BOSE - EINSTEIN CONDENSATION AND SUPERFLUIDITY IN SOLID STATE SYSTEMS

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LECTURE 1

BEC - definition
BEC - final state properties
GP equation
GP possible solutions

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WHAT IS IT ABOUT

Bose-Einstein condensation in atomic systems - the dream and discovery.
History of the experimental observation of BEC state in atomic systems. Most important experimental results including techniques of laser cooling, absorption spectroscopy and interferometry.

Solid state systems - introduction
Most important properties of solid state systems. This include: band diagrams, electron and hole concepts, doping. Further on we will focus on simple heterostructures - interfaces, quantum wells, quantum wires, quantum dots.

Quasiparticles.
Excitations in the solid state from the point of view of new quasiparticle creation. Concept of excitons (ground and excited states), phonons, photons, magnons with the possibility for those particles to condense.

More complex quasiparticles.
Various types of polaritons: phonon-polaritons, exciton-polaritons, plasmon-polaritons, magnon-polaritons. Dressed states.

WHAT IS IT ABOUT

Exciton-polaritons.
The properties of exciton-polaritons in details as they are very good candidates to observe BEC. At this point it is important to construct the complex photonic systems: the Bragg mirrors and microcavity structures. Differences between the spontaneous emission, weak coupling and strong coupling. Similarity of microcavity with quantum wells to VECSEL structure.

Bose-Einstein condensation of exciton-polaritons.
The first experiment demonstrating polaritonic BEC. Differences between the atomic and polaritonic BEC. The first and second order coherence.

Bose-Einstein condensation of exciton-polaritons - details.
Differences between the BEC state and polariton laser. Experimental results of polariton lasing in various type semiconductor systems: II-VI, III-V wide and narrow bandgap materials. Josephson effect.

WHAT IS IT ABOUT

Superfluidity of exciton-polaritons.
Short history of experimental observation of superfluid state in various systems. The properties of the superfluid state. The first experimental results that demonstrate the superfluid state of exciton-polaritons.

Full and half vortices - stationary.
The appearance of the vortices at the beak of (or at the birth) of the superfluid state. Introduction and the most important physical properties of the classical and quantum vortices. Properties of full and half vortices with the most prominent experimental results in this subject.

Vortices - propagating in the wake of an obstacle.
Vortices propagating in the wake of an obstacle. Role of the superfluid velocity: supersonic and subsonic. Solitons.

WHAT IS IT ABOUT

BEC of pure excitons.
Before the exciton-polariton physics, the first attempt to create the condensed state were performed with pure excitons. The most important results in excitonic BEC (direct excitons, indirect-excitons, Cu_2O excitons).

Magnons.
The concept and the most important results from the BEC of magnons and short look at any other BEC possibility in solid state system.

TWO LAST WEEKS

Summary and EXAM preparation
Overview and list of take home messages.
Before: mind map of the subjects discussed during the lecture. Work in the group or individually. Personal notes and discussed publications are required in order to attend this lecture.

EXAM - REPORT in one of the following forms
- public presentation of one idea/paper/subject (10 min + questions & explanations)
- written report on one idea/paper/subject (can be in polish) (5 A4 pages minimum)
- your suggestions are welcome

BOSE - EINSTEIN CONDENSATION

CONDENSATE ?

