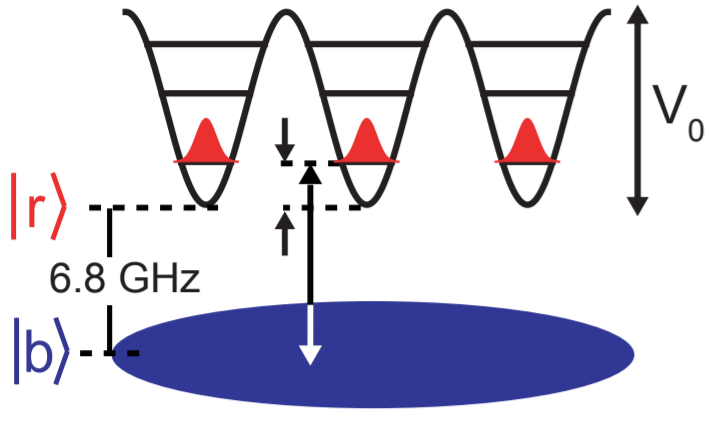


Driven Dynamics beyond the Born-Oppenheimer Approximation: Nonadiabatic Diffraction of Matter Waves

Jeremy Reeves, Ludwig Krinner, Michael Stewart, Arturo Pazmino, and Dominik Schneble
 Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794-3800, USA

Experimental Scheme and Orbital Transfer



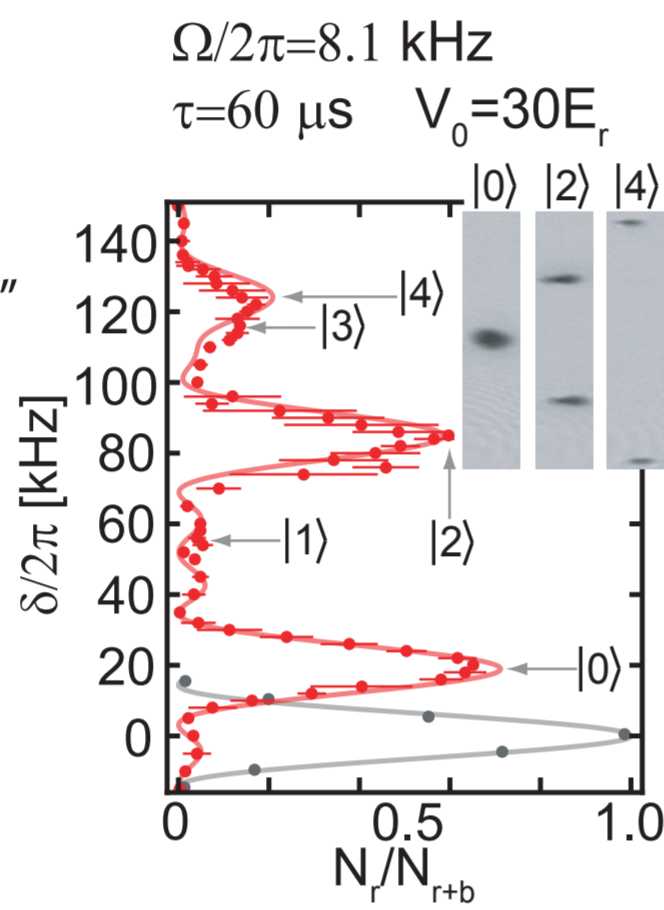
A BEC is coupled to the deep wells of a state-selective optical lattice via microwave driven hyperfine ground state transitions.

The Hamiltonian in the presence of Rabi coupling

$$H = \frac{\hat{p}^2}{2m} \mathbf{I} + \frac{\hbar}{2} \begin{pmatrix} 2V_0 / \hbar \sin^2(kz) - \delta & \Omega \\ \Omega & \delta \end{pmatrix}$$

Band Spectroscopy

Selectively transfer atoms into bands of the lattice. Band occupation is probed with a "band map" (right). $\Omega\tau = \pi$ in the $V_0 = 0$ case, line shapes are given by the Fourier transform of the pulse and Franck-Condon overlap of the band and free particle states.



