubit experiments, denoting the two types of measurements as  $A$  (in which the pushout of  $|1\rangle$  atoms is applied) and  $B$  (in which the pushout is disabled). For each measurement procedure, statistics were obtained by observing the four two-qubit states, consisting of ‘lost’ or ‘present’ for each qubit. The  $A$  vector associates these as  $|0\rangle$  and  $|1\rangle$ , so  $A_{ij}$  (for  $i, j \in \{0, 1\}$ ) denotes the probability of identifying the left and right atom in 0, 1 through the simple loss/presence analysis. However, the atoms can be not only in the qubit states 0, 1, but they can also be lost from the trap or in the Rydberg state, which in both cases will be detected as ‘lost’. Denoting  $C$  as the computational subspace containing  $|0\rangle$  and  $|1\rangle$ , and denoting  $\bar{C}$  as anything outside this subspace (including Rydberg population or loss), the  $B$  vector measures whether the atoms are in  $C$  (either  $|0\rangle$  or  $|1\rangle$ ), or not ( $\bar{C}$ ), so it is denoted  $B_{ij}$  where  $i, j \in \{C, \bar{C}\}$ .

[0108] Both  $A_{ij}$  and  $B_{ij}$  can be explicitly expressed in terms of the underlying atomic populations  $p_{\alpha\beta}$ , where  $\alpha, \beta \in \{0, 1, \bar{C}\}$ , as follows:

$$A_{00} = p_{00} \quad (31)$$

$$A_{01} = p_{01} + p_{0\bar{C}} \quad (32)$$

$$A_{10} = p_{10} + p_{\bar{C}0} \quad (33)$$

$$A_{11} = p_{11} + p_{1\bar{C}} + p_{\bar{C}1} + p_{\bar{C}\bar{C}} \quad (34)$$

$$B_{CC} = p_{00} + p_{01} + p_{10} + p_{11} \quad (35)$$

$$B_{C\bar{C}} = p_{0\bar{C}} + p_{1\bar{C}} \quad (36)$$

$$B_{\bar{C}C} = p_{\bar{C}0} + p_{\bar{C}1} \quad (37)$$

$$B_{\bar{C}\bar{C}} = p_{\bar{C}\bar{C}} \quad (38)$$

[0109] Measuring  $A_{ij}$  and  $B_{ij}$ , one can now solve for the atomic populations of interest:  $p_{00}$ ,  $p_{01}$ ,  $p_{10}$ , and  $p_{11}$ .

$$p_{00} = A_{00} \quad (39)$$

$$p_{01} = A_{01} - B_{c\bar{c}} + p_{1\bar{c}} \quad (40)$$

$$p_{10} = A_{10} - B_{\bar{c}c} + p_{\bar{c}1} \quad (41)$$

$$p_{11} = A_{11} - B_{c\bar{c}} - B_{\bar{c}c} - B_{\bar{c}\bar{c}} + (p_{0\bar{c}} + p_{\bar{c}0}) \quad (42)$$

[0110] Since all probabilities are non-negative and  $B_{c\bar{c}} + B_{\bar{c}c} + B_{\bar{c}\bar{c}} = 1 - B_{cc}$ , lower bounds are obtained for the true populations:

$$p_{00} = A_{00} \quad (43)$$

$$p_{01} \geq A_{01} - B_{c\bar{c}} \quad (44)$$

$$p_{10} \geq A_{10} - B_{\bar{c}c} \quad (45)$$

$$p_{11} \geq A_{11} - (1 - B_{cc}) \quad (46)$$

[0111] This is the analysis carried out for the Bell state populations, the CNOT truth table, and the Toffoli truth table (extended to three qubits). For the truth tables, the analysis is carried out for each measurement configuration (corresponding to a different input computational basis state) separately, shown as the rows in the matrices in **FIGS. 8A-B** that shows the probability distribution (shown in percentage points) of different output configurations both with and without the pushout pulse, as described above.

#### Correcting for State Preparation and Measurement Errors

[0112] The problem of correcting a measured fidelity for state preparation and measurement (SPAM) errors is considered below.  $P$  is denoted as the probability to correctly initialize and measure all qubits; generally,  $P = (1-\epsilon)^N$  for a single-particle error rate of  $\epsilon$ . The measured fidelity is related to the ‘corrected fidelity’ according to:

$$\mathcal{F} = P \times \mathcal{F}^c + (1 - P) \times \mathcal{F}^{false} \quad (47)$$

Here  $\mathcal{F}^{false}$  denotes the false contribution to the measured fidelity signal in cases in which SPAM errors occur. The main subtlety in performing the correction is properly evaluating the potential false contribution  $\mathcal{F}^{false}$ .

