Exploring long-range interacting quantum many-body systems with Rydberg atoms

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Hannover, November 2015
Motivation: Quantum simulation

Idea:

• Mimicking one quantum system by another which is: cleaner, more controlled, better observable

Motivation:

• Study fundamental questions of many-body physics. (Quantum) phase transitions, topology, quantum magnetism, out-of-equilibrium physics, thermalization, disorder, …. in 1, 2 or 3 dimensions.

Challenge:

• Design experiments to be described by a specific Hamiltonian: Theory and experiment often go hand-in-hand
Simulating solid-state systems

Prime example: **Optical lattices**

Solid-state Mott insulator (V2O3)  
Ultracold atomic Mott insulator

Quantum simulators can explore *fundamentally new* many-body settings!
Why Rydberg atoms?

Controlled long-range interactions

Neutral ground state atoms – state of the art:
- Feshbach tunable contact interactions
- Weak magnetic dipolar interactions

Rydberg atoms:
- Strong dipolar interactions
- Interactions laser controlled and state selective
- Designable spatial dependence

Applications in Q-simulation, Q-information and Q-metrology!
Examples of Rydberg Q-sim experiments

Excitation transport

\textit{Günter}, Science 2013

Spin chain dynamics

\textit{Barredo}, PRL 2015

Dissipative systems

\textit{Malossi}, PRL 2014

Rydberg crystals

\textit{Schauß}, Science 2015

Note: List not complete
Outline

One lonely excitation: *A scalable superatom*

Multiple excitations: *Dynamics and spatial order*

Ground state physics: *Dynamical crystallization*

The future: *Rydberg dressing*
The setting

Single 2d sample
Uniform laser coupling
In-situ detection
The machine

Laser table

Main table

Pictures: C. Lünig
The experimental setup

- Prepare atoms in single 2d plane
- Engineer initial density distribution
- Rydberg excitation
- Image the atoms

*Sherson, Nature 2010*
Site resolved imaging of ground state atoms

- Freeze the atomic distribution
  (ramp lattices to ~300 μK)
Site resolved imaging of ground state atoms

- Freeze the atomic distribution (ramp lattices to \( \sim 300 \, \mu \text{K} \))

- Use laser cooling (molasses) to
  - induce fluorescence
  - cool the atoms
Site resolved imaging of ground state atoms

- Freeze the atomic distribution (ramp lattices to ~300 μK)
- Use laser cooling (molasses) to
  - induce fluorescence
  - cool the atoms

Imaging of Rydberg atoms: Be patient for a few more slides ...
Local control of the atoms

- Focus laser beam on selected sites
- Use **microwave** to drive the spin flip

*Weitenberg*, Nature 2011
Writing atomic patterns

Digital mirror device (DMD)

to objective and atoms
Writing atomic patterns

Digital mirror device (DMD) to objective and atoms

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Ultimate initial state control

Engineering the density distribution

Initial Mott insulator

DMD mask
Ultimate initial state control

Engineering the density distribution

Initial Mott insulator

DMD mask

An atom cookie
Ultimate initial state control

Engineering the density distribution

- Initial Mott insulator
- DMD mask
- An atom cookie

- Precisely defined edge
- Total atom number 6dB below shot-noise

![Probability Distribution Graph]

--

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Hannover, November 2016
Rydberg superatoms

J. Zeiher, P. Schauß, S. Hild, T. Macrì, I. Bloch, and C. Gross,
A “normal” atom (0.5 μm)
A “normal” atom (0.5 μm)
A Rydberg atom (250 μm)
Rydberg atoms

Highly excited atoms

- Hydrogen-like wavefunction $E_{nlj} = -\frac{\text{Ry}}{(n - \delta_{lj}(n))^2}$

*Saffman*, Rev. Mod. Phys. 2010
Rydberg atoms

Highly excited atoms

- Hydrogen-like wavefunction
  \[ E_{nlj} = - \frac{\text{Ry}}{(n - \delta_{lj}(n))^2} \]

