

Quantum simulation with circular Rydberg atoms of strontium

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CIRCULAR RYDBERG ATOMS

• Circular states properties :

- Circular Rydberg states are highly-excited states with maximum angular momentum ($m = l = n - 1$).
- They exhibit **really long lifetime**, in the 10's of ms range.
- Their large dipole-dipole coupling make them a great tool for metrology or quantum simulation.
- Circular states with different n are coupled via micro-wave radiation (50 GHz). So we can use two circular states to simulate a spin system, and look at the dynamics over long time-scale.

• Circularization :

- Three photons excitation to the $n = 52$ Rydberg manifold.
- DC Electric field to split the different m levels by Stark effect.
- Radio-frequency pulse with $\sigma +$ polarization to go in the circular state.

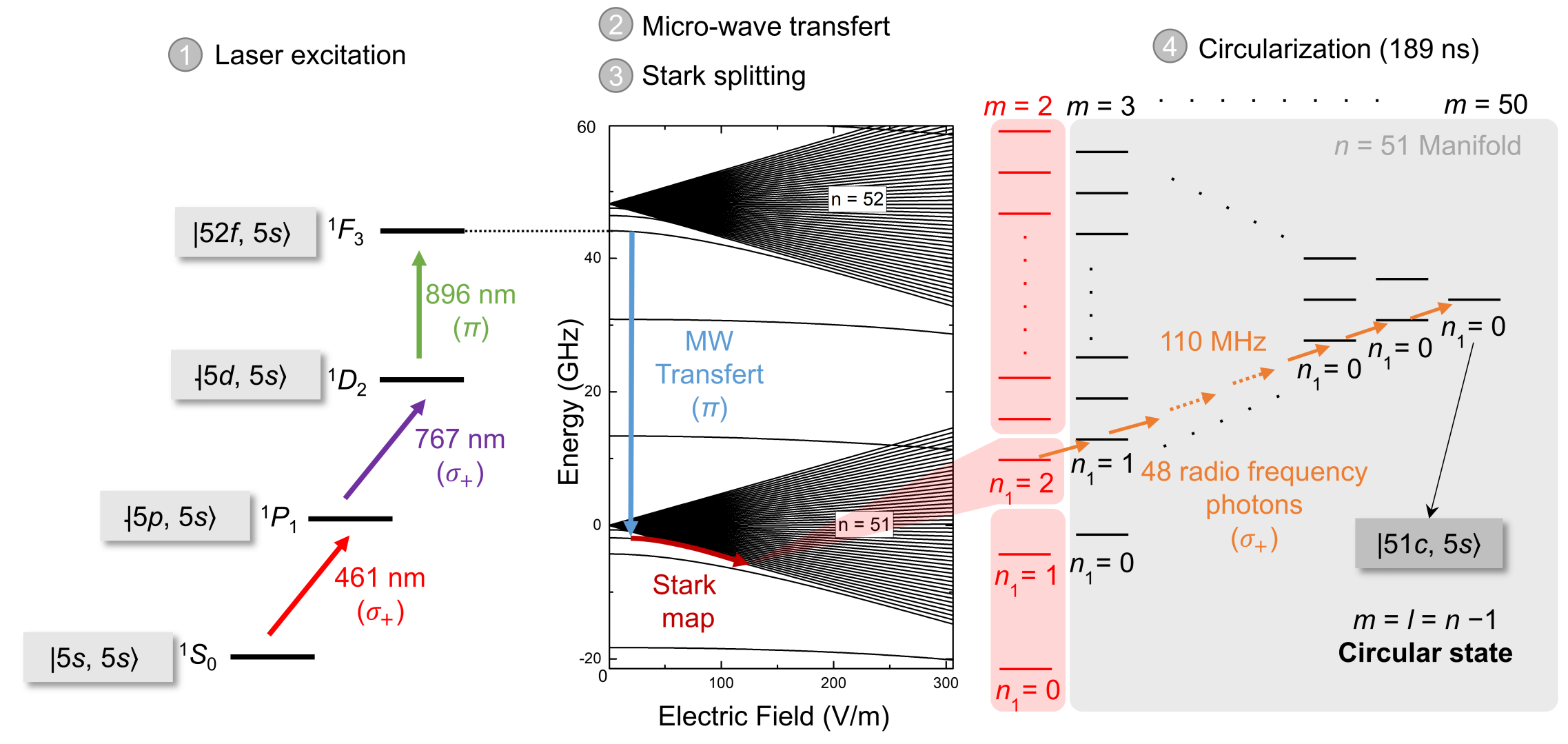


Fig1 Rydberg excitation and circularization process.