[0113] Experimentally, the SPAM error is  $\epsilon = 1.2(1)\%$  per qubit, consisting of two effects: first, the optical pumping into  $|0\rangle$  has an error probability of  $0.7(1)\%$  constituting a state preparation error. Second, there is a small chance that an atom can be lost due to a background collision either before or after the Bell state circuit is performed. Loss before the circuit contributes as a state preparation error; loss after the circuit but prior to the readout fluorescence image contributes as a measurement error. The total background loss contribution is  $0.5(1)\%$  error per atom.

#### Bell State Fidelity

[0114] The total probability that no errors occur on either of two qubits is  $P = 97.6(2)\%$ . Equation (47) holds for both the population measurement and the parity oscillation measurement separately. The population measurement explicitly only counts lower bounds on the population of atoms within the qubit subspace (see Section: “State Readout Through Atom Loss” above). Therefore, in cases where an atom is lost, there is no false contribution to the measured fidelity. However, the measured fidelity does not distinguish between atoms pumped into magnetic sublevels outside of the qubit subspace. It is estimated that in cases where one of the two atoms is prepared in an incorrect magnetic sublevel ( $1.4(2)\%$  probability), there can be a false contribution of  $\mathcal{F}^{false} = 1 - \cos^2\left(\frac{7\pi}{8}\right) \approx 15\%$  (calculated by evaluating the quantum circuit shown in **FIG 3A** with one atom not participating). The lower bound on the measured probabilities  $p_{00} + p_{11} \geq 95.8(3)\%$  therefore sets a lower bound on the corrected populations:  $p_{00}^c + p_{11}^c \geq 97.9(4)\%$ .

[0115] On the other hand, the parity oscillation amplitude receives no false contribution from cases where an atom is prepared in the wrong sublevel or is lost, because this error is independent of the accumulated phase and therefore does not oscillate as a function of the phase accumulation time. The false contribution is therefore  $\mathcal{F}^{false} = 0$ . In this case, the coherence  $C$  (given by the amplitude of the parity oscillations) is related to the corrected coherence by  $C = P \times C^c$ . Since  $C = 94.2(4)\%$ , a corrected coherence of  $C^c = 96.5(4)\%$  is obtained. The total SPAM-corrected Bell state fidelity, then, is  $\mathcal{F}^c = \frac{1}{2}(p_{00}^c + p_{11}^c + C) \geq 97.2(3)\%$ .

#### CNOT Truth Table

[0116] The truth table is measured by performing the CNOT gate on each computational basis state. The basis states are prepared with finite fidelity, as measured and shown in **FIG. 3E**. For each basis state, one wishes to assess how the finite output fidelity in the target state compares to the finite initialization fidelity to determine how well the gate performs on this input state. A probability  $P_{ij}$  of no SPAM error occurring for each measurement setting is established (where  $ij$  denotes the setting in which the computational basis state  $|ij\rangle$  is initialized). Additionally, a lower bound is measured on the output probability in the target state,  $\mathcal{F}_{ij}$ .

[0117] False contributions to the measured fidelity are now considered. When an error involving atom loss occurs, there is no false contribution to fidelity, since fidelity only measures atom population within the qubit subspace. Alternatively, in cases where the wrong computational basis state is prepared, then  $\mathcal{F}^{false}$  is bounded above by the largest unwanted element of the truth table, or  $< 4\%$ . The total false contribution, therefore, is  $(1 - P) \times \mathcal{F}^{false} < (3\%) \times (4\%) \lesssim 0.1\%$ . This contribution is below the measurement resolution and is not accounted for. The corrected fidelity is therefore given

by  $\mathcal{F}_{ij}^c = \frac{\mathcal{F}_{ij}^{meas}}{p_{ij}}$ . The average corrected truth table fidelity, given by the average of  $\mathcal{F}_{ij}^c$ , is

therefore  $\mathcal{F}_{\text{CNOT}}^c \geq 96.5\%$ , as shown in Table 2 below.

#### Toffoli Truth Table

[0118] The same analysis is performed to evaluate the corrected Toffoli truth table fidelity as for the CNOT truth table. The average corrected truth table fidelity is  $\mathcal{F}_{\text{Toff}}^c \geq 87.0\%$ , as shown in Table 2 below.

Table 2.

|                        | Raw Outcomes | Lower bound | Corrected |
|------------------------|--------------|-------------|-----------|
| Bell state populations | 97.6%        | 95.8%       | 97.9%     |
| Bell state coherences  | 94.2%        | 94.2%       | 96.5%     |
| Bell state fidelity    | 95.9%        | 95.0%       | 97.2%     |
| CNOT: Input 00         | 97.3%        | 95.0%       | 96.5%     |
| 01                     | 96.4%        | 94.9%       | 97.9%     |
| 10                     | 93.3%        | 93.3%       | 96.3%     |
| 11                     | 94.4%        | 93.1%       | 95.4%     |
| CNOT Truth table       | 95.5%        | 94.1%       | 96.5%     |
| Toffoli: Input 000     | 90.3%        | 73.1%       | 75.1%     |
| 001                    | 88.9%        | 82.6%       | 86.2%     |
| 010                    | 87.4%        | 73.0%       | 76.0%     |
| 011                    | 90.3%        | 86.7%       | 90.0%     |
| 100                    | 90.4%        | 84.3%       | 87.4%     |

|                     |       |       |       |
|---------------------|-------|-------|-------|
| 101                 | 91.6% | 91.6% | 95.7% |
| 110                 | 90.3% | 87.0% | 90.5% |
| 111                 | 93.3% | 91.0% | 95.0% |
| Toffoli Truth table | 90.3% | 83.7% | 87.0% |

