Observation of Bose-Einstein Condensation in a Dilute Atomic Vapor

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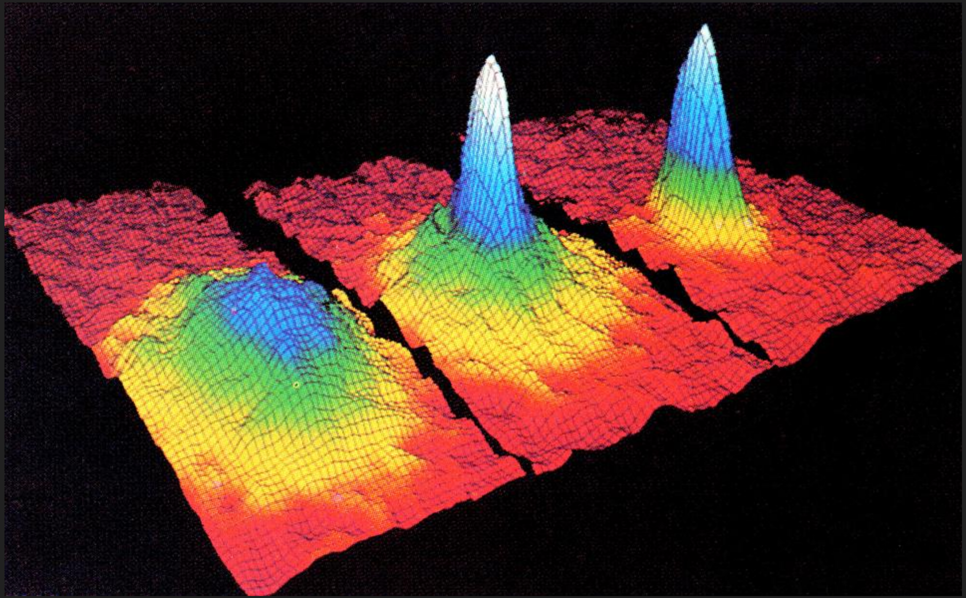

Science 14 Jul 1995;
Vol. 269, Issue 5221, pp. 198-201
DOI: 10.1126/science.269.5221.198

Presented by

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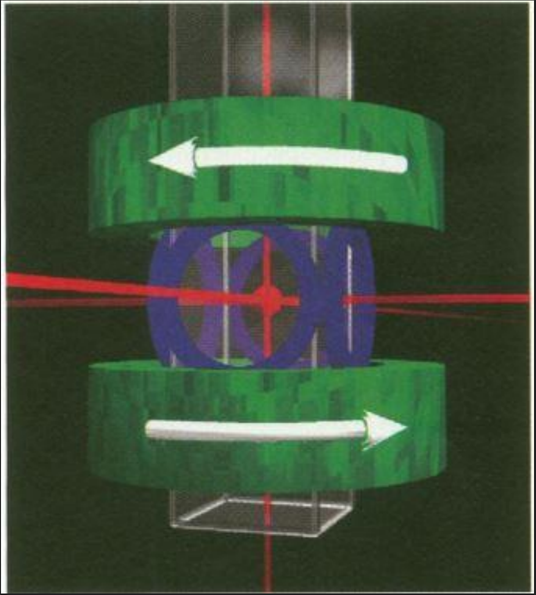

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Prediction of Bose-Einstein Condensates

- Predicted by Satyendra Nath Bose and Albert Einstein in 1924:
  - Gas of non-interacting bosons will develop macroscopic population of the ground state.
  - The gas forms a giant matter wave.