ALKALINE-EARTH PROPERTIES

• Autoionization :

- Exciting the core electron, while the other is in a Rydberg state will cause the two electrons to collapse and the Rydberg electron will be ionize.
- This effect does not occur for circular Rydberg state because of the small overlap between the two wavefunction [2].
- This can be used to detect selectively circular and non circular states.

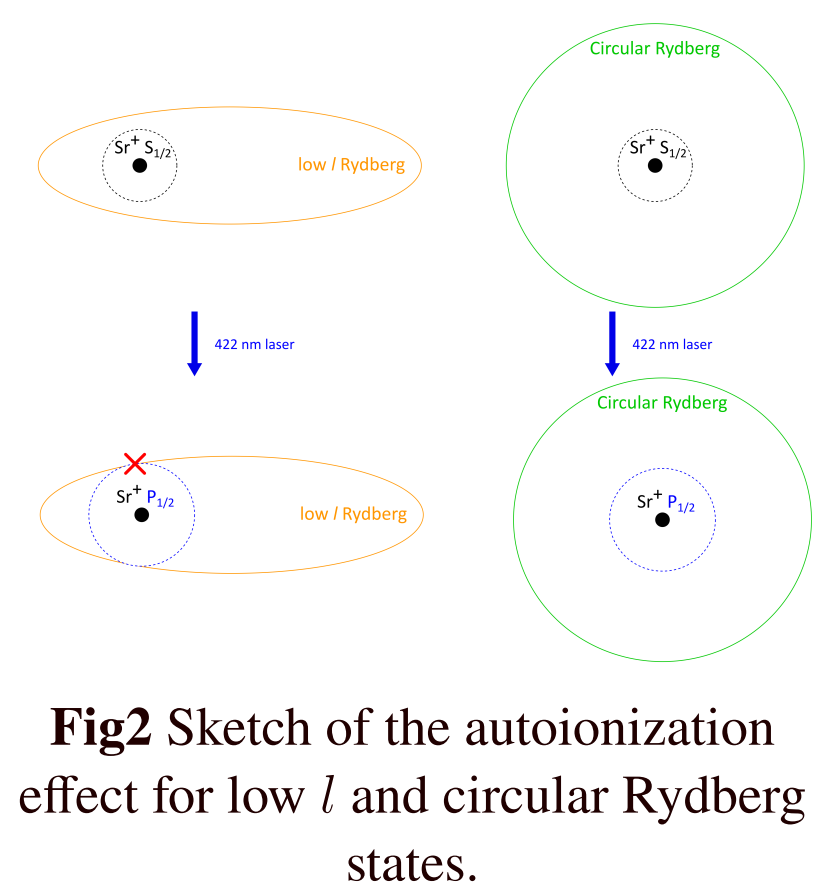


Fig2 Sketch of the autoionization effect for low l and circular Rydberg states.

• Two electrons interactions :

- The main idea is to excite one electron to the circular state and use the remaining **optically active Ionic core** to manipulate the system.
- The coupling between the ionic core quadrupole moment and the electric field gradient of the Rydberg electron will give rise to a energy shift of the $4d$ sublevels of the ionic core.
- We used Raman spectroscopy to measure this effect for different values of n .