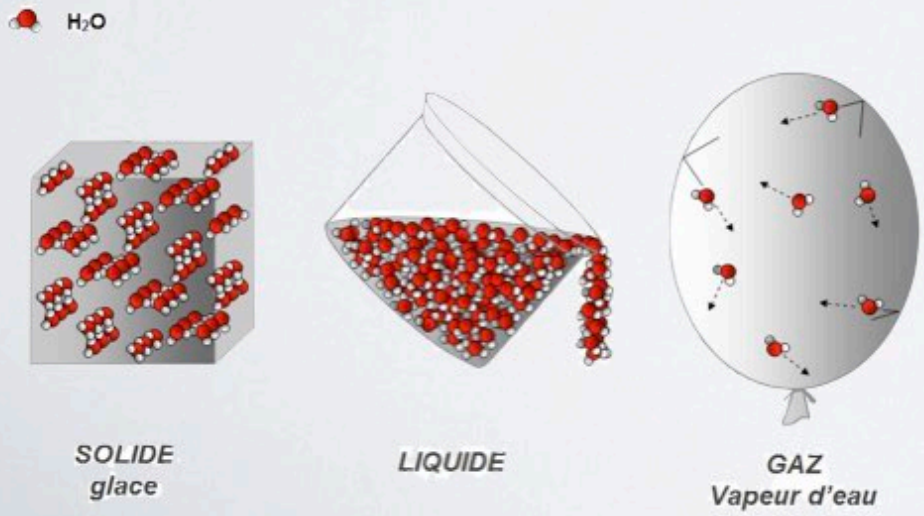
- new state of matter (bosons) at low temperature

STATES OF MATTER:

(most common)

phase transition ↕

- solid
- liquid
- gas
- plasma



BUT ALSO (less common):

- non classical states as glasses, gels, sols
- superconductors
- superfluids
- supersolids
- quantum hall effect states
- supercritical liquids
- degenerate matter
- strange matter
- Rydberg matter
- and many more...

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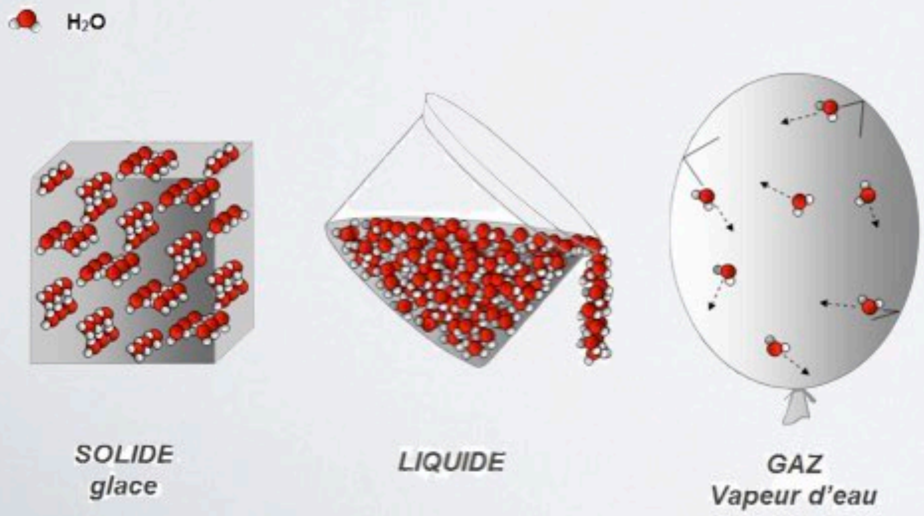
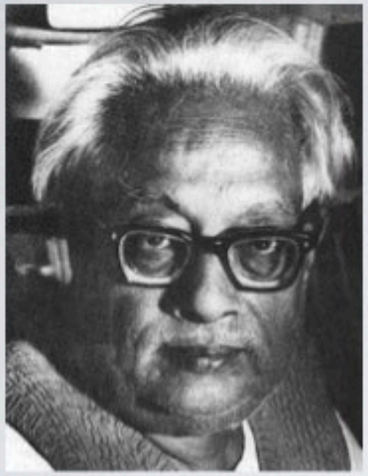


CONDENSATE theoretical discovery 1924 - 1925

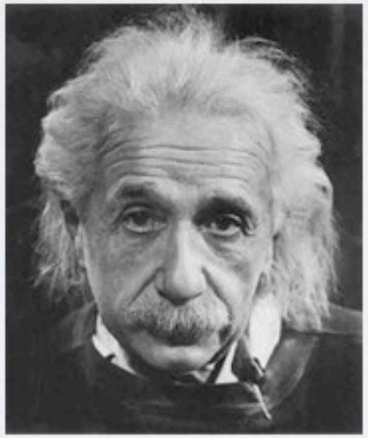


Satyendra Natah Bose

Quantum statistics of light quanta (photons)