#### Limited Tomography of Toffoli Gate

[0119] The truth table of the Toffoli gate provides a representation of the magnitude of the matrix elements of the gate expressed in the logical basis. However, the measured populations carry no information about the relative phases between the different entries. Performing a similar procedure as the truth table, but rotating the Toffoli gate to act on the  $X$ -basis instead of the  $Z$ -basis makes it possible to recover some information about these phases. A restricted version of such a procedure has been used before as a way to characterize the fidelity of the Toffoli gate, and has been dubbed “Limited Tomography”. The procedure consists of initializing all the computational basis states in the  $Z$ -basis, and then applying an  $X(\pm\pi/2)$  rotation to all qubits before and after a Toffoli gate, in the quantum circuit shown in **FIG. 9**. The sign is chosen to be  $X(+\pi/2)$  when the target qubit is initialized in  $|0\rangle$  and  $X(-\pi/2)$  when the target qubit is initialized in  $|1\rangle$ . Conditioning the sign of the rotation on the state of the target qubit enforces that the target qubit is always in the same state  $|+\rangle_y$  prior to the action of the Toffoli gate itself.

[0120] The Toffoli gate implemented herein, which includes a spin echo pulse that acts as a global  $X(\pi)$  gate (shown in **FIG. 4B**) is described ideally by the unitary matrix:

$$T_{\text{Ideal}} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & i & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -i \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \quad (48)$$

[0121] Performing the limited tomography procedure on this unitary should result in the following output truth table:

$$\text{Lim}[T_{\text{Ideal}}] = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \quad (49)$$

where each row shows the target output probabilities for a given input state. However, if the Toffoli gate is allowed to deviate from the ideal unitary by arbitrary phases  $\phi_j$  according to

$$T_{\phi} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & ie^{i\phi_1} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & ie^{i\phi_2} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -ie^{i\phi_3} \\ 0 & 0 & 0 & 0 & e^{i\phi_4} & 0 & 0 & 0 \\ 0 & 0 & 0 & ie^{i\phi_5} & 0 & 0 & 0 & 0 \\ 0 & 0 & -e^{i\phi_6} & 0 & 0 & 0 & 0 & 0 \\ 0 & e^{i\phi_7} & 0 & 0 & 0 & 0 & 0 & 0 \\ -e^{i\phi_8} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \quad (50)$$

then the limited tomography truth table reflects this phase deviation. In particular, each truth table matrix element in which the limited tomography should produce unity will instead result in a peak probability of  $|\frac{1}{8}\sum_j e^{i\phi_j}|^2$ . The average fidelity of the limited tomography truth table therefore reflects how close the phases on the Toffoli unitary are

to their ideal values, and can only reach unity if each phase is correct. The measured limited tomography truth table is shown in **FIG. 10**, where the raw target probabilities average to 88.0(3)%. Since four of the measurement configurations are precisely global  $X(\pi)$  gates applied to the other four input states, these output distributions can be compared to properly account for leftover Rydberg populations, similar to the procedure discussed above in the section “State Readout Through Atom Loss.” The limited tomography fidelity is therefore established to be  $\mathcal{F} \geq 81.5(5)\%$ . Corrected for SPAM errors, the fidelity is  $\geq 86.2(6)\%$ .

[0122] It is worth noting that the limited tomography protocol only makes use of four of the eight  $X$ -basis input states, as seen from the fact that the target qubit is always initialized in  $|+\rangle$ . This makes four out of the eight measurements equivalent to the other four up to a global  $X(\pi)$  rotation at the end. Comparing these two sets of measurements gives a constraint on the probability of leakage out of the qubit subspace, similarly to the approach described above in the section “State Readout Through Atom Loss.”

#### Parallel Gate Implementation in a Contiguous Array

[0123] Embodiments described above involve parallel multi-qubit gate implementation on separated pairs of atoms, where the inter-pair interaction is negligible. However, one can extend this protocol to parallel gate implementation in a contiguous chain of atoms **1100**, as illustrated in **FIGS. 11A** and **11B**. Consider an additional local addressing laser system **1130** that can address an arbitrary subset of atoms, using, for example, an acousto-optic deflector. Specifically, one can select a wavelength for this laser such that the imparted light shift affects the  $|0\rangle$  and  $|1\rangle$  states equally, but differently from the Rydberg state  $|r\rangle$ . In such a case, the light shift from this additional local addressing laser **1130** does not apply any qubit manipulations, but instead simply shifts

the effective Rydberg resonance by  $\delta$ , as shown in **FIG. 11A**. Near-infrared wavelengths tuned far from any ground state optical transition ( $\lambda \gtrsim 820$  nm) are suitable for Rubidium. As shown in **FIG. 11B**, the local addressing lasers are focused onto a subset of qubits on which one aims to perform parallel multi-qubit gates. The global Rydberg coupling laser **1120** is tuned to the light-shifted resonance, so that only the locally addressed atoms are coupled to the Rydberg state for gate implementation **1110**.

