An Intimate Gathering of Bosons

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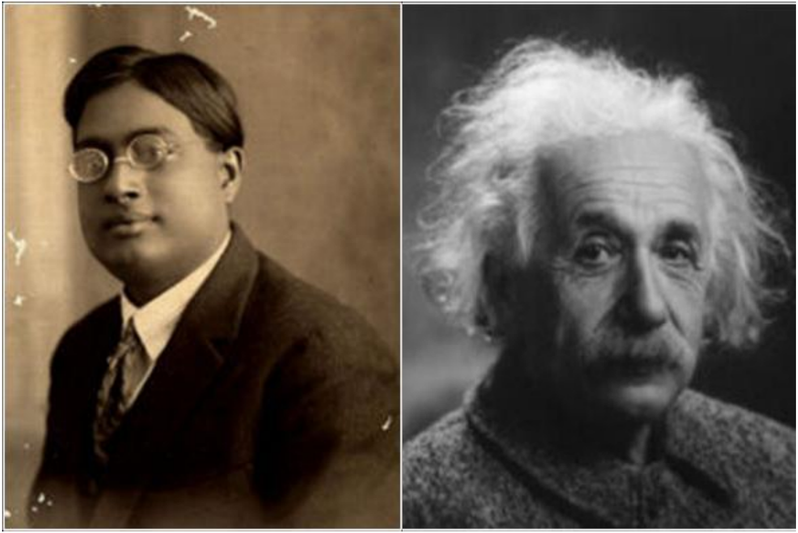
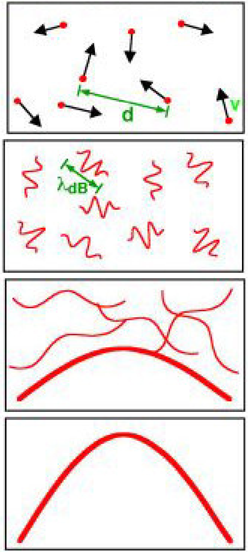
Bose-Einstein condensation



What is Bose-Einstein condensation (BEC)?



High Temperature T:
thermal velocity v
density d^{-3}
"Billiard balls"

Low Temperature T:
De Broglie wavelength
$\lambda_{dB}=h/mv \propto T^{-1/2}$
"Wave packets"

$T=T_{crit}$:
Bose-Einstein Condensation
$\lambda_{dB}=d$
"Matter wave overlap"

T=0:
Pure Bose condensate
"Giant matter wave"

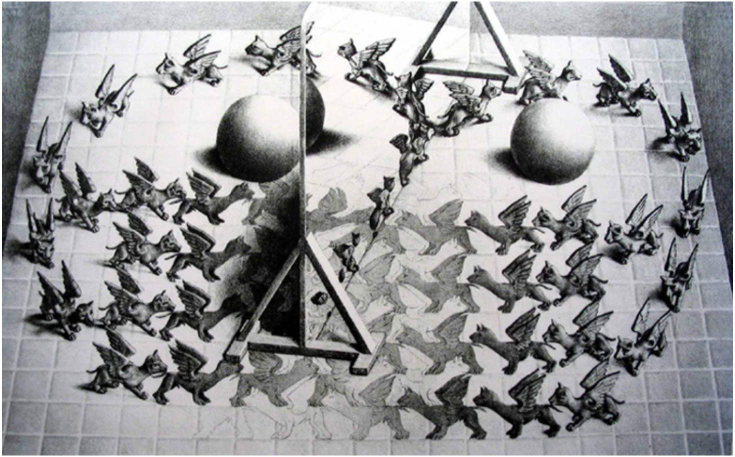
Bose-Einstein condensation

$$\rho = n{\Lambda_{\mathrm{deB}}}^3 = 2.612375349\ldots$$

with

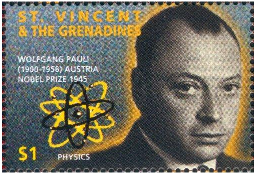
$$\Lambda_{\mathrm{deB}} = \frac{h}{\sqrt{2\pi m k_B T}}$$

Bosons and Fermions



Usual examples: electrons, protons, neutron (fermions), photon (boson)
Example: ^{3}He (I=$^1/_2$) and ^{4}He (I=0), or ^{6}Li (F=$^1/_2$,$^3/_2$) and ^{7}Li (F=1,2)

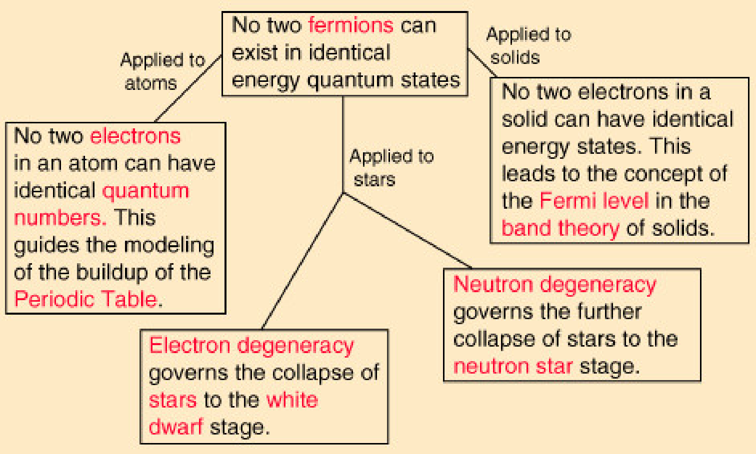
Pauli exclusion principle



The Pauli exclusion principle is a quantum mechanical principle formulated by Wolfgang Pauli in 1925. It states that no two identical fermions may occupy the same quantum state simultaneously.