S. N. Bose, Z. Phys. 26, 178 (1924)

- many photons in the same quantum state
- indistinguishability of two particles in the same quantum state

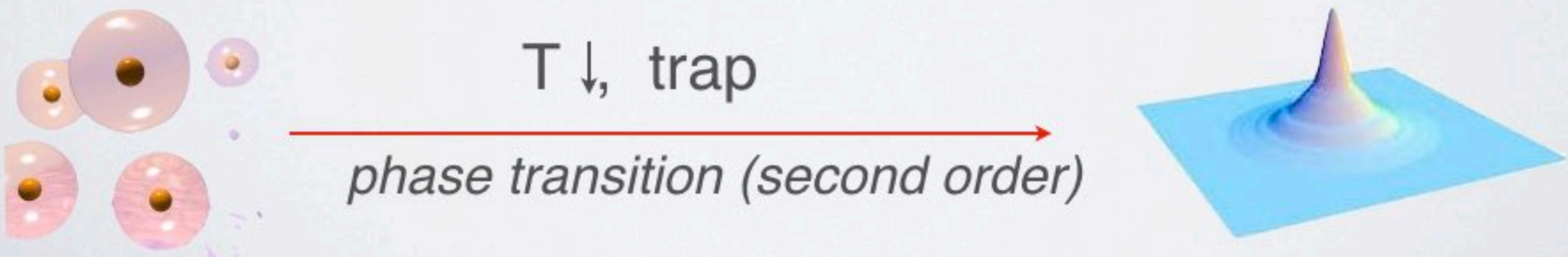


Albert Einstein

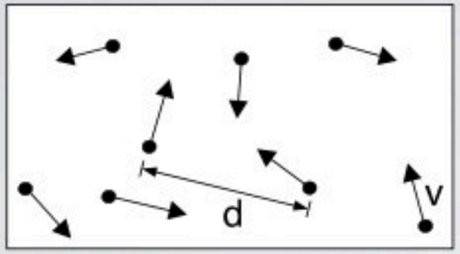
Not only light but also matter (bosons) may have the same properties.

A. Einstein, Sitzungsber. Preuss. Akad. Wiss., Bericht 3, p. 18 (1925)

Method:



CLASSICAL VS QUANTUM NATURE



Gas - delocalized classical objects described within the classical thermodynamics law

quantum nature is revealed at particular conditions

Is something considered as being material particles can sometimes behave like a wave?

now that it was clear that a wave can sometimes behave like particles

Louis de Broglie

Noble prize 1929

$$p = mv \qquad p = \frac{h}{\lambda}$$

$$mv = \frac{h}{\lambda}$$

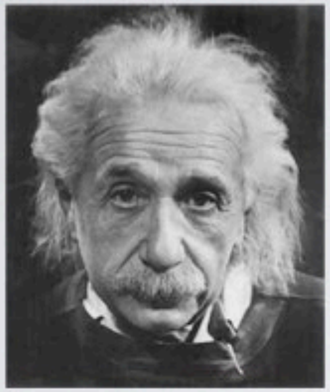
$$\lambda = \frac{h}{mv}$$

This expression allows for the calculation of wave-length of a particle in motion

Davisson and Thomson confirmed experimentally the observation of de Broglie. They received the Nobel prize in 1937.

np. 0.2 kg ball moving with a speed of 15m/s has de Broglie wavelength of 2.21e-34m

Davisson–Germer experiment (1923-27) @ Bell Labs



Albert Einstein

Noble prize 1921
for photoelectric effect:
light - discrete and localized quanta of energy

