Bose-Einstein Condensation

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1.0 Introduction:

The first theoretical description of Bose-Einstein condensation (BEC) in an ideal gas dates from 1924, when Einstein published his articles on the Quantum theory of an ideal gas. This theory was extended to describe the interacting Bose gas in 1947 by Bogoliubov, who introduced a mean field theory to account for atom-atom interactions in the trapped gas. Although the atomic densities in Bose-Einstein condensates are comparably low (10^{12} to 10^{14} atoms per cubic centimeter), interactions significantly alter the properties of the macroscopic wave function in many respects. The first experimental realization of Bose-Einstein condensation was achieved simultaneously by E. Cornell, W. Ketterle and C. Wieman in 1995 and was rewarded with the Nobel prize in 2001. These experiments were performed in (weakly confining) 3D magnetic traps, making BECs in 3D traps is well described by the theory section. However, as experimental tools for the creation and manipulation of Bose-Einstein condensates evolved, the quantum system could be studied in more unusual situations. Due to the development of strongly confining trapping mechanisms and geometries, it became possible to realize BECs in reduced dimensions (1D, 2D), periodic traps or complex potential landscapes. Occasionally, the 3D Thomas-Fermi theory breaks down in strongly confining directions and the (noninteracting) single particle character may determine the properties of the wave packet in these dimensions.

We must remember that one of the greatest achievements who donated to the creation of BEC experiments was the Laser Colling, first proposed by Wineland and Dinh and by Theodor W. Hansch and Arthur Leonard Schawlow in 1975 and became applicative by Steven Chu, Claude Cohen-Tannoudji and William D. Phillips who were awarded the 1997 Nobel Prize in Physics for their work in laser cooling.

In Ben-Gurion University we have two Atom Chip experiments one is fully functional and the other is in construction stages. In addition we have a fabrication facility who gives fabrication services to other labs world wide including including our own, for example one of the Atom-Chip for Hidelberg university has made in our fab. The Atom Chip Lab researchers and Dr. Ron Folman puts Ben-Gurion University on the front line of atomic and photonic research.

1.1 Statistic Mechanic approach:

If we shall see the physical behavior of a class of systems in which, while the intermolecular interaction are still negligible, the effects of quantum statistics play an important roll.

The Phase Space, introduced by Willard Gibbs in 1901, is a space in which all possible states of a system are represented, with each possible state of the sys-
tem corresponding to one unique point in the phase space. The phase space can refer to the space that is parametrized by the macroscopic states of the system, such as pressure, temperature, etc. [Wiki PhaseSpace]

In these systems the temperature of the particle $T$ and the particle density $n$ of the system no longer conform to the criterion:

$$n\lambda^3 \equiv \frac{n\hbar^3}{(2\pi m kT)^{3/2}} \ll 1 \quad (1.1)$$

where $\lambda \equiv \hbar/(2\pi mkT)^{1/2}$ is the mean thermal wavelength of the particles. When the value $(n\lambda^3)$ becomes on the order of unity, the behavior of the system becomes significantly different from the classical one and is characterized by typical quantum effects. It is evident that a system is more likely to display quantum behavior when it is relatively low temperature and/or has a relatively high density particles.

More than that the system will obey the Bose-Einstein statistic or Fermi-Dirac statistic. The properties of these two systems are quite different. In the present paper we will deal with systems belong to the first category, BEC.

1.2 Thermodynamic behavior of an ideal Bose gas:

While Einstein wrote the number of particles for an ideal Bose gas he got a formula that quite resembles to Planck distribution (in case of photons $\mu = 0$):

$$N(E) \equiv \sum_{\epsilon} \langle n_\epsilon \rangle \equiv \sum_{\epsilon} \frac{1}{e^{(\epsilon - \mu)/kT} - 1} \quad (1.2.1),$$

where $\beta \equiv 1/k_BT$ (1.2.2). While $z$ is the fugacity of the gas which is related to the chemical potential $\mu$ through the formula:

$$z \equiv \exp(\mu/kT) \quad (1.2.2)$$

Due to the fact that $ze^{-\beta \epsilon}$ is less than a unity, for all $\epsilon$. For large volume $(V)$, the spectrum for single-particle state is almost continuous though we can replace the summation with integral:

$$\frac{N}{V} = \frac{2\pi}{\hbar^3} (2m)^{3/2} \int_0^\infty \frac{\epsilon^{1/2}d\epsilon}{ze^{\epsilon/kT} - 1} + \frac{1}{V} \frac{z}{1-z} \quad (1.2.3)$$

Due to the fact that the lower limit of the integral give no donation we have to write separately the donation of $\epsilon = 0$ state in the formula.