A more rigorous statement of this principle is that, for two identical fermions, the total wave function is anti-symmetric. For electrons in a single atom, it states that no two electrons can have the same four quantum numbers, that is, if n, l, and ml are the same, ms must be different such that the electrons have opposite spins.
In relativistic quantum field theory, The Pauli principle follows from applying a rotation operator in imaginary time to particles of half-integer spin. It does not follow from any spin relation in nonrelativistic quantum mechanics.

Application of Pauli principle



No two fermions can exist in identical energy quantum states

Applied to atoms

No two electrons in an atom can have identical quantum numbers. This guides the modeling of the buildup of the Periodic Table.

Applied to solids

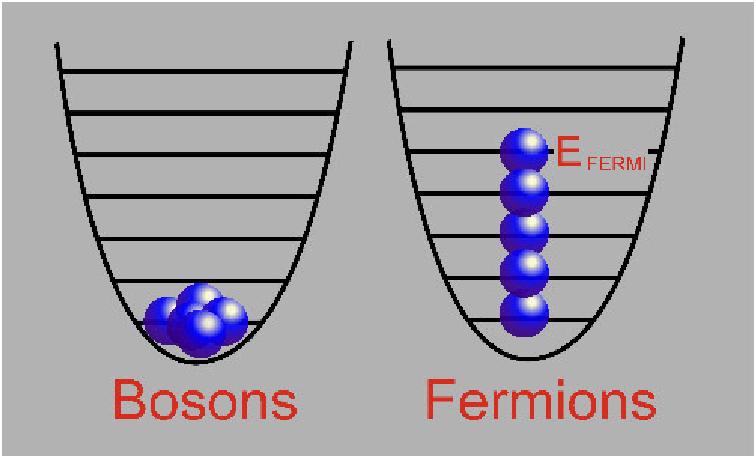
No two electrons in a solid can have identical energy states. This leads to the concept of the Fermi level in the band theory of solids.

Applied to stars

Electron degeneracy governs the collapse of stars to the white dwarf stage.

Neutron degeneracy governs the further collapse of stars to the neutron star stage.

Population of states



Outline

1. How to produce a Bose-Einstein condensate
    - Step 1: Light pressure
    - Step 2: Optical molasses
    - Step 3: Magnetic trapping
2. Observation of BEC
3. What to do with a Bose-Einstein condensate
    - Sound propagation
    - Bosons *versus* Fermions
    - Atom laser

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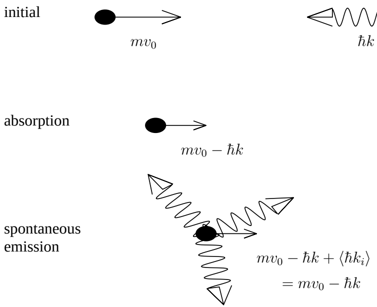
Light pressure



recoil “kick”

$$v_r = \frac{\hbar k}{m} \approx 3 \text{ cm/s (Na)}$$

thermal

$$v \approx 1000 \text{ m/s}$$

$$N_{\text{stop}} \approx 33.000 \text{ fotons}$$

lifetime

$$\tau = 16 \text{ ns}$$

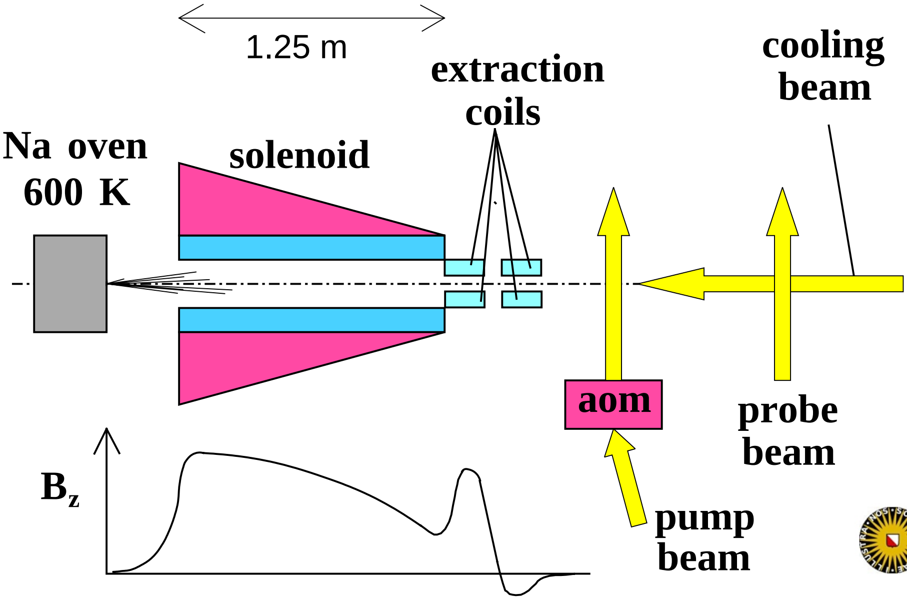
$$T_{\text{stop}} \approx 1 \text{ msec}$$

