Interactions Between Pairs Of Cs Rydberg Atoms

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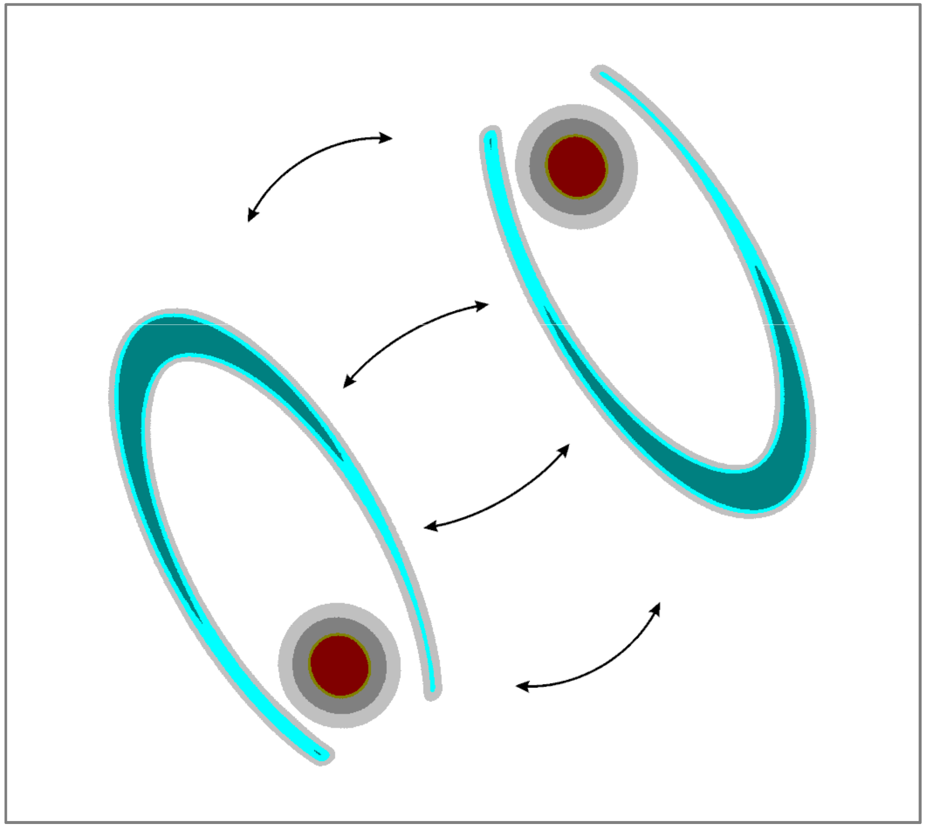
Outline

- 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

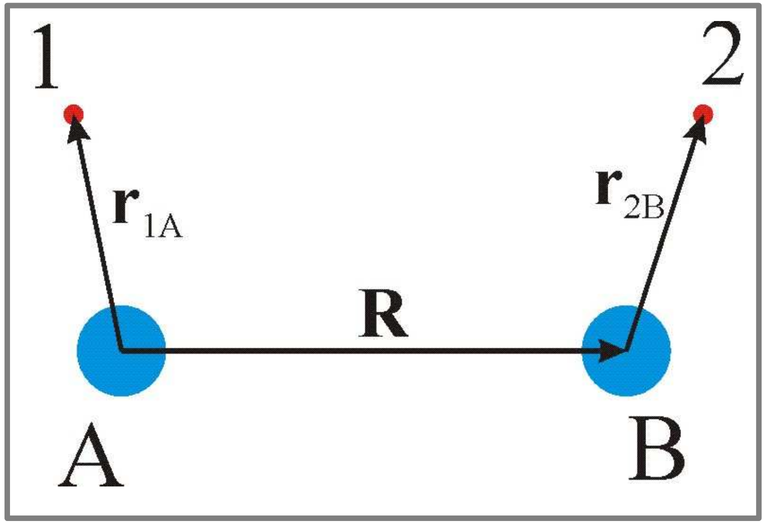
- Includes dipole and quadrupole contributions
- Diagonalized in the Stark shifted basis with $\boldsymbol{E} \parallel R$
  - *Thanks Arne!*

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

where the multipole operator is

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

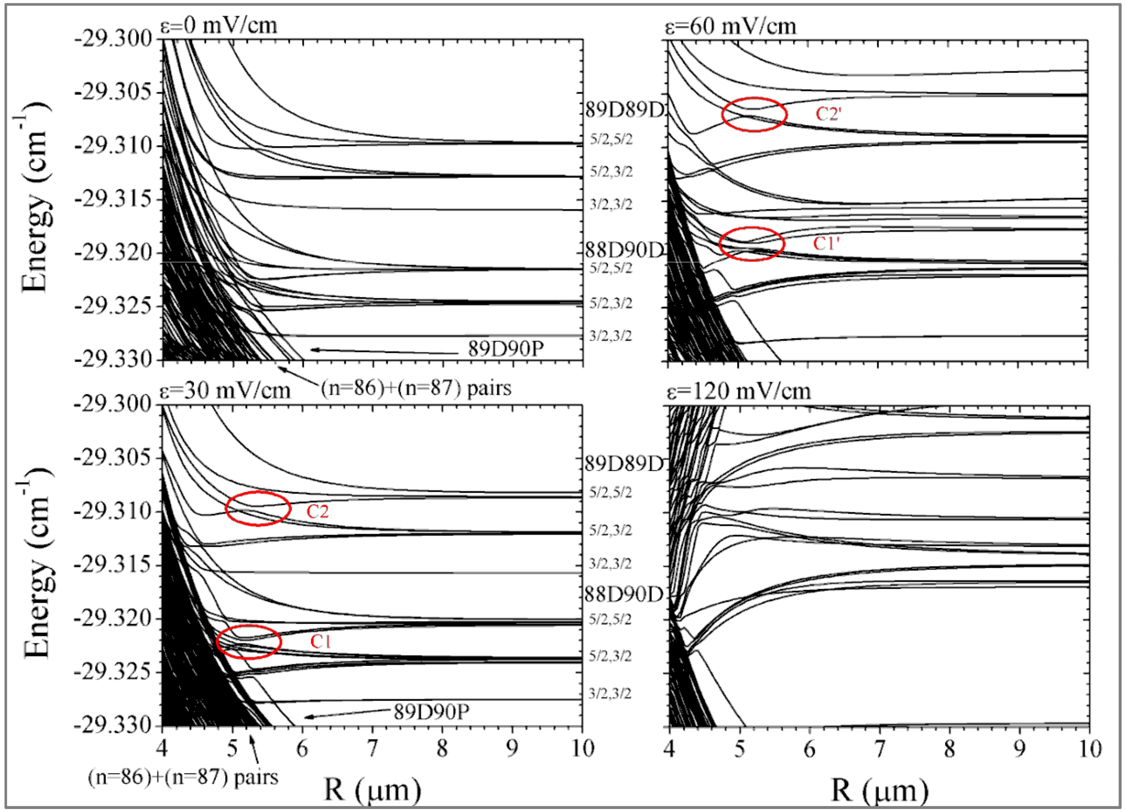
and $f_{L_1 L_2 M} = \dfrac{(L_1 + L_2)!}{[(L_1+M)!(L_1-M)!(L_2+M)!(L_2-M)!]^2}$