This accumulation of a macroscopic fraction particles into single state $\epsilon = 0$ leads to the phenomenon of Bose-Einstein condensation. The number of particals in $\epsilon = 0$ energy level is: $\frac{N}{V} = N_0 \quad (1.2.4)$, from the integral (1.2.3) we can calculate the number of particals in higher energy levels:

$$N - N_0 = \zeta(3) \left( \frac{k_BT}{\hbar n_0} \right)^3 \quad (1.2.5)$$
with ζ(x) the Riemann Zeta function. By imposing \( N_0 \to 0 \) we can find the critical temperature for Bose-Einstein condensation:

\[
T_c = \frac{\hbar w_{h_0}}{k_B} \left( \frac{N}{\zeta(3)} \right)^{1/3} = 0.94 \frac{\hbar w_{h_0}}{k_B} N^{1/3}
\] (1.2.6)

For this kind of system, the adequate thermodynamic limit is \( N \to \infty, w_{h_0} \to 0 \), keeping \( N w_{h_0}^3 \) constant, as it guarantees a constant local density in the thermal gas. Hence, the critical temperature \( T_c \) is well defined in the thermodynamic limit. With equation (1.2.3) and \( T < T_c \) we obtain the condensate fraction in the thermodynamic limit:

\[
\frac{N_0}{N} = 1 - \left( \frac{T}{T_c} \right)^3
\] (1.2.7)

Note that at \( T = T_c \), \( n(0) \lambda_{dB}^3 = \zeta(3/2) \approx 2.61 \). While \( \lambda_{dB} = \left[ 2\pi \hbar^2 / (mk_BT) \right]^{1/2} \) is the deBroglie wavelength and \( n(0) \) the density at the trap center.

### 2.1 The non-interacting Bose gas:

Bose-Einsein condensation describes quantum phase transition in bosonic gases, which leads to a macroscopic population of the ground state of an external trapping potential. This transition take place at non-zero temperatures. Let us look on neutral atoms who trapped in an external 3D harmonic potential:

\[
V_{trap} = \frac{m}{2} (w_x^2 x^2 + w_y^2 y^2 + w_z^2 z^2),
\] (2.1)

where \( m \) is the atomic mass and \( w_i \) is the trap oscillation frequencies in the three spatial directions.

Assuming an ideal (non-interacting) gas, the Hamiltonian can be written as sum of single particles with well known eigenenergies:

\[
\epsilon_{n_x,n_y,n_z} = \sum_{i=x,y,z} \left( n_i + \frac{1}{2} \right) \hbar w_i,
\] \( \{ n_x, n_y, n_z \in \mathbb{I}_{positive} \} \) (2.2)

We can see that the \( N \) particles ground state of non-interacting bosons in harmonic potential is product state

\[
\Phi_0(r) = \left( \frac{m w_{h_0}}{\hbar} \right)^{3/4} \exp \left( -\frac{m}{2\hbar} \sum_{i=x,y,z} w_i x_i^2 \right)
\] (2.3)

where \( w_{h_0} = (w_x w_y w_z)^{1/3} \) (2.4) is the geometric mean of the harmonic trap oscillation frequencies.

The atomic density distribution is \( n(r) = N |\Phi_0(r)|^2 \) (2.5), the spatial extension of the ground state wave function is independent of \( N \) and drive from width of the gaussian distribution (2.3):

\[
a_{h_0} = \sqrt{\frac{\hbar}{m w_{h_0}}} \quad (2.6)
\]

The size of the ground state wave function \( a_{h_0} \) fixes an important length scale of the system; it is usually of the order of \( a_{h_0} \approx 0.1 - 1 \mu m \). At finite temperature, only a certain fraction of the atoms populate the ground state, the
others being thermally distributed among exited states. The size of the thermal cloud is usually much larger than $a_{hh_0}$: assuming a harmonic trapping potential like (2.3) and a classical Boltzmann distribution, we obtain a gaussian width of $R_{\text{therm}} = a_{hh_0} \left( \frac{k_B T}{\hbar \omega_{hh_0}} \right)^{1/2}$ for the thermal cloud, which largely exceeds the ground state size, as $k_B T \gg \hbar \omega_{hh_0}$. Therefore, the onset of Bose-Einstein condensation can be identified by a build up of a sharp peak in the central region of the density distribution.

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Figure 1: Bimodal distribution [GSU BEC Homepage]

2.2 The interacting Bose gas at zero temperature:
Atom-atom interactions significantly modify the properties of the Bose gas at the critical temperature (e.g. the spatial shape of the wave function) and thus have to be taken into account. The Hamiltonian for interacting particles in an external trapping potential $V_{\text{trap}}$ in second quantization is:

$$\hat{H} = \int dr \hat{\Psi}^\dagger(r) \left( -\frac{\hbar^2}{2m} \nabla^2 + V_{\text{trap}} \right) \hat{\Psi}(r) + \frac{1}{2} \int dr dr' \hat{\Psi}^\dagger(r) \hat{\Psi}^\dagger(r') V_{(r-r')} \hat{\Psi}(r') \hat{\Psi}(r) \quad (2.2.1)$$

Here, $\hat{\Psi}(r)$ and $\hat{\Psi}^\dagger(r)$ are the bosonic creation and annihilation operators while $V_{(r-r')}$ is the interaction potential for two atoms located at position $r$ and $r'$.