$$l_{\text{stop}} \approx 0.5 \text{ m}$$

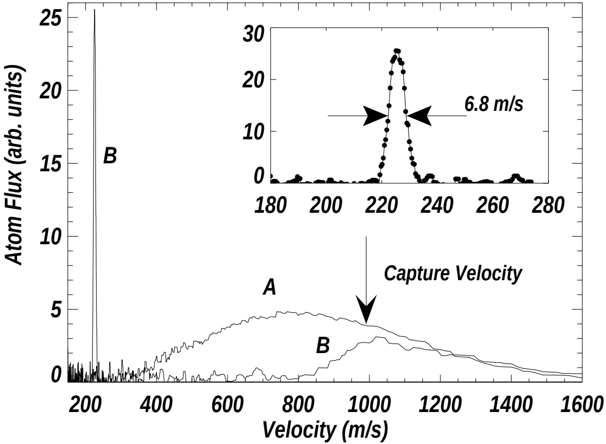
acceleration

$$a \approx 9 \times 10^5 \text{ m/s}^2$$

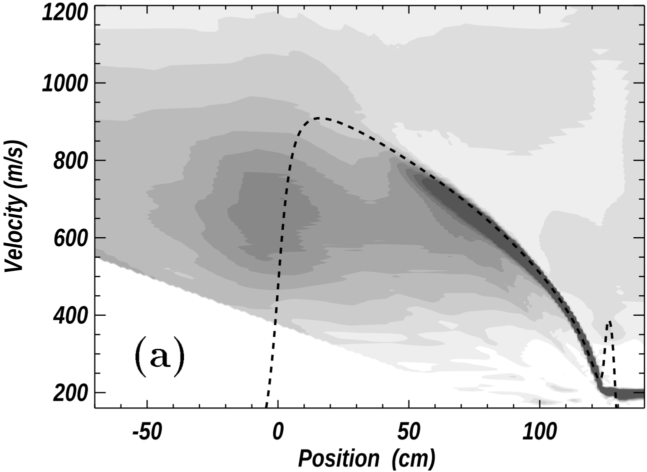
Zeeman technique



Velocity distribution

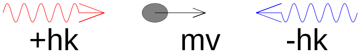


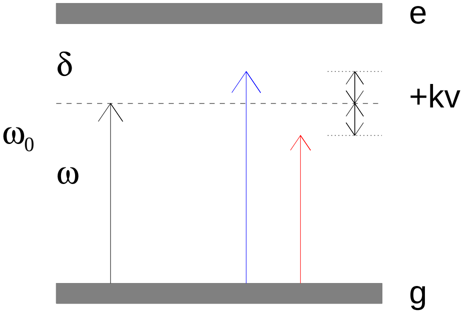
Funnel for atoms

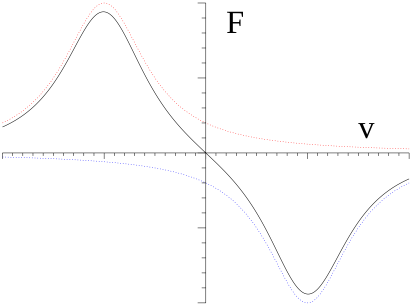


Contour map of the velocity and position of atoms in the solenoid

Laser cooling



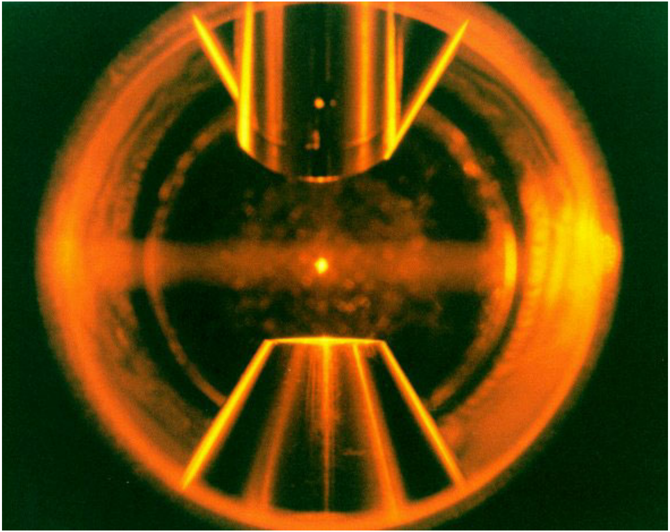




Cooling limit: Damping by Doppler tuning vs. heating by random recoil

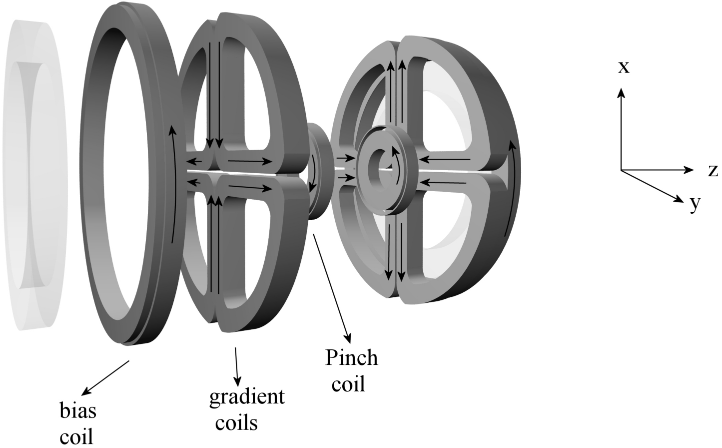
$$kT_{\mathrm{D}} = \frac{\hbar\Gamma}{2} \qquad [\mathrm{Na} : 240\mu\mathrm{K}]$$

