# Rydberg Atoms

## INTRODUÇÃO À FÍSICA ATÔMICA E MOLECULAR

INSTITUTO DE FÍSICA DE SÃO CARLOS-USP

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# Contents

# 1. Introduction

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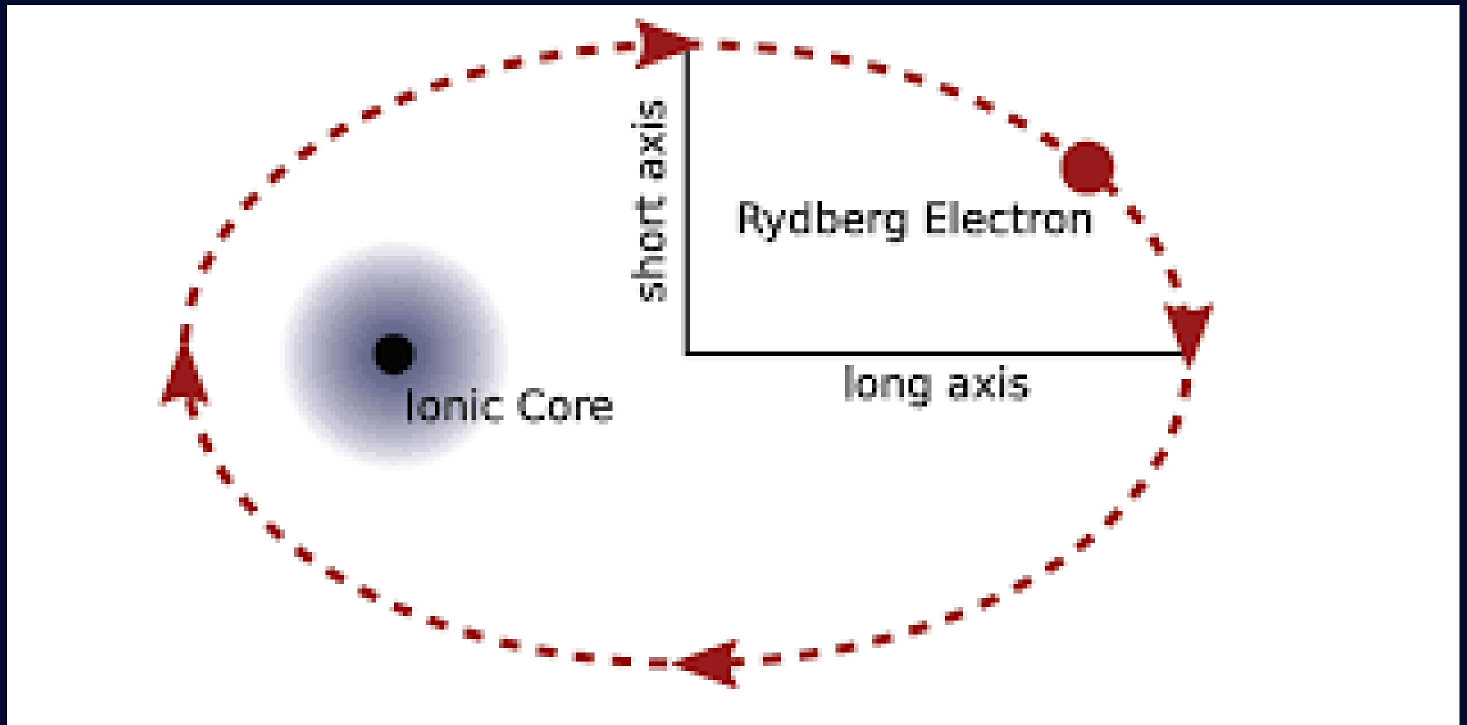
## 1.1. What are Rydberg atoms?

- Atoms with an eletron in a state with high principal quantum number n.
  - Good coupling with fields.
  - Long range dipole-dipole interactions.



# 1. Introduction

## 1.2. History

- 1890 - Empirical equation to several frequencies in the hydrogen spectrum ( Johannes Rydberg ).

