Many-Body Interactions in a Restricted Dimensionality Sample of Ultracold Rydberg Atoms

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Ultracold Highly-Excited Atoms

Resonant exchange of internal energy between atoms in a nearly frozen Rydberg gas

Atomic beam: Atoms exchange energy through the dipole-dipole interaction in binary collisions

Ultracold sample: Many-body phenomena play an important role in the nearly frozen sample

Ultracold Plasmas

Direct photoionization of the ultracold sample

Spontaneous evolution from ultracold Rydberg atoms to an ultracold plasma
Resonant Rydberg-Rydberg Collisions

\[ ns + ns \rightarrow np + (n - 1)p \]


Spectroscopic resolution scales with speed (interaction time) \( \sim v^{3/2} \)

Transform limited collisions, interaction time less than collision time

Orientation dependence and intracollisional interference
Ultracold Rydberg-Rydberg interactions

Anderson et. al. PRL 80 249 (1998)
Mourachko et. al. PRL 80 253 (1998)

Average atom spacings ~ 10 μm
Typical velocities ~ 40 cm/s
Interaction strength ~0.25 MHz
The many-body interaction

\[ s + s' = p + p' \]
\[ s + p = p + s \]
\[ s' + p' = p' + s' \]

\[ V = \frac{\mu \mu'}{r^3} \] resonant at a specific static field

\[ \gamma = \frac{\mu^2}{r^3} \] always resonant

\[ \Gamma = \frac{\mu'^2}{r^3} \]

Anderson et. al. PRL 80 249 (1998)
Controlling Many-Body Interactions

Mourachko et. al. PRA 70, 031401(R) (2004)
4 Field wire voltages are set to provide the electric field at the trap.

Field Ionization pulse applied to left pair of wires.
resonant dipole-dipole interaction

Energy vs. Field (V/cm)

34p: j=3/2, mj=1/2
j=3/2, mj=3/2
j=1/2, mj=1/2

32d: j=5/2, mj=1/2
j=5/2, mj=3/2
j=5/2, mj=5/2
j=3/2, mj=1/2
j=3/2, mj=3/2

l=20, j= 21/2 mj=1/2
n=30

Field (V/cm)

Signal Strength (arb.)

Time (ns)

34p Signal
32d Signal

Quantum computing

Many-body effects can be enhanced by tailoring the mixture of Rydberg states excited

interaction strength = 0.10

volume is long (500 m)

interaction strength = 0.15

Since the beam waist is close to

interaction strength = 0.20

Volume is long (500 m)

limited to a maximum of 9 atoms

Interaction strength = 0.25 MHz

Typical velocities ~ 40 cm/s

Interaction strength ~ 0.25 MHz

Transform limited collisions, interaction time less than collision time

M. J. Renn and T. F. Gallagher, PRL

spectroscopic resolution scales with speed (interaction time) ~

D. S. Thompson, et. al. PRL

Ultracold Rydberg-Rydberg interactions

Interaction strength ~ 0.25 MHz

The many-body interaction

V = 1/70/r

Anderson et. al. PRL 80, 70, 031401(R) (2004)
Dipole orientation

- Static voltage on each wire to create electric field (E)
- HV pulse applied to back pair of wires
- Electrons pushed to detector

- Dipoles are randomly located within the volume of the beam
- Volume is long (500 µm) and thin (~10 µm)
- Since the beam waist is close to the interatomic spacing, the excited sample is nearly one dimensional.

\[ V = \frac{\mu \cdot \mu' - 3(\mu \cdot \hat{r})(\mu' \cdot \hat{r})}{r^3} \]
Dipole orientation

**Graph 1:**
- y-axis: 34p Fraction
- x-axis: Field (V/cm)
- Green line: 90°
- Black line: 45°

**Graph 2:**
- y-axis: relative interaction strength (arb.)
- x-axis: angle (deg.)
Many-body effects play an important role in the exchange of energy among atoms in an ultracold Rydberg gas. Ultracold highly-excited atoms can be manipulated by changing the spatial arrangement of atoms.

**Interaction strength**

\[
\text{interaction strength} = \frac{33\text{p integrated signal}}{31\text{d} + 33\text{p integrated signal}}
\]

**Experiment**

- **Varying Dimension and Density**
  - 60 atoms for \(L = 500 \mu \text{m}\)
  - 30 atoms for \(L = 500 \mu \text{m}\)
  - \(r = 20 \mu \text{m}\)
  - \(r = 6.5 \mu \text{m}\)

**Data**

- Graph showing interaction strength vs. field (V/cm)
- Data points
- Background

**Additional Notes**

- Interaction strength is approximately \(0.25 \text{ MHz}\).
- Typical velocities are \(40 \text{ cm/s}\).
- Transform limited collisions, interaction time less than collision time.
Data

- Data is binned by number of Rydberg atoms

- number calibration from:

  trap density $X$ excited volume $X$ excitation prob.
Many-body interactions in a cold sample can be controlled by tailoring the mixture of Rydberg states excited. Build Rydberg atom clusters and crystals in which each atom is precisely positioned. The many-body interaction strength is given by:

\[ \gamma = \frac{V_2}{r^3} \]

where \( V_2 \) is the interaction strength, typically resonant dipole-dipole interaction. Transformed limited collisions, interaction time less than collision time.

