BOSE-EINSTEIN CONDENSATION

Modern Physics

Spring 2002

Arnulf Materny

IT TOOK SOME TIME ...

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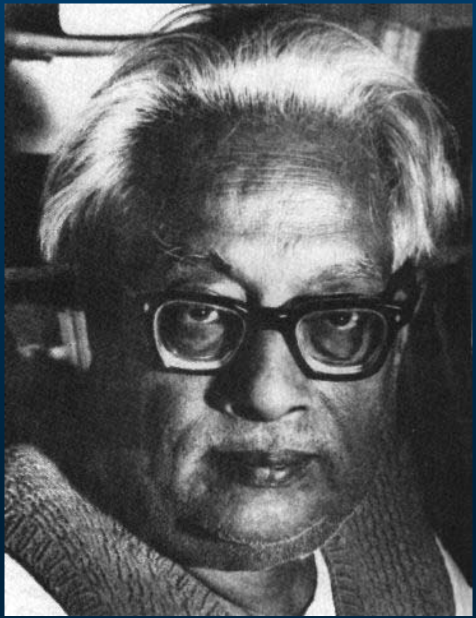
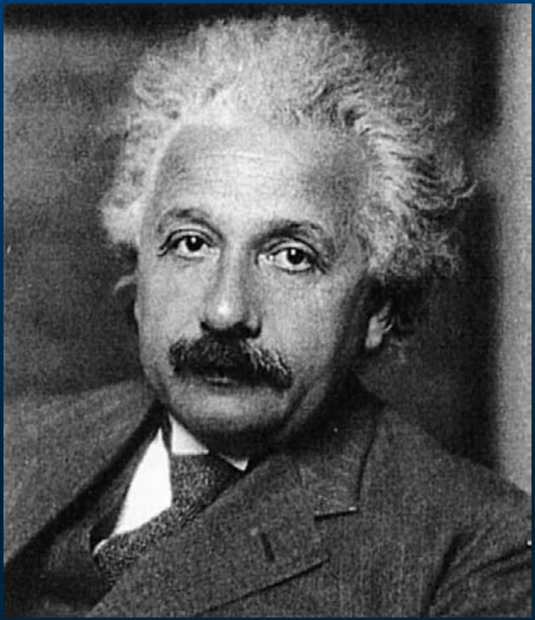


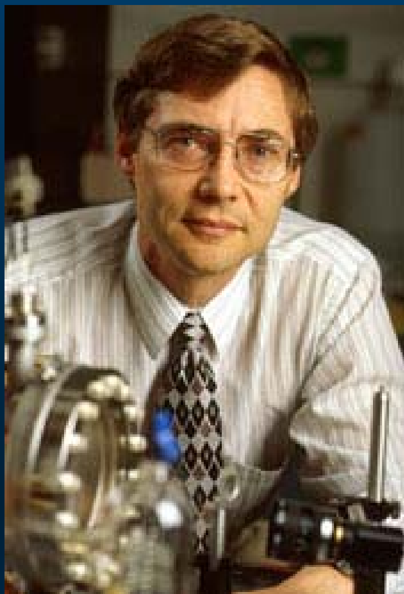
Satyendranath Bose
(1894-1974)



Albert Einstein
(1879-1955)

Prediction 1924:
Condensation of atoms results in a new form of matter at the coldest temperatures in the universe ...

It took some time ...



Carl E. Wieman
Univ. Colorado Boulder

Eric A. Cornell
NIST

Wolfgang Ketterle
MIT

Nobel Prize 2001:
"for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates"

Temperature and Absolute Zero

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- Why do some things feel hot and others cold?
  - The motion of atoms in gases, liquids, and solids is related to the temperature.
  - High temperature means fast motion, low temperature slow motion.
  - Motion is related to energy – kinetic energy – which can be transferred.
- Can temperature be related to the speed of atoms?
  - Yes!
- Does a certain temperature mean that the atoms in a gas have a certain speed?
  - No!

