Formation and decay of a Bose-Einstein condensate in the higher band of a double well optical lattice

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Motivation

- Simulations of condensed matter systems with atoms in optical lattices.
- The new thing is, we can modify the lattice and the band structure in real time.
- Bose condensation in different dimensionalities. In particular we are going from a 1D to a 3D system.
- BEC's beyond Feynman's 'no-node' theorem in excited metastable bands.
- The lattice we are going to study is inspired by a neat experiment.
  [G.Wirth et al.,Nature Physics,doi:10.1038/nphys1857(2010)]

2D Lattice potential with weak confinement in the 3rd direction

- The mathematical form for the trapping potential is

  $$V(x, y) = -|V_0| \left(\cos^2 k_L x + \cos^2 k_L y + 2\cos\theta \cos k_L x \cos k_L y\right).$$

  In addition, it is important to note that there is also a weak harmonic trapping potential in the z-direction.

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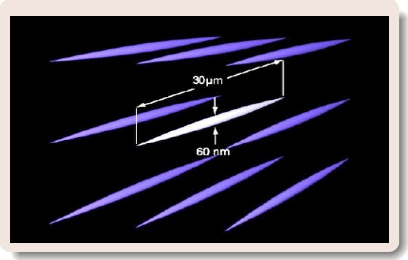
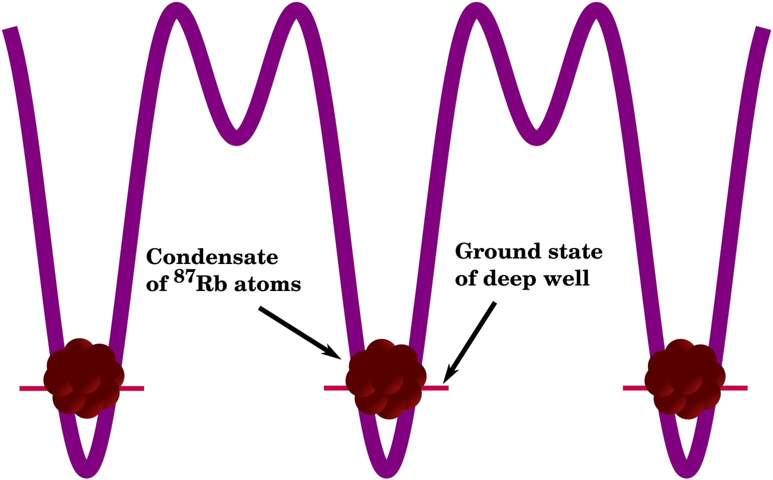
- The trapped atoms look like a 2D array of cigars.



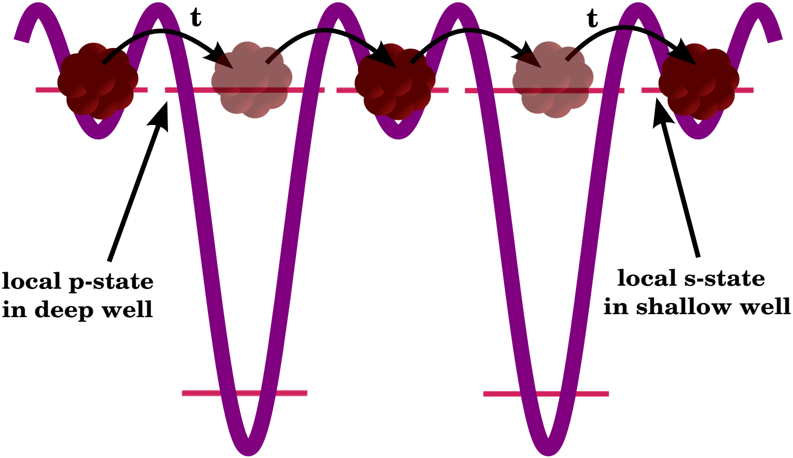
How do they populate the excited bands? Step#1



