Dark State Optical Lattice with a Subwavelength Spatial Structure

180319

Group Intro.

joint quantum institute
RESEARCH
PORTO GROUP

- James V. Porto
- Ph. D: Cornell University
  - Superfluidity of ^{3}He in aerogel
- University of Maryland, NIST
- Research Areas
  - Cold Atoms in Optical Lattices
  - Interacting Photons
  - Ultracold Rb/Yb Mixtures

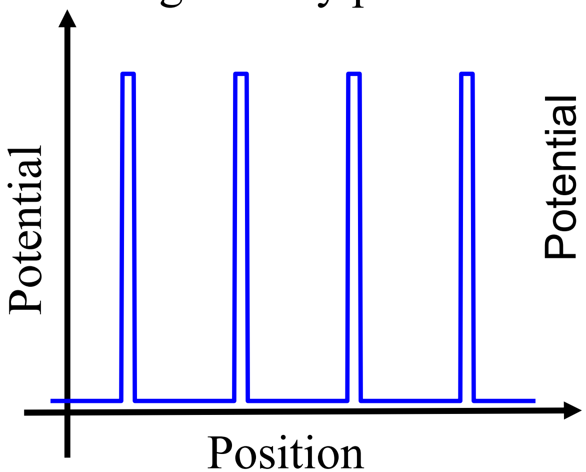
Publication

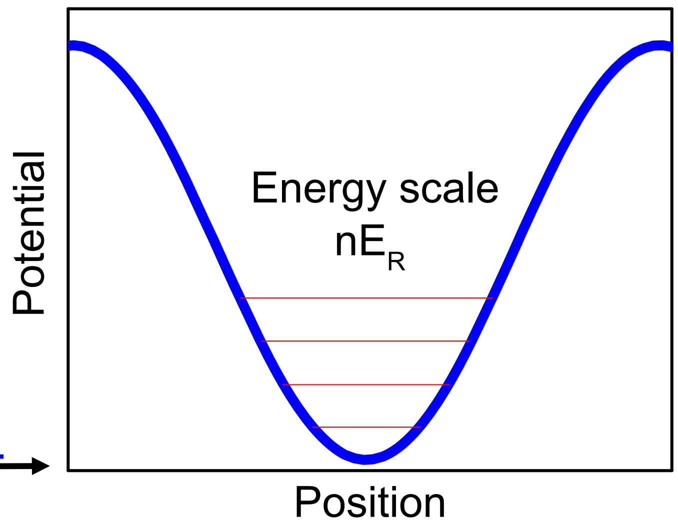
Dark State **Optical Lattice** with a Subwavelength Spatial Structure ← Today's paper
Dissipation induced dipole blockade and anti-blockade in driven **Rydberg** systems
Spontaneous avalanche dephasing in large **Rydberg** ensembles
Anomalous Broadening in Driven Dissipative **Rydberg** Systems
Nonlinear looped band structure of Bose-Einstein condensates in an **optical lattice**

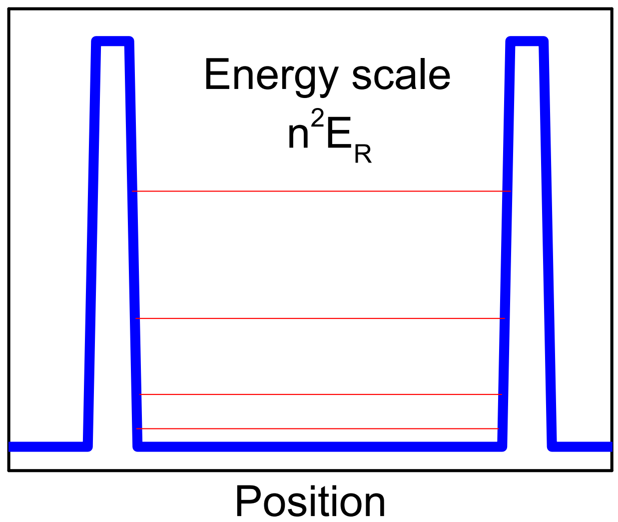
What they did

- Optical potentials with subwavelength spatial structure
- Kronig-Penney potential(widths below λ/50 ~ 10 nm)
- Study the band structure
- Subwavelength motional control of atoms
  - creation of narrow tunnel junctions for quantum gases
  - building sharp-wall box-like traps
  - studying Anderson localization with random strength in the barrier height

