Detection of single Rydberg excitations in mesoscopic ensembles

Ema Stopar
Supervisor: dr. Peter Jeglič
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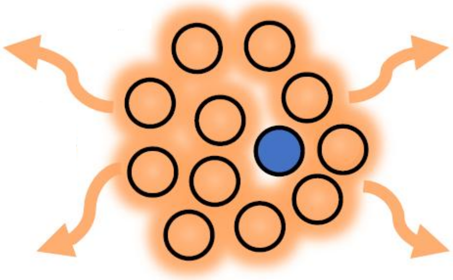
UNIVERSITY OF LJUBLJANA
FMF
Faculty of Mathematics and Physics

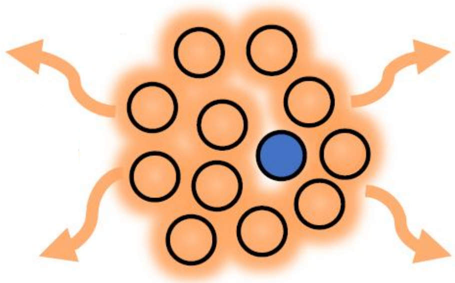


Contents

- motivation for exploring new detection techniques
- Rydberg atoms: physical properties
- electromagnetically induced transparency (EIT) based detection
- Autler-Townes detection scheme
- performance of the Autler-Townes detection scheme

- we assume a cold atomic ensemble already trapped in an optical tweezer
- *mesoscopic* = large enough to show collective behaviour, yet much smaller than a macroscopic cloud

Motivation



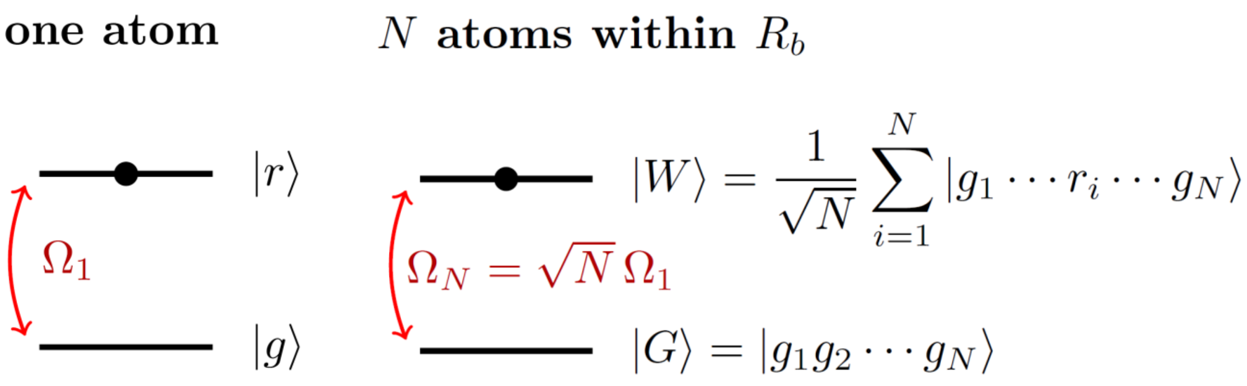
- atoms in optical tweezers: platform for quantum simulation and quantum computation

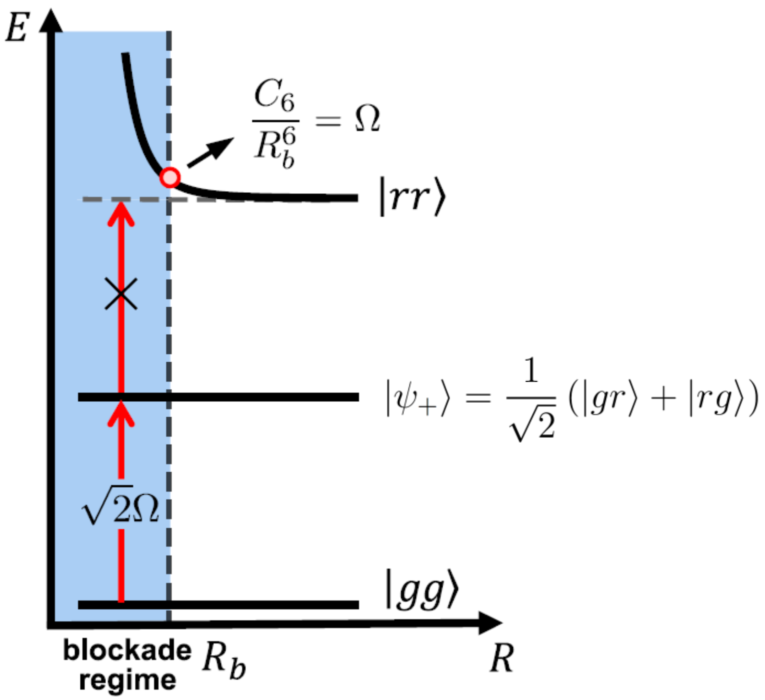
  Rydberg atoms interact strongly → implementation of quantum gates
- readout is essential
- Rydberg atom detection is difficult
- mesoscopic ensembles can amplify the signal of a single Rydberg excitation

