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研究課題名（和文）Rydberg atoms at sub-micron distance with overlapping electronic clouds

研究課題名（英文）Rydberg atoms at sub-micron distance with overlapping electronic clouds

研究代表者
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研究者番号：１０８４４１８６

交付決定額（研究期間全体）：（直接経費）　　2,200,000円

研究成果の概要（和文）：We trap Rubidium87 atoms in optical tweezers, excite the atoms to Rydberg states with picosecond pulsed lasers and study the ultrafast (nanosecond-scale) dynamics between the atoms which is driven by the dipole-dipole interaction.

研究成果の学術的意義や社会的意義
This project demonstrated that it is possible to prepare and use ultracold atoms in large array of optical tweezers. Moreover, for the first time, we demonstrated a coherent interaction-driven dynamics between two single atoms, in only a few nanosecond.

研究成果の概要（英文）：We trap Rubidium87 atoms in optical tweezers, excite the atoms to Rydberg states with picosecond pulsed lasers and study the ultrafast (nanosecond-scale) dynamics between the atoms which is driven by the dipole-dipole interaction.
First, we succeeded in constructing a ultra-high vacuum experimental setup, forming laser-cooled cloud of Rb atoms, and trapping and imaging single Rb atoms in an array of up to 800 holographic tweezers. Then, we developed novel holographic methods for bringing two atoms as close as 1.2 micrometer, and applied advanced cooling techniques to bring the atoms in the motional quantum ground-state of the tweezers. Finally, we realized a new ultrafast (10 ps) excitation scheme to efficiently bring the atoms into a Rydberg state. The preparation success has been improved from 10 % to 75 %.
Combining all these techniques, we observed a dipole-dipole driven energy exchange between two close-by Rydberg atoms, in a regime unexplored so far.

研究分野：Atomic, molecular and optical physics

キーワード：Quantum physics　Rydberg atoms　Dipole dipole coupling　Optical tweezers　Ultracold atoms　Ultrafast excitation

１．研究開始当初の背景

Rydberg atoms **A Rydberg atom is one in a highly excited electronic state** (typically with a principal quantum number n > 20), characterized by **a large electronic cloud** with a size scaling as $n^2 a_0$, with a_0 the Bohr radius. Consequently, properties of Rydberg atoms are enhanced compared to ground-state atoms and they have given, to experimental physicists, **a rich playground to explore quantum physics.** A first example is the strong coupling of Rydberg atoms to microwave radiations, a consequence of the large electric dipole $d \propto n^2 a_0 e$ formed by the positively-charged nucleus and the valence electron. This led, for example, to the non-destructive measurement of microwave photons in a cavity (Haroche, Nobel lecture 2012). Another consequence of the large electronic cloud of a Rydberg atom is that it will **strongly interact with another Rydberg atom**, even at large interatomic separation R.

Interaction between two Rydberg atoms Let us first consider the case where **two Rydberg atoms are sufficiently far apart** such that their electronic clouds do not overlap, i.e., $R > R_{LR}$ where the latter is the Le Roy radius (0.5 um for n = 40). In this case, the interaction is dominated by electrostatic terms, which are usually decomposed into a multipole expansion where the leading term is usually the second-order dipole-dipole coupling, i.e., **the van der Waals (vdW) interaction**, scaling as $C_6 \; / R^6$ (with C_6 a coefficient depending on the Rydberg states). The vdW interaction has been extensively studied both theoretically and experimentally. The C_6 coefficient can be computed analytically using perturbation theories, and are in excellent agreements with the result of spectroscopy experiments (e.g., Béguin2013).

While at large distance the interaction follows a van der Waals behavior, it is not true at shorter one (but still larger than R_{LR}), as **strong mixing between the various Rydberg orbitals can give rise to surprising effects**. One of them is the existence of **Rydberg macro-dimers**: molecular bound states with interatomic separation in the micrometer range. Their observation is a current hot topic in the atomic physics community, with recent exciting results in disordered ensemble (Saßmannshausen2016) or with atoms loaded in an optical lattice (Hollerith2018). Here, analytical calculations are not possible due to the large number of Rydberg states mixing together and one has to rely on numerical solvers.