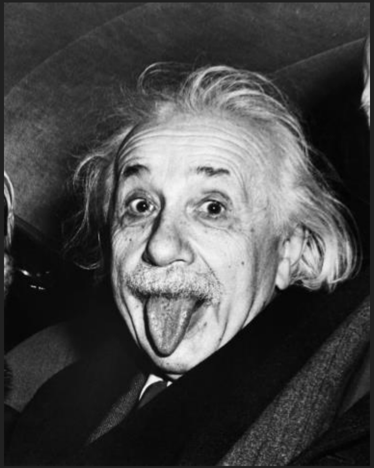


Image source

A Quantum State of Matter

- De Broglie wavelength is larger than mean interatomic spacing:
  - Phase space density:

$$\rho_{ps} = n(\lambda_{db})^3 \geq 2.612$$

- Interactions raise the energy, necessitating a weakly-interacting, dilute gas

$$\lambda_{db} = \frac{h}{\sqrt{2\pi mkT}}$$

- Critical temperature for BEC: $T_c \approx 3.3125 \frac{\hbar^2 n^{2/3}}{mk}$ ~ 10^{-7} K

How to cool a dilute gas

- Laser cooling: incident photons slow down gas particles.
  - Figures 1-3.1: Laser has longer wavelength than absorption line
    - Only approaching particles can absorb
  - Figures 3.2 & 3.3: Photons are re-emitted in random direction

- Evaporative cooling:
  - Laser-cooled atoms loaded into magnetic trap
  - Higher energy atoms are allowed to escape

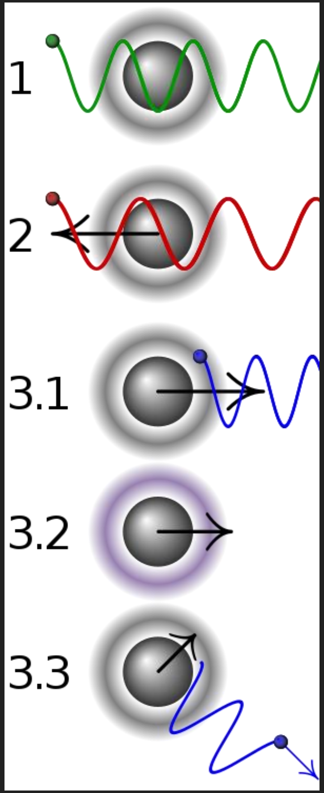


Image by Cmglee

BEC Work Prior to 1995

Laser cooling pioneered by Steve Chu/Bill Phillips in the 1970s: Magneto-Optical Trap (MOT) of sodium

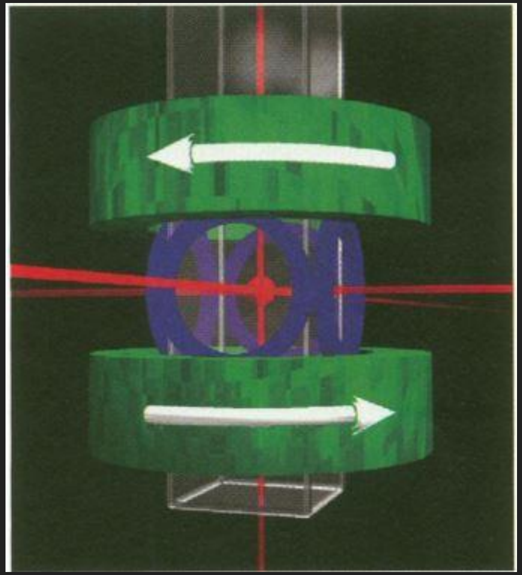
Randy Hulet (95) - published less conclusive work on a lithium-7 experiment which showed lensing of laser light around the condensate, couldn’t do time of flight

Wolfgang Ketterle (94-95) - did BEC work with sodium. In late 1994 experimental issues likely prevented him from being the first

Locally - Lin and Wolfe (93) at UIUC showed BEC of paraexcitons in stressed Cu_2O.