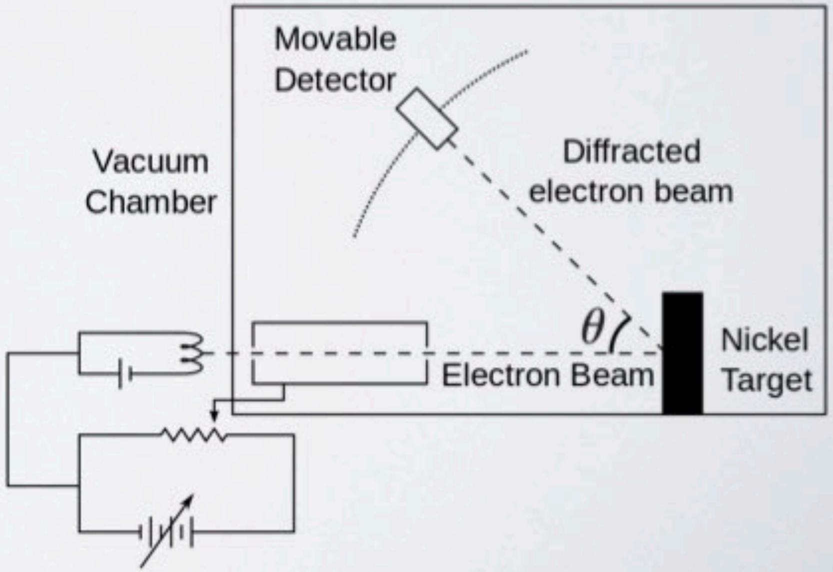
Louis de Broglie

Noble prize 1929
the wave–particle duality theory
all matter displays the wave–particle duality of photons

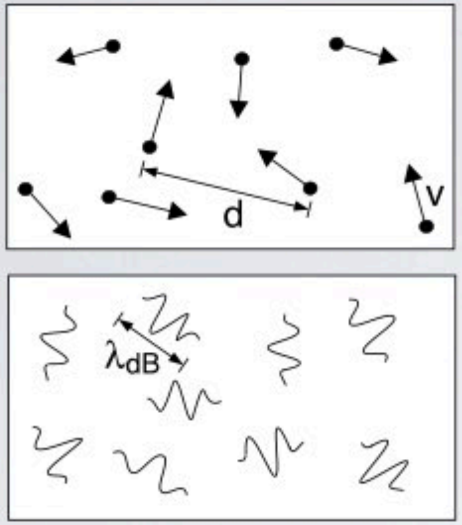
Lester Germer *Clinton Davisson*

Noble prize 1937
for his discovery of electron diffraction

According to the de Broglie relation, electrons with kinetic energy of 54 eV have a wavelength of 0.167 nm. The experimental outcome was 0.165 nm via Bragg's law, which closely matched the predictions. As Davisson and Germer state in their 1928 follow-up paper, „…The reflection data fail to satisfy the Bragg relation for the same reason that the electron diffraction beams fail to coincide with their Laue beam analogues." However, they add, "**The calculated wave-lengths are in excellent agreement with the theoretical values of h/mv** …." So although electron energy diffraction does not follow the Bragg law, it did confirm de Broglie's equation.



