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

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Experimental Scheme and Orbital Transfer

The Hamiltonian in the presence of Rabi coupling

\[ H = \frac{\hat{p}^2}{2m} + \frac{\hbar}{2} \left( 2V_{\text{ext}} / \Omega \sin^2(kz) - \frac{\delta^2}{\Omega^2} \right) \]

Band Spectroscopy

Selectively transfer atoms into bands of the lattice. Band occupation is probed with a "band map" (right). \( \Omega_{\text{latt}} \) in the \( V_{\text{ext}}=0 \) case, line shapes are given by the Fourier transform of the pulse and Franck-Condon overlap of the band and free particle states.

Dressed State Picture

Bare state basis

Nonadiabatic case: weak coupling

- resonance condition satisfied twice per lattice site
- \( \theta = \pi/2 \) (blue), \( \theta = 0 \) (red)

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

- weak coupling gives light shifts \( z \propto \Omega^2 / 2 \) as expected for a two level system
- upper states see off-resonant light shift \( z \propto \Omega^{(2)} / 4 \)
- For \( \hbar \Omega > E_0 \) 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 Diffrr.

Connecting to Kapitza-Dirac Diffraction

For strong coupling \( \hbar \Omega \gg V_e \), internal and external dynamics decouple. Regain envelopes for standard Raman-Nath diffraction:

\[ P_{\text{non}}(\tau) = \frac{\exp(-\frac{\tau^2}{2\sigma^2(\tau)})}{\sqrt{2\pi}\sigma(\tau)} \]

Condensate Dynamics

In-situ atom interferometry

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

Resonant Driving

Weak coupling \( \Omega < E_0 \frac{\gamma}{2} = 14.8 \text{ kHz} \)

Rabi oscillations with \( \Omega \) reduced by the Franck-Condon overlap:

\[ \Omega \gg \frac{\gamma}{2} \]

Osc. contrast \(-100\%\), up to small detuning effects.

Strong coupling \( \hbar \Omega > E_0 \)

Reduction of oscillation amplitude is inconsistent with Rabi dynamics.

Coherent oscillations between \( \hbar \Omega \) and \( 2\hbar k \) momentum states. The internal and external dynamics oscillate in phase, locked together.