DETECTION OF SINGLE RYDBERG EXCITATIONS IN MESOSCOPIC ENSEMBLES

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This paper discusses a method recently proposed by Schmidt *et al.* for detecting a single Rydberg excitation in mesoscopic atomic ensembles. The physical background of the problem is first introduced through Rydberg blockade and collective excitations. The main focus of this paper is a readout scheme based on Autler–Townes-induced optical pumping. In this approach, the presence of a Rydberg excitation is converted into a difference in the ground-state population of the surrounding ensemble, which can later be measured by fluorescence imaging. In comparison with detection schemes based on electromagnetically induced transparency, the method is more robust against probe detunings and line shifts. Its performance shows that a single Rydberg excitation can be reliably detected in mesoscopic ensembles.

ZAZNAVA POSAMEZNIH RYDBERGOVIH VZBUDITEV V MEZOSKOPSKIH ANSAMBLIH

Članek obravnava nedavno predlagano metodo za detekcijo posamezne Rydbergove vzbuditve v mezoskopskem atomskem ansamblu, ki so jo razvili Schmidt in sodelavci. Najprej je predstavljeno fizikalno ozadje metode, ki temelji na Rydbergovi blokadi in kolektivnih vzbuditvah. Osrednji del članka je posvečen detekcijski shemi, ki uporablja optično črpanje, nadzorovano z Autler–Townesovim razcepom atomskih energijskih nivojev. Pri tem se prisotnost Rydbergove vzbuditve preslika v spremembo zasedenosti drugega hiperfinega osnovnega stanja okoliškega ansambla, ki jo lahko izmerimo s fluorescenčnim slikanjem. V primerjavi z detekcijskimi shemami na osnovi elektromagnetno inducirane transparentnosti je metoda manj občutljiva na odmike frekvenc laserskih polj od resonančnih atomskih prehodov. Pokazano je, da je mogoče posamezno Rydbergovo vzbuditev zanesljivo zaznati v mezoskopskih atomskih ansamblih.

1. Introduction

Neutral atoms trapped in optical tweezers have become an important platform for quantum simulation and quantum information processing because atomic states can be prepared, manipulated, and read out with high precision using laser light [1–4]. This platform becomes especially powerful when the atoms are excited to Rydberg states, whose strong interactions extend over distances comparable to typical interatomic separations. A single Rydberg excitation can therefore influence many surrounding atoms, enabling the implementation of quantum gates, the preparation of collective excitations, the study of correlated many-body dynamics and other applications in quantum simulation and quantum computing [1–3].

For these applications, reliable detection of Rydberg excitations is essential. Two well-established detection techniques are fluorescence imaging and ionization. Fluorescence imaging, in which resonant light causes atoms to scatter photons that are collected by a camera, is routinely used for the detection of ground-state atoms. Rydberg excitations, however, do not generally permit the same direct fluorescence readout. They can instead be detected by ionization, but this process removes the excited atom from the trap and therefore destroys the atomic register. It is thus desirable to develop a method that maps the presence of a Rydberg excitation onto a fluorescence-detectable signal without removing the atoms from the trap.

A suitable setting for such detection schemes is provided by mesoscopic atomic ensembles confined in optical tweezers. Here, the term mesoscopic refers to ensembles containing a few to a few hundred atoms. Such ensembles are large enough to exhibit collective behaviour while remaining sufficiently small for controlled preparation and readout in a single optical tweezer. Ensembles confined

in a single optical tweezer provide a natural setting for collective excitation and ensemble-assisted readout [5–7].

In this paper, we discuss an established ensemble-assisted detection scheme based on electromagnetically induced transparency, demonstrated by Xu *et al.* [6], and a more recent method proposed by Schmidt *et al.* [8] that addresses some of the limitations of the established scheme. Both methods rely on collective effects enabled by Rydberg blockade, which is introduced in the following section.