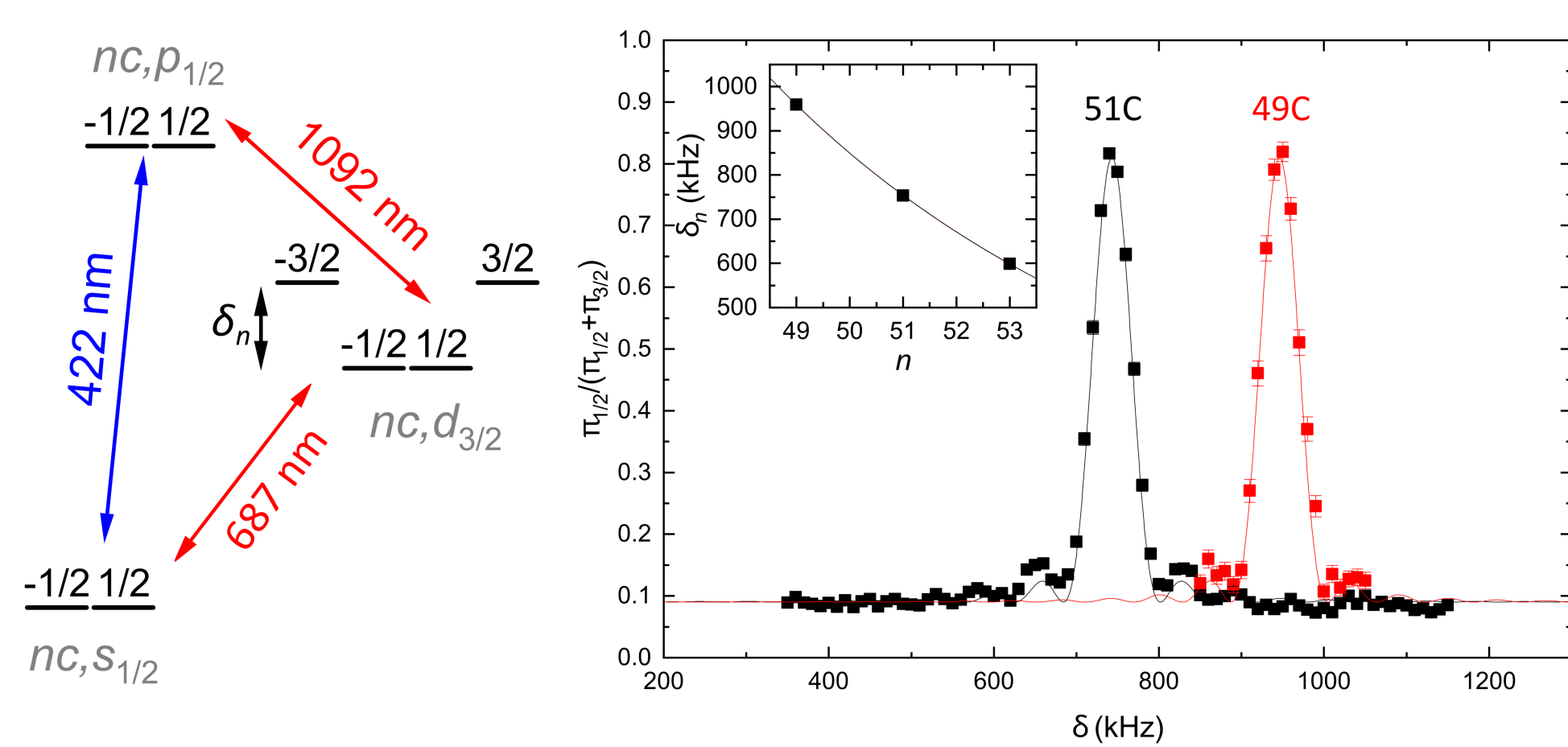


Fig3 a, b (a) : Energy levels Sr Ion, (b) : Laser spectroscopy : Raman transfer between $d\ 3/2\ |m| = 3/2$ and $d\ 3/2\ |m| = 1/2$ for two circular states. [3].

• Cooling a superposition :

- We demonstrated that we can slow an atomic beam of circular atoms using doppler cooling on the 422 nm Ionic core transition [4].
- It allows us to **cool down a superposition of circular states** without decoherence.
- In a quantum simulator this can be used to cool down the atoms in the traps during the simulation.
- Decoherence caused by the energy shift of the d sublevels can be suppressed using dynamical decoupling method.

