Master program in Physics
Seminar 2

Detection of Single Rydberg Excitations in Mesoscopic Ensembles

Author: Ema Stopar
Advisor: dr. Peter Jeglič

Ljubljana, April 2026

Abstract

This seminar discusses a method for detecting a single Rydberg excitation within atomic ensembles. The physical background of the problem is first introduced through Rydberg blockade and collective excitations. The main focus of this seminar 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 EIT-based detection schemes, the method is more robust against probe detunings and line shifts. Its performance shows that a single Rydberg excitation can be reliably detected in small mesoscopic ensembles.

Contents

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, because they enable strong interactions over micrometer distances, making it possible to implement quantum gates, prepare collective states, and study correlated many-body dynamics [1–3]. For such applications, reliable state detection is an essential part of the protocol, since the result of a quantum simulation or computation ultimately has to be extracted by measurement. Detecting ground-state atoms is comparatively straightforward, for example by fluorescence imaging, where resonant light makes the atoms scatter photons that are then collected by a camera. A Rydberg excitation, however, does not usually allow such a direct optical readout. One possible detection method is ionization, but this is destructive because the atom is removed from the trap. In many applications this is undesirable, since the atomic register is then lost after the measurement. For this reason, it is important to develop readout methods that can reveal the presence of a single Rydberg excitation with minimal disturbance of the atomic system. One particularly useful setting for such schemes is provided by mesoscopic atomic ensembles confined in optical tweezers. In this context, mesoscopic refers to an ensemble that contains several atoms and already exhibits collective behavior, but is still much smaller and more con-

trollable than a macroscopic atomic cloud. Although optical tweezer arrays are most commonly operated with a single atom per site, small ensembles in an individual trap are easier to prepare and they offer a natural route to collective effects and ensemble-assisted readout [5–7]. The physical origin of this collective regime is the Rydberg blockade mechanism, which is important because it enables the conditional dynamics required in quantum information processing.

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 [1, 2].

The basic idea can already be seen in the simplest case of two atoms, as shown in Fig. 1. 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 this excitation is no longer

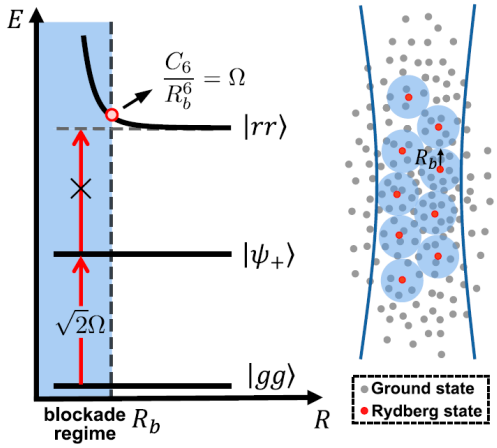

Figure 1: Strong Rydberg–Rydberg interactions shift the doubly excited state and define a blockade radius R_b. Within the blockade volume, a mesoscopic ensemble supports at most one shared Rydberg excitation. Adapted from Ref. 2.

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, collective excitation can be performed 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.

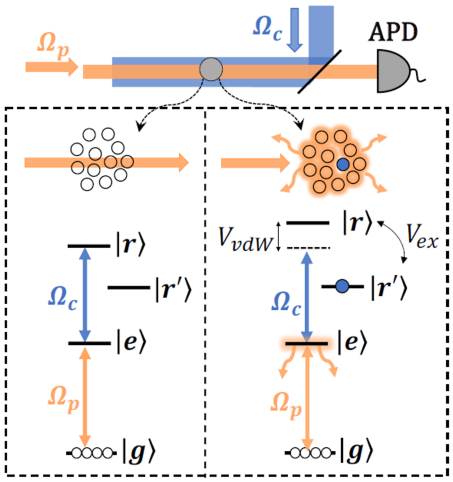

Figure 2: EIT-based detection. The surrounding sample atoms are driven in the ladder configuration $|g\rangle \leftrightarrow |e\rangle \leftrightarrow |r\rangle$ by the probe field and the coupling field. Under EIT conditions, the sample is nearly transparent and many probe photons are transmitted to the photodiode (APD) (left). If the control atom is excited to $|r'\rangle$, the interaction with the sample Rydberg state $|r\rangle$ shifts the upper level, removes the EIT condition, and strongly reduces the transmitted probe signal as the ensemble absorbs the probe light (right). Adapted from Ref. 6.