$\theta < \pi/2$

How do they populate the excited bands? Step#2

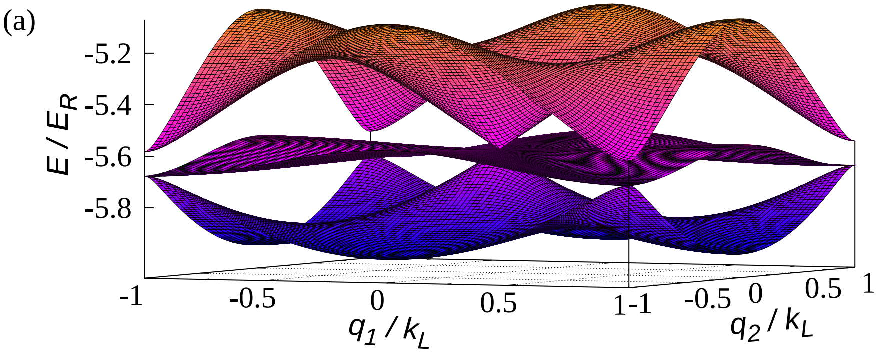
Tunneling re-distributes the atoms among all sites.



$\theta > \pi/2$

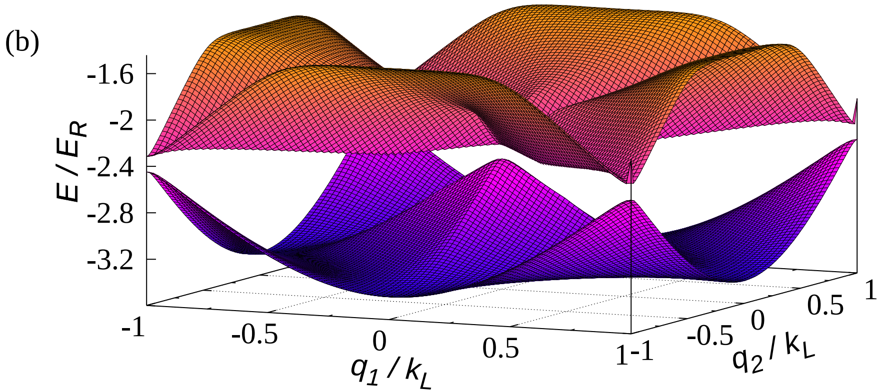
Band Structure in a plane wave basis

- The 2^{nd}, 3^{rd} and 4^{th} bands.
- The atom population is maximum in the 2^{nd} band, followed by the 3^{rd} and 4^{th} bands.



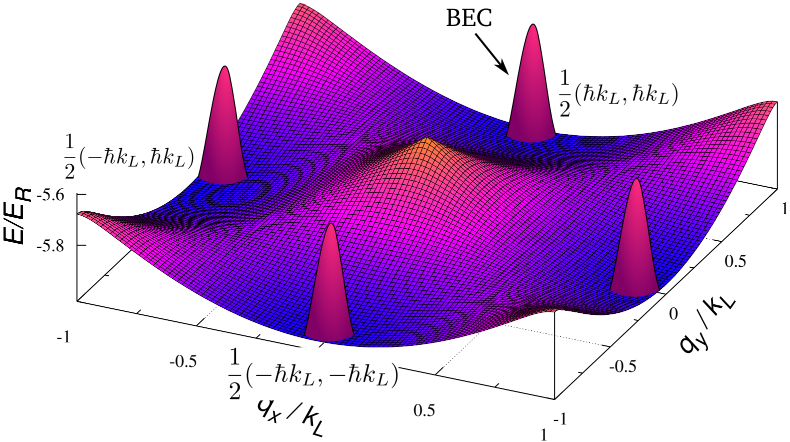
Band Structure in a plane wave basis

- The 5^{th} and 7^{th} bands.
- These higher bands provide channels for collision-aided decay of the condensate from the 2^{nd} band.