Resonant Driving

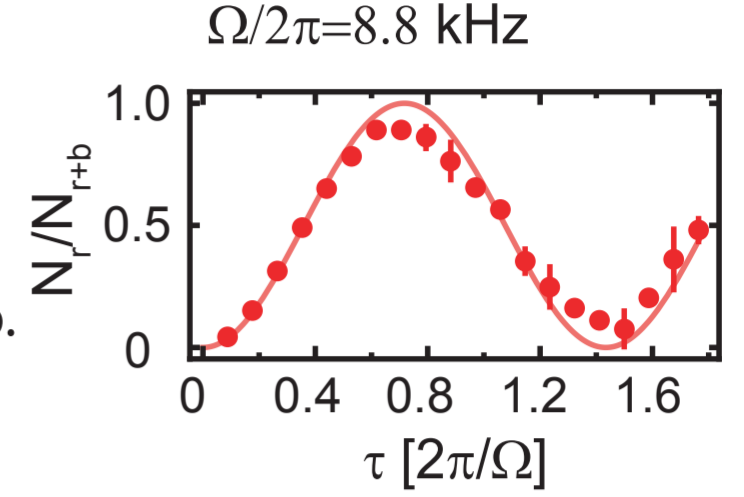
Weak coupling

$$\Omega < E_r^{(2)} = 14.8 \text{ kHz}$$

Rabi oscillations with Ω reduced by the Franck-Condon overlap.

$$\Omega \rightarrow \langle \varphi_{n=0,r} | \psi_b \rangle \Omega = 0.72 \Omega$$

Osc. contrast $\sim 100\%$, up to small detuning effects.

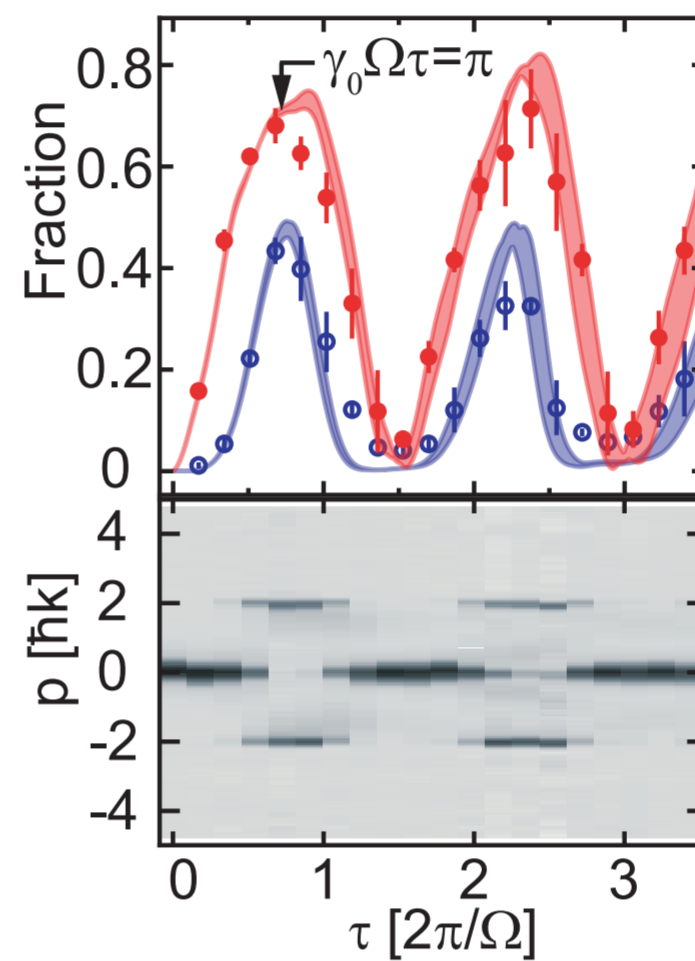


$$\Omega/2\pi = 17 \text{ kHz}$$

$$\bullet N_r/N_{r+b} \quad \circ N_{b,\pm 2}/2N_b$$

Strong coupling

$$\hbar\Omega > E_r^{(2)}$$

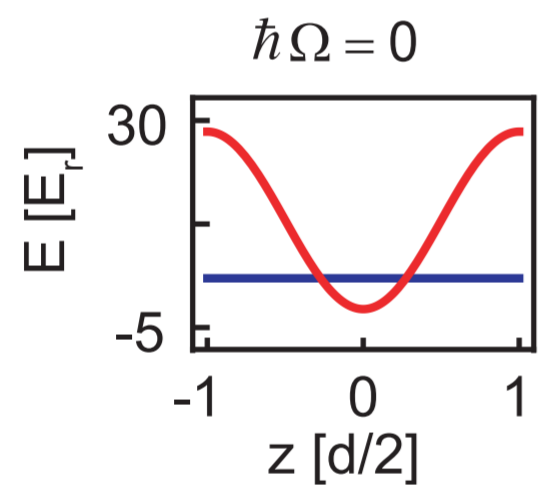


Reduction of oscillation amplitude is inconsistent with Rabi dynamics.

