Optical tweezers for a bottom-up assembly of few-atom systems

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ABSTRACT

Tightly focused laser beams form optical tweezers that can hold and manipulate individual atoms. They give superb control over microscopic quantum systems and have paved the way for bottom up assembly of few-atom systems. Such assembled systems provide an ideal starting point for many fundamental studies of atomic interactions and few-atom phenomena. Here we review the present stage of these fields, as well as some of the basic experimental techniques required for these experiments. Figure from [74].

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1. Introduction

Optical tweezers are light beams that hold microscopic particles. The technology was pioneered by Arthur Ashkin, who was awarded the Nobel prize for the achievement in 2018. Optical tweezers are applied across a range of scientific disciplines and are used, for example, to manipulate biological cells [1] and nano-particles [2]. Today they provide basic experimental infrastructure for controlling and manipulating individual particles as small as atoms. The optical tweezers hold the individual atoms in a sheltered vacuum environment, thereby minimizing unwanted interference from the surroundings. While doing so, they can exploit the high degree of flexibility offered by modern optics to control the tweezer beams in order to manipulate and move the individual atoms [3–5]. This makes optical tweezers a preferred tool for fundamental studies of atomic interactions, but also for example for holding individual atoms in high Q optical cavities for QED experiments [6,7] or placing individual atoms near the surface of nanophotonic devices to generate hybrid quantum systems [8,9].

The development of optical tweezers technology for manipulating individual atoms is largely driven by their potential use in quantum technologies, such as quantum information processing [10]. In particular, there is a focus on using atoms excited to Rydberg states, as the long range interaction between such provides an excellent way of entangling atoms in separate optical tweezers, which allow for implementing the necessary quantum gate for a universal quantum computer [11]. The study of of interacting Rydberg atoms in optical tweezers is therefore a burgeoning field of research, with regularly published excellent reviews [12–17].

The tweezer platform lends itself well to fundamental physics studies. Optical tweezers enable the bespoke arrangement of individual atoms, a long held ambition amongst physicists [18]. This allows physicists to assemble few-body systems from the bottom up, thereby realizing an unprecedented level of experimental control. It gives the capability to isolate the process under study and directly observe the outcome of individual events. This provides extraordinary insight, omitting the need to infer the microscopic dynamics from large ensemble measurements. In the latter, it is often difficult to discriminate between the effects of a range of different microscopic processes that may occur.

Here we review experiments that use few atoms in optical tweezers for fundamental studies of their interactions and few-body physics. The remaining of this review is structured as follows: Section II introduces the mechanism behind how optical tweezers hold atoms (Section II A), how to load an optical tweezer with a single atom (Section II B), and how to subsequently move the atoms around (Section II C). Section II is intended to introduce readers new to the field to some of the important techniques in
it, but the range of techniques used is too extensive for a complete review here. For additional information, for example on how to cool individual atoms to the ground state of the tweezer [19–24], how to perform fluorescence imaging of individual atoms [25–29], and how to determine the internal state of an atom in the tweezer [30–33], the reader will have to refer to the literature. Section III reviews fundamental studies of atom-atom interactions including molecule formation experiments, and Section IV covers some of the few-body experiments facilitated by the optical tweezer platform. Finally, Section V discusses some future avenues for the tweezer platform.

2. Basic techniques

Multiple techniques are employed in experiments with individual atoms in optical tweezers. Although new experimental designs emerge regularly [34] they typically involve a setup of the kind outlined in Figure 1. A magneto optical trap laser cools and traps a group of atoms. A relatively high numerical (NA) aperture lens focuses one (or more) laser beam(s) (‘micro-trap beam’ in Figure 1) into the laser cooled group of atoms to form the tweezer(s). The same high NA lens forms the objective lens in a microscope that images fluorescence from the atoms onto a low-light sensitive camera such as an Electron Multiplying CCD (EMCCD) camera, and/or a photon counter.

