Investigation of the dynamics of a Bose-Einstein condensate in a moving optical potential

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Outline

Dynamics of a BEC in a periodic potential

Linear Regime - low atomic density (expanded BEC)

- stable dynamics of the system is well described in terms of Bloch theory
- investigation of Bloch oscillations, Wannier-Stark ladders, and Landau-Zener tunneling

NonLinear Regime - high atomic density (trapped BEC)

A dilute atomic Bose-Einstein condensate in an external potential is described by the Gross-Pitaevskii equation

$$i\hbar \frac{\partial}{\partial t}\Phi(\mathbf{r},t) = \left(-\frac{\hbar^2 \nabla^2}{2m} + V_{ext}(\mathbf{r}) + g\left|\Phi(\mathbf{r},t)\right|^2 \right)\Phi(\mathbf{r},t)$$

kinetic term — external potential — interactions - non linear term

- the Bloch waves are not stable solutions of the Gross Pitaevskii equation (GPE)

- dynamical & energetic instabilities

EXPERIMENT: TIME EVOLUTION OF A HARMONICALLY TRAPPED CONDENSATE LOADED INTO A MOVING 1D OPTICAL LATTICE

Instabilities of a trapped BEC in a moving optical lattice

A repulsive condensate in a periodic potential may suffer both:

ENERGETIC INSTABILITY

When the system flows with velocity v>c, then the system can lower its energy by emitting phonons (Landau criterion) (in the presence of dissipative processes)

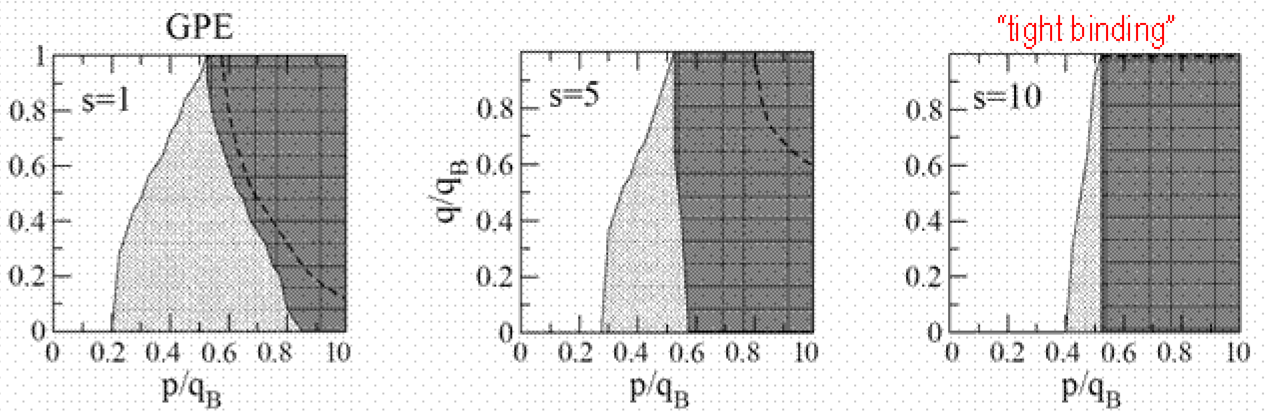
DYNAMICAL INSTABILITY

the frequency of some modes in the excitation spectrum has a nonzero imaginary part. The occupation of these modes grows exponentially in time and rapidly drives the system away from the steady state.

Stability diagram for a BEC in an 1D optical lattice: full 3D calculations by M. Modugno, C. Tozzo, and F. Dalfovo **cond-mat/0405653** (previously in 1D: Wu and Niu PRA **64** 061603 (2001))

$s = V_0/E_R$
p = condensate quasimomentum
q = excitation quasimomentum

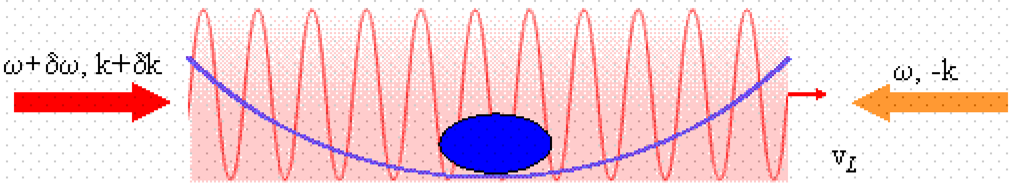
energetic instability
dynamical & energetic instability