2. Rydberg blockade and collective excitations

The essential property of a Rydberg atom is that its outer electron is very far from the nucleus. As a result, the atom is highly polarizable and therefore very sensitive even to weak electric fields. This also means that two nearby Rydberg atoms can interact strongly at large, micrometer distances [1, 7]. This interaction can be described by a van der Waals potential,

$$V(R) = \frac{C_6}{R^6}. \tag{1}$$

An important consequence of this interaction is the Rydberg blockade. If one atom in a certain volume is already excited to a Rydberg state, the interaction shifts the energy of the state in which both atoms are excited. When this shift becomes larger than the linewidth of the excitation laser, the second excitation is no longer resonant, so simultaneous excitation of two nearby atoms becomes unlikely. The characteristic distance below which this occurs is called the Rydberg blockade radius R_b and the corresponding blockade volume is the spherical region of radius R_b around a Rydberg-excited atom [1, 2].

The basic idea can already be seen in the simplest case of two atoms. Resonant excitation couples the two-atom ground state $|gg\rangle$ to the symmetric single-atom excited state

$$|\psi_+\rangle = \frac{1}{\sqrt{2}}\left(|gr\rangle + |rg\rangle\right). \tag{2}$$

The doubly excited state $|rr\rangle$ is shifted by the interaction and becomes inaccessible when the distance between the atoms is less than the blockade radius ($R < R_b$).

The same idea extends naturally to a mesoscopic ensemble containing N atoms within one blockade volume. In that case, the system can still support only a single Rydberg excitation, but, because the atoms are indistinguishable, this excitation is no longer associated with one specific atom. Instead, it is shared collectively by the whole ensemble and is described by the singly excited state

$$|W\rangle = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} |g_1 g_2 \cdots r_i \cdots g_N\rangle, \tag{3}$$

which is often referred to as a superatom. The coupling between the collective ground state $|G\rangle = |g_1 g_2 \cdots g_N\rangle$ and the shared excitation $|W\rangle$ is enhanced to

$$\Omega_N = \sqrt{N}\,\Omega_1, \tag{4}$$

where Ω_1 is the single-atom Rabi frequency [5, 8]. This enhancement arises because the laser couples $|G\rangle$ equivalently to N possible single-atom excitations, so the corresponding transition amplitudes add constructively. As a result, the collective excitation can be prepared faster than for a single atom. The same collective response is also useful for detection, because it allows the presence of a single Rydberg excitation to be converted into a measurable optical signal of the surrounding atoms. One of the most common detection schemes based on this idea uses electromagnetically induced transparency, or EIT.

3. EIT-based ensemble detection

Electromagnetically induced transparency is an optical effect in which a medium that would normally absorb a weak probe field becomes transparent when a second, coupling field is applied. This happens when the probe and coupling fields are resonant with the corresponding transitions. This is called the EIT condition.

The basic idea of the EIT detection scheme is to use a nearby mesoscopic ensemble as an optical amplifier. The excitation that we want to detect is carried by a single control atom prepared in the Rydberg state $|r'\rangle$. Around this control atom, there is a sample ensemble whose atoms are driven in a ladder configuration $|g\rangle \leftrightarrow |e\rangle \leftrightarrow |r\rangle$ by a weak probe field Ω_p and a stronger coupling field Ω_c. When the control excitation is absent and the probe and coupling fields are resonant, the sample becomes nearly transparent to the probe light, and many transmitted photons reach the photodiode. The situation changes if the control atom is excited to $|r'\rangle$. In that case, the interaction between the atom in state $|r\rangle$ and the atom in state $|r'\rangle$ shifts the Rydberg level of the sample atoms and destroys the EIT condition [6]. The sample then absorbs the probe light, and the number of transmitted photons decreases strongly. In this way, the presence or absence of a single Rydberg excitation is mapped onto a much larger optical signal produced by the whole ensemble. This makes the method collectively enhanced, but it also means that the signal depends on a narrow EIT resonance and is therefore rather sensitive to detunings and line shifts. This is the main reason for considering the Autler–Townes-based detection scheme.

4. Autler–Townes-based ensemble detection

A more robust readout can be obtained by keeping the same ensemble-assisted detection strategy, but replacing the narrow EIT transparency condition with an Autler–Townes-based scheme.

