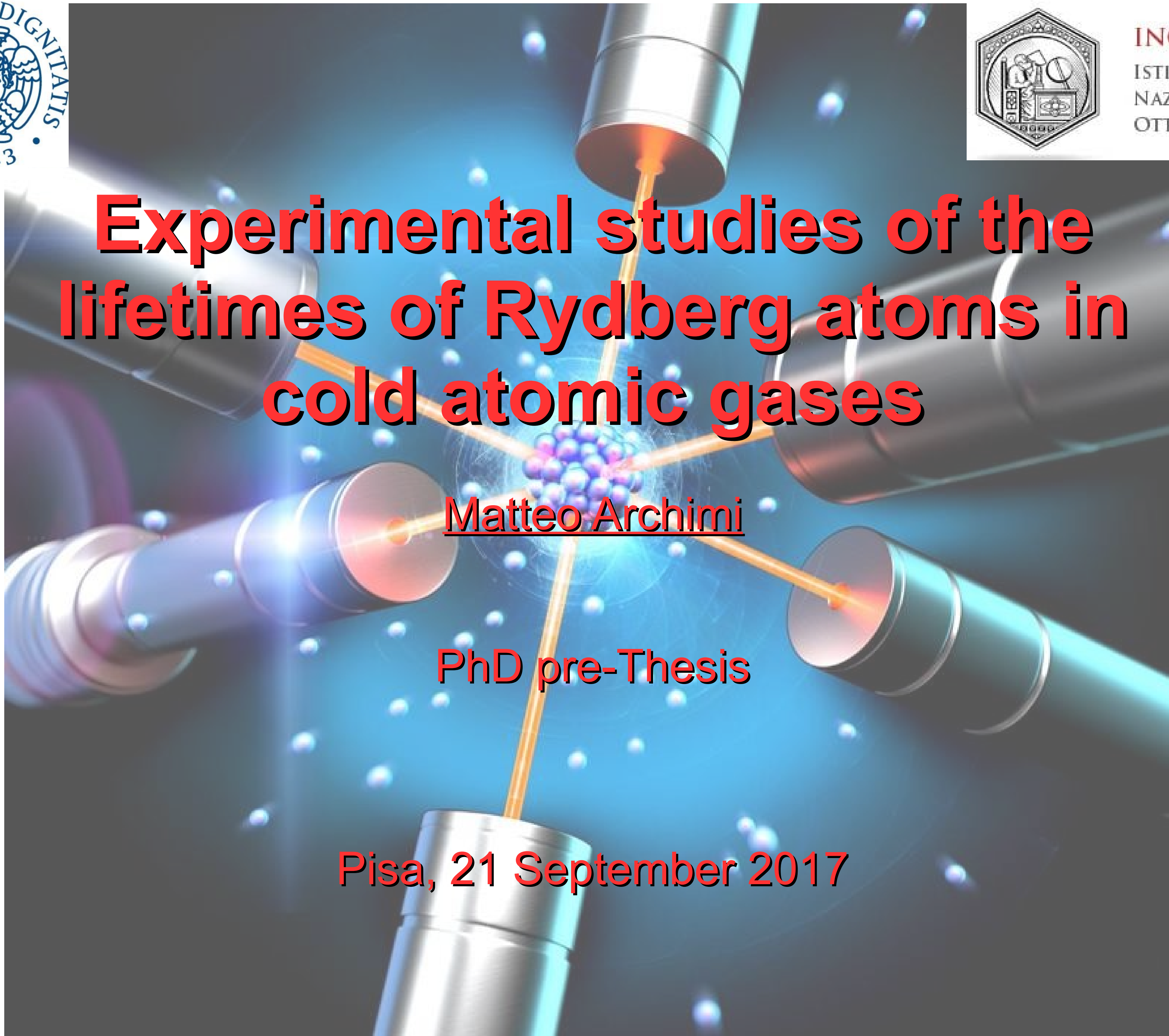

Experimental studies of the lifetimes of Rydberg atoms in cold atomic gases

Matteo Archimi

PhD pre-Thesis

Pisa, 21 September 2017

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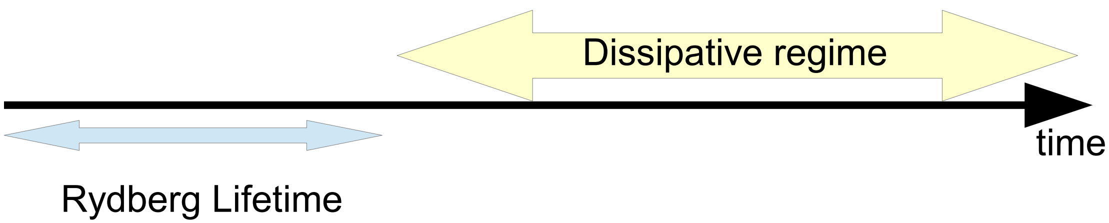
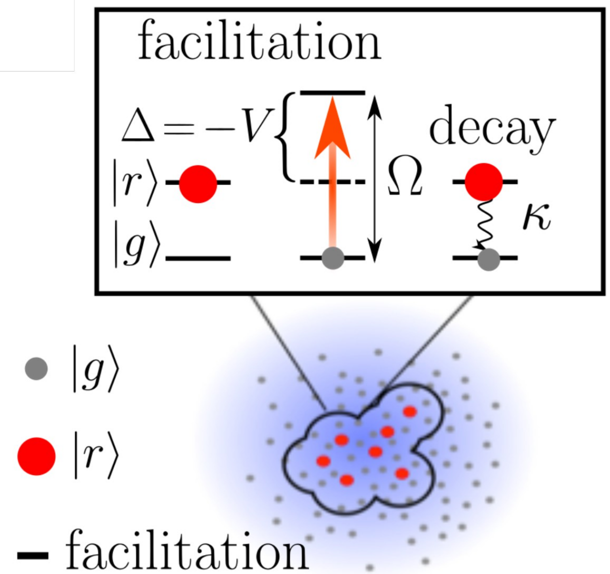
General introduction

Dynamics of Rydberg atoms in dissipative regime.



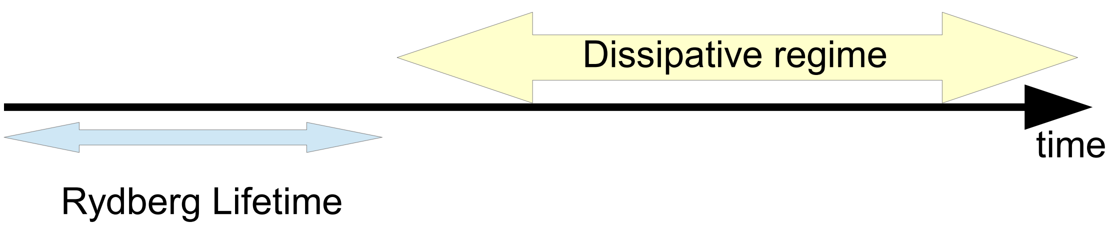


Two opposing processes:

- Facilitation;
- Spontaneous decay.

General introduction

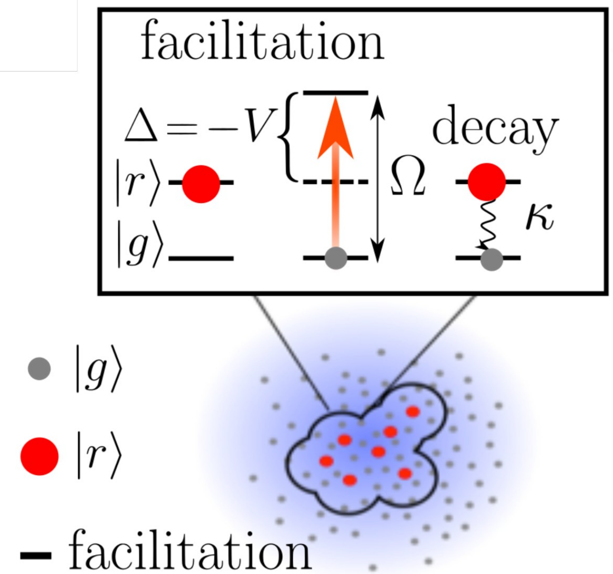
Dynamics of Rydberg atoms in dissipative regime.

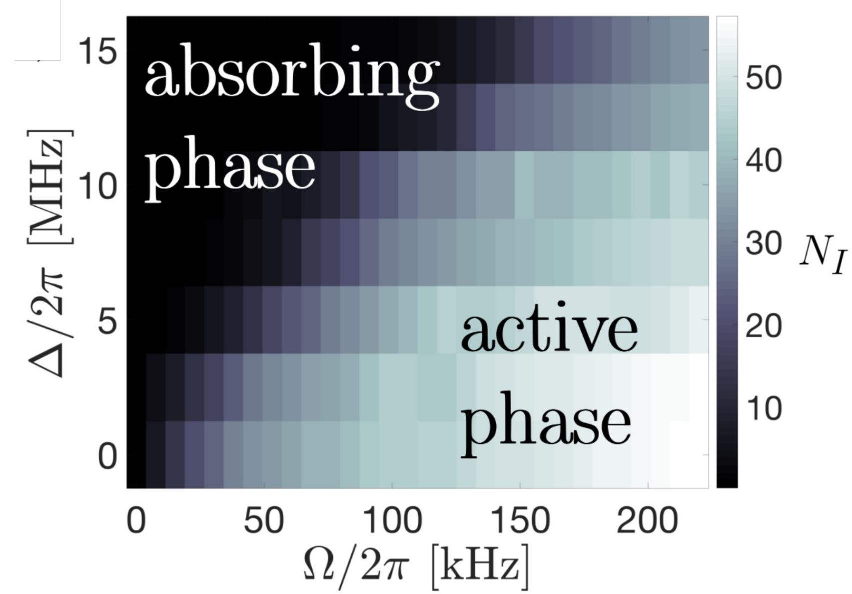


Two opposing processes:

- Facilitation;
- Spontaneous decay.

Absorbing phase state transition





Rydberg atoms

Exaggerated properties with respect to ground state atoms.

Scaling with $n^*=(n-\delta_{qdt})$:

- Binding energy: $(n^*)^{-2}$
- Orbital radius: $(n^*)^{2}$
- Lifetime: $(n^*)^{3}$
- Polarizability: $(n^*)^{7}$
- Van der Waals coefficient: $(n^*)^{11}$

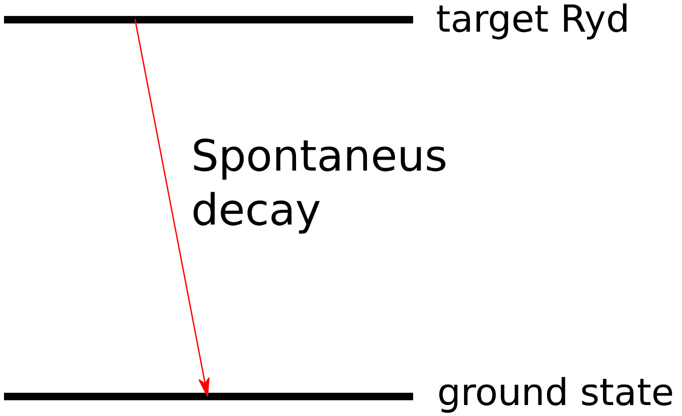
Several applications:

- Many body physics;
- Quantum technologies.