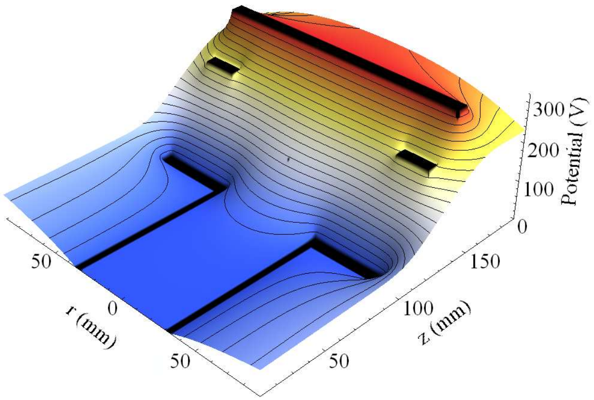
M. R. Flannery, D. Vrinceanu, and V. N. Ostrovsky, J. Phys. B **38**, S279 (2005)

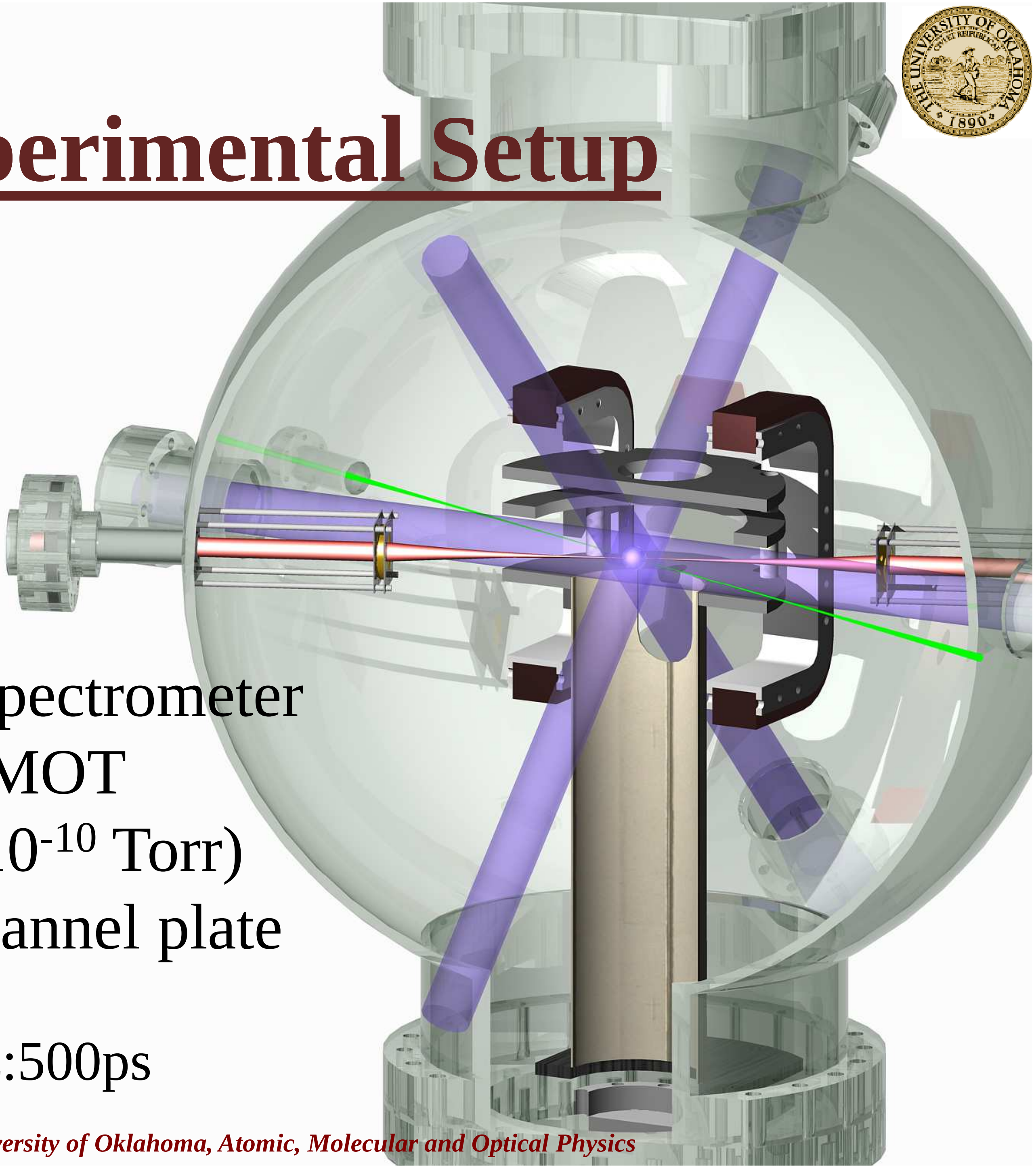
E-Fields and Avoided Crossings

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



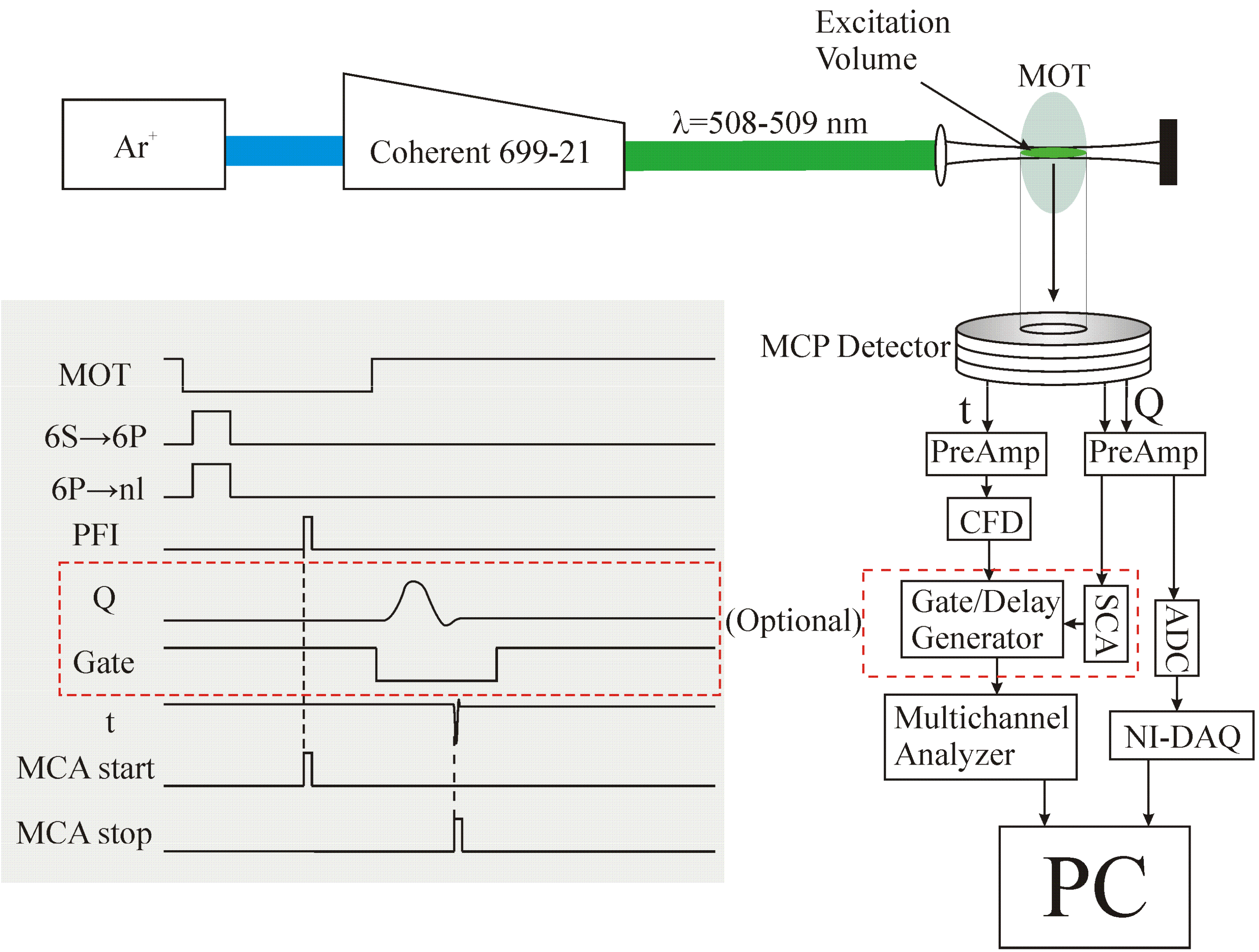
Experimental Setup





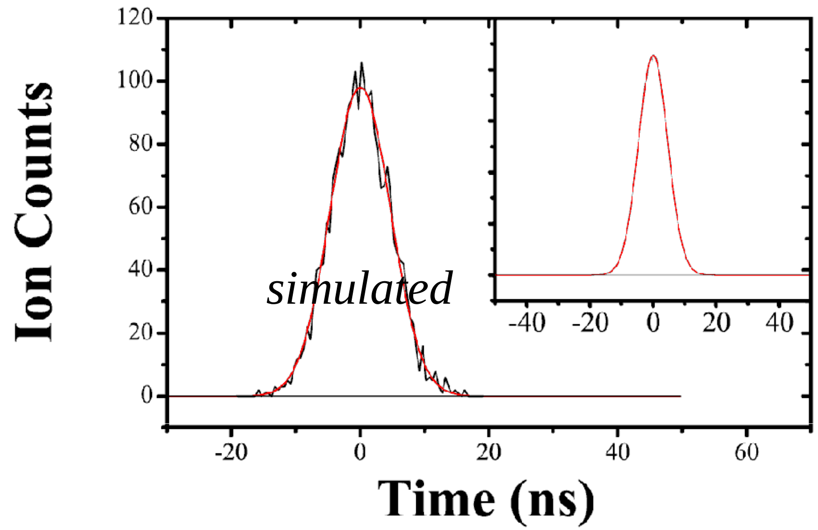
- Time-of-Flight spectrometer
- Centered on Cs MOT