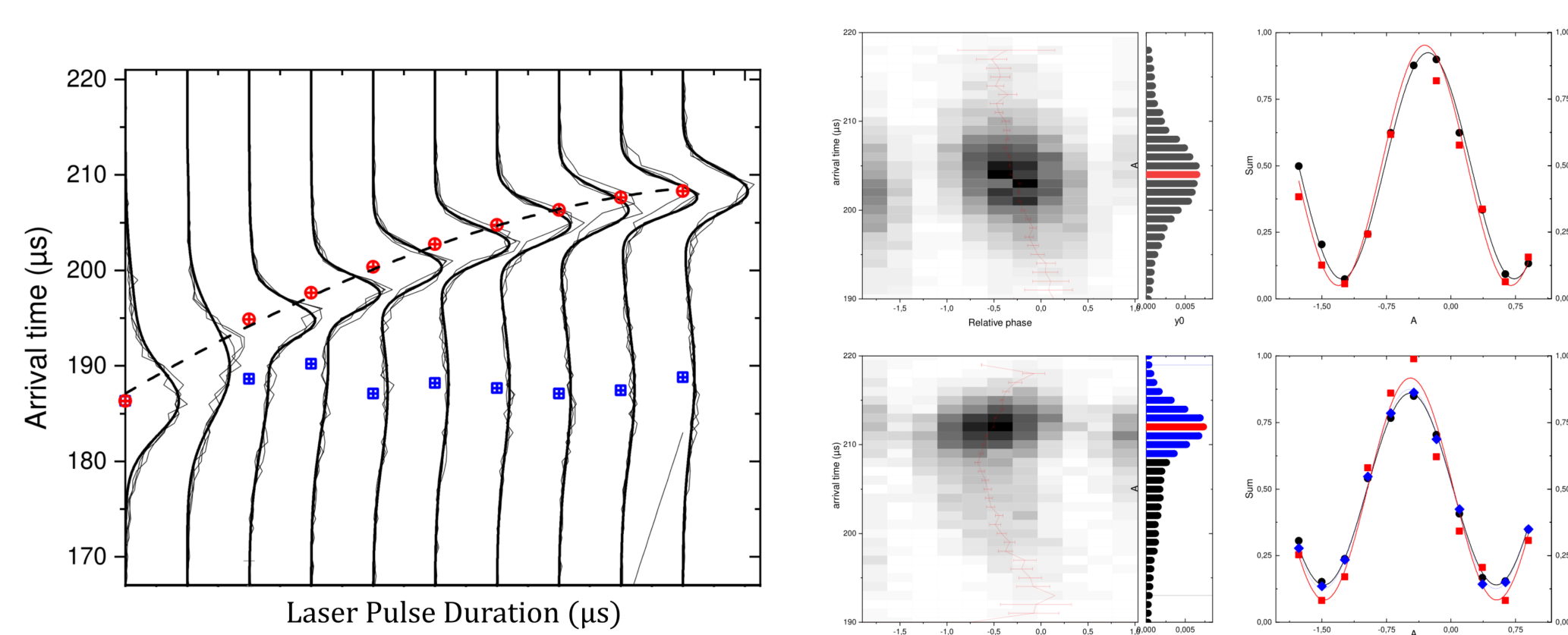


Fig4 a, b (a) : Arrival time of the circular atoms with doppler slowing, (b) : Ramsey fringes between 51c and 50c with and without slowing.

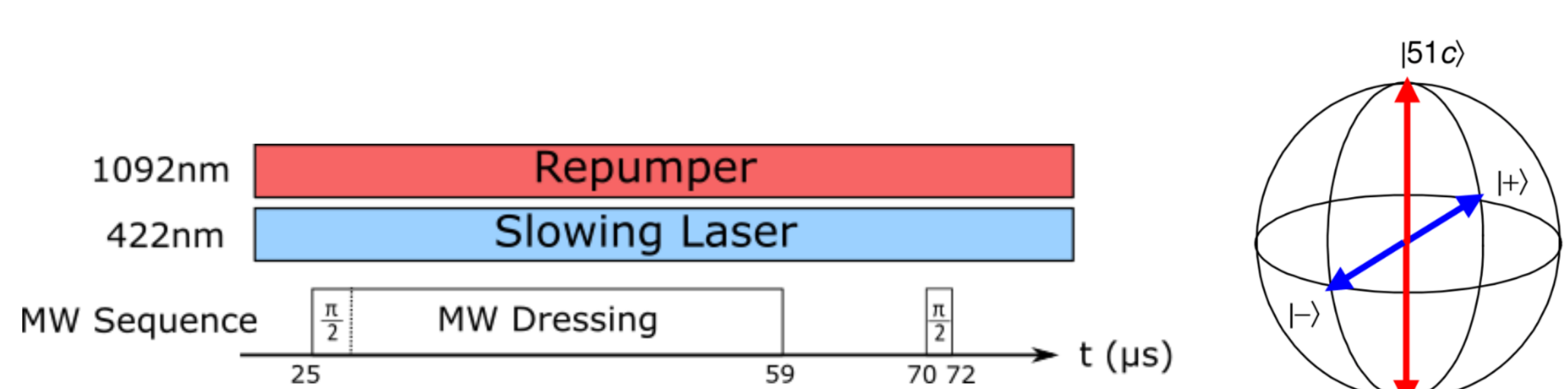


Fig5 Experimental Sequence with dynamical decoupling.

