（様式３）

博士論文の要旨

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論文題目：強相関・極低温リュードベリ原子気体を用いた量子多体ダイナミクスの研究

Quantum many-body problems dominate over a variety of physical and chemical phenomena ranging from the emergence of superconductivity and magnetism in solid materials to chemical reactions in liquids. Understanding many-body problems is thus one of the central goals of modern sciences and technologies. However, it is extremely difficult to solve quantum many-body problems with classical computers since the number of states grows exponentially with the number of particles in the system. Accordingly, another new approach referred to as "quantum simulation", where many-body problems are experimentally simulated with highly-controllable artificial quantum many-body systems, attracts much attention recently. Atomic, Molecular and Optical (AMO) Physics has recently been emerging as an ideal platform for quantum simulation. Its latest developments include studies on many-body correlations induced by long range interactions. From this viewpoint Rydberg atoms are expected as the most promising building blocks of artificial quantum many-body systems for quantum simulators, due to their large dipole moments and high controllability of the nature and strength of their interactions.

In this thesis I have succeeded in constructing a new quantum many-body system of a Rydberg-atom crystal, in which we load a Bose-Einstein condensate of ultracold rubidium atoms, whose temperature is nearly absolute zero kelvin, into an optical-lattice potential, whose lattice spacing is 532 nanometer, and excite those many atoms to Rydberg states with an ultrashort pulsed laser, so that we can control their interaction strength and character. Moreover, with this system we have succeeded for the first time in creating a "metal-like quantum gas", in which Rydberg electronic orbitals are spatially overlapped between the neighboring lattice sites [M. Mizoguchi *et al.,* "Ultrafast Creation of Overlapping Rydberg Electrons in an Atomic BEC and Mott-Insulator Lattice", Phys. Rev. Lett. **124**, 253201 (2020)].

In order to confirm the creation of the "metal-like quantum gas", we have studied spontaneous ionization of the Rydberg-atom crystal. Beyond a threshold principal quantum number where Rydberg orbitals of neighboring lattice sites overlap with each other, the atoms efficiently undergo Penning ionization resulting in a drastic change of ion-counting statistics, sharp increase of avalanche ionization, and the formation of an ultracold plasma. These observations signal the actual creation of the "metal-like quantum gas", which is further confirmed by a significant difference in ionization dynamics between a Bose-Einstein condensate and a Mott insulator.

The experimental results can be summarized in the following simple model shedding new light onto the ionization dynamics of an ultracold Rydberg gas: When the wave-function overlap is negligible, ionization occurs only through accidental primary ions being created, e.g., by motion-induced Penning ionization or other processes. The electrons freed by this process might eventually ionize other Rydberg atoms in an avalanche-like process. Only a small fraction of the Rydberg gas gets ionized actually, and formation of an ultracold plasma is excluded. If, however, spontaneous initial Penning ionization is facilitated by laser excitation of overlapping Rydberg-pair states, subsequent avalanche processes result in ionization of large fractions of Rydberg atoms and efficient formation of an ultracold plasma. This reasoning also explains the striking contrast between the Bose-Einstein condensate and Mott insulator.

The ionization and plasma formation under precisely controlled initial conditions demonstrated in this thesis provides a novel path toward the study of the competition between kinetic energy and electron-electron interactions in crystal structures. This competition underlies a vast range of the most elusive phenomena in strongly correlated physics. The present work provides us with a better understanding of the stability of many-body Rydberg systems and the mechanism for ultracold plasma formation. In the system constructed in this thesis, which is characterized by very low temperature and controlled atomic-pair distance, Penning ionization sets in at times shorter than 60 nanoseconds once the electronic-pair wave function shows significant overlap. This finding is consistent with previous theoretical predictions. For a pair of atoms with overlapping electronic wave functions the timescale for Penning ionization is estimated to be around 1-20 nanosecond. This allows observation of delocalized electron states using our ultrafast Ramsey interferometry with attosecond precision on picosecond timescales before they decay through Penning ionization.

This brand new "ultrafast quantum simulator", where we have combined an artificial quantum many-body system and ultrafast coherent control with attosecond precision for the first time, would develop into a pathbreaking platform for quantum simulation.