When the interatomic distance becomes comparable or smaller than the Le Roy radius, **the electronic clouds start to overlap**. Here, rather than the classical electrostatic interaction considered so far, **quantum effect such as charge overlap and exchange interaction are expected** to dominate the coupling between the two Rydberg atoms. On the theory side, **little is known about this regime** as taking into account these quantum effects is tremendously more difficult than simply considering the classical electrostatic forces. One effect known to occur is **Penning ionization** where one atom is de-excited to a lower Rydberg state while the other is ionized. There seems to be no reported result about the precise timescale of this ionization process (supposed to occur at the nanosecond scale), nor about any other phenomena related to quantum effects between two cloud-overlapping Rydberg atoms. The reason why **experiments in this regime could not be performed so far lies in the difficulty of preparing two atoms at a precise sub-micron interatomic separation.**

２．研究の目的

The objective is to study a system of 2 Rydberg atoms, closed enough (typ. 0.5-1 um) for their electronic orbitals to overlap. The plan is (1) to trap Rubidium (Rb) and/or Cesium (Cs) in submicron-sized optical tweezers, (2) to cool these atoms to < 1 uK (enough to remove oscillation of the atoms in the traps), and (3) to excite the atoms to Rydberg state and perform spectroscopy.

３．研究の方法

- Optical tweezers, holography
- Laser-cooling, Raman sideband cooling
- Picosecond-puled lasers, non-linear optics

４．研究成果

Optical tweezers apparatus The vacuum system, specially designed for experiments with cold Rydberg atoms, have been assembled and successfully brought to the Ultra-High Vacuum regime. A magneto-optical trap setup was installed and used to trap and cool Rb or Cs atomic clouds. An holographic optical system comprised of a Spatial Light Modulator and an objective system (NA = 0.45, then 0.75) was introduced to create arrays of optical tweezers inside each of which a single atom can be trapped with 50% probability. Trapping of single atoms was demonstrated by fluorescence imaging. After upgrade of the high-NA (0.75) specially-designed objective, the size of the optical tweezers has been drastically reduced from 1.5 um down to 0.6 um. Consequently, it was possible to trap two atoms at a distance of 1.2 micrometer, the first objective of this research program.

Raman sideband cooling A series of effort was then conducted to reduce the atoms' motion using "Raman sideband laser cooling". This technique, making use of motion-*assisted spin*-flip to remove quanta of motion, requires the coherence time of the atom's *electronic spin to be much longer tha*n the atom's motional period in the trap (7 *microseconds in the radial direction, 30 in the axial direction). This coherence time was* initially measured to be ~1 microsecond, limited by large fluctuating 'effective' magnetic *field created by the trap polarization (vector light shift). After applying several mitigation techniques, the coherence time could be increased first up to 100 microseconds* *and then later to 1 ms. Followingly, we applied the cooling technique and reduced the radial motion down to a mean motional quantum of <0.05, where the atom position uncertainty (~30 nm) is now limited by quantum rather than thermal fluctuations. The cooling along the axial direction, which is more challenging due to the slower motion requiring even longer coherence time, has also been successfully implemented, thus completing the second objective of this research program.*

Ultrafast excitation Experiments with Rydberg atoms are typically achieved in timescale of microseconds by using continuous-wave lasers. In contrast, our group has been leading an original effort to excite atoms to Rydberg states in a timescale of ~10 picosecond (5 orders of magnitude faster). However, this has so far been accompanied by a quite small fraction (<10%) of the atoms coherently excited in the Rydberg state, which causes an obvious problem to clearly observe interactions between only two atoms (the probability to excite the two atoms being only 1%). In this research program, I solved this issue by implementing a new excitation scheme (two successive single-photon excitation instead of an effective two-photon transfer) with which we demonstrated Rabi oscillations to the Rydberg level up to 3π, enough for complete transfer to the Rydberg state (with a π-pulse) and an impressive upgrade over the previously maximum 0.2π (with $\sin^2(0.2\ \pi/2) \sim 10\%$).