Varied dimension and density, controlling many-body interactions. Time dependence.

Field ionization pulse applied to left pair of wires. Field wire voltages are set to provide the ion volume. Laser and detector used for excitation probabilistic.

For example, a cold sample with 30 atoms for \( L = 500 \mu m \) and 60 atoms for \( L = 500 \mu m \).

In 1D, for a beam waist of 19 \( \mu m \), the interaction strength is varied from 0.02 to 0.32.

In 2D, for an interatomic spacing of \( 10 \mu m \), interaction strength is varied from 0.02 to 0.32.

In 3D, the relative interaction strength can be observed.

The graphs show the fractal dimension as a function of the number of atoms, with different colors indicating different radii. The graphs indicate that the fractal dimension increases with the number of atoms, especially for smaller radii.
Simulation

- Diagonalize dipole-dipole interaction matrix and allow atoms to interact

\[
\begin{array}{c}
33 \text{p} \\
31 \text{d} \\
n=29
\end{array}
\]

- atoms are stationary
- spin and angular effects are ignored
- limited to a maximum of 9 atoms
- simulate a 500 \(\mu\)m tube of atoms by dividing into sub-volumes to get higher densities
- calculate probabilities based on centrally placed atom

\[
\begin{array}{c}
\text{field-tuned interaction} \\
\text{always resonant interactions}
\end{array}
\]
Results

Interaction strength vs number of Rydberg atoms for different interatomic spacings and interaction times.

- For $r = 5 \mu m$, the interaction strength increases sharply for the first 20 atoms and then plateaus.
- For $r = 15 \mu m$, the interaction strength increase is smoother and the plateau is reached more gradually.
- For $r = 6.5 \mu m$, the interaction strength increase is even more gradual and the plateau is reached at a lower value.

Similar trends are observed for the interaction strength vs number of Rydberg atoms for interaction times of $t = 5 \mu s$ and $t = 3 \mu s$. The graphs show that the interaction strength increases with the number of Rydberg atoms, with a stronger effect for smaller interatomic spacings and shorter interaction times.

The graphs provide insights into the dynamics of ultracold Rydberg atoms, highlighting the role of interatomic spacing and interaction time in determining the interaction strength and thus the behavior of the system.
Atomic beam: Atoms exchange energy through the dipole-dipole interaction in binary collisions.

Spontaneous evolution from ultracold Rydberg atoms to an ultracold plasma.

V

\[ \mu \]

Resonant Rydberg-Rydberg Collisions

\[ \mu \]

\[ n_r \]

Orientation dependence and intracollisional interference.

Transform limited collisions, interaction time less than collision time.

Gallagher et. al. PRA 58 1905 (1982).

Mourachko 249 (1998)

The many-body interaction

\[ \pi \]

\[ \pi \]

always resonant

Anderson PRL 111.60

Vacuum Chamber

f=115mm.

Trap

rotating filter

\[ n=30 \]

\[ j=1/2, m_j=1/2 \]

\[ 21 \]

Time (ns)

\[ \mu \]

back pair of wires

dimensional.

Since the beam waist is close to 

\[ 10 \]

\[ 34p \]

Fraction

\[ 0.50 \]

\[ 0.02 \]

angle (deg.)

\[ \mu \]

\[ m \]

interaction strength

\[ 100 \]

\[ 60 \]

atoms for 

\[ m \]

\[ 2 \]

field (V/cm)

\[ 30 \]

atoms for 

\[ m \]

\[ 33 \]

\[ 31 \]

d

interaction

\[ 0.04 \]

\[ 0.12 \]

\[ 0.30 \]

\[ 20 \]

\[ 600 \]

\[ 6 \]

\[ 25 \]

\[ 60 \]

\[ 200 \]

\[ 25 \]

\[ 175 \]

\[ 10 \]

\[ 600 \]

\[ 6 \]

Dimensionality

\[ 125 \]

\[ 50 \]

\[ 32d \]

→

Data

Many-body effects can be enhanced by tailoring the mixture of Rydberg states excited.

Build Rydberg atoms clusters and crystals in which each atom is precisely positioned.

Plotting a graph showing the time dependence of the interaction strength for 3D and 1D systems. The x-axis represents the number of Rydberg atoms, and the y-axis represents the interaction time. The color scale represents the interaction strength (fraction of Rydberg atoms interacting).
Time Dependence

Number of Rydberg atoms vs. interaction time for 3D and 1D systems. 

30 atoms and 60 atoms graphs show interaction strength vs. time for 1D and 3D systems.
Conclusions

Many-body effects play an important role in the exchange of energy among atoms in an ultra-cold sample.

Many-body effects can be enhanced by tailoring the mixture of Rydberg states excited.

Many-body effects can also be manipulated by changing the spatial arrangement of atoms.

Future Directions

Build Rydberg atoms clusters and crystals in which each atom is precisely positioned.

Quantum computing.
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Ultracold Plasmas

Dimensionality

Graph showing interaction strength vs. interatomic spacing for different radii and times.

\[ \Gamma = \frac{V}{r^3} \]

Varying Dimension and Density

Future Directions

Quantum computing
Results