[0124] With such a system, one could illuminate all pairs of adjacent atoms **1131** and **1132** on which one intends to perform two-qubit gates, and then, by tuning the Rydberg laser to the light-shifted resonance, one would perform the multi-qubit gate on all pairs in parallel. The only constraint is that there must be sufficient space between addressed pairs **1131** and **1132**, such that the interaction (cross-talk) between them is negligible in a particular layer of gate implementation.

#### Multi-qubit Gates on Fully-Blockaded Ensembles of $N$ Qubits

[0125] Consider an ensemble or grouping of  $N$  fully-blockaded qubits ( $N=K$ ), where at most one qubit can be excited into the Rydberg state  $|r\rangle$  at a time. The atomic qubits have two non-interacting qubit states  $|0\rangle$  and  $|1\rangle$ , in addition to the interacting Rydberg state  $|r\rangle$ . Under the action of a laser drive which couples the state  $|1\rangle$  to the state  $|r\rangle$  with Rabi frequency  $\Omega$  and detuning  $\Delta$ , the atomic ensemble evolves as an effective two level system with an ‘enhanced’ Rabi frequency that depends on how many of the atoms begin in the qubit state  $|1\rangle$  (rather than  $|0\rangle$ ). There are  $N+1$  such possible configurations, with the number of atoms beginning in  $|1\rangle$  (denoted by  $M$ ) ranging from 0 to  $N$ . Each such system evolves according to an enhanced Rabi frequency  $\sqrt{M}\Omega$ .

[0126] The most general  $N$ -qubit gate that can be implemented by the global laser pulse protocol described herein involves each of these  $N+1$  configurations (labeled  $|M\rangle$ ),

for  $M$  from 0 to  $N$ ) returning to their initial state, with a phase accumulation of  $\phi_M$ . More concretely, if  $U$  is a unitary which describes the action of the gate, then each initial configuration  $|M\rangle$  evolves according to  $U|M\rangle = e^{i\phi_M}|M\rangle$ . Two aspects of this expression are emphasized:  $|\langle M|U|M\rangle|^2 = 1$  denotes the fact that the state  $|M\rangle$  returns to its initial state (up to a phase factor) by the end of the gate operation. The second aspect is  $\text{Arg}[\langle M|U|M\rangle] = \phi_M$ , which characterizes this phase factor. The gate can therefore be characterized by the phases  $\{\phi_0, \phi_1, \dots, \phi_N\}$ . Two additional notes: firstly, since  $|M=0\rangle$  contains no qubits in  $|1\rangle$ , this state is uncoupled by the laser field, and therefore evolves trivially:  $U|M=0\rangle = |M=0\rangle$ . Therefore,  $\phi_0 = 0$ . Secondly, two different gates are considered to be ‘equivalent’ if they are related only by the action of single-qubit gates. The particular single-qubit gate considered herein is  $Z(\theta)$ , which was defined above as the single qubit phase gate applied to all qubits. This gate adds a phase  $\theta$  for each qubit in state  $|1\rangle$ . That is, the state  $|M\rangle$  evolves as  $Z(\theta)|M\rangle = e^{iM\theta}|M\rangle$ . If a gate  $U$  is characterized by phases  $\{\phi_0, \phi_1, \dots, \phi_N\}$ , then this gate is considered to be equivalent to the gate characterized by  $\{\phi_0, \phi_1 + \theta, \dots, \phi_N + N\theta\}$ . Since  $\phi_0 = 0$  always, and one can choose  $\theta = -\phi_1$ , this gate  $U$  is equivalent to a gate  $V$  with phases  $\{0, 0, \phi_2 - 2\theta, \dots, \phi_N - N\theta\}$ . Thus, any gate is equivalent to another gate in which  $\phi_0 = \phi_1 = 0$ .

[0127] When designing a gate, the specified phases are:  $\phi_2, \phi_3, \dots, \phi_N$ . There are  $N-1$  such phases to choose. All configurations are additionally specified to return to their initial state, which imposes  $N$  additional constraints. There are, therefore, a total of  $2N-1$  constraints on the desired gate implementation.