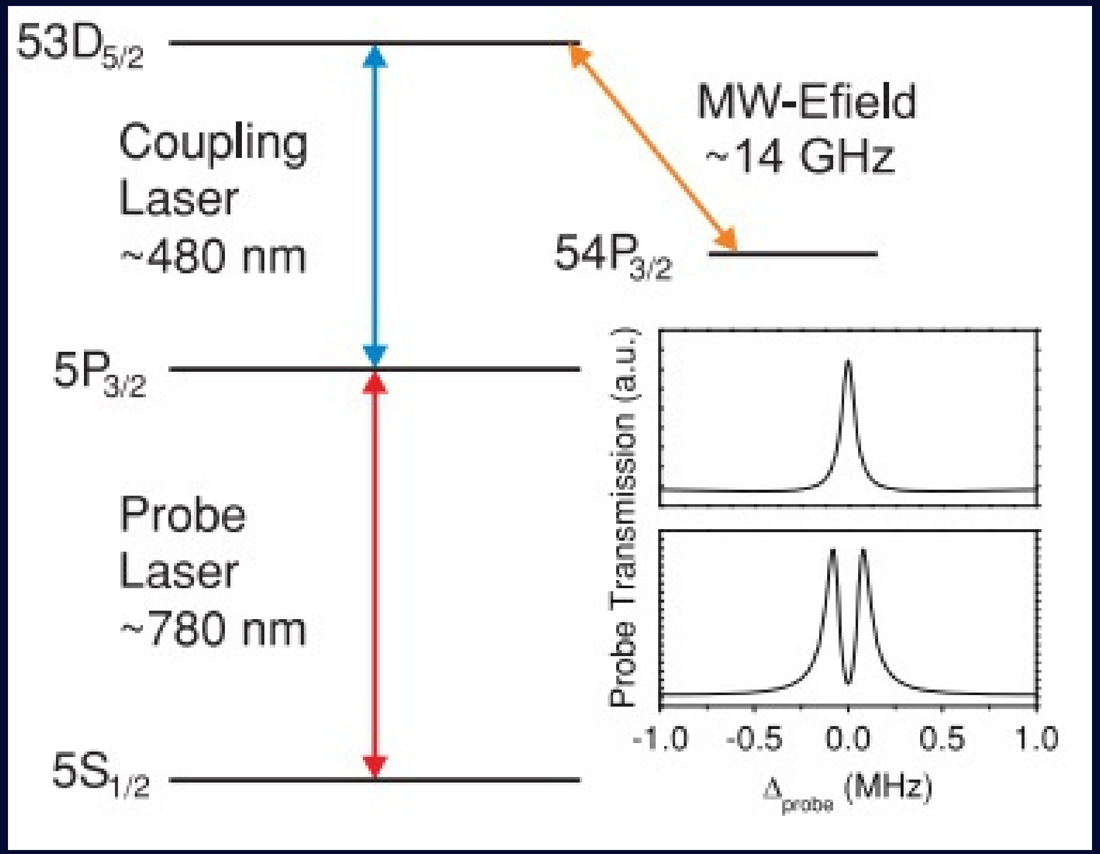
$$f = R_H \left( \frac{1}{m^2} - \frac{1}{n^2} \right)$$

- Bohr and Som-merfeld, quantizing the angular momentum of the electrons’ orbits.

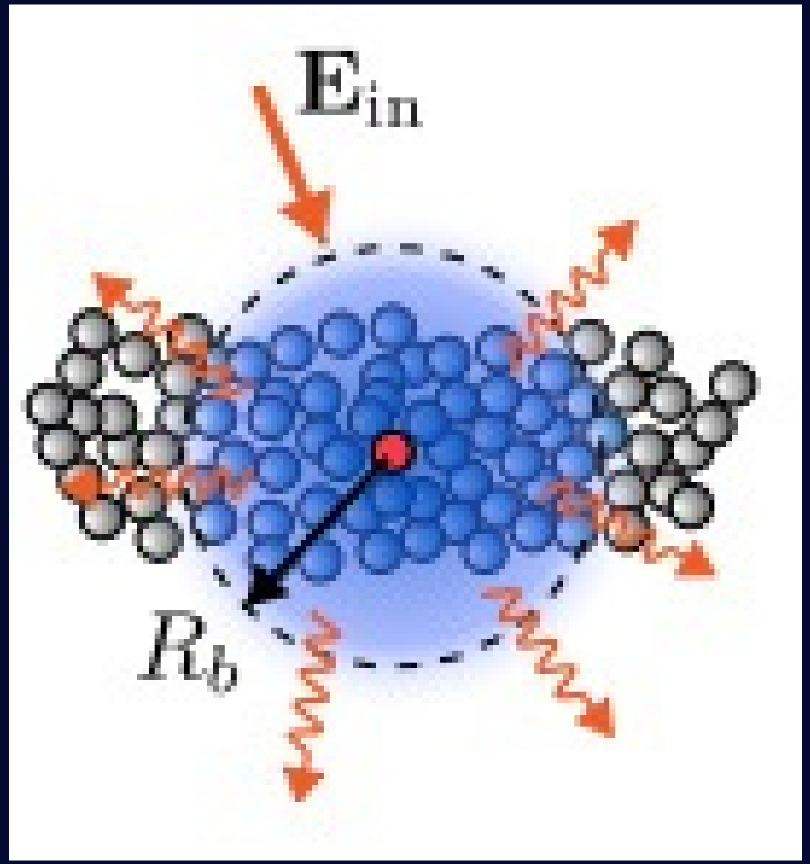
# 1. Introduction

## 1.3. Aplications

High sensibility sensors*




Nonlinear optics**




*H. Fan et al., J. Phys. B At. Mol. Opt. Phys. 48, 202001 (2015)