DEVELOPMENT OF A TWEezer EXPERIMENT

• Cold atoms of strontium :

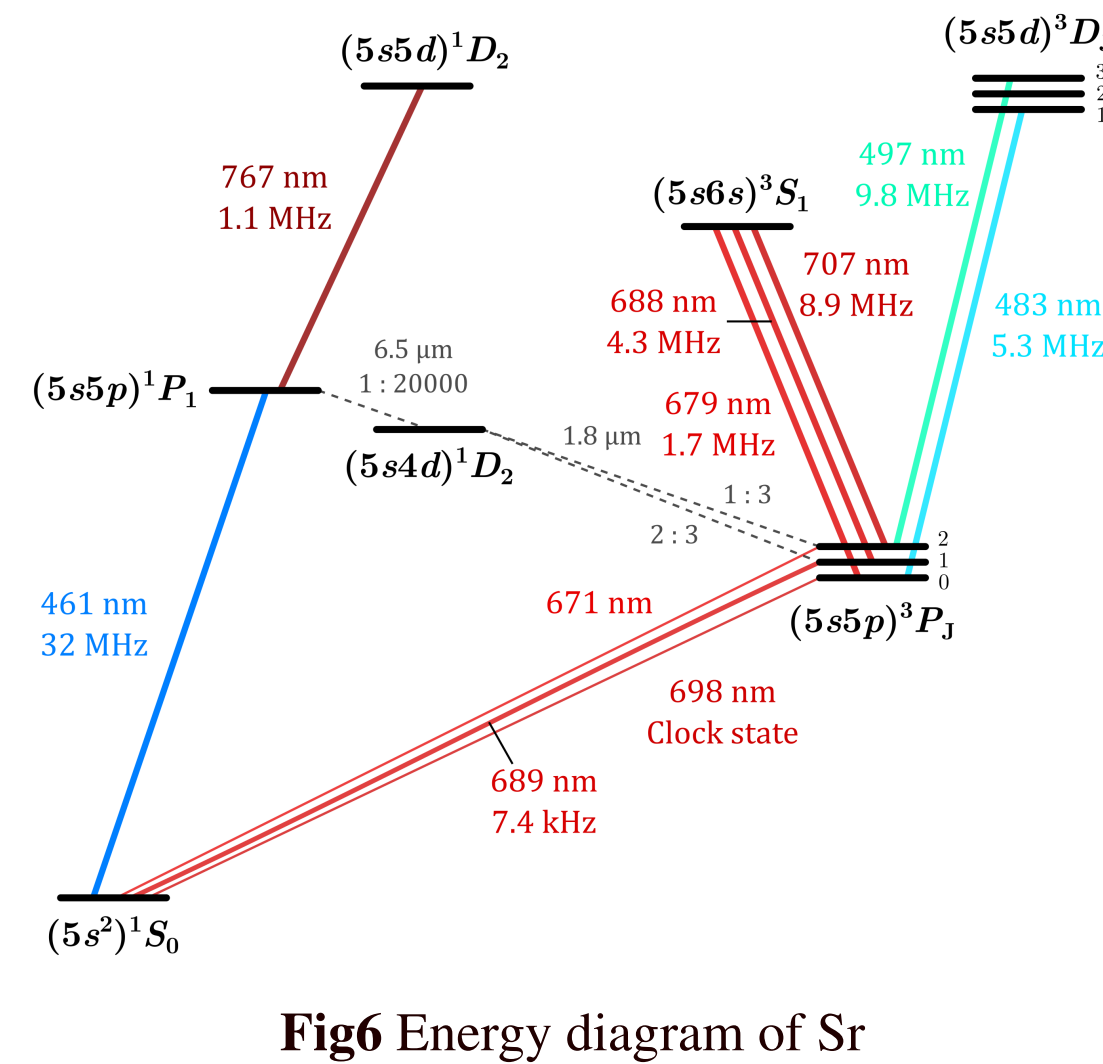


Fig6 Energy diagram of Sr

- Blue MOT at 461 nm, 32 MHz down to 1 mK.
- Needs of repumper to avoid optical pumping in the clock state.
- Red MOT at 689 nm, 7.4 kHz to a final temperature below 1 μ K.
- **Optical tweezer at 515 nm** (magic for 3P1) or 813 nm (magic for the clock).