Cold Atoms



D:/upload/Phys2000/bec/lascool4.html

Magnetic Trap



Cloverleaf trap

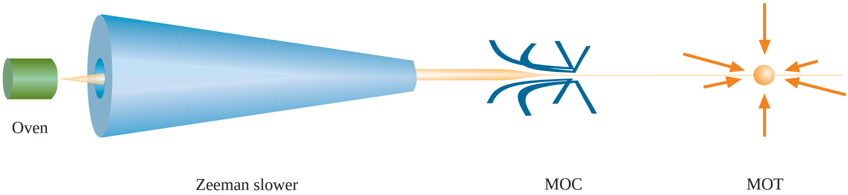
Evaporation

1. Cools a cup of coffee
2. Cools apples by overtree sprinkling
3. Is used in technical water coolers
4. Globular clusters do it by evaporation of stars
5. Compound nuclei do it by evaporating neutrons
6. Atom coolers love it.

Evaporative cooling of a trapped gas is based on the preferential removal of atoms with an energy higher than the average energy, followed by thermalization of the gas by elastic collisions.

In order to force the cooling to proceed at a constant rate, the evaporation threshold may be lowered as the gas cools (forced evaporation).
`D:/Upload/Phys2000/bec/xevap_cool.html`

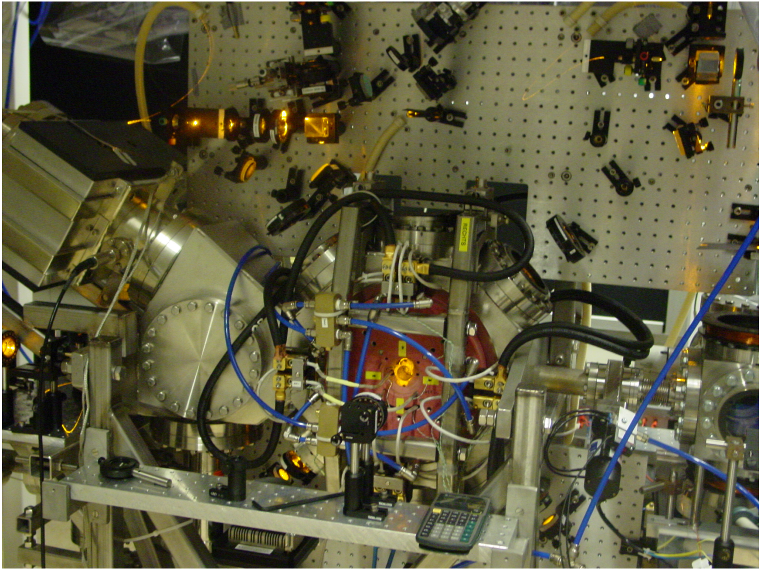
Experimental feasibility



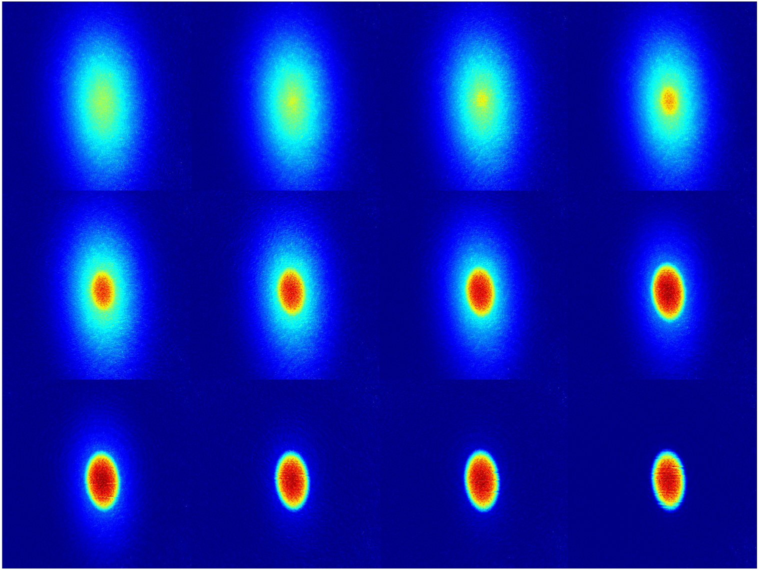
Properties of the trapped atoms	N	n (atoms/cm^3)	$T(\mu K)$
MOT	1.2×10^{10}	3×10^{11}	320
magnetic trap	8×10^{9}	3×10^{11}	340
evaporative cooling	1.5×10^{8}	8×10^{13}	0.3