**M. Moreno-Cardoner, D. Goncalves, e D. E. Chang, Phys. Rev. Lett. 127, 263602 (2021).

# 2. Exciting Rydberg states

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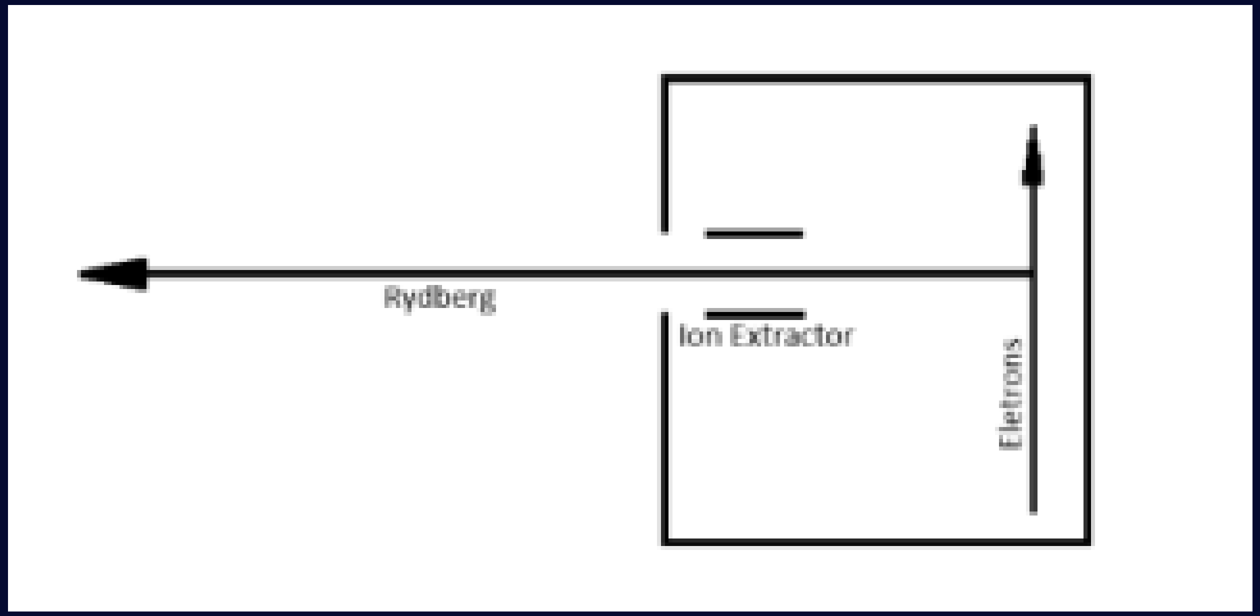
## 2.1. Eletron impact

$$e^- + A \rightarrow A \quad nl + e^-$$

Transfering energy from the electrons beam to the vallence eletron on the atom.