2.1. Trapping

The laser beam forming an optical tweezer can hold an atom due to its spatially dependent intensity profile. This gives rise to a spatially dependent interaction energy between the atom and the light field. The interaction energy will act as a potential energy for the motion of the atom, such that it looses kinetic energy when the interaction energy increases. The origin of the interaction energy stems from the light’s electric field inducing an electric

Figure 1. Illustration of optical tweezer setup for manipulation of individual atoms. Unlabeled red arrows: Magneto optical trap beams. Figure from [35].
dipole in the atom, which in turn has an interaction energy with the electric field. The interaction therefore takes the form $- \mathbf{d} \cdot \mathbf{E}$ where $\mathbf{d}$ is the electric dipole moment and $\mathbf{E}$ the electric field, and the potential energy the atom experiences is often deemed the optical dipole potential. As a result, optical tweezers are also often called optical dipole traps or microtraps. Below we discuss the potentials that the optical tweezer exerts on the atom.

### 2.1.1. Two-level atom

Two-level atoms in light fields are a standard topic in many physics textbooks [36], and both the atom and the light field can be treated quantum mechanically. This may at first glance appear excessive as optical tweezers use powerful light beams where the quantum fluctuations in the photon number are negligible compared to the average photon number. The light can therefore be treated classically, however this does not provide significant simplification, while the quantum treatment provides clear, intuitive pictures that are also useful when dealing with spontaneous emission.

The eigen states of the atom-light system are called ‘dressed states’ and to compute the potential that the tweezer beam exerts on the atom, one computes their eigen-energies as a function of the position of the atom. For a spatially-varying tweezer beam, the light-atom interaction energy varies, and when the tweezer light frequency is far off the atomic resonance frequency, second order perturbation theory gives the dressed state energies and thereby the potential energy experienced by an atom in a given dressed state to be:

$$
\Delta E = \frac{\left| \langle 2 | \mathbf{d} | 1 \rangle \cdot \varepsilon_L \right|^2}{\varepsilon_0 c} \frac{\hbar \omega_0}{(\hbar \omega_L)^2 - (\hbar \omega_0)^2} I(|\mathbf{R}|)
$$

where $|1\rangle$ and $|2\rangle$ are the two electronic states of the atom, $\mathbf{d}$ the dipole operator, $\varepsilon_L$ the polarization vector of the tweezer light, $\omega_L$ the laser frequency, $\hbar \omega_0 = E_2 - E_1$ with $E_1$ ($E_2$) the energy of $|1\rangle$ ($|2\rangle$) in the absence of the tweezer, and $I(|\mathbf{R}|)$ is the local intensity of the tweezer laser at the atomic position $\mathbf{R}$. In addition to only keeping second order energies, Equation (1) also assumes the photon number in the tweezer beam is high. We have kept the so-called counter-rotating term, which is often omitted in what is known, as the ‘rotating wave approximation’. However, many modern experiments with individual atoms in optical tweezers use light frequencies very far from atomic resonances, and in this case the counter rotation term is not negligible. If one, as an example, uses a tweezer laser with a wavelength of 1064 nm for experiments with Rb, then the magnitude of the counter-rotating term is 15% of the co-rotating term for the D2 line, that has a resonant wavelength of 780 nm.
Equation (1) gives the energy shift of the dressed state with atomic part $|1\rangle$ in the absence of coupling to the light, regardless whether it is the ground or excited state. From the definition of $\omega_0$ we see that ground and exited states are shifted in opposite directions, and that the ground state is high-field seeking (attracted to high intensity regions) for tweezer laser frequencies below the atomic resonance frequency.

### 2.1.2. Multi-level atom

The above two-level atom treatment highlights the main concepts of how optical tweezers for atoms work. While it might be relevant in some cases when a tweezer laser frequency is such that it mainly interacts with one transition in the atom, then the large detunings often used means that the multilevel nature of the atom can not be ignored. However, it is straightforward to generalize Equation (1) to multilevel atoms, and one then gets:

$$\Delta E_n = \frac{1}{\varepsilon_0 c} I(R) \sum_{m\neq n} |\langle m|d|n \rangle|^2 \frac{(E_n - E_m)}{(E_n - E_m)^2 - (\hbar \omega_L)^2}$$

(2)

where the sum is over all atomic states that state $|n\rangle$ have dipole allowed transitions to, which are the states $|m\rangle$ for which $\langle m|d|n \rangle \neq 0$. Information about the oscillator strengths for transitions in different atoms, and thereby the relevant dipole operator matrix element, can be found in Ref [37].

