Title: Realizing topological edge states with Rydberg-atom synthetic dimensions

Speakers: Thomas Killian

Collection: Cold Atom Molecule Interactions (CATMIN)

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Abstract: "A quantum system evolving on a manifold of discrete states can be viewed as a particle moving in a real-space lattice potential. Such a synthetic dimension provides a powerful tool for quantum simulation because of the ability to engineer many aspects of the Hamiltonian describing the system. In this talk, I will describe a synthetic dimension created from Rydberg levels in an 84-Sr atom, in which coupling between the states is induced with millimeter-waves. Tunneling amplitudes between synthetic lattice sites and on-site potentials are set by the millimeter-wave amplitudes and detunings respectively. Alternating weak and strong tunneling in a one-dimensional configuration realizes the single-particle Su-Schrieffer-Heeger Hamiltonian, a paradigmatic model of topological matter. I will also briefly describe our recent results creating ultralong-range Rydberg molecule (ULRRM) dimers in an interacting Bose gas and probing nonlocal three-body spatial correlations with ULRRM trimers.
Kanungo, S.K., Whalen, J.D., Lu, Y. et al. Realizing topological edge states with Rydberg-atom synthetic dimensions. Nat Commun 13, 972 (2022). https://doi.org/10.1038/s41467-022-28550-y
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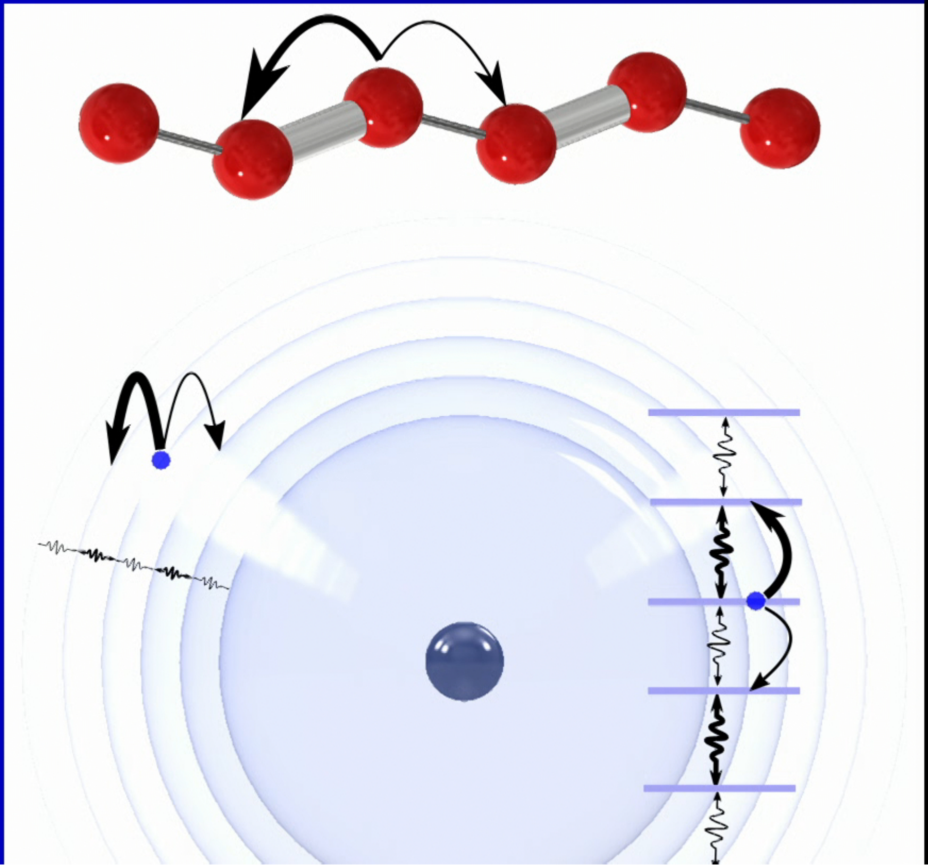
Rydberg Atom Synthetic Dimensions

Thomas C. Killian
F. Barry Dunning
Kaden R. A. Hazzard
Soumya Kanungo
Joe Whalen, Yi Lu, M. Yuan, S. Dasgupta

Rice University and Rice Center for Quantum Materials



CATMIN, Waterloo, 2022

Outline

- Rydberg Atom Synthetic Dimensions
- Realizing the Su-Schrieffer-Heeger (SSH) Hamiltonian and topological edge states
- Future directions

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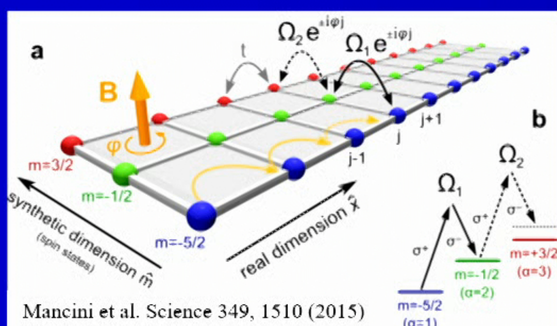
- Rydberg Atom Synthetic Dimensions
- Realizing the Su-Schrieffer-Heeger (SSH) Hamiltonian and topological edge states
- Future directions
- Measuring three-body spatial correlations Ultralong-range Rydberg molecules (ULRRMs)
  - Builds off of work with H. Sadeghpour, and R. Schmidt
- ULRRMs in strongly interacting gases
  - S. Yoshida, J. Burgdorfer, Vienna University of Technology

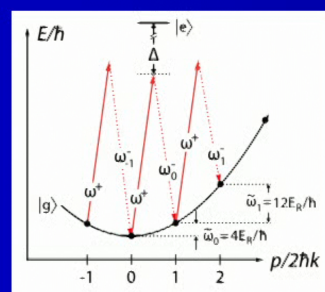
Synthetic Dimensions

TABLE I. Summary of various proposals and realizations for synthetic dimensions

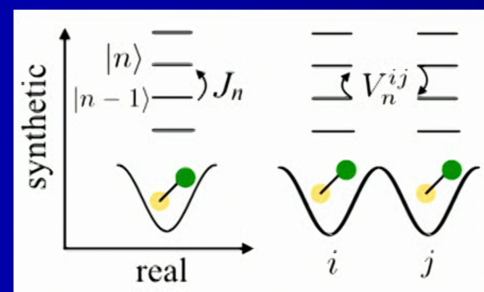
Physical system	What states are used	How states are coupled	Number of extra dimensions studied
Atoms[13,34,35]	Hyperfine states	Raman lasers	1 (only few sites)
Atoms[36,37]	Electronic states	Clock lasers	1 (only two sites)
Atoms[45]	Angular momentum of molecules	Microwaves	1 - 2
Atoms[38,39]	Momentum states	Bragg transitions	No upper limit
Atoms/Photons[44,50]	Spatial eigenmodes	Shaking	1 - 3
Photons[51–53]	Orbital angular momentum	Spatial light modulator	1
Photons[54,55]	Frequency modes	Temporal modulation	No upper limit
Photons[56]	Angular coordinate of resonator	Dispersion of resonator	1 (continuous dimension)
Photons[57–60]	Arrival time of pulses	Coupled optical paths of different lengths	1 - 2
Generic[46–48]	Floquet states	Temporal modulation	No upper limit



Mancini et al. Science 349, 1510 (2015)



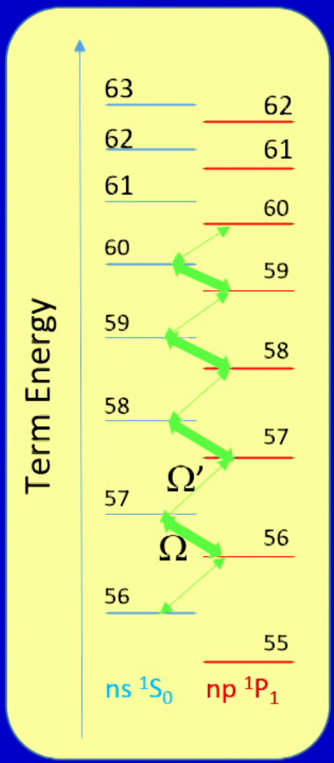
Gadway, PRA **92**, 043606 (2015)

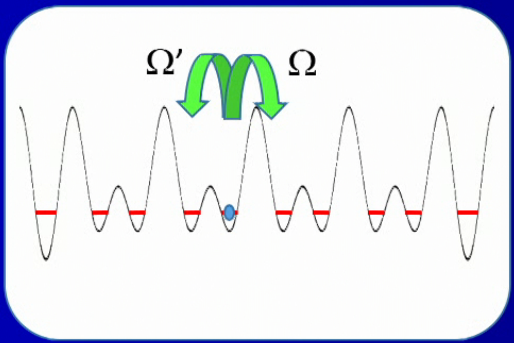


Sundar et al. Scientific reports 8, 3422 (2018).

Ozawa, T., Price, H.M. Topological quantum matter in synthetic dimensions. *Nat Rev Phys* **1**, 349–357 (2019)

Rydberg Atom Synthetic Dimensions

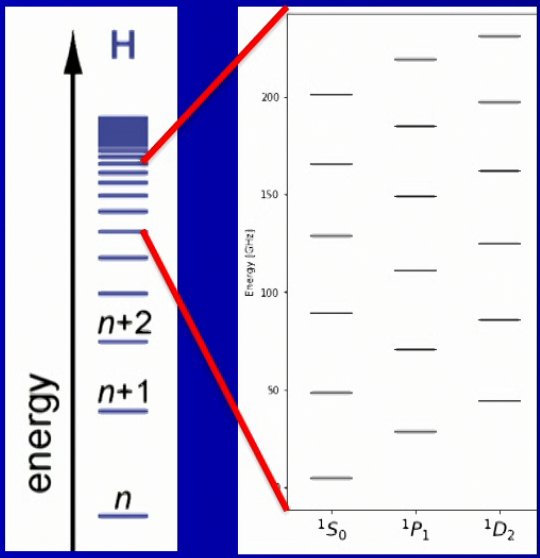




- Occupied synthetic lattice site corresponds to Rydberg state
- Tunneling created by near-resonant microwave fields: rate set by intensities and transition matrix elements
- Synthetic space configuration (dimension, topology) set by coupling pattern
- On-resonance microwaves create degenerate lattice states; chemical potential set by detuning

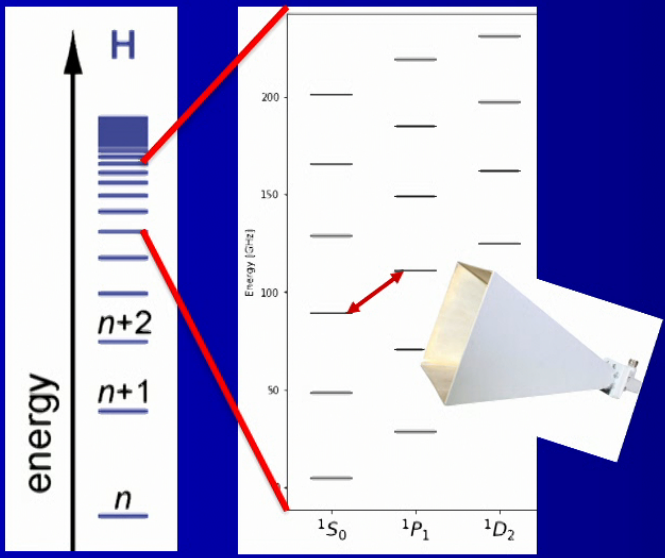
Rydberg Atom Synthetic Dimensions

- Many States
- Long lifetimes



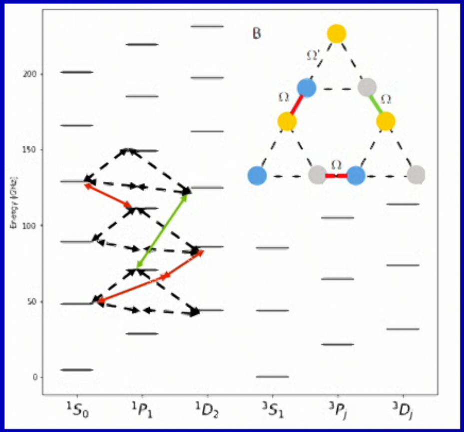
Rydberg Atom Synthetic Dimensions

- Many States
- Long lifetimes
- Flexible state coupling
  - ~1-100 GHz frequency difference, $1/n^3$ scaling
  - Advanced commercial microwave components
  - Large electronic matrix element
    - ~ 1-10 MHz Rabi frequency easily achievable.