CLASSICAL VS QUANTUM NATURE

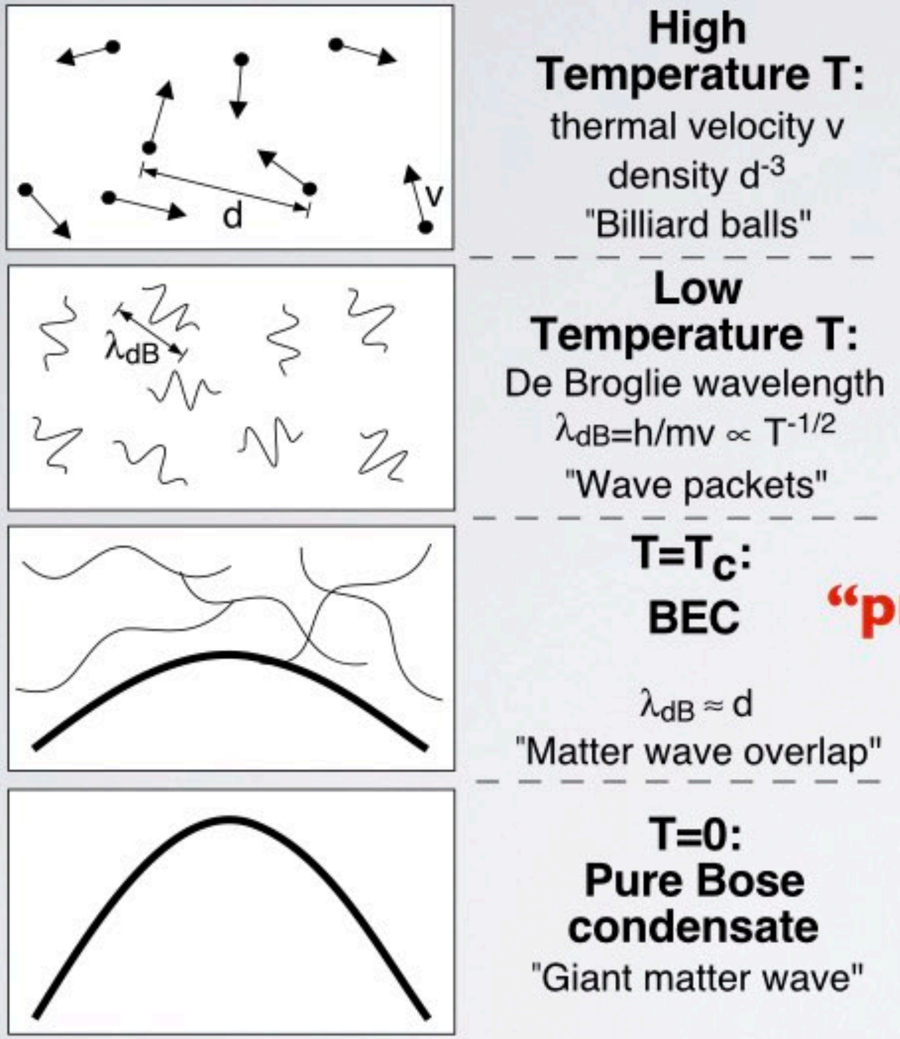


Gas - delocalized classical objects described within the classical thermodynamics law

quantum nature is revealed at particular conditions

At nanokelvin temperatures the thermal de Broglie wavelength exceeds 1 μm which is about 10 times the average spacing between atoms

CONDENSATE (scheme)



Wysoka temperatura:
"kule bilardowe"

Niska temperatura:
"paczka falowa"

Temperatura krytyczna:
"przekrywanie się paczek falowych"
"zupa kwantowa" nierozróżnialnych cząstek

Zero bezwzględne:
"makroskopowa fala materii"

source: WHEN ATOMS BEHAVE AS WAVES: BOSE-EINSTEIN CONDENSATION AND THE ATOM LASER
W. Ketterle, Nobel Lecture, December 8, 2001

CONDENSATE

- Macroscopic number of particles is occupying one single quantum state of the lowest energy in the system
- (important: there is no statistical limit to the number bosons that can occupy a single state!)
- All particles are described by one macroscopic wave-function
- This macroscopic wave function is also an order parameter of the system