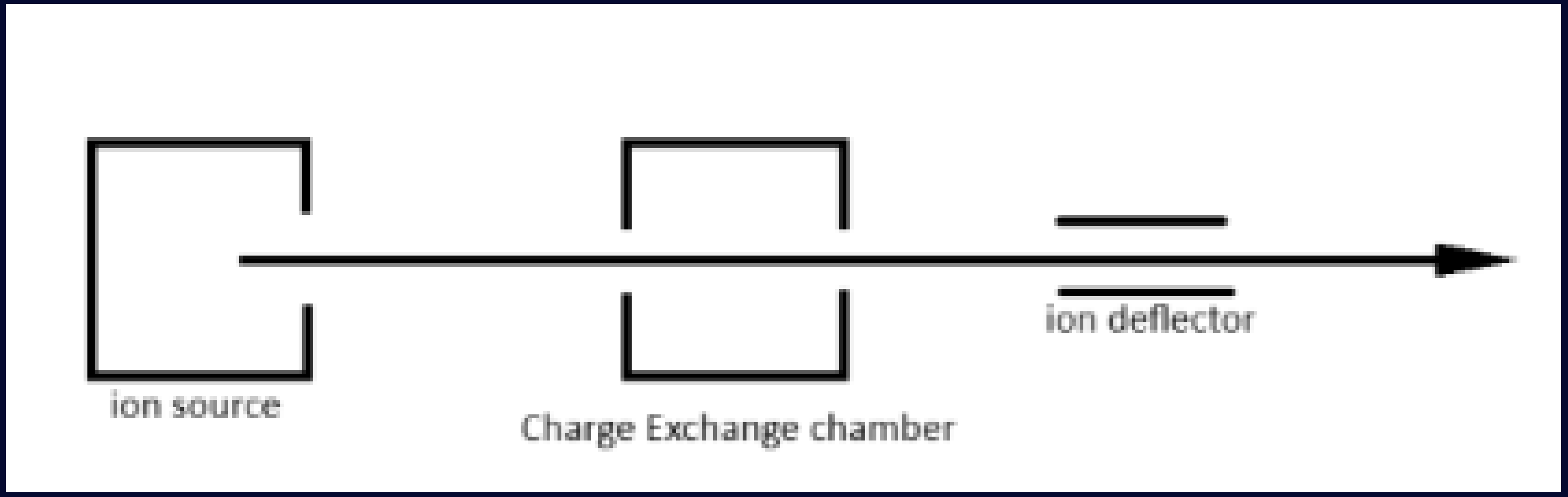


# 2. Exciting Rydberg states

## 2.2 Charge exchange

$$A^+ + B \rightarrow A \quad nl + B^+$$

Ions in the ion beam capture electrons from the rare gases in the charge exchange chamber.

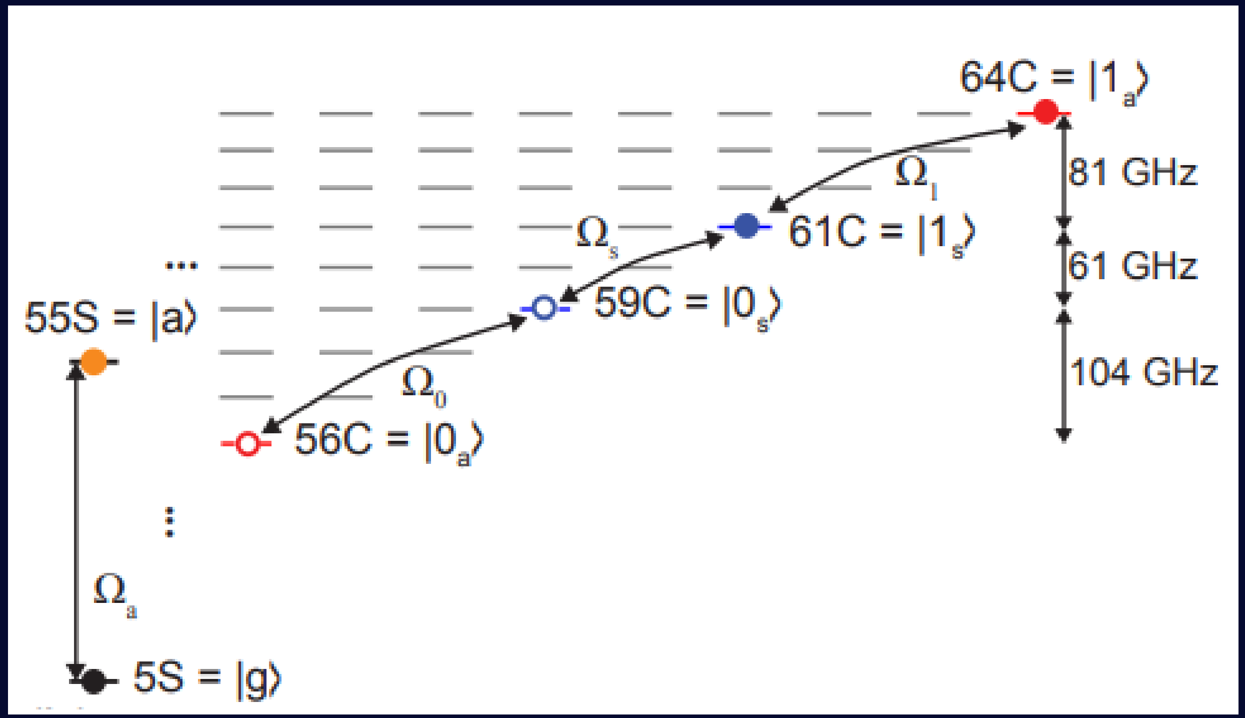


# 2. Exciting Rydberg states

## 2.3. Optical excitation

$$hf + A \rightarrow A \quad nl$$

A photon in resonance with the atomic transition is absorbed, and this energy causes the atom to transition to a higher energy state.