TEMPERATURE AND ABSOLUTE ZERO

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Maxwell Speed Distribution:

$$f(v) = 4\pi\left(\frac{M}{2\pi RT}\right)^{\frac{3}{2}} v^2 \exp\left(-\frac{Mv^2}{2RT}\right)$$

Temperature and Absolute Zero

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- What does absolute zero mean?
  - Temperature scale in Physics: Kelvin
  - Absolute zero: $T = 0$ K
- Does $T = 0$ K mean that *e.g.* atoms in a gas are not moving any more?
  - Maxwell's description would say "yes"
  - However, it is more difficult ...
- Remember the "Quantum Hall Effect"!
  - Extremely low temperature $\rightarrow$ quantum description becomes important

QUANTUM STATISTICS

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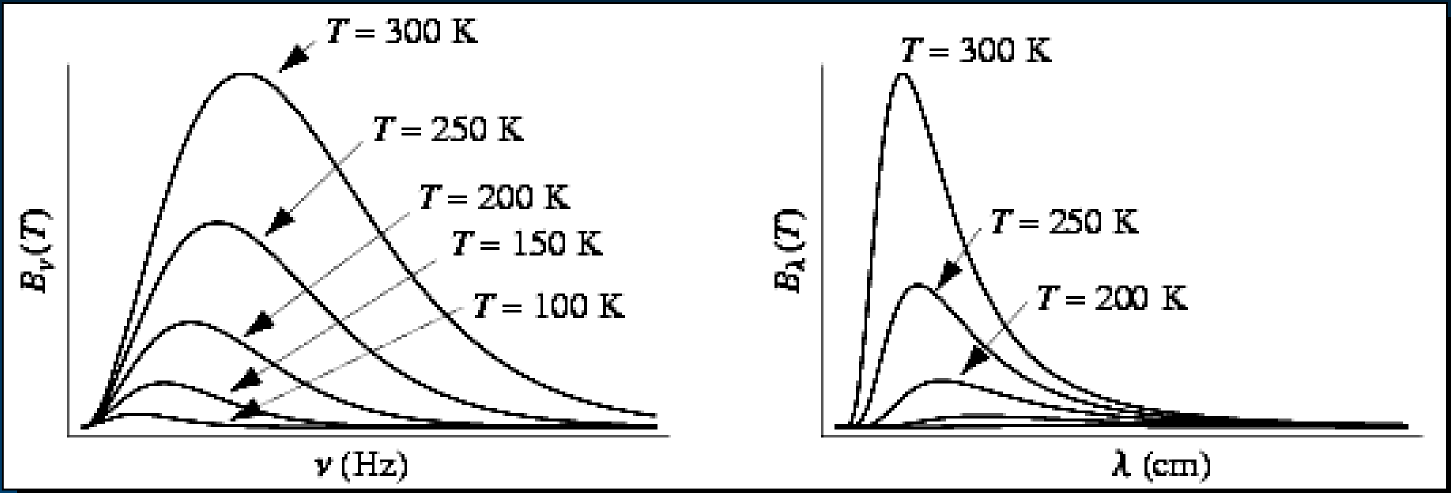
- You already should know one quantum statistics:
  - Planck's Law describes the "specific intensity" of photons emitted from a "black body" at a certain temperature

$$B_\nu(T) \equiv \frac{dI}{d\nu} = \frac{2h}{c^2}\frac{\nu^3}{e^{h\nu/kT}-1}$$

$h\nu =$ Photon energy

$kT =$ Thermal energy



QUANTUM STATISTICS

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- Was it really Planck who derived "Planck's Law"?
  - No!
  - In 1924 **Satyendra Nath Bose** suggested that Photons
    - occupy different states
    - the number of photons is not conserved
  - **Albert Einstein** supported this idea and generalized it to the description of atoms

