論文 / 著書情報
Article / Book Information

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Category(English)	Doctoral Thesis
種別(和文)	論文要旨
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（博士課程）
Doctoral Program

論 文 要 旨

THESIS SUMMARY

専攻： Department of	物性物理学 専攻	申請学位（専攻分野）： Academic Degree Requested	博士 Doctor of （ 理学 ）
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要旨（英文800語程度）
Thesis Summary（approx.800 English Words ）

This thesis is organized in seven chapters.

Chapter 1: Introduction – This chapter starts with an overview of the historical background of laser cooling and the Bose-Einstein condensate, followed by an explanation on the importance of quantum simulators for studying the physics of high temperature cuprate superconductors. A system of ultra-cold atoms trapped in periodical potentials created by light interference is a novel candidate for realizing quantum simulation of the two-dimensional Fermi-Hubbard model (FHM). The FHM is believed to contain all the ingredients required to produce d-wave superconductivity, which is the key for understanding the mechanism of the cuprate superconductors. The major obstacle to observe the d-wave superconducting phase is to reduce the temperature of the atoms well below the Neel temperature ($T/T_F \sim 0.01$), which is much smaller than the best current attainable temperatures using ultra-cold atoms ($T/T_F \sim 0.1$). I continue the explanation with the introduction on the concept of the "quantum gas microscope", a high-resolution fluorescence imaging device capable of resolving individual atoms trapped in a two-dimensional optical lattice, which is useful for measuring and reducing the temperature of atoms. Finally, I mention the purpose of the thesis, which is to create a quantum gas microscope using ytterbium atoms for realizing the quantum simulation of the FHM.

Chapter 2: Ytterbium – This brief chapter mentions the properties of ytterbium atoms and the important energy levels used for the experiment.

Chapter 3: Quantum gas microscope - In this chapter I explain the requirements to realize a quantum gas microscope, focusing on the feasibility of applying different fluorescence imaging strategies to ytterbium atoms. Fluorescence techniques used on other quantum gas microscopes (using Rb, Li and K) consists on cooling the atoms while observing the resultant fluorescence. The polarization gradient cooling, Raman cooling and electromagnetically induced transparency (EIT) cooling used in those experiments are not applicable to the ytterbium species due to the absence of hyperfine splitting and the lack of Zeeman sublevels in the ground state. I continue the chapter analyzing the possibility of applying Doppler cooling combined with magic-wavelength potentials as a fluorescence strategy. In addition, I propose a new "deep potential" method, which consists in creating a very deep potential in the excited state and a shallow potential in the ground one. The feasibility of the proposed method together with an analysis of the lifetime limitations are studied in detail with the help of a semi-classical simulation. Finally, I introduce the concept of solid immersion lens (SIL), which is a semi-spherical lens useful for increasing the numerical aperture of the microscope system.

Chapter 4: Experiment: Transport of atoms to the SIL surface – To load ultra-cold ytterbium atoms into a two-dimensional optical lattice, the atoms are first required to be confined in a pancake-shaped region which is thinner than the depth of field of the objective lens. This chapter focuses in the experimental method used to 1) create a cloud of ultra-cold ytterbium atoms using a Magneto-Optical trap, 2) transfer the cooled atoms to a distance of 20μm under the surface of the SIL using optical-tweezers, 3) create a Bose-Einstein condensate and 4) compress the condensate of atoms into a thin pancaked-shaped cloud. In order to create a condensate and compress it into a thin layer, I realized a new technique for creating and manipulating an "optical accordion" under the surface of the SIL. The technique consists in reflecting an incident (accordion) beam into the flat surface of the lens which creates a standing wave with controllable periodicity. Details of this technique and analysis of the experimental results are fully covered in this chapter.

Chapter 5: Experiment: Fluorescence imaging - In this chapter, the experimental method to load the thin condensate of atoms under the surface of the solid immersion lens into a two-dimensional optical lattice is first explained, followed by an analysis of the fluorescence images that were obtained with the quantum gas microscope using the "deep potential" strategy proposed in chapter 3. The following aspects of the microscope are covered: 1) resolution of the microscope, 2) algorithm used to reconstruct the original atomic distribution, 3) lifetime analysis and 4) reconstruction fidelity.

Chapter 6: Extension to fermionic isotopes – Here, I explain the requirements to extend the quantum gas microscope of ytterbium atoms to the ^{173}Yb fermionic isotope. To determine whether the "deep potential" is possible in the presence of a hyperfine splitting interaction, the total Hamiltonian containing both the AC stark interaction and the hyperfine splitting interaction is numerically calculated. For high light intensities, a breaking of the hyperfine splitting is observed as an analog to the Paschen-Back effect ocurring under high magnetic fields. In consequence, I estimate that the current quantum gas experiment is applicable to the fermionic ^{173}Yb fermionic isotope with only minor changes.

Chapter 7: Conclusions – In the last chapter, after a brief summary of the experimental results, I compare the performance of the quantum gas microscope of ytterbium atoms presented on this work with different quantum gas microscope using other species, focusing on the characteristics of the "deep potential" method proposed here. I suggest some ideas to improve the performance of the microscope, as well as mentioning the remaining tasks and future challenges.