Quantum Logic Gates with Neutral Atoms in Optical Lattices

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The heart of quantum computation is entanglement - the superposition of different quantum states of many two state systems (qubits) which form the register of the quantum computer. The requirements for implementing a quantum computer seem to be almost contradictory. On the one hand the qubits must strongly couple to one another and to an external field to produce the conditional-logic operations and resulting entanglement required for computation. On the other hand any coupling to other external influences must be minimized because it leads to decoherence which destroys the superpositions necessary for quantum parallelism. Neutral atoms trapped in a far-off resonance optical lattice may be able to satisfy these conflicting criteria. The adjustable parameters of the lattice (e.g. laser polarization, frequency, intensity) allow one to design interactions for which atoms interact strongly via dipole-dipole interactions during logical interactions but otherwise are isolated from each other and the environment. Dissipation arising from spontaneous photon scattering can be suppressed to an arbitrary degree given weak atomic saturation. The scattering rate scales as $\gamma_s = s\Gamma$, where s is the saturation parameter proportional to the excited state population, and $\Gamma \sim k^3 \left| d_{eg} \right|^2 / \hbar$ is the spontaneous emission rate with k the wave number of the photon and d_{eg} the dipole matrix element between the ground and excited states. For atoms spaced at distances small compared to the optical wavelength, retardation effects are negligible, and the level shift arising from the near field dipole-dipole interaction scales as $V_{dd} \sim \langle d_1 \rangle \langle d_2 \rangle / r_{12}^3$, where $\langle d \rangle$ is the expectation value of the dipole and r_{12} is the characteristic separation between the dipoles. For weak (non-saturated) excitation, $\langle d \rangle \sim \sqrt{s}\, d_{eg}$, in which case the ratio of the scattering rate to interaction energy time scales as $\kappa \equiv V_{dd} / \hbar\gamma_s \sim \left(kr_{12}\right)^{-3}$. Thus, if the atoms are tightly confined to relative distances small compared to the wavelength, one can induce a coherent dipole-dipole interaction with negligible photon scattering. The key feature is that while the coherent level shift can be enhanced by many orders of magnitude through tight confinement, the cooperative spontaneous emission rate cannot be enhanced by more than a factor of two (Dicke superradiant state) over that of an isolated atom.

We consider the implementation of a controlled not gate for alkali atoms trapped in a 3D far-off-resonance optical lattice. By rotating the polarizations of the lattice laser beams, atoms can be moved together so that they occupy the same well. By applying a “catalysis laser” which excites an electric dipole only for atoms in the logical-1 state, the state of a target atom can be flipped conditional on the dipole-dipole level shift induced by the control atom. After the logic gate is performed, one can “turn off” the dipole and move the atoms to distances where they no longer interact. These features make optical lattices particularly robust to decoherence.