Outline

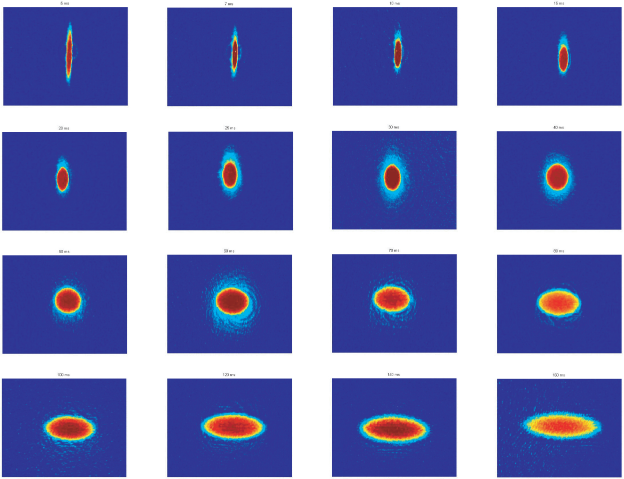
Current setup



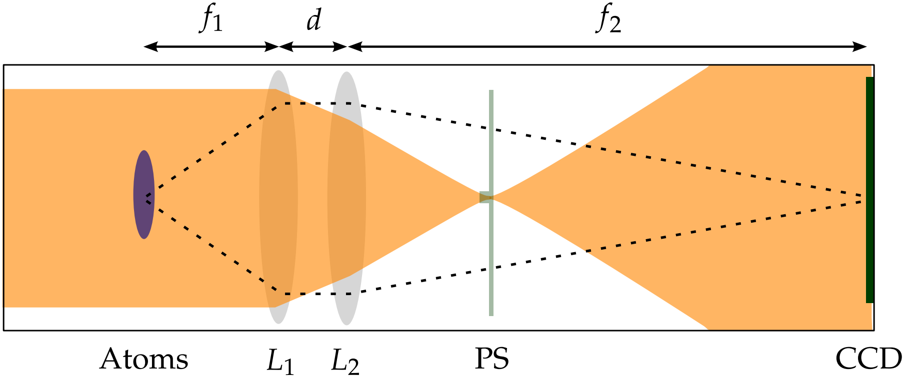
Bose-Einstein condensation–The last stages



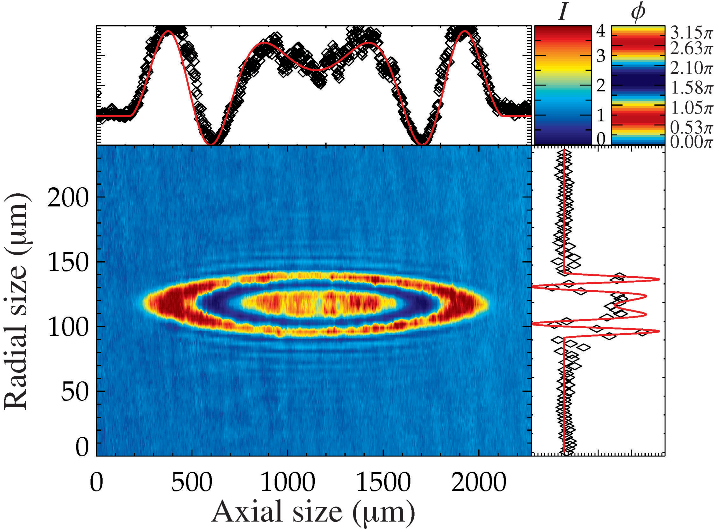
Expansion of the cloud



Phase contrast imaging–setup



Phase contrast imaging–images



Characteristic values

Dark magneto-optical trap	
Temperature	320 μK
Number of particles	1.2×10^{10} atoms
Density	3×10^{11} atoms/cm^3
Magnetic trap	
Trap frequencies	ν_r=96 Hz and ν_z=16→1.08 Hz
Number of particles	8×10^9 atoms
Elastic scattering rate	10 collisions/s
Bose-Einstein condensation	
Evaporation ramp	40 s
Number of particles	2.5×10^8 atoms
Density	2.5×10^{14} atoms/cm^3
Chemical potential	3.5 kHz
Temperature	300 nK

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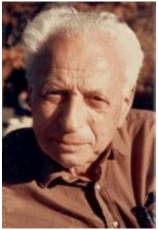
Topic One

Sound propagation

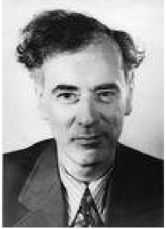
"Observation of second sound"

Tisza-Landau two-fluid hydrodynamics (1938-1941)



Tisza

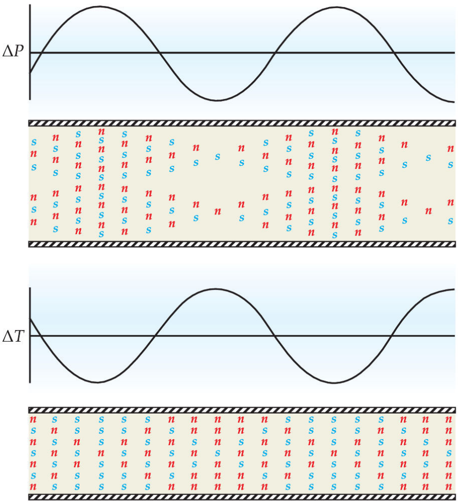
Superfluid: component of liquid which is associated with macroscopic occupation (BEC) of one single-particle state. Carries zero entropy, flows without dissipation with an irrotational velocity.



Landau

Normal fluid: comprised of incoherent thermal excitations, behaves like any fluid at finite temperatures in local thermodynamic equilibrium. This requires strong collisions.