From Equation (2) we see that the energy shift is proportional to the local intensity of the tweezer beam. This means that an atom in a particular dressed state moving in an inhomogeneous laser beam will experience a potential energy proportional to the local intensity of the laser beam. Figure 2 shows a calculation based on Equation (2) of the energies of all the states on the D2 line of $^{85}$Rb for a tweezer wavelength of 1064 nm. We see that higher lying states cause the excited states to be shifted more than the ground states. This can be problematic in some experiments, as atoms in the excited states experience a repulsive potential from the tweezer light. A strong repulsive excited state potential may lead to heating or potentially atom loss, if they spend an appreciable amount of time in these states. However, by appropriate choice of tweezer wavelength, higher lying states can sometimes reverse the sign of the energy shift of an excited state (see Equation (2)) making the tweezer potential attractive for this state as well. A tweezer wavelength, where this is done to the degree that the excited state energy shift is identical to the ground state energy shift, is called a 'magic wavelength', as it eliminate spectral broadening of the atomic transition due to the tweezer light. Use of such magic wavelengths can be a powerful tool in optical tweezer experiments [25]. Finally, it is worth noting that non-paraxial tweezers, which many experiments use, inevitable lead to spatially
varying polarizations. This leads to \( m_F \) dependent light shifts of the ground states, that the pure linear polarization assumption of Figure 2 predicts \( m_F \) independent [20].

2.2. Loading

There are numerous techniques allowing for preparation of few-atom systems in optical tweezers or micro-traps. We focus on those relevant to bottom up assembly. Information regarding optical lattice methods [38–40], top-down methods where single- or few-atom systems are isolated from many-atom systems [41–43], or efficient transfer of a predetermined atom number from a magneto optical trap [44] can be found in the literature.

The relatively small confining potentials that optical tweezers supply mean that atoms need to be laser-cooled to be trapped in it. The tweezers are therefore typically loaded from a cloud of laser cooled atoms, for example in a magneto optical trap. Once the optical tweezer is turned on, the laser cooling will cool atoms that diffuse into the tweezer causing the atoms to get trapped. For few-atom experiments, it is important to determine the atom number in the tweezer.
2.2.1. **Probabilistic loading**

The conceptually simplest way to load an optical tweezer with a given number of atoms is to use probabilistic loading [31]. If one wishes to load a single atom into a tweezer in this scheme, the optical tweezer is loaded by a random number of atoms from a cloud of laser-cooled atoms. After detecting the number of atoms in the tweezer the experiment then progresses if it is the desired number. The drawback of this method is the relative low probabilities it provide for obtaining a desired number of atoms. Poisson statistics show that the probability of loading one atom has a maximum of 37%. While this sufficient to load a single tweezer with an atom, it rapidly leads to very low success probabilities if multiple tweezers needs to be loaded, each with a single atom. Probabilistic loading based on Poisson statistic is therefore rarely used today.

2.2.2. **Collisional enhanced loading**

Many inelastic atomic collisions release sufficient energy that the participating atoms can escape the relatively low trapping potentials that optical tweezers provide. This can enhance the probability for loading exactly one atom into an optical tweezer beyond the limit of probabilistic loading.

The concept of how inelastic collisions can enhance loading was first demonstrated using light assisted collisions in optical lattices [45] and was later adapted in numerous variations in optical tweezers. If an optical tweezer is loaded by a random number of atoms, and these are then subject to an inelastic collision process that release an energy large compared to the tweezer potential, then colliding atoms will be lost from the tweezer. The atoms are then lost in pairs until collisions cease when two atoms are no longer present. The result is that the tweezer ends up loaded with either zero or one atom with the two options having equal probability of about 50%, constituting a significant improvement over probabilistic loading.