- UHV system (~10^{-10} Torr)
- Z-Stack microchannel plate detector
  – res. x-y:20μm, z:500ps

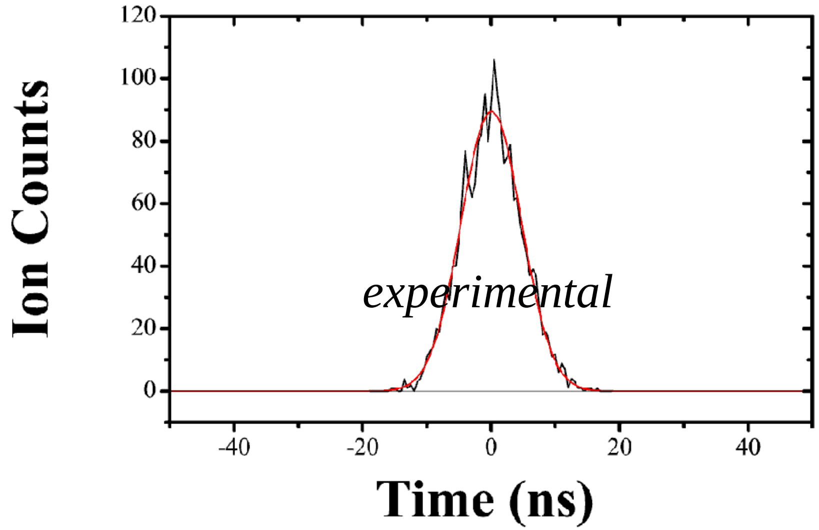
Signals and Timing



Time-of-Flight Distributions

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





Temperature Measurement

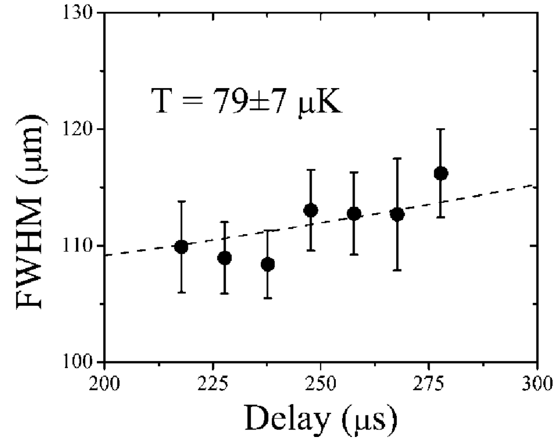
- Resolution of spectrometer calibrated using thermal expansion
  - Gaussian distribution