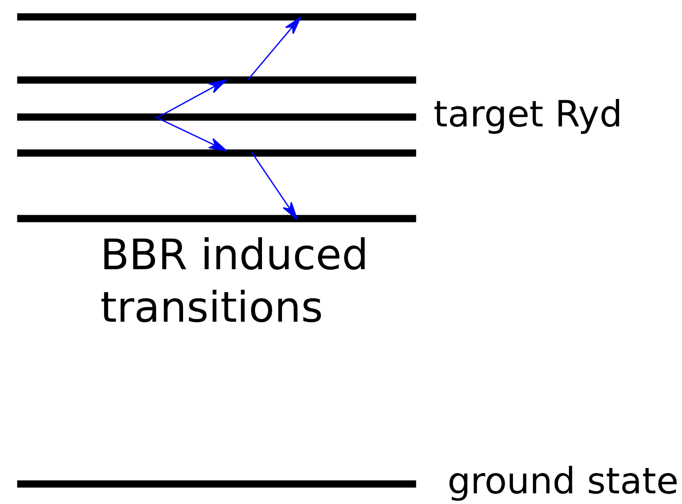
The lifetime of Rydberg atoms

Two effects contribute to the lifetime of Rydberg atoms:

Spontaneous emission



Blackbody induced transitions



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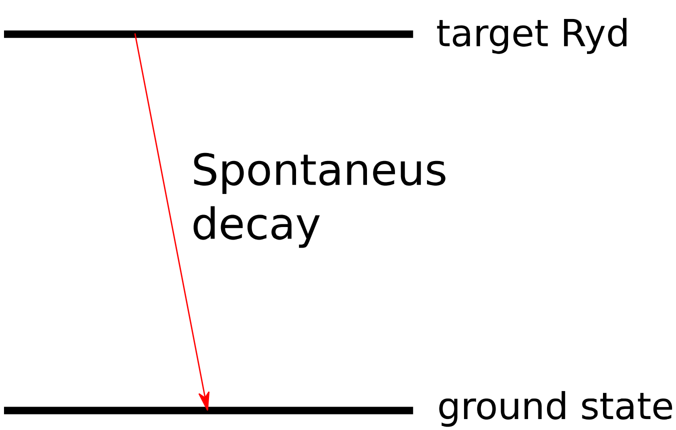

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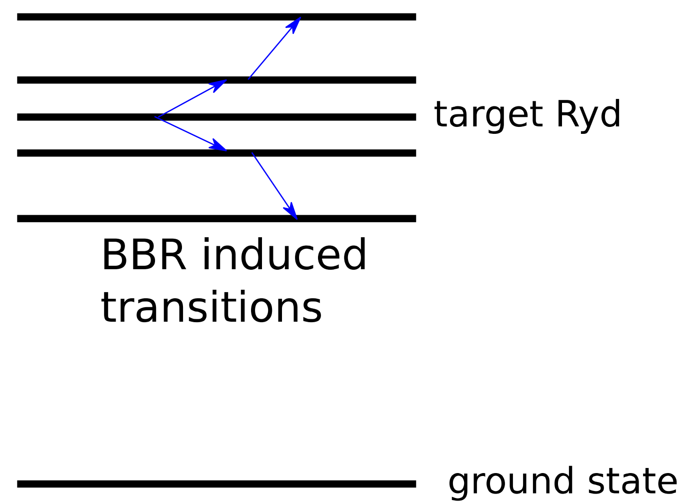
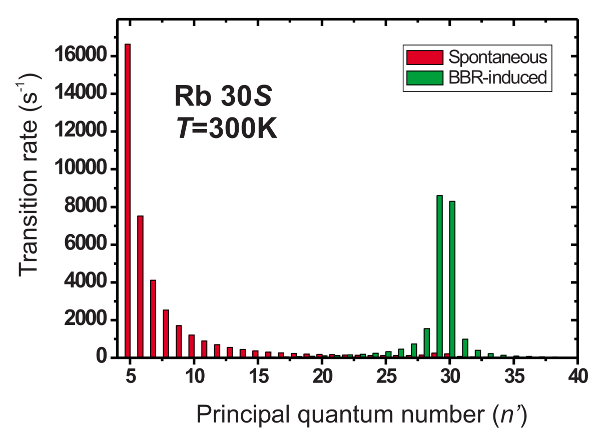


$$\frac{1}{\tau_{eff}} = \Gamma_0 + \Gamma_{BBR} = \frac{1}{\tau_0} + \frac{1}{\tau_{BBR}}$$



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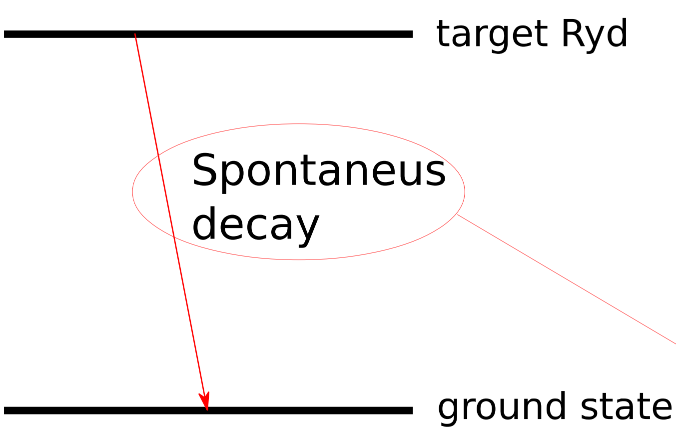

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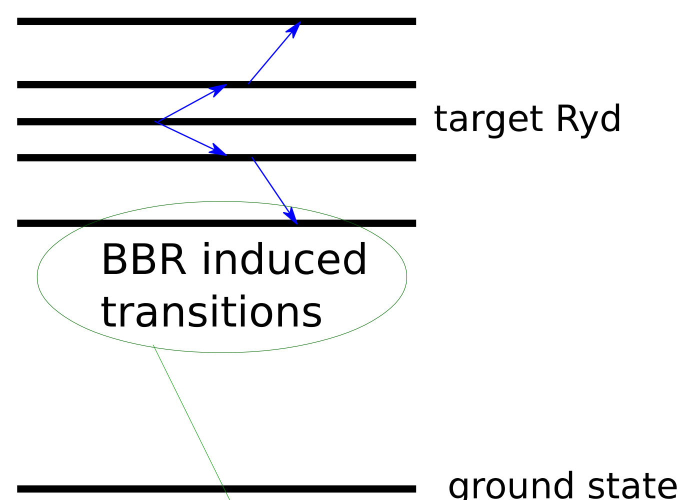
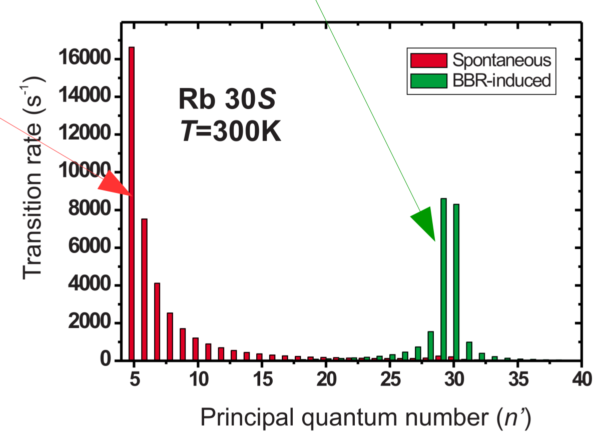
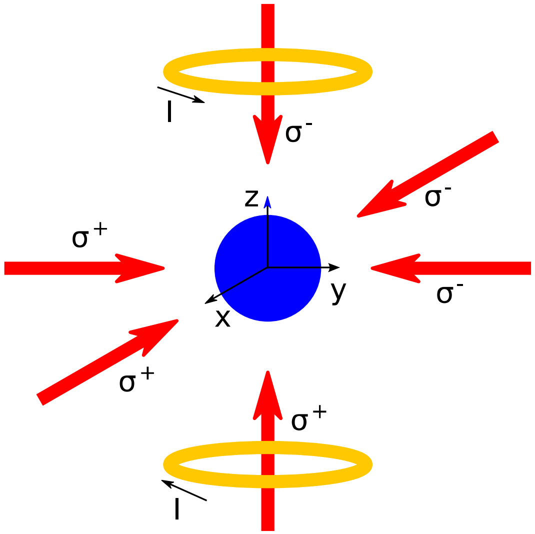
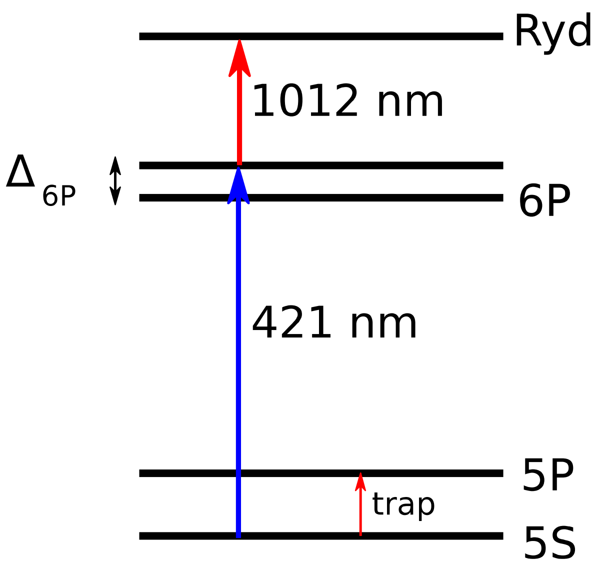




The experimental apparatus

Preparation: Atoms cooled and trapped with lasers and magnatic fields: magneto-optical trap