$$f(E) = \frac{1}{Ae^{E/kT} - 1}$$

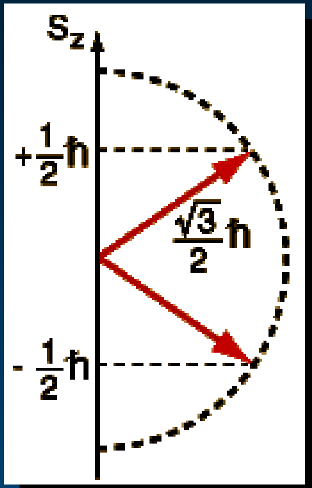
QUANTUM STATISTICS

- Was Einstein right with his assumption?
  - Yes and no!
  - The "Bose-Einstein" statistics is only valid for bosons
- What is a boson?
  - Particles having integer spin (*e.g.* photons, neutrons, ...)
- What else exists?
  - Particles having half-integer spin (*e.g.* electrons, ...) - **fermions**
- What is "spin"?
  - The intrinsic angular moment of the particle

For electrons:

$$S = \sqrt{s(s+1)}\,\hbar$$

$$s = \frac{1}{2}$$



QUANTUM STATISTICS

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- What is the difference between these types of particles?
  - Only two fermions can be in one energy state (spin up and spin down) – "Pauli exclusion principle"
  - Unlimited number of bosons can collect in the same energy state
- And?

That makes the difference!!!

Bose-Einstein Condensation

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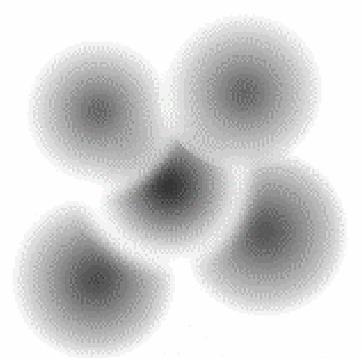
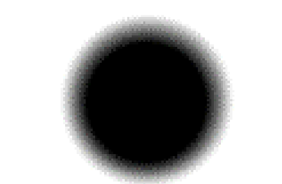
- What does Bose-Einstein condensation mean?
  - Compare to liquid-gas system:
    - Liquid ≡ atoms in ground energy state
    - Gas ≡ atoms in excited states
- What does a Bose-Einstein condensate look like?
  - Ground energy state means equal quantum mechanical wavefunction for all atoms
  - Atoms can not be distinguished any more
  - Huge De Broghlie wavelength at low temperature results in overlapping wavefunctions
  - "Super atoms" are formed



Some very cold atoms



Some atoms in a BEC condensate

Bose-Einstein Condensation

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- Can all bosons form Bose-Einstein condensates?
  - No!
  - Photons cannot – Why?

Probability that a particle will have energy *E*

$$f(E) = \frac{1}{Ae^{E/kT} - 1}$$

The quantum difference which arises from the fact that the particles are indistinguishable

For photons, A=1, so the occupation of very low energy states can increase without limit!

→ **No condensation possible!**

BOSE-EINSTEIN CONDENSATION

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- What is different for atoms?
  - The number is limited and independent of temperature

$$A = e^{-\mu / kT} \rightarrow f(E) = \frac{1}{e^{(E-\mu)/kT} - 1}$$

μ is the "chemical potential"
(energy required to add an additional particle to the system)

