Toward Quantum Simulation with Circular Rydberg Atoms


Classical simulation of N-spin arrays:
• Exact diagonalisation only for $N \approx 50$
• Dynamics hard to simulate

→ Quantum simulation!

Requirements:
• Spins $\frac{1}{2}$ in a defect free array with arbitrary geometry
• Long lifetimes and strong interactions
• Fully tunable Hamiltonian

Spin $\frac{1}{2}$: circular Rydberg states
• Circular levels: $n \gg 1, l = m_l = n - 1$, orbit $\approx n^2 a_0$
• Long-lived states: $\approx 30$ms at 0K, up to 50s in a spontaneous emission inhibition structure
• Huge dipole-dipole interaction at few microns, tunable by static electric and magnetic fields
• Spin $\frac{1}{2}$ = Two circular states
• Effective longitudinal and transverse magnetic field = MW dressing

→ XXZ Hamiltonian with dynamically tunable parameters:

$$H/\hbar = \frac{\Delta}{2} \sum_j \sigma_j^z + \frac{\Omega}{2} \sum_j \sigma_j^x + J_z \sum_{\langle j,j'\rangle} \sigma_j^z \sigma_{j'}^z + J \sum_{\langle j,j'\rangle} (\sigma_j^x \sigma_{j'}^x + \sigma_j^y \sigma_{j'}^y)$$

T.L. Nguyen et al., PRX 8, 011032 (2018)
2D trapping of cold circular Rydberg atoms in a cryostat

**Preparation and detection:**
- Cryogenic environment at 4K
- Atomic cloud of $^{87}$Rb, molasses-cooled to 10μK
- Two-photon optical excitation, then MW transfert and RF adiabatic passage for circularization
- Detection: state-selective field ionization

**Lifetime of circular states:**
- Circular state populations $p_n$
- $52_{C}^C$, $54_{C}^C$, $55_{C}^C$
- $52_{D}^D$, $54_{D}^D$, $55_{D}^D$
- $51_{C}^C$, $53_{C}^C$, $54_{C}^C$

**Trapping detection:**
- Ponderomotive trapping: Rydberg atoms = **low field seeker**
- Hollow beam (LG$_{0,1}$) produced by a SLM
  - Trap depth ≈ 80μK
- Thermal **broadening of the cloud** in an electrical field gradient encoded in the broadening of the line
- Spectroscopy of an **electrical-field-sensitive MW transition** between Rydberg states
  - Trapping over 10ms without atom loss, first laser trapping of circular Rydberg states

T. Cantat-Molrecht et al., PRR 2, 022032 (2020)
R.G. Cortiñas et al., PRL 124, 123201 (2020)
**New setup for single-atom trapping**

- All former capabilities (MOT, Rydberg excitation, circularization) + **optical trap**
- **Single atom displacement**
- Atom detection by **fluorescence**
- New Rydberg excitation scheme
- Preliminary UHV chamber at 300K

**Trap array generation:**

- **Phase modulation** of a laser beam with a spatial light modulator (SLM)
- **Optical Fourier transform** with short focal aspheric lens hold in a sapphire cube
- Gerchberg-Saxton phase-retrieval algorithm $\rightarrow$ phase mask to produce an **array**
- Phase mask to produce a **bottle beam** (BoB) for 3D trapping

**Single fundamental atom trapping:**

- Laser cooling of Rb atoms and dipole trapping in **optical tweezer**, 2.5mW per trap, $w = 1.1\mu m$
- **Fluorescence imaging**

**Histogram:** sub-Poissonian distribution of atoms
$\rightarrow$ **Separated histogram:**
- **efficient atom detection**

\[
F_{\text{atoms}} = TF[e^{i(q_{\text{BoB}} + i\varphi_{\text{array}}}] = F_{\text{BoB}} * F_{\text{array}}
\]
Rydberg excitation of single atoms

**Laser excitation to Rydberg states:**
- **Electric field** offset and gradients precise control with goldened electrodes
- Optical pumping to $5S_{1/2}, F = 2, m_F = +2$ → *state purification*
- Two-photon laser $\pi$-pulse to $5D_{5/2}, m_J = +5/2$

**Rydberg preparation, two modes of detection:**
- **Ionisation** in a electric field and ions detection with a channeltron
- **Fluorescence**: excitation to untrapped Rydberg atoms → no fluorescence

Next steps

**Room temperature setup:**
- Single circular-atom trapping
- Two-atom interaction measurement

**Cryostat:**
- UHV chamber - cryostat swapping → circular atom lifetime x 100
- New quantum simulation