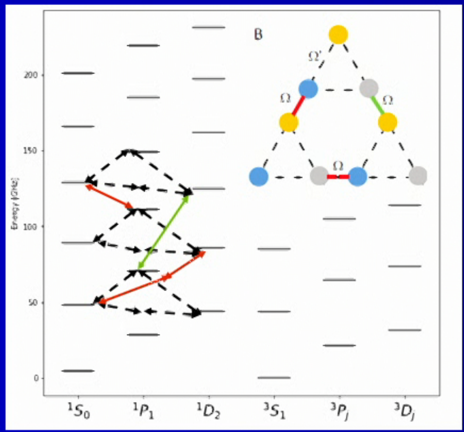
A Few Possibilities

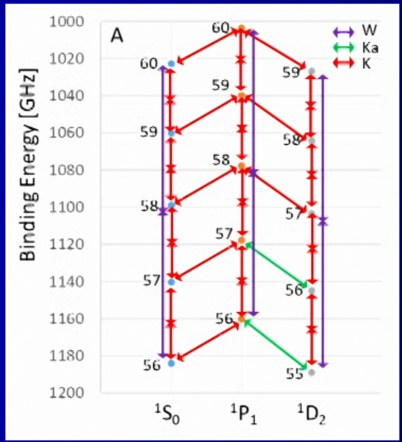
- Higher dimensions

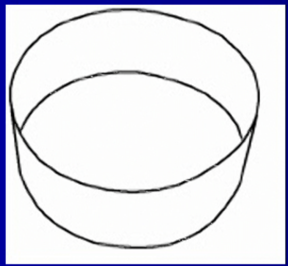


A Few Possibilities

- Higher dimensions
- Topologies not easily accessible in real space

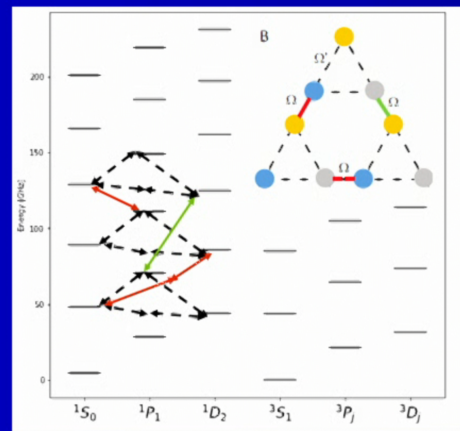


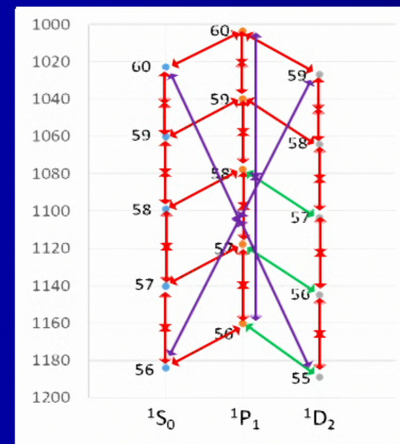


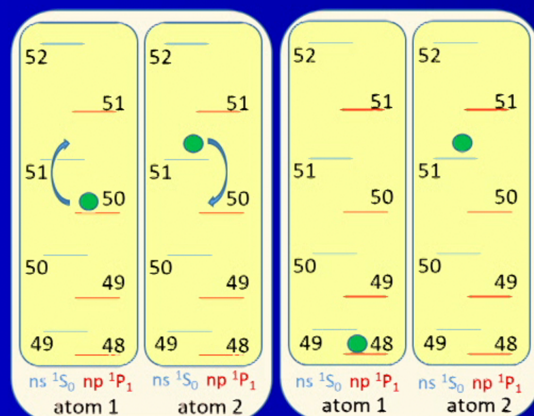


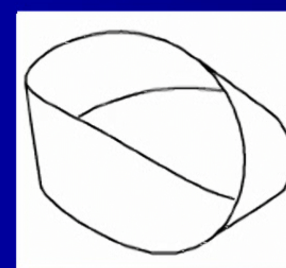
A Few Possibilities

- Higher dimensions
- Topologies not easily accessible in real space
- Potential for Floquet drives, synthetic fields, disorder, dissipation, and many-body interacting states









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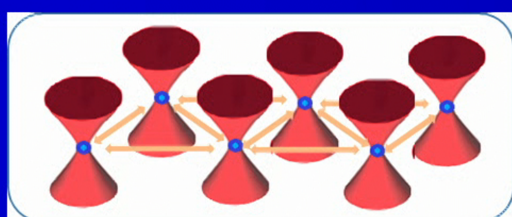
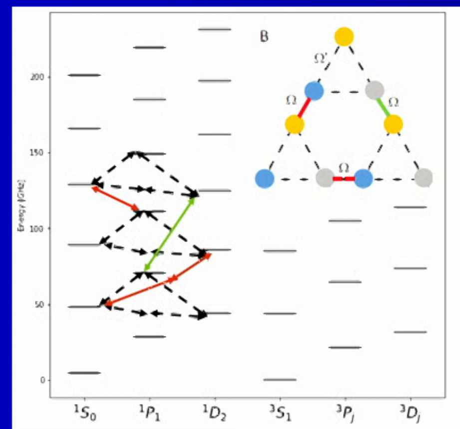
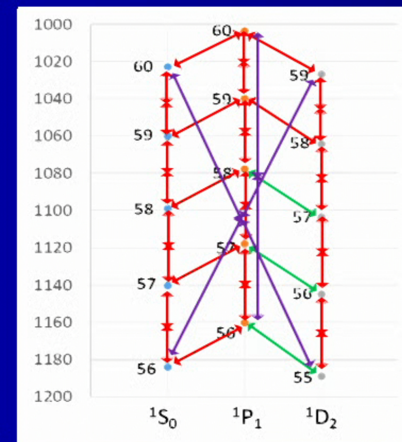
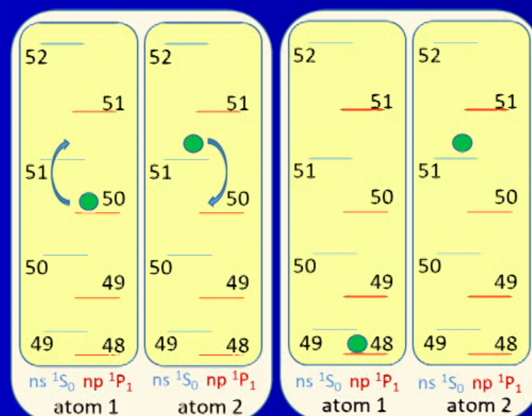
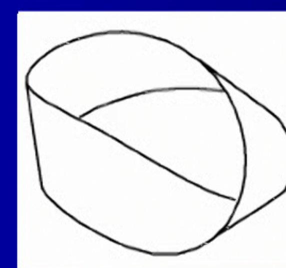
- Many-body interacting systems when combined with optical tweezers











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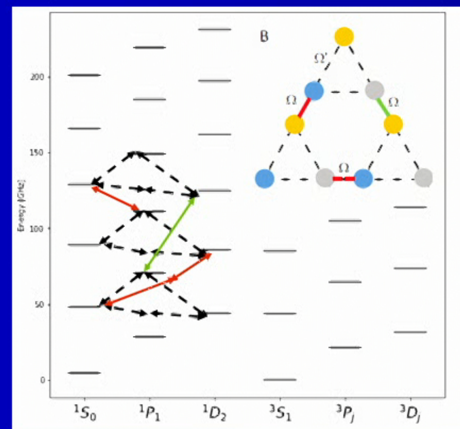
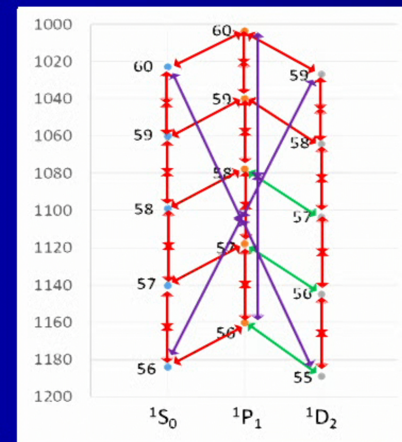
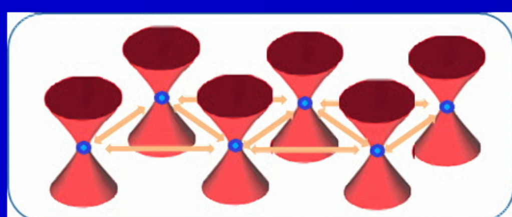
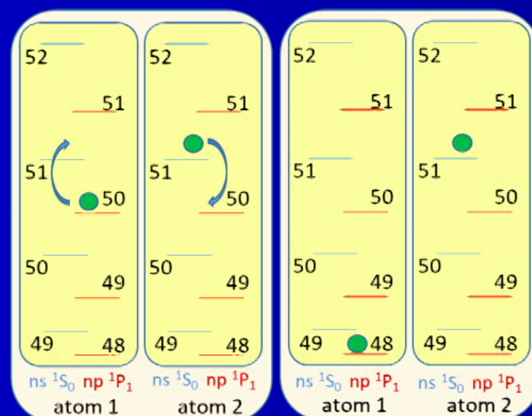
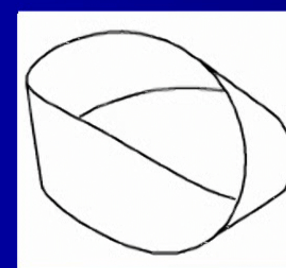




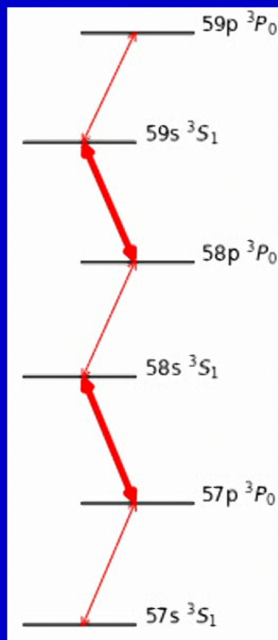




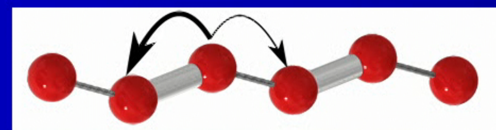


- Topological band-structures

Concrete Example: Su-Schrieffer-Heeger (SSH) Hamiltonian



^{84}Sr



$$\hat{H}_{\text{lattice}} = \sum_{i=1}^{5}(-hJ_{i,i+1}|i\rangle\langle i+1| + \text{h.c.}) + \sum_{i=1}^{6} h\delta_i|i\rangle\langle i|$$

- 1D lattice (Finite)
- N unit cells (2N sites with sublattices A and B)
- Alternating strong and weak tunneling
- No on-site potential
- Simplest model with topological behavior
- Chiral symmetry – all Hamiltonian terms are between sublattices

Realizing topological edge states with Rydberg-atom synthetic dimensions

S. K. Kanungo[1,2], J. D. Whalen[1,2], Y. Lu[1,2], M. Yuan[1,2,3,4], S. Dasgupta[1,2], F. B. Dunning[1], K. R. A. Hazzard[1,2] & T. C. Killian[1,2]

NATURE COMMUNICATIONS | (2022)13:972 | https://doi.org/10.1038/s41467-022-28550-y

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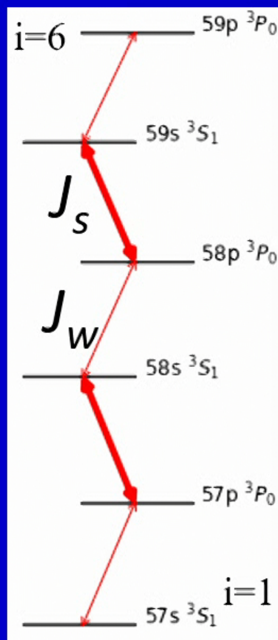
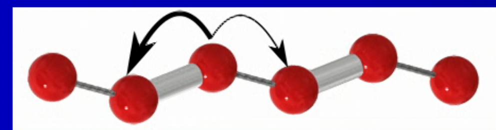


^{84}Sr



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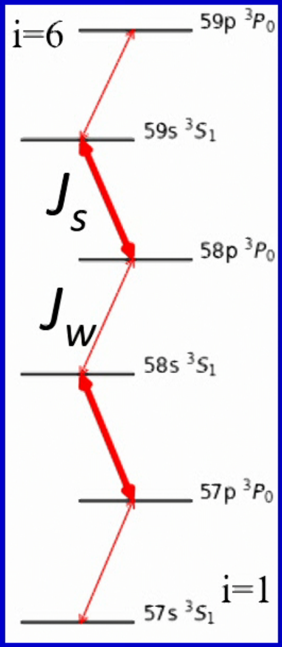
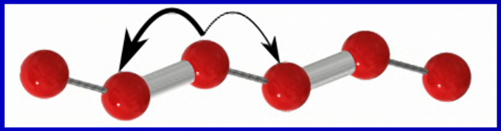
$$\begin{bmatrix} 0 & J_w & 0 & 0 & 0 & 0 \\ J_w & 0 & J_s & 0 & 0 & 0 \\ 0 & J_s & 0 & J_w & 0 & 0 \\ 0 & 0 & J_w & 0 & J_s & 0 \\ 0 & 0 & 0 & J_s & 0 & J_w \\ 0 & 0 & 0 & 0 & J_w & 0 \end{bmatrix}$$