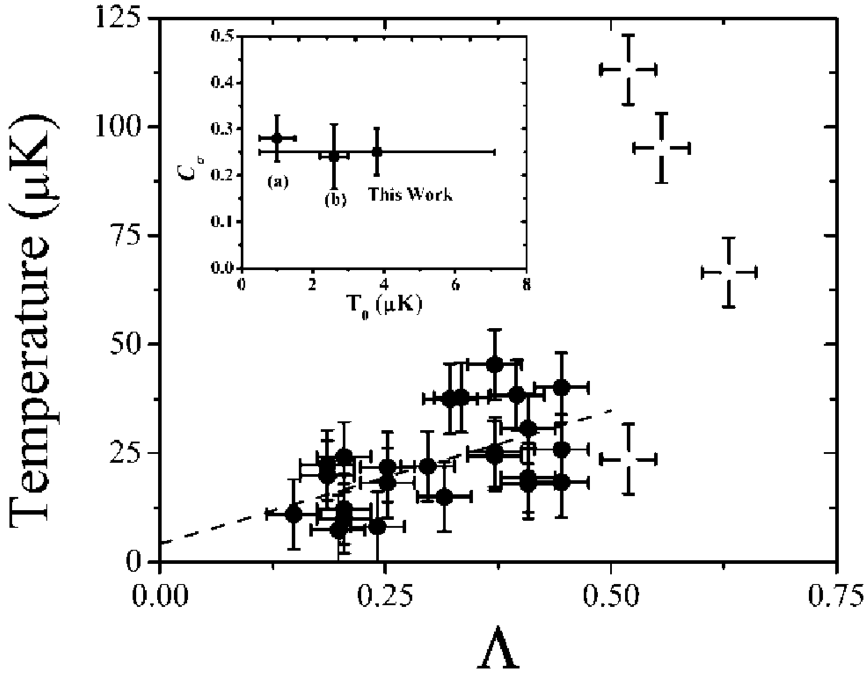
$$f(z,t) \propto e^{-mz^2 4ln2/\Delta z^2}$$

$$\Delta z = \sqrt{\Delta {z_0}^2 + \frac{8ln2k_B T}{m}\tau^2}$$

  - Velocity resolution of ***2.5 cm/s***
  - Light shift parameter $\Lambda = \Omega^2/|\delta|\Gamma$

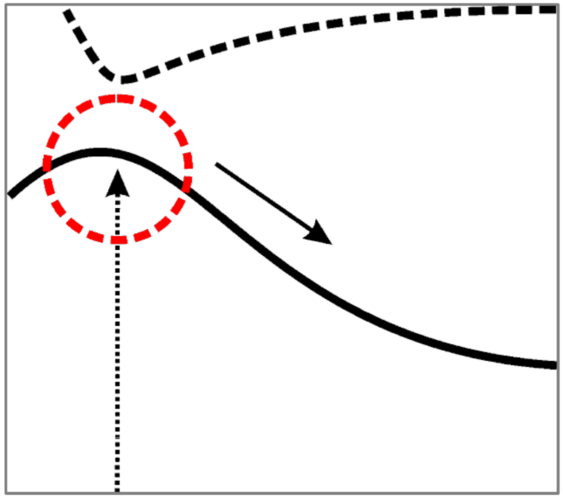
$$T = T_0 + 2 \times C_\sigma T_D \left(\frac{\Omega^2}{|\delta|\Gamma}\right)$$

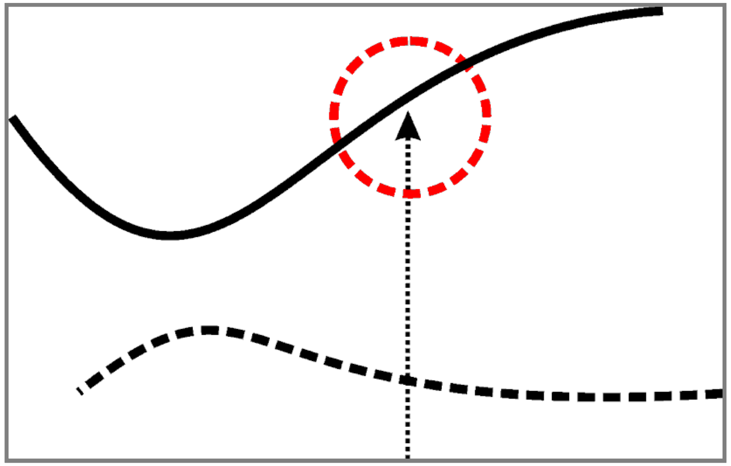




PI Collisions vs. Macrodimers

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

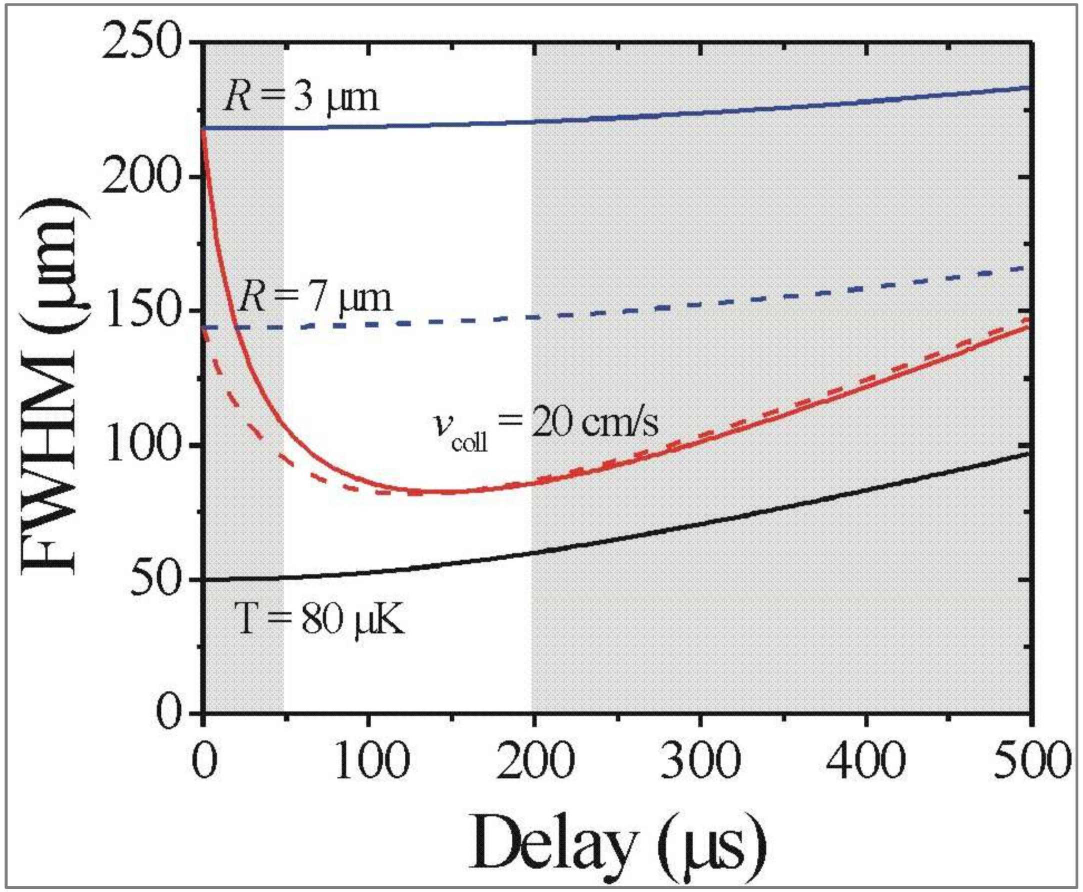




- ***Macrodimer*** can be excited in a well
  - Excitation with narrow band cw laser light causes *R* to have ***fixed distribution***
  - ***Vibrational period (~2 μs) < excitation time (~5 μs)***