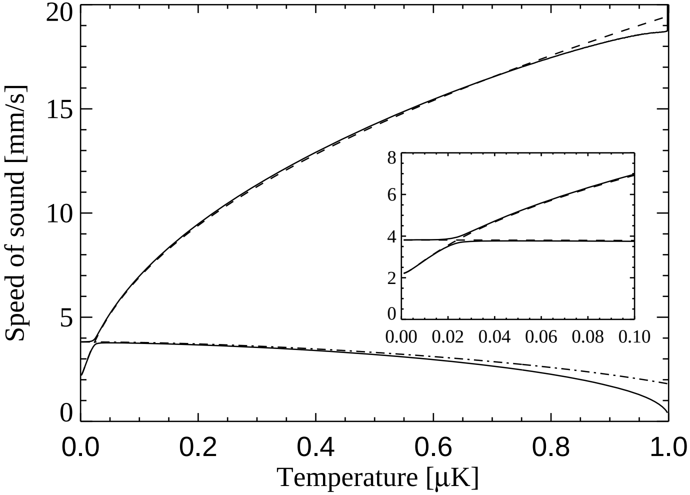
First and second sound in liquid helium



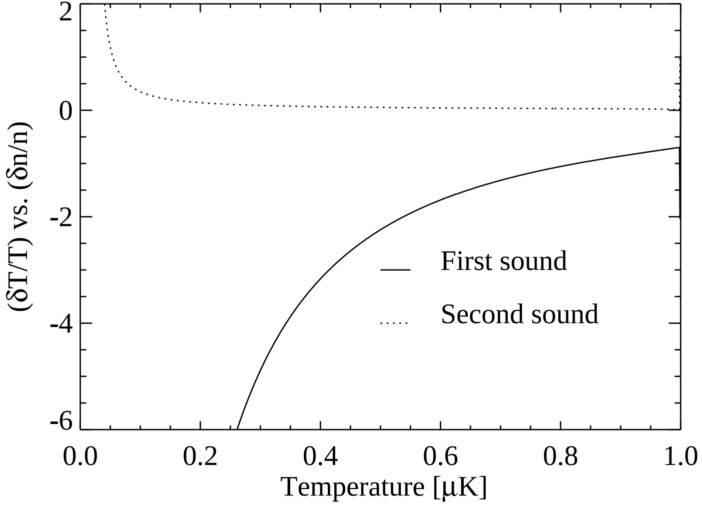
First sound
Pressure wave
In-phase

Second sound
Temperature wave
Out-of-phase

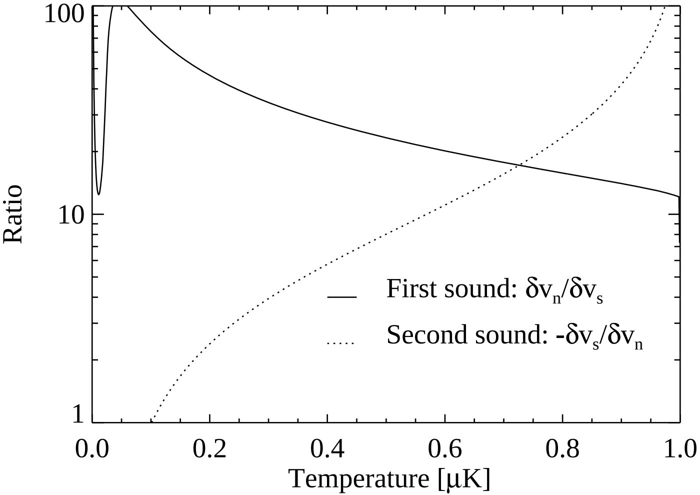
Speed of sound



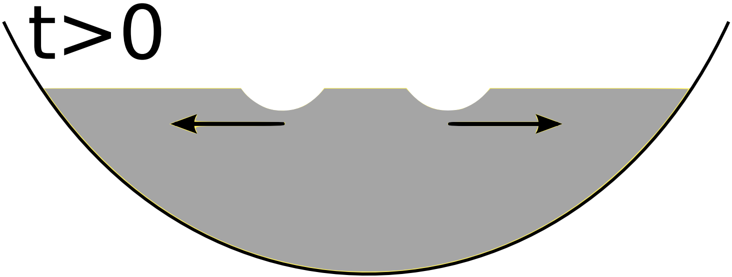
Density or temperature wave?



In-phase or out-of-phase?

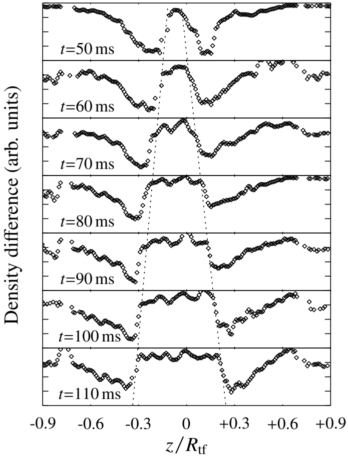


Generating sound



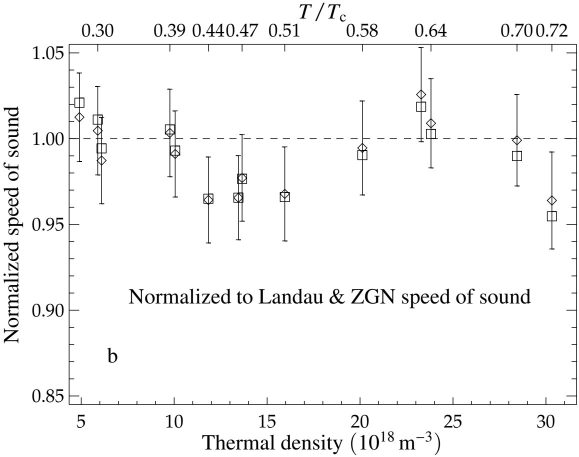
- Grow the condensate with blue detuned dipole beam in center
- At $t = 0$ shut off dipole beam
- Wait & see

Detecting sound



Sound propagation in a Bose-Einstein condensate at finite temperatures, R. Meppelink *et al.*, Phys. Rev. A **80**, . . . (2009), online 12 October 2009.