- Extreme interactions (huge polarizability)
  
  (van der Waals: \( V = \frac{C_6}{r^6} \))
  (dipole-dipole: \( V = \frac{C_3}{r^3} \))

Saffman, Rev. Mod. Phys. 2010
Rydberg atoms

Highly excited atoms

- Hydrogen-like wavefunction: \[ E_{nlj} = -\frac{\text{Ry}}{(n-\delta_l(n))^2} \]

- Extreme interactions (huge polarizability)
  (van der Waals: \( V = \frac{C_6}{r^6} \) dipole-dipole: \( V = \frac{C_3}{r^3} \))

\[ \text{Tunability!} \]

\[ C_6 \propto n^{11} \]

\[ \tau \propto n^2 \]

\[ \tau \approx 40 \text{ \( \mu \)s \@ \( n = 40 \) } \]

**Saffman**, Rev. Mod. Phys. 2010
The dipole blockade

Two photon laser coupling

Laser parameters:

- Rabi frequency: $\Omega = \frac{\Omega_1 \Omega_2}{2\delta}$
- Detuning $\Delta$

The dipole blockade

Two photon laser coupling

Laser parameters:

- Rabi frequency: $\Omega = \frac{\Omega_1 \Omega_2}{2\delta}$
- Detuning $\Delta$

Interaction exceeds all relevant energy scales on $\mu$m scales!

Blockade radius: $R_b = \sqrt[6]{C_6/\hbar\Omega}$

Jaksch, PRL 2000 | Lukin, PRL 2001
Driving a superatom

- **Extreme nonlinearity:** At most one excitation
- **Symmetry!**
- **Coupling to W-state**

\[
|W\rangle = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} |g_1, g_2, \ldots, r_i, \ldots, g_N\rangle
\]

 christian gross, mpq
Driving a superatom

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- **Coupling to W-state**

\[ |W\rangle = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} |g_1, g_2, \ldots, r_i, \ldots, g_N\rangle \]

**Signature of a superatom**

\[
\Omega_W = \langle G | \hat{d} | W \rangle \frac{E}{\hbar} \\
= \frac{1}{\sqrt{N}} \sum_{i=1}^{N} \langle g_1, \ldots, g_N | \hat{d} | g_1, g_2, \ldots, r_i, \ldots, g_N \rangle \frac{E}{\hbar} \\
= \sqrt{N} \Omega \\
\Rightarrow \sqrt{N} \text{ – scaling of the Rabi frequency} \]
Many experiments already ... 

Paris  
(Browaeys, Grangier) 

Atlanta  
(Kuzmich) 

Madison  
(Saffman) 

Gaetan, Nat. Phys. 2009 

Dudin, Nat. Phys. 2012 

Ebert, PRL 2014
Imaging single Rydberg atoms

Quantum gas microscope
Imaging single Rydberg atoms

Quantum gas microscope

Coupling

nS
480nm
5P_{3/2}
780nm
5S_{1/2}
Imaging single Rydberg atoms

Quantum gas microscope

Coupling

- nS
- 480 nm
- 5P_{3/2}
- 780 nm
- 5S_{1/2}

Blowout

- nS
- 5P_{3/2}
- 780 nm
- 5S_{1/2}
Imaging single Rydberg atoms

Quantum gas microscope

Coupling

\[ \text{5S}_{1/2} \rightarrow \text{5P}_{3/2} \, 780\text{nm} \]

\[ \text{nS} \rightarrow \text{5S}_{1/2} \, 480\text{nm} \]

Blowout

\[ \text{5S}_{1/2} \rightarrow \text{5P}_{3/2} \, 780\text{nm} \]

\[ \text{5P}_{3/2} \rightarrow \text{nS} \, 480\text{nm} \]

De-pumping

\[ \text{5S}_{1/2} \rightarrow \text{5S}_{1/2} \]

\[ \text{5P}_{3/2} \rightarrow \text{5S}_{1/2} \]