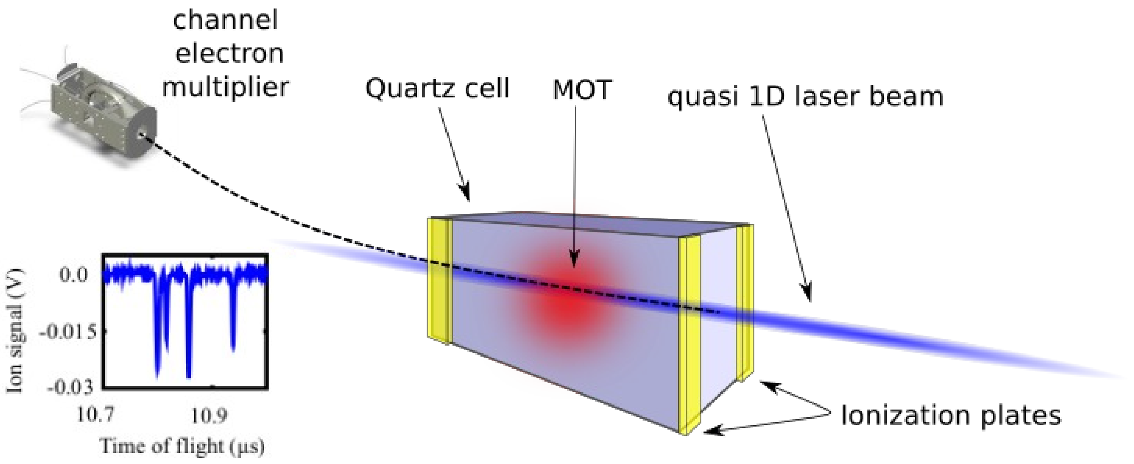


Excitation: Excited with two photon excitation from ground state Rydberg state

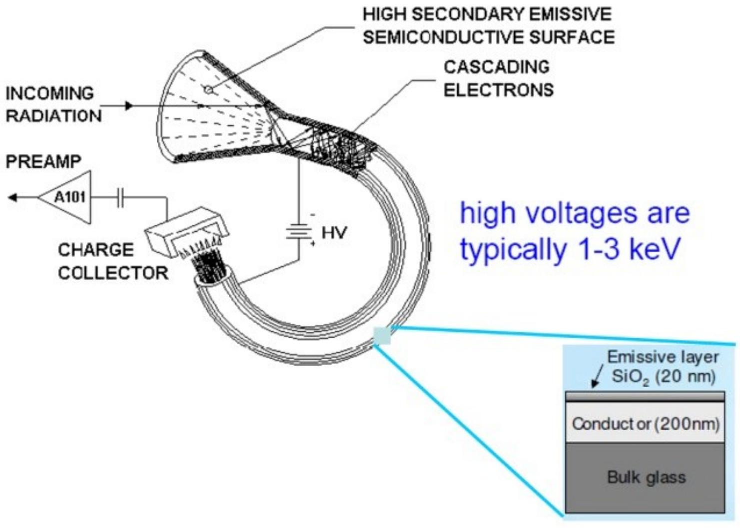
$$\Omega_{tot} = \sqrt{\left(\frac{\Omega_{421}\Omega_{1012}}{2\Delta_{6P}}\right)^2 + \Delta^2}$$

The experimental setup

Detection: Rydberg atoms are field ionized and accelerated towards a channeltron



The channeltron converts an incident ion to an electrical signal



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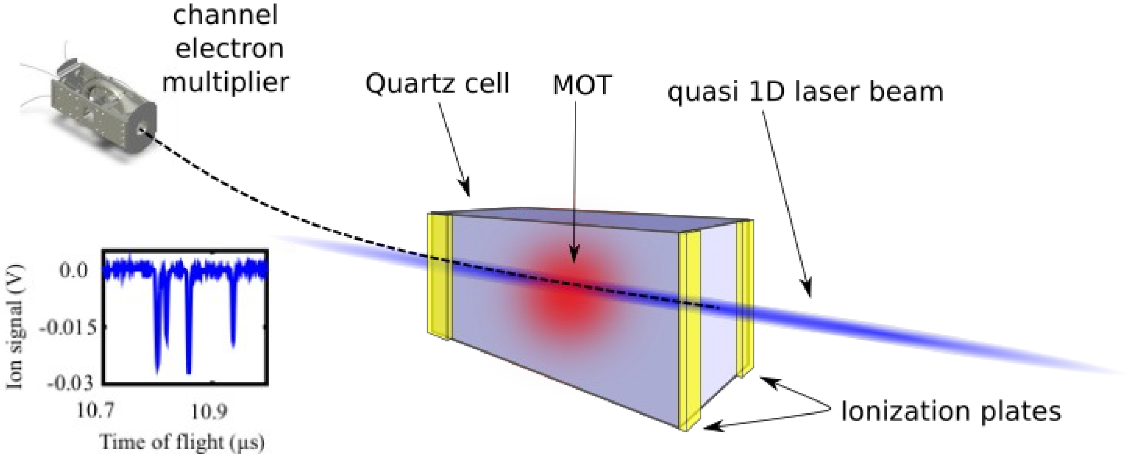
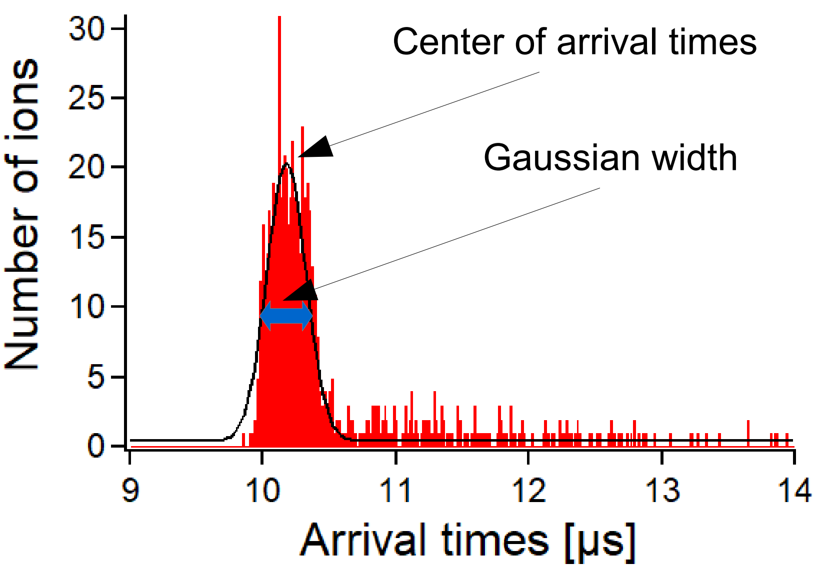


We can record:

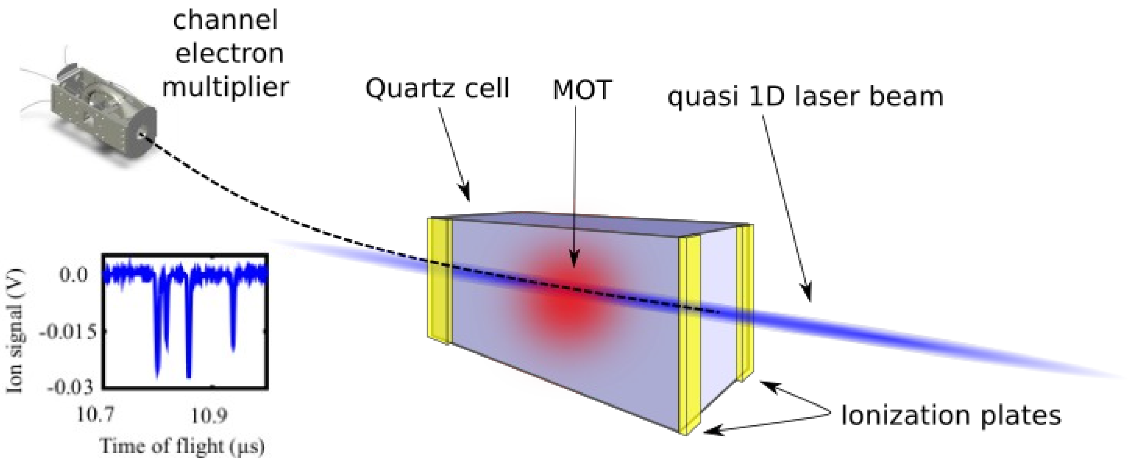
- Mean number of ions <N>;
- Standard deviation σ;
- Mandel paramenter $Q = \frac{\sigma^2}{<N>} - 1$;
- Arrival time distribution.

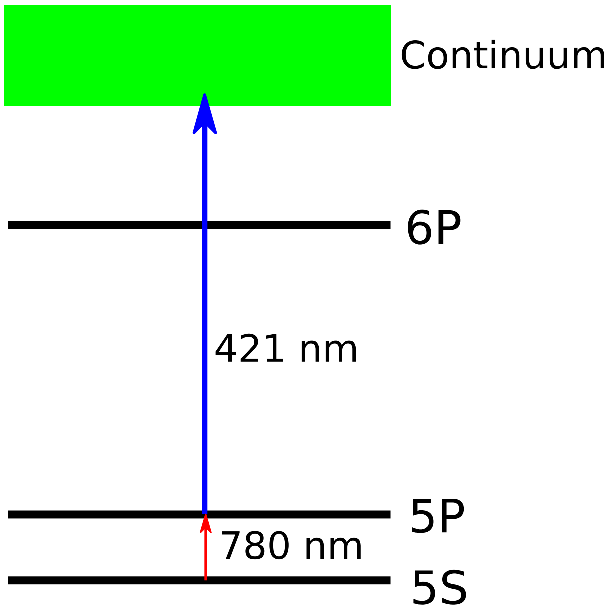


The experimental setup

Two main parts for detection:

- Ionization of Rydberg atoms;
- Acceleration to channeltron.



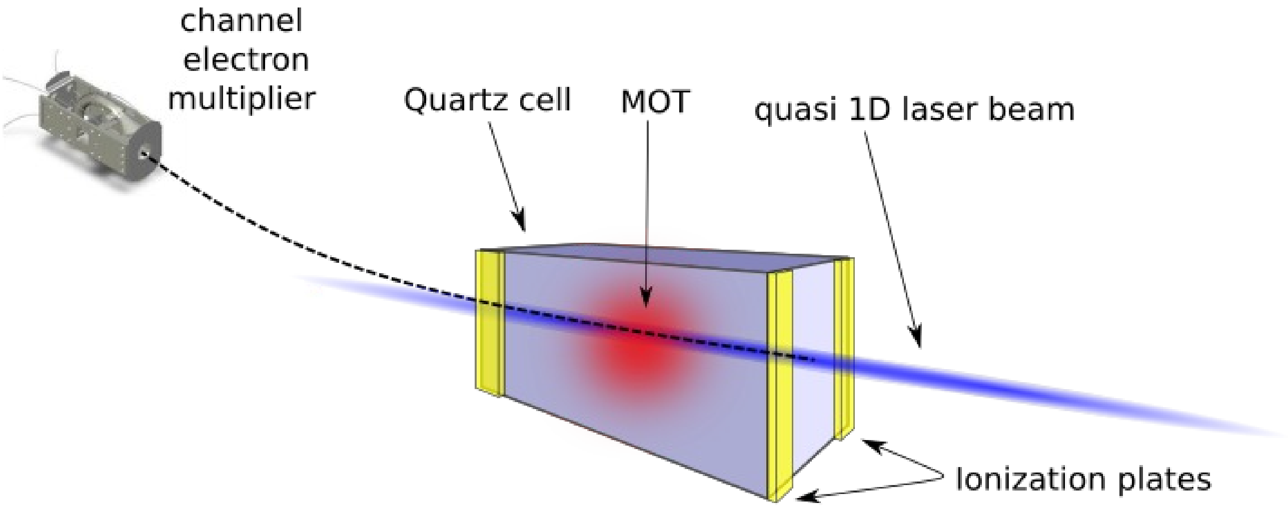


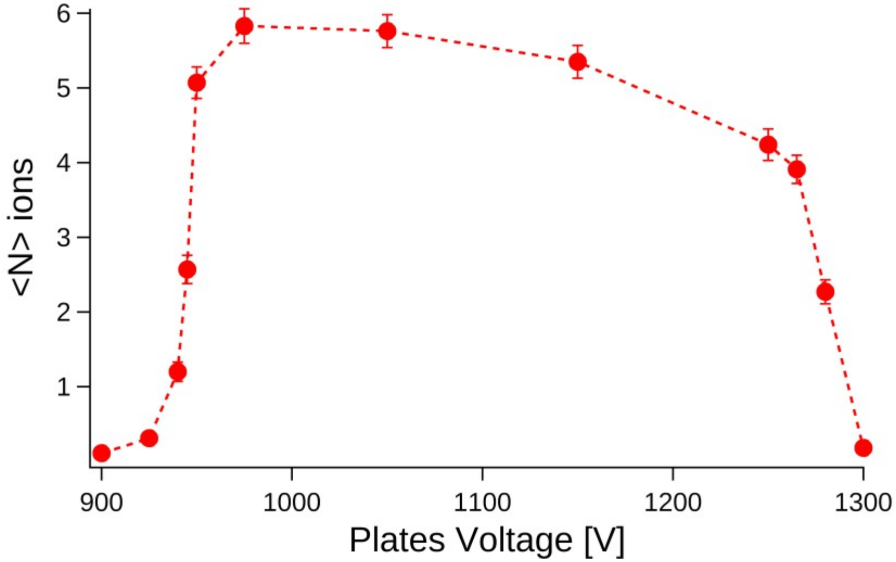
First we focus on the trajectories.