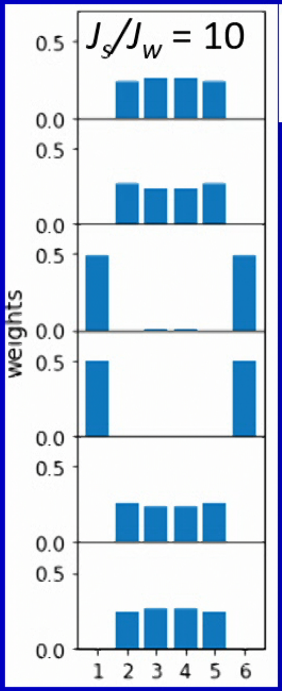
Eigenstates
{| β >}

SSH Eigenstates in Topological Configuration: Edge States



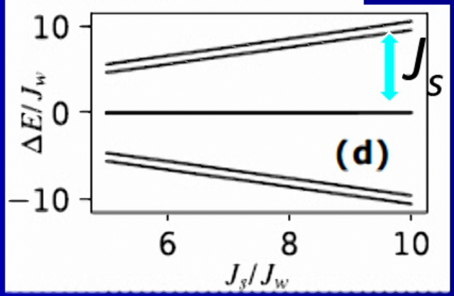
^{84}Sr



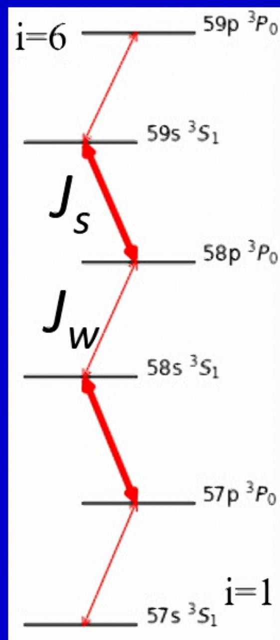


Eigenstate
{| β >} decomposition

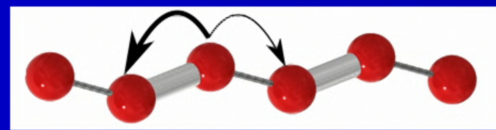
Band Structure

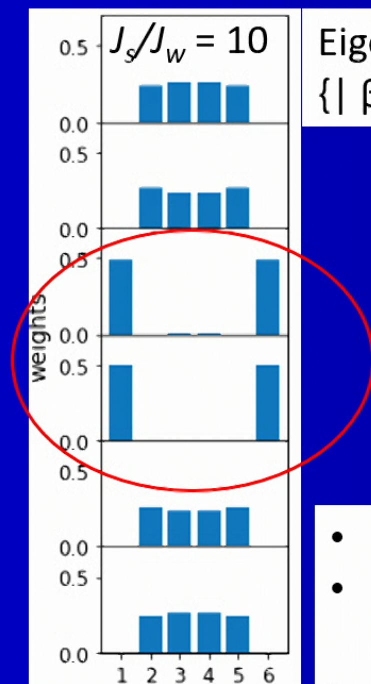


SSH Eigenstates in Topological Configuration: Edge States

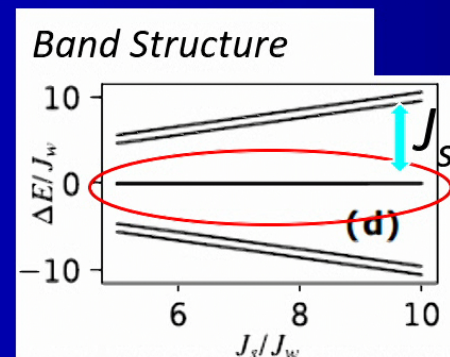


^{84}Sr



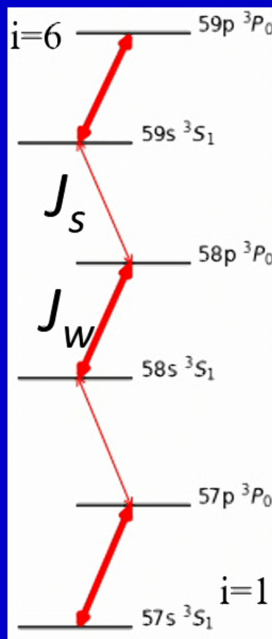


Eigenstate
{| β >} decomposition



- *Edge states with energy=0*
- *Robust to perturbations preserving chiral symmetry*
- *Signature of SSH model in topological configuration*

SSH Eigenstates in Trivial Configuration



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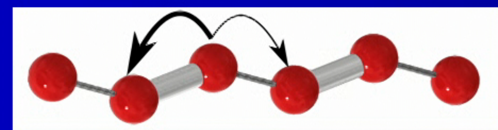
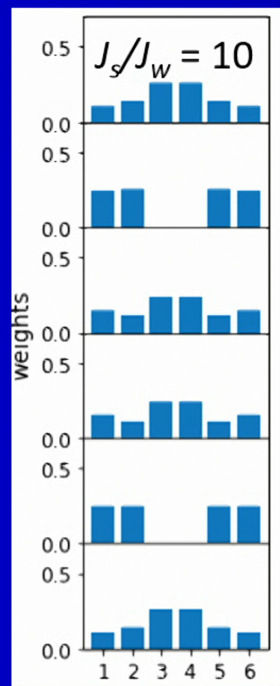
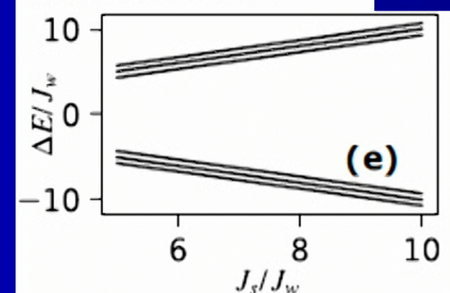




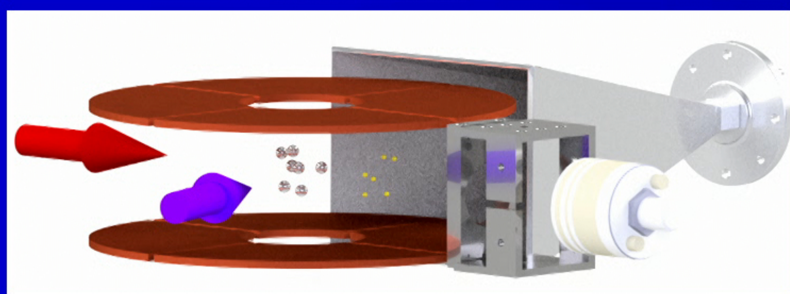
Eigenstate
{| β >} decomposition

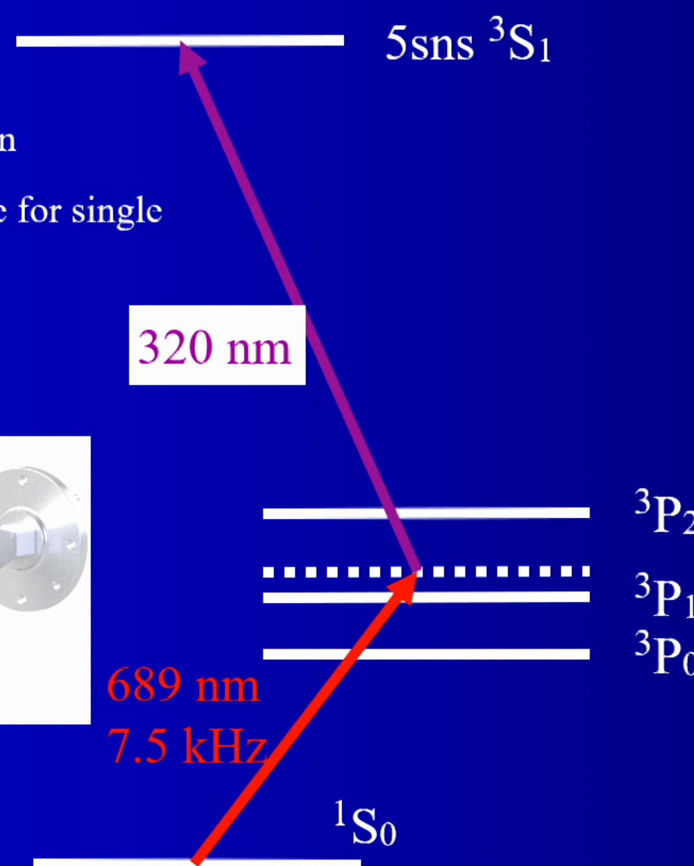
Band Structure



Experimental Details

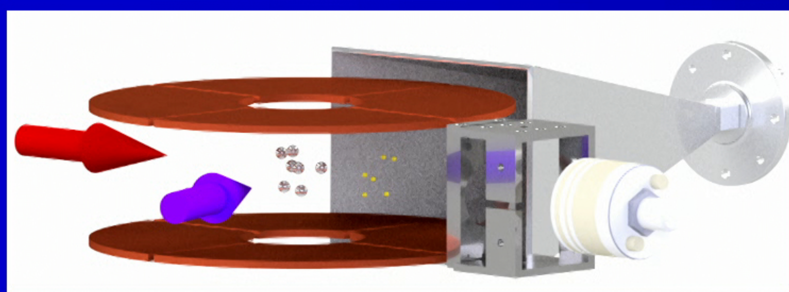
- 1064 nm optical dipole trap
- ^{84}Sr thermal Bose gas $\leq 10^{12}$ cm^{-3}
- Weak, pulsed (5 μs) two-photon excitation
- One or zero Rydberg excitations per pulse for single particle dynamics in synthetic space

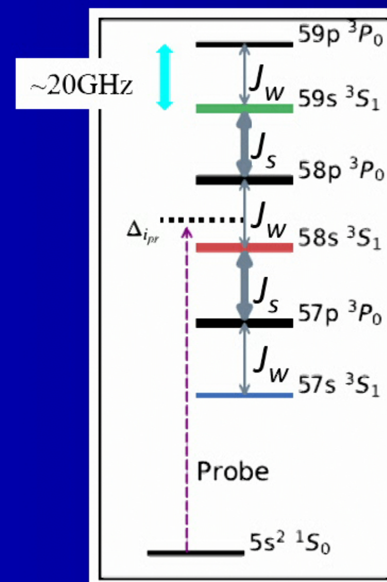




Experimental Details

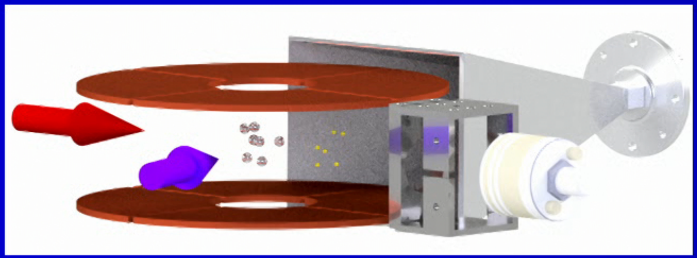
- 1064 nm optical dipole trap
- ^{84}Sr thermal Bose gas $\leq 10^{12}$ cm^{-3}
- Weak, pulsed (5 μs) two-photon excitation
- One or zero Rydberg excitations per pulse for single particle dynamics in synthetic space
- Microwaves applied during the excitation
  - 4G field lifts degeneracy of 5sns $^3S_1$ states

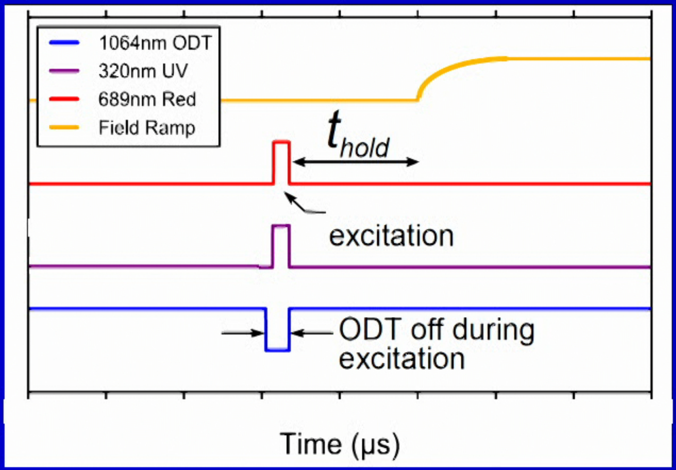


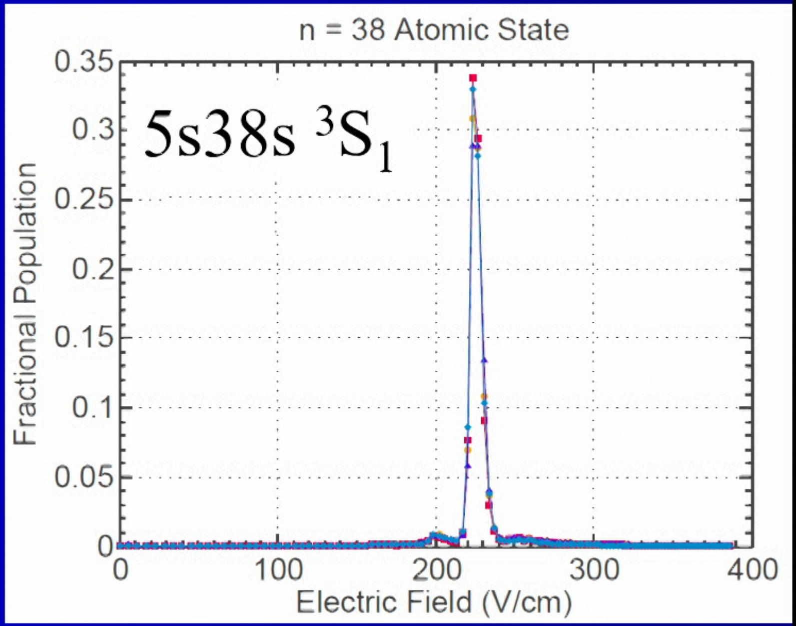


Ω=2J up to 4 MHz

Selective Field Ionization and Charged Particle Diagnostics

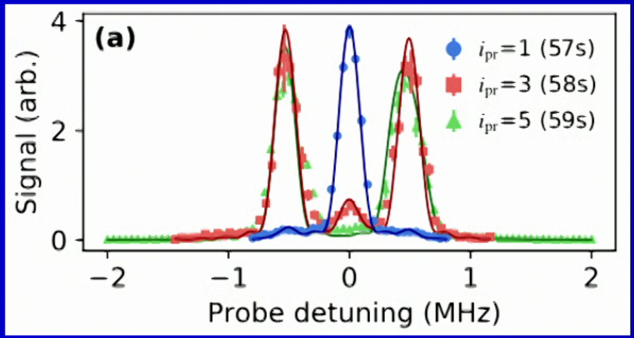




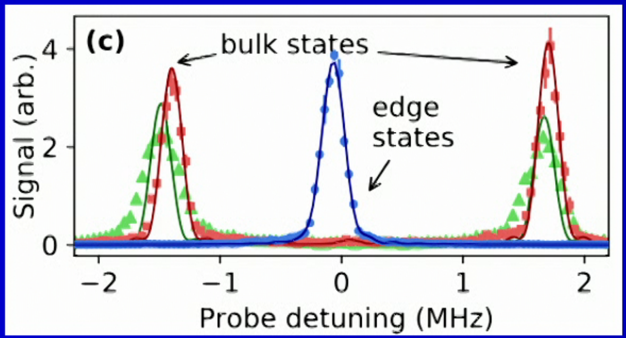


Ionization field decreases as $1/n^4$

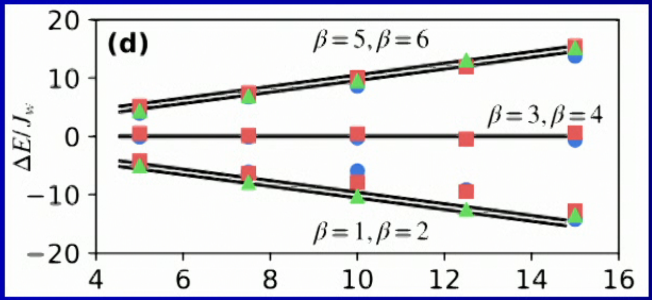
Band Structure



Increase J_s/J_w

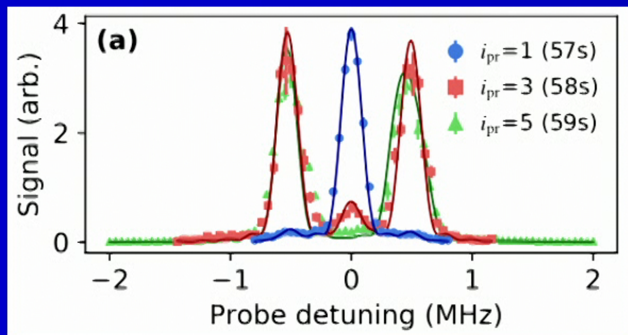


- Combining the spectra at 1, 3 and 5.
- Bulk and edge states are apparent
- Bulk states not resolve