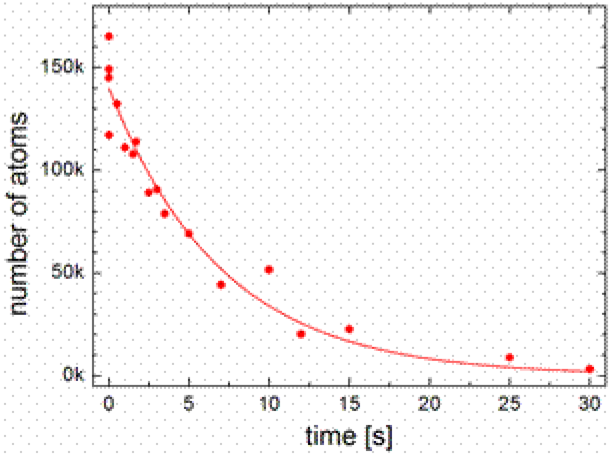
Experimental probe of instability

We adiabatically switch on a moving optical lattice in order to load the trapped BEC in a state with well defined quasimomentum **q** and band index **n**.

The moving optical lattice is produced with the interference of two counterpropagating off-resonant laser beams with different frequencies.



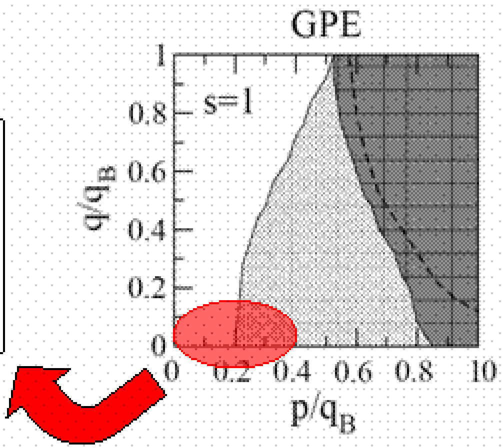
Regardless of which is the mechanism responsible for the onset of instability, losses of atoms in the condensate ground state are expected.



Exponential fit of number of atoms vs. time

Energetic instability

Investigate in low quasimomentum regime



energetic instability

dynamical & energetic instability

$s=V_0/E_R$

p condensate quasimomentum

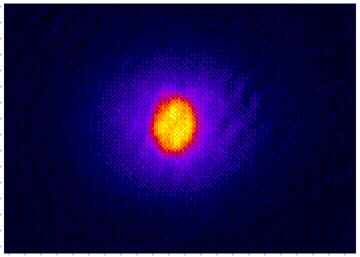
q excitation quasimomentum

Stability diagram for a BEC in an 1D optical lattice: full 3D calculations by M. Modugno, C. Tozzo, and F. Dalfovo **cond-mat/0405653**