2.3 The Gross-Pitaeavskii equation:

Weak interactions can be described by a mean field theory, when the atomic density $n$ is much smaller than the number of atoms in a cube of volume $a^3$ (scattering length), or, equivalently, the so called gas parameter $a^3 n \ll$ (in a 3D system). In 1D, this weakly interacting regime is characterized by $g' \ll$
\[ \frac{\hbar n}{\sqrt{m}}, \ g \text{ being the interaction coupling constant (equation 2.3.3).} \]

In 1947, Bogoliubov formed the basis of a mean field theory for dilute gases by decomposing the field operator \( \hat{\Psi} \) to a complex wave function \( \Phi(r,t) \) describing the condensate wave function and the so called depletion \( \hat{\Psi}' \), describing the non-condensed fraction:

\[ \hat{\Psi}(r,t) = \Phi(r,t) + \hat{\Psi}'_{r,t} \quad (2.3.1) \]

Assuming a macroscopic population of the ground state, \( \Phi(r,t) \) is now complex number and condensates density distribution is given by

\[ n_0(r,t) = |\phi(r,t)|^2 \quad (2.3.2) \]

Combining the ansatz (2.3.1) and the Hamiltonian (2.2.1) and using the Heisenberg equation, we obtain:

\[ i\hbar \frac{\partial}{\partial t} \hat{\Psi}(r,t) = \left[ \hat{\Psi}(r,t) \right] \hat{H} \quad (2.3.2) \]

\[ = \left[ -\frac{\hbar^2 \nabla^2}{2m} + V_{\text{trap}}(r) + \int dr' \hat{\Psi}^\dagger_{(r',t)} V(r'-r) \hat{\Psi}_{(r',t)} \right] \hat{\Psi}(r,t). \]

To first approximation, we will set \( \Phi \) for \( \hat{\Psi} \). This is justified since in Bose-Einstein condensates, the condensate fraction can easily be above 90% (in contrast to \( \approx 10\% \) in \( ^4\text{He} \) superfluid).

For ultra cold atoms, scattering mostly occurs in the symmetric s-wave channel. Therefore, the atomic interaction can be described by a contact interaction with a delta function pseudo potential \( g\delta^3(r-r') \) where \( g \) is a coupling constant, derived from the s-wave scattering length \( a \):

\[ g = \frac{4\pi\hbar^2}{m} \quad (2.3.3) \]

Together with (2.3.2) we obtain the Gross-Pitaevskii equation for the condensate wave function:

\[ i\hbar \frac{\partial}{\partial t} \Phi(r,t) = \left( -\frac{\hbar^2 \nabla^2}{2m} + V_{\text{trap}}(r) + g |\Phi(r,t)|^2 \right) \Phi(r,t) \quad (2.3.4) \]

For a static system, we write \( \Phi(r,t) = \phi(r) \exp(-i\mu t/\hbar) \), \( \phi \) being real and normalized to the total particle number \( \int \phi^2 dr = N_0 = N \). By this the Gross-Pitaevskii equation (2.3.4) becomes:

\[ \left( -\frac{\hbar^2 \nabla^2}{2m} + V_{\text{trap}}(r) + g |\Phi(r,t)|^2 \right) \phi(r) = \mu \phi(r) \quad (2.3.5) \]

a Schrodinger equation with a nonlinear interaction term, which is proportional to the local density \( n(r) = |\phi(r)|^2 \). In the absence of interactions \( (g = 0) \) (2.3.5), reduces to the usual Schrodinger equation for a single particle.

### 2.4 The Thomas-Fermi approximation:

As mentioned above, the Gross-Pitaevskii equation (2.3.5) can be applied in weakly interacting (or dilute) systems. These terms have to be used with precaution: scaling equation (2.3.5) to natural units (lengths measured in \( a_{\text{ho}} \), densities in \( a_{\text{ho}}^{-3} \) and energies in \( \hbar \omega_{\text{ho}} \)), we obtain
Written in this way, it becomes clear, that the atomic interactions and the kinetic energy scale as:

\[
\frac{E_{\text{int}}}{E_{\text{kin}}} \propto \frac{N a}{\hbar \omega_0} \quad (2.4.2)
\]