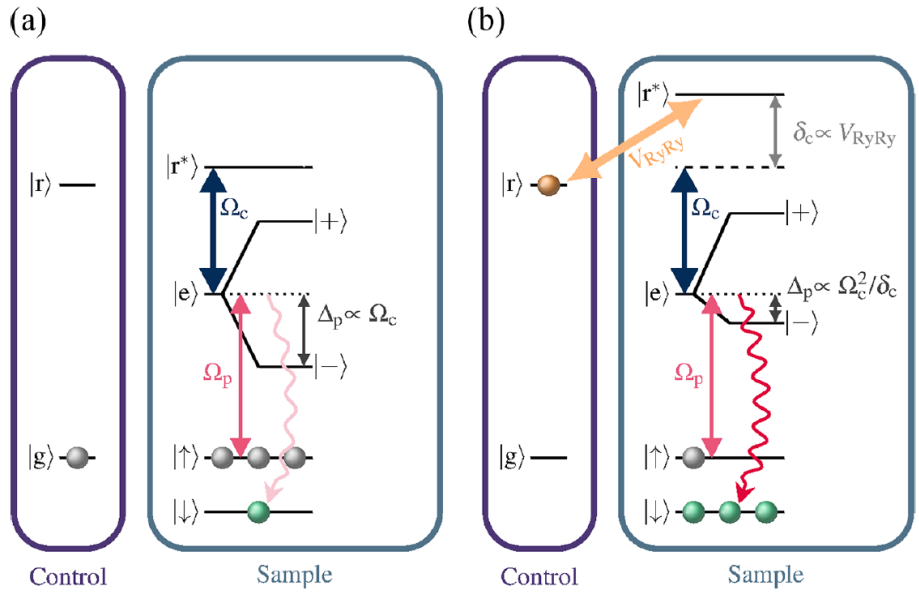

Figure 1. Simplified level scheme of the Autler–Townes-based detection method. A weak probe field drives the lower transition $|\uparrow\rangle \leftrightarrow |e\rangle$, while a strong coupling field Ω_c drives $|e\rangle \leftrightarrow |r^*\rangle$. (a) In the absence of a nearby control excitation, strong coupling mixes $|e\rangle$ and $|r^*\rangle$ into two dressed resonances and suppresses probe scattering, so the transfer to $|\downarrow\rangle$ is weak. (b) In the presence of a control excitation $|r\rangle$, the Rydberg–Rydberg interaction V_{RyRy} shifts the auxiliary state $|r^*\rangle$, modifies the dressed-state energies, and brings one dressed resonance closer to the probe frequency. Probe scattering is then restored and population transfer into $|\downarrow\rangle$ is enhanced. Adapted from Ref. [8].

The basic level structure is shown in Figure 1. The sample atoms are initially prepared in the

ground state $|\uparrow\rangle$, where $|\uparrow\rangle$ and $|\downarrow\rangle$ denote two hyperfine states of the atomic ground-state manifold. A weak probe field drives the transition $|\uparrow\rangle \leftrightarrow |e\rangle$, while a much stronger coupling field drives the upper transition $|e\rangle \leftrightarrow |r^*\rangle$. The physical signal in this scheme is created by probe scattering, that is, by repeated excitation of atoms from $|\uparrow\rangle$ to the intermediate state $|e\rangle$ by the probe field, followed by spontaneous decay. Since part of this decay leads to the second stable ground state $|\downarrow\rangle$, repeated scattering events gradually transfer population from $|\uparrow\rangle$ to $|\downarrow\rangle$. This population transfer is the optical pumping mechanism used for detection [8].