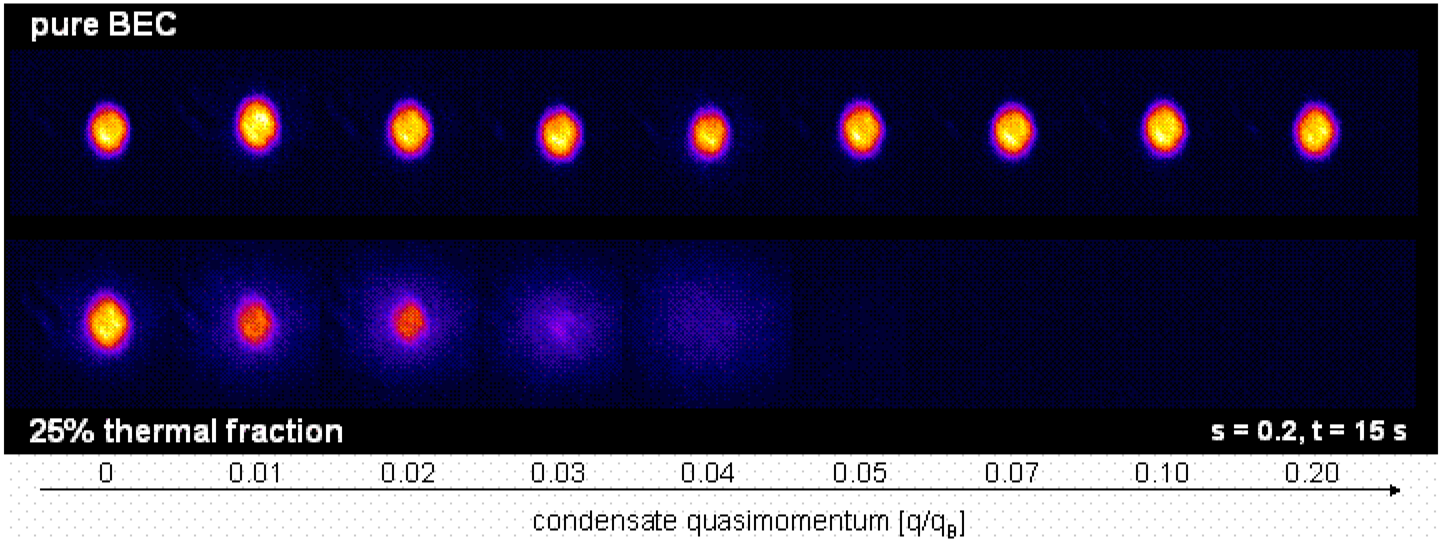
The experiment is performed in the presence of a dissipative process:

THERMAL COMPONENT

$T \sim T_C$



Energetic instability



We attribute this behaviour to the onset of **energetic instability** (in a inhomogeneous system), occurring in the presence of dissipative processes, as those provided by the thermal fraction.

Energetic instability for an inhomogeneous sample

We expect energetic instability for: $v > c \propto \sqrt{n}$

Since the BEC is not homogeneous, the threshold for the activation of energetic instability is not sharp. A fraction of the BEC (dependent on q) has a local sound velocity higher than the velocity of the lattice (Landau criterion)

⇓

knowing the BEC density distribution one can calculate the fraction of atoms having a sound velocity greater than the center of mass velocity

$$f_{q_0}(q) = \sqrt{1-\left(\frac{q}{q_0}\right)^2}\left[1+\frac{1}{2}\left(\frac{q}{q_0}\right)^2\right]\theta\left(1-\frac{q}{q_0}\right)$$

where: $\theta(x)$ Heaviside function q_0 threshold value for homogeneous cylindrical condensate

⇓

expected number of atoms :

initial number of atoms

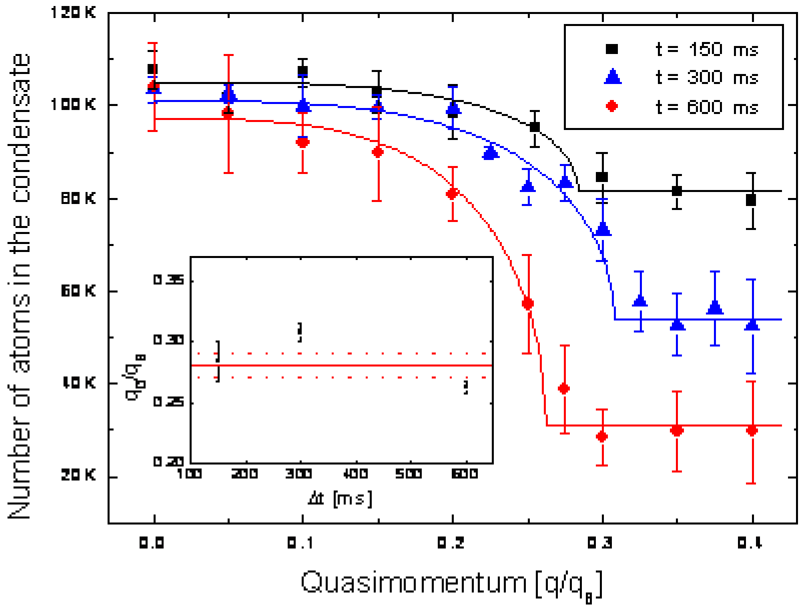
fraction of atoms having c>q (stable fraction)