Kronig-Penney potential



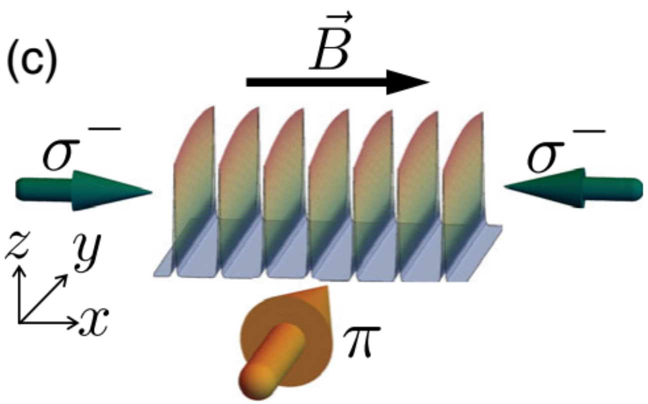


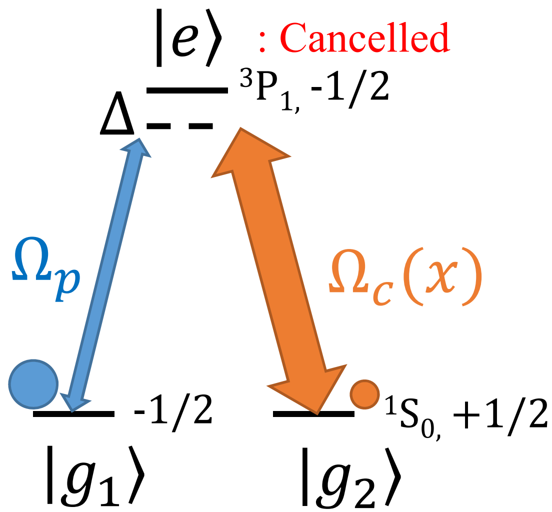


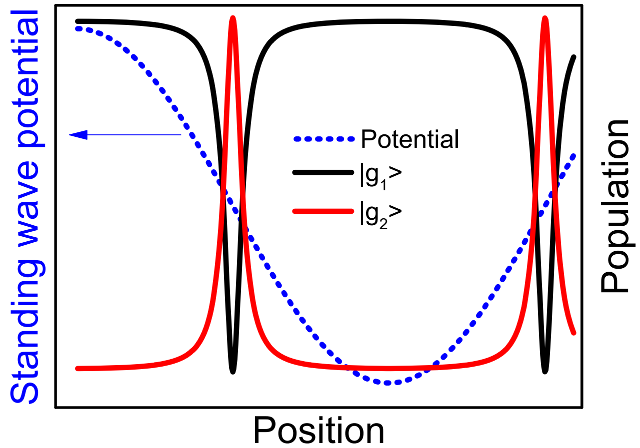
Schematics

- Standing wave light along x axis(Ω_c), traveling wave light along y axis(Ω_p)
- Dark state: $|E_0(x)\rangle = \sin\big(\alpha(x)\big)\,|g_1\rangle - \cos\big(\alpha(x)\big)\,|g_2\rangle$ → Eigenstate of internal state basis for fixed x

  where $\alpha(x) = \arctan\big[\Omega_c(x)/\Omega_p\big]$
- If $\Omega_p/\Omega_c = \epsilon \ll 1$, dark state changes composition over a narrow region.
- Atoms remain in the dark state under a adiabatic approx.(slowly moving atom)