A common way to induce inelastic collisions to deplete the atom population to zero or one is to expose the atoms in the tweezer to the laser cooling beams used to load it. These are typically red detuned from an atomic resonance and will induce light assisted collisions [46] by exciting colliding atoms to an electronically excited molecular interaction potential when the internuclear separation is at the Condon radius (see red arrow in Figure 3). Upon excitation the atoms strongly attract and accelerate towards each other, but will spontaneously emit at a later stage, indicated by the red serpentine arrow in Figure 3. However, the pair will have gained the difference in interaction energy between the internuclear separation at which they were excited and the one at which they spontaneously emitted a photon. This energy is typically large and the colliding atom pair is lost from the tweezer.
As alluded to in the previous paragraph, the very laser beams that load the optical tweezer also induce the light assisted collisions. This is used in a particular variation of the scheme known as collisional blockade loading [28,48,49]. This happens when the optical tweezer volume is very small, such that the inelastic collisions rate when two atoms are present, is much higher than the loading rate of atoms into the tweezer. The timescale for loss due to the inelastic collisions will thus be fast, such that it can be considered instantaneous compared to the typical time between loading events. In this regime tweezer occupancies above one atom are effectively blockaded since both atoms are lost almost instantaneously when a second atom is loaded. As the tweezer is loaded, the occupancy will therefore flip between zero and one every time another atom enters. Over time, the tweezer will therefore be populated by a single atom half the time.

The ease with which 50% loading can be achieved by using light assisted collisions induced by readily available laser beams, means that variations of this technique are the workhorse in loading optical tweezers with individual atoms. Since its first implementation using $^{87}\text{Rb}$ [28] collisional enhanced loading is successfully employed for a range of elements and isotopes. These include Potassium [24], Caesium [50], Sodium [51], and Strontium [52]. While light assisted collisions are the most commonly used inelastic collisions for isolating individual

![Figure 3](image_url). Homo-nuclear light assisted collisions in alkali metals. The excited state has a long range $S^\text{P}_0$ asymptote. When light, that is red detuned from the free atom resonance, excites an atomic pair (vertical red arrow), it is transferred to the attractive excited state molecular interaction potential, from which they can spontaneously decay (red serpentine arrow). Blue detuned light (blue vertical arrow) will excite the pair to the repulsive interaction potential. Figure from [47].
atoms in optical tweezers, other collisions have also been employed. Experiments with metastable Helium in optical tweezers utilize Penning ionization in a similar way to generate a single atom source [53].

It is finally worth noting that the nonlinear nature of collisional loss also yield sub-Poissonian number fluctuations when an atom number greater than one is targeted [54]. This happens because the loss rate per atom increase with the number of atoms, thereby suppressing the uncertainty in the atom number.

2.2.3. Near deterministic or blue detuned loading
When both partners in a collision are lost we end with a 50% chance to have a single atom. However, a collisional process where only one of the collision partners is lost from the tweezer leads to the atoms being lost one by one until only a single atom is present and the loss ceases. This will present a deterministic way of preparing exactly one atom in an optical tweezer.

Blue detuned light assisted collisions allow the design of inelastic light assisted collisions where only one of the collision partners is lost [55]. In light assisted collisions induced by light that is blue detuned relative to the atomic resonance, the pair is excited to the repulsive molecular interaction potential [56] (blue arrow in Figure 3). The energy released in an inelastic light assisted collision is then limited by the detuning of the light inducing it [57]. If the detuning is chosen such that the maximal energy released is smaller than twice the confining potential of the optical tweezer, then a collision will not release sufficient energy for both colliding atoms to be lost. If the collision releases enough energy for one of the atoms to be lost but not both, then one atom may or may not escape the tweezer depending on how the atoms share the released energy. The pair’s center of mass motion at the time of the collision determines how they share the released energy, and whether none or one atom are lost as a result. Figure 4 illustrates how adding laser cooling to the process will make the process repeat until an atom is lost as a consequence of a collision. When the atoms share the released energy approximately equally such that none of the atoms are lost, then laser cooling will remove the energy released before the next inelastic collision occurs. The chance that two collisions occur before the energy released in the first is removed is suppressed by the drop in atomic density when the atoms have high energy. In this way, light assisted collisions will keep occurring until one of the collision partners are lost, with the chance that two atoms are lost strongly suppressed.