Rydberg atoms

highly excited atoms

- high sensitivity to electric fields
- strong van der Waals interaction over micrometer distances $\propto \frac{1}{R^6}$
- Rydberg blockade: simultaneous excitation of more than one atom within the Rydberg blockade radius R_b becomes unlikely





Wu et al. A concise review of Rydberg atom based quantum computation and quantum simulation, Chin. Phys. B, 2021

Electromagnetically induced transparency

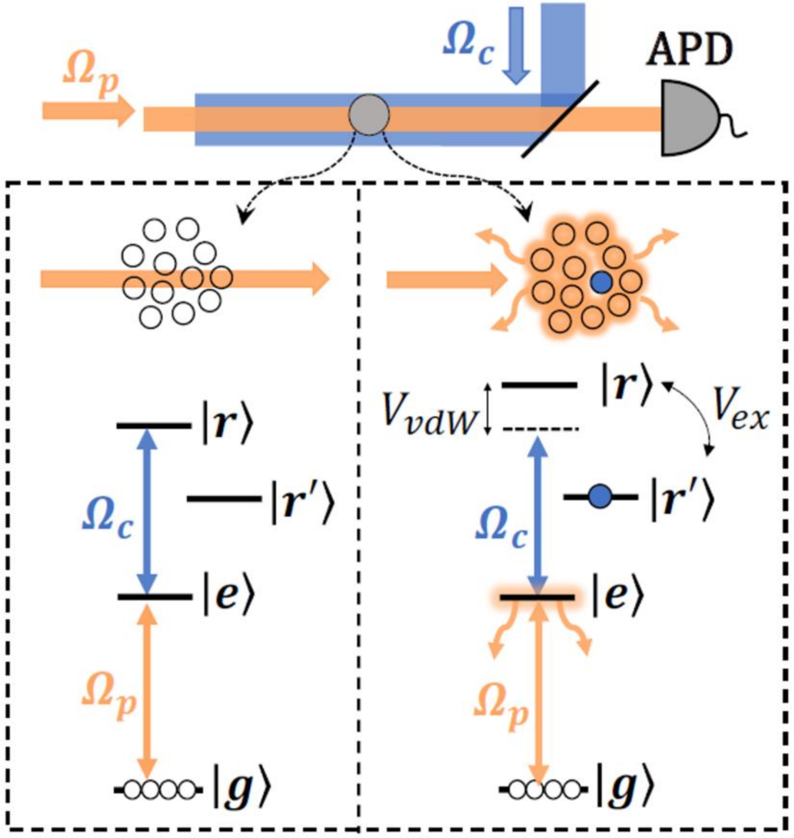
Coupling field makes an absorbing medium transparent.

readout signal = transmitted probe light

EIT condition: probe and coupling fields are resonant with transitions

A single Rydberg excitation is converted into a much larger signal produced by the whole ensemble.

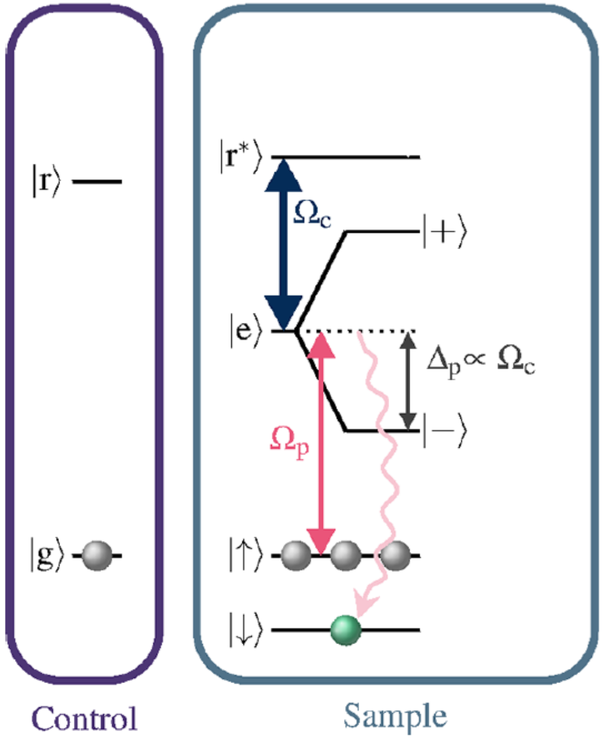
- limitation: strong sensitivity to detunings and line shifts