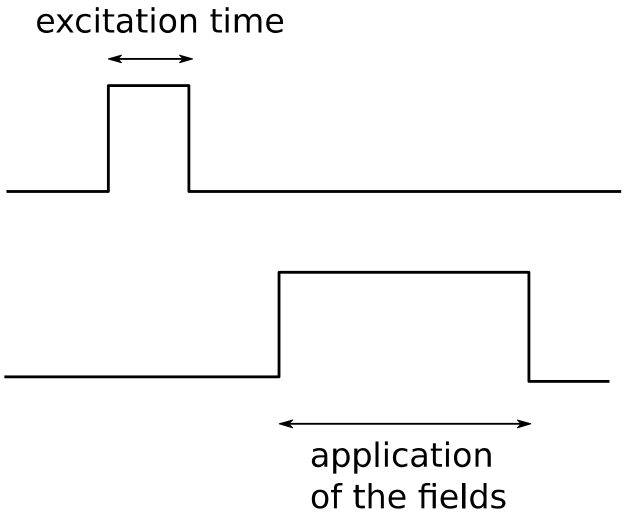
Ions produced by photoionization from 5P

Characterization of the detection: trajectories of the ions

Change the value of the voltages







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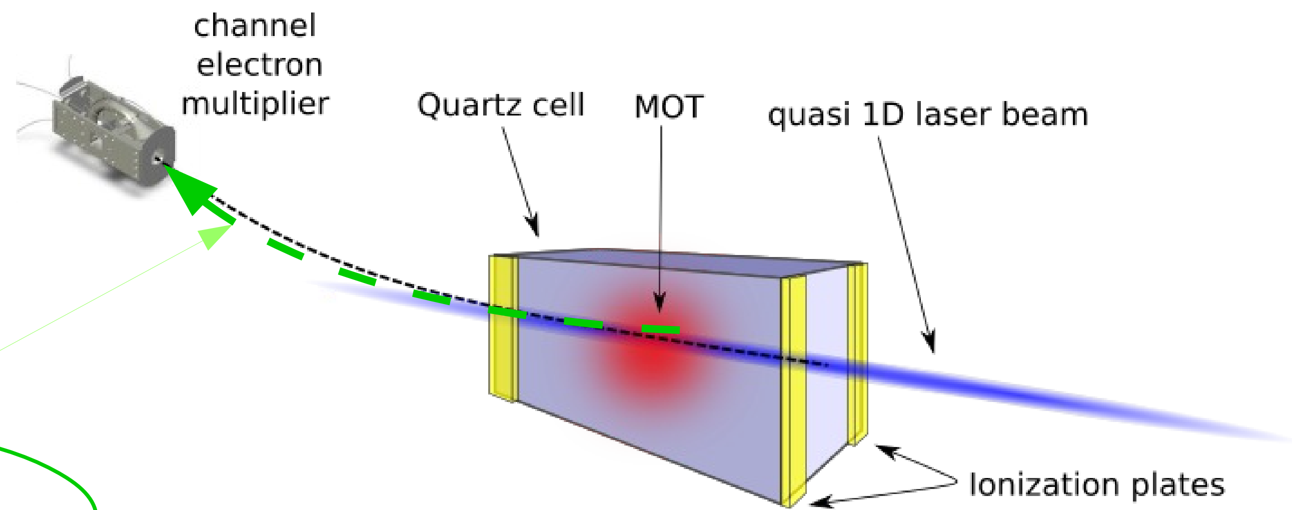

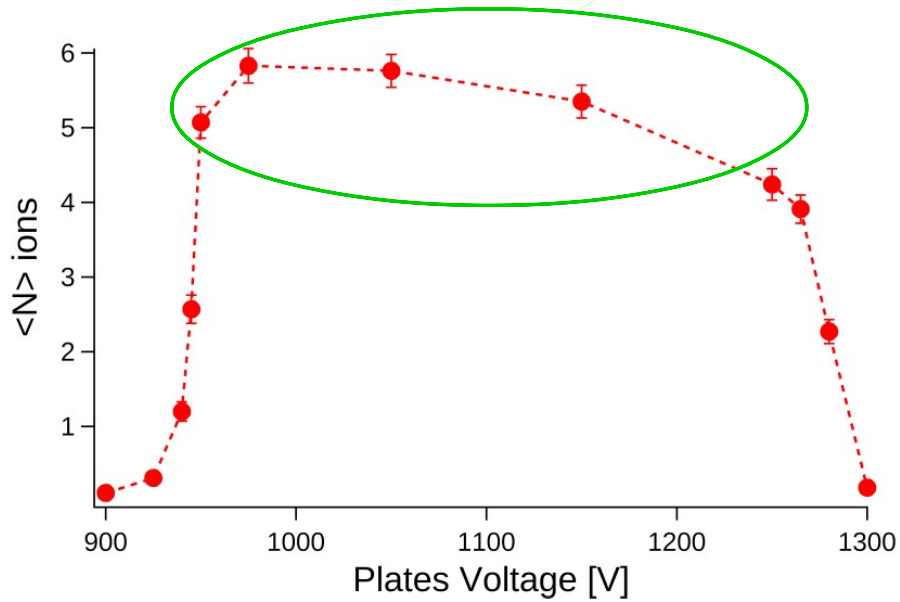

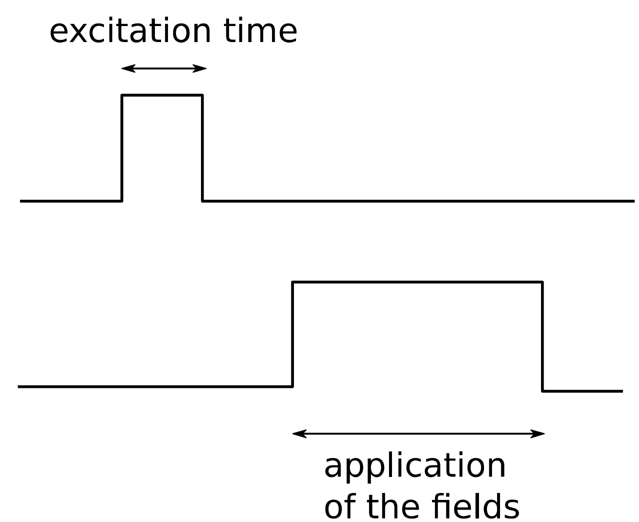

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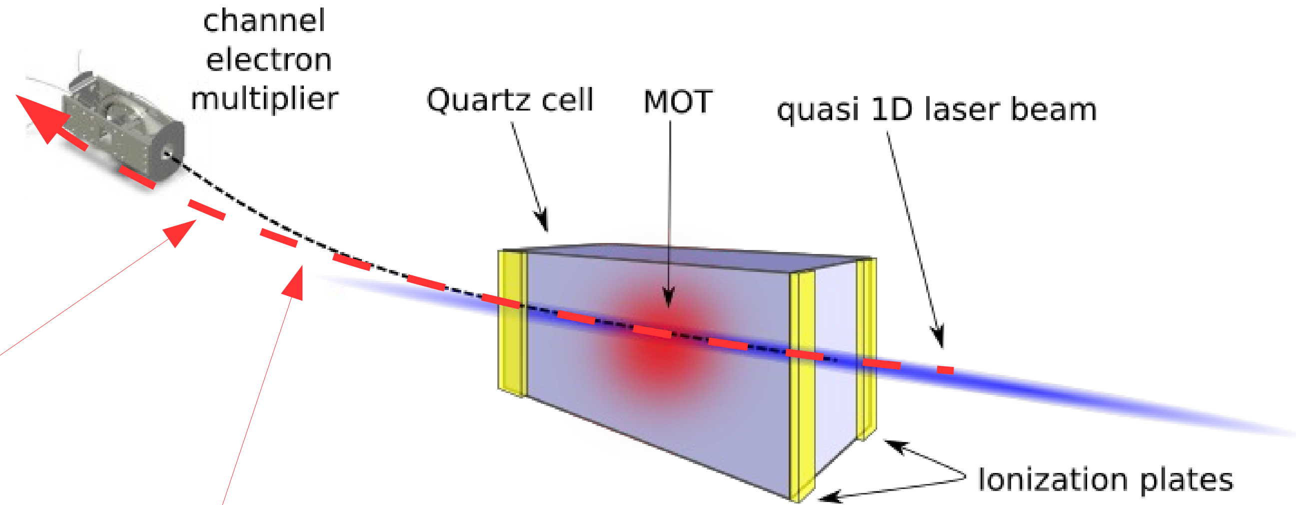