For experiment to succeed we need to to keep the ratio between 50 and 5000, showing that although we are in a dilute system \((na^3 \ll 1)\), interactions determine the wave function properties. As the interaction energy dominates over the kinetic energy in many configurations, one can simply neglect the (first) kinetic term in equation (2.3.5) and this way obtain the Thomas-Fermi approximation for \(\phi(r)\):

\[
n(r) = \left| \frac{\phi^2(r)}{\phi(0)} \right| = \frac{\mu - V_{\text{trap}}(r)}{\tilde{g}} \quad (2.4.3)
\]

for \(\mu > V_{\text{trap}}(r)\) and \(n = 0\) elsewhere. For a harmonic trap, this approximation gives a density distribution of the shape of an inverted parabola with a maximal density

\[
n(0) = \frac{\mu}{\tilde{g}} \quad (2.4.4)
\]

at the center of the trap. The size of the condensate is described by the Thomas-Fermi radii:

\[
R_{\perp} = \sqrt{\frac{2\mu}{m w_{\perp}}} \quad (2.4.6)
\]

\[
R_{\parallel} = \sqrt{\frac{2\mu}{m w_{\parallel}}} \quad (2.4.6)
\]

For rather isotropic traps, one can use a single Thomas-Fermi radius \(R\), based on the geometric mean \(\sqrt{w_{x,y,z}}\) of the trap frequencies. Together with the normalization of the wave function to density, we can calculate the chemical potential to

\[
\mu = \frac{\hbar w_{x,y,z}}{2} \left( \frac{15N a}{\hbar \omega_0} \right)^{2/5} \quad (2.4.7)
\]

Inserting expression (2.4.7) into the expression for the Thomas-Fermi radius (2.4.6), we obtain:

\[
R = a_{h0} (15N)^{1/5} \left( \frac{a}{a_{h0}} \right)^{1/5} \gg a_{h0} \quad (2.4.8)
\]

which means, as \((a/a_{h0}) \gg N^{-1}\), that interactions increase the size of the condensate compared to the non-interacting case, where the condensate extension is \(\approx a_{h0}\) (see equation (2.3)). The Thomas-Fermi approximation is valid, when \(\hbar w_{x,y,z} \ll ng\). In strongly anisotropic (cigar shaped) traps, this may well be the
case in the longitudinal direction, whereas in the transverse direction, the confinement may be so strong, that the kinetic energy term may not be neglected. In this scenario, no simple solution for the Gross-Pitaevskii equation can be found, the condensate shape may deviate significantly from the parabolic shape.

3 Experimental setup:

There are few ways reaching the BEC stage, at the Atom Chip Laboratory at Ben-Gurion University we use the a fabricated Z trap chip. This technique makes the BEC process slightly different due to the fact you can reach with the laser toward the atomic cloud only from above. To solve this problem during the MOT process we use the chip as a reflecting mirror. After solving this problem we can look at the benefits of Atom Chip device. In such a device one can implant nano wires over the chip surface while passing cornets via these wires it is possible to manipulate the atomic cloud and see its behavior over different types of magnetic fields.

The road map for reaching BEC over atom chip is the following:

1. Magnetic optical Trap (MOT).
2. Molasses (Laser cooling).
3. Optical pumping.
5. RF Cooling.
7. Experimental stage.
8. Absorption Imaging.

**MOT:** A magneto-optical trap also known as the "Zeeman shift optical trap," or "ZOT." The position-dependent force is created by using appropriately polarized laser beams and by applying an inhomogeneous magnetic field to the trapping region. Through Zeeman shifts of the atomic energy levels, the magnetic field regulates the rate at which an atom in a particular position scatters photons from the various beams and thereby causes the atoms to be pushed to a particular point in space. In addition to holding the atoms in place, this greatly increases the atomic density since many atoms are pushed to the same position.

To make a condensate, Rb atoms are first collected and trapped from a vapor pressure of $10^{-11}$ torr in the MOT chamber. After the atoms are cooled down to around $150\mu K$. 
Optical Molasses: An optical molasses is a single-frequency light field which can be used to dampen atomic motion, based on the mechanism of Doppler cooling. In a simple one-dimensional version it is made of two counter-propagating laser beams the frequency of which is tuned slightly below an atomic absorption resonance. As a result, a motion of an atom in the direction of one of the beams will lead to a Doppler shift so that the absorption rate for the counter-propagating beam is increased, while the absorption rate for the opposite laser beam is reduced. Effectively there is a dissipative light force which is always directed opposite to the motion and therefore serves to reduce that motion.

At this stage the temperature of the atomic cloud is reduced below the Doppler limit and reaches about $35\mu K$, without any atom loss.

Optical Pumping: Now the atoms are pumped into the highest $M$ level of the ground state by repeated absorption and reemission of photons. If we only provide right-circularly-polarized photons, then $\Delta M = +1$ for every absorption. The atoms can reemit any kind of photon, so on average $\Delta M = 0$ for reemission. A few iterations of this, and all the atoms end up in the highest $M$ level of the ground state.

Magnetic Trap: Then using Z shape wire + bias filed in order to generate an Ioffe-Pritchard trap for the atoms.

RF Cooling: This technique is commonly used to lower the temperature of a group of atoms. In this process we put the atoms in a flask-shaped magnetic field.
Due to collisions some atoms will become much more energetic than others and they will escape the trap, removing energy from the system and reducing the temperature of the remaining group. This process is similar to cooling a hot cap of coffee.