[0128] A laser pulse sequence ansatz is defined to implement any target gate which is specified by  $2N-1$  constraints. The sequence will consist of  $4N-6$  laser pulses, each at detuning  $\Delta$  and of duration  $\tau$ , with laser phase shifts in between each pulse specified by relative phase shifts  $\xi_1, \xi_2, \dots, \xi_{4N-7}$ . Symmetry is imposed on the palindromic phase

shifts, such that  $\xi_i = \xi_{(4N-6-i)}$ , resulting in just  $2N-3$  independent phase shifts to choose. There are a total  $2N-1$  degrees of freedom to choose, including all phase shifts,  $\Delta$ , and  $\tau$ . Note that this number of degrees of freedom matches the number of constraints to satisfy in the target gate operation.

[0129] Optionally, the pulse duration  $\tau$  is chosen such that one of the configurations  $|M\rangle$  returns back to its initial state after each laser pulse. This is accomplished by setting  $\tau = 2\pi/\sqrt{\Delta^2 + M\Omega^2}$ . In practice,  $\tau$  is chosen such that  $M=N$  because it results in the fastest gate operation. This choice reduces one degree of freedom in the laser pulse sequence, but it ensures that configuration  $|M\rangle$  returns to its initial state by the end of the pulse sequence, and therefore satisfies one constraint in the target gate. There are now  $2N-2$  additional degrees of freedom and  $2N-2$  additional constraints to satisfy. One can numerically solve for the set of laser pulse parameters using numerical constraint solvers such as Mathematica, and thereby select the laser frequency, pulse duration, and phase shifts based on the conditional-phase angle  $\theta$  of the controlled phase gate. Solutions have been found for all target gates tested up through  $N=5$ .

[0130] The gate phases  $\phi_1, \phi_2, \dots, \phi_N$  define the effect of the gate on the qubit system. Some such choices are well known as  $C^{N-1}Z(\phi)$ , or a multiqubit controlled phase gate. In particular, this corresponds to  $\phi_1 = \phi_2 = \dots = \phi_{N-1} = 0$ , and  $\phi_N = \phi$ . For  $N = 2$ , this corresponds to a maximally entangling two-qubit gate called the controlled-phase gate (which is equivalent to any other maximally entangling two-qubit gate such as controlled-NOT, or CNOT). This gate is frequently utilized in quantum algorithms. For  $N \geq 3$ , this gate is equivalent to a  $N$ -qubit Toffoli gate and is also often used in quantum algorithms. These gates can be decomposed into a large number of individual two-qubit gates, but it may be advantageous to implement the  $N$ -qubit gate directly if that can be done natively on the quantum hardware, rather than to decompose it

and implement a large number of individual gates separately. For example, 5 two-qubit gates are required to implement one three-qubit controlled-controlled-phase (CCZ) gate. Example solutions for multiqubit controlled phase gates  $C^{N-1}Z(\pi)$  are provided below, with all phase shift values  $\xi_i$  given in units of radians. Note that all phase shifts  $\xi_i+2\pi$  are equivalent to  $\xi_i$ .

[0131] For  $N = 2$ , as discussed above,  $\Delta/\Omega = 0.377371$ ,  $\xi_1 = 3.90242$ . For  $N = 3$ , multiple solutions are found, with 4 sample solutions presented in Table 3. Note that Solution 3 is the same solution discussed above, with  $\xi_2+2\pi$  and  $\xi_3+2\pi$ .

Table 3.

| Parameter       | Solution 1 | Solution 2 | Solution 3 | Solution 4 |
|-----------------|------------|------------|------------|------------|
| $\Delta/\Omega$ | -0.0570895 | -0.267234  | -0.229481  | -0.776102  |
| $\xi_1$         | 0.150574   | -1.5427    | 0.586978   | -1.4483    |
| $\xi_2$         | -0.530291  | 1.37871    | -1.7508    | 0.688775   |
| $\xi_3$         | 2.0049     | 0.989935   | -0.0580888 | 1.45666    |

[0132] For  $N = 4$ , multiple solutions are found, with 4 sample solutions presented in Table 4.

Table 4.

| Parameter       | Solution 1 | Solution 2 | Solution 3 | Solution 4 |
|-----------------|------------|------------|------------|------------|
| $\Delta/\Omega$ | 0.133612   | 0.424491   | 0.404323   | 1.07756    |
| $\xi_1$         | -0.550646  | 0.726549   | -0.642575  | 0.0251141  |
| $\xi_2$         | 0.989158   | 1.26989    | -0.725974  | 2.07618    |
| $\xi_3$         | 1.05129    | -0.584564  | -0.966666  | -0.337474  |
| $\xi_4$         | -0.832328  | -0.82851   | -0.291719  | -1.08468   |
| $\xi_5$         | -0.206509  | -1.1908    | 0.893183   | -0.800534  |

[0133] For  $N = 5$ , multiple solutions are found, with 2 sample solutions presented in Table 5.