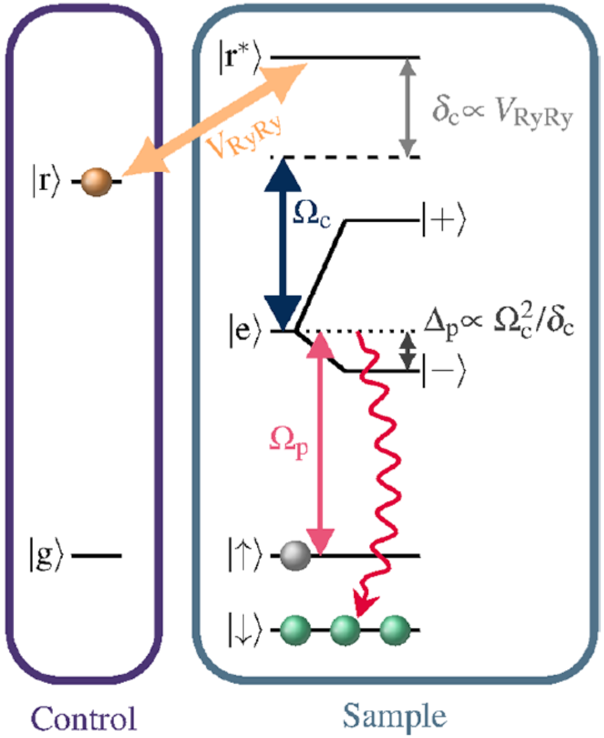


Xu et al. Fast Preparation and Detection of a Rydberg Qubit Using Atomic Ensembles, PRL 127, 050501 (2021)

Autler-Townes scheme

readout signal = population transfer from $|\uparrow\rangle$ to $|\downarrow\rangle$, induced by probe scattering and read out by fluorescence imaging

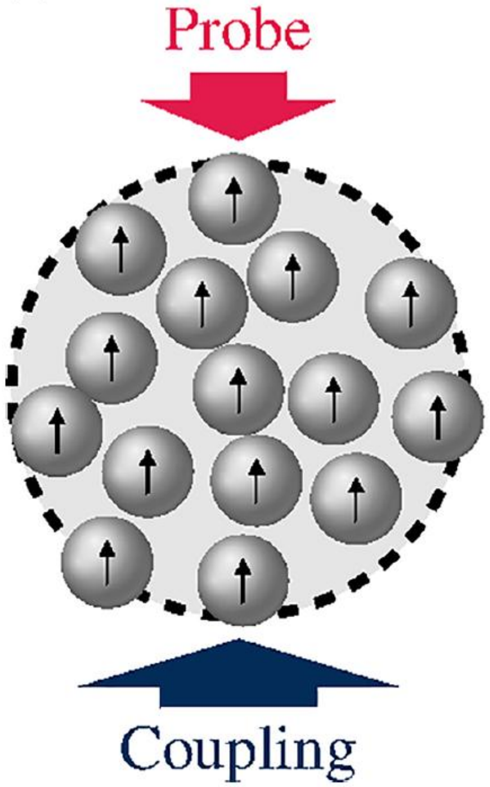




S. Schmidt, A. Thielmann, T. Niederpruem, and H. Ott. Fast and robust detection of single Rydberg excitations in mesoscopic ensembles. Physical Review A, 112(3):033114, 2025.