$$N(q,t) = (N_0 + b(t))f_{q_0}(q) + b(t)$$

atoms remaining in the condensate once it is entirely unstable

$$N(q,t) = (N_0 - b(t))f_{q_0}(q) + b(t)$$

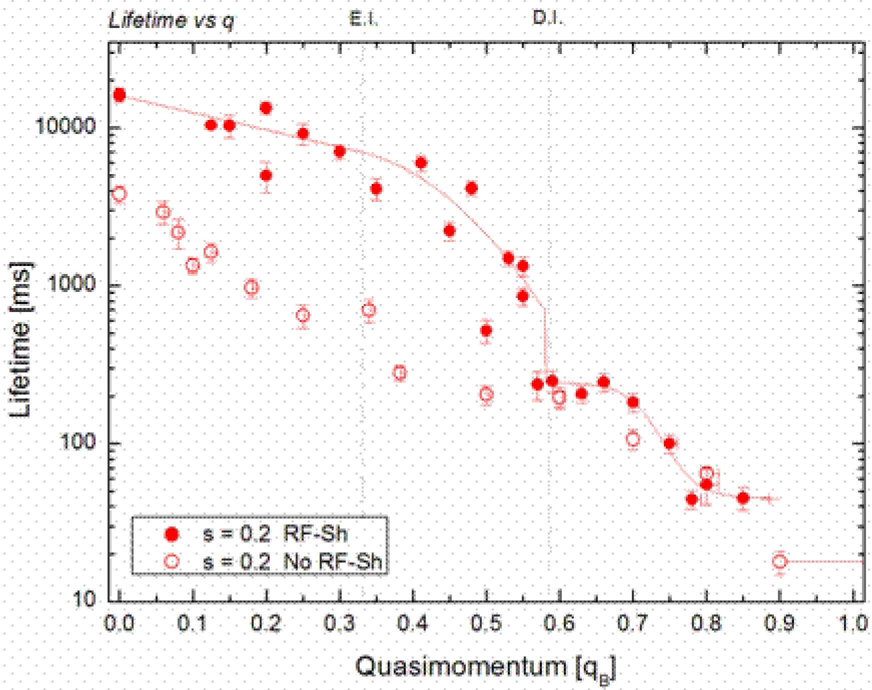
s = 0.2
35% thermal fraction



q_0 threshold value for homogeneous cylindrical condensate

Energetic instability timescale:
$\tau \approx$ **400 ms**

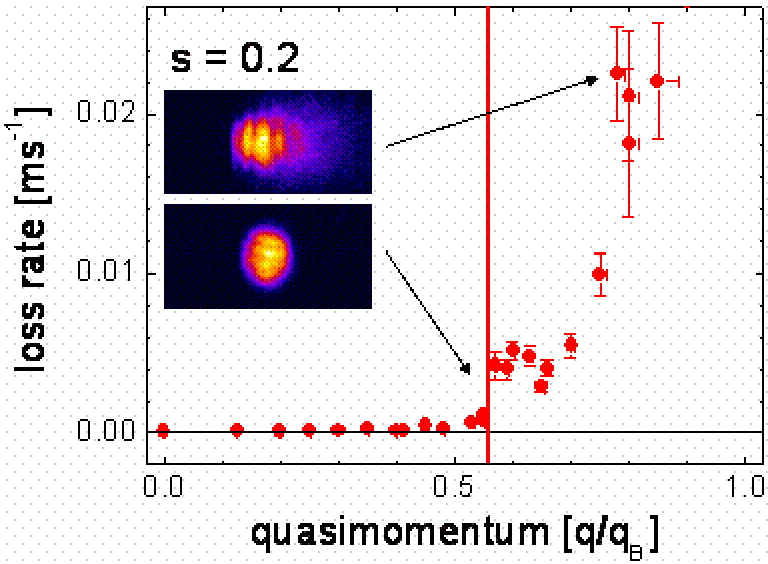
Removing energetic instability



Without the RF-shield, the transition to the DI regime is masked by the effect of energetic instability.