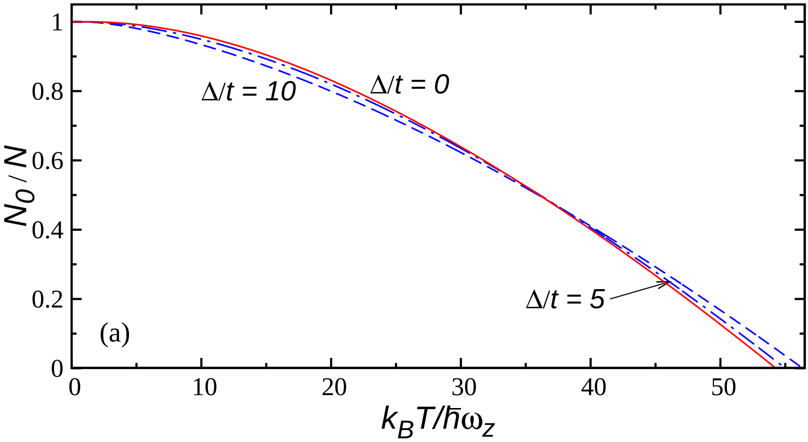
Tight binding calculation of the band structure and formation of a Bose Einstein Condensate

First excited band, as a function of 2D quasi momenta, in the 1st Brillouin zone.



Critical temperature for a non-interacting Bose gas

- At $\Delta/t = 0$, the adjacent s and p orbitals are resonant.
- The corresponding critical temperature is $k_B T_c \approx 55\hbar\omega_z$.



Lattice transformation and final temperature

We model the lattice transformation to be

- adiabatic with respect to the onsite energies in each well,
- rapid with respect to tunneling energy between adjacent wells.
- The final temperature T_f drastically depends on Δ.

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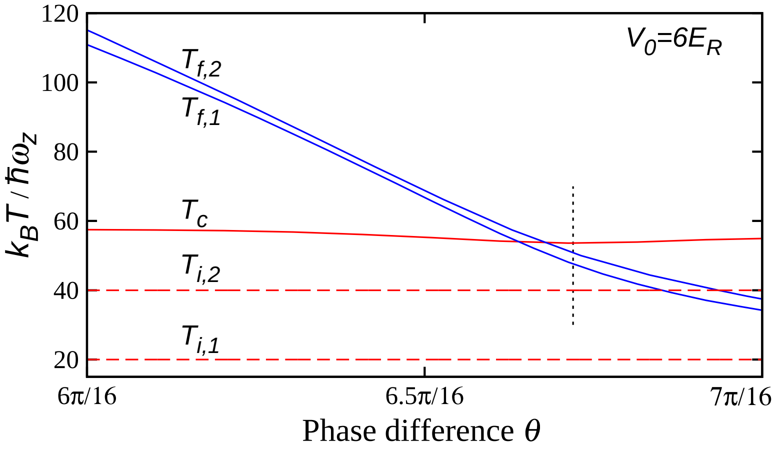
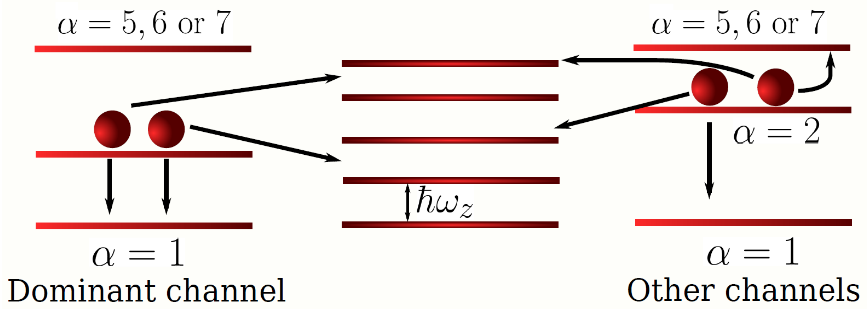


Decay channels for the condensate

- The condensate formed in the 2^{nd} band decays to the ground band by a 2 body collision aided decay process.
- Allowed decay channels require the band gaps $\delta_{12} \geq \delta_{\alpha 2}$ for $\alpha > 2$.
- Energy conservation is provided by the oscillator states along z axis.