Comparison to theory



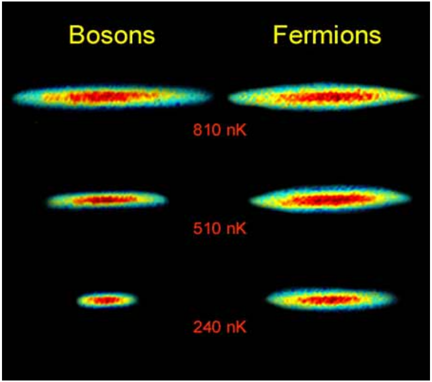
Sound propagation in a Bose-Einstein condensate at finite temperatures, R. Meppelink *et al.*, Phys. Rev. A **80**, . . . (2009), online 12 October 2009.

Topic Two

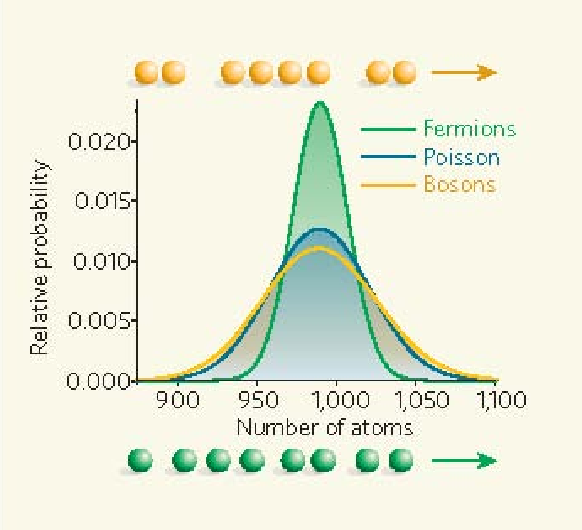
Bosons *versus* Fermions

“How quantum statistics changes everything”

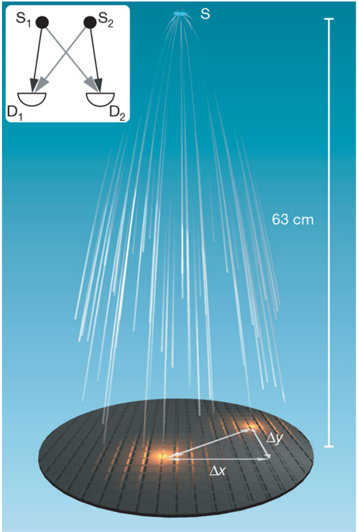
“Fermi” pressure



Bunching or anti-bunching

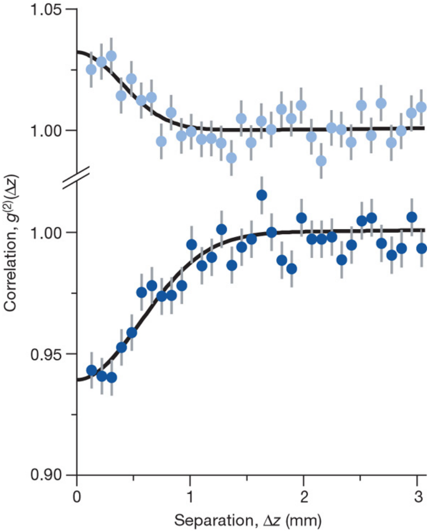


Bunching or anti-bunching



Jeltes *et al.*, Nature 2007

Bunching or anti-bunching



Jeltes *et al.*, Nature 2007

Topic Four

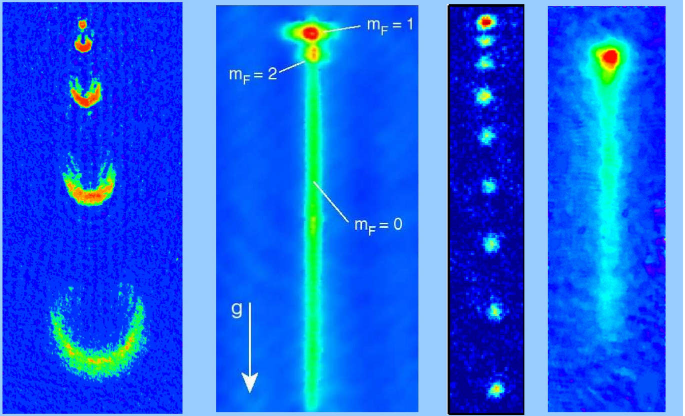
Atom laser

“The creation of a continuous flow of Bose-condensed atoms”