# 3. Rydberg states wave function

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Hydrogen like Hamiltonian:

$$\left(-\frac{\nabla^2}{2}-\frac{1}{r}\right)\psi = W\psi$$

Should works with atoms with a single valence electron far from the nucleus.

Angular soluction:

$$Y_{lm}(\theta,\phi) = \sqrt{\frac{(l-m)!}{(l+m)!}\frac{2l+1}{4\pi}}P_l^m(cos\ \theta)\ e^{im\phi}$$

*T. F. Gallagher, Cambridge monographs on atomic, molecular and chemical physics: Rydberg atoms series number 3 (Cambridge University Press, Cambridge, England, 2011).

# 3. Rydberg states wave function

The radial equation can be written as:

$$\frac{\partial^2 \rho}{\partial r^2} + \left[2W + \frac{2}{r} - \frac{l(l+1)}{r^2}\right]\rho = 0$$

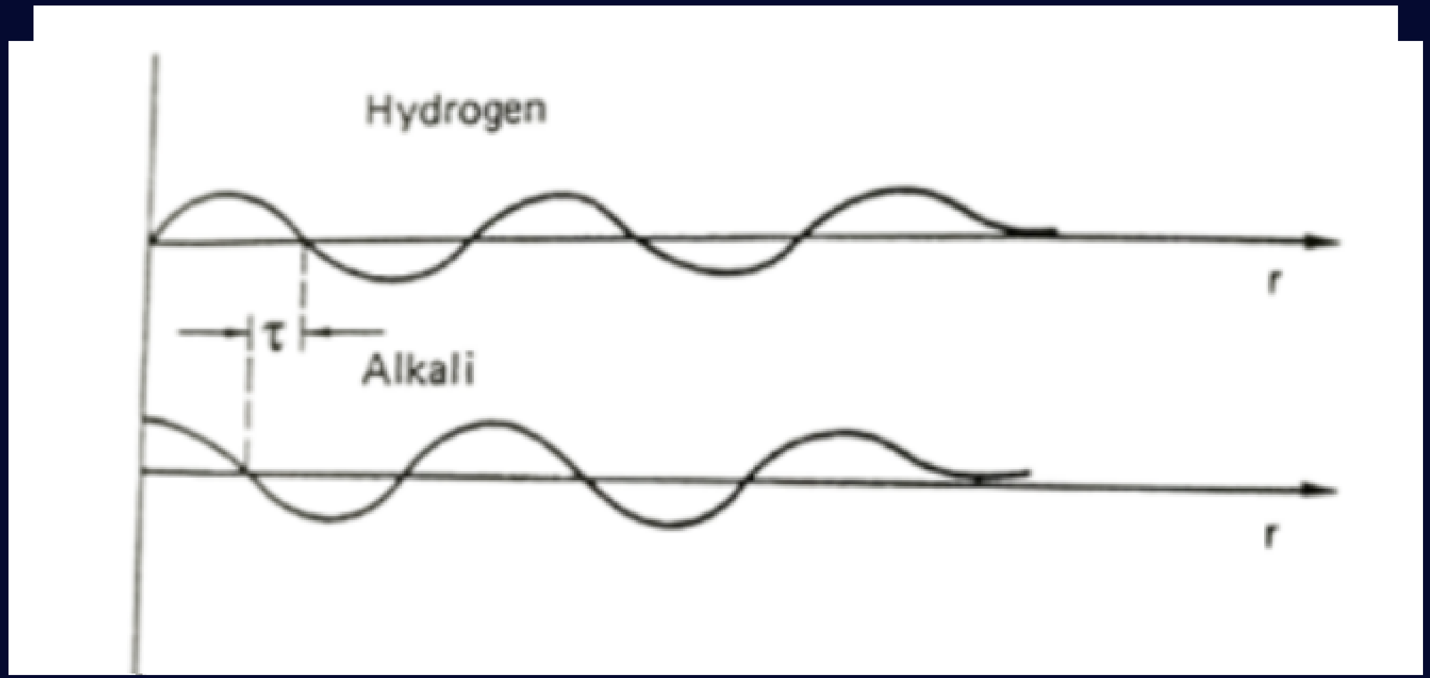
Which is the Coulomb equation. For our problem, we can consider two solutions, but taking into account the boundary conditions, only the regular solution remains. This can be written as:

$$f \to u(\beta, l, r)\ sin\ \pi\beta \ - \ v(\beta, l, r)e^{i\pi\beta}$$

*M. J. Seaton, Rep. Prog. Phys. 46, 167 (1983).