CONDENSATE WAVE-FUNCTION

The condensate wave-function is complex and can be described by $\psi = \psi(\vec{r},t)$

amplitude $|\psi(\vec{r},t)|$

and phase $\theta(\vec{r},t)$

The condensate wave-function:

$$\psi(\vec{r},t) = \sqrt{n(\vec{r},t)}\, e^{i\theta(\vec{r},t)}$$

where: $n = |\psi(\vec{r},t)|^2$

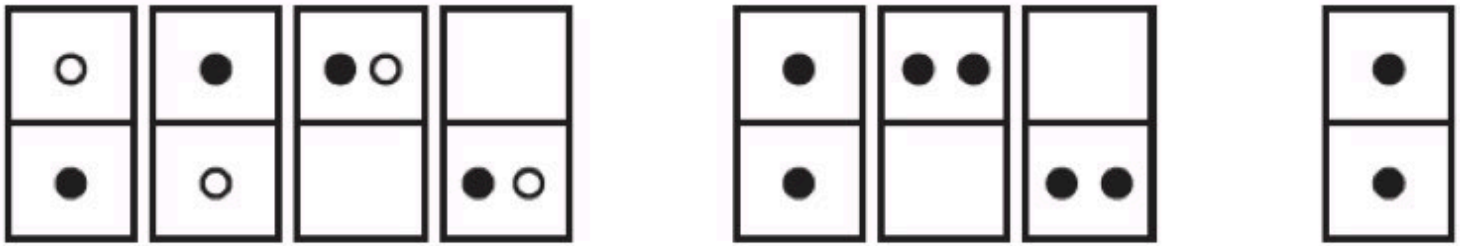
QUANTUM STATISTICS

- How to distribute particles on possible quantum states ?

problem determined by quantum statistics- the symmetry of the wave function upon a permutation of the particles.

- Let's consider two particles which can be distributed in two boxes

- What is a probability in each case to find **two particles in one box**?



Distinguishable bosons (like classical particles)

Indistinguishable bosons (bosonic particles at quantum limit)

