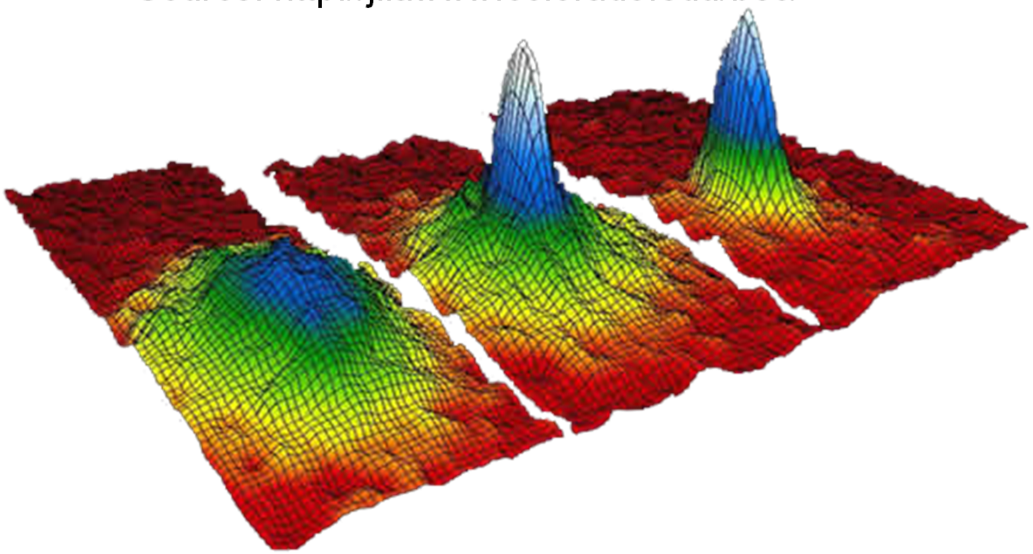
Source: http://jilawww.colorado.edu/bec/



Jahan Claes, Alex Finnegan, Stephen Gill

OBSERVATION OF BOSE-EINSTEIN CONDENSATION IN A DILUTE ATOMIC VAPOR

M.H. Anderson, J.R. Ensher, M.R. Matthews, C.E. Wieman, E.A. Cornell
Science 269 (1995) 198–201.

Outline

-Background

Explanation of a Bose-Einstein condensate (BEC) and previous developments

-Summary of the Paper

Overview and critical analysis of the data and conclusions

-Impact of the paper

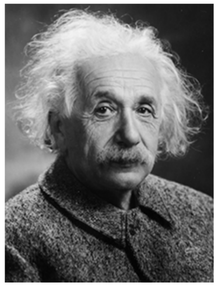
Citations and further developments in BECs

What is a Bose-Einstein condensate?
A macroscopic occupation of the ground state

Theoretical development:

1924- Bose develops the statistical distribution of non-interacting bosons. This distribution is the famous Bose-Einstein statistics.

1924- Einstein shows that a non-interacting Bosonic gas will flood the ground state below a critical temperature, the Bose-Einstein condensation temperature.



The basic theory is familiar undergraduate statistical mechanics.

Requirements for a BEC

What does the critical temperature tell us? $T = \frac{2\pi\hbar}{mk_B}\left(\frac{n}{2.612}\right)^{2/3}$

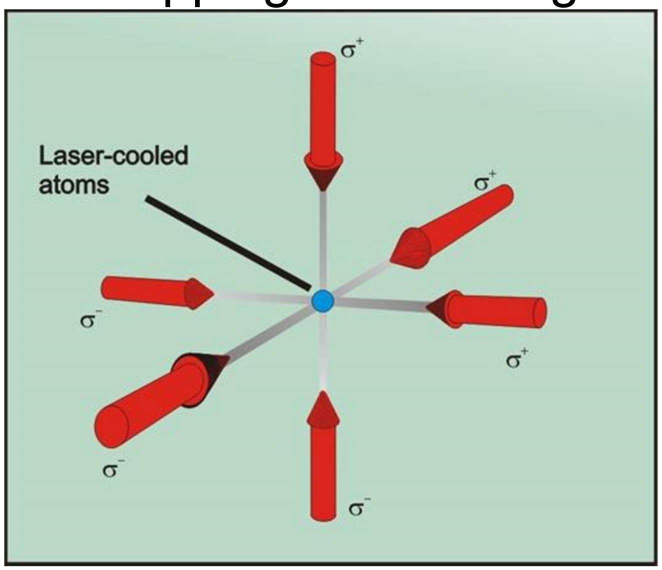
Quantum concentration is $n_Q = \left(\frac{MkT}{2\pi\hbar^2}\right)^{3/2}$ $\longrightarrow$ $n/n_Q > 2.612$ for BEC.