Whether the optical pumping is suppressed is determined by the strong coupling field. Its role goes beyond simply connecting the bare states $|e\rangle$ and $|r^*\rangle$, since it mixes them so strongly that the relevant eigenstates of the coupled atom–light system become light-induced superpositions rather than the bare atomic states themselves. These new eigenstates are called dressed states with energies that are equal to

$$\Delta E_{\pm} = -\frac{\hbar\delta_c}{2} \pm \frac{\hbar}{2}\sqrt{\Omega_c^2 + \delta_c^2}, \tag{5}$$

where Ω_c is the Rabi frequency of the coupling field and δ_c is its detuning from the upper transition [8]. Because they have different energies, the probe no longer couples with a single resonance associated with the intermediate state $|e\rangle$, but two shifted resonances instead. This is known as the Autler–Townes splitting.

The simplest case of no nearby control excitation being present and the coupling field being resonant ($\delta_c = 0$) is shown in Figure 1(a). The dressed-state energies then reduce to

$$\Delta E_{\pm} = \pm\frac{\hbar\Omega_c}{2}, \tag{6}$$

which is the usual symmetric Autler–Townes doublet. The effective probe detuning then is

$$|\Delta_p| = \frac{\Omega_c}{2}. \tag{7}$$

For sufficiently large Ω_c the probe is far from resonance and scattering is strongly suppressed [8].

The situation is different when a nearby control atom carries the Rydberg excitation $|r\rangle$, as shown in Figure 1(b). Because of the Rydberg–Rydberg interaction, the control atom interacts strongly with the sample atoms prepared in state $|r^*\rangle$. This shifts the energy of $|r^*\rangle$ and therefore makes the coupling field effectively detuned, so that δ_c becomes finite. In the regime $\delta_c \gg \Omega_c$, the dressed-state energies can be approximated as

$$\Delta E_{\pm} = -\frac{\hbar\delta_c}{2} \pm \left(\frac{\hbar\delta_c}{2} + \frac{\hbar\Omega_c^2}{4\delta_c}\right), \tag{8}$$

so that one of the dressed resonances moves much closer to the probe transition [8]. The corresponding effective probe detuning is then

$$|\Delta_p| = \frac{\Omega_c^2}{4\delta_c} \ll \frac{\Omega_c}{2}, \tag{9}$$

which means that optical pumping is restored [8].

The physical consequence of this mechanism is illustrated in Figure 2. In the absence of a nearby Rydberg excitation, strong coupling suppresses probe-induced scattering and the sample remains predominantly in $|\uparrow\rangle$. In the presence of the control excitation, the interaction shifts the energy of the state $|r^*\rangle$, restores scattering, and drives population transfer into $|\downarrow\rangle$. In this way, the presence or absence of a single Rydberg excitation is mapped onto the ground-state population of the surrounding ensemble. The resulting population difference can then be measured by ordinary fluorescence imaging, which is one of the main practical advantages of the scheme. Compared with EIT-based readout, the Autler–Townes signal is thus stored in a stable ground-state population and is less sensitive to detunings and line shifts as it does not depend on maintaining a narrow transparency condition.

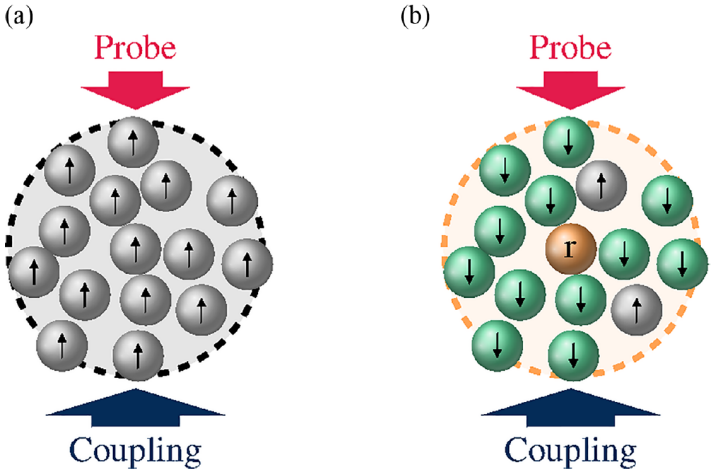

Figure 2. Basic idea of the Autler–Townes-based detection scheme. The sample ensemble is initially prepared in the ground state $|\uparrow\rangle$ and addressed by a weak probe field and a strong coupling field. (a) In the absence of a nearby control excitation, Autler–Townes splitting suppresses probe scattering and the sample remains predominantly in $|\uparrow\rangle$. (b) In the presence of a control excitation $|r\rangle$, the Rydberg–Rydberg interaction shifts the energy of the state $|r^*\rangle$, restores probe scattering, and enhances transfer to the second hyperfine ground state $|\downarrow\rangle$. Adapted from Ref. [8].

5. Performance of the Autler–Townes scheme

Having established the basic idea of the Autler–Townes protocol, we can now examine its performance. The main goal is to understand how the signal and contrast vary with the probe detuning and coupling strength, and what this implies for the final detection error.

Two quantities are especially useful for this discussion. The first is the sample transfer probability P, which describes how efficiently the sample atoms are transferred from $|\uparrow\rangle$ to $|\downarrow\rangle$. It therefore measures the absolute size of the signal. The second is the transfer ratio

$$R = \frac{P}{P_{\mathrm{noRyd}}}, \tag{10}$$

where P_{noRyd} denotes the transfer probability in the absence of a control Rydberg excitation. This ratio therefore measures how well the cases with and without a control excitation can be distinguished.

Figure 3 summarizes the behaviour of the transfer probability P and the transfer ratio R. As shown in Figure 3(a), the transfer probability decreases with the coupling strength, and it is broadened over a wider interval of probe detunings. The latter is one of the central advantages of the Autler–Townes protocol, because it makes the method less sensitive to small frequency fluctuations and light shifts. By contrast, Figure 3(b) shows that the transfer ratio R improves for stronger coupling, although the absolute transfer decreases. The two figures therefore illustrate an important trade-off between stronger coupling, which improves the contrast, and weaker coupling, which improves the signal strength. The most useful operating regime lies between these two limits [8].

To connect these quantities with the final readout performance, it is also useful to consider the detection infidelity. Here infidelity simply means the probability that the protocol gives the wrong result, namely that it incorrectly identifies whether the control Rydberg excitation is present or absent.

Figure 4 shows the final practical consequence of the Autler–Townes scheme. The detection error decreases for larger sample ensembles, since a larger number of atoms produces a stronger optical signal. At the same time, the infidelity is already relatively low even for modest ensemble sizes. It is also worth noting that in the parameter range shown here, the lowest infidelity is obtained

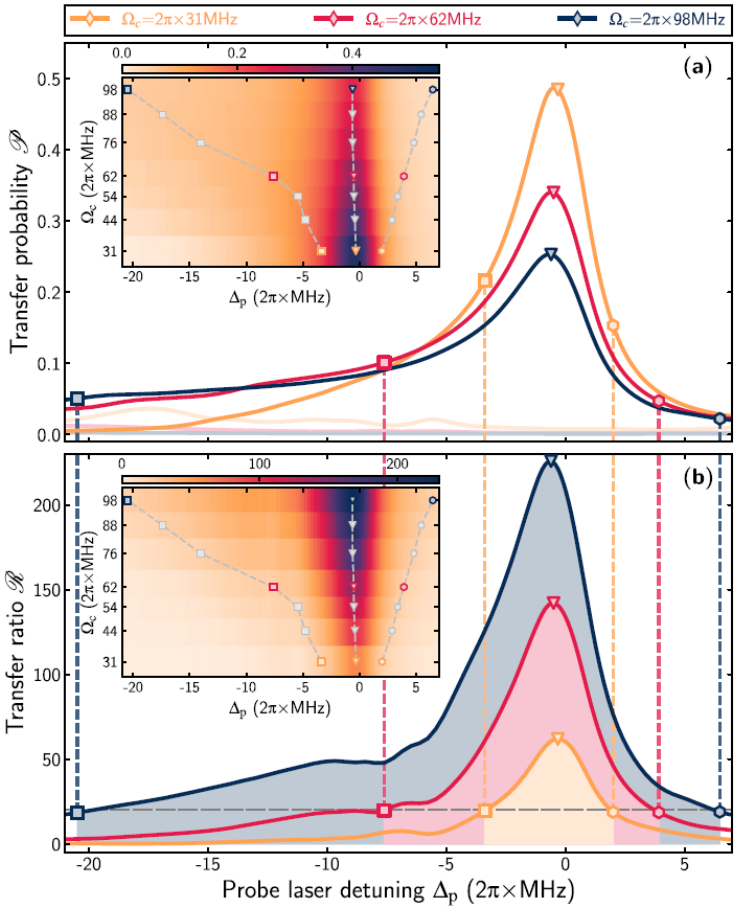

Figure 3. Performance of the Autler–Townes scheme. (a) Sample transfer probability P as a function of probe detuning Δ_p for different coupling strengths Ω_c. Semi-transparent lines show the transfer probability in the absence of a control Rydberg excitation. (b) Transfer ratio $R = P/P_{\mathrm{noRyd}}$, which measures the contrast between the cases with and without a control excitation. Adapted from Ref. [8].

for the weaker coupling strengths, indicating that in the examined cases the benefit of a larger absolute transfer outweighs the improved contrast obtained at stronger coupling. Taken together, these results show that the Autler–Townes protocol is robust with respect to probe detuning and capable of high-fidelity detection in mesoscopic ensembles.

6. Conclusion

This paper discussed how a single Rydberg excitation can be detected through the collective optical response of a nearby mesoscopic ensemble. After introducing the basic physics of the problem, namely Rydberg blockade and collective excitation, two ensemble-based readout strategies were compared. While the EIT-based method relies on the loss of transparency, the Autler–Townes-based scheme converts the presence of a control excitation into a stable ground-state population difference that can later be measured by fluorescence imaging.

The results show that the Autler–Townes protocol remains effective over a broadened range of probe detunings and is therefore less sensitive to small frequency fluctuations and line shifts than EIT-based detection. At the same time, it can achieve low detection infidelity in mesoscopic ensembles. In this way, the Autler–Townes scheme provides a robust and practical method for the readout of single Rydberg excitations.

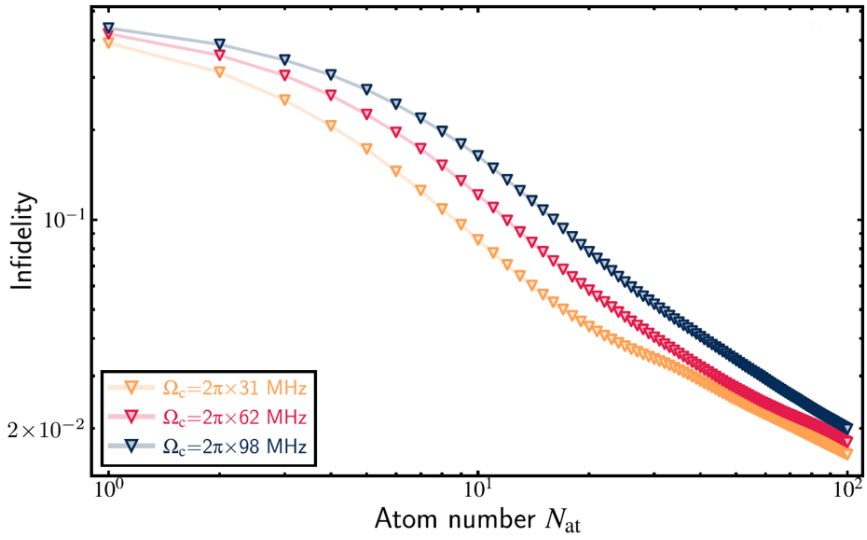

Figure 4. Detection infidelity, defined as the probability of incorrectly identifying whether a Rydberg excitation is present or absent, of the Autler–Townes protocol as a function of coupling strength Ω_c and sample atom number N_{at}. Larger ensembles lead to lower infidelity, while in the parameter range shown here the lowest infidelity is obtained for the weaker coupling strengths. Adapted from Ref. [8].

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