Detection efficiency: 65%
Rabi oscillations

1 atom
Rabi oscillations

![Graph showing Rabi oscillations with 1 atom and 8 atoms.](image)

1 atom
8 atoms
Rabi oscillations

![Graph showing Rabi oscillations with probability on the y-axis and time (µs) on the x-axis. The graphs compare the behavior of 1 atom, 8 atoms, and 18 atoms.](image)

- 1 atom
- 8 atoms
- 18 atoms
Rabi oscillations

1 atom
8 atoms
18 atoms
41 atoms
Rabi oscillations

1 atom
8 atoms
18 atoms
41 atoms
85 atoms
Rabi oscillations

![Graph showing Rabi oscillations with different probability over time for 1 atom, 8 atoms, 18 atoms, 41 atoms, 85 atoms, and 130 atoms.]

- 1 atom
- 8 atoms
- 18 atoms
- 41 atoms
- 85 atoms
- 130 atoms
Rabi oscillations

![Graph showing Rabi oscillations for different numbers of atoms: 1 atom, 8 atoms, 18 atoms, 41 atoms, 85 atoms, 130 atoms, 186 atoms.](image)

- 1 atom
- 8 atoms
- 18 atoms
- 41 atoms
- 85 atoms
- 130 atoms
- 186 atoms
Scaling the superatom

- Fitted exponent $0.48 \pm 0.10$
- W-state scaling between 1 and 190 atoms
Breaking the dipole blockade

Largest system 15x15 sites (186 atoms)

- Decay time: 0.34μs
Breaking the dipole blockade

Largest system 15x15 sites (186 atoms)

- Decay time: 0.34μs

Double Rydberg events
Breaking the dipole blockade

Largest system 15x15 sites (186 atoms)
  - Decay time: 0.34μs

Only single Rydberg events
  - Decay time: 0.91μs

Double Rydberg events
Exploring the transverse Ising Model with long-range interactions

Seriously breaking the blockade

Let's drive Rabi oscillations….
Frozen gas Rydberg physics

Dynamics on sub-μs timescales → no atomic motion

\[ \hat{H} = \hbar \frac{\Omega}{2} \sum_i \left( |r\rangle \langle g|^{(i)} + |g\rangle \langle r|^{(i)} \right) - \hbar \Delta \sum_i \hat{n}_r^{(i)} + \sum_{i \neq j} \frac{V_{ij}}{2} \hat{n}_r^{(i)} \hat{n}_r^{(j)} \]
Long-range interacting transverse Ising model

\[ \hat{H} = \hbar \frac{\Omega}{2} \sum_i \left( |r\rangle \langle g|^{(i)} + |g\rangle \langle r|^{(i)} \right) - \hbar \Delta \sum_i \hat{n}_r^{(i)} + \sum_{i \neq j} \frac{V_{ij}}{2} \hat{n}_r^{(i)} \hat{n}_r^{(j)} \]

\[ \hat{H} = \hbar \Omega \sum_i \hat{S}_x^{(i)} + \left( \mathcal{H} - \hbar \Delta \right) \sum_i \hat{S}_z^{(i)} + \sum_{i \neq j} \frac{V_{ij}}{2} \hat{S}_z^{(i)} \hat{S}_z^{(j)} \]
A closer look to the data

Superposition of different many-body states

Energy

43S_{1/2}

5S_{1/2}

Ω, Γ
A closer look to the data

Superposition of different many-body states
Emerging spatial order

Post select according to the number of excitations

<table>
<thead>
<tr>
<th>$n_e = 2$</th>
<th>$n_e = 3$</th>
<th>$n_e = 4$</th>
<th>$n_e = 5$</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Single shot" /></td>
<td><img src="image2.png" alt="Single shot" /></td>
<td><img src="image3.png" alt="Single shot" /></td>
<td><img src="image4.png" alt="Single shot" /></td>
</tr>
<tr>
<td><img src="image5.png" alt="Ensemble" /></td>
<td><img src="image6.png" alt="Ensemble" /></td>
<td><img src="image7.png" alt="Ensemble" /></td>
<td><img src="image8.png" alt="Ensemble" /></td>
</tr>
</tbody>
</table>
## Emerging spatial order

