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Controlling individual atoms with optical tweezers

Marvin Weyland^a, Mikkel F. Andersen^a, Rhys A. B. Hobbs^a, Lucile Sanchez^a, Poramaporn Ruksasakchai^a, and Stuart S. Szigeti^b

^aDepartment of Physics, University of Otago, Dunedin 9054, New Zealand

^bDepartment of Quantum Science, Research School of Physics, The Australian National University, Canberra 2601, Australia

ABSTRACT

We capture individual rubidium-85 atoms in steerable optical tweezers with high efficiency to study atomic interactions with a known number of atoms. These tweezers allow us to capture and move individual atoms, and to prepare them in a specific quantum states. We show the usefulness of this platform to study atomic interactions like individual molecule formation and spin changing collisions.

Keywords: atomic physics, individual atoms, molecule formation, spin changing collisions

1. INTRODUCTION

Optical tweezers have enabled the control and study of individual atoms and their interactions. It is now possible to deterministically load an optical tweezer with exactly one atom¹ and to do so with high efficiency.² In recent years this experimental platform showed the first production of individual molecules by combining two individually held single atoms.^{3,4} Furthermore, individual atoms in optical tweezers are an ideal platform for investigating entanglement between atoms^{5,6} and a promising platform for new quantum computers.^{7,8}

Here, we will present two atomic physics applications that study the interactions of atoms in optical tweezers: molecule formation dynamics and spin changing collisions.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

2.1 Atom preparation

Our individual atom manipulation apparatus uses a multi-step process in order to capture a single rubidium-85 atom in an optical tweezer, as shown in Fig. 1. Atoms are cooled and slowed using a magneto-optical trap (MOT), capturing several thousand atoms (1). The MOT is further compressed to increase the atomic density in the region of the optical tweezers (2). Up to three tweezers are created from 35 mW of 1064 nm light each. The tweezers are focused to a spot size of 1.1 μm through a high-NA lens (NA=0.55) and separated by 4.5 μm .⁹ Activating them in the space of the compressed MOT captures on the order of 10 atoms per tweezer (3). We then

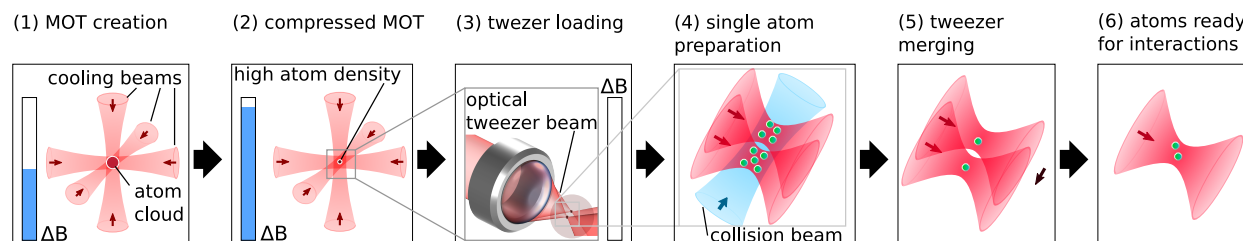


Figure 1. Atom loading sequence: (1) atoms are loaded into a magneto optical trap. (2) A compressed MOT increases the atom density sufficiently for effective loading into the optical tweezers. (3) Between one and three optical tweezers are activated to capture several atoms per tweezer from the compressed MOT. (4) Light-assisted collisions eject all but one atom per optical tweezer with high efficiency. (5) The tweezers with exactly one atom each are merged to transfer all atoms into one tweezer. (6) An optical tweezer with a precisely known number of atoms is prepared.

employ light assisted collisions to eject all but one atom from each tweezer.¹ This light creates an interaction between two rubidium atoms which transfers enough energy to the atom pair for exactly one atom to get ejected from the tweezer.¹⁰ Specifically, the light is blue-detuned by 85 MHz from the D1-transition in rubidium-85 and produces an unstable Rb_2 molecule,¹⁰ which upon decay transfers the required energy to the atoms. This process continues until there is only one atom left, at which point atom ejection stops because no atom pair is present. With this technique we reach a single atom preparation efficiency of 84% (4). These individual atoms are further cooled to reach temperatures of around 10 μK . They can be further transferred into a specific quantum state, for which we have a combination of optical pumping and Raman transfer schemes available. Finally, we merge the optical tweezers by moving them through space until they overlap (5), thereby producing one optical tweezer with a known number of atoms to be used in our studies of atomic interactions (6).

