1 Introduction

Rydberg atoms are coupled by long-range dipole-dipole interactions [1]. They attract a lot of attention for their important role in studying fundamental problems as well as potential applications in quantum control in few- and many-body systems, quantum information processing, quantum calculation, etc. [2-10]. The research discussed in this dissertation is focusing on the influence of the DD interactions on the electron dynamics of cold Rydberg atoms. Three projects are presented in this dissertation, including both introduction of experimental setup and simulation results, respectively. Common experimental setups and background knowledge are also provided.

1.1 Motivation

One of my lab's main efforts is to explore and manipulate quantum dynamics in atomic and molecular systems. A series of projects have been or are implemented to accomplish this effort. These projects help people to understand fundamental science in atomic physics. More than that, they may contribute to potential practical applications from designing many-body systems that simulate model condensed matter systems, to quantum information storage and processing, to the development of new radiation sources and detectors.

Work done by previous graduates Xiangdong Zhang [11] and Mary Kutteruf [12] have pushed the effort a big step. The project "Probing Time-Dependent Electron Interactions in Double Rydberg Wavepackets" done by Xiangdong Zhang helps us understand more about electron interactions within individual atoms. The project "Coherence in Rydberg Atoms: Measurement and Control" done by Mary Kutteruf extended the exploration to the interactions between electric fields and wavepackets in an ensemble of Rydberg atoms. My project is an extent of their work but also a relatively independent research, which is to explore the interactions between Rydberg atoms within an ensemble. Another current graduate student Brian Richards is working on utilizing such interactions. Our projects are like puzzle chunks, working together to make the whole picture more complete.

My project to explore the influence of dipole-dipole interactions on wavepackets of Rydberg atoms has been divided into three sub-projects. First one is to explore the role of DD interactions in suppressing generation of collective decay in an ensemble of cold Rydberg atoms (Chapter 5). The second one is to explore the influence on wavepackets' evolution by DD interactions (Chapter 6). And the final one is to explore the coherence transfer via DD interactions (Chapter 7). Those three sub-projects help us understand better about what the DD interactions do in an ensemble of cold Rydberg atoms.

1.2 Rydberg Atoms and the Dipole-Dipole Interactions

Rydberg atoms are atoms in which an electron is excited to a state with a high principal quantum number. Usually this number is larger than 10. They are good systems for studying atom dynamics. The details about Rydberg atoms and their properties can be found in references such as [1], and are described in Chapter 3.

Dipole-Dipole interactions can influence neighboring Rydberg atoms. Classically the interaction is the result of the electric forces between electrons and the positively charged ion cores to which they are bound. When coupled by dipole-dipole interactions, Rydberg atoms should not be considered as individuals but rather a system. Details of dipole-dipole interactions, both from classical view and quantum physics prospective, can be found in Chapter 3.

1.3 Atomic Units

Atomic units (au or a.u.) are commonly used in atomic physics research. For convenience, we define:

$$\hbar = m_e = e = 4\pi\varepsilon_0 = 1 \tag{1.1}$$

where $\hbar$ is Planck's constant divided by 2π, m_e is the mass of the electron, -e is the charge. We obtain the conversion factors between a.u. and SI units as shown in Table 1.1.

Quantity	Value in atomic units	Value in SI units
Length	1	$5.2917721092(17)\times10^{-11}$ m
Energy	1	$4.35974417(75)\times10^{-18}$ J
Time	1	$2.418884326505(16)\times10^{-17}$ s
Velocity	1	$2.1876912633(73)\times10^{6}$ m·s^{-1}
Force	1	$8.2387225(14)\times10^{-8}$ N

Temperature	1	$3.1577464(55)\times10^{5}$ K
Pressure	1	$2.9421912(19)\times10^{13}$ Pa
Electric field	1	$5.14220652(11)\times10^{11}$ V·m^{-1}
Electric potential	1	$2.721138505(60)\times10^{1}$ V
Electric dipole moment	1	$8.47835326(19)\times10^{-30}$ C·m
Magnetic field	1	2.35×10^{5} T

Table 1.1: Atomic units to SI units conversion factors.

1.4 Dissertation Structure

Subsequent chapters describe the experimental approach, numerical simulations and several independent projects. Each project contains both experimental description and simulation description. Additional details and common aspects of all experiments are in chapters 2 and 3.

Chapter 2 provides the information about experimental setups. It introduces the apparatus commonly used in the experiments, as well as the daily operation. More details about some instruments could be found in their respective manuals and the dissertations from previous students who worked in this lab.

Chapter 3 talks about physics concepts commonly involved in the experiments, and their mathematical expression in simulations. It is not practical to put every simulation code line used in this dissertation, but by following the models described in Chapter 3, one could reconstruct the simulations in a fairly straightforward way.

Chapter 4 describes a search for the collective decay in cold Rydberg gases. We found no evidence for superradiance, despite the results reported by other groups. Our analysis suggests that, due to dipole-dipole dephasing, our null result is the expected one.

Chapter 5 describes an exploration of Rydberg wavepacket evolution in dipole-dipole coupled atoms. Our results show, through experiment and simulation, that in dipole-dipole coupled atoms, the wavepackets are not evolving independently, and variations in the coupling strength between pairs of atoms lead to macroscopic dephasing of the electronic wavepacket motion.

Chapter 6 describes a study of coherence transfer between wavepackets on different atoms via resonant dipole-dipole interactions. We observe evidence for the development of wavepacket motion in one set of atoms driven by wavepacket evolution in neighboring atoms. We confirm the coherence transfer by measuring the relative phase between the initial and induced wavepacket oscillations, suggesting the creation of entangled atom pair states with a dynamically evolving Rydberg wavepacket on one, and only one, atom in each pair. Simulations support our interpretation.

Chapter 7 summarizes the work done in this dissertation and briefly discusses the work in the future.

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2 Experimental Setup

This chapter contains the general experimental setup for the research discussed in this dissertation. It introduces the apparatus and procedure for state excitation, laser cooling, pulse amplification, THz pulse generation, data collection, etc. It also provides procedures for maintenance and daily operation. All experiments are performed on Newport RS 3000 optical tables to reduce mechanical vibrations, in a temperature controlled room to reduce external thermal fluctuations. Other than specifically noted, the repetition rate of all experiments is 15 Hz. Before beginning experiments in the lab, participants must have taken the laboratory safety training.