Post select according to the number of excitations

<table>
<thead>
<tr>
<th>$n_e$</th>
<th>Single shot</th>
<th>Ensemble</th>
<th>Ensemble aligned</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
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<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
<tr>
<td>4</td>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
</tr>
<tr>
<td>5</td>
<td><img src="image13.png" alt="Image" /></td>
<td><img src="image14.png" alt="Image" /></td>
<td><img src="image15.png" alt="Image" /></td>
<td><img src="image16.png" alt="Image" /></td>
</tr>
</tbody>
</table>
The blockade radius

Distance correlations between Rydberg atoms

\[ g^{(2)}(r) = \frac{\sum_{i \neq j} \delta_{r, r_{ij}} \langle n_i n_j \rangle}{\sum_{i \neq j} \delta_{r, r_{ij}} \langle n_i \rangle \langle n_j \rangle} \]

Imperfections:

- Hopping during detection: 1%
- Hopping before detection: 0.5\(\mu m\)
- Finite blow out: 0.2 atoms/image
Sweeped excitation: Adiabatic ground-state preparation


The ground state phase diagram

\[ \hat{H} = \hbar \Omega \sum_i \hat{S}_x^{(i)} + (\mathcal{I} - \hbar \Delta) \sum_i \hat{S}_z^{(i)} + \sum_{i \neq j} \frac{V_{ij}}{2} \hat{S}_z^{(i)} \hat{S}_z^{(j)} \]
Dynamical crystallization

Coherent control of many-body systems through adiabatic sweeps

PRL 104, 043002 (2010)  PHYSICAL REVIEW LETTERS  week ending 29 JANUARY 2010

Dynamical Crystallization in the Dipole Blockade of Ultracold Atoms

T. Pohl,1,2 E. Demler,2,3 and M. D. Lukin2,3

1Max Planck Institute for the Physics of Complex Systems, 01187 Dresden, Germany
2TTAMP-Harvard-Smithsonian Center for Astrophysics, Cambridge Massachusetts 02138, USA
3Physics Department, Harvard University, Cambridge Massachusetts 02138, USA

(Received 26 July 2009; revised manuscript received 23 October 2009; published 27 January 2010)
Tracking the crystallization

![Diagram showing the crystallization process with parameters such as Detuning, Δ/2π, and Rabi frequency, Ω/2π, on the x-axis and y-axis respectively. The excitation number is indicated on the right side of the diagram.](image)

1D chains
Tracking the crystallization

1D chains

Detuning, $\Delta/2\pi$ (kHz)

Rabi frequency, $\Omega/2\pi$ (kHz)

Excitation number

Exc. probability

Position
Tracking the crystallization

2D chains

Excitation number

Detuning, $\Delta/2\pi$ (kHz)

Rabi frequency, $\Omega/2\pi$ (kHz)

Exc. probability

Position

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Tracking the crystallization

1D chains
1D Rydberg chains: Different lengths

Goal: measure crystal compressibility \( \chi = \frac{\partial n_e}{\partial \Delta} \propto \frac{\partial n_e}{\partial \ell} \)

- Excitations vs. detuning: \( N_e \propto \sqrt[6]{\Delta} \)
- Excitations vs. length: \( N_e \propto \ell \)
1D Rydberg chains: Different lengths

Goal: measure crystal compressibility \( \chi = \frac{\partial n_e}{\partial \Delta} \propto \frac{\partial n_e}{\partial \ell} \)

- Excitations vs. detuning: \( N_e \propto \sqrt[6]{\Delta} \)
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DMD cutting:
Keep 3xN sites
1D Rydberg chains: Different lengths

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- Excitations vs. length: \( N_e \propto \ell \)

DMD cutting:
Keep 3xN sites
Rydberg crystals – compressibility

Rydberg excitation number vs. chain length
Rydberg crystals – compressibility

Rydberg excitition number vs. chain length

- **Plateaus** of equal height
  - Vanishing compressibility on the plateaus
2D Rydberg crystals

Swept excitation localizes the excitations!