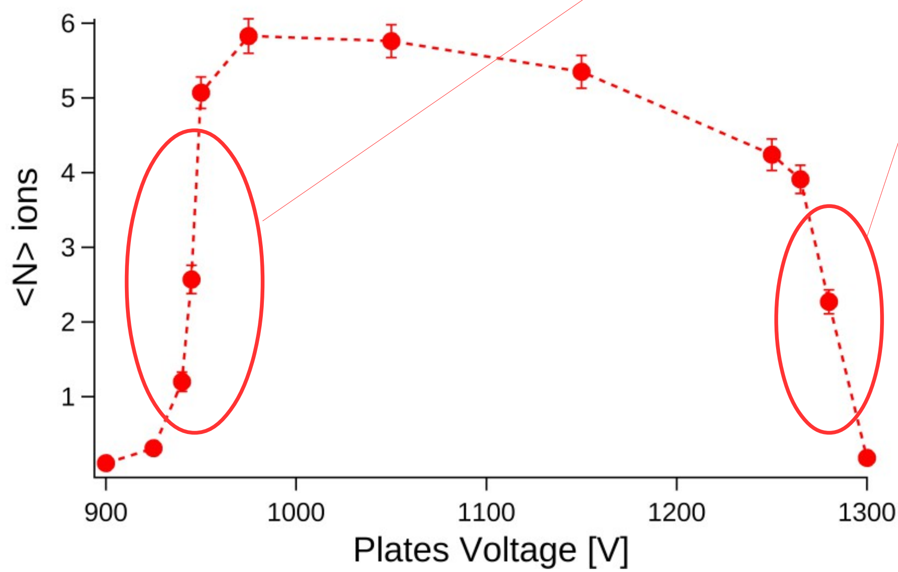

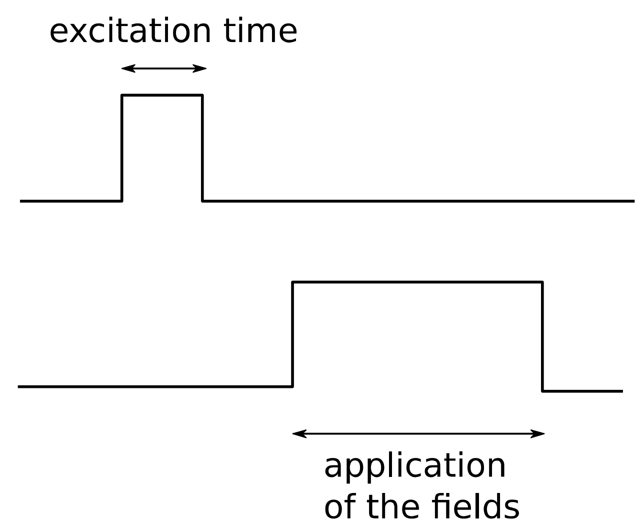

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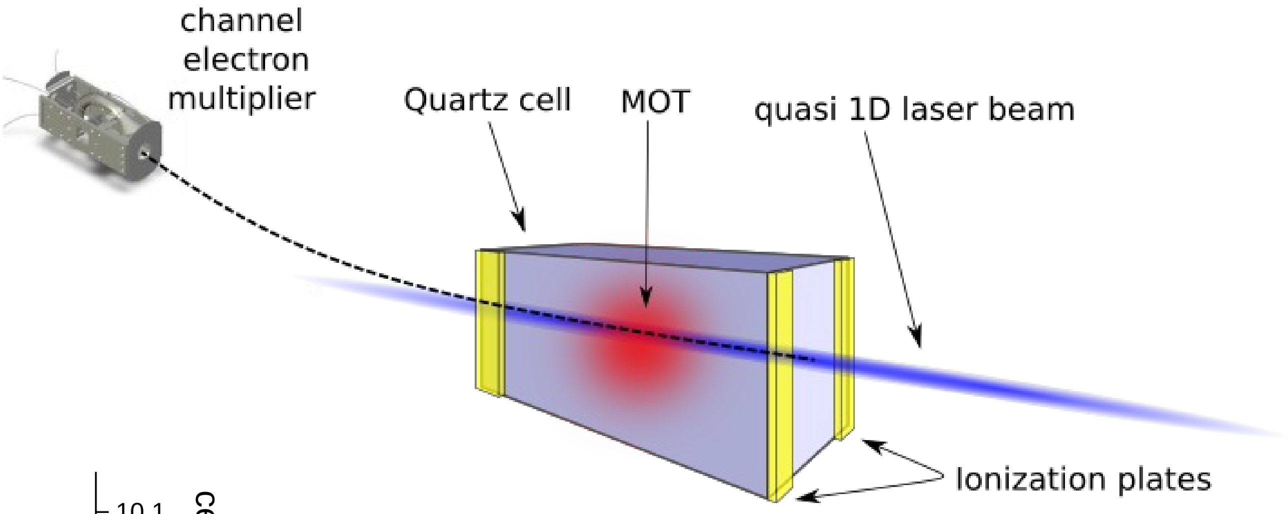

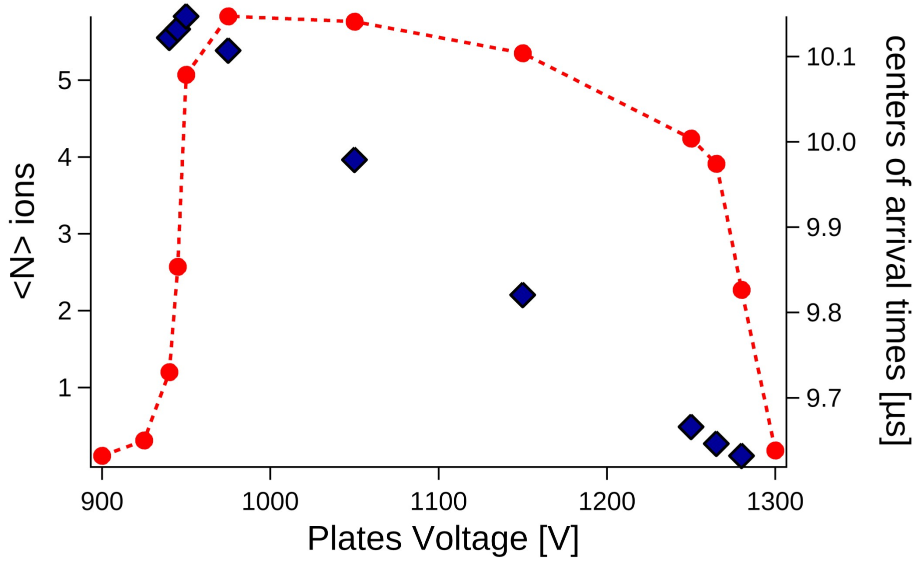

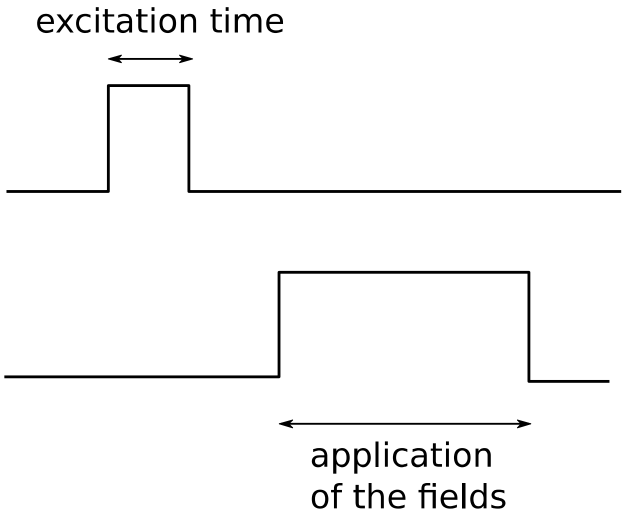

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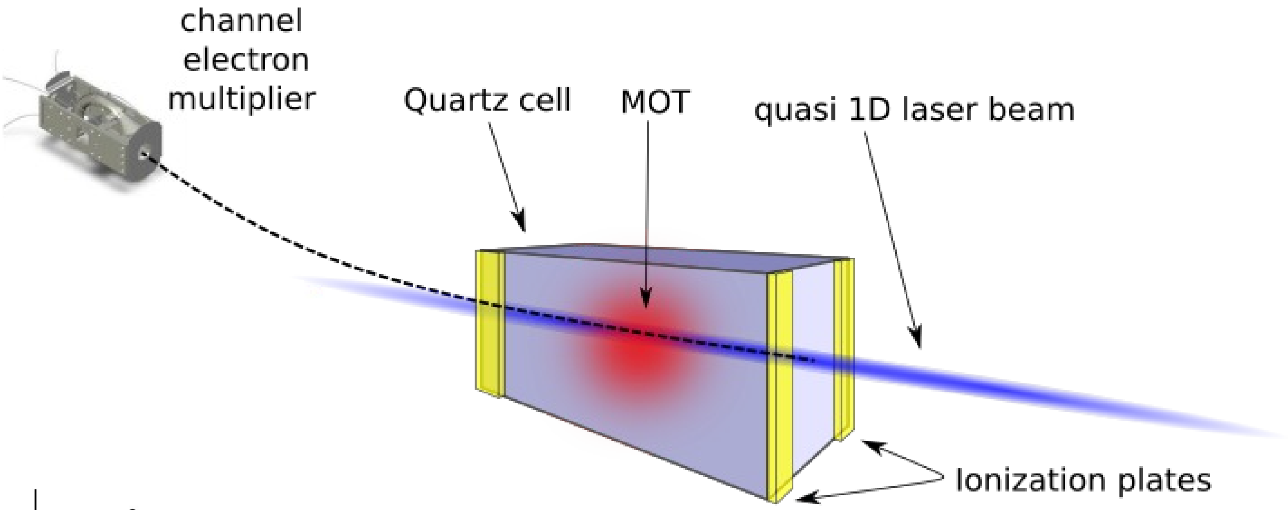

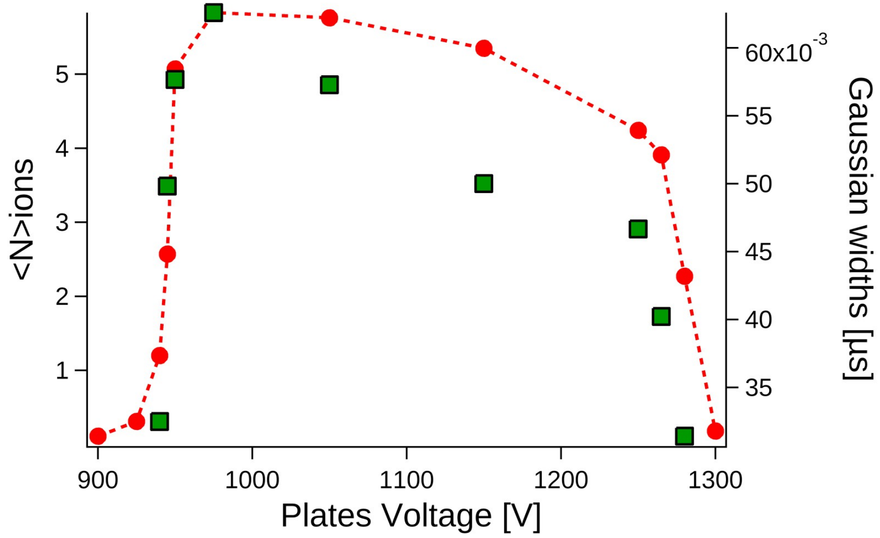

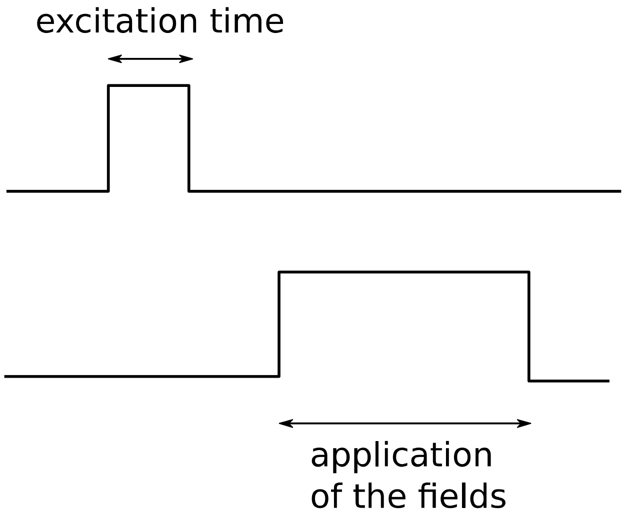

Characterization of the detection: electric fields in the cell

Electric fields in the cell:

- Complex configuration of potentials inside the apparatus;
- Quartz cell is dielectric, screening effects.