# 3. Rydberg states wave function

We now, need to make a correction for an electron that has a considerable probability of being found near the ionic nucleus, obtaining a phase due to the action of the new potential.




it is possible to express this phase as:

$$\tau = \int_0^{r_0} \left\{ [W - V_{eff}(r)]^{\frac{1}{2}} - \left[W + \frac{1}{r}\right]^{\frac{1}{2}} \right\} \sqrt{2}\, dr$$

# 3. Rydberg states wave function

We can simplify this equation by considering only the difference between the potentials :

$$\tau = \int_0^{r_0} V_d(r) \left(\frac{r}{2}\right)^{\frac{1}{2}} \quad dr.$$

Thus, the new solution to the radial equation in terms of the phase will be given by:

$$\rho(r) = f(W, l, r)\ cos\ \tau - g(W, l, r)\ sin\ \tau$$

# 3. Rydberg states wave function

Considering the new boundary conditions, we can define the new wave function, with the potential correction for the electron near the ionic nucleus.

$$\psi = \frac{Y_{lm}[f(W,l,r)\ cos\ \pi\delta_l - g(W,l,r)\ sin\ \pi\delta_l]}{r}$$

In which the allowed energies are given by:

$$W = -\frac{1}{2(n-\delta_l)^2}$$

And the quantum defects for each state with quantum number l are given by:

$$\delta_l = \frac{\tau}{\pi}$$

# 4. Quantum processor

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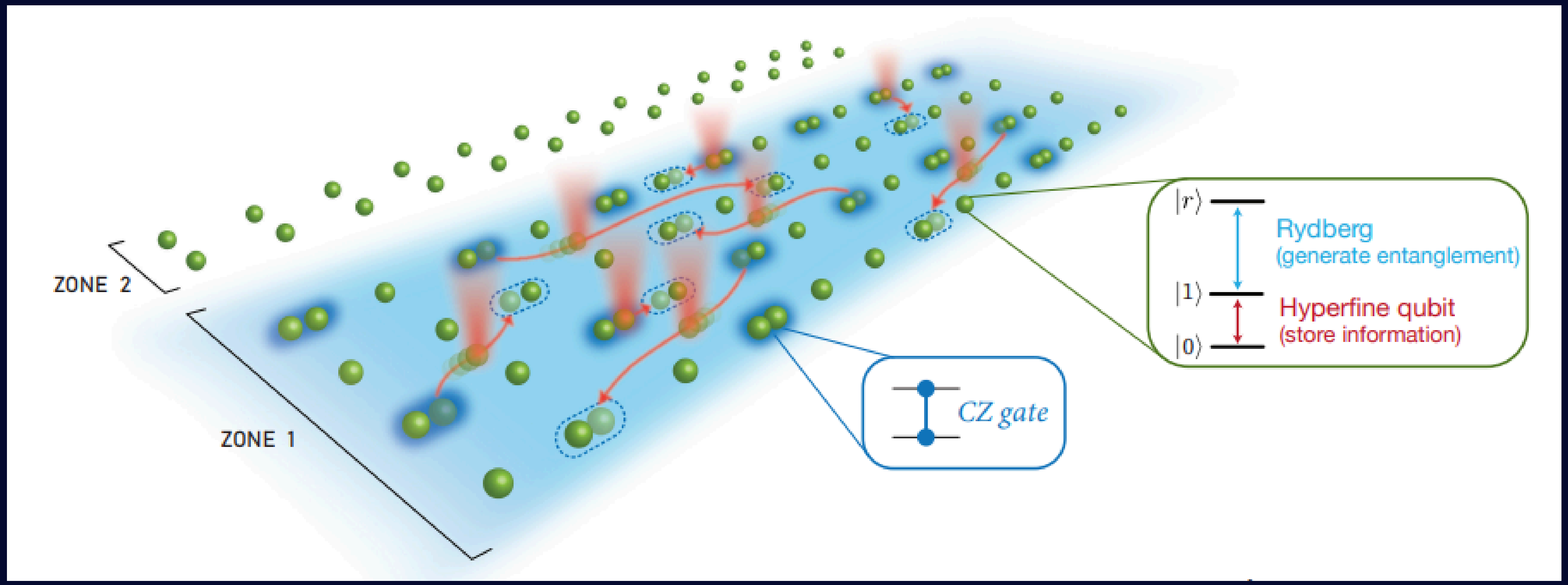
**A quantum processor based on coherent transport of entangled atom arrays**