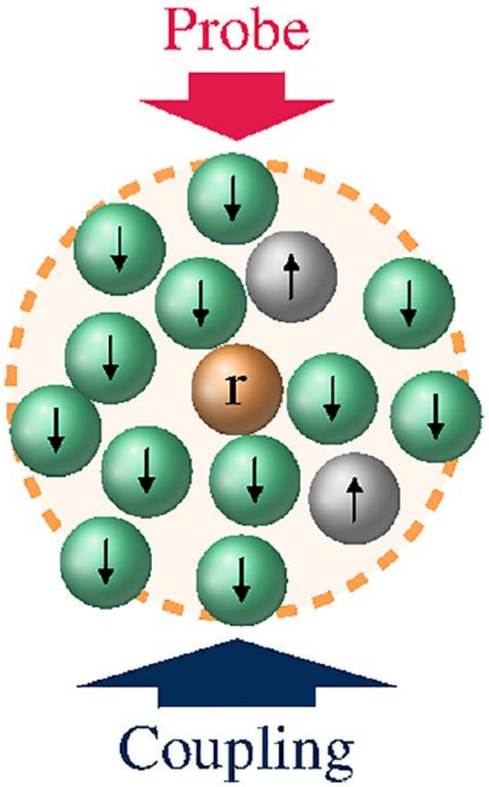
Autler-Townes scheme

a) no Rydberg atom present



→ the optical pumping is suppressed

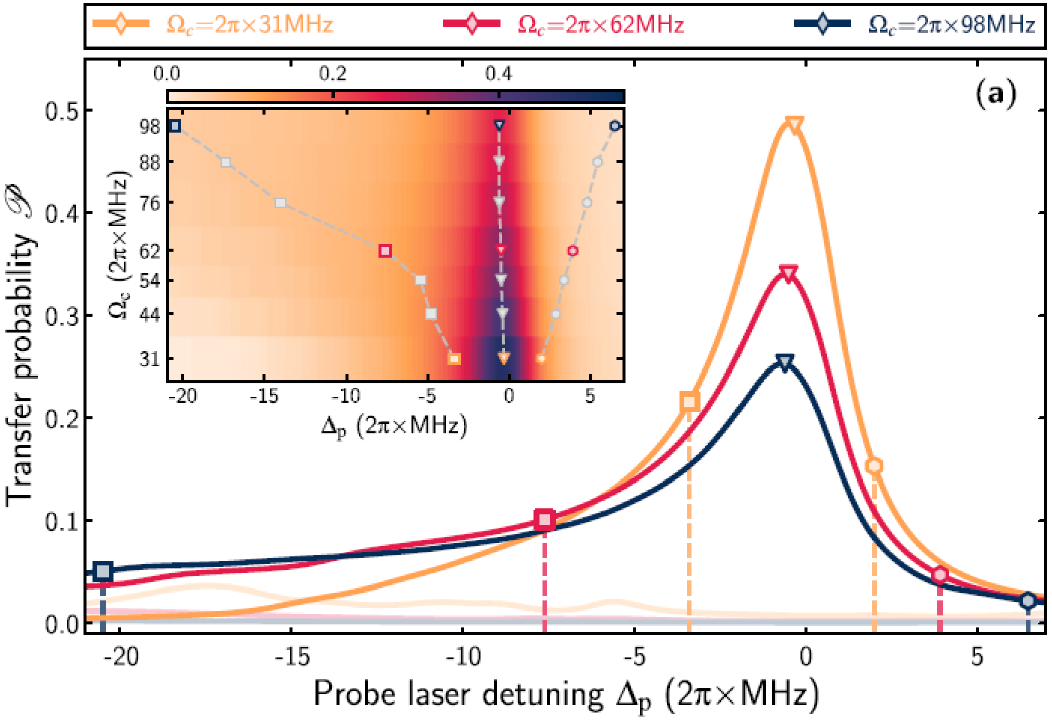
b) with Rydberg atom present



→ the optical pumping is restored

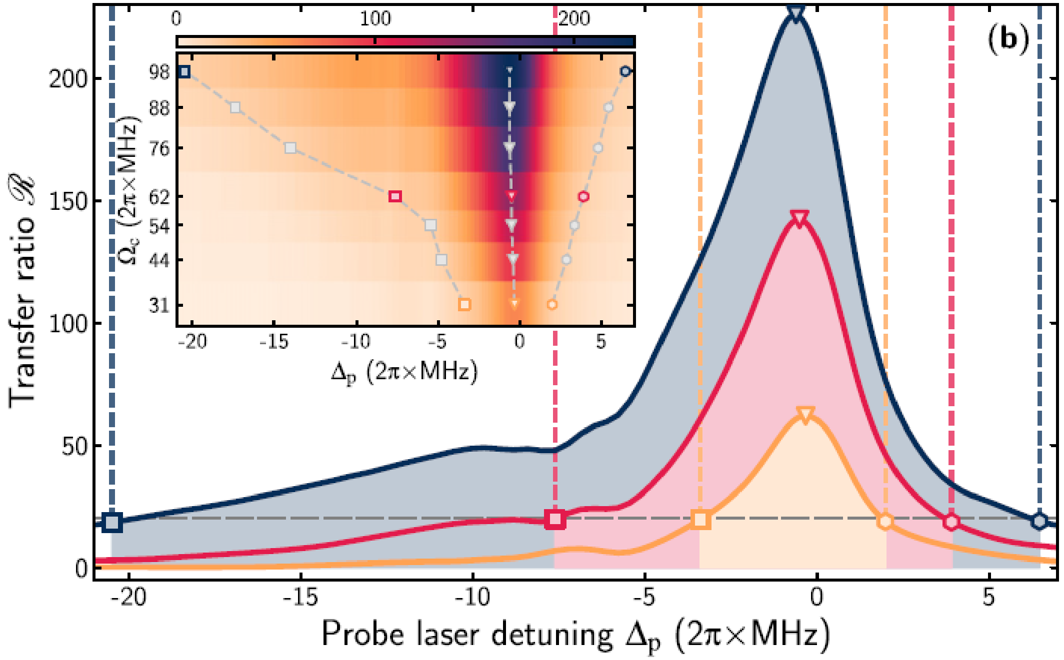
Performance of Autler-Townes scheme

Transfer probability P: signal strength



Transfer ratio R: contrast between cases with

$R = P/P_{\mathrm{noRyd}}$ and without control excitation



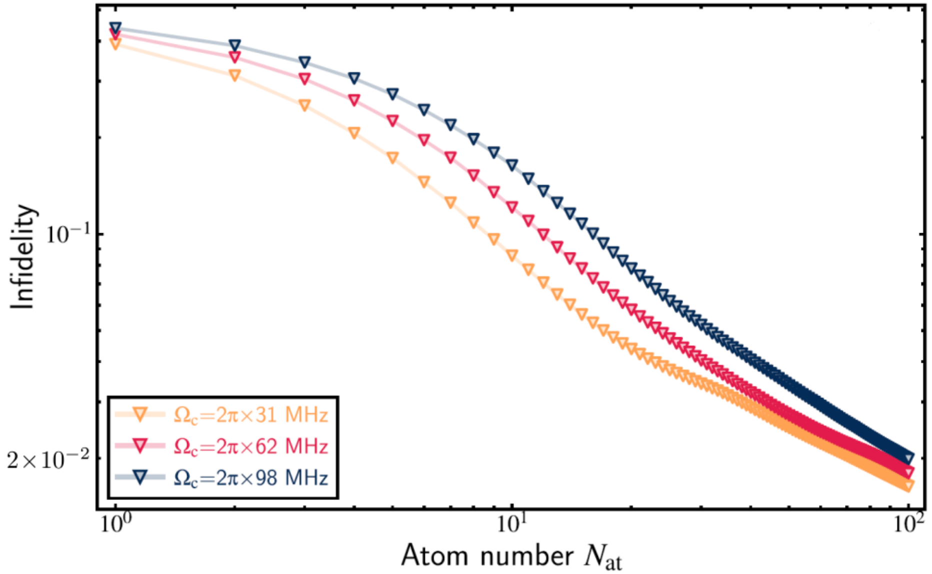
S. Schmidt, A. Thielmann, T. Niederpruem, and H. Ott. Fast and robust detection of single Rydberg excitations in mesoscopic ensembles. Physical Review A, 112(3):033114, 2025.

→ larger for weaker coupling

→ larger for stronger coupling

Performance of Autler-Townes scheme

detection infidelity: probability of incorrectly deciding whether the control Rydberg excitation is present or not



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→in the cases examined the larger absolute transfer outweighs the improved contrast

→relatively low even for mesoscopic ensembles

Conclusions

- A single Rydberg excitation can be detected indirectly through the collective optical response of a nearby mesoscopic ensemble.
- The key physical ingredient is the Rydberg blockade, which enables collective behaviour.
- EIT-based detection provides collective amplification but is sensitive to detuning and line shifts.
- The Autler–Townes scheme maps the signal onto a stable ground-state population, enabling fluorescence imaging.
- Its performance shows robust readout against detunings and line shifts, together with high-fidelity detection in mesoscopic ensembles.

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