CHAPTER 1

Introduction

1.1 Motivation

Linear nature of quantum mechanical world implies that all eigenstates can be manipulated, i.e. by a quantum logic gate, at the same time. Such massive quantum parallelism would enable a quantum processor to perform a large number of calculations simultaneously. In consequence of the superposition, the quantum bits (qubits) can do things that ordinary bits cannot. Since all eigenstates encoded into a quantum register are coherent, suitable quantum algorithms could exploit the quantum interference and delayed measurements to observe the weights cancellation that leaves only a very small number of calculated answers. For a few repeated computations, the distribution of informative outcomes pertaining to all parallel inputs would lead to an exponential speedup over classical computers.

Although the capabilities of a quantum processor to harness laws of quantum mechanics are exceptionally appreciated in the theoretical point of view, viable technologies are facing practical problems in preparing a robust multiple-qubit composite that satisfies the DiVincenzo criteria [1]. Nearly three decades have passed since the universal quantum computer was first proposed [2], several efficient and promising candidates for such physical system are still under investigations [3]. Among those approaches, trapped neutral atoms provide a number of attractive features, e.g. weak interaction with neighbors and the ability to initialize all qubits in a simple fiducial state, which make them outstanding for controlling quantum decoherence.

Along the pathway of using cold neutral atoms, the realization of quantum computer strongly depends on the specific preparing techniques and the method for coupling single atoms. In addition to the standard Doppler cooling techniques [4–6], the trapped atoms can be further cooled to the motional ground state of the potential wells [7], and their electronic states can be prepared in a desired quantum state using standard techniques of optical pumping [8]. The electronic, spin and motional (oscillation and translation) states provide degrees of freedom for defining unique qubits. The optical trap itself and external fields make available a variety of manipulations for coherent control of such states. Making all these to a profitable account inherently directs to the most widely studied trapping technology, the optical lattices [9] is an artificial periodic potentials of light that can store cold atoms as a crystal and also open innovative manipulation possibilities such as parallel operations in a quantum computer. Fig.(1.1) shows an illustrative model of optical lattice.

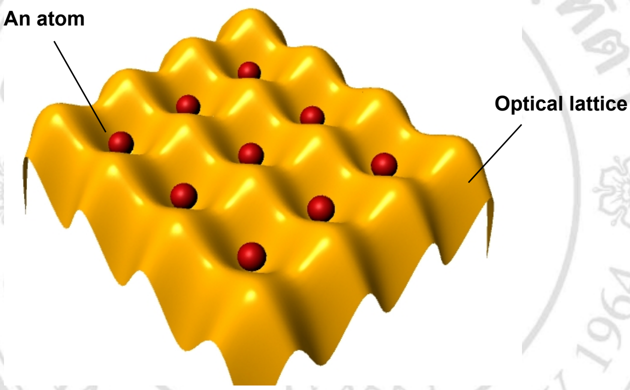

Figure 1.1: Optical lattice potentials (yellow) formed by superposition of orthogonal standing waves. The lattice can be approximated by array of harmonic oscillator potentials at each lattice site where an atom (red sphere) can be trapped.

To perfectly imitate a crystal, the ability to deterministically fill each optical well with an atom, hence qubits, is fundamentally crucial. Since the physics of each individual optical lattice site is the same as that of an optical microtrap, mastering the technique for efficient loading of a single atom in a far off-resonant dipole trap would implement scalable quantum computing as desired. There are achievements in trapping single atom in optical confinement in the past several years. The isolation of single ionic atoms was achieved in 1980, where the ions were trapped in a radio frequency electric field trap [10]. In 2001, the group of P. Grangler can trap a single neutral atom of rubidium-87 in the very small focus of far-off resonance laser beam with probability of 50% in collisional blockade regime [11] and they detect fluorescence signal of trapped atoms [12]. In 2009, Greiner's group can prepare single atoms in two-dimensional optical lattices by inducing phaser transition in an ultracold atomic emsemble loaded from Bose-Einstein condensate [13]. T. Grunzweig and coworkers provide the near-deterministic preparation of a single atom in an optical micro trap with probability of 82.7% in 2010 [14, 15]. Grunzweig and his co-workers use the technique based on light-assisted cold collisions. They apply an external laser field to stimulate inelastic scattering process of atoms in a far-off resonance trap. It can be expected that an atom in a colliding pair may gains enough kinetic energies to escape the trap. Eventually, there will be only one atom remain.

In this thesis, a mechanism for determinism of single-atom loading is proposed to be achievable via a forced path that combines the two-photon excitation of molecular Rydberg states [16] and the blue-detuned light-assisted collision [17]. The mechanism relies on the fact that i) the dipole force from an optical dipole trap or an optical lattice usually pins the cold ground state atoms at the bottom of the trap while the effect is negligible for the Rydberg ones [18] and ii) Rydberg states have very long radiative lifetime. When a ground-state colliding atomic pair is excited to a repulsive semi-molecular potential between Rydberg atom and ground-state atom, the two atoms repel from each other and only the Rydberg atom has a chance for exiting the trap due to no confining force exerting on it. If this *one-body collisional loss* is induced for many times, there are eventually only two atoms left in the trap. The same collisional process would force one atom to stay in the ground state and the other, the Rydberg one, always escapes no matter what the relative velocities of the two cold atoms with respect to the trap. Therefore, the final outcome could be that there is only one atom remaining in the trap.

In order to determine a semi-molecular potential appropriated for single-atom loading mechanism, this work presents the experimental investigation of repulsive interaction between two rubidium atoms excited to a molecular Rydberg state. The signature of usable repulsive potential was explored through light-induced trap loss in one-dimensional optical lattice due to blue-detuned two-photon excitation.

1.2 Thesis outline

This thesis presents the work carried out to develop and explore an idea of exploiting the adiabatic energy levels of Rydberg states of Rb_2 to improve single-atom loading efficiency in an optical dipole trap. The structure of this thesis is as follow.

Chapter 2 is an overview about basic concepts of laser cooling and trapping techniques including magneto-optical trap, optical dipole trap and optical lattice. These concepts are frequently mentioned throughout the thesis and it relies on the atom-photon interaction. The chapter also presents the theoretical background that are necessary for the development of our single-atom loading mechanism. It includes i) theoretical model of long-range interaction potential of molecular Rydberg state of Rb_2, ii) stimulated two-photon transition, and iii) blue-detuned light-assisted cold collision.

Chapter 3 presents our purposed mechanism that utilizes the repulsive interaction potential of Rb_2 in a molecular Rydberg state to increase the efficiency of single-atom loading in an optical dipole trap. The experimental condition for achieving a near-deterministic single-atom loading was developed and discussed in this chapter.

Chapter 4 details the experiment and results of light-induced trap loss measurement chosen for exploring the possibility of the single-atom loading mechanism using Rydberg state. The data presented in this chapter were collected at the Centre for Quantum Technologies (CQT), Singapore.