RF-forced evaporative cooling is applied to cool the atoms down to a temperature just above the critical temperature for forming a BEC. To promote the efficiency of the evaporative cooling, the chamber must have a low pressure, i.e., in the range of $10^{-11}$ torr.

**Chip loading:** An atom chip uses its lithographically fabricated circuit patterns to generate magnetic traps on its substrate surface. Due to the fact that the magnetic field gradient scales as $1/r^2$ where $r$ is the distance from a wire on an atom chip, the distance from a trap to the chip surface can be easily reduced down to $<100\mu m$ and only a very low current (around 1 A) is required to create a much tighter trap that dramatically reduces the evaporation time.

**Experimental stage:** After reaching BEC we can start the stage we have been waiting for, to experiment the different qualities of BEC, in the appendix I will present the summary from the last BEC07 that held in Sant Feliu, Spain 15-20 September 2007 to see the front line in the BEC experiments.

**Absorption Imaging:**

The atoms are imaged with a 50 µs-long imaging pulse. Prior to this imaging pulse, all the magnetic fields are shut down in order to avoid Zeeman splitting of the resonance transitions. Also should close all the trapping light.

Two types of imaging measurements being performed:

1. **Time-of-flight (TOF),** where one turn off all the light and magnetic fields (thus releasing the atoms from the trap) and let the atoms expand freely. The cloud fall with gravity and expands as no force applies on it. After some time (4-20 millisecond) we image the atoms by shining the laser beam through the atom cloud and into the CCD camera.

2. **In situ imaging,** wherein picturing the atoms while they are still confined in the trap; in this case some of the atoms are out of resonance with the imaging beam, and only a fraction of the atoms are measured.

**Analyzing:** For analyzing the properties of the atoms, need to be taken 3 different absorption images: background, without atoms, and with atoms (after some TOF or in situ). Then subtract the background image from each of the two images and take the logarithm of the ratio between the two images. The result is an absorption image of the atom cloud, where different colors represent different optical densities. This analysis of the images is simply to extract the optical density according to Lambert-Beer’s Law:

$$\frac{T_{\text{trans}}}{T_{\text{in}}} = \exp(-n_{at}\sigma_{abs}) \approx 1 - n_{at}\sigma_{abs} \quad (3.01)$$
Figure 3: Atom-chip BEC lifetime. (a) Phase-Space density PSD vs time. (b) 9 ms TOF absorption images with different times in the trap.
4 Appendix:

4.01 Summery of BEC07 convention Sant Feliu, Spain 15-20 September 2007:


In this work, we report on the phase fluctuations in Bose-Einstein condensates (BEC) trapped in an elongated trap and discuss the robustness of chip-based BEC interferometry against the phase fluctuations. With controlled phase fluctuations in condensates, the effect of phase fluctuations on the phase coherence in the matter-wave interferometry is studied experimentally. It is shown that phase fluctuations in elongated condensates are likely to degrade interference fringes, and consequently the performance of the matter-wave interferometry, but we find experimental conditions with which the matter-wave interferometry is robust enough to determine the relative phase from the interference fringes. In addition, the phase diffusion is monitored up to approx 23ms after splitting with variable amount of phase fluctuations.

2. ”Quantum fluctuations in the dynamical formation of BEC” Timothy G. Vaughan, Joel F. Corney and Peter D. Drummond

We simulate the formation of Bose-Einstein condensates, through evaporative cooling. By treating the evaporative cooling as a quantum dynamical, non equilibrium process, we find spontaneous formation of transient vortices and residual centre-of-mass oscillations. For small systems, where these effects are large, the Onsager-Penrose criterion for Bose condensation is no longer a useful indication of the presence of a condensate. Instead, we formulate criteria in terms of higher-order correlation functions.

3. ”Towards the observation of a Schrodinger cat in a two mode Bose-Einstein condensate” J. Esteve, A. Weller, C. Gross, J. Appmeier and M. Oberthaler

Entanglement in a two mode Bose-Einstein condensate has attracted tremendous theoretical interest in the past ten years. However, the experimental observation of entangled states in such a system remains an extraordinary challenge. We will present the latest results from our experimental setup where the two mode model is realized by trapping the condensate in an optical double well potential. Measurements showing the mean field behavior of the system at finite temperature will be reviewed. Possibly, beyond mean field dynamics will be presented.

4. ”Atom interferometry with a non interacting BEC” M. Fattori, C. D’Errico, G. Roati, M. Zaccanti, M. Modugno, M. Jona Lasinio, G. Modugno and M.Inguscio

A non-interacting Bose Einstein condensate is the matter-wave analogue
to the optical laser and therefore the ideal source for atom interferometry. Unfortunately atomic interactions seriously limit the coherence time in BEC atom interferometers. We show that it is possible to strongly reduce such decoherence, working close to a magnetic Feshbach resonance and tuning the s-wave scattering length to zero. In particular we analyze Bloch oscillations of a 39K BEC in a vertical optical lattice and explore our ability to cancel the interactions. Our results are interesting since we are performing atom interferometry with a nearly ideal coherent matter wave. This system is a promising sensor for measuring forces with high spatial resolution.