J_s/J_w

State Decomposition



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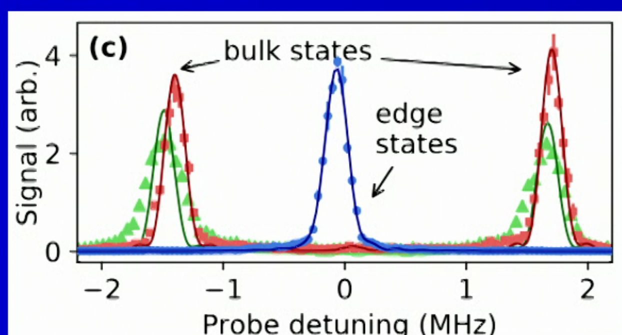
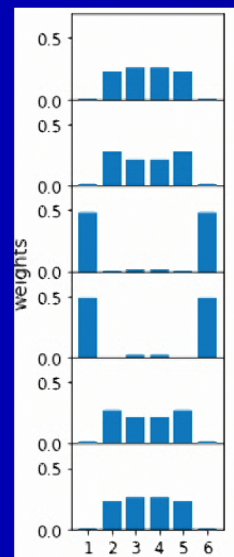
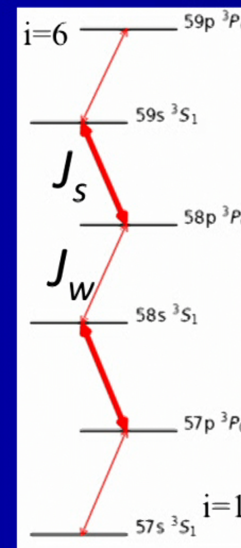
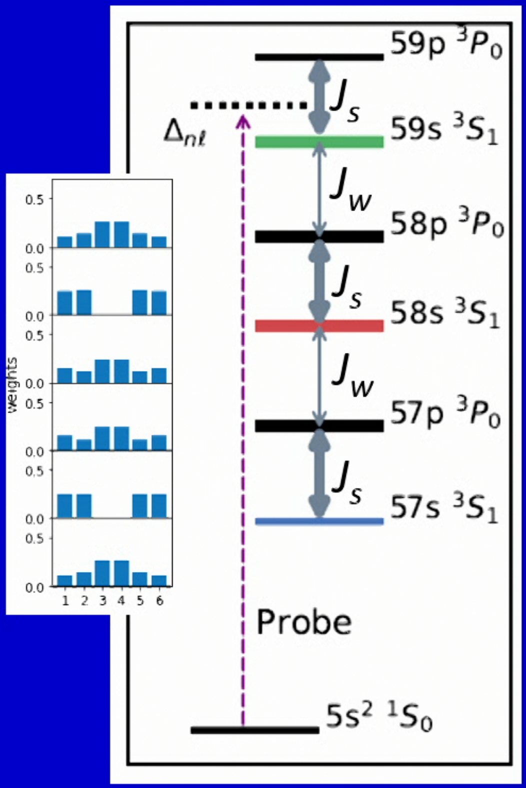


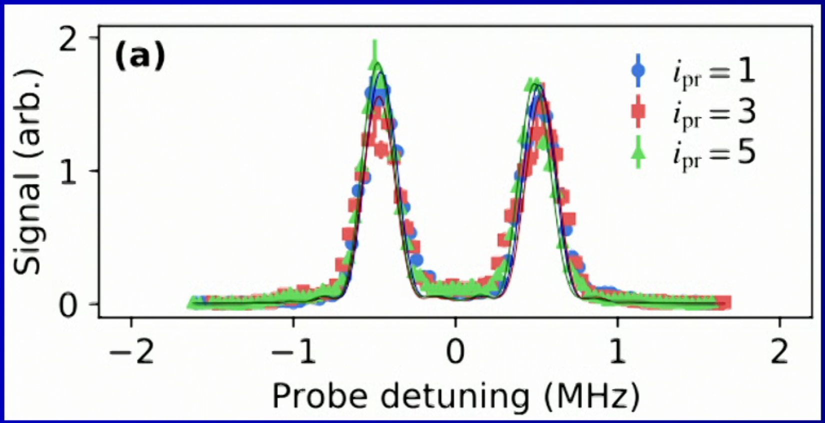


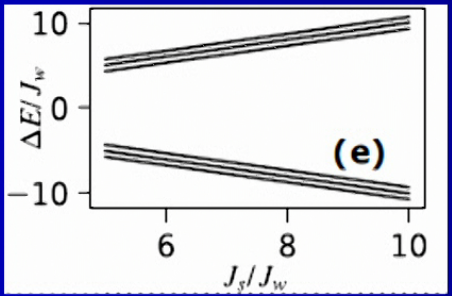


- State with energy=0 is localized on edge (i=1, 57s)
- Localization increases with J_s / J_w
- Peak strengths follow expectation of direct diagonalization

Trivial Configuration

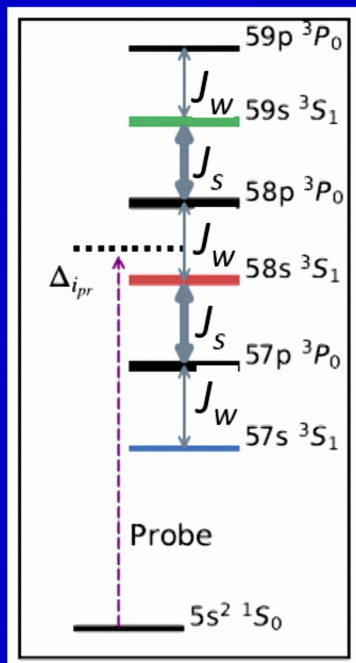


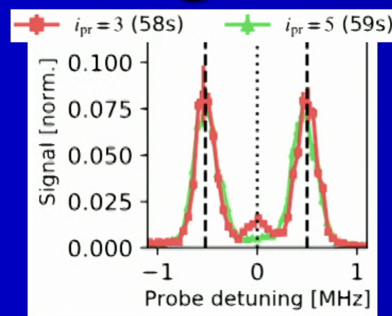




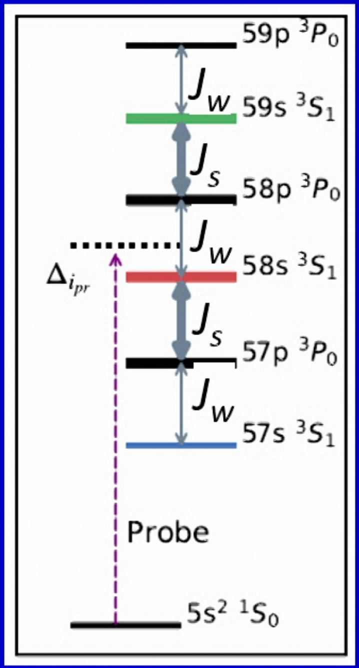
- No edge states

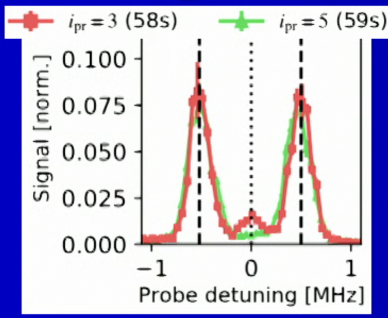
Effects of Perturbations on the Edge States





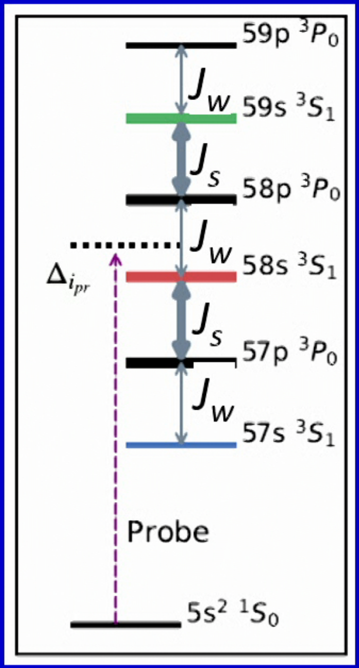
Effects of Perturbations on the Edge States

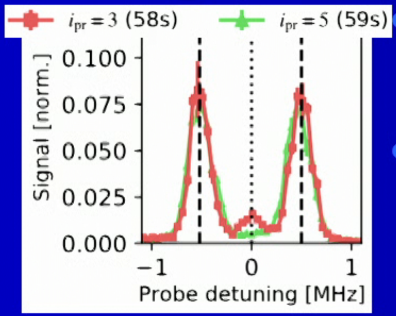




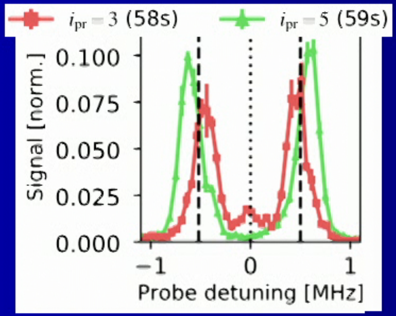
- Tunneling amplitude variations

Effects of Perturbations on the Edge States

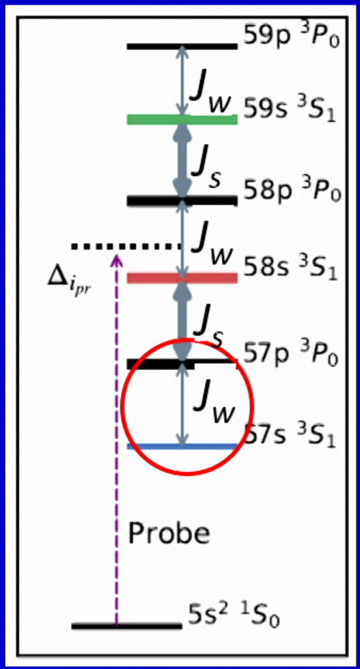


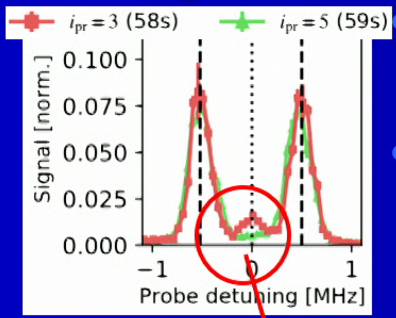


- Tunneling amplitude variations
- No effect on edge state energy



Effects of Perturbations on the Edge States





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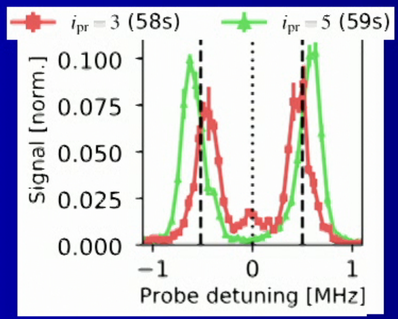
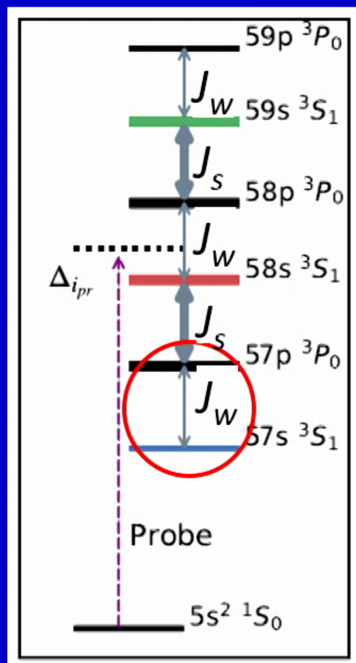
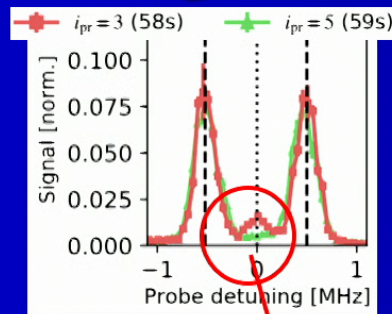