Coherent oscillations between $0\hbar k$ and $\pm 2\hbar k$ momentum states. The internal and external dynamics oscillate in phase, locked together.

Dressed State Picture

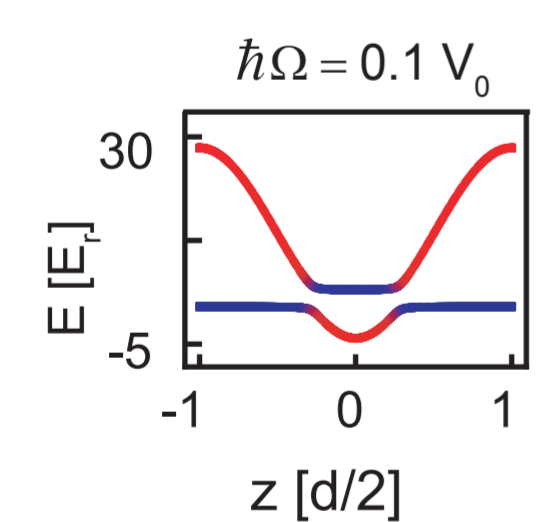
Bare state basis



- resonance condition satisfied twice per lattice site

$$\theta = \pi/2 \quad \theta = 0$$

Nonadiabatic case: weak coupling



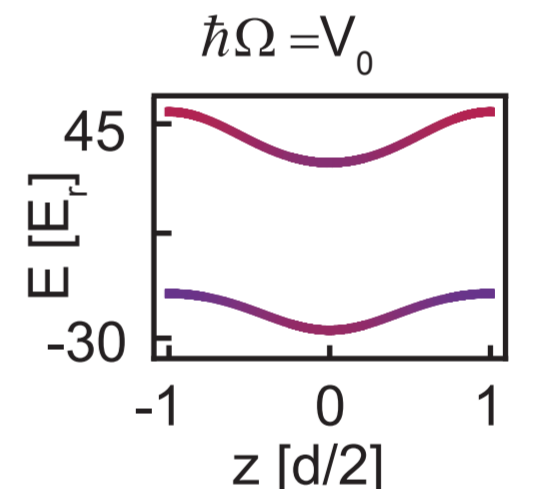
- Born-Oppenheimer approximation fails
- mixing angle varies rapidly and its gradient cannot be neglected

Adiabatic dressed states

- weak variation of the mixing angle; neglect kinetic energy
- coupling (larger than all other energy scales) splits the adiabatic potentials

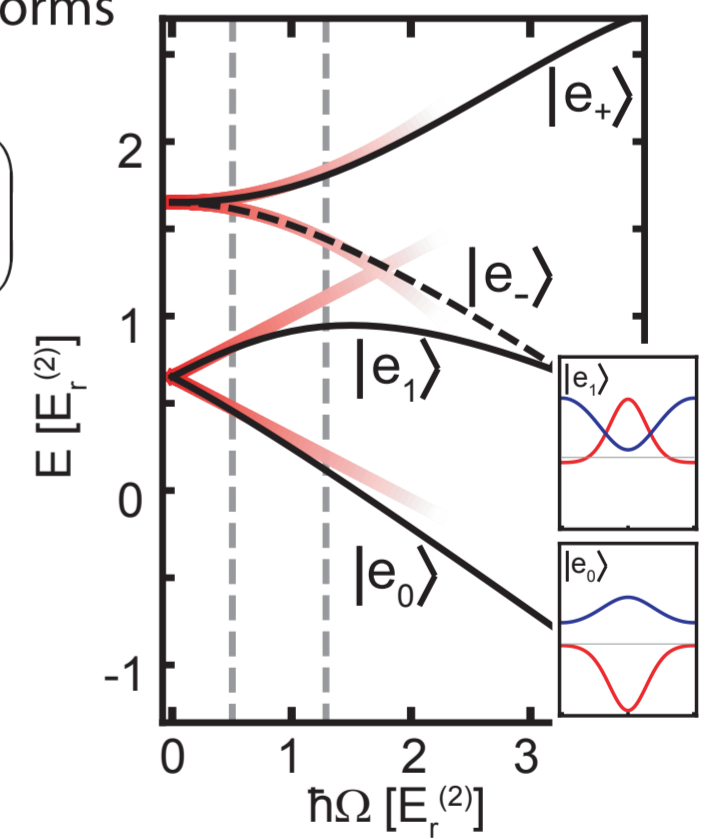
$$H = \begin{pmatrix} V_+(\Omega, \delta, z) & 0 \\ 0 & V_-(\Omega, \delta, z) \end{pmatrix} \quad \begin{pmatrix} |\chi_+\rangle \\ |\chi_-\rangle \end{pmatrix} = \begin{pmatrix} -\sin\theta & \cos\theta \\ \cos\theta & \sin\theta \end{pmatrix} \begin{pmatrix} |r\rangle \\ |b\rangle \end{pmatrix}$$