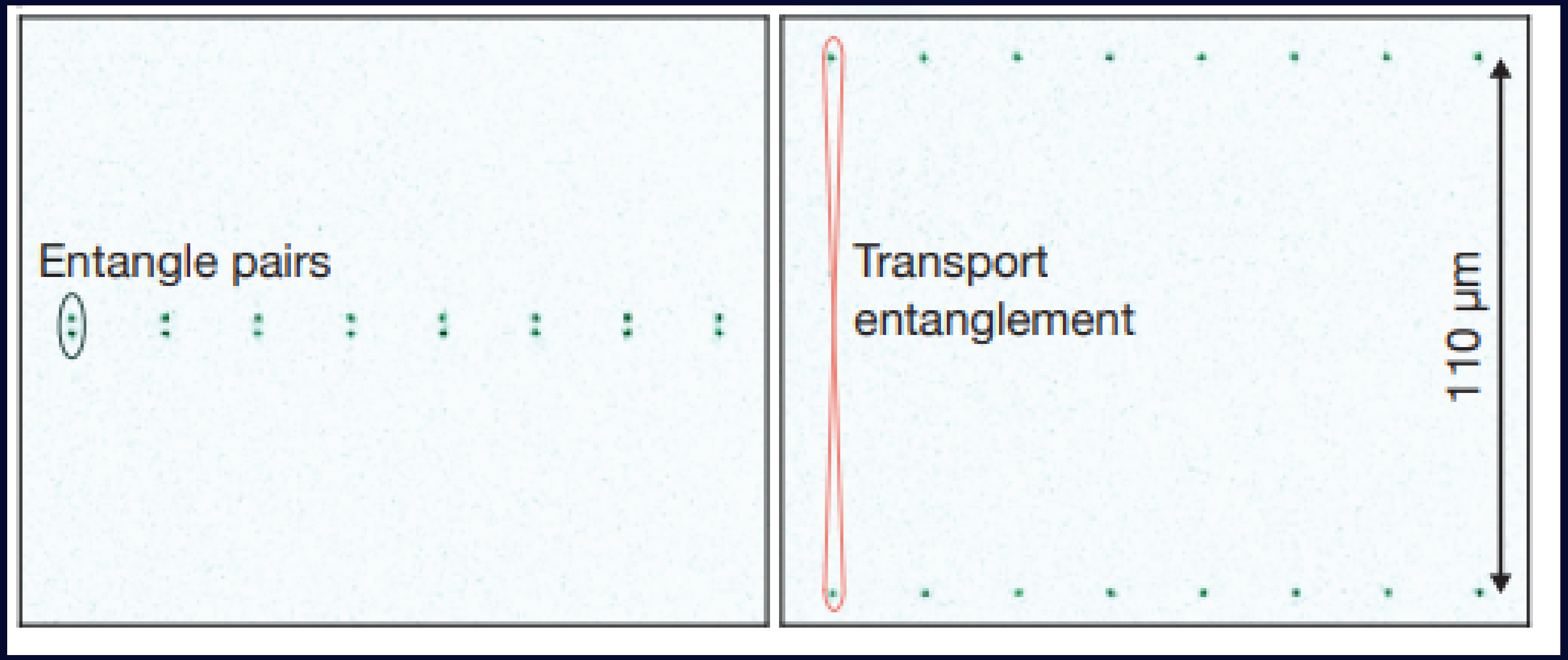
Dolev Bluvstein[1], Harry Levine[1,†], Giulia Semeghini[1], Tout T. Wang[1],
Sepehr Ebadi[1], Marcin Kalinowski[1], Alexander Keesling[1,2], Nishad Maskara[1],
Hannes Pichler[3,4], Markus Greiner[1], Vladan Vuletić[5], and Mikhail D. Lukin[1]
[1] *Department of Physics, Harvard University, Cambridge, MA 02138, USA*
[2] *QuEra Computing Inc., Boston, MA 02135, USA*
[3] *Institute for Theoretical Physics, University of Innsbruck, Innsbruck A-6020, Austria*
[4] *Institute for Quantum Optics and Quantum Information, Austrian Academy of Sciences, Innsbruck A-6020*
[5] *Department of Physics and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA.*
[†] *Current affiliation: AWS Center for Quantum Computing, Pasadena, CA 91125.*

This is a cold atom experiment, located at Harvard University, they have a system of optical tweezers capable of transporting atoms with high precision.

# 4. Quantum processor

They use the long-range interactions of Rydberg states to generate entanglement between atoms, making CZ gates in parallel in hyperfine states {|0> and | 1> } using rydberg transition |1> -> |r>.