- Introducing on-site potential by varying detuning of microwave field

$$\hat{H}_{\text{lattice}} = \sum_{i=1}^{5}(-hJ_{i,i+1}|i\rangle\langle i+1| + \text{h.c.}) + \sum_{i=1}^{6} h\delta_i |i\rangle\langle i|$$

Effects of Perturbations on the Edge States





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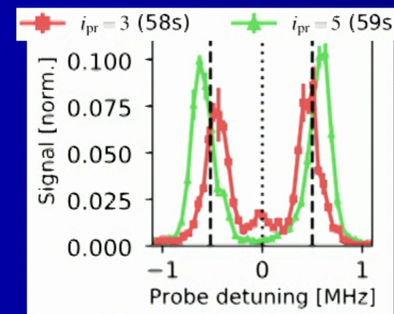

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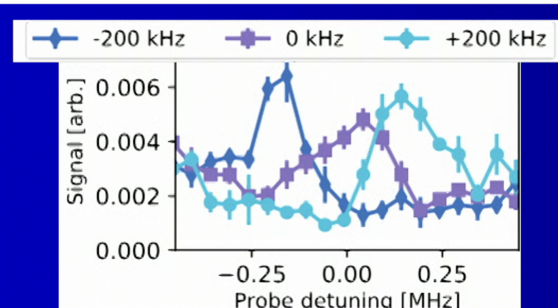
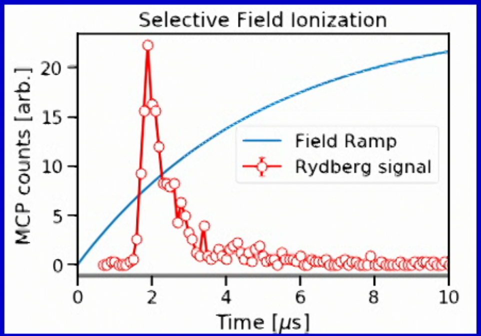
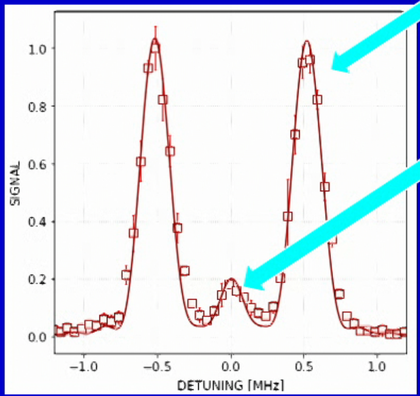
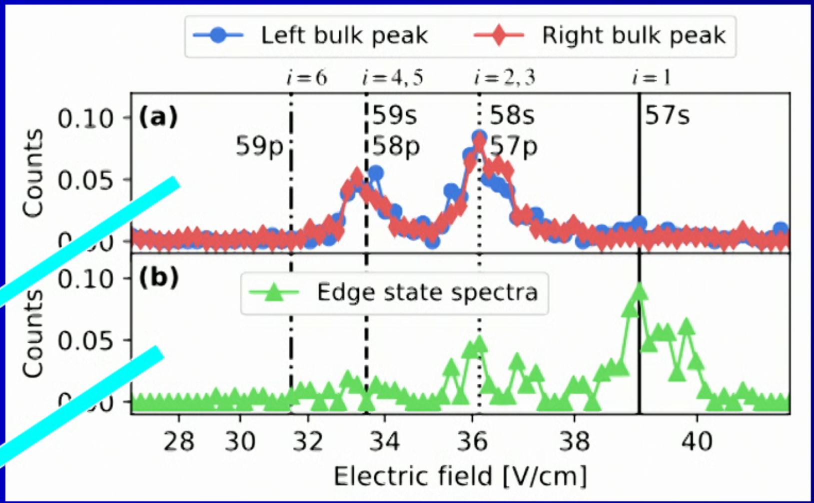


Selective Field Ionization: State Decomposition

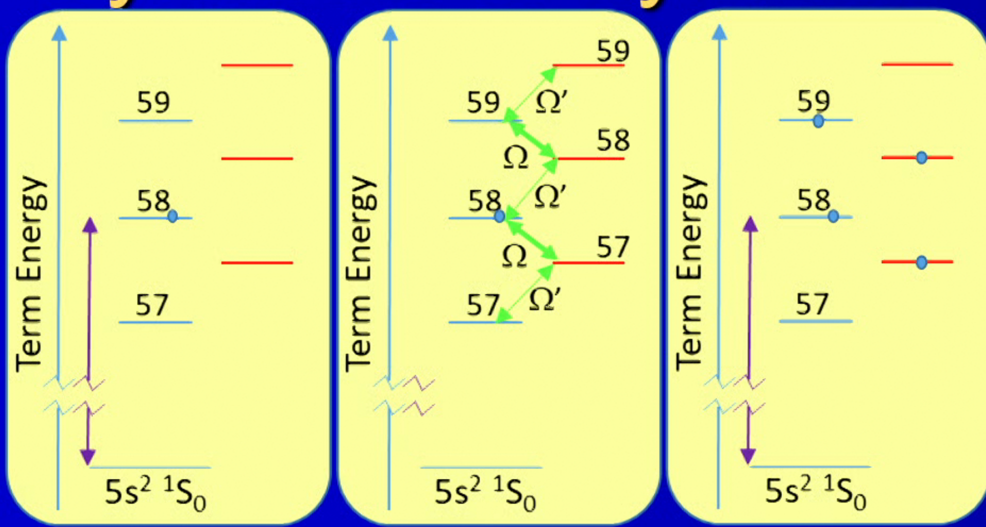


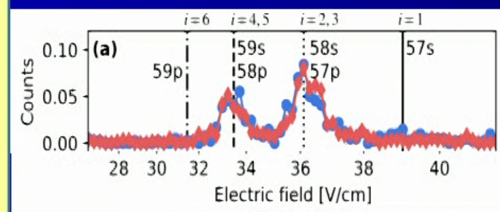


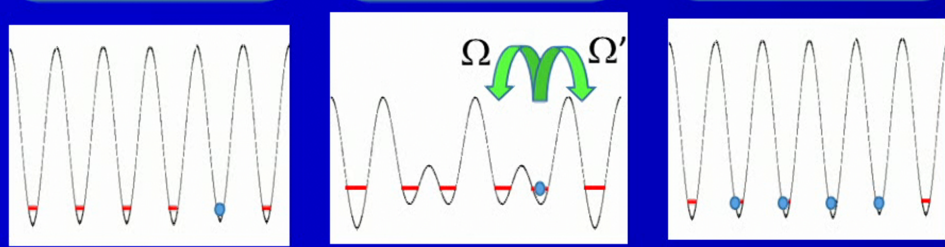


- Ionization field decreases as $1/n^4$
- With Sr quantum defects – two site resolution

Selective Field Ionization: Dynamics in Synthetic Dimension



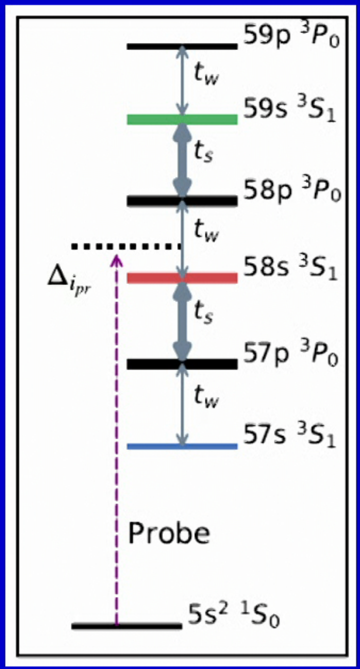




- Create localized particle
- Apply desired Hamiltonian for evolution time
- Freeze wave packet

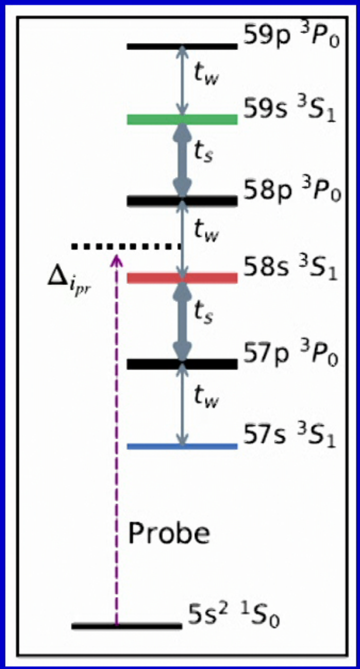
- SFI provides decomposition (site occupancy)
- Bulk vs edge state trajectories

Challenges

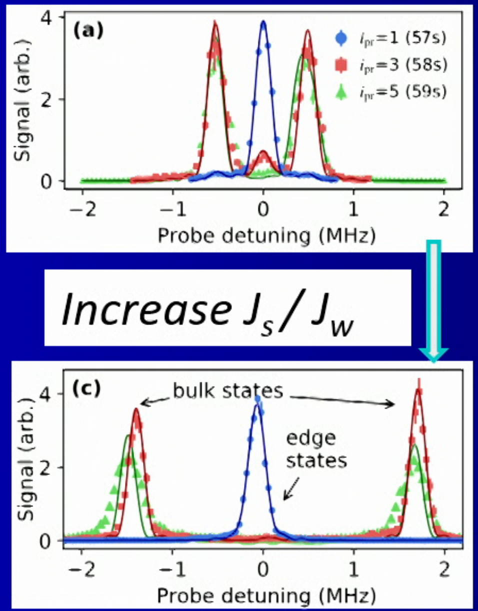


59p $^3P_0$
t_w
59s $^3S_1$
t_s
58p $^3P_0$
t_w
$\Delta_{i_{pr}}$
58s $^3S_1$
t_s
57p $^3P_0$
t_w
57s $^3S_1$
Probe
$5s^2\ ^1S_0$

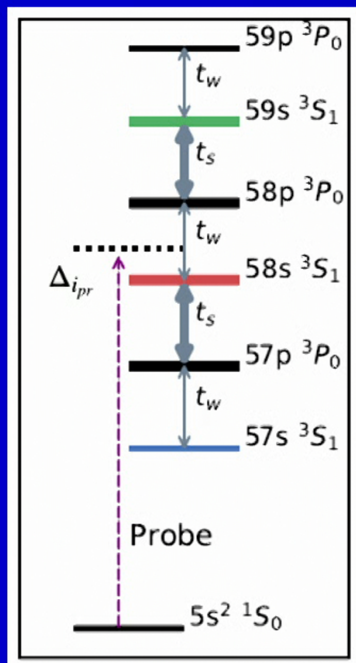
Challenges



- AC Stark shifts
- Hardware complexity with increasing number of states/lattice sites
- Decoherence
  - 40 us lifetime at n=60
  - Variation with state and microwave power



Challenges



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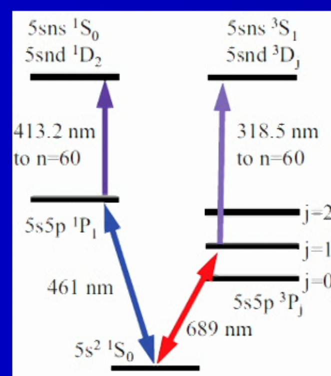
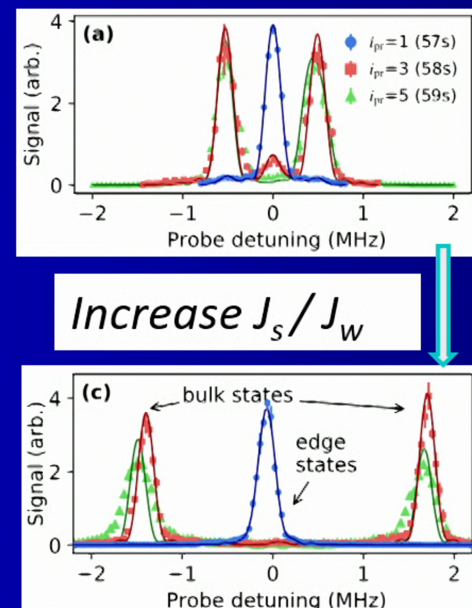




- Switching to singlet Rydberg levels
  - Lower state density

Intermission Conclusions

- Rydberg synthetic dimensions: a new platform for quantum simulation
  - Single-particle band structure demonstrated
    - SSH model and topological edge states
  - Next:
    - Dynamics
    - Larger spaces
    - Multi-particle systems

Post-doc positions open

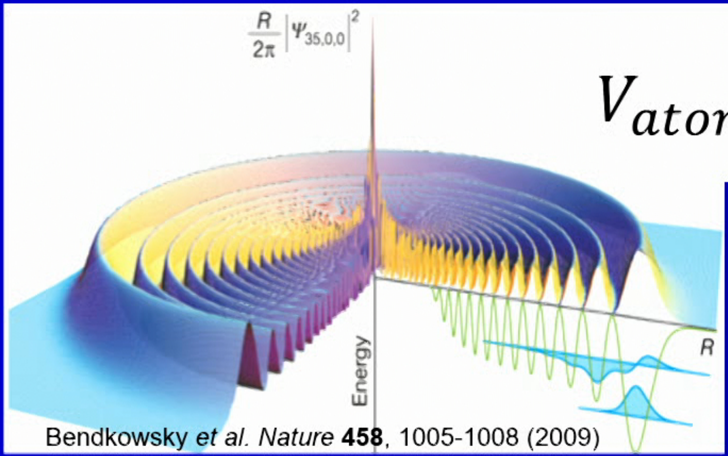
Thanks

- F. Barry Dunning, Kaden Hazzard
- Soumya Kanungo, Yi Lu, Chuanyu Wang, Robert Brienza