$$\cos 2\theta = -\delta(z) / \sqrt{\Omega^2 + \delta(z)^2}$$



- diagonalization of potential transforms momentum operator:

$$\hat{p} \Rightarrow \begin{pmatrix} \hat{p} - \langle \chi_+ | \hat{p} | \chi_+ \rangle & \langle \chi_- | \hat{p} | \chi_+ \rangle \\ \langle \chi_+ | \hat{p} | \chi_- \rangle & \hat{p} - \langle \chi_- | \hat{p} | \chi_- \rangle \end{pmatrix}$$



- weak coupling gives light shifts $\pm \gamma_{n=0} \Omega/2$ as expected for a two level system
- upper states see off-resonant light shift $\pm \gamma_{n=0} \Omega^2/4\delta$
- For $\hbar\Omega > E_r^{(2)}$ higher momentum states get mixed into the dressed states, and the resulting "free" eigenstates of the dressed system take on periodicity of the lattice

Emergence of Adiabatic Diffr.

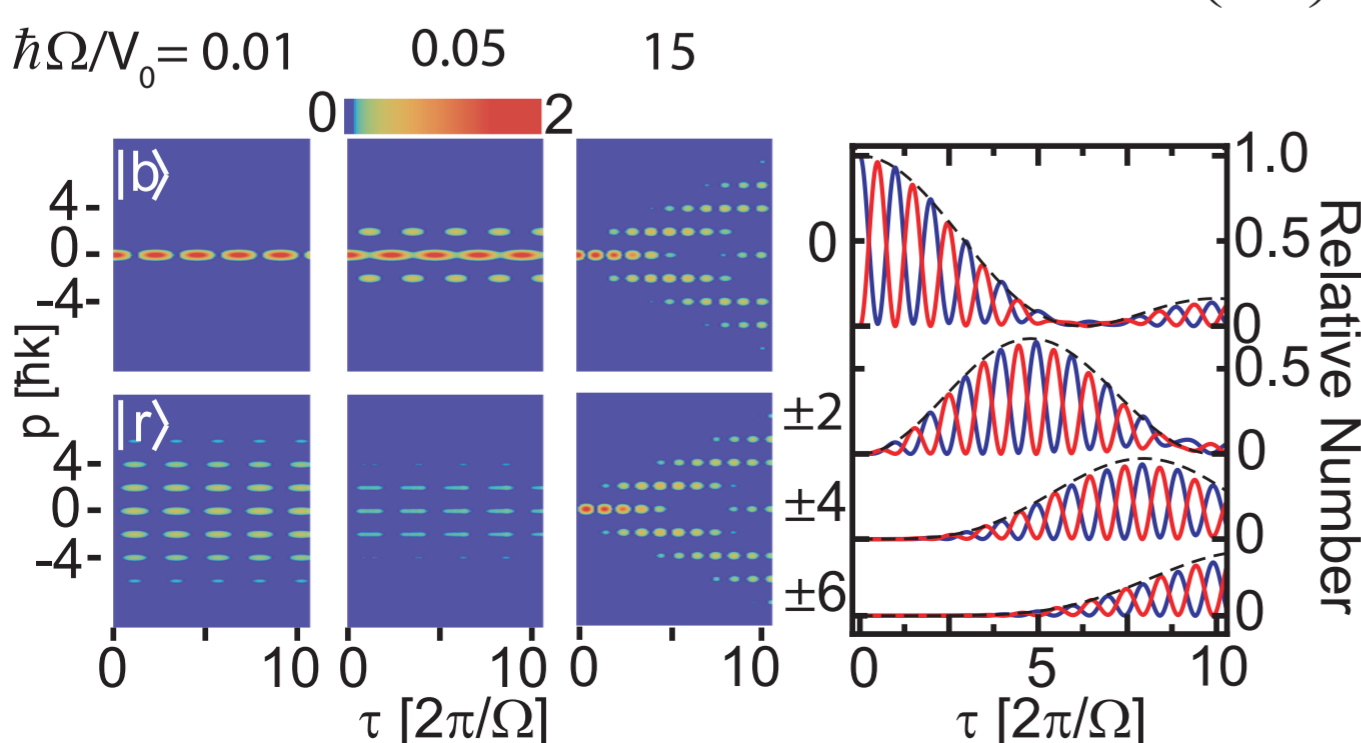
Connecting to Kapitza-Dirac Diffraction

For strong coupling $\hbar\Omega > V_0$, internal and external dynamics decouple.