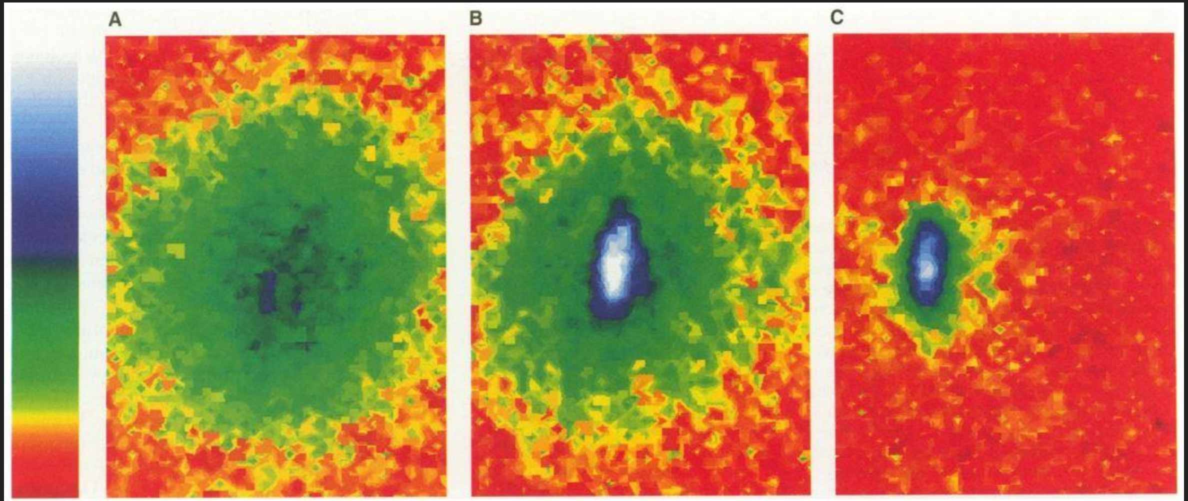
Experimental Setup

1. Vapor loaded magneto-optical trap (MOT) ~ 300 s loading time
2. "Dark MOT" used to increase density
3. Load into a magnetic trap for evaporative cooling
   a. No species of atom is in stable equilibrium when held in a magnetic trap
   b. "Time-Orbiting Potential" used to give an averaged field zero
4. Evaporative cooling increases phase space density by reducing T and increasing n.
5. Time of flight and absorption imaging used to measure the spatial and velocity distributions of the condensate
6. Relevant Measurements: 170 nK, $n=2*10^{12}$ cm^{-3}



Anisotropic velocity distribution

- Distribution found from time-of-flight measurements
- Phase space density and a (rough) estimation of particle number



False color imaging of gas before and after condensate forms. Color indicate the velocity distribution, note the elliptic shape of the distribution after the phase transition.

Interpreting Results

- Anisotropic velocity distribution signature of ground state wavefunction
  - In thermal equilibrium, velocity distribution is isotopic, regardless of confining potential
  - For this setup, ground state wave function follows symmetry of Hamiltonian, and is anistropic in radial direction
- Back-of-the-envelope calculation indicate several hundred particles in ground state
- Same calculation shows average phase space density is above 2.61, in agreement with theoretical results

Extensions and Citations of Results

Bose-Einstein Condensation of Lithium (Hulet, 1997)

- Negative scattering length, normally prevents BEC
- Theory predicts max 1400 atom BEC of ^{7}Li
- Mean field interaction energy balanced by kinetic pressure of gas, metastable BEC

All-Optical Formation of an Atomic Bose-Einstein Condensate (Barrett, 2001)

- Loaded gas from Magneto-optical trap to crossed lasers.
- BEC using two crossed CO_2 laser beams
- Evaporative cooling achieved by lowering laser power

Critiques of Paper

Pros:

- First evaporative cooling down a dilute trapped gas below 170 nK.
- First success in cooling collections of bosonic particles and first experimental demonstration of Bose-Einstein Condensation.

Cons:

- The phase-space density of condensate calculated via experiment data doesn't match the theoretical prediction ($\rho_{ps_E} = 0.3, \rho_{ps_T} = 2.61$).
- The bosonic condensation has to be destroyed in order to measure the velocity distribution and observe the BEC.

Summary

- First experimental observation of BEC
- First demonstration of magnetic evaporative cooling
- Macroscopic visualization of ground state wavefunction