We measure the Stark shift to know the actual field on atoms:

$$\Delta E = -\frac{1}{2}\alpha\mathcal{E}^2$$

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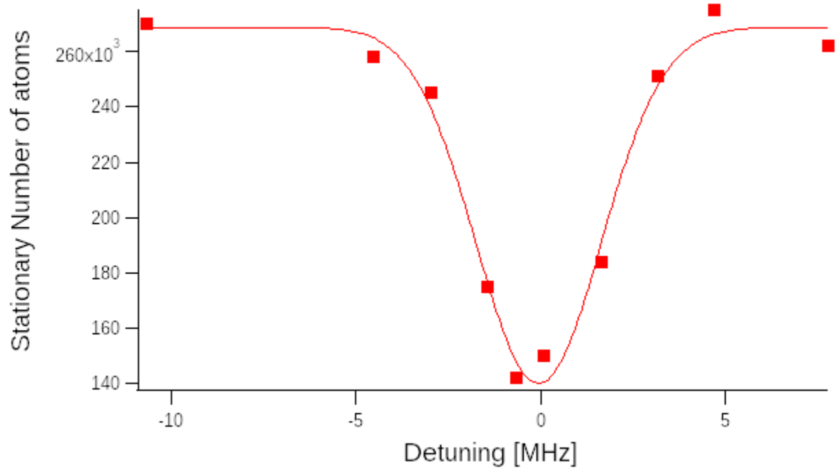
Loss of atom from the MOT:

$$\frac{dN(t)}{dt} = L - \Gamma_0 N(t) - \Gamma_{Ryd} N(t)$$

$$\Gamma_{ryd}(\nu) = \Gamma_0 \left(\frac{N_0}{N_{stat}(\nu)} - 1 \right)$$



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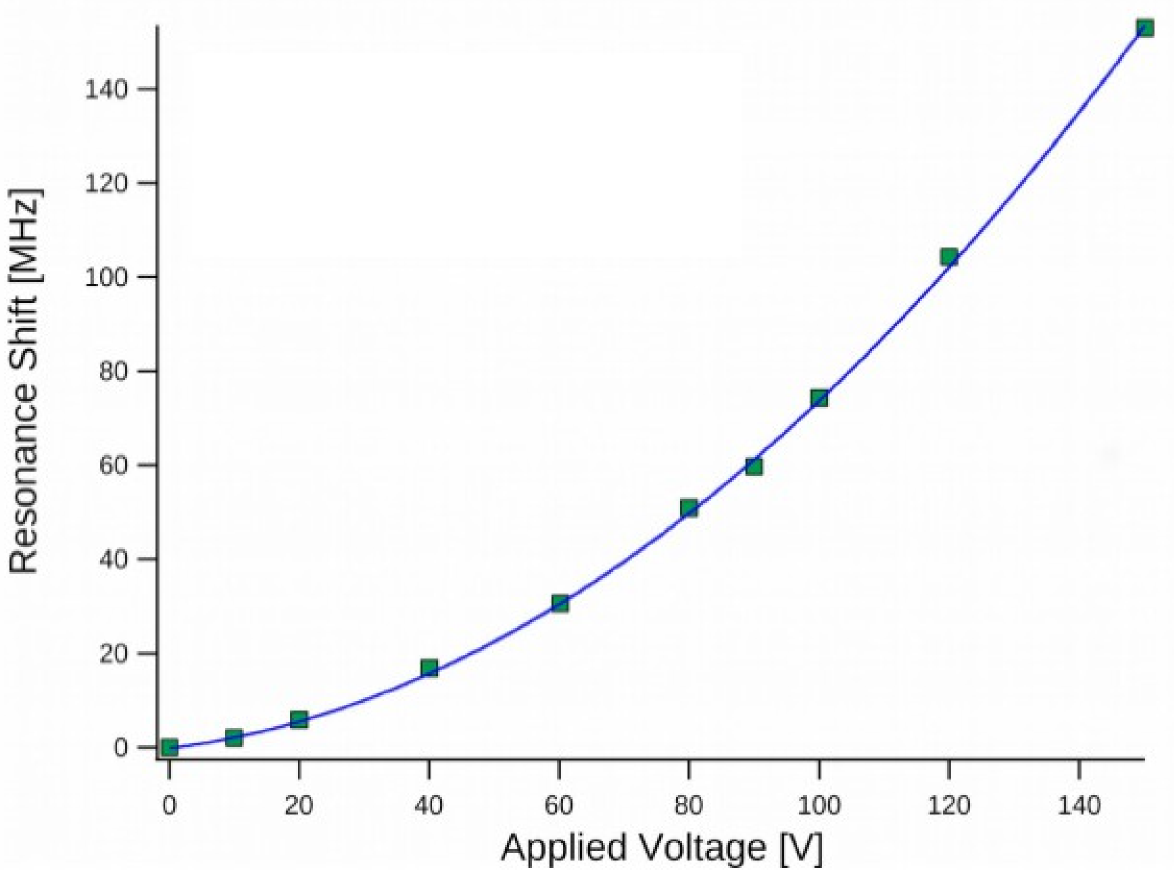


Fit of the data on the quadratic Stark shift:

$$\Delta E = -\frac{1}{2}\alpha\mathcal{E}^2$$

$$f(\nu) = y_0 - \frac{1}{2}\alpha_{70S}\left(\gamma V - E_0\right)^2$$

$$\alpha_{70S} = 557.4\frac{MHz}{Vcm^{-2}}$$

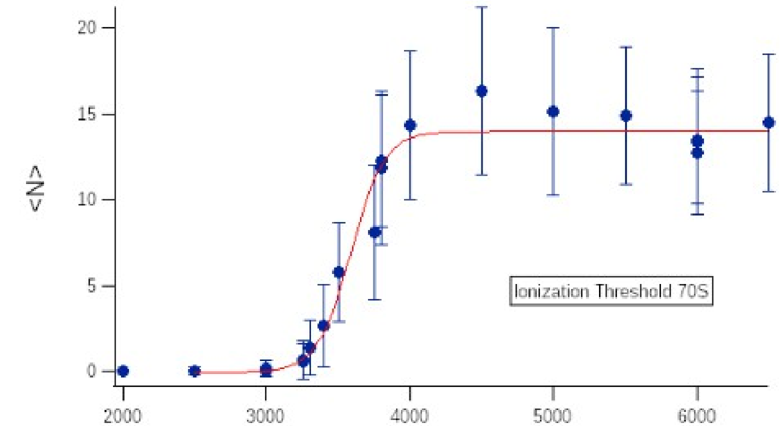
$$E_0 = (-6.7 \pm 0.2) \times 10^{-2}\,\mathrm{V/cm}$$

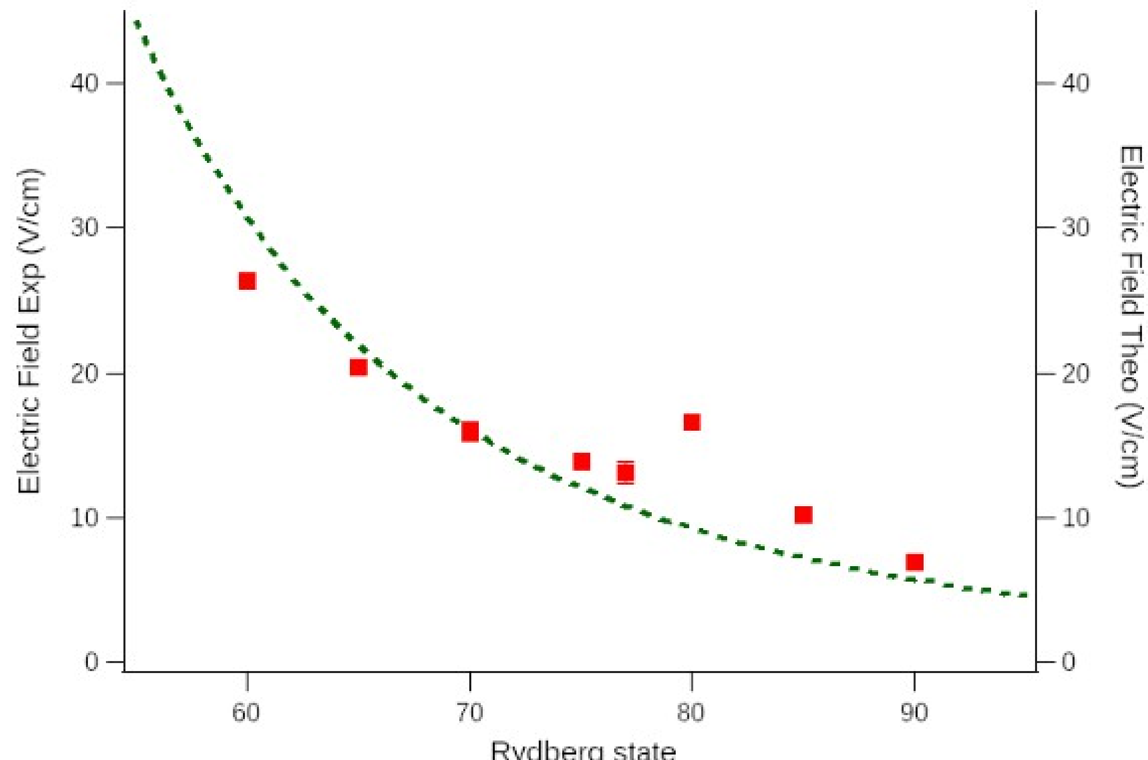
$$\gamma = (4.52 \pm 0.02) \times 10^{-3}\,\mathrm{cm}^{-1}$$

Characterization of the detection: ionization threshold

Calibration electric fields + trajectories

Measurement of ionization threshold





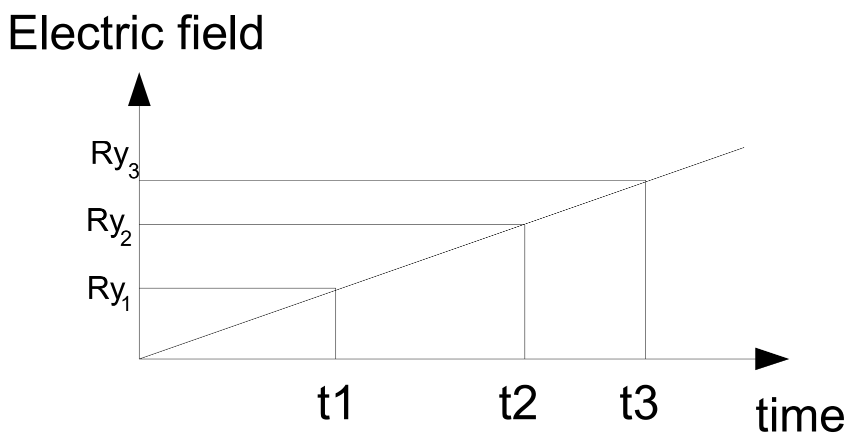
Calculated value:

$$E_{thr} = \frac{m_e^2 e^5}{16(4\pi\epsilon_0)^3 \hbar^4} \frac{1}{(n^*)^4}$$

The lifetime of Rydberg atoms

We count the number of atoms in a Rydberg state as a funtion of time, and obtain an exponential decay.

Typical measurement:
Switch on the ionization fields with slowly increasing sweep. Rydberg atoms ionized in different moments.