Regain envelopes for standard Raman-Nath diffraction:

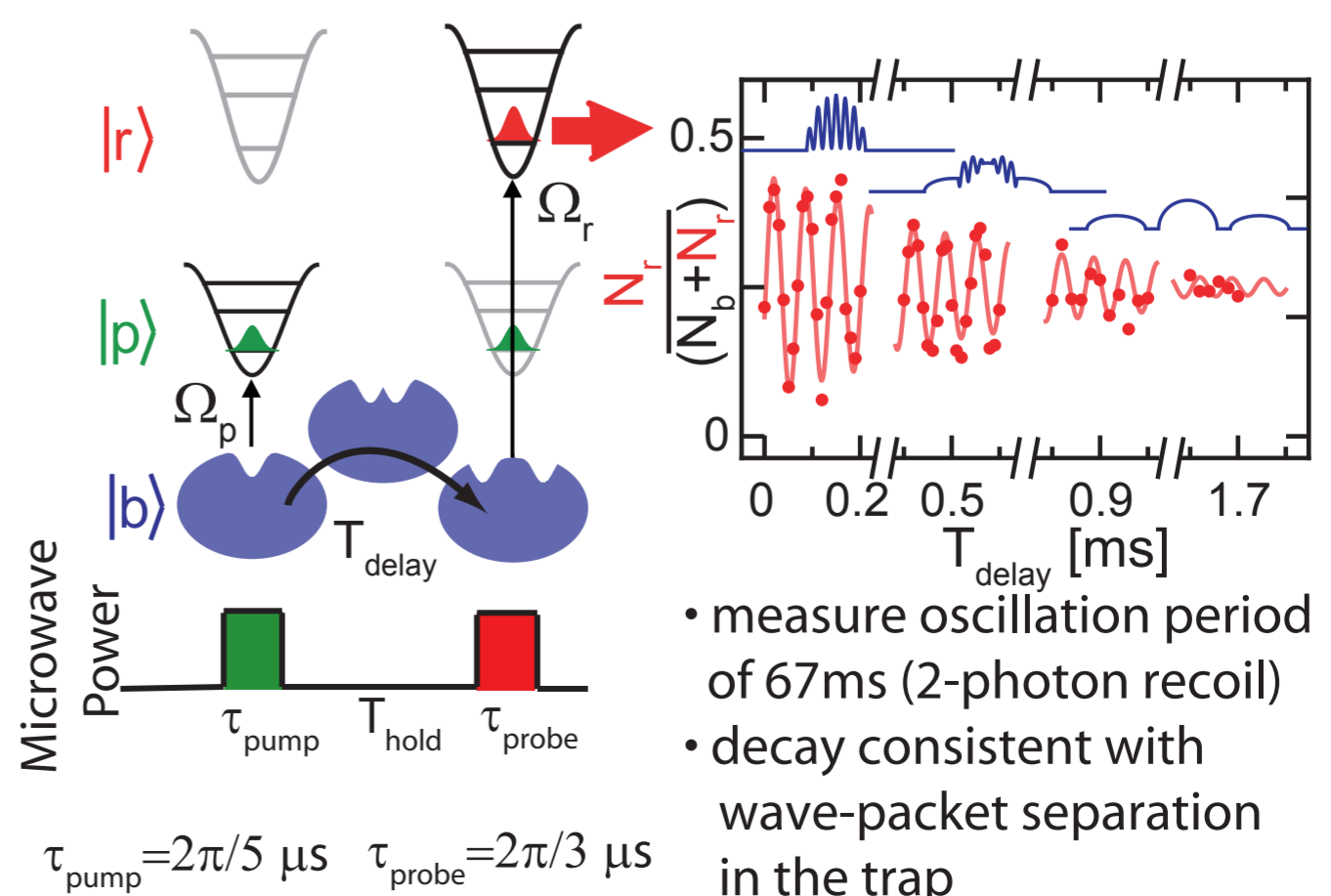
Time dynamics from nonadiabatic to adiabatic

$$P_{2n\hbar k}(t) = J_n^2 \left(\frac{V_0 t}{2\hbar} \right)$$



Condensate Dynamics

In-situ atom interferometry



- measure oscillation period of 67ms (2-photon recoil)
- decay consistent with wave-packet separation in the trap

$$\tau_{\text{pump}} = 2\pi/5 \mu\text{s} \quad \tau_{\text{probe}} = 2\pi/3 \mu\text{s}$$