After step (4) in Fig. 1 we take an image of the atoms to confirm that the tweezers were successfully loaded. For this, the tweezers are imaged non-destructively using an EMCCD camera while exposing the atoms to imaging light close to the D1-transition of rubidium-85 at 795 nm (cf. Fig. 3) and collecting light scattered by the atoms. These images are used to screen for experimental realizations with the desired number of optical tweezers loaded.

2.2 Optical tweezer creation

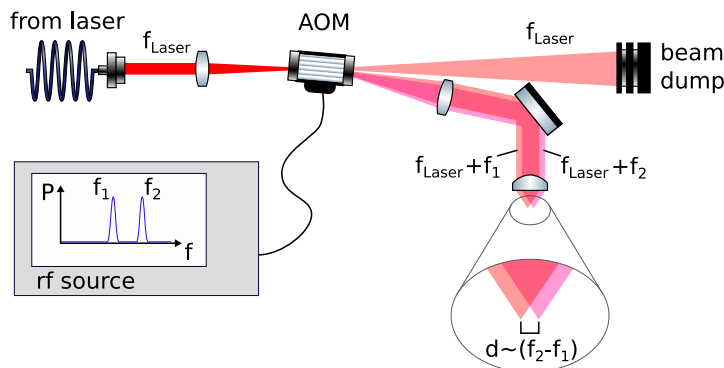


Figure 2. Simplified beam path for the creation of several steerable optical tweezers from one laser beam. The light is deflected by an acousto optic modulator (AOM), creating several different beams. These are recombined by the high-NA lens to focus the light, with the exact focal point depending on the deflection angle caused by the AOM.

Due to the small size of our optical tweezers of 1.1 μm , we need to steer them and keep their position stable with micrometre precision in order to overlap several tweezers. The solution to this problem is to create all tweezers from the same laser beam. A simplified version of this setup is shown in Fig. 2. We utilize an acousto optic modulator (AOM), which deflects the laser beam, and lets us choose and change this deflection angle. In an AOM, the laser light is scattered off an acoustic wave travelling through a crystal. The deflection depends on the frequency of the acoustic wave. Feeding the AOM with two tones simultaneously creates two waves, each deflecting the light at a slightly different angle. When these beams are refocused by the high-NA lens to create the optical tweezer, the position of the focal point depends on the original deflection, thereby separating the two tweezers. Because the beam path for both tweezers is identical except for the deflection by the AOM, the tweezers' relative position is stable. In our experiments, we use one stationary tweezer, created from light deflected by a 112 MHz acoustic wave in the AOM. Additionally, up to two further tweezers can be created on each side of the stationary tweezer by additional acoustic waves of around 20 MHz separation from the central tweezer, creating a separation of 4.5 μm . In Fig. 2 only one addition tweezer is shown, creating a total of two optical tweezers. By changing the frequency of the AOM during the experiment, we can move the tweezers along the direction of separation. When the frequency difference between two tweezers is low enough, this setup ensures that the tweezers overlap in space without requiring alignment of the individual tweezers.

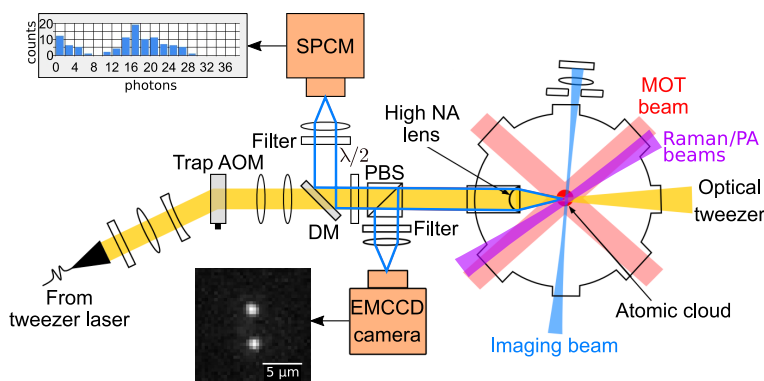


Figure 3. Sketch of the experimental setup and all relevant laser beam paths. Atoms are collected by the MOT (red beams) and loaded into the optical tweezer (yellow beam). Photoassociation or Raman beams (purple beam), specific to the experiment facilitate molecule formation and transfers between different internal state. The atoms are detected using imaging light (blue beam), which gets scattered by the atoms and detected by an EMCCD camera and a single photon counting module (SPCM).