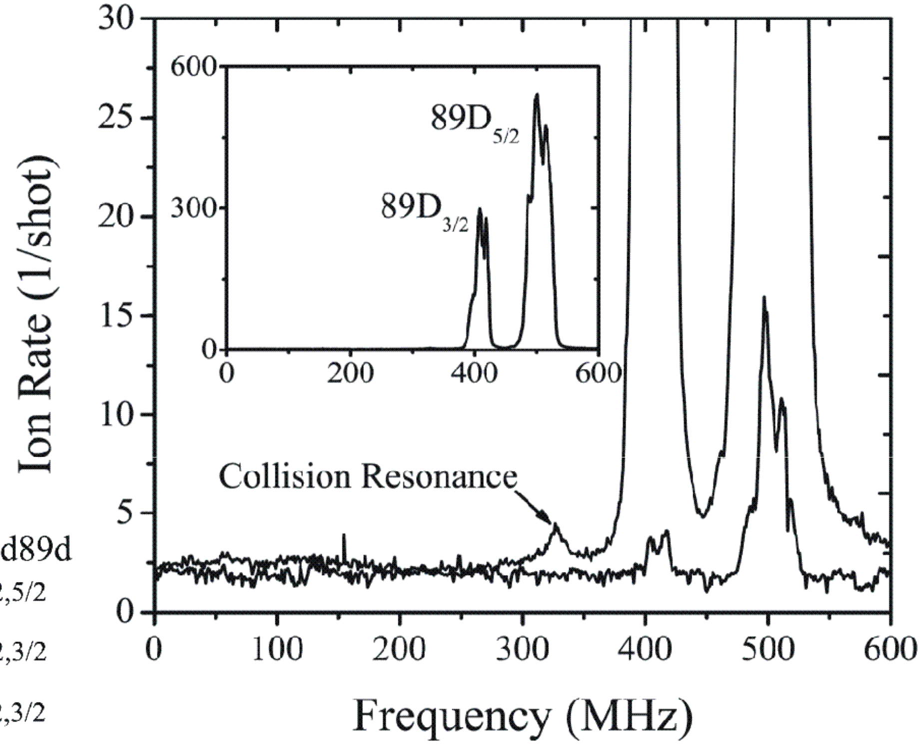
Delay Dependence of TOF Distributions

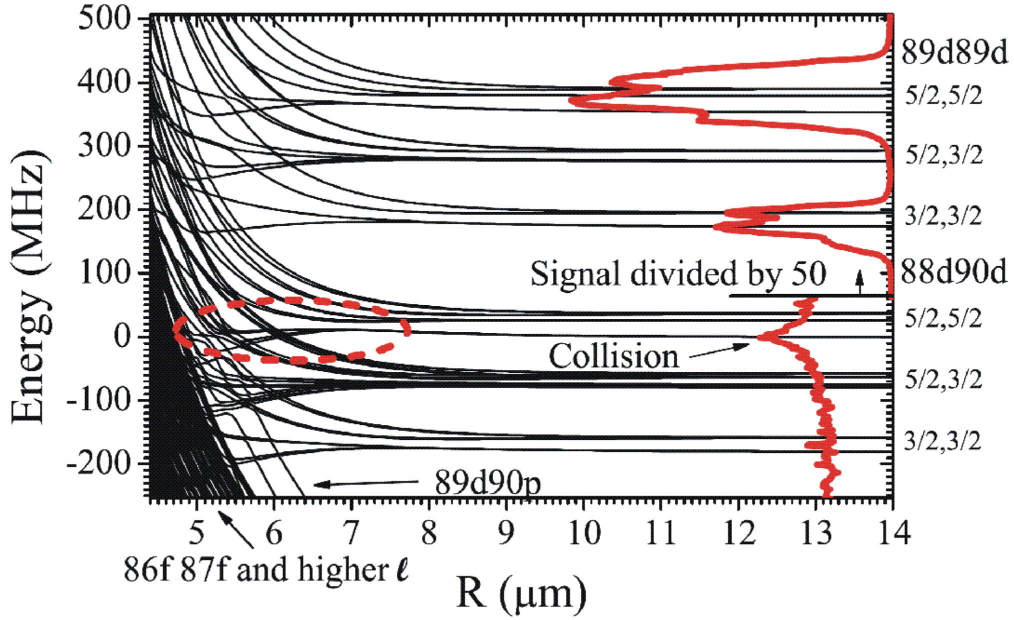
- Coulomb repulsion in TOF identifies pair interaction
  - Expansion at short delay can identify *R* as constant
  - Expansion at long delay is a direct measure of v_{coll}.