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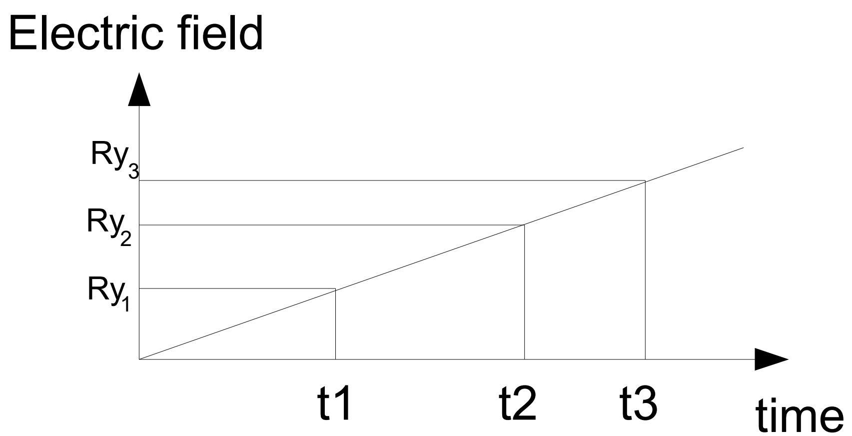
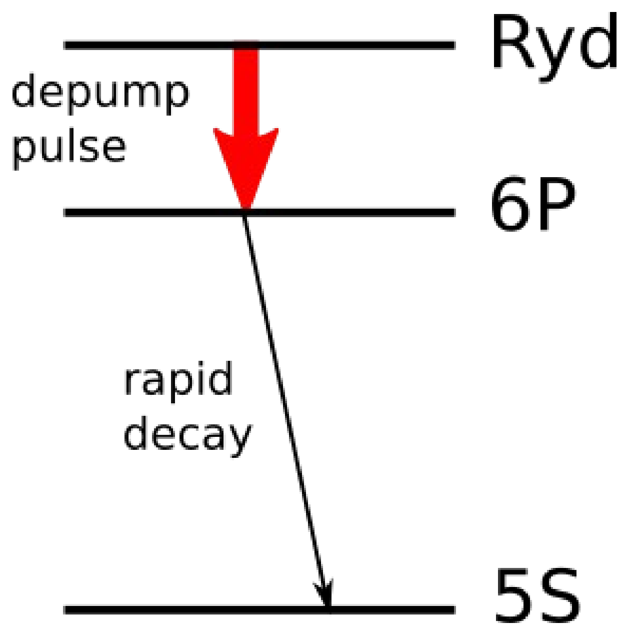
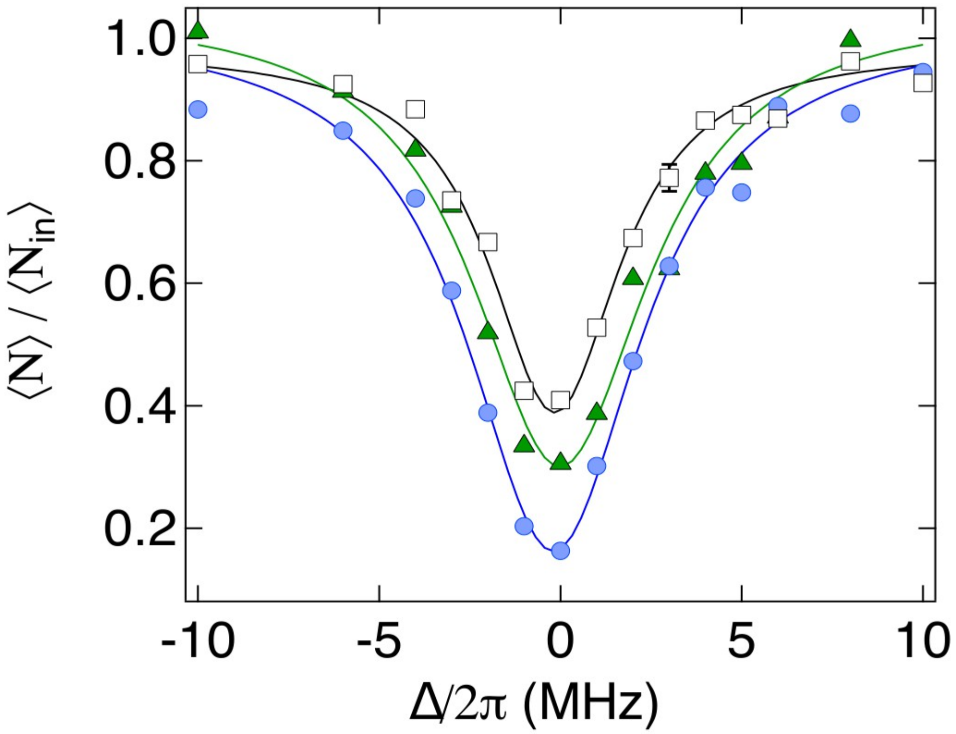


Difficult to apply for high n because ionization thresholds are very near.

We use the *depump technique*

The lifetime of Rydberg atoms: depump technique

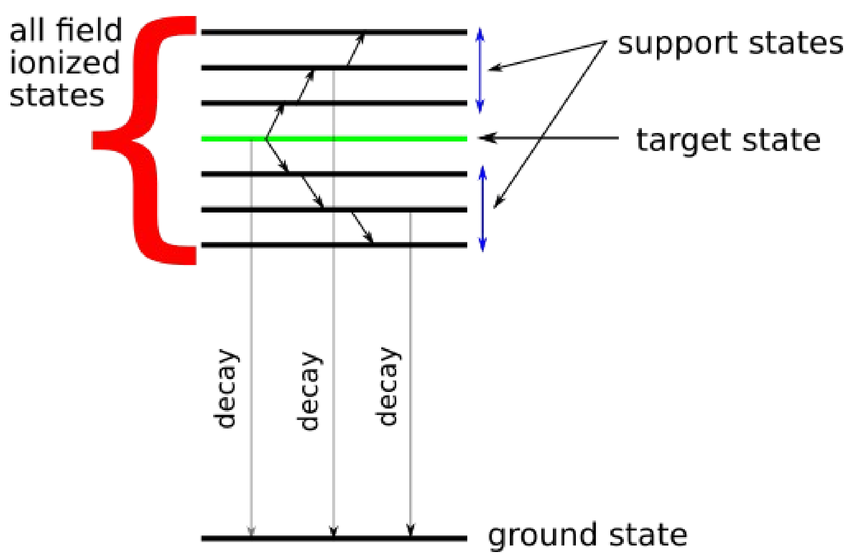


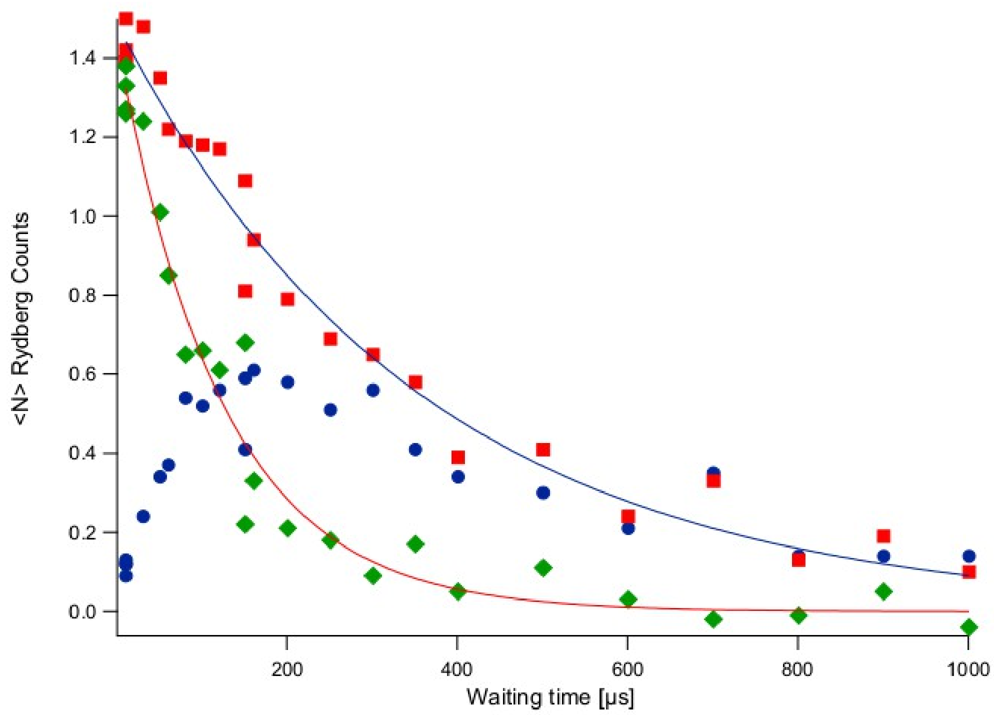


Measurement of the lifetime

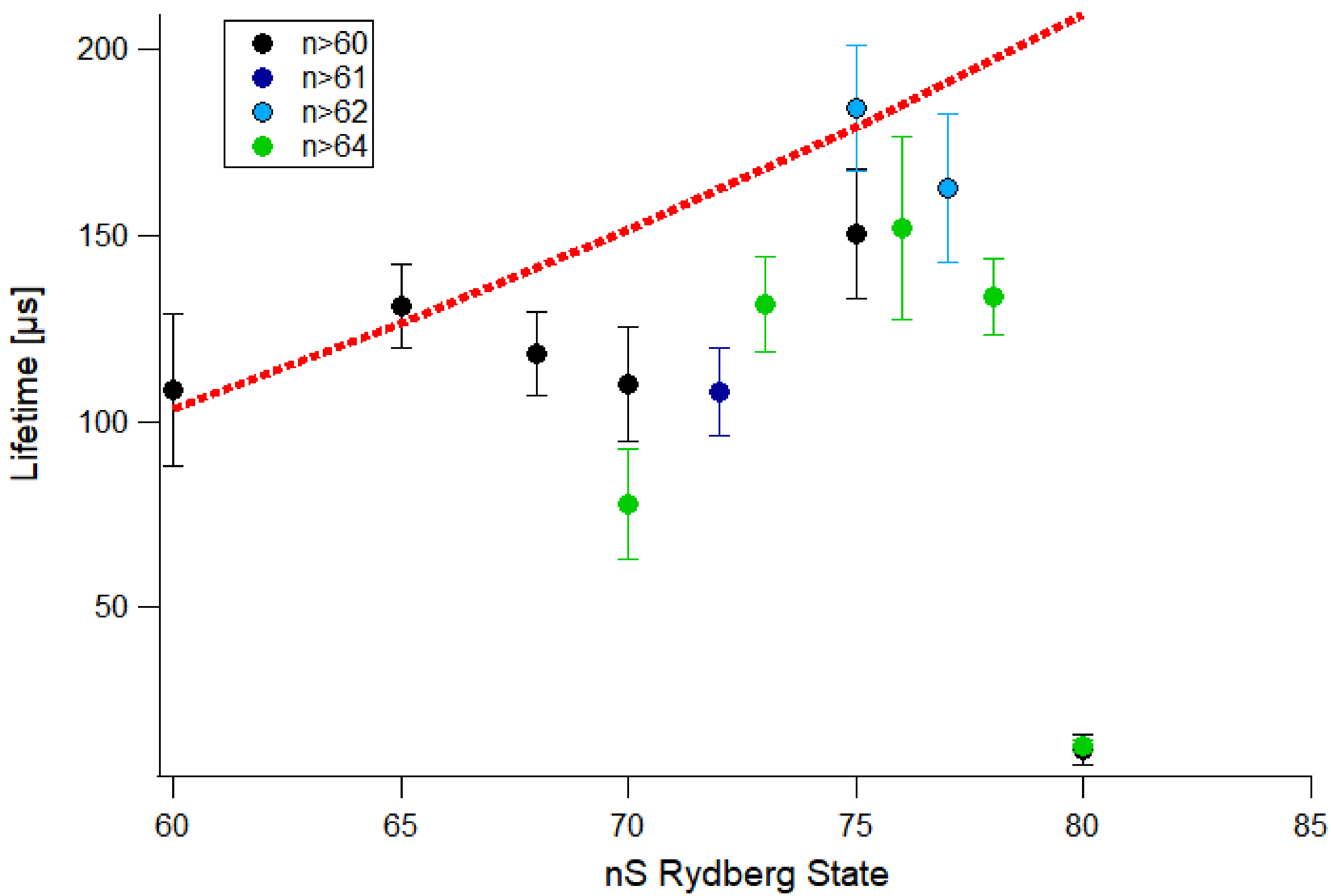
Two parts:

- Excite atoms, wait and ionize all Rydberg atoms;
- Excite atoms, wait, depump atoms in the *target state*, and ionize the other (*support states*)

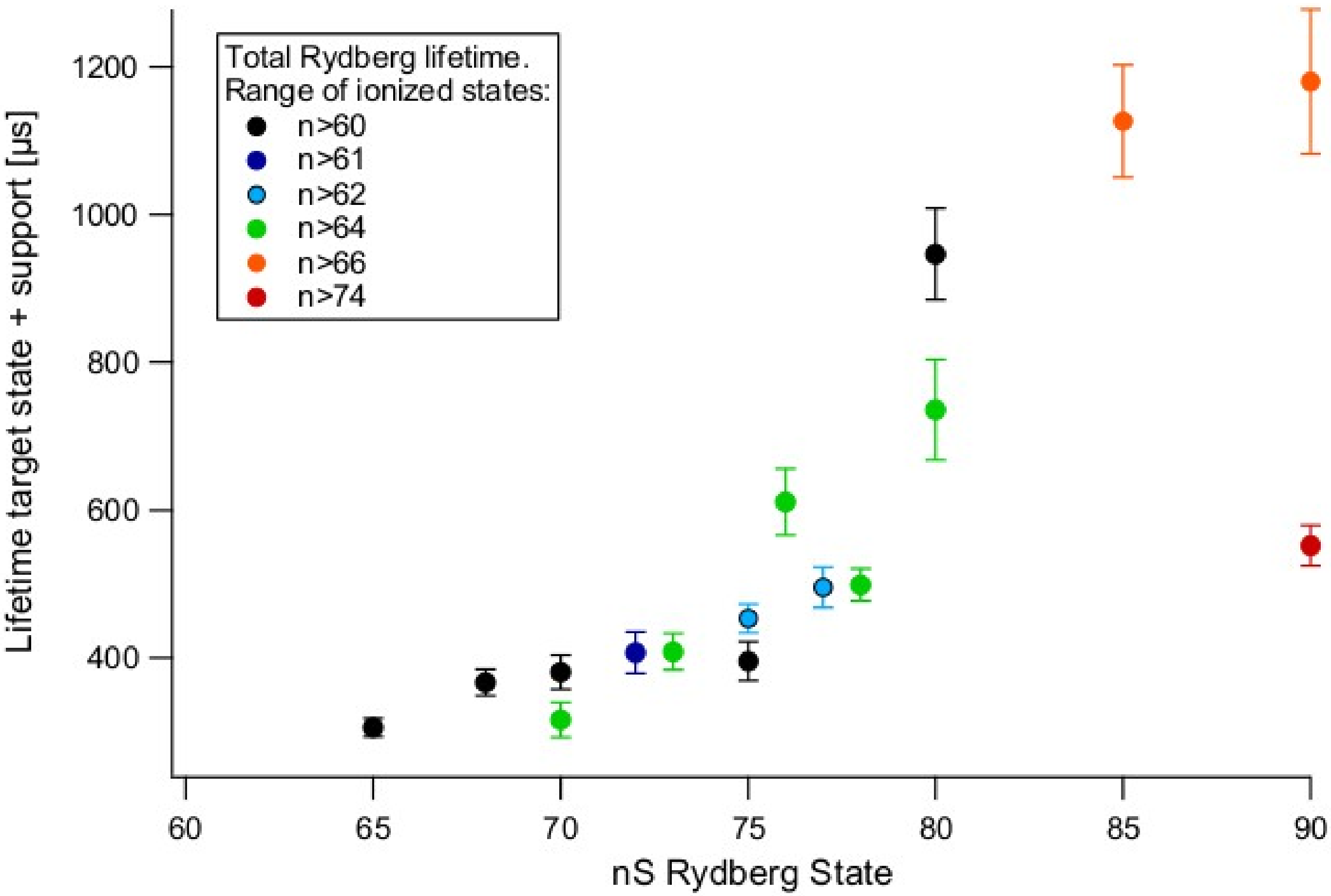


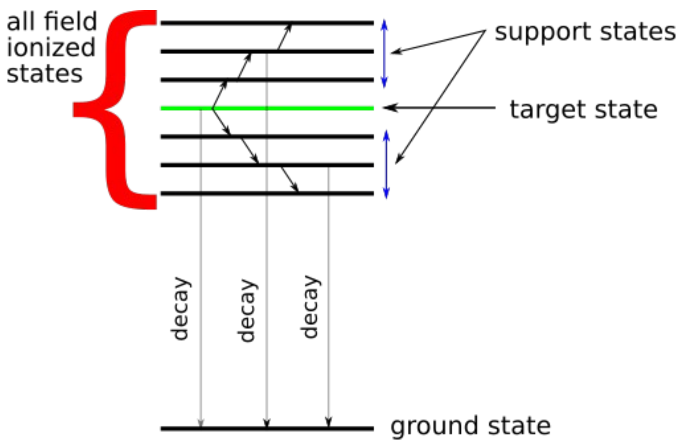


Measurement of the lifetime: lifetime of the target state

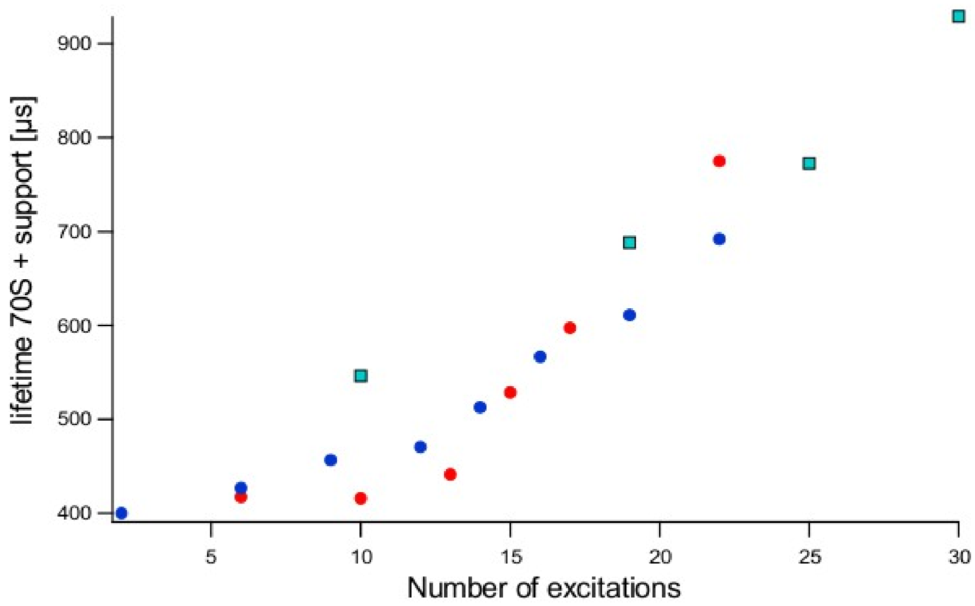


Measurement of the lifetime: lifetime of the target state+support states



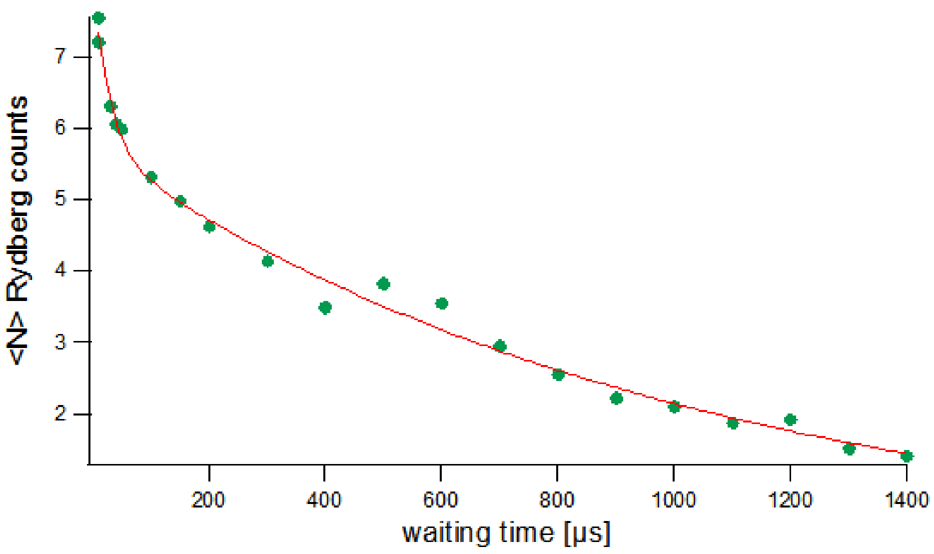


Measurement of the lifetime: effects of interactions



Dependence of the target+support lifetimes on the number of initial excitations

Anomalous initial fast decay, deviation from simple exponential decay for high lying Rydberg states.



Conclusions

- I have presented the results on the measurements of the lifetimes of Rydberg atoms;
- Good agreement with theoretical calculation between n=60 and n=80;
- Unexpected deviation from the theory for n>80;
- Dependence with number of Rydberg atoms and non-exponential decay suggest effects of interactions.

The results obtained during my PhD led to the following publications:

- *De-excitation spectroscopy of strongly interacting Rydberg gases,* C. Simonelli, M. Archimi, L. Asteria, D. Capecchi, G. Masella, E. Arimondo, D. Ciampini, O. Morsch, arXiv:1707.01382, submitted to Phys. Rev. A (2017);
- *Experimental signatures of an absorbing-state phase transition in an open driven many-body quantum system,* R. Gutierrez, C. Simonelli, M. Archimi, F. Castellucci, E. Arimondo, D. Ciampini, M. Marcuzzi, I. Lesanovsky, O. Morsch, arXiv:1611.03288, submitted to Phys. Rev. A (2017).