Outline

- Rydberg Atom Synthetic Dimensions
- Realizing the Su-Schrieffer-Heeger (SSH) Hamiltonian and topological edge states
- Future directions
- Measuring three-body spatial correlations Ultralong-range Rydberg molecules (ULRRMs)
  - Builds off of work with H. Sadeghpour, and R. Schmidt
- ULRRMs in strongly interacting gases
  - S. Yoshida, J. Burgdorfer, Vienna University of Technology

Electron-Atom Interaction and Ultralong-Range Rydberg Molecules



Bendkowsky *et al. Nature* **458**, 1005-1008 (2009)

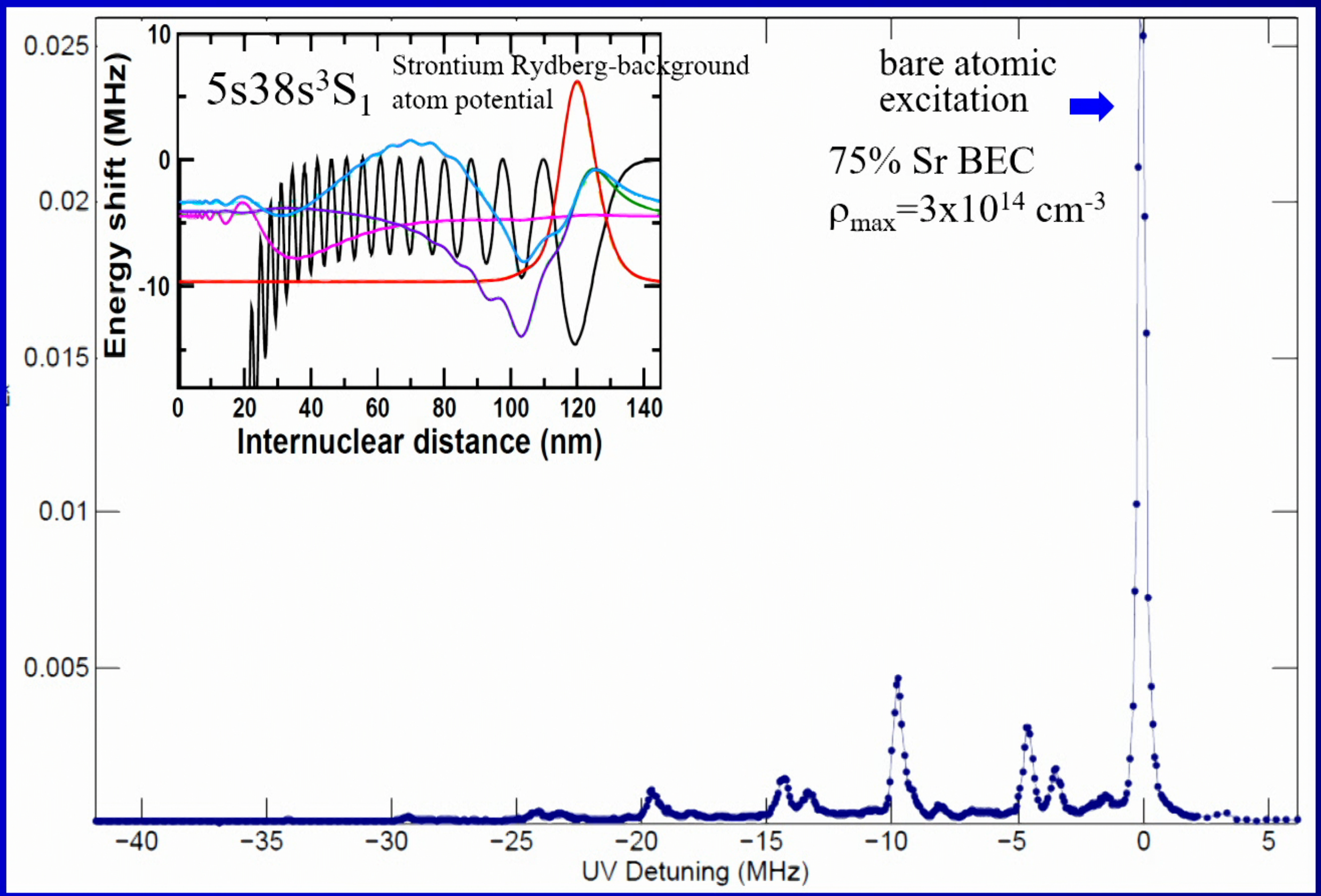
$$V_{atom}(R) \approx \frac{2\pi h^2 A_s}{m_e}|\Psi_{ns}(R)|^2$$

Ψ_{ns}(R): Rydberg electron wave function

A_s: e-atom s-wave scattering lengths
m_e: electron mass

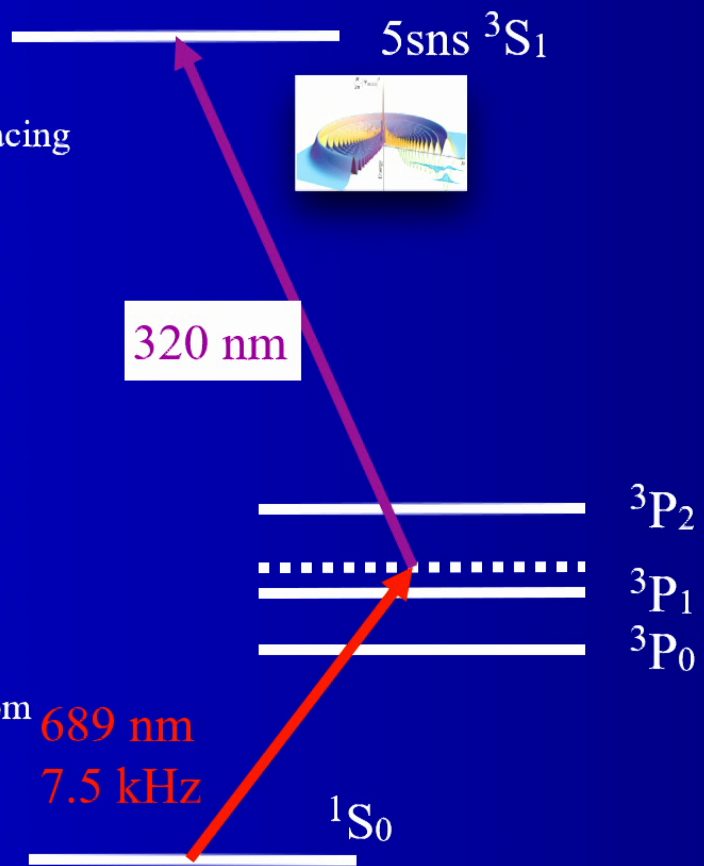
- Greene, Dickinson, and Sadeghpour, Phys. Rev. Lett. 85, 2458 (2000)
- Electron probability density in Rydberg atom forms potential wells that can bind ground state atoms
- Binding energies of MHz for any element with $A_s<0$
- Molecules could be observed with ultracold atoms

ULRRM in 84-Sr BEC

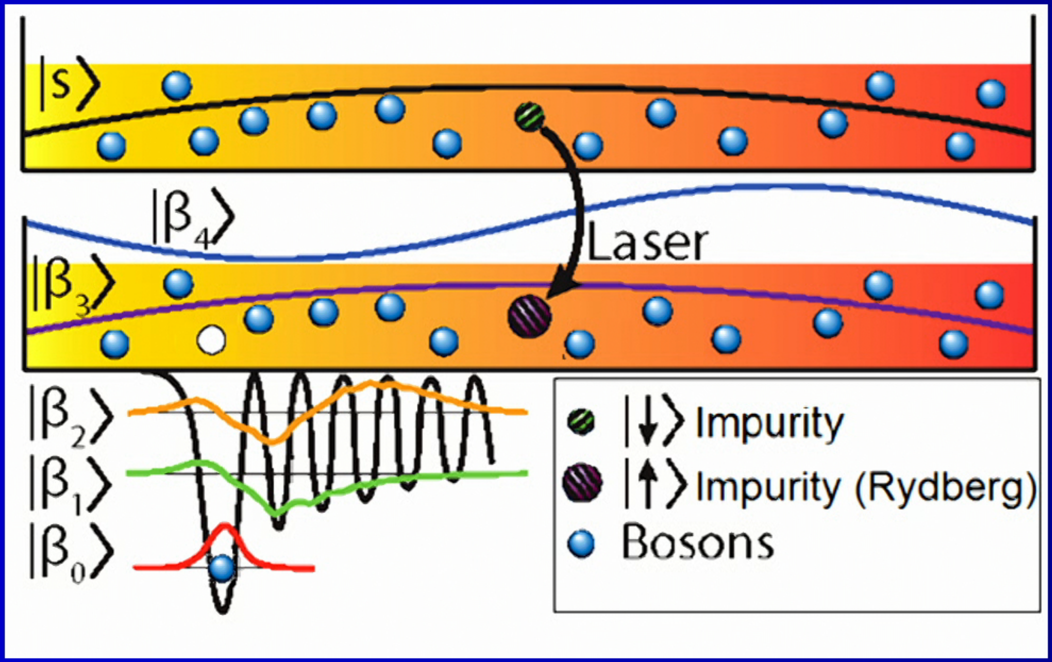


Rydberg Molecules of Sr

- 1064 nm optical dipole trap
- ^{84}Sr thermal Bose gas and BEC
  - $\leq 3\times10^{14}$ cm^{-3}, 80 nm inter-particle spacing
- ^{86}Sr thermal Bose gas
  - $\leq 1\times10^{13}$ cm^{-3}
- ^{87}Sr thermal Fermi gas with I=9/2
  - $\leq 1\times10^{13}$ cm^{-3}
- Simple structure
  - No hyperfine or fine structure
  - $^{1}S_{0}$ ground-state perturber
  - No p-wave resonance for electron-atom scattering



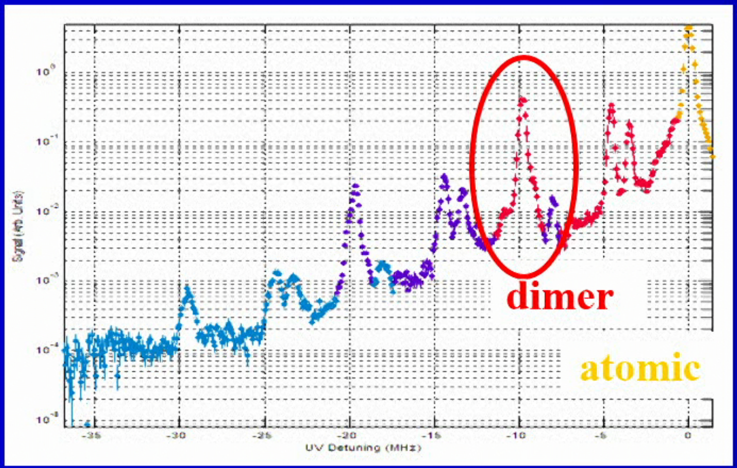
Probing Spatial Correlations with Ultralong-Range Rydberg Molecules

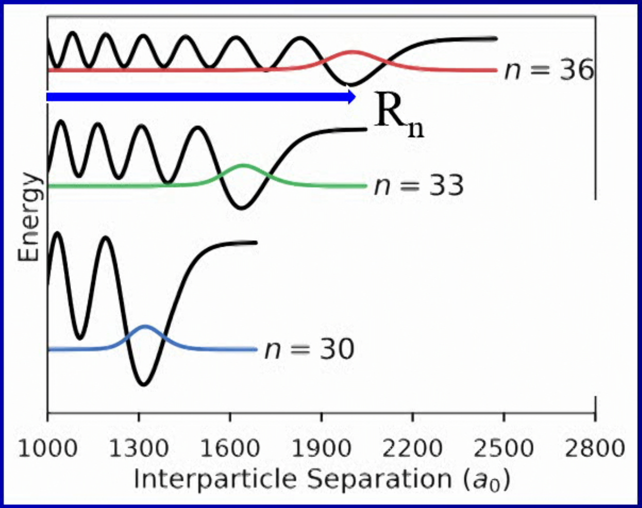


- Excitation to a molecular state requires the presence in the initial gas of atoms with correct separation

Most Deeply Bound Dimer: Mapping the Pair Correlation Function

- Deepest-bound Rydberg-dimer state localized at $R_n \sim 1.8 n^2 a_0$
- Excitation rate to this state proportional to probability of finding two particles with correct separation
  - $\Gamma \propto g^2(R_n) = \frac{\langle \Psi^\dagger(\vec{r})\Psi^\dagger(\vec{r}+\vec{R}_n)\Psi(\vec{r}+\vec{R}_n)\Psi(\vec{r})\rangle}{\langle \Psi^\dagger(\vec{r})\Psi(\vec{r})\rangle^2}$
  - pair-correlation function