In the presense of the RF shield, the transition is clearly visible.

Investigating dynamical Instability

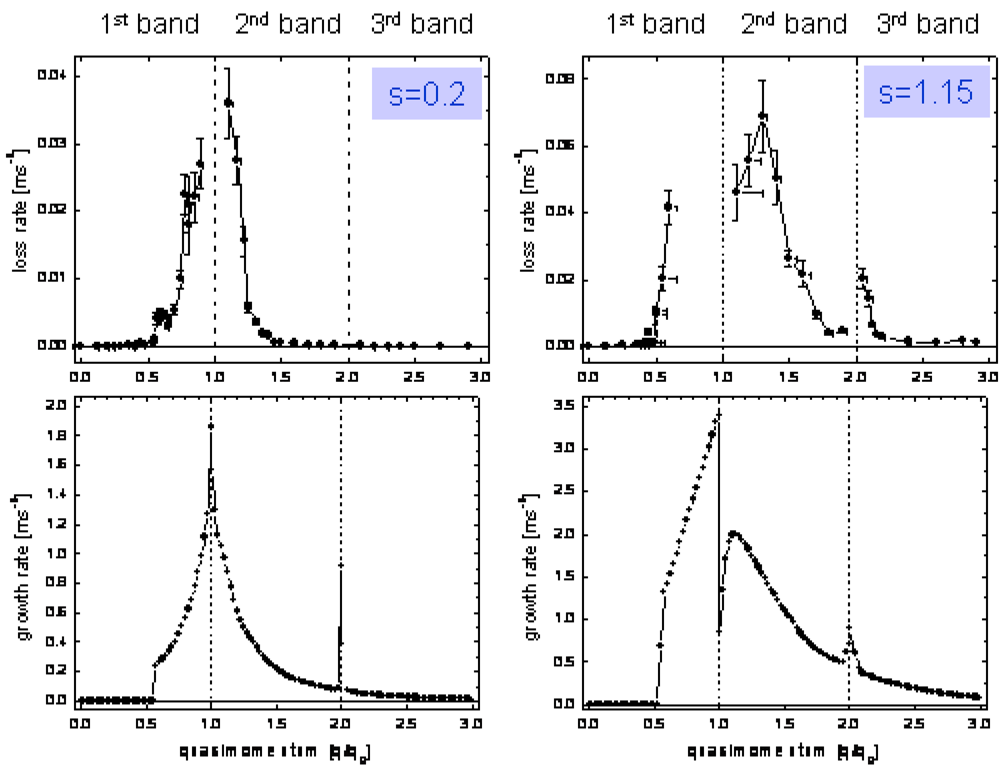


signatures

- A threshold value of quasimomentum at which the atom loss rate dramatically increases.

- Deeply in the dynamically unstable regime we observe the appearance of some complex structures in the expanded BEC density profile

Dynamical instability in the higher bands



experiment

atom **loss rate**
from the BEC

↕

theory

growth rates of
the most dynamically
unstable modes, *M, Modugno*
(from the linear stability
analysis of the NPSE :
Introduced by L. Salasnich *et al.*, PRA **65**, 043614 (2002))

L. Fallani, L. De Sarlo, J. E. Lye, M. Modugno, R. Saers, C. Fort, and M. Inguscio, PRL ***93*** *140406 (2004)*

Conclusions

- Instabilities in the NonLinear Regime - high atomic density (trapped BEC)

EXPERIMENT: TIME EVOLUTION OF A HARMONICALLY TRAPPED CONDENSATE LOADED IN A MOVING 1D OPTICAL LATTICE

- ✓ Evidence of energetic instability in the presence of a thermal component
- ✓ Evidence of dynamical instability
- ✓ Good agreement between the experimental loss rates and the theoretical growth rates of dynamical instability
- ✓ Deeply in the dynamically unstable regime appearance of complex structures (loss of coherence in the atomic sample)
- ✓ energetic instability destroys the system on a longer timescale with respect to dynamical instability (exponential growth)