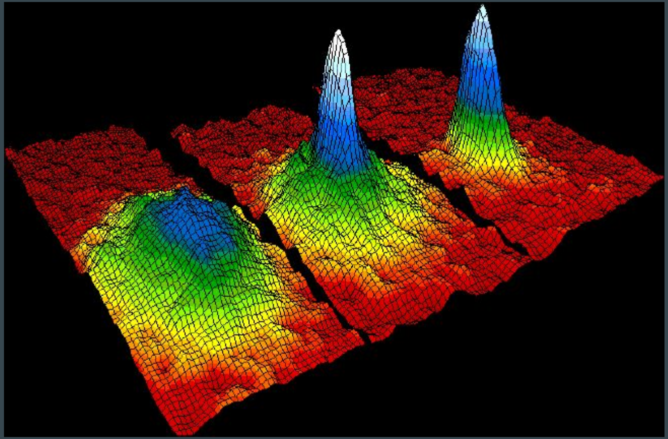
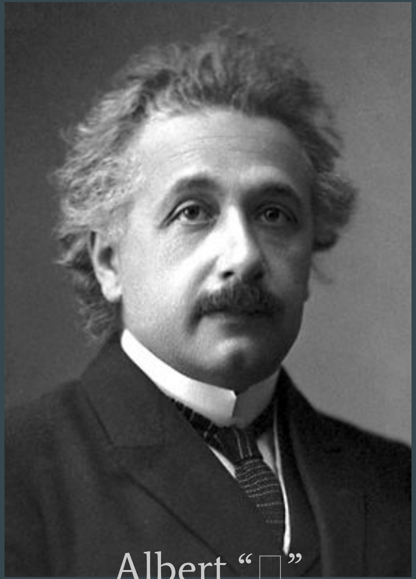
Bose-Einstein Condensate

Satyendra Nath Bose



Daniel Green



Albert “□” Einstein

Background

$$u(\nu) = \frac{8\pi h\nu^3}{c^3}\frac{1}{e^{\beta h v} - 1}$$

- Bose-Einstein statistics were first introduced in a 1923 paper by Satyendra Nath Bose titled "Planck's law and the light quantum hypothesis"
- In it, he attempted to derive Planck's radiation law without classical physics (since this was a quantum mechanical law)
- After his paper was rejected by *Philosophical Magazine*, he sent a copy directly to Albert Einstein who was so impressed with the paper that he personally translated it and submitted it for publication in *Zeitschrift für Physik* in 1924
- Over the next two years, Einstein published a series of 3 papers titled "Quantum Theory of a Monatomic Ideal Gas" in which the BEC state was first predicted

Bose-Einstein Statistics

$$\bar{n}_{\mathrm{k}} = \frac{1}{e^{\beta(\epsilon_{\mathrm{k}} - \mu)} - 1}$$

- The combined efforts of Bose and Einstein resulted in a breakthrough in the understanding the statistical mechanics of bosons (particles with integer spins like photons and ^{4}He atoms)
- Unlike half-integer spin fermions, bosons are not restricted by the Pauli exclusion principle and can simultaneously occupy the same state as an identical particle
- In the high-temperature limit, the Bose-Einstein distribution resembles the classical Maxwell-Boltzmann distribution
- The ability of bosons to co-occupy energy states meant that at sufficiently low temperatures (a fraction of 1 K), bosons in an ideal Bose gas would “condense” into the ground state via a process called Bose-Einstein condensation

Bose-Einstein Condensation

- An ideal Bose gas experiences Bose-Einstein condensation below a critical temperature, T_C

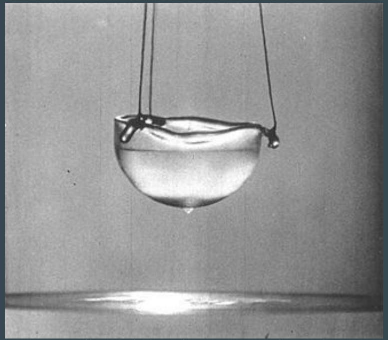
$$k_B T_C = \left(\frac{n}{\zeta(3/2)}\right)^{2/3} \frac{2\pi\hbar^2}{m} \approx 3.3125 \frac{\hbar^2 n^{2/3}}{m}$$

- Below T_C, macroscopic occupation of the ground state begins to occur meaning the fraction of particles in the ground state as $N \to \infty$ is nonzero
- An important condition for Bose-Einstein condensation is the overlap of deBroglie wavelengths ($\mathcal{D} \gg 1$)

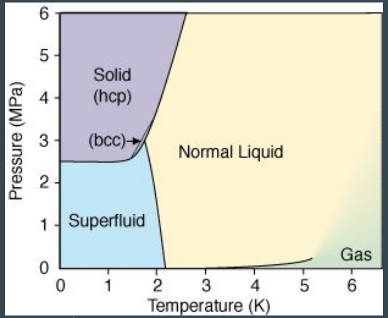
$$\mathcal{D} = n\Lambda_{\text{dB}}^3 \qquad \Lambda_{\text{dB}} = \frac{h}{\sqrt{2\pi m k_B T}}$$