PI Collision Measurement

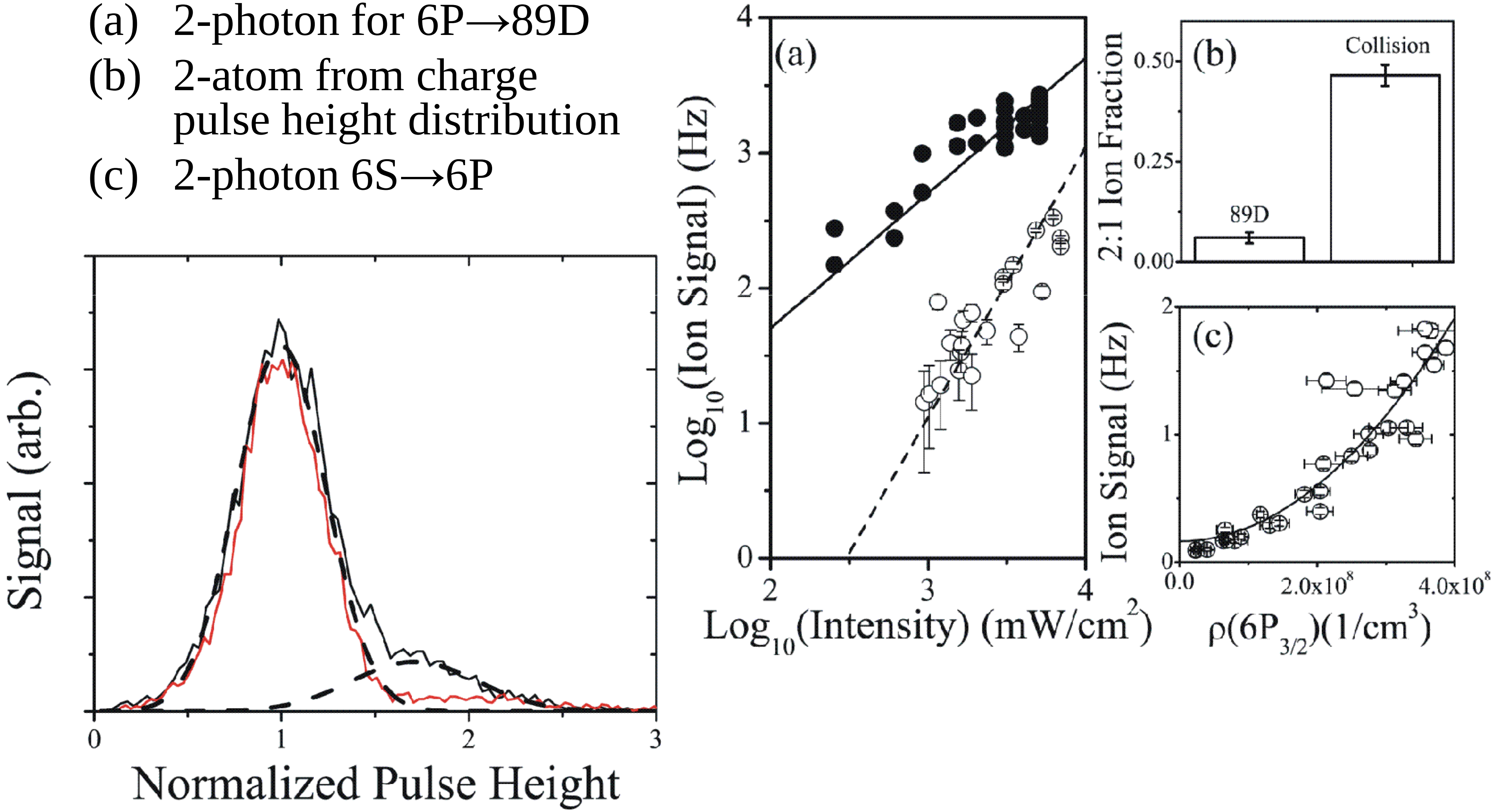
- Pair resonance observed near 89D+89D
  - No prominent well





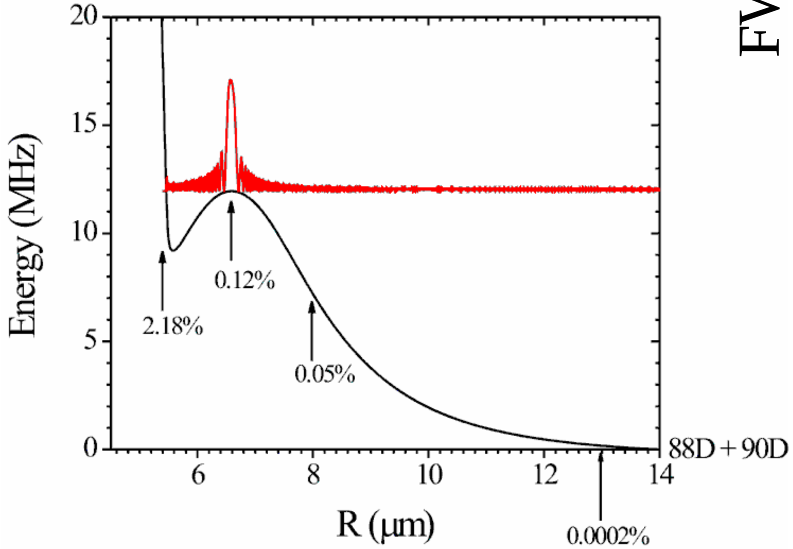
Pair Identification

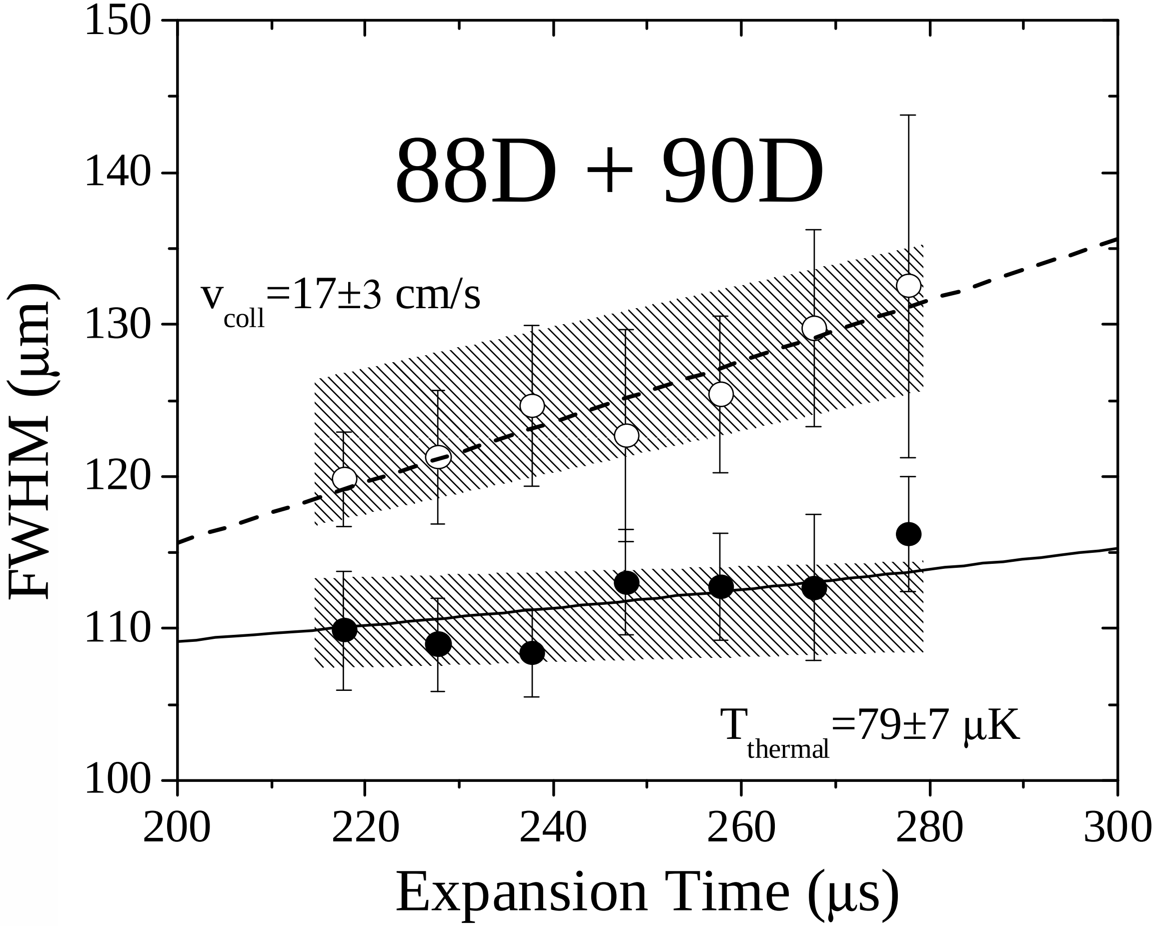
(a) 2-photon for 6P→89D
(b) 2-atom from charge pulse height distribution
(c) 2-photon 6S→6P