• Trapping Circular States :

- Circular states of Alkali can be trapped using the ponderomotive potential of the electron. But since they are attracted to the minimum of light intensity, a bottle-beam geometry is needed, which requires more power and is difficult to implement.

- Here we will use the polarizability of the Ionic core to trap the atom in a gaussian dipole trap.
- The ponderomotive potential of the Rydberg electron will decrease the polarizability.
- To trap excited state of the Ionic core, it's necessary to use a two colors trap, by adding a laser at around 1100 nm.

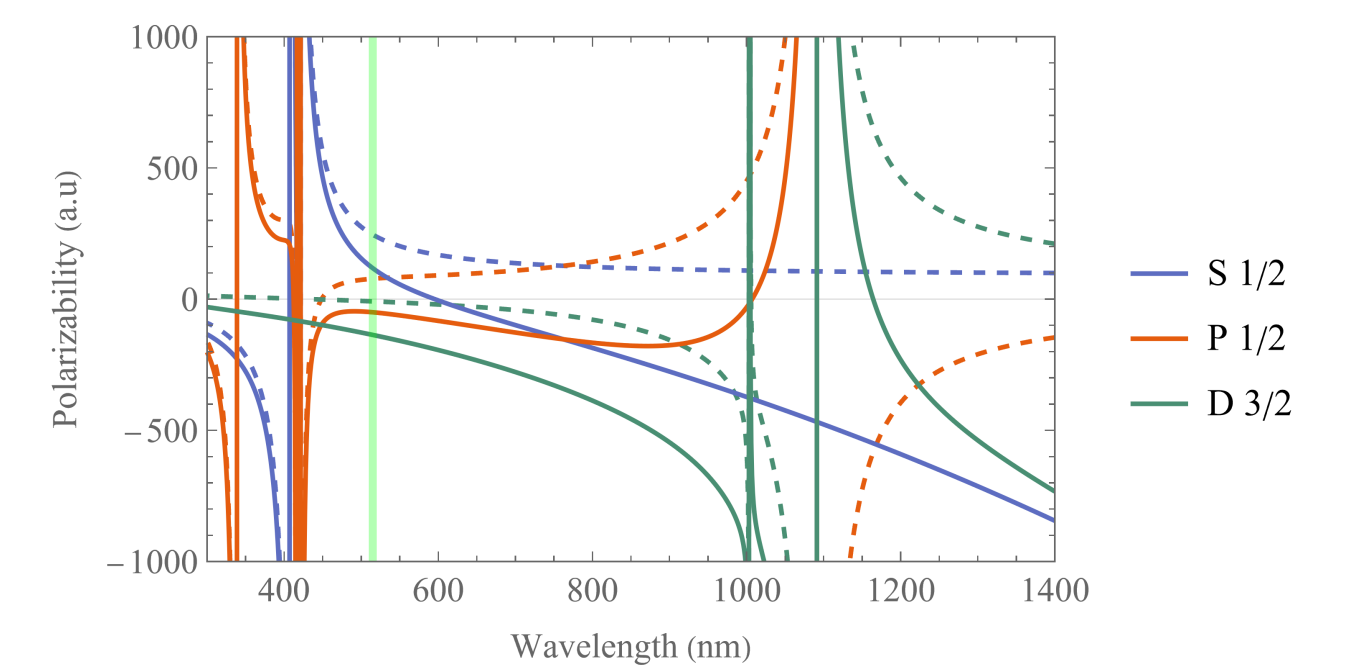


Fig7 Polarizability of Sr+ with Rydberg electron

• QND Measurement

- We want to use the Ionic core to **image the atoms in the circular states without destroying them**.
- Similarly to what is used in trapped ions experiments, atoms in a specific n circular state can be excited into the $d\ 5/2$ state, making them unable to fluoresce.
- By resolving the electric quadrupole shift, we can choose which circular state we want to detect.

• New Experimental setup :

- Cryogenic setup at 4 K.
- Superconducting coils able to create a magnetic field gradient of 160 gauss/cm.
- Electrodes around the chamber for sigma+ radio-frequency pulse.
- 2D array of optical tweezer at 515 nm, generated by Spatial Light Modulator, to trap ground state atoms and circular states.
- Detection by ionisation and fluorescence imaging at 422 nm.