Connection to Superfluidity

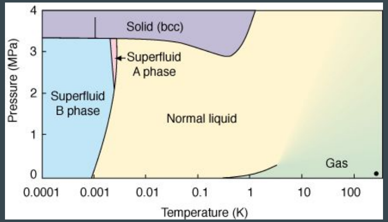
- In 1938, Fritz London suggested that the superfluidity of ^4He is a result of the partial Bose-Einstein condensation
- However, since superfluid helium is a liquid, the atoms interact strongly with each other and the BEC state applies to ideal gases of noninteracting particles
- As a result, Bose-Einstein condensation is does not tell the entire story of superfluid ^4He
- Fermionic ^3He becomes superfluid at lower temperatures when bosonic Cooper pair formation allows partial Bose-Einstein condensation to occur



Superfluid helium "climbing" out of its container



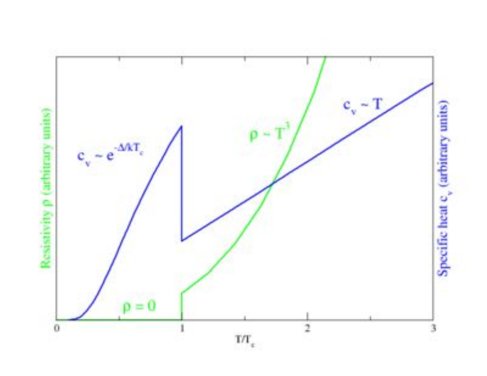
^4He phase diagram



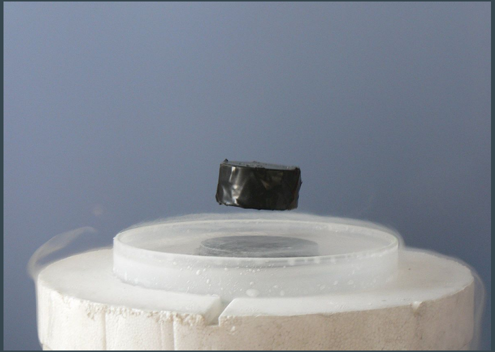
^3He phase diagram

Connection to Superconductivity

- In 1957, John Bardeen, Leon Cooper, and John Schrieffer published the BCS theory of superconductivity
- They argued that at low temperatures, some of the fermionic electrons form Cooper pairs (with integer spin)
- These pairs behave like bosons and can co-occupy the ground state via Bose-Einstein condensation
- This condensation creates a band gap between the BCS ground state and the lowest excited state
- This band gap prevents scattering excitations that cause finite resistivity in normal conductors



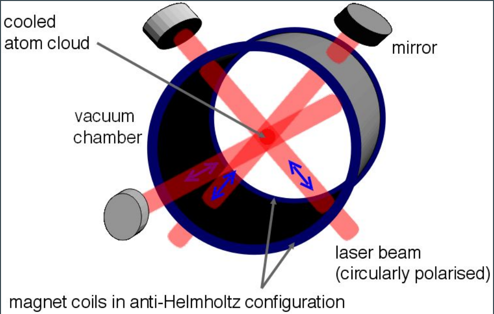
Plot demonstrating the resistivity and specific heat of a sample near the superconducting phase transition



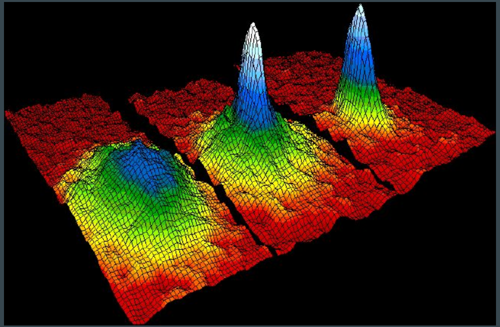
A magnet levitating above a superconductor via the Meissner effect

Synthesizing Bose-Einstein Condensate

- It wasn't until the 1990s that a Bose-Einstein condensate was first synthesized
- Atoms of alkali metals were the ideal samples since they can be easily trapped and cooled using a magneto-optical trap (MOT)
- In 1995, Eric Cornell and Carl Wiemann (JILA) created a BEC of ~2000 ^{87}Rb atoms cooled to less than 170 nK
- Later that year, Wolfgang Ketterle (MIT) created a much larger BEC sample of 5×10^5 ^{23}Na atoms
- The three shared the 2001 Nobel Prize for Physics



A diagram of a magneto-optical trap; MOTs areused to cool and trap atoms in BEC experiments



Velocity-distribution data for a gas of Rubidium atoms before and after BEC phase transition

Here’s a brief video about Bose-Einstein condensation...