Interactions Between Pairs Of Cs Rydberg Atoms

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Outline

• Pair Interactions
• Experimental Apparatus
• Time-of-Flight Velocity Distributions
• Photo-Initiated Collision Measurement
• Macrodimer Measurements
Rydberg Atom Pair Interactions

- Interesting for a variety of reasons
  - Resonant energy transfer
  - Dipole Blockade
  - Exotic states of matter
    - *Macrodimers*
- Requires detailed knowledge of Pair interaction potentials
Calculations by Matrix Diagonalization

- Includes dipole and quadrupole contributions
- Diagonalized in the Stark shifted basis with $E \parallel R$
  
  Thanks Arne!

$$V(R, r_{1A}, r_{2B}) = \sum_{L_1, L_2 = 1}^{N} \sum_{M = -L}^{L} \frac{(-1)^{L_2} f_{L_1 L_2 M}}{R^{L_1 + L_2 + 1}} Q_{L_1 M}(r_{1A}) Q_{L_2 - M}(r_{2B})$$

where the multipole operator is

$$Q_{LM}(r) = \left\{ \frac{4\pi}{2L + 1} \right\}^{1/2} r^L Y_{LM}(\vec{r})$$

and

$$f_{L_1 L_2 M} = \frac{(L_1 + L_2)!}{[(L_1 + M)!(L_1 - M)!(L_2 + M)!(L_2 - M)]^2}$$


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E-Fields and Avoided Crossings

- Electric fields have a strong influence on avoided crossings
  - Existence of wells depends on $E$
  - Pairs may be bound or dissociative
  - *Photoinitiated (PI) Collisions*
  - *Macrodimmers*
Experimental Setup

- Time-of-Flight spectrometer
- Centered on Cs MOT
- UHV system (~10^{-10} Torr)
- Z-Stack microchannel plate detector
  - res. x-y: 20µm, z: 500ps
Signals and Timing

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Time-of-Flight Distributions

- Expansion of TOF distribution depends on:
  - *Thermal* velocity
  - Recoil velocity determined by *collision* exit channel
  - *Coulomb repulsion*
Temperature Measurement

- Resolution of spectrometer calibrated using thermal expansion
  - Gaussian distribution
    \[ f(z, t) \propto e^{-mz^24ln2/\Delta z^2} \]
    \[ \Delta z = \sqrt{\Delta z_0^2 + \frac{8ln2k_BT}{m}\tau^2} \]
  - Velocity resolution of 2.5 cm/s
  - Light shift parameter
    \[ \Lambda = \Omega^2/|\delta|\Gamma \]
    \[ T = T_0 + 2 \times C_\sigma T_D \left( \frac{\Omega^2}{|\delta|\Gamma} \right) \]
PI Collisions vs. Macrodimers

- **PI collision** can occur from excitation at a stationary point
  - Collision products gain velocity $v_{\text{coll}}$ determined by the energy of the exit channel

- **Macrodimer** can be excited in a well
  - Excitation with narrow band cw laser light causes $R$ to have *fixed distribution*
  - Vibrational period ($\sim 2 \mu s$) $<$ excitation time ($\sim 5 \mu s$)
Delay Dependence of TOF Distributions

- Coulomb repulsion in TOF identifies pair interaction
  - Expansion at short delay can identify $R$ as constant
  - Expansion at long delay is a direct measure of $v_{\text{coll}}$. 

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PI Collision Measurement

- Pair resonance observed near 89D+89D
  - No prominent well
Pair Identification

(a) 2-photon for 6P→89D
(b) 2-atom from charge pulse height distribution
(c) 2-photon 6S→6P
Exit Velocity Measurements

- Expansion the result of thermal and exit velocities
  - $88D + 90D$ resonance is a collision process.
  - Exit velocity of $17 \pm 3 \text{ cm/s}$

**Graph:**
- $v_{\text{coll}} = 17 \pm 3 \text{ cm/s}$
- $T_{\text{thermal}} = 79 \pm 7 \mu\text{K}$
Choosing n for Molecular States

- Lower principal quantum number advantageous for measurements of Coulomb repulsion for bound states.
  - Lower n → resonances are farther from atomic lines
  - **Pros:**
   - Less atomic background signal
   - Deeper wells
  - **Con:**
   - Less oscillator strength

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Ion Rates and TOF Velocity Distributions

- Ion rate is **quadratic**
- Coulomb repulsion easily resolved from TOF distributions
  - Black: atomic state
  - Red: molecular resonance

\[ \text{Delay} = 38 \ \mu s \]
The red line is a Monte Carlo simulation of collision with thermal velocity recoil.

- Circles are molecule data
- Triangles are atomic data (dashed line is fit to thermal expansion)

\[ \varepsilon = 224 \text{ mV/cm} \]
\[ \varepsilon = 205 \text{ mV/cm} \]
\[ \varepsilon = 190 \text{ mV/cm} \]
\[ \varepsilon = 158 \text{ mV/cm} \]
Future Directions

• Investigate angular distribution of Macrodimers
  – 3D imaging to study applied $E$ spatial dependence

• Measure macrodimer \textit{lifetimes} by observing state distribution of products

• Perform detailed spectroscopy of wells
  – Electric field dependence of wells
The Group

• James Shaffer
  – Arne Schwettmann: contributed calculations of pair interactions
  – Jonathan Tallant: assisted with experiments
  – Donald Boothe: currently assisting Arne with calculations


• K. R. Overstreet, A. Schwettmann, J. Tallant, D. Booth, and J. P. Shaffer, “Observation of Cs Rydberg atom macrodimers” (in submission)

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Pair Excitation

• Near resonant 2-photon transition
  – Excitation rate increased due to proximity to nearest atomic duplicate pair state
  – Pair interact strongly at short $R$ and mixes in $nD$ state character
  – Excitation rate higher for higher $n$