Table 5.

| Parameter       | Solution 1 | Solution 2 |
|-----------------|------------|------------|
| $\Delta/\Omega$ | 0.388209   | -0.23195   |
| $\xi_1$         | -0.206364  | -1.0802    |
| $\xi_2$         | -0.893626  | -0.22098   |
| $\xi_3$         | -0.342458  | 0.028781   |
| $\xi_4$         | -0.664964  | 0.358192   |
| $\xi_5$         | -1.32371   | -0.527308  |
| $\xi_6$         | 1.18947    | 1.70135    |
| $\xi_7$         | -0.58071   | 0.986371   |

[0134] While gates of the form  $C^{N-1}Z(\pi)$  (characterized by  $\phi_1 = \phi_2 = \dots = \phi_{N-1} = 0$ , and  $\phi_N = \pi$ ) are often of interest in implementing quantum algorithms, another interesting option is considered herein that is enabled by the flexible choice of target phases described above. In particular, consider the implementation of a pairwise  $CZ(\pi)$  gate on each pair of atoms in the system. This algorithm produces a special fully entangled state called a fully connected cluster state, which is equivalent (up to local qubit operations) to a Greenberger-Horne-Zeilinger (GHZ) state, a type of highly entangled state that has known uses in quantum error correction and quantum metrology. The GHZ state has the form  $\frac{1}{\sqrt{2}}(|00 \dots 0\rangle + |11 \dots 1\rangle)$ .

[0135] Since the  $CZ(\pi)$  gate on a single pair can be understood as adding a  $\pi$  phase shift on basis states in which both qubits in the pair begin in  $|1\rangle$ , the action of  $CZ(\pi)$  on *all* pairs in the system can be understood as adding a  $\pi$  phase shift for *all* pairings of qubits in the basis state which are in  $|1\rangle$ . For the basis state  $|M\rangle$ , which is the superposition of all combinations of  $M$  qubits beginning in  $|1\rangle$ , there are exactly  $\binom{M}{2} = \frac{M(M-1)}{2}$  pairings of qubits which incur a  $\pi$  phase shift. Therefore, the total phase shift for the state  $|M\rangle$  is exactly  $\pi \times \frac{M(M-1)}{2}$  (modulo  $2\pi$ ). For  $N=3$ , this corresponds to  $\phi_1 =$

$0, \phi_2 = \pi, \phi_3 = \pi$ . A set of parameters suitable to implement this fully connected cluster state preparation for  $N=3$  is listed in Table 6.

Table 6.

| Parameter       | Solution  |
|-----------------|-----------|
| $\Delta/\Omega$ | 0.462332  |
| $\xi_1$         | 0.0119499 |
| $\xi_2$         | 1.39725   |
| $\xi_3$         | 0.495255  |

#### Global Pulses With Time-dependent Intensity and Detuning Profiles

[0136] The most general pulse that could be described would be a laser pulse with total duration  $T$ , and with a time-dependent intensity profile  $I(t)$  and a time-dependent detuning profile  $\Delta(t)$ , each defined for  $0 \leq t \leq T$ , optionally such that the time-dependent values of the laser intensity, the laser frequency, laser phase, and pulse duration are selected based on the conditional-phase angle  $\theta$ . These profiles in principle can be any function of time, but practical experimental limitations set upper and lower bounds on the values of the functions. For example, there is a practical limit on the maximum value of  $I(t)$  (how much laser power is available), and there is a practical limit on the range of  $\Delta(t)$  (how far the laser can be smoothly detuned). Experimental limitations also set bounds on the continuity and smoothness of these functions or equivalently the frequency spectrum of these profiles. High frequency components above some limit (dependent on implementation choice) are not possible to realize experimentally.

[0137] Within this restricted (but still expansive) space of possible intensity and detuning profiles, how is one found that implements the target gate? One approach is to numerically simulate the behavior of the atomic system according to a given laser pulse

(characterized by  $I(t)$  and  $\Delta(t)$ ), and then optimize the laser pulse profile according to the simulated response of the system, and thereby selecting the time-dependent values of the laser intensity, the laser frequency, pulse duration, and laser phase to achieve a desired fidelity of the quantum gate. In particular, starting from a fixed initial state for the atomic system  $|\psi_0\rangle$ , one can identify what the ideal output state would be for the target gate. For example, the target gate can be represented as a unitary operator  $U_{gate}$ , in which case the target output state is  $|\psi_{target}\rangle = U_{gate}|\psi_0\rangle$ . The actual gate implemented by a laser pulse with  $I(t)$  and  $\Delta(t)$  would result in a numerically simulated output state  $|\psi_{sim}\rangle$ . A figure of merit can be defined that characterizes how close the simulated output state is to the target output state: the fidelity  $\mathcal{F} = |\langle\psi_{target}|\psi_{sim}\rangle|^2$ . The fidelity is bounded by  $\mathcal{F} \leq 1$ , with  $\mathcal{F} = 1$  for an ideal gate. The functions  $I(t)$  and  $\Delta(t)$  can be modified to maximize the simulated fidelity.