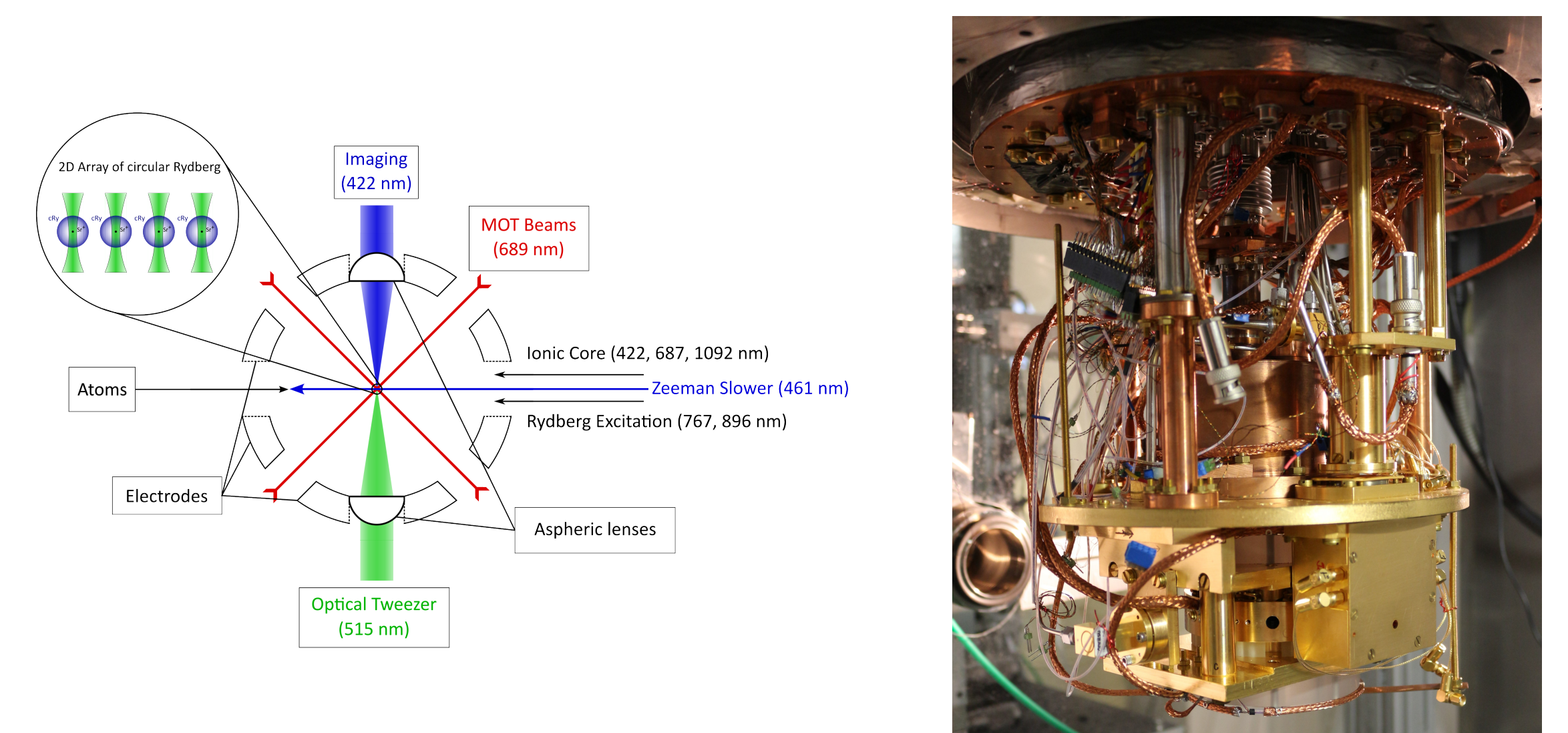


Fig3.e Diagram of the experimental setup.

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- [2] TEIXEIRA ET AL. Preparation of Long-Lived, Non-Autoionizing Circular Rydberg States of Strontium, *Physical Review Letter*, 2020.
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- [4] LACHAUD ET AL. Slowing a coherent superposition of Rydberg states, *In preparation*, 2023.