$$\text{for } T \rightarrow 0: \quad \mu \rightarrow -\frac{T}{N}$$

→ **All *N* atoms can condensate**

Bose-Einstein Condensation

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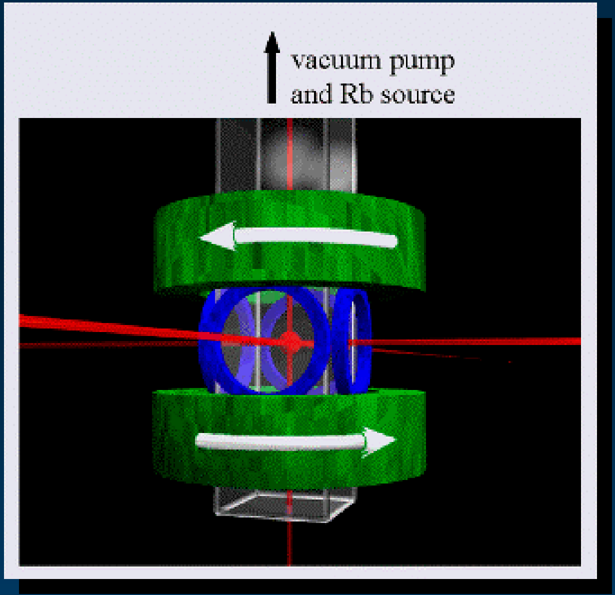
- Really all?
  - O.k., not all ...
  - The formation depends on the interaction of the atoms
  - *E.g.* ^{4}He atoms only condensate to about 15% resulting in a two-component system showing "Superfluidity"
- By the way, the Quantum Hall Effect as well as "Superconductivity" have to do with Bose-Einstein condensation!

How can a Bose-Einstein condensate be made?

- In 1995 the first realization was achieved by cooling in two stages
  - Laser cooling and trapping
  - Magnetic trapping and evaporative cooling
- Substance: ^{87}Rb atoms
- Temperature reached: T<170 nK
- Density: 10^{14} atoms / cm^3 (10^{-5} times the density of air)



LASER COOLING AND TRAPPING

- Doesn't laser light heat up things?
  - Only if it is absorbed!
- How does laser light cool atoms?
  - Photons can be inelastically scattered from atoms
  - Inelastically → kinetic energy of atoms is reduced
  - Remember: reduced kinetic energy → lower temperature

LASER COOLING AND TRAPPING

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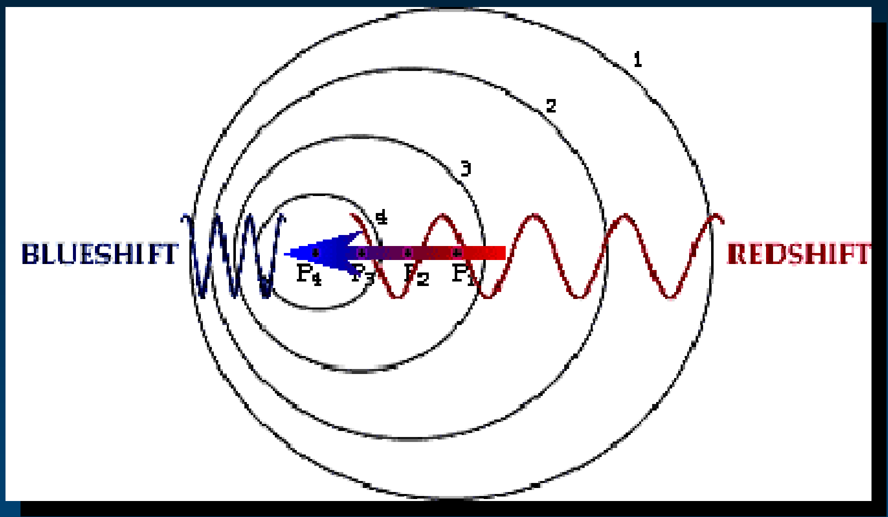
- Can any laser be used?
  - No, "resonance conditions" have to be fulfilled
  - Resonance means that the photon energy has to fit to the energy transitions within the atoms
  - The laser color has to be chosen right and kept stable

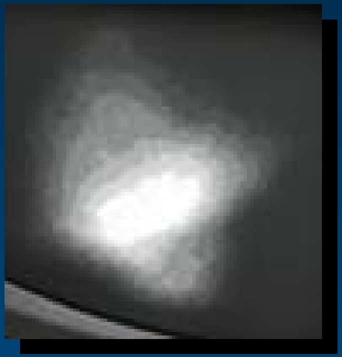
LASER COOLING AND TRAPPING

- Maxwell distribution → speed range for given *T*
- Atoms move in all directions
- How can the laser pick out atoms with the right speed and direction?
  - Motion → Doppler effect has to be considered!