[0138] Accordingly, in a first example embodiment, the present invention is a method of operating a quantum gate on a grouping of qubits. In the 1<sup>st</sup> aspect of the first example embodiment, the method comprises selecting values for a set of parameters of at least a first and a second laser pulse, the parameters selected from a relative phase shift, a laser frequency, a laser intensity, and a pulse duration; and applying the at least first and second laser pulses to all qubits within a grouping of  $N$  qubits, where  $N$  is equal to two or more, thereby coupling a non-interacting quantum state  $|1\rangle$  to an interacting excited state  $|r\rangle$ , such that each qubit that begins in quantum state  $|1\rangle$  returns to the state  $|1\rangle$  upon completion of the at least first and second laser pulses, and such that qubits in the grouping are mutually blockaded, for example dipole blockaded or Rydberg blockaded.

[0139] In a 2<sup>nd</sup> aspect of the first example embodiment, each qubit can be an atomic qubit, an ionic qubit, or a molecular qubit.

[0140] In a 3<sup>rd</sup> aspect of the first example embodiment, all qubits in the grouping are mutually blockaded. Other features and example features of the method are as described above with respect to the 1<sup>st</sup> through the 2<sup>nd</sup> aspects of the first example embodiment.

[0141] In a 4<sup>th</sup> aspect of the first example embodiment, the durations of the at least the first and the second pulses is selected so that if all qubits in the grouping begin in the quantum state  $|1\rangle$ , then all qubits in the grouping return to the quantum state  $|1\rangle$  upon completion of each of the at least the first and the second laser pulses. For example, the laser frequency of each pulse is detuned from the resonance transition between  $|1\rangle$  to  $|r\rangle$  by a detuning  $\Delta$  and the pulse duration  $t$  is equal to  $t = 2\pi/\sqrt{\Delta^2 + N\Omega^2}$ , where  $\Omega$  is the Rabi frequency of the laser pulses. Other features and example features of the method are as described above with respect to the 1<sup>st</sup> through the 3<sup>rd</sup> aspects of the first example embodiment.

[0142] In a 5<sup>th</sup> aspect of the first example embodiment, one or more of the laser intensity, laser frequency, pulse duration, and laser phase is selected to achieve a desired fidelity of the quantum gate. Other features and example features of the method are as described above with respect to the 1<sup>st</sup> through the 4<sup>th</sup> aspects of the first example embodiment.

[0143] In a 6<sup>th</sup> aspect of the first example embodiment, at least the first and the second pulses form a palindromic sequence of pulses. Other features and example features of the method are as described above with respect to the 1<sup>st</sup> through the 5<sup>th</sup> aspects of the first example embodiment.

[0144] In a 7<sup>th</sup> aspect of the first example embodiment, the gate is a controlled-phase gate  $C^{N-1}Z(\theta)$ , wherein  $\theta$  is a conditional-phase angle. For example,  $N$  is 2. In another example, the quantum gate is a controlled phase (CZ) gate, and  $N=2$ . In yet other examples, the laser frequency, the pulse duration, and the phase shift are selected based

on the conditional-phase angle  $\theta$  of the controlled phase gate. In yet further examples, the laser frequency is detuned from the resonance transition between  $|1\rangle$  to  $|r\rangle$  by a detuning  $\Delta$  and the laser intensity is selected such that the Rabi frequency of the laser pulses is  $\Omega$ . For example, the laser frequency, the laser intensity, the pulse duration, and the phase shift are selected such that the conditional-phase angle  $\theta=\pi$ . Other features and example features of the method are as described above with respect to the 1<sup>st</sup> through the 6<sup>th</sup> aspects of the first example embodiment.

[0145] In an 8<sup>th</sup> aspect of the first example embodiment, N is 3. In the 8<sup>th</sup> aspect, the quantum gate can be a controlled-controlled phase ( $C^2Z(\theta)$ ) gate having a conditional-phase angle  $\theta$ . For example, the laser frequency, pulse duration, and phase shifts of each of the at least the first and second laser pulses are selected based on the conditional-phase angle  $\theta$ . Other features and example features of the method are as described above with respect to the 1<sup>st</sup> through the 7<sup>th</sup> aspects of the first example embodiment.

[0146] In a 9<sup>th</sup> aspect of the first example embodiment, N is 3, and the method comprises applying a sequence of six pulses. The sequence of six pulses can be palindromic. Other features and example features of the method are as described above with respect to the 1<sup>st</sup> through the 8<sup>th</sup> aspects of the first example embodiment.

[0147] In a 10<sup>th</sup> aspect of the first example embodiment, the method comprises applying a sequence of  $4N-6$  pulses. The sequence of pulses can be, for example, palindromic. Other features and example features of the method are as described above with respect to the 1<sup>st</sup> through the 9<sup>th</sup> aspects of the first example embodiment.