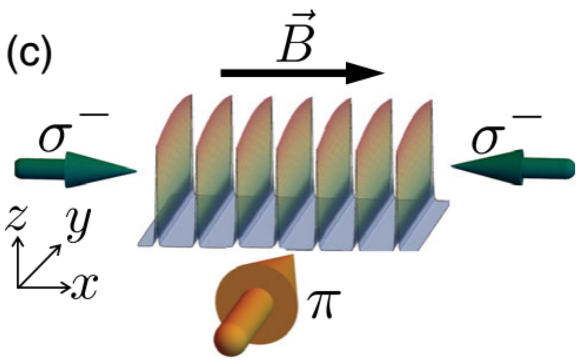


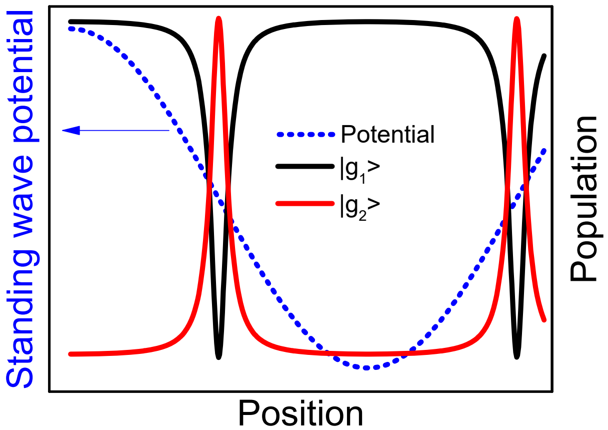
Schematics

- Atoms remain in the dark state under a adiabatic approx.(slowly moving atom)
- $\langle x|H|E_0(x)\rangle = \langle x|\left(\frac{\boldsymbol{P}^2}{2M}+U\right)|E_0(x)\rangle \Rightarrow \left(\frac{(\boldsymbol{P}-\boldsymbol{A})^2}{2M}+U(x)+V(x)\right)\psi_{E_0}(x)$
- For example, $\boldsymbol{P}|E_0(x)\rangle = -i\hbar\nabla|E_0(x)\rangle$

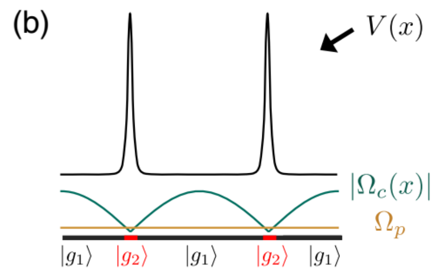
$$= \underbrace{-i\hbar\nabla\sin(\alpha(x))\,|g_1\rangle + i\hbar\nabla\cos(\alpha(x))\,|g_2\rangle}_{\text{Momentum term due to the state composition change}} + \underbrace{\sin(\alpha(x))\,\boldsymbol{P}|g_1\rangle - \cos(\alpha(x))\,\boldsymbol{P}|g_2\rangle}_{\text{Usual momentum term}}$$

- Kinetic energy associated with large gradient($\boldsymbol{P} = i\hbar\boldsymbol{\nabla}$) in the wave function gives rise to a potential. => Artificial scalar gauge potential



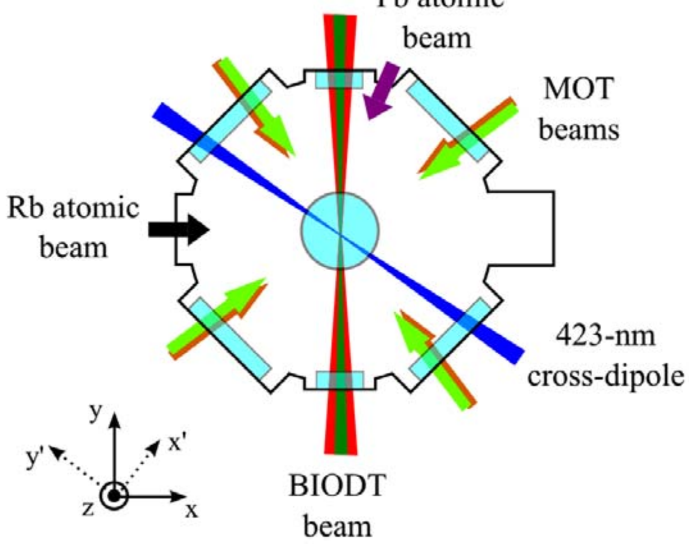


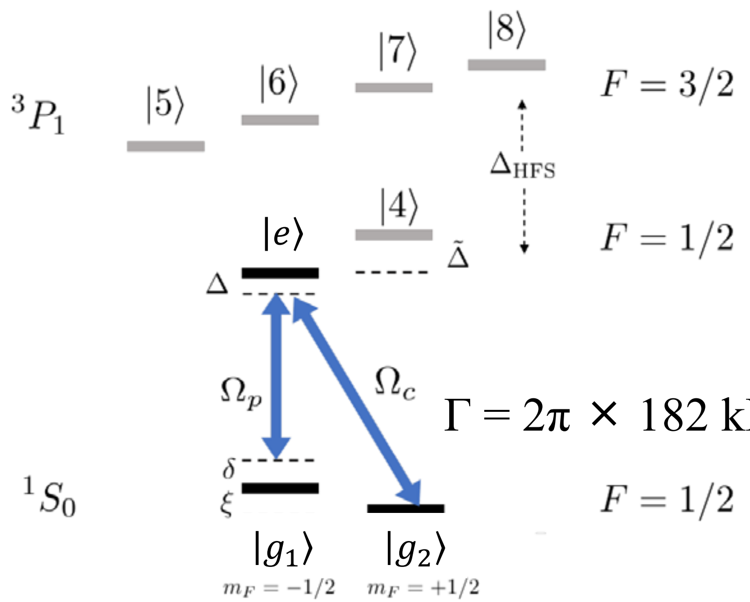
$$V(x) = \frac{\hbar^2}{2m}\left(\frac{d\alpha}{dx}\right)^2 = E_R\frac{\epsilon^2\cos^2(kx)}{[\epsilon^2+\sin^2(kx)]^2},$$