Laser Cooling and Trapping

- Still there is motion in three dimensions – how can all the atoms be cooled and trapped?
  - The laser beams have to come from all directions!
  - Additionally coils are arranged such that in the middle of the cell a small and at the edges a bigger magnetic field is produced
    - Magnetic field shifts resonance energy of atoms
    - "Magnetic Doppler effect" → lasers push atoms into center
    - Formation of "optical molasses"



Magnetic Trapping

- By laser cooling a temperature of $T \approx 0.1$ mK is achieved
- For further cooling:
  - Lasers must be switched off
  - New trap has to be used: magnetic trap
  - Application of strong magnetic fields

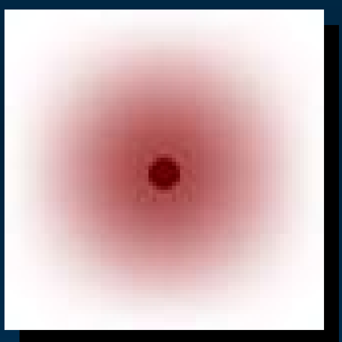
Evaporative Cooling

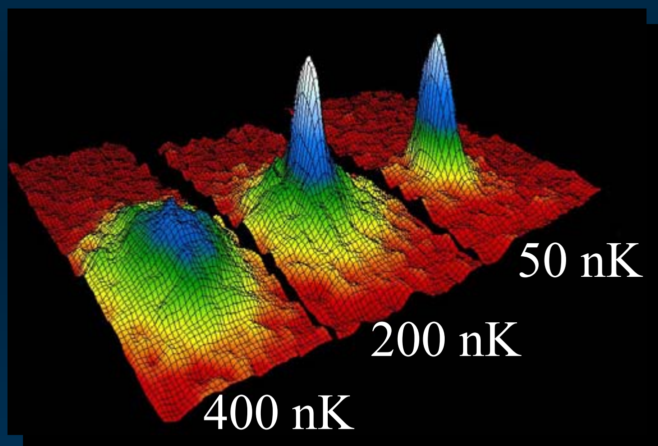
- The principle of "evaporative cooling" is well known
  - Remove the hottest particles (blowing away the vapor)
  - Keep the coldest particles (liquid in cup)

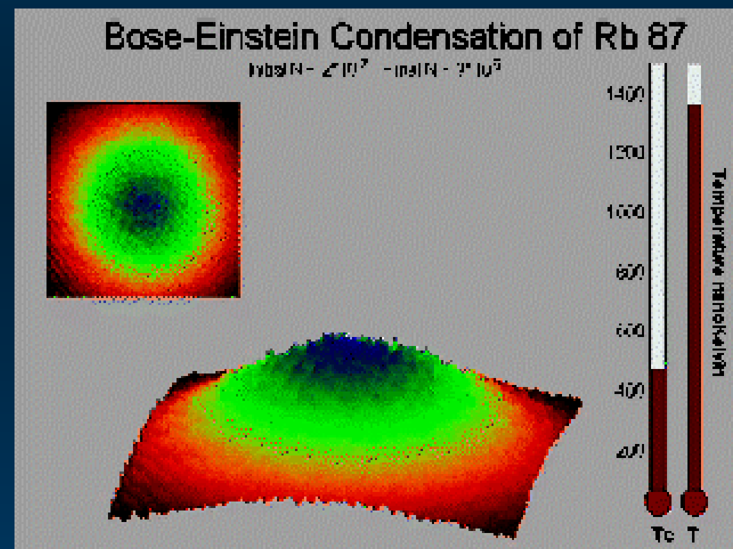
- How is this cooling done for atoms in a magnetic trap?
  - Lower the potential wall → atoms with higher energy escape

WHAT DOES A BOSE-EINSTEIN CONDENSATE LOOK LIKE?

- By illumination with red light (Rb absorption) and use of a microscope, the condensate can be seen surrounded by not yet condensated atoms







- Why is the condensate still spread?
  - Heisenberg's uncertainty principle:

$$\Delta x \cdot \Delta p \geq \hbar$$

CAN BOSE EINSTEIN CONDENSATES BE USED FOR ANYTHING?

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