Exit Velocity Measurements

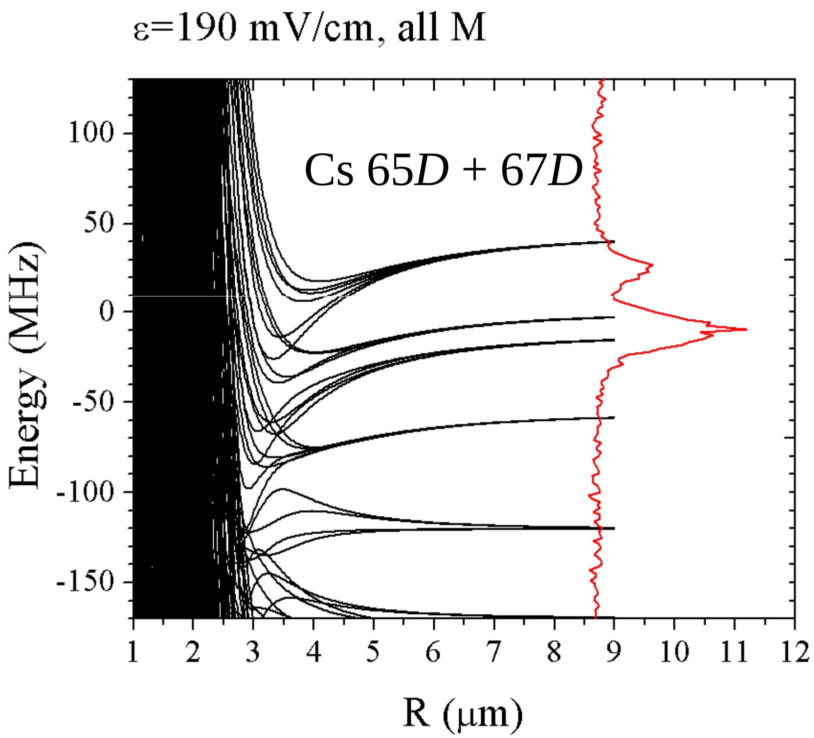
- Expansion the result of thermal and exit velocities
  - 88D + 90D resonance is a ***collision*** process.
  - Exit velocity of ***17±3 cm/s***





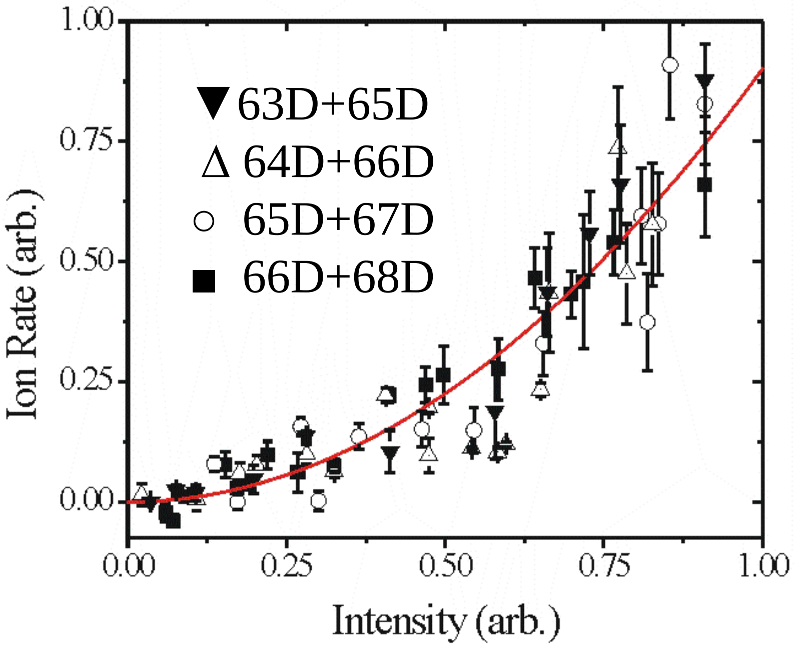
Choosing n for Molecular States

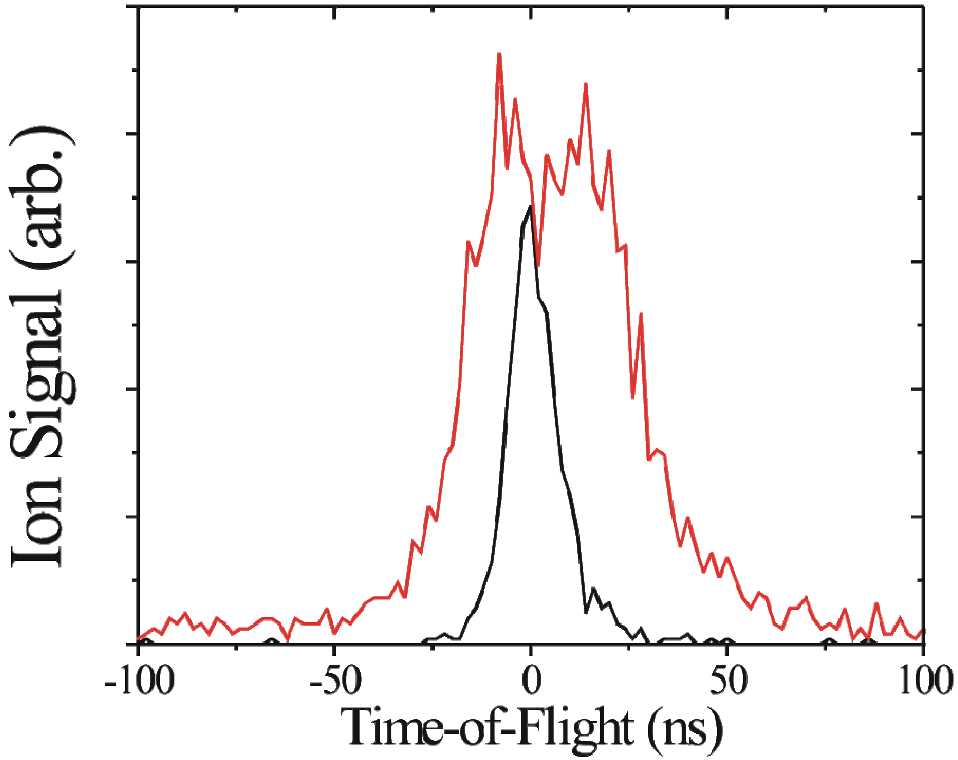
- Lower principal quantum number ***advantageous*** for measurements of Coulomb repulsion for bound states.
  - Lower n → resonances are farther from atomic lines
    - **Pros**:
      - Less atomic background signal
      - Deeper wells
    - **Con**:
      - Less oscillator strength