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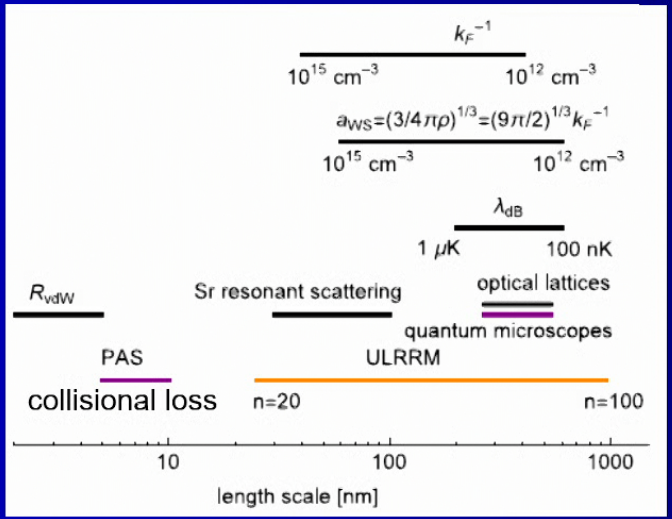
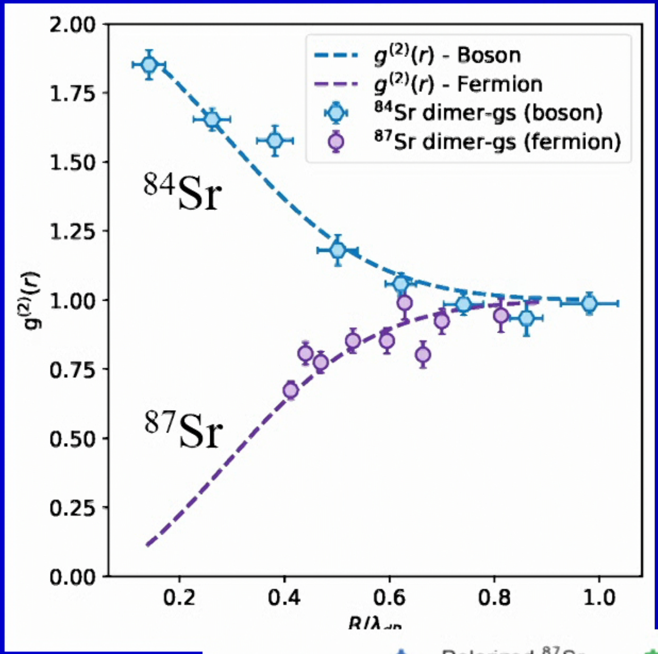
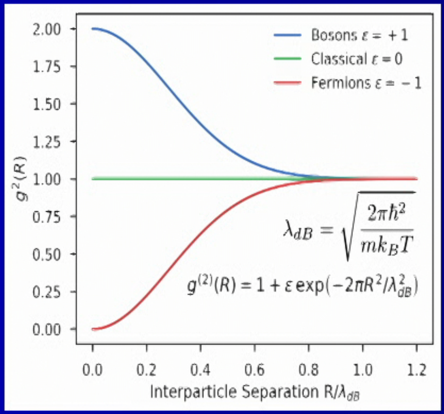
  - pair-correlation function
- Powerful probe:
  - Vary R_n
  - select isotopes (mixtures), internal states
  - in situ
  - excellent time resolution

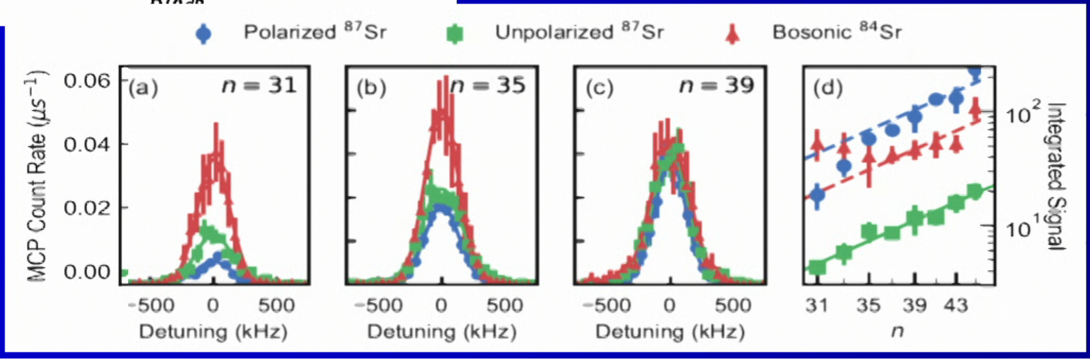


Thermal Bosons vs. Fermions





- Unpolarized fermions in ^{87}Sr – 10 ground states
- Nearly classical gas
- Provides normalization

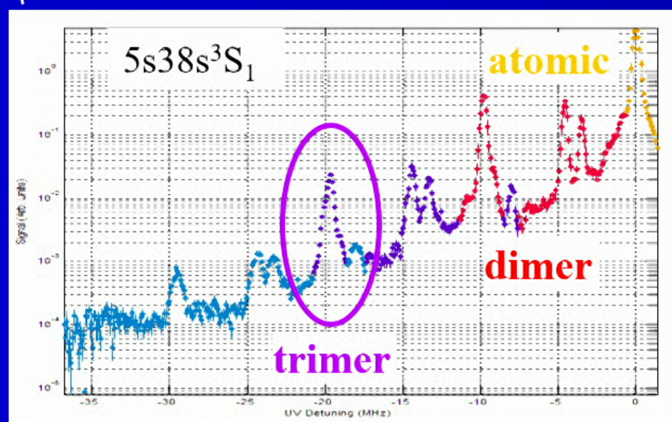


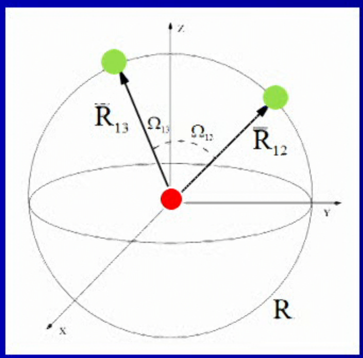
Most Deeply Bound Trimer: Angle-averaged Three-body Correlations

- Deepest-bound Rydberg-trimer state localized at $R_n \sim 2n^2 a_0$
- Excitation rate to this state proportional to probability of finding three particles with correct separation from central atom

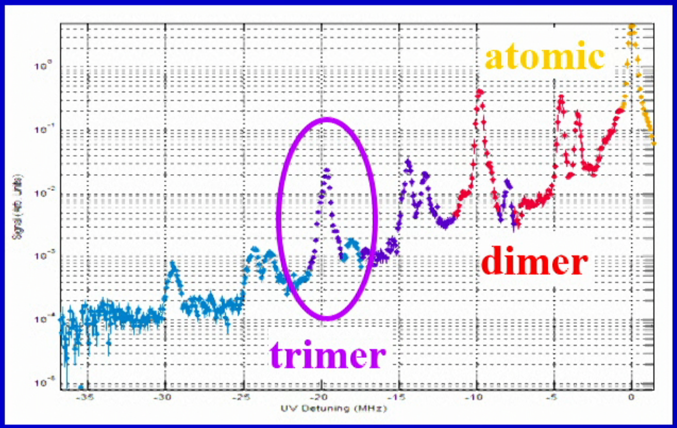
- $\Gamma \propto \left\langle g^{(3)}(R_{12}=R_n, R_{13}=R_n, \Omega_{12}, \Omega_{13}) \right\rangle_{\Omega_{12},\Omega_{13}} =$

$$\left\langle \frac{\langle \Psi^\dagger(\vec{r})\Psi^\dagger(\vec{r}+\vec{R}_{12})\Psi^\dagger(\vec{r}+\vec{R}_{13})\Psi(\vec{r}+\vec{R}_{13})\Psi(\vec{r}+\vec{R}_{12})\Psi(\vec{r})\rangle}{\langle \Psi^\dagger(\vec{r})\Psi(\vec{r})\rangle^3} \right\rangle_{\Omega_{12},\Omega_{13}}$$

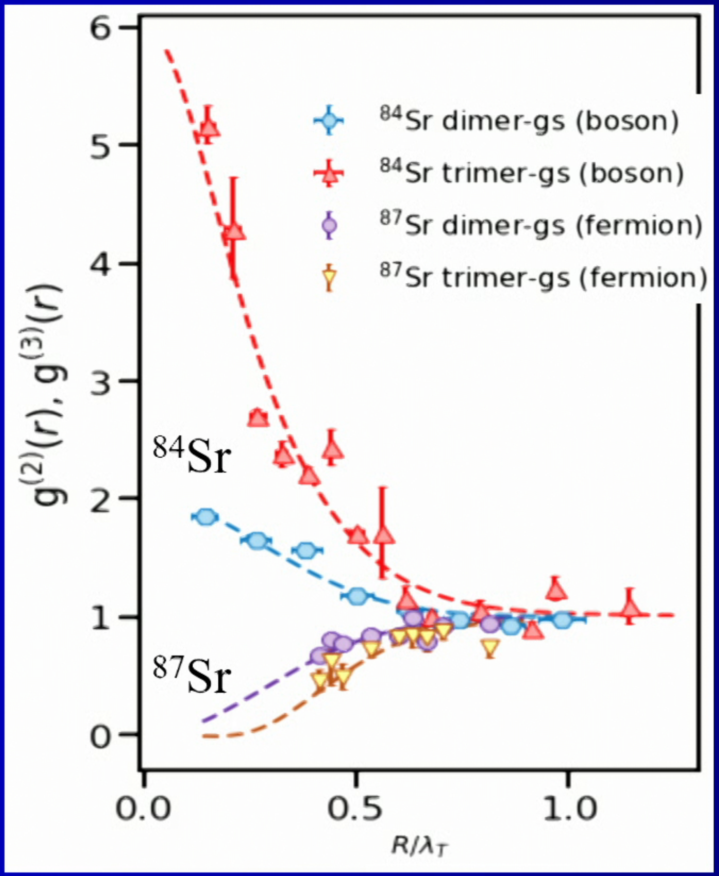




Angle-averaged Three-body Correlations

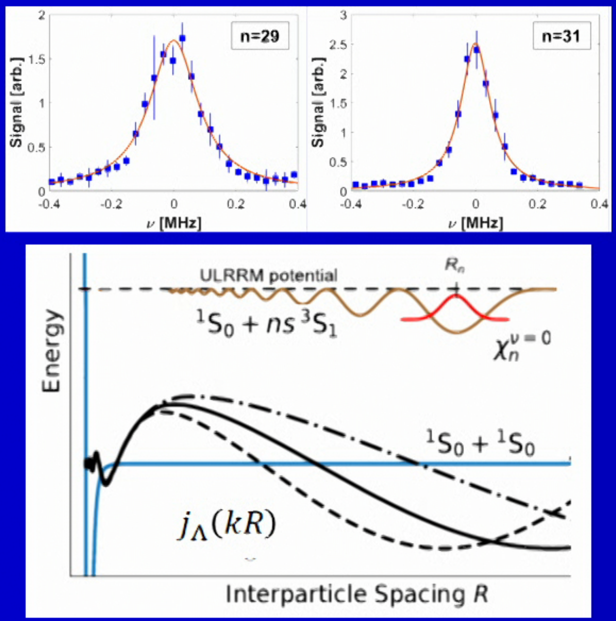


- Ratio of signal to that of unpolarized fermions in ^{87}Sr – 10 ground states
- Also normalized for density and laser intensity

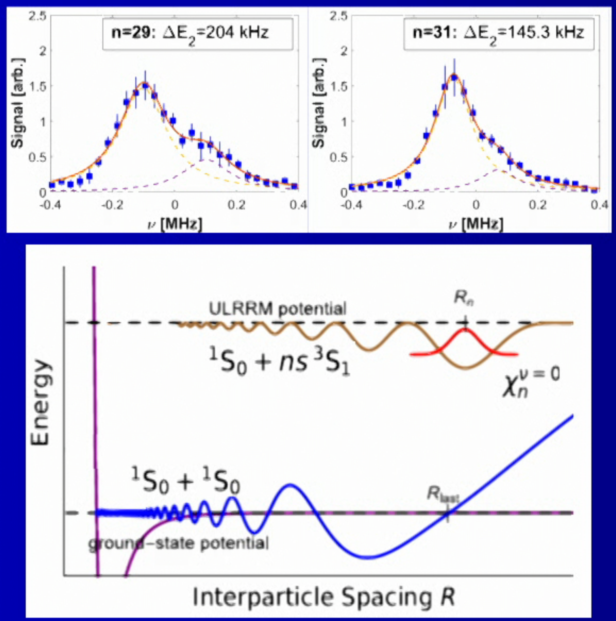


ULRRM Dimer Spectra:
^{86}Sr –Effects of interaction in initial gas

^{84}Sr ν=0 dimer



^{86}Sr ν=0 dimer

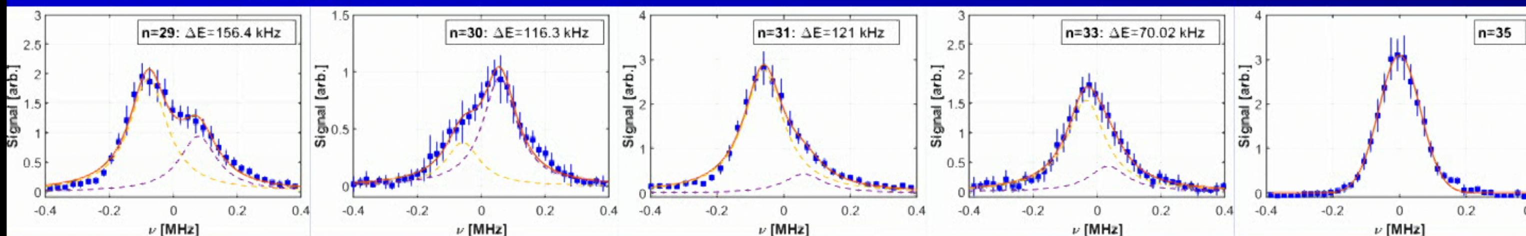


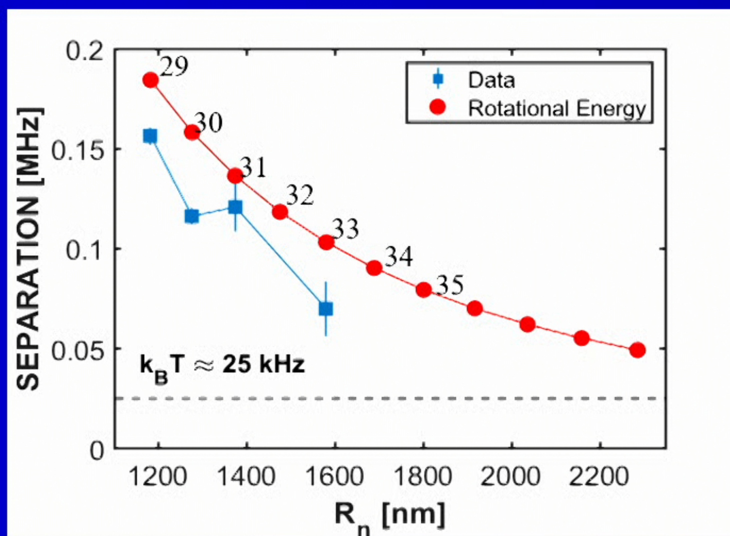
	86	84
86	**811**	**32**
84	-	**123**

Sr scattering lengths (a_0)