5. ”Dense packets of cold atoms: production and manipulation”
   David Guery-Odelin
   In this poster, I will summarize the results we have recently obtained on the production of dense packets of ultracold atoms. We have studied the physics of evaporation ramp of a cloud trapped in an elongated dipole trap. We also address the issue of the transportation of those packets. Our aim is to couple those packets to a guide at a high rate in presence of evaporative cooling to generate the equivalent of a continuous laser of matter-waves.

6. ”Phase Sensitive Recombination of two Bose-Einstein Condensates on an Atom Chip”
   The recombination of two split Bose-Einstein condensates on an atom chip is shown to result in heating which depends on the relative phase of the two condensates. This heating reduces the number of condensate atoms between 10% and 40% and provides a robust way to read out the phase of an atom interferometer without the need for ballistic expansion. The heating may be caused by the dissipation of dark solitons created during the merging of the condensates.

7. ”Quantum Turbulence in a Trapped Bose-Einstein Consensate”
   Michikazu Kobayashi and Makoto Tsubota
   We propose quantum turbulence in trapped Bose-Einstein condensates by numerically studying the Gross-Pitaevskii equation. Combining rotations around two axes, we induce quantum turbulent state in which quantized vortices are not crystallized but tangled.

8. ”Coherent transport of light in cold atoms”
   G. Labeyrie, D. Wilkowski, C. Mueller, R. Kaiser, C. Miniatura, D. Delande
   We present an overview of our study of transport of near-resonant light in optically-thick clouds of cold atoms. Using the coherent backscattering interference as a probe of coherent transport, we identified and analyzed three decoherence mechanisms in such media, due to the atomic internal structure, the residual atomic motion and the saturation of the atomic
transition. Future prospects toward the observation of strong localization are discussed.

We propose a method for the detection of quantum phases of multicomponent gases through quantum non demolition measurements performed by sending off-resonant, polarized light pulses through the gas. We show that various strongly-correlated phases of spinor Bose gases in an optical lattice and fermionic superfluidity can be identified by detecting the quantum fluctuations and mean values of the polarization of the transmitted light.

10. "Manipulation of cold atoms on a superconductive atom-chip" T. Mukai, C. Hufnagel, and F. Shimizu
Our recent results on the manipulation of atoms trapped on a superconducting wire atom-chip will be presented.

11. "Permanent magnetic atom chips: BEC and vast magnetic lattices" S.W. Whitlock, R. Gerritsma, Th. Fernholz, R.J.C. Spreeuw
We describe a self-biased, fully permanent magnet atom chip used to study ultracold atoms and to produce a Bose-Einstein condensate (BEC). Radio frequency spectroscopy is used for in-trap analysis and to determine the temperature of the atomic cloud. The formation of a Bose-Einstein condensate is observed as a narrow peak appearing in the radio frequency spectrum. We also present experiments with a BEC above a lithographically patterned magnetic film chip, containing vast 2D lattices containing \( \approx 1000 \) magnetic traps per mm\(^2\). We present our results on loading the magnetic lattice and discuss prospects to use them as quantum registers.

We present the status of two atom chip experiments which we currently set up in Munich. The goal of the first experiment is to investigate the dynamics of small Bose-Einstein condensates in microwave near-fields on an atom chip. Microwave near-fields are a key ingredient for atom chip applications such as quantum information processing, atom interferometry, and chip-based atomic clocks. We have integrated miniaturized microwave guiding structures on an atom chip, using a newly developed lithographic fabrication process for chips with multiple layers of metalization. The micrometer-sized structures allow to generate microwave near-fields with unusually strong gradients. Through microwave dressing of hyperfine states, state-selective double-well potentials can be created. One goal of the experiment is to investigate whether these potentials can be used to
generate entanglement between small Bose-Einstein condensates on the atom chip. The second experiment aims at observing the coupling of a Bose-Einstein condensate to the mechanical oscillations of a nanoscale cantilever with a magnetic tip. At room temperature, the thermal oscillations of the cantilever tip induce spin-flip transitions of the magnetically trapped atoms to untrapped states. This is similar to an atom laser experiment, with the mechanical resonator generating the radio-frequency magnetic field for output coupling. By detecting the loss of atoms from the trap, we intend to use the BEC as a sensitive probe for the mechanical motion of the cantilever, which allows a time-resolved detection of the thermal amplitude fluctuations. At cryogenic temperatures, back-action of the atoms onto the cantilever is significant and the system represents a mechanical analog of cavity quantum electrodynamics. In this regime, the BEC could be used as a coolant or a coherent actuator for the nanomechanical resonator. The coupling could be used to transfer nonequilibrium states of the BEC, which consists of a few thousand atoms, to the mechanical system, which consists of several billions of atoms.