Atom lasers

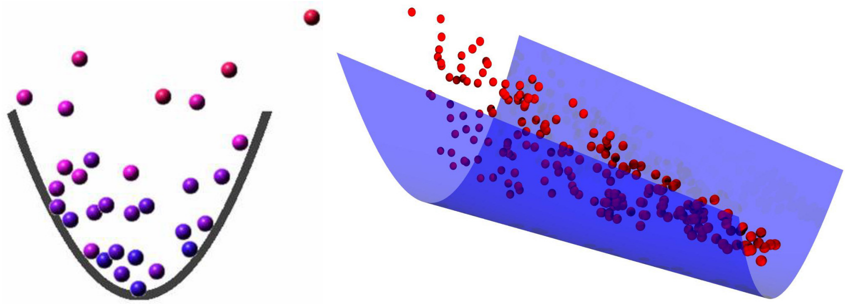
Atom laser gallery

Height:
5, 2, 0.5, 1 mm



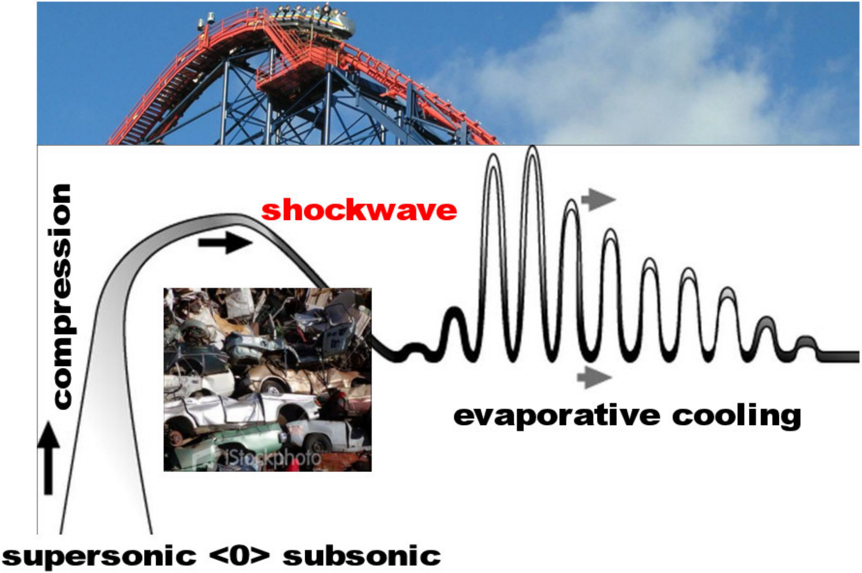
MIT '97 Munich '99 Yale '98 NIST '99

Evaporative cooling

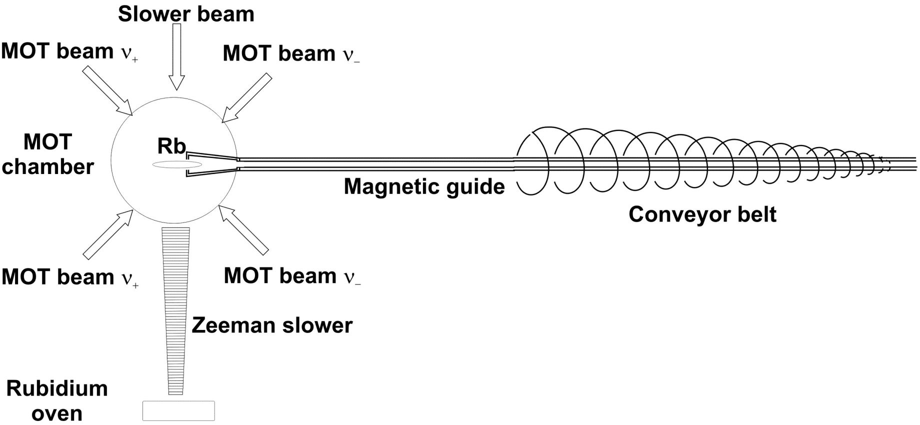


Trap geometry *vs.* Beam geometry

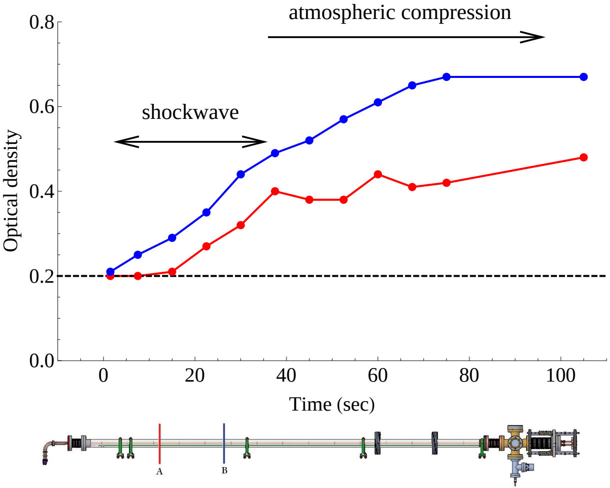
"The rollercoaster"



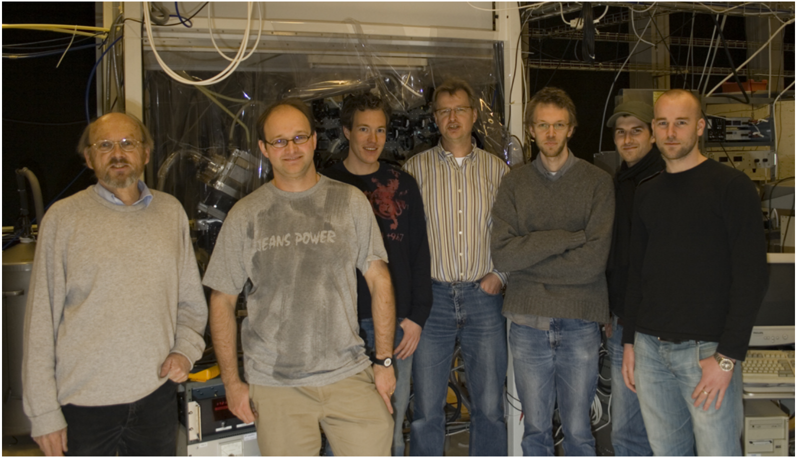
Atom laser setup



Shockwave


atmospheric compression
shockwave
Optical density
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
Time (sec)
A
B

The Crew



Not on the picture: Henk Stoof (theoretician), Louise Kindt (Atom laser)