Resolved Rotational States

^{86}Sr ν=0 dimer

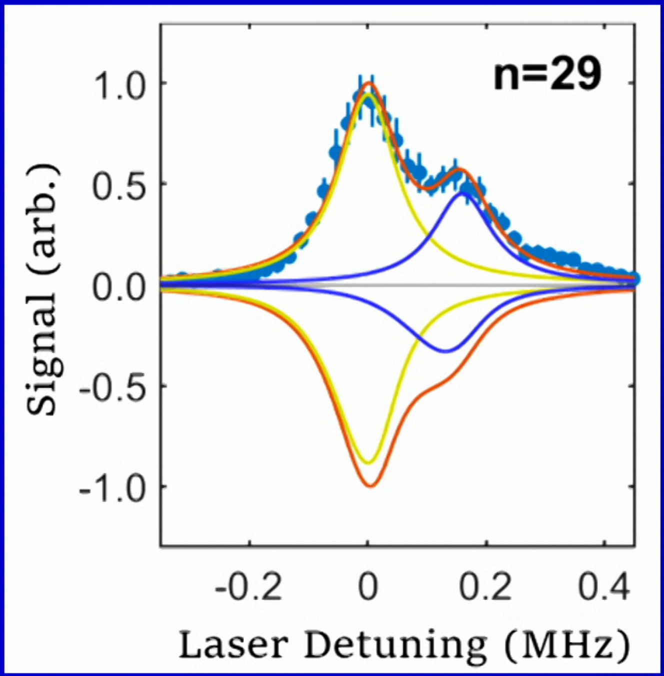




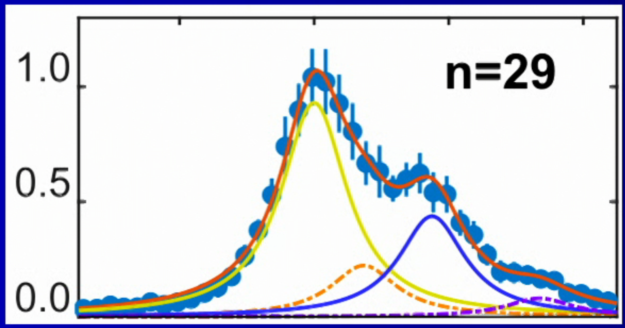
- Splitting closely matches the energy difference between $\Lambda = 2$ and Λ =0 rotational states of the ^{86}Sr ν=0 dimer
- $E_\Lambda = \frac{\hbar^2 \Lambda(\Lambda+1)}{2\mu R_n^2}$
- Why not visible in ^{84}Sr?
- Selection rules?
- Energy?
- Surprising intensity patterns?

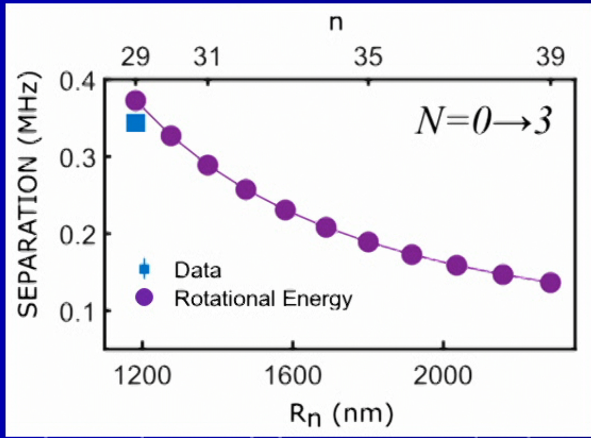
Unexpected Components

^{86}Sr ν=0 dimer



4-line fit

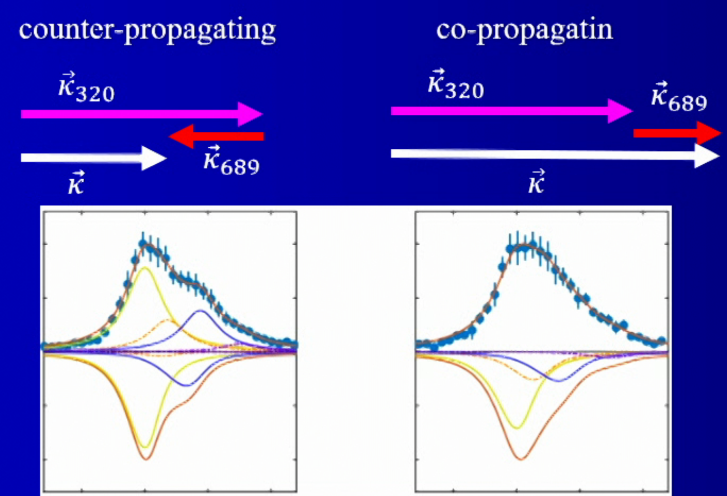




- Additional peak positions match that of $N = 1, 3$
- How is $N \neq l$? (initial l even only)

Photon Recoil

- Because of the large internuclear separation, the total momentum $\vec{\kappa}$ of the two excitation photons ($\vec{\kappa}_{689} + \vec{\kappa}_{320}$) gives a kick to the relative motion of the particles in the initial and final state
- Modified Frank-Condon overlap integral
- Excitation of additional angular momentum states



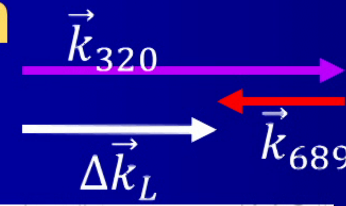
n = 29 @ T = 1200 nK

$$F_{n,N,M_N}(\vec{k}) = \frac{1}{\sqrt{2}}\left\langle n, N, M_N \middle| e^{-i(\vec{\kappa}/2)\cdot\vec{R}_n} + (-1)^N e^{i(\vec{\kappa}/2)\cdot\vec{R}_n} \middle| \vec{k} \right\rangle$$

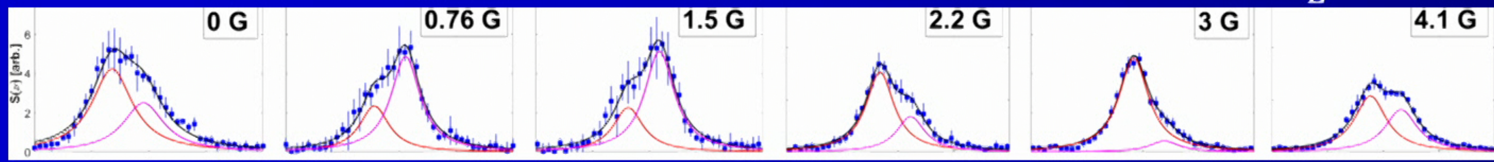
final state

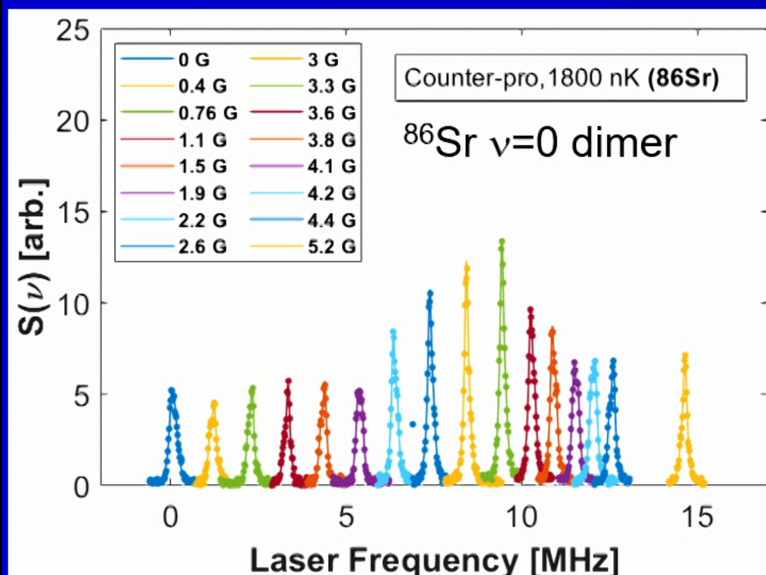
initial state for relative motion

^{86}Sr ULRRM Dimer Spectra: Magnetic Field Variation

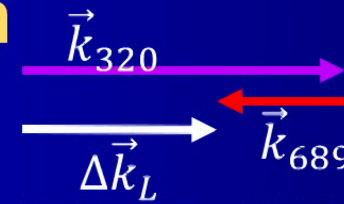


^{86}Sr ν=0 n=30 dimer, T=300nK

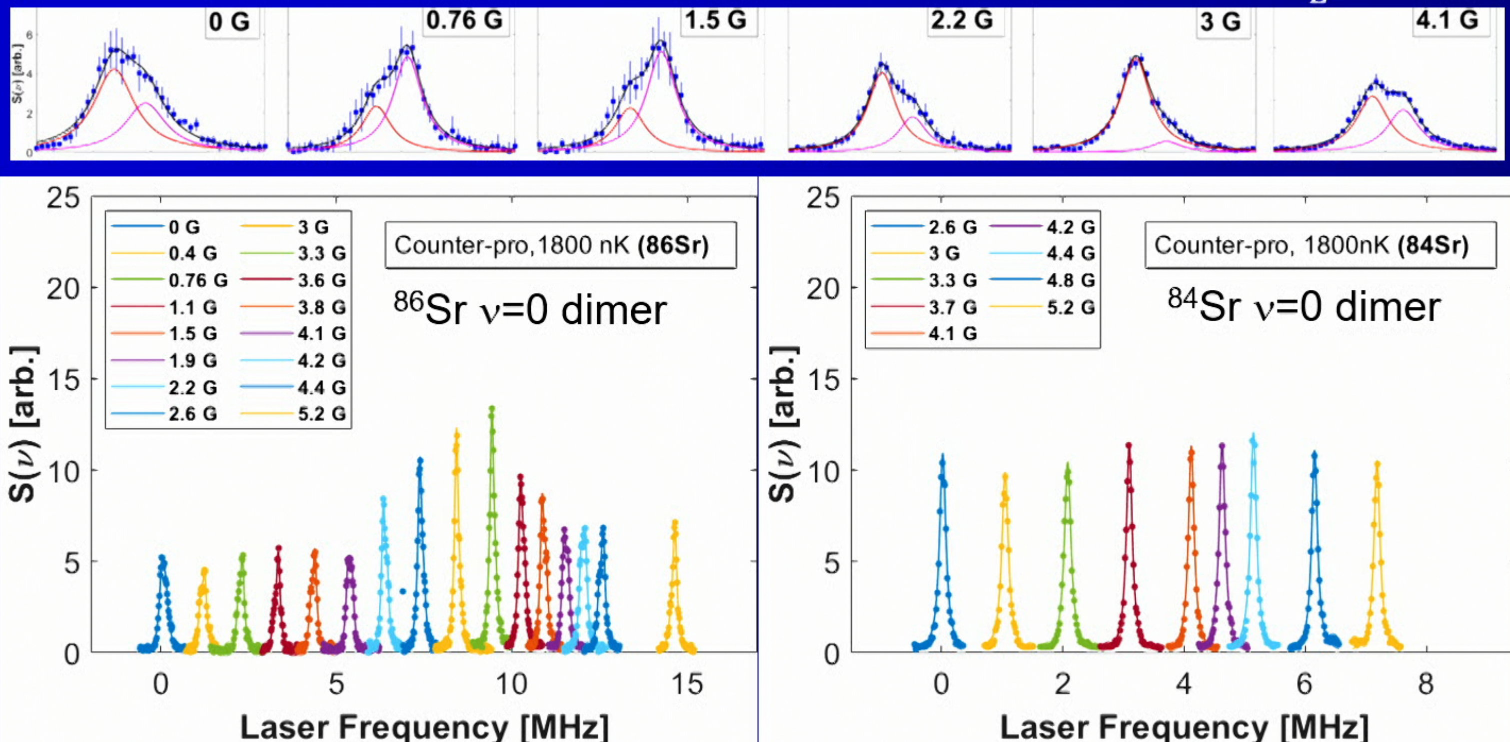




^{86}Sr ULRRM Dimer Spectra: Magnetic Field Variation



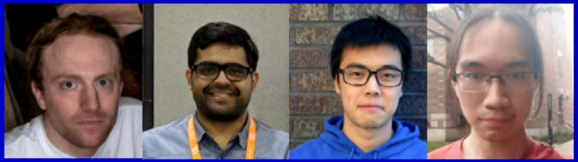
^{86}Sr ν=0 n=30 dimer, T=300nK



Rydberg Molecule Conclusions

- Ultralong-Range Rydberg molecules in strontium
- New probe of correlations in ultracold gases
- Resolved rotational states in photoexcitation spectrum
- Effects of interactions and photon recoil
- Many open questions

Thanks



- F. Barry Dunning, Soumya Kanungo, Yi Lu, Chuanyu Wang, Joe Whalen
- Hossein Sadeghpour, Richard Schmidt, Marcel Wagner, Shuhei Yoshida, Joachim Burgdorfer

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