Ultrafast interaction Following the above-mentioned progresses (pairs of atoms at distance down to 1.2 μm, cooling to the motional quantum ground-state, enhanced Rydberg excitation, e), I have investigated the ultrafast interaction between two atoms excited to a particular Rydberg state experiencing an enhanced resonant dipole-dipole coupling. Our observation indicates that an entangled state of two atoms could be produced in ~3 nanoseconds, more than 100 times faster than current entangling operations between Rydberg atoms obtained with continuous-wave lasers. These results successfully concludes this research program.

５．主な発表論文等

〔雑誌論文〕　計2件（うち査読付論文　0件／うち国際共著　0件／うちオープンアクセス　2件）

１．著者名 Yeelai Chew, Takafumi Tomita, Tirumalasetty Panduranga Mahesh, Seiji Sugawa, Sylvain de Leseleuc, Kenji Ohmori	４．巻 -
２．論文標題 Ultrafast energy exchange between two single Rydberg atoms on the nanosecond timescale	５．発行年 2021年
３．雑誌名 Under review (currently preprint)	６．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） 10.48550/arXiv.2111.12314	査読の有無 無
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 －

１．著者名 V. Bharti, S. Sugawa, M. Mizoguchi, M. Kunimi, Y. Zhang, S. de Leseleuc, T. Tomita, T. Franz, M. Weidemuller, K. Ohmori	４．巻 -
２．論文標題 Ultrafast Many-Body Dynamics in an Ultracold Rydberg-Excited Atomic Mott Insulator	５．発行年 2022年
３．雑誌名 Under review (currently preprint)	６．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） 10.48550/arXiv.2201.09590	査読の有無 無
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 －

〔学会発表〕　計5件（うち招待講演　2件／うち国際学会　1件）

１．発表者名 DE LESELEUC Sylvain
２．発表標題 Observation of a symmetry-protected topological phase of interacting bosons with Rydberg atoms
３．学会等名 IOP Publishing. A VIRTUAL CONFERENCE QUANTUM2020（国際学会）
４．発表年 2020年

１．発表者名 DE LESELEUC Sylvain
２．発表標題 Many body phyics with arrays of optical tweezers
３．学会等名 New Developments of Applied Physics. Workshop of University of Tokyo（招待講演）
４．発表年 2021年

１．発表者名
DE LESELEUC Sylvain

２．発表標題
Quantum simulation and computation with assembled arrays of Rydberg atoms

３．学会等名
The 7th IMS Mesoscopic Science Forum

４．発表年
2019年

１．発表者名
DE LESELEUC Sylvain

２．発表標題
Ultrafast energy exchange between two single Rydberg atoms on the nanosecond timescale

３．学会等名
GiRyd Status Workshop 2022（招待講演）

４．発表年
2022年

１．発表者名
DE LESELEUC Sylvain

２．発表標題
Raman sideband cooling of 800 atoms to the quantum ground-state of optical tweezers

３．学会等名
JPS March Meeting 2022

４．発表年
2022年

〔図書〕　計0件

〔出願〕　計2件

産業財産権の名称 量子シミュレータおよび量子シミュレーション方法	発明者 大森 賢治, Sylvain de Leseleuc, 他6人	権利者 浜松ホトニクス株式会社, 大学共同利用機関法
産業財産権の種類、番号 特許、特願2020-145826	出願年 2021年	国内・外国の別 国内

産業財産権の名称 量子シミュレータおよび量子シミュレーション方法	発明者 大森 賢治, Sylvain de Leseleuc, 他6人	権利者 浜松ホトニクス株式会社, 大学共同利用機関法
産業財産権の種類、番号 特許、特願2020-145812	出願年 2021年	国内・外国の別 国内

〔取得〕　計0件

〔その他〕

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6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関