Decay rate $\Gamma_{22\to 1\alpha}$

$$\Gamma_{22\to 1\alpha} = \frac{N_0(N_0-1)}{2M^2}\gamma_{22\to 1\alpha}(\mathbf{K}_0, 0) + \sum_{\mathbf{K},m'} \frac{N_0 n(\mathbf{K},m')}{M^2}\gamma_{22\to 1\alpha}(\mathbf{K}, m')$$

- The first term refers to collisional loss involving two condensate atoms.
- The second term sums over the collisional losses involving one condensate atom and another thermal atom in the second band.

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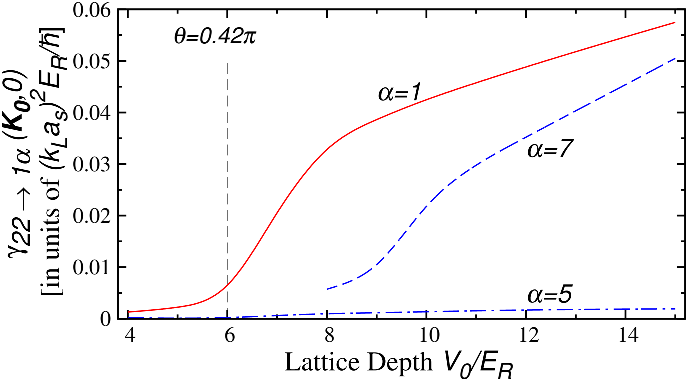

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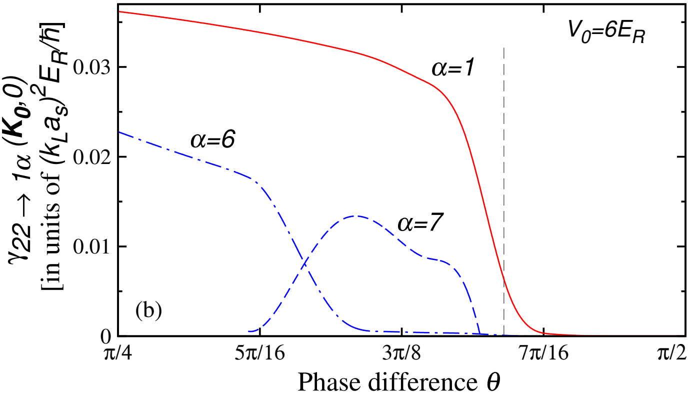
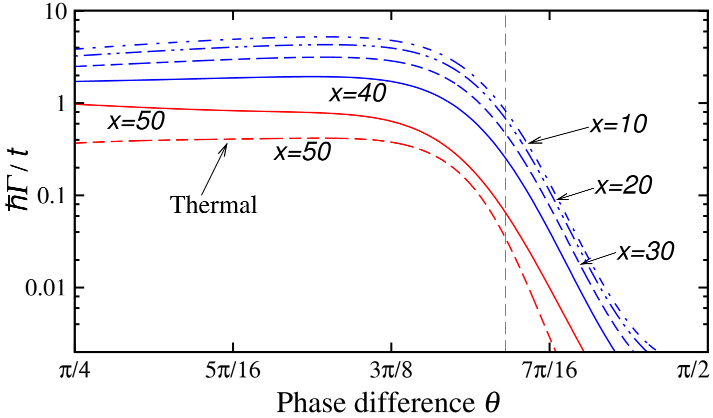


Total Decay rate $\Gamma = \sum_\alpha \Gamma_{22\to 1\alpha}$

- For $\Delta/t \approx 0$, $T_f \approx T_c$. At these parameter values, the corresponding tunneling energy $t \gg \hbar\Gamma$. Thus, for chosen parameter values, these higher bands are metastable.
- In the figure below, $x = k_B T/\hbar\omega_z$.



Summary

- We have theoretically analyzed the formation of a BEC in the excited band of a double well optical lattice, at the edge of the first and second Brillouin zone.
- The lattice transformation process leading to atom population in the higher bands leads to a heating of the atom cloud.
- The final temperature reached, $T_f \gtrsim T_c$, thus the condensate fraction is relatively small.
- For a collision aided decay process, the dominant channel involves both atoms decaying to the ground band.
- The decay rate Γ and the final temperature T_f drastically depends on the detuning between the s and p orbitals.
- The thermal contribution to the decay rate is as large as the collisional loss involving both condensate atoms.