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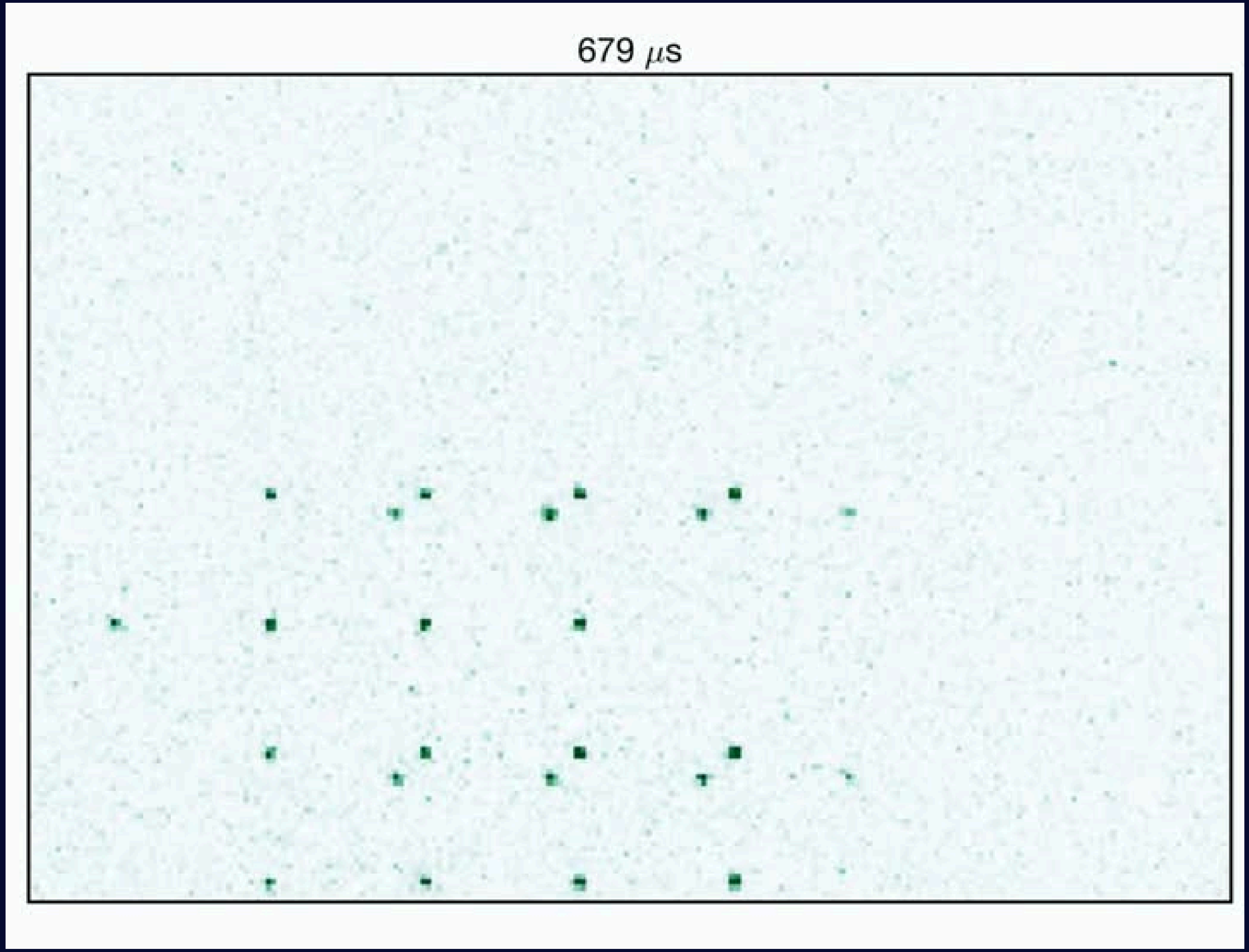

# 5. Conclusion

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- Similarity between the wave function of Rydberg atoms with a single valence electron and the wave function of hydrogen. This gives a good understanding of the wave function of Rydberg states

- Rydberg atoms are highly applicable in quantum technologies, and their “exaggerated” characteristics can be exploited in a variety of ways.

# 6. References


[1] Jonathon Sedlacek Harald Kübler Shaya Karimkashi Haoquan Fan, Santosh Kumar and James P Shaffer. Atom based rf electric field sensing. J. Phys. B: At. Mol. Opt. Phys. 48, 2015.

[2] D. Goncalves M. Moreno-Cardoner and D. E. Chang. Quantum nonlinear optics based on two-dimensional rydberg atom arrays. Phys. Rev. Lett. 127, 263602, 2021

[3] Thomas F. Gallengher. Rydberg Atoms. Cambridge university Press, 2005.

[5] M J Seaton. Quantum defect theory. Rep. Prog.Phys., Vol. 46, 1983.

[6] Giulia Semeghini Tout T. Wang Sepehr Ebadi Marcin Kalinowski Alexander Keesling Nishad Maskara Hannes Pichler Markus Greiner Vladan Vuletić Mikhail D. Lukin Dolev Bluvstein, Harry Levine. A quantum processor based on co-herent transport of entangled atom arrays. Nature volume 604, pages451–456, 2022.