[0148] In a second example embodiment, the present invention is a method of operating a quantum gate on a grouping of qubits. In a 1<sup>st</sup> aspect of the second example embodiment, the method comprises: selecting time-dependent values for a set of parameters of a laser pulse, the parameters selected from a laser phase, a laser frequency,

a laser intensity, and a pulse duration; and applying the laser pulse to all qubits within a grouping of  $N$  qubits, where  $N$  is equal to three or more, thereby coupling a non-interacting quantum state  $|1\rangle$  to an interacting excited state  $|r\rangle$ , such that each qubit that begins in quantum state  $|1\rangle$  returns to the state  $|1\rangle$  upon completion of the laser pulse, and such that qubits in the grouping are mutually blockaded, for example, dipole blockaded or Rydberg blockaded.

[0149] In a 2<sup>nd</sup> aspect of the second example embodiment, each qubit can be an atomic qubit, an ionic qubit, or a molecular qubit.

[0150] In a 3<sup>rd</sup> aspect of the second example embodiment, all qubits in the grouping are mutually blockaded. Other features and example features of the method are as described above with respect to the 1<sup>st</sup> through the 2<sup>nd</sup> aspects of the second example embodiment.

[0151] In a 4<sup>th</sup> aspect of the second example embodiment, the time-dependent values of the laser intensity, laser frequency, pulse duration, and laser phase are selected to achieve a desired fidelity of the quantum gate. Other features and example features of the method are as described above with respect to the 1<sup>st</sup> through the 3<sup>rd</sup> aspects of the second example embodiment.

[0152] In a 5<sup>th</sup> aspect of the second example embodiment, the gate is a controlled-phase gate  $C^{N-1}Z(\theta)$ , wherein  $\theta$  is a conditional-phase angle. Other features and example features of the method are as described above with respect to the 1<sup>st</sup> through the 4<sup>th</sup> aspects of the second example embodiment.

[0153] In a 6<sup>th</sup> aspect of the second example embodiment,  $N$  is 3. Other features and example features of the method are as described above with respect to the 1<sup>st</sup> through the 5<sup>th</sup> aspects of the second example embodiment.

[0154] In a 7<sup>th</sup> aspect of the second example embodiment,  $N$  is 3 and the quantum gate is a controlled-controlled phase ( $C^2Z(\theta)$ ) gate having a conditional-phase angle  $\theta$ . For example, the time-dependent values of the laser intensity, the laser frequency, laser phase, and pulse duration are selected based on the conditional-phase angle  $\theta$ . In another example, the conditional-phase angle  $\theta = \pi$ . Other features and example features of the method are as described above with respect to the 1<sup>st</sup> through the 6<sup>th</sup> aspects of the second example embodiment.

[0155] In a third example embodiment, the present invention is a device. In one aspect of the third example embodiment, the device comprises: a grouping of  $N$  qubits, where  $N$  is equal to two or more; and a coherent light source configured to, given selected values for a set of parameters of at least a first and a second laser pulse, the parameters selected from a relative phase shift, a laser frequency, a laser intensity, and a pulse duration: apply at least the first and second laser pulses to all qubits within the grouping of  $N$  qubits, thereby coupling a non-interacting quantum state  $|1\rangle$  to an interacting excited state  $|r\rangle$ , such that each qubit that begins in quantum state  $|1\rangle$  returns to the state  $|1\rangle$  upon completion of the at least first and second laser pulses, and such that qubits in the grouping are mutually blockaded.

[0156] Other features and example features of the third example embodiment are described above with respect to various aspects of the first example embodiment.

[0157] In a fourth example embodiment, the present invention is a device. In one aspect of the fourth example embodiment, the device comprises: a grouping of  $N$  qubits, where  $N$  is equal to three or more; and a coherent light source configured to, given selected time-dependent values for a set of parameters of a laser pulse, the parameters selected from a laser phase, a laser frequency, a laser intensity, and a pulse duration: apply the laser pulse to all qubits within a grouping of  $N$  qubits, thereby coupling a non-

interacting quantum state  $|1\rangle$  to an interacting excited state  $|r\rangle$ , such that each qubit that begins in quantum state  $|1\rangle$  returns to the state  $|1\rangle$  upon completion of the laser pulse, and such that qubits in the grouping are mutually blockaded.

[0158] Other features and example features of the fourth example embodiment are described above with respect to various aspects of the second example embodiment.

[0159] Having thus described several illustrative embodiments, it is to be appreciated that various alterations, modifications, and improvements will readily occur to those skilled in the art. Such alterations, modifications, and improvements are intended to form a part of this disclosure and are intended to be within the spirit and scope of this disclosure. While some examples presented herein involve specific combinations of functions or structural elements, it should be understood that those functions and elements may be combined in other ways according to the present disclosure to accomplish the same or different objectives. In particular, acts, elements, and features discussed in connection with one embodiment are not intended to be excluded from similar or other roles in other embodiments. Additionally, elements and components described herein may be further divided into additional components or joined together to form fewer components for performing the same functions. Accordingly, the foregoing description and attached drawings are by way of example only, and are not intended to be limiting.