Early experiments with the two natural Rubidium isotopes achieved loading efficiencies exceeding 90% [35,58]. They used Sisyphus cooling techniques to provide the laser cooling required for the enhanced loading scheme. However, this implementation requires relatively deep optical tweezers demanding high tweezer laser power to make sizable arrays of
tweezers. In more recent work, loading of Rb atoms using $\Lambda$-enhanced grey molassis omitted the need for additional laser cooling beams and allowed for loading of significantly more shallow optical tweezers while maintaining a high loading efficiency close to 90% [59]. The latter technique has also proven efficient for loading Na atoms, which pose unique challenges due to their small mass [25].

2.3. Dynamic tweezers

Studies of few-body physics with optical tweezers requires the ability to move, and potentially merge, tweezers. When only one tweezer needs to move a mirror reflecting that beam can be controlled using transducers [60,61]. For more tweezers, common methods include programmable spatial light modulators [5,62–64], acousto-optical deflectors (AODs) [4,51,52,59,65–68], or a combination of both [3,69,70]. Using dynamical tweezers allows for atom sorting [71] to generate defect free structures [3–
from randomly loaded arrays, and the merging of tweezers to realize tweezers populated with a given atom number \([66]\) or particular combination of atoms \([50,51,60]\).

An AOD can conveniently conduct quick changes of dynamical tweezers when the RF signals that drive it are altered. If one wishes to generate a linear array of tweezers, one can place the AOD in the Fourier plane of the tweezer plane and drive the AOD with multiple RF signals within the AOD’s bandwidth (Figure 5). Each RF signal will then result in a tweezer where the amplitude will determine the strength of a given tweezer and the RF frequency determines its position along the array. An atom in a particular tweezer can then be moved by sweeping the RF frequency, thereby moving the tweezer and dragging the atom along. For 2D motion, one needs two orthogonally mounted AODs. This also allows for generation of a 2D array of tweezers \([59,72,73]\). However, it gives fewer control degrees of freedom at disposal than tweezers in the array, making individual trap optimization challenging \([72]\). If multiple tweezers generated from the same laser beam need to be merged, such as illustrated in Figure 6, different tweezers will be frequency shifted differently by the AOD. When they start to overlap, there will therefore be a strong beat between the tweezer light beams causing the atoms to feel a rapidly varying confining potential. When the timescale of this is sufficiently fast the atoms will experience a time average potential, but if the beat is slower, it will

![Figure 6](image_url). Atom-atom interaction experiment using movable optical tweezers. Right panel: Fluorescence images of the atoms at different positions during the experiment. Figure from [74].
lead to rapid heating of the atoms and atom loss. To avoid heating and loss, the traps need to merge when their frequency difference is still sufficiently high for the atoms to experience a time average potential.

Spatial light modulators effectively offer complete control over a light beam and can therefore be used for any tweezer geometry. However speed can be limited and it can be computationally heavier to generate the holograms required for moving atoms around with multiple tweezers [75].

3. Atom-atom interactions in optical tweezers

The ability to prepare an exact atom number or particular combinations of atomic species in an optical tweezer, combined with the capability to directly observe the outcome of events makes this an ideal platform to study atom-atom interactions. It allows for observation of effects that are hidden by ensemble averaging when the microscopic dynamics are inferred from measurements on macroscopic samples. This has led to observation of several surprising results that had been overlooked when the processes was studied in large ensembles [66].

3.1. Molecular interactions

Atoms’ ability to bind and form molecules is key to our understanding of the natural world. Yet experimental advances continuously reveal new aspects of the underlying physics.

3.1.1. Molecules in the electronic excited states

Early studies focused on light-induced processes. When light is used to photo-associate a pair of atoms to an electronically excited molecular state, it will rapidly decay, resulting in the light assisted inelastic collision

![Figure 7](image.png)

Figure 7. When the photo-association laser frequency is scanned, atoms are resonantly lost in pairs as it match transitions from two free atoms to an electronically excited molecular state.
illustrated in Figure 3. As mentioned previously, excitation to the repulsive molecular interaction potential can lead to only one of the collision partners lost [55]. Subsequent studies show that when an atomic pair is photo-associated to states close to the dissociation threshold, the energy released after the pair has decayed to two free atoms in their electronic ground state is often surprisingly small, despite the large excited state binding energy [76]. When atomic pairs are photo-associated to deeper bound molecular states, these can be resolved individually (see Figure 7). In 2018, a heteronuclear molecule (NaCs) was photo-associated into particular excited state molecular states [51], and a recent study showed that pair correlations influence the photo-association dynamics profoundly, when there are only two atoms present in the tweezer. This gives rise to far more complex dynamics than have been observed in large ensembles as illustrated in Figure 8 [77].

