1. About Bose-Einstein Condensation (BEC)

2. BEC Production

3. Evaporative Cooling

4. Absorption Imaging

5. Interference Between Two Bose Condensates

6. Summary
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History of BEC

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  Describe with thermal velocity $v$, number density $n$, distance between atoms $d$
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De-Broglie Wavelength

with Planck constant $h$, Boltzmann constant $k_B$ and mass of atoms $m$
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- $T = 0$ K: pure BEC, described by one single wavefunction
Prerequisites

- Ultracold bosonic gases, Ultra-high vacuum
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- Bosons: integer spin
  Fermions: half integer spin and governed by Pauli-Principle
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\[ \lambda_{DB} \approx d = n^{-1/3} \Rightarrow T_C(n) = \frac{\hbar^2}{2\pi mk_B} \cdot n^{2/3} \]

with critical temperature \( T_C(n) \)
I.e. \( T_C(n) \approx 100 \) nK for dilute gases at densities of \( 10^{14} \) cm\(^{-3}\)
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- Phase-space density \( D \) crucial for BEC

\[ D = n \cdot \lambda_{DB}^3 \quad D \geq 2.612 \]
Many-body ground state

\[ \psi(\vec{r}, t) = \psi(\vec{r}) e^{-i\mu t} \]

with ground state energy / chemical potential \( \mu \)
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Dynamic: Gross-Pitaevski equation

\[ i\hbar \frac{\partial}{\partial t} \psi(\vec{r}, t) = \left[ -\frac{\hbar^2}{2m} \cdot \nabla^2 + U(\vec{r}) + \tilde{U} |\psi(\vec{r}, t)|^2 \right] \psi(\vec{r}, t) \]

with harmonic potential \( U(\vec{r}) = \frac{1}{2} m(\omega_x^2 x^2 + \omega_y^2 y^2 + \omega_z^2 z^2) \) and \( \tilde{U} = 4\pi\hbar^2 a/m \)

describing two body collisions

Thomas-Fermi limit \((n \tilde{U} \gg \hbar \omega_x, \omega_y, \omega_z)\): neglect term for kinetic energy

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Zeeman-Slowing reduces velocity & temperature by Laser-cooling.
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- provides high flux ($10^{12}$ slow atoms per second) which enables more than $10^{10}$ atoms to be loaded into the MOT in one or two seconds
- Zeeman-slowed Sodium beam has velocity of 30 m/s corresponding to kinetic energy of 1 K
Magneto-Optical-Trap (MOT)

- S. Chu, C. Cohen-Tannoudji & W. D. Phillips received the Nobel Prize of Physics for development of methods to cool and trap atoms with laser light in 1997
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- I.e. for sodium temperatures between 50 µK and 100 µK
- Provides phase-space density $D \approx 10^{-6}$: still too low for phase transitions
Magnetic Trapping

- Magnetic Trapping of neutral atoms first observed in 1985
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- Major role: Accomodate pre-cooled atoms and compress them \(\Rightarrow\) high collision rates and evaporative cooling
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Excellent tool for evaporative cooling
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- Evaporated atoms carry away more than average energy $\Rightarrow$ temperature decreases
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- Technique was extended to alkali atoms in 1994 by combining Evaporative Cooling with Laser Cooling
Radio frequented (RF) radiation flips atomic spin $\Rightarrow$ attractive trapping force turns into repulsive force and expels atoms from trap.
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Energy selective ⇒ only atoms with $E > \hbar |m_F|(\omega_{RF} - \omega_0)$ with rf frequency $\omega_0$ which induces spinflips at the bottom of the trap

Other atoms rethermalyze

Advantage: No need to weaken trapping potential in order to lower depth. Atoms evaporate from whole surface where RF resonance condition is fullfilled ⇒ 3D in velocity space
Rethermalization: Scattering processes lead to new distribution.
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Favorable ratio between elastic collision rate (provides Evaporative Cooling) and inelastic collision rate (leads to trap loss and heating) required
RF Induced Evaporation

- Rethermalization: Scattering processes lead to new distribution
- Favorable ratio between elastic collision rate (provides Evaporative Cooling) and inelastic collision rate (leads to trap loss and heating) required
- Provides phase-space density \( D \geq 2.612 \)
Horizontal sections taken through center of velocity distribution
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- At 4.1 MHz: just little remains of noncondensate fraction
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Switching off trap ⇒ condensate falling down (gravity) and ballistically expands
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Illuminating atoms with nearly resonant laser beam and imaging shadow cast on charge-coupled device camera (CCD-camera)
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Cloud heats up by absorbing photons (about one recoil energy per photon)
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- Single destructive image
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Single destructive image
Provides reliable density distributions of which properties of condensates and thermal clouds can be inferred
2D probe absorption images after 6 ms time of flight
Width of images is 870 µm
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Velocity distribution of cloud just above transition point
Absorption Imaging

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- Velocity distribution of cloud just above transition point
- Shows difference between isotropic thermal distribution and elliptical core attributed to expansion of dense condensate
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  Width of images is 870 µm
- Velocity distribution of cloud just above transition point
- Shows difference between isotropic thermal distribution and elliptical core attributed to expansion of dense condensate
- Almost pure condensate (after further evaporative cooling)
Produced in vapor of $^{87}$Rb atoms
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- Fraction of condensed atoms first appear near $T = 170$ nK & $n = 2.5 \cdot 10^{12}$ cm$^{-3}$
  Could be preserved for more than 15 seconds
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Nonthermal, anisotropic velocity distribution expected of minimum-energy quantum state of magnetic trap
Evidence for coherence of BEC’s
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Cut atom trap in half (double-well potential) by focusing far-off-resonant laser light into center of magnetic trap
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Cool atoms in these two halves to form two independent condensates
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- Quickly turn off laser and magnetic fields, allowing atoms to fall and expand freely
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Cool atoms in these two halves to form two independent condensates

Quickly turn off laser and magnetic fields, allowing atoms to fall and expand freely

Both condensates start to overlap and interfere with each other
Interference pattern of two expanding condensates after 40 ms time of flight for 2 different powers of Argon-ion laser light (3 & 5 mW)
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- Fringe periods 20 & 15 µm
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- Fields of view: horizontally: 1.1 mm
  vertically: 0.5 mm
Recent experiment: drop tower (Center of Applied Space Technology and Microgravity 'ZARM' Bremen)
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- Capturing cold atoms in magneto-optical trap (MOT)
- Loading Ioffe-Pritchard trap, creating BEC consisting of $10^4 \ ^{87}\text{Rb}$ atoms
Evolution of BEC and asymmetric Mach-Zehnder interferometer (AMZI) visualized by series of absorption images of atomic densities separated by 1 ms.
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Interferometer starts at time $t_0$ after release of BEC
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Interferometer starts at time $t_0$ after release of BEC

Two counter-propagating light beams of frequencies $\omega$ and $\omega + \delta$ creates coherent superposition of two wave packets that drift apart, redirects and partially recombines them
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- Condensate has anisotropic density distribution
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Condensate has anisotropic density distribution

Interference between two condensates is evidence for coherence of BEC’s
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