Experimental details

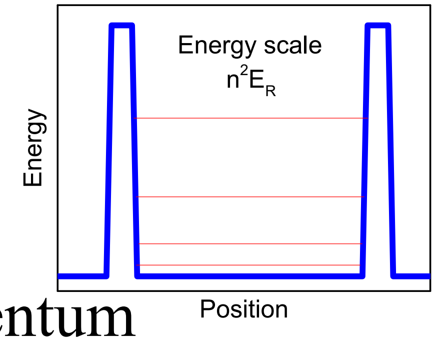
- Atom: ^{171}Yb
- Sympathetic cooling with ^{87}Rb atoms
- Yb MOT – Rb MOT – RF evaporation – load Rb – Dipole evaporation – remove Rb (T ~ 300 nK)
- Optically pump to $|g_1\rangle$ state and populate dark state by turning on Ω_{c1}, Ω_p, and Ω_{c2}, one by one.



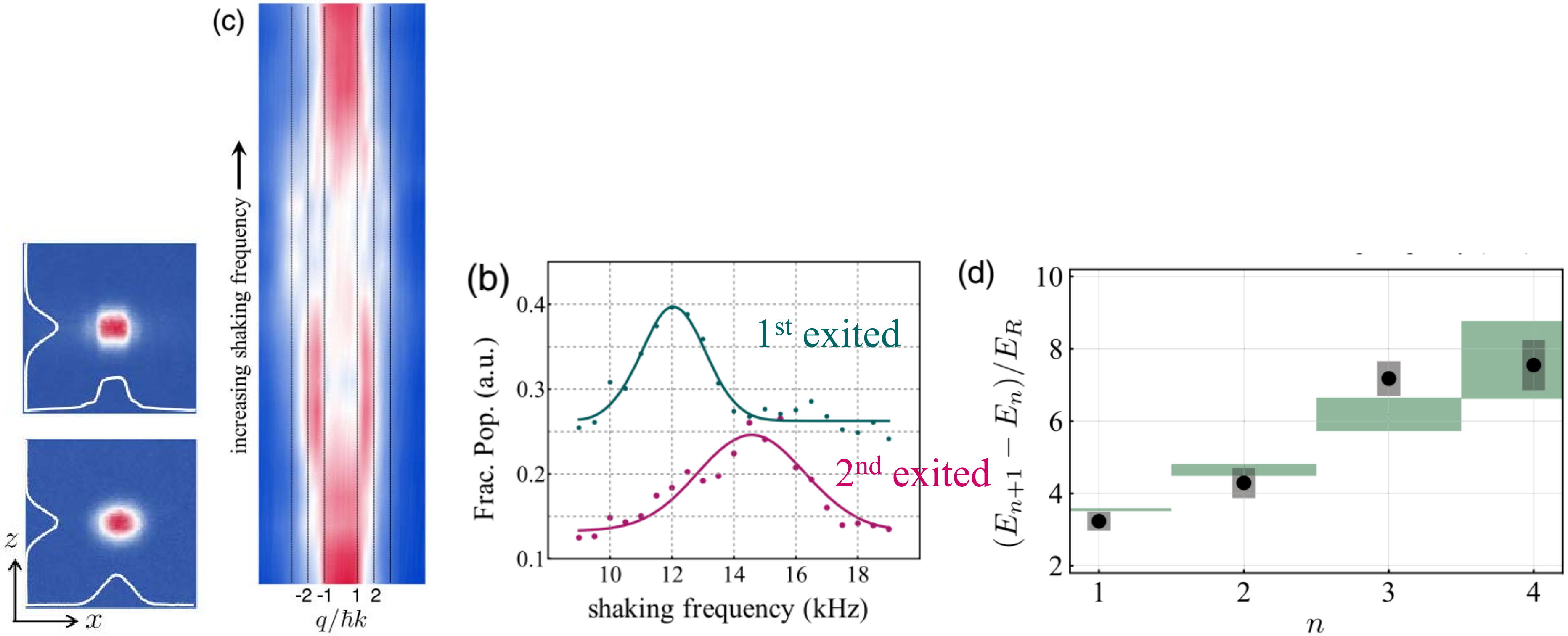


$\Gamma = 2\pi \times 182$ kHz

Band mapping



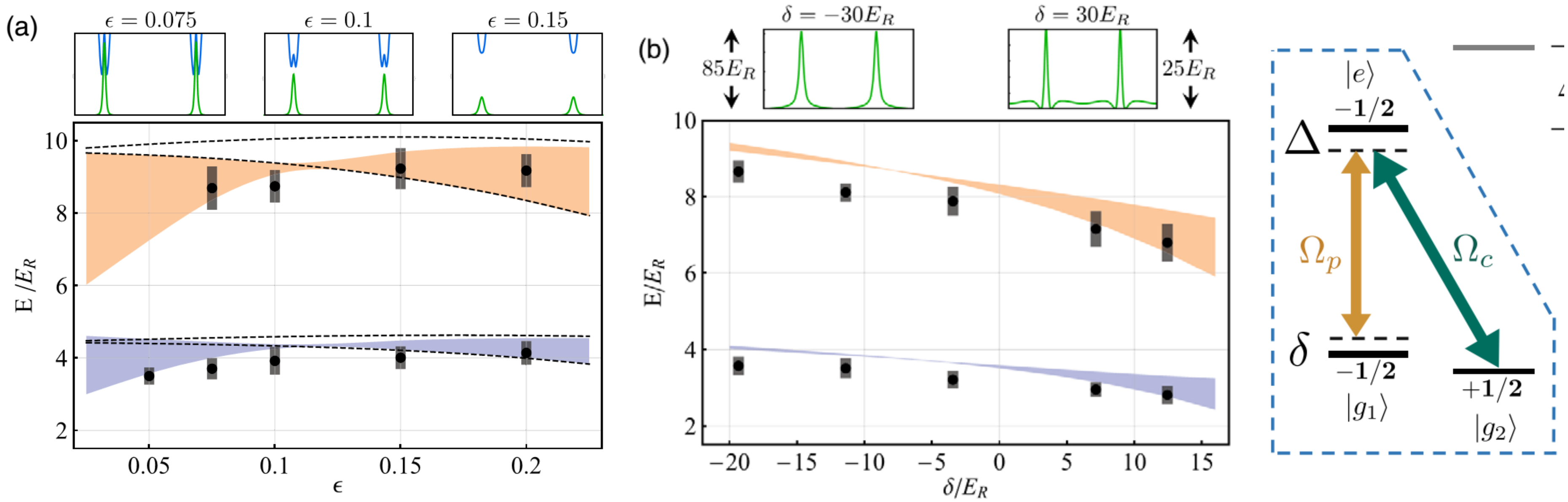
- Use time-of-flight (TOF) images to measure the momentum
- Excite atoms to higher bands by shaking the lattice
- Excitation depends on shaking frequency
- Energy spacing increases as n increases (E_n scales as n^2E_R)



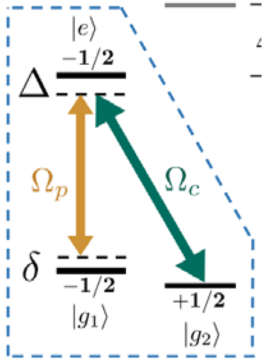
Barrier strength and perturbation

- Energy of KP lattice is independent of barrier strength
- By varying $\Omega_p(\epsilon)$, measured energy spacing
- When $\delta \neq 0$, the state experience additional potential and band structure changes