3.1.2. Molecules in the electronic ground states
For molecules to be long lived they need to be formed in their electronic ground state. This has been the focus of a recent series of studies. These have demonstrated the formation of weakly bound molecules by Raman transitions [78,79] magneto association [80], and by coupling the pair’s relative motion and spins [81]. Recently, a polar NaCs molecule was produced in its rovibrational ground state [82] which could become a key resource for molecule-based quantum simulation.

3.2. Interactions between atoms in their ground states
Atoms have rich interactions, and many processes do not involve molecule formation. The first experiment involving hetero-nuclear interactions between two atoms in an optical tweezer studied inelastic hyperfine changing collisions between the two abundant isotopes of Rb
The ability to detect the internal states of atoms facilitates investigations of elastic interactions such as spin-changing collisions. Their population dynamics lead to near-perfect correlations between the internal states of two thermal atoms [74]. Combining a range of state of the art atom manipulation techniques with spin-exchange interactions can entangle two transportable atoms in tweezers, thereby providing a way to utilize atoms’ inherent ground state interactions to entangle q-bits in a quantum register [83]. Finally, the strong confinement of an optical tweezer facilitates spectroscopic techniques that can determine the atoms’ interaction energies. This provides efficient methodology to characterize atoms’ interaction in the tweezers [84].

Most studies of atomic interactions focus on pairwise interactions. But the capability to assemble exact atom numbers higher than two presents an exciting opportunity to study more complex interactions. A study of collisional dynamics in atomic triads used the ability to directly observe the outcome of individual events, which makes it possible to discriminate between two-body loss events and three-body recombination [66]. This is challenging in many-atom experiments where only an overall loss rate is measured, making it hard to extract the individual contributions of different microscopic processes.

4. Few-body physics in optical tweezers

The superior control that make the optical tweezer platform potent for studies of atom-atom interactions also make it an ideal platform for fundamental studies of few-body physics. The few-body regime is of particular interest because it displays its own range of unique physical phenomena, but also because it is the bridge between single-particle and many-body physics. It is key to understanding how complex many-body phenomena emerge from simple single particle physics. A splendid illustration of this is ref [85], which shows how collective light scattering phenomena develop as more atoms are added to an optical tweezer.

The superb control that can be achieved over few atoms in optical tweezers has led to the demonstration of the matter wave Hong-Ou-Mandel effect for two independently prepared bosonic atoms. The atoms were ground state cooled in separate optical tweezers and the tweezers were reconfigured to allow for tunneling between them revealing the two-body quantum interference of the Hong-Ou-Mandel effect [65].

The large flexibility that bottom up assembly of few-atom systems offers, makes this a promising direction for the future. It complements techniques where few-atom systems are isolated from larger ensembles [86] and opens new possibilities.
5. Outlook

Manipulating single atoms in optical tweezers is by now a proven technique for a range of fundamental physics studies. Yet, there is no doubt that it is still a rapidly developing platform that will enable new and exciting research in the future. These developments may enable physicists to build strongly correlated states of matter from the bottom up [87], an exciting prospect that may aid an understanding of many-body problems.

Interaction studies with atoms are paving the way for similar studies with molecules in optical tweezers. This future direction is driven by rapid advancements in laser cooling and trapping of certain classes of molecules [88], expanding the potential from those that can be build from individual atoms as described in Section III A 2.

The motivation for developing the optical tweezer platform for manipulation of individual atoms is not limited to its use in fundamental physics studies. It also stems from its potential use for quantum technology research [12,14,15,72]. The latter area will undoubtedly continue to play a leading role, whether targeted at quantum information processing or quantum sensing and metrology.

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