Ion Rates and TOF Velocity Distributions

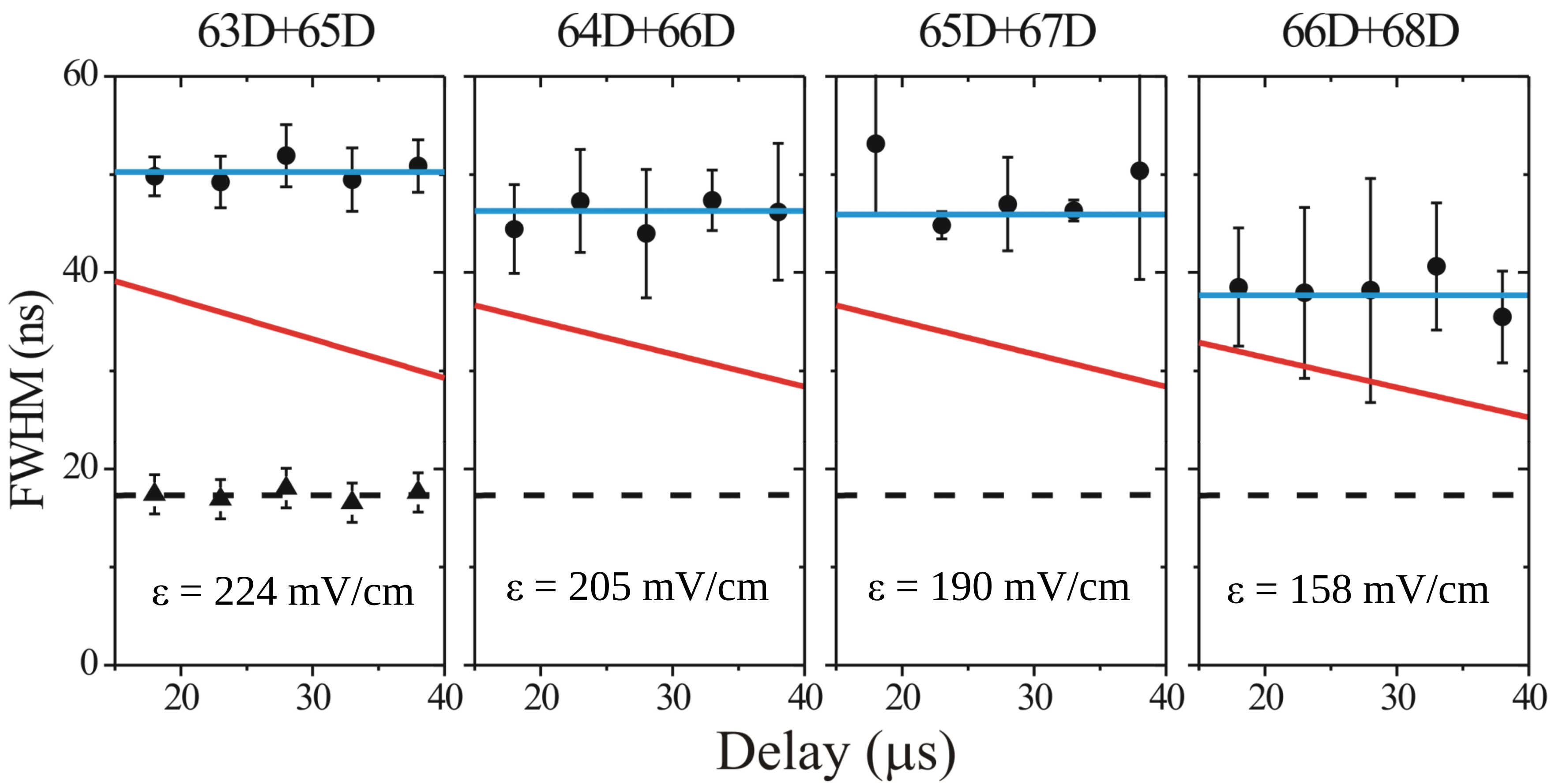
- Ion rate is ***quadratic***
- Coulomb repulsion easily resolved from TOF distributions
  - Black: atomic state
  - Red: molecular resonance





Delay = 38 μs

Width vs. Delay Measurements



- 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)

Future Directions

- Investigate angular distribution of Macrodimers
  - 3D imaging to study applied *E* spatial dependence
- Measure macrodimer ***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

Publications

- K. Overstreet, J. Franklin and J.P. Shaffer, “Zeeman effect spectroscopically locked Cs diode laser for atomic physics,” Rev. Sci. Instrum. **75**, 4749 (2004).
- Arne Schwettmann, Jack Franklin, K. Richard Overstreet, and James P. Shaffer, “Stark slowing asymmetric rotors: Weak-field-seeking states and nonadiabatic transitions” J. Chem. Phys. **123**, 194305 (2005)
- K. R. Overstreet, P. Zabawa, J. Tallant, A. Schwettmann, and J. P. Shaffer, “Multiple scattering and the density distribution of a Cs MOT” Opt. Express **13**, 9672 (2005)
- J. Tallant, K. R. Overstreet, A. Schwettmann, and J. P. Shaffer , “Sub-Doppler magneto-optical trap temperatures measured using Rydberg tagging” Phys. Rev. A 74, 023410 (2006)
- Arne Schwettmann, Jeff Crawford, K. Richard Overstreet, and James P. Shaffer, “Cold Cs Rydberg-gas interactions” Phys. Rev. A 74, 020701 (2006)
- K. Richard Overstreet, Arne Schwettmann, Jonathan Tallant, and James P. Shaffer, “Photoinitiated collisions between cold Cs Rydberg atoms” Phys. Rev. A 76, 011403 (2007)
- Arne Schwettmann, Chris McGuffey, Savith Chauhan, K. Richard Overstreet, and James P. Shaffer, “Tunable four-pass narrow spectral bandwidth amplifier for use at ~508 nm” Appl. Opt. 46, 1310 (2007)
- Arne Schwettmann, K. Richard Overstreet, Jonathan Tallant, and James P. Shaffer, “Analysis of long-range Cs Rydberg potential wells” J. Mod. Opt. **54**, 2551 (2007)
- K. R. Overstreet, A. Schwettmann, J. Tallant, D. Booth, and J. P. Shaffer, “Observation of Cs Rydberg atom macrodimers” (*in submission*)

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 *n*D state character
  - Excitation rate higher for higher *n*