2.3 Detection

After the desired interactions took place, the experimental outcome is encoded in the number of remaining atoms. This can happen by atom loss through the studied process - as in the case of photoassociation - or by selectively ejecting atoms in a specific quantum state via a push-out technique - as in the case of spin changing collisions.

The number distribution of remaining atoms is determined by detecting the amount of photons scattered during a second imaging light exposure. For this we use a single photon counter which detects around 4% of the scattered photons. By performing every experiment at least 600 times, these photon counts create a distribution which encodes the probability of each possible number of atoms to survive the experiment. We find the contributions of different atom number survival by measuring control distributions with a known number of atoms and performing a maximum likelihood fit of a mix of the control distributions to the experimental outcome.

3. APPLICATIONS OF THE PLATFORM

Our ability to control individual atoms lets us investigate interactions between different atoms as well as between an atom and light at the single event level. This unprecedented precision enables us to gain more insight into the studied processes than is possible in large-sample experiment because undesired many-body interactions are simply "switched off". A main interest of our studies are correlations between two atoms and their impact on other interactions.

3.1 Photoassociation dynamics

Photoassociation of two atoms allows us to build individual molecules from our trapped atoms.⁴ This completely new way of controlled individual molecule assembly opens up the production and study of new and exotic molecules not accessible in any other way.³ We investigated how the molecule formation takes place in exactly two atoms compared to a large ensemble.

In photoassociation, light of the correct wavelength transfers two free atoms (blue energy curve in Fig. 4) into a molecule in an electronically excited state (red energy curve). For this transition to occur, the atoms need to be at a specific distance from each other, called the Condon radius (r_c). Thus, photoassociation is sensitive to the probability for the atoms be at the correct distance, quantum-mechanically described by the relative-position wave function at the distance r_c (see inset of Fig. 4). For photoassociation of cold atoms at a small Condon radius, wave functions have either a maximum (peaked states) or a zero-crossing (nodal states) when the atoms are in the same place, shown exemplary by $\phi_1(x)$ and $\phi_2(x)$ in Fig. 4. These wave functions are conserved when two atoms collide - a vastly different situation from a large sample of atoms where constant collisions between two atoms change the wave functions relative to other atoms, essentially washing out any correlations. This probability to find another atom at a specific distance from one atom is known as the pair-correlation function and the dependence of photoassociation on the pair-correlation at the Condon radius r_c suggests it can be used at a tool to measure the pair-correlation function.

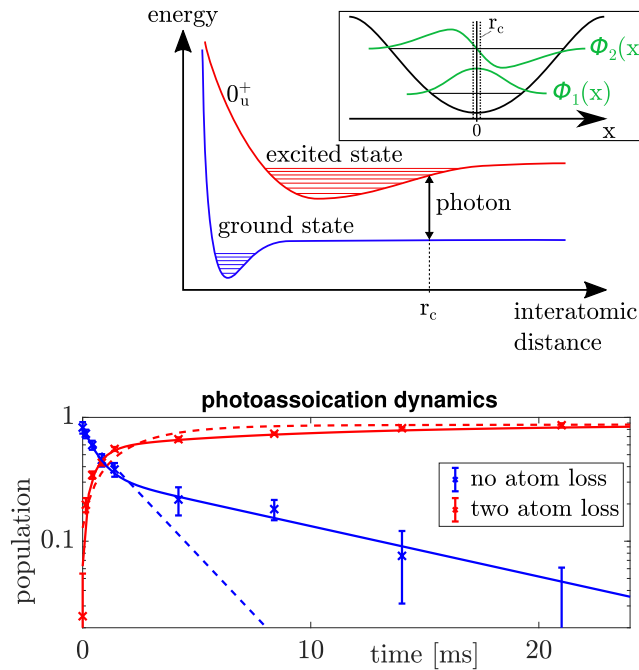


Figure 4. Sketch of the bound-state molecular energy curves for a diatomic molecule. A photon couples the unbound ground state to the bound excited state at an interatomic distance r_c , the Condon radius. Inset: One-dimensional cut through the relative position wave function of two atoms in an optical tweezer with a typical Condon radius marked to illustrate the different scales.⁴