13. ”Atom entanglement from light scattering on BEC’s” K.M.R. van der Stam, R. Meppelink, J.M. Vogels, and P. van der Straten
Using light scattering on Bose-Einstein condensates we study the entanglement of atoms. In the light interaction with the condensate, atoms are scattered in both the forward and the 'counterintuitive' backward direction, which results in entangled atom pairs. We have enhanced the backscattering by driving the process using two frequencies and observe an equal balance between the forward and backward scattered atoms. We compare our results to a semi-classical model and obtain reasonable agreement between model and experiment. We detected the so-called end-fire modes of the light scattering and observe under certain conditions only one end-fire mode, which enhances the entanglement. Finally, we have applied noise correlations spectroscopy to directly observe the entangled pairs and will show the first results of these measurements.

14. ”Novel Complex Atom Traps” Wolf von Klitzing and Igor Lesanovsky
We demonstrate a novel class of trapping potentials, time-averaged adiabatic potentials (TAAP), which allows the generation of a large variety of traps for quantum gases and matter-wave guides for atom interferometers. Multiple traps can be coupled through controllable tunneling barriers or merged altogether. We present analytical expressions for pancake-, cigar-, and ring-shaped traps. The TAAP traps can be created in a standard magnetic quadrupole trap using RF fields together with low frequency modulation fields. The ring-geometry is of particular interest for guided matter-wave interferometry as it provides a perfectly smooth waveguide of controllable diameter, and thus a tunable sensitivity of the interferometer. The flexibility of the TAAP makes possible the use of Bose-Einstein condensates as coherent matter-waves in large area atom interferometers.
4.02 BEC experiments:

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Figure 4: BEC Formation [1]

Figure 5.2: BEC formation by superimposing an electrostatically formed attractive potential (‘dimple’) onto a 1D magnetic trap. The time sequence shown starts with a thermal cloud in the original trap (\(V_{dimple} = 0\)). After the dimple is switched on (\(V_{dimple} = 3.5V\)), atoms start to accumulate near the electrode and a condensate is eventually formed, purely by means of the electrostatic potential. The signature of the BEC in the time-of-flight images (expansion time 10ms) is clearly visible as the enhanced density of thermal atoms in the dimple is much less pronounced and not detectable for thermal atoms. This was verified in a separate experiment.

Figure 4: BEC Formation [1]
Figure 2.30: Dynamic splitting of an atom cloud. A single trap is gradually (within 15ms) turned into a double well potential by ramping the voltage on one electrode down while two neighboring electrodes are slowly charged. *(top)* Fluorescence images of the atoms during different stages of the experiment. The inserts schematically show the polarities and voltages (darker shading corresponds to higher voltage) during the different phases of the experiment. *(center)* The density profile clearly shows the gradual splitting of a single cloud into two. *(bottom)* The corresponding potentials along the axis of free motion in the magnetic guide.

Figure 5: Dynamic splitting of an atom cloud[1]
Figure B.2: (left) Atom chip assembly: The U-wire structure for the MOT (Sect. 3.1.1) and an additional structure containing Z-shaped wires in several sizes (Sect. 3.1.2) are connected to high-current vacuum feedthroughs. The atom chip is mounted directly on top of these wire structures. (center) Schematic drawing of the vacuum chamber. The actual ‘science’ chamber consists only of a small octagonal steel body (small rectangle at the bottom of the picture) containing the atom chip. The rest of the chamber serves mainly vacuum diagnostics and allows fast and efficient pumping. (right) Photograph of a clear view of the chamber before (top, side view) and after (bottom, bottom view) optics and coils were mounted.

Figure 6: Atom Chip Assembly [1]
Figure 3.9: Absorption images taken in situ (left) and after 5ms time-of-flight (center) during the transfer from Cu-Z-trap to the chip. The in situ images are magnified and the transverse direction is scaled up by a factor of 4 with respect to the longitudinal direction. (right) Transverse trap frequencies $\omega_\perp$ (blue line) during the transfer and corresponding temperatures (red circles). The adiabatic cooling and heating due to slight changes in $\omega_\perp$ are clearly visible. During the transfer, the atoms are moved towards the chip surface and, due to a $\sim 200\mu$m misalignment between Cu and chip wire, to the right.

Figure 7: Absorption images [1]
Figure 2.11: Time sequence of atoms released from the reservoir trap into the spiral shaped guide. (left) Fluorescence images. Atoms that have reached the end of the guide (center of the spiral) are reflected from a potential barrier and propagate in the backward direction. (right) One-dimensional density distributions along the path of the spiral, extracted from the experimental data and Monte-Carlo (MC) simulations (solid and dashed curves, respectively). In the inserts, the corresponding velocity distributions obtained by the same MC calculations are depicted. In those plots, a clear signature of the reflection is visible, the part of the cloud propagating backwards is clearly separated from that propagating in the forward direction.
Figure 9: Omni-directional Guide[1]

Figure 2.9: Omni-directional guide. (left) Chip design: The wires are shown as black lines, the white areas are grounded parts of the chip surface. The insert shows a microscope image of a detail of the spiral shaped wire guide. (right) Fluorescence of a magnetically trapped cloud and its reflection from the chip surface just before the guide is loaded. The guiding wires are visible through scattered imaging light.