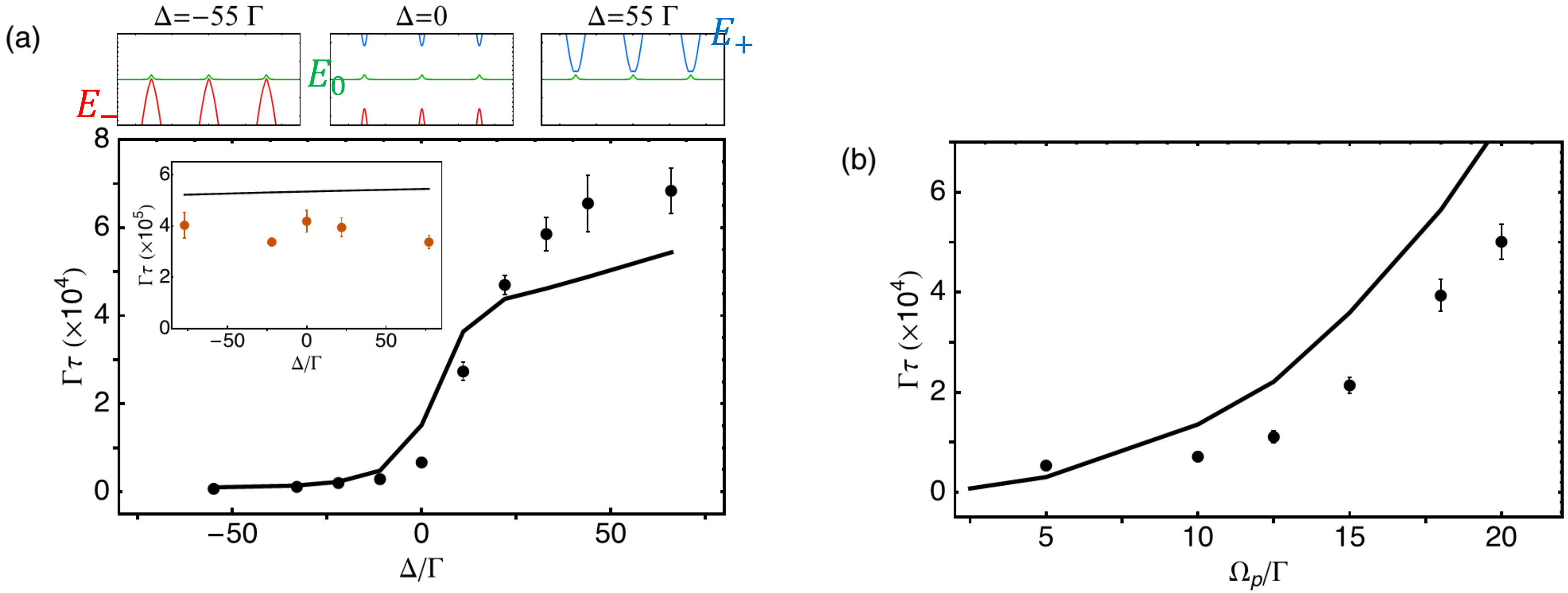
$$V(x) = \frac{\hbar^2}{2m}\left(\frac{d\alpha}{dx}\right)^2 = E_R \frac{\epsilon^2 \cos^2(kx)}{[\epsilon^2 + \sin^2(kx)]^2},$$



Dissipation



- Dark state lifetime is significantly longer for $\Delta > 0$.
- When $\Delta < 0$, exiting into the energy allowed E_- state via nonadiabatic bright state coupling
- Nonadiabatic bright state coupling also leads to dissipation dependence on the laser power.



Q&A

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Editors' Suggestion Featured in Physics

Dark State Optical Lattice with a Subwavelength Spatial Structure

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We report on the experimental realization of a conservative optical lattice for cold atoms with a subwavelength spatial structure. The potential is based on the nonlinear optical response of three-level atoms in laser-dressed dark states, which is not constrained by the diffraction limit of the light generating the potential. The lattice consists of a one-dimensional array of ultranarrow barriers with widths less than 10 nm, well below the wavelength of the lattice light, physically realizing a Kronig-Penney potential. We study the band structure and dissipation of this lattice and find good agreement with theoretical predictions. Even on resonance, the observed lifetimes of atoms trapped in the lattice are as long as 44 ms, nearly 10^5 times the excited state lifetime, and could be further improved with more laser intensity. The potential is readily generalizable to higher dimensions and different geometries, allowing, for example, nearly perfect box traps, narrow tunnel junctions for atomtronics applications, and dynamically generated lattices with subwavelength spacings.

Q&A

Q. Why they used Yb instead of Rb?

A. I think Yb^{171} has small scattering length and this non-interacting property seems essential for simplifying KP potential experiment. (If particles are interacting, then KP potential would not clear)

Q. Why does the time-of-flight image of the dark state has square shape?

A. Because $k_B T$ is less than the band gap, the band edge of first Brillouin zone shows sharp edge in the time-of flight image.

Q. What's the meaning of trap lifetime?

A. Sorry for the misleading words. Lifetime in this paper means lifetime of the dark state. Because of non-adiabatic coupling, population of $|E_0\rangle$ goes to $|E_\pm\rangle$ states. In this context, lifetime of the dark state is measured.