Figure 5. Dynamics of photoassociation of exactly two atoms in an optical tweezer. Photoassociation is observed as two atom loss. The dynamics cannot be modeled with a single exponential decay (dashed lines) but show good agreement with a two-timescale model (solid lines), interpreted as fast molecule formation from peaked relative position wave functions and slow molecule formation from nodal relative position wave functions.⁴

We perform photoassociation measurements at a Condon radius of 4.3 nm, significantly smaller than the size of the atom confinement by the optical tweezer of 1.1 μm . In this situation, there is a good separation between wave functions with a peak at zero atom-atom separation and wave functions with a zero-crossing at that point.

Figure 5 shows an example of the observed dynamics. We observe molecule formation as the loss of two atoms (red crosses), while no molecule formation leads to survival of both atoms (blue crosses). The molecule formation cannot be modeled using the single timescale - the behaviour expected from a rate equation with one fixed rate (dashed lines in Fig. 5). Instead, molecule formation with two photoassociation rates shows good agreement with the data (solid lines in Fig. 5). A theoretical analysis shows that the dynamics should be driven by many different photoassociation rates - one for each allowed relative position wave function. These group into two distinct classes - fast photoassociation for peaked states and slow photoassociation for nodal states - with the differences of the rates within each class too small to be distinguished experimentally.

We tested our explanation using a theoretical description, where photoassociation is modeled as a loss process at the Condon radius.⁴ These calculations show similar dynamics as the experiment, and furthermore show that photoassociation depletes the atom pair density at low separation

3.2 Spin changing collisions

Individual atoms in optical tweezers are an ideal platform to investigate spin changing collisions.¹¹ When we prepare two atoms in the same quantum state, these can collide and change their spin states.

As a first step, we investigated the spin changing collisions which create an atom pair in two specific quantum states. Figure 6 shows this measurement. The original quantum state $|0,0\rangle$ gets converted to $\hat{S}|1,-1\rangle$ and $\hat{S}|2,-2\rangle$ by spin changing collisions between the atoms. The fit (solid lines) assumes that no other states are created and shows very good agreement with the measurement. This demonstrated our high amount of control over the quantum states of the atoms via collisions.

4. CONCLUSIONS AND OUTLOOK

The optical tweezer platform has enabled the control of individual atoms and now allows studies of atom-atom interactions in the most controllable system yet. New findings that photoassociation dynamics are influenced by atom pair-correlations already provide more insight into the process than many-body experiments did in the past.

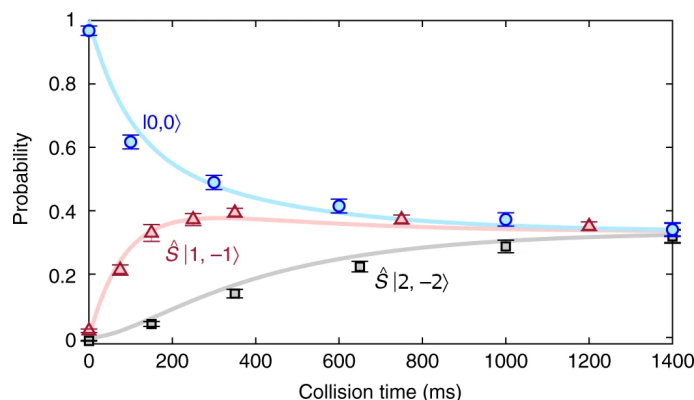


Figure 6. Measurement of the quantum state of the atom-pair. $|0,0\rangle$ denoted the original quantum state the atoms were prepared in, while $\hat{S}|1,-1\rangle$ and $\hat{S}|2,-2\rangle$ are the states populated by spin changing collisions.¹¹

Extending these measurements to three atoms will allow us to test theoretical predictions of pair correlation in the far more complex three-body system. Furthermore, spin changing collisions between exactly two atoms can be controlled in optical tweezers. The created atoms pairs are a candidate for the creation of entangled atoms.¹¹ The chance to generate thermally robust entanglement between two atoms makes this platform an interesting candidate for future quantum sensing and quantum computer applications.

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