Figure 10: $^7$Li atoms in Z trap[1]

Figure 2.17: In situ fluorescence image of a cloud of thermal $^7$Li atoms trapped in an elongated Z-trap based on a wire with a cross section as small as $1 \times 1 \mu m^2$ [195]. This wire tolerated a current density of $> 1.5 \times 10^7 A/cm^2$, and atoms could be trapped down to distances of 6\(\mu\)m from the wire (chip) surface.
Figure 11: Thermal cloud in Z trap[1]

Figure 2.18: A thermal atom cloud confined in a Z-trap can be split by overcompensating $B_{||_{\text{wire}}}$ with a stronger $B_{||_{\text{axial}}}$. (left) Typical equipotential surfaces for the combined (top) and split (bottom) case. (right) Demonstration experiment with thermal $^{87}\text{Rb}$ atoms. The in situ absorption images (appendix B.5) are taken from the direction parallel to the wire plane and perpendicular to the center wire of the (copper wire) Z-trap (Sect. 3.1.2).

Figure 2.25: Numerical calculations of (planar) current densities in different geometries. The current density magnitudes (false colors) are normalized to the value at each of the central wires. The directions are indicated as stream lines. (left) The current flowing through a straight wire ‘spreads out’ at a wire junction. (center) The behavior at a wire crossing is similar. (right) The current flow through a Z-shaped wire can deviate significantly from a simple ‘stick model’ approximation in which thin wires are assumed to replace the real wires at their respective centers. The geometry shown is the one used underneath the atom chip for BEC production (Sect. 3.1.2).

Figure 12: Trap numerical calculations[1]
Figure 2.28: Within a string of six electrodes, an arbitrary subset of traps can be operated (almost) independently (the longitudinal confinement in one trap is slightly higher if the neighboring trap is operated than if it is not). (top) False color fluorescence image of all six traps in operation (indicated by ‘+’-signs). (bottom) A subset of four traps (‘0’s indicate grounded electrodes).

Figure 13: String of six electrodes[1]

Figure 3.6: Phase space density increase over more than 7 orders of magnitude during a 10 s cooling sweep to BEC in the Cu-Z-trap. The inserts show absorption images (10 ms time-of-flight) at equal scales (except magnified BEC in first insert from the right). In this example, the trap contained initially \( \sim 4 \times 10^7 \) atoms at \( \sim 360 \mu \text{K} \). The final BEC contains \( \sim 3 \times 10^4 \) atoms. The trap changes from essentially linear \( \partial \mathcal{B}/\partial \mathcal{r} \approx 400 \text{G/cm} \) for hot atoms to harmonic \( \omega_\perp = 2\pi \times 440 \text{Hz}, \omega_\parallel = 2\pi \times 40 \text{Hz} \) for cold atoms.

Figure 14: Phase space density BEC[1]
Figure 15: Time-of-flight sequence [1]

Figure 3.16: Time-of-flight sequence (2ms...12ms, 1ms steps, from left to right) of a BEC released from a chip trap, falling under the influence of gravity. The change in aspect ratio between the extensions in the horizontal and vertical directions, respectively, is characteristic of an expanding BEC. In this example, a current of 2A was driven through the 100μm-Z-wire, the bias fields were $B_1 = 25G$, $B_{p,ext} = 1G$ which leads to $\omega_{x} = 2\pi \times 1.6kHz$ and $\omega_{y} = 2\pi \times 23Hz$. The number of atoms in the almost pure condensates was $\sim 10^5$.

Figure 16: Zoom on the Z trap [1]

Figure 3.20: The transverse position of an atomic cloud above a broad wire (100μm-Z in this case) can be directly determined by vertical absorption imaging. (top) The direct image reveals the features on the chip, the atom cloud is just visible in the center of the central broad wire. The random structures on the mirror surface are speckle patterns. (bottom) Processed absorption picture (divided by reference image without atoms): The atoms are clearly visible and the speckle patterns are reduced.
Figure 5.3: Time sequence (70ms) of a BEC released from a trap to a guide. The center row contains eight absorption images taken from a direction almost orthogonal to the chip surface. The expansion and movement of the cloud (and its reflection) along the guide (time step 10ms) is clearly visible. The additional images (top and bottom) are examples of time-of-flight (10ms) images of the expanding cloud (horizontal imaging). The 1D density profiles show that a pure condensate gradually turns into a thermal cloud during the transport (Gaussian fits to the thermal fraction plotted as red lines).

Figure 17: BEC time sequence [1]
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