Fermions

QUANTUM STATISTICS

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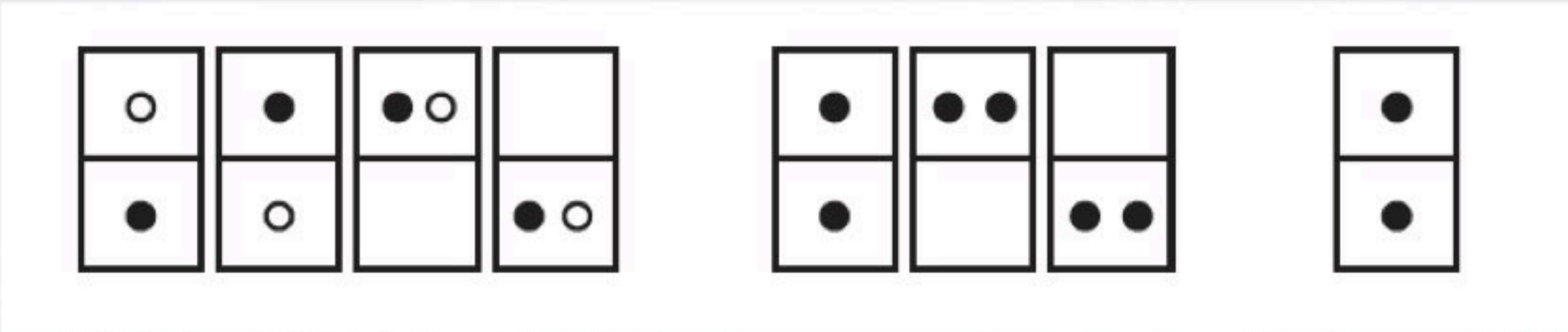
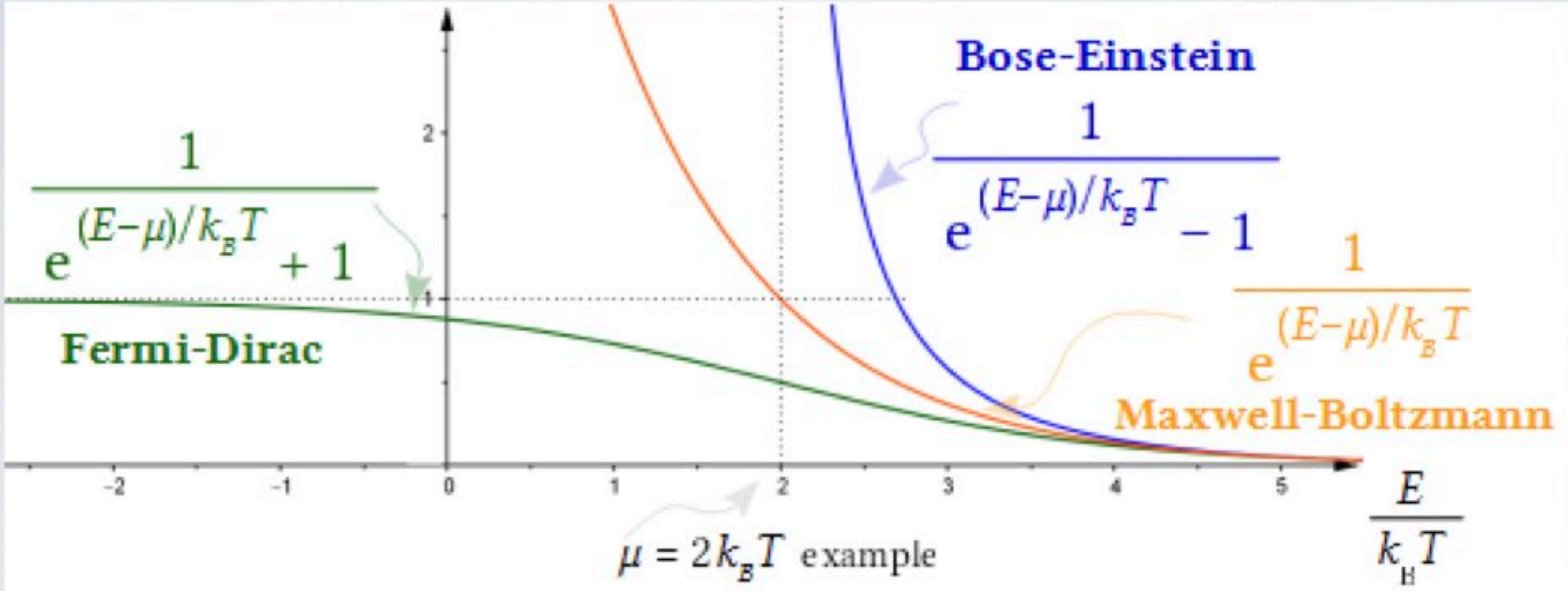


Distinguishable bosons (like classical particles)	*Indistinguishable bosons (bosonic particles at quantum limit)*	*Fermions*
$\frac{1}{2}$	$\frac{2}{3}$	0

Bose - Einstein, Fermi-Dirac and Maxwell-Boltzmann distributions



there is no statistical limit to the number bosons that can occupy a single state

MACROSCOPIC POPULATION

From the point of view of statistics

- gas of noninteracting bosons
- energy levels are measured from the lowest energy level (zero)
- the grand canonical ensemble is the best to describe the probability distribution
- system is in contact with reservoir - to exchange energy and particles
- the constants are: the chemical potential and the temperature

Bose–Einstein distribution gives the average occupation number of particles in state *v*:

$$f(\epsilon_\nu) = \frac{1}{e^{\frac{\epsilon_\nu - \mu}{k_B T}} - 1}$$

The chemical potential **μ** must be negative, otherwise the Bose–Einstein distribution would be negative for some of the levels

CONDENSATE

The condensate wave-function: $\psi = \psi(\vec{r}, t)$

The interaction potential: $V(\vec{r_1} - \vec{r_2}) = g\,\delta(\vec{r_1} - \vec{r_2})$

Describes the dilute limit:
average spacing between particles > scattering length

Single particle wave-function satisfies the Gross-Pitaevskii time-dependent equation:

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

$$n = \left|\psi(\vec{r}, t)\right|^2$$