No sweep  
Sweep, small cloud  
Sweep, large cloud
2D Rydberg crystals

Swept excitation localizes the excitations!

No sweep | Sweep, small cloud | Sweep, large cloud

Some single shots
2D Rydberg crystals

Some single shots
The future: Rydberg dressing

New directions for quantum simulations

Flexible spin models
Glaetzle, PRL 2015 | van Bijnen, PRL 2015

Supersolids
Henkel, PRL 2010 | Pupillo, PRL 2010 | ...

And more:

Dipolar Fermions
Dauphin, PRA 2012 | Xiong, PRA 2014 | Li, Nat. Comm. 2015

Quantum metrology
Bouchoule, PRA 2002 | Gil, PRL 2014
Rydberg dressing concepts

Admix a little bit of Rydberg to the ground state

\[ 1g > \sim 1 r > = 1g > + \frac{\Omega}{2\Delta} 1 r > \]

Admixture \( \epsilon = \Omega / 2\Delta \)

Lifetime \( \tau = \tau_R / \epsilon^2 \)

Interaction \( V_0 = \Omega^4 / 8\Delta^3 \)

Rydberg dressing concepts

Admix a little bit of Rydberg to the ground state

Admixture $\epsilon = \Omega / 2\Delta$

Lifetime $\tau = \tau_R / \epsilon^2$

Interaction $V_0 = \Omega^4 / 8\Delta^3$

Requires high Rabi frequency!
Rydberg dressing concepts

Admix a little bit of Rydberg to the ground state

\[ |1g\rangle \rightarrow |1g\rangle + \frac{\Omega}{2\Delta} |r\rangle \]

Admixture: \[ \epsilon = \frac{\Omega}{2\Delta} \]

Lifetime: \[ \tau = \frac{\tau_R}{\epsilon^2} \]

Interaction: \[ V_0 = \frac{\Omega^4}{8\Delta^3} \]

Direct UV coupling!

Requires high Rabi frequency!

Revealing the interaction potential

Probing via Ramsey interferometry

- At short times: phase \( \sim \) interactions
- Directly “image” the dressing potential

\[ |\uparrow\rangle \text{ state feels pair potential} \]

**Ising Hamiltonian**

\[
\hat{H} = \sum_{i,j,(i\neq j)} \frac{V_{ij}}{2} \hat{S}_i^z \hat{S}_j^z + \sum_i [\mathcal{I}_i + V_{iLS}^i] \hat{S}_i^z
\]
Rydberg dressing – first signs

PRELIMINARY
Rydberg dressing – first signs

Dressing time (μs) 1/V₀ ≈ 500 μs

Inducing a long range potential works!
Summary

- Scalable superatoms
- Multiple excitations → Dynamics
- Rydberg crystals
- Rydberg dressing → First steps

The team

T. Yefsah  J. Zeiher  S. Hild
J.-Y. Choi  S. Hollerith  I. Bloch
P. Schauß  T. Fukuhara  M. Cheneau
R.v.Bijnen  T. Pohl
Starting 2016: RyD-QMB

(= Rydberg dressed quantum many-body physics)

Developing a new Q-sim platform: Rydberg dressing with potassium

Goals:

Flexible spin models
Glaetzle, PRL 2015 | van Bijnen, PRL 2015

Supersolids
Henkel, PRL 2010 | Pupillo, PRL 2010 | ...
Starting 2016: RyD-QMB

(= Rydberg dressed quantum many-body physics)

Flexible spin models
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Interested in a PhD project?
Contact me!