For $n/n_Q > 2.612$, the thermal de Broglie wavelength is greater than the mean spacing between particles, i.e., a BEC is a macroscopic quantum object.

For a gas of Bosonic atoms, the attainable densities require ultracold temperatures for a BEC to emerge.

Previous work in creating ultracold atomic systems

Laser cooling techniques pioneered by Steven Chu and others allow for trapping and cooling of atomic vapors.



source: Physikalisch-Technische Bundesanstalt

However, limitations of laser cooling prevent the technique from generating a BEC.

In this paper, the authors use laser cooling as a means to prepare their samples.

Previous work in creating ultracold atomic systems

Magnetic traps were used to evaporatively cool spin-polarized hydrogen.

VOLUME 59, NUMBER 6 PHYSICAL REVIEW LETTERS 10 AUGUST 1987

Magnetic Trapping of Spin-Polarized Atomic Hydrogen

Harald F. Hess
AT&T Bell Laboratories, Murray Hill, New Jersey 07974
and
Greg P. Kochanski, John M. Doyle, Naoto Masuhara, Daniel Kleppner, and Thomas J. Greytak
Department of Physics and Center for Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 6 May 1987)

VOLUME 61, NUMBER 8 PHYSICAL REVIEW LETTERS 22 AUGUST 1988

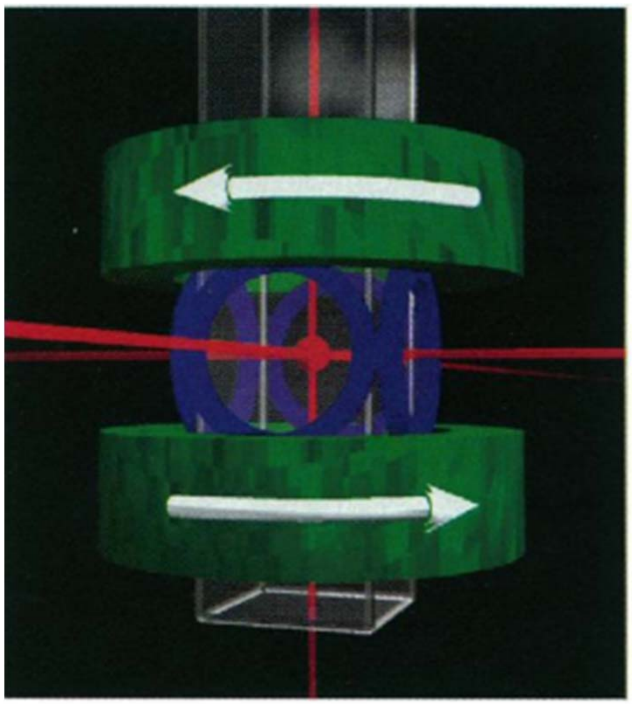
Evaporative Cooling of Spin-Polarized Atomic Hydrogen

Naoto Masuhara, John M. Doyle, Jon C. Sandberg, Daniel Kleppner, and Thomas J. Greytak
Department of Physics and Center for Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
and
Harald F. Hess and Greg P. Kochanski
AT&T Bell Laboratories, Murray Hill, New Jersey 07974
(Received 1 June 1988)

Uses a combination of magnets to create a confining potential.

Can cool atoms to temperatures lower than laser cooling.

The magneto-optical trap: the key to obtaining a BEC



Laser cooling is used to prepare Ru-87 atoms in a magnetic trap.

The magnets (shown in green and blue in image) provide an effective harmonic potential confinement within the trap.

An additional radio frequency magnetic field (not shown in diagram) accomplishes evaporation cooling by removing higher energy atoms from the trap.