As shown in Fig. 2, 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 $|r\rangle$ and $|r'\rangle$ 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.

The basic level structure is shown in Fig. 3. 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

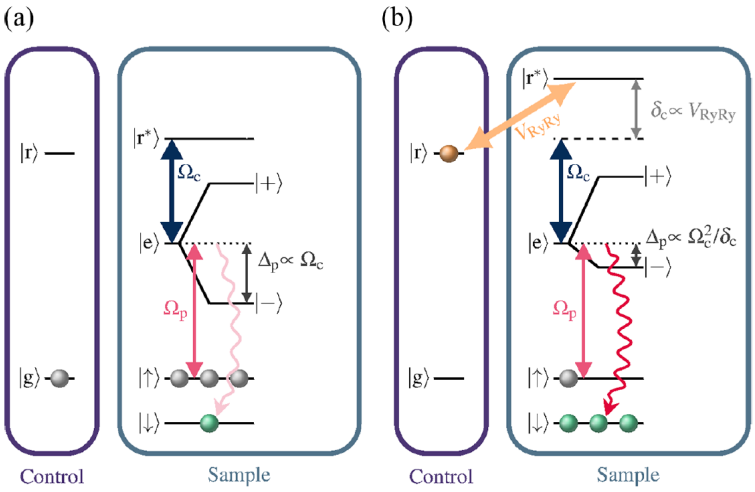

Figure 3: Simplified level scheme of the Autler–Townes-based detection method. A weak probe field drives the lower transition $|\uparrow\rangle \leftrightarrow |e\rangle$, while a strong coupling field Ω_c drives $|e\rangle \leftrightarrow |r^*\rangle$. (a) In the absence of a nearby control excitation, 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.

no longer sees 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 Fig. 3(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 is then

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

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 Fig. 3(b). Because of the Rydberg–Rydberg interaction, the control excitation interacts strongly with the state of the sample $|r^*\rangle$. 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. 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].

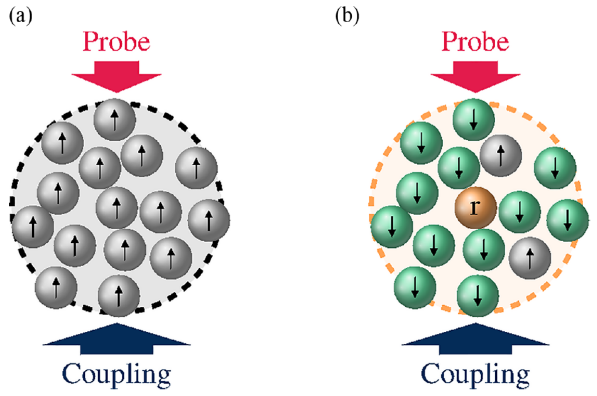

Figure 4: Basic idea of the Autler–Townes-based detection scheme. The sample ensemble is initially prepared in the ground state $|\uparrow\rangle$ and addressed by a weak probe field and a strong coupling field. (a) In the absence of a nearby control excitation, Autler–Townes splitting suppresses probe 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 state $|r^*\rangle$, restores probe scattering, and enhances transfer to the second hyperfine ground state $|\downarrow\rangle$. Adapted from Ref. 8.

The physical consequence of this mechanism is illustrated more directly in Fig. 4. 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 $|r^*\rangle$, 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.

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.

Fig. 5 summarizes the behavior of the transfer probability P and the transfer ratio R. As shown in Fig. 5(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, Fig. 5(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

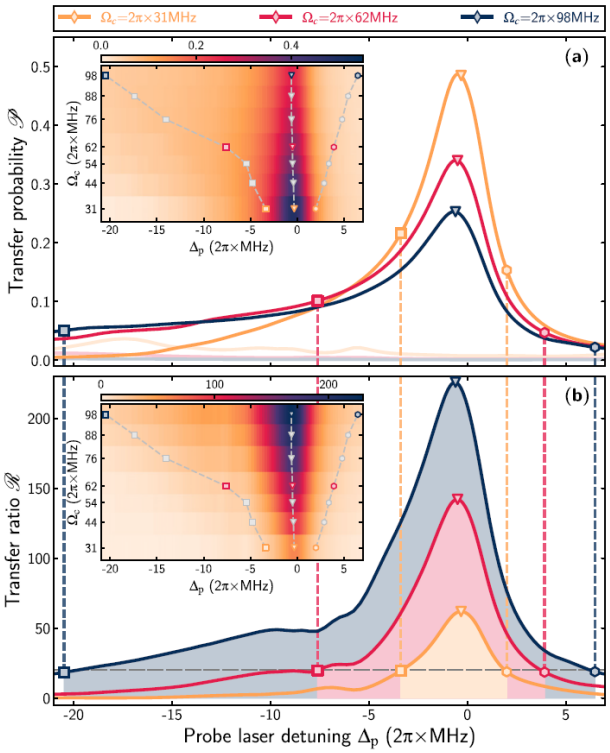

Figure 5: Performance of the Autler–Townes scheme. (a) Sample transfer probability P as a function of probe detuning Δ_p for different coupling strengths Ω_c. Semi-transparent lines show the transfer probability in the absence of a control Rydberg excitation. (b) Transfer ratio $R = P/P_{\mathrm{noRyd}}$, which measures the contrast between the cases with and without a control excitation. Adapted from Ref. 8.

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.

Fig. 6 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

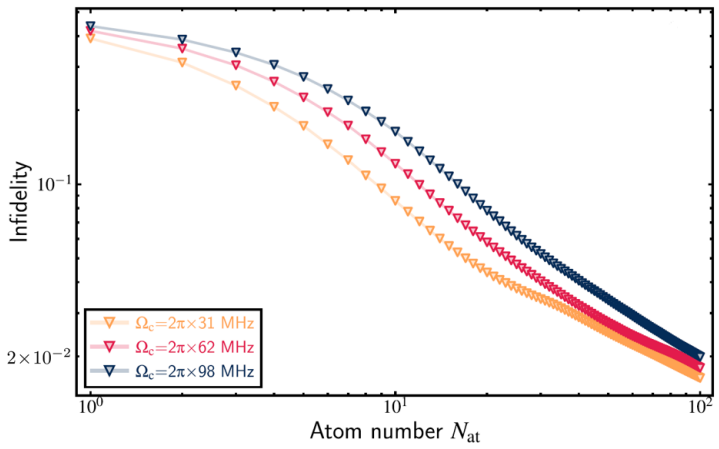

Figure 6: Detection infidelity of the Autler–Townes protocol as a function of coupling strength Ω_c and sample atom number N_{at}. Larger ensembles lead to lower infidelity, while in the parameter range shown here the lowest infidelity is obtained for the weaker coupling strengths. Adapted from Ref. 8.

worth noting that in the parameter range shown here, the lowest infidelity is obtained 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 seminar 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.

References

[1] M. Saffman, T. G. Walker, and K. Molmer. Quantum information with Rydberg atoms. *Reviews of Modern Physics*, 82(3):2313–2363, 2010. doi: 10.1103/RevModPhys.82.2313.

[2] A. Browaeys and T. Lahaye. Many-body physics with individually controlled Rydberg atoms. *Nature Physics*, 16(2):132–142, 2020. doi: 10.1038/s41567-019-0733-z.

[3] M. Morgado and S. Whitlock. Quantum simulation and computing with Rydberg-interacting qubits. *AVS Quantum Science*, 3(2):023501, 2021. doi: 10.1116/5.0036562.

[4] X. Wu, X. Liang, Y. Tian, F. Yang, Ch. Chen, Y. Liu, M. K. Tey, and L. You. A concise review of Rydberg atom based quantum computation and quantum simulation. *Chinese Physics B*, 30(2):020305, 2021. doi: 10.1088/1674-1056/abd76f.

[5] M. Ebert, M. Kwon, T. G. Walker, and M. Saffman. Coherence and Rydberg blockade of atomic ensemble qubits. *Physical Review Letters*, 115(9):093601, 2015. doi: 10.1103/PhysRevLett.115.093601.

[6] W. Xu, A. V. Venkatramani, S. H. Cantu, T. Šumarac, V. Kluesener, M. D. Lukin, and V. Vuletić. Fast preparation and detection of a Rydberg qubit using atomic ensembles. *Physical Review Letters*, 127(5):050501, 2021. doi: 10.1103/PhysRevLett.127.050501.

[7] D. Comparat and P. Pillet. Dipole blockade in a cold Rydberg atomic sample. *Journal of the Optical Society of America B*, 27(6):A208–A232, 2010. doi: 10.1364/JOSAB.27.00A208.

[8] S. Schmidt, A. Thielmann, T. Niederpruem, and H. Ott. Fast and robust detection of single Rydberg excitations in mesoscopic ensembles. *Physical Review A*, 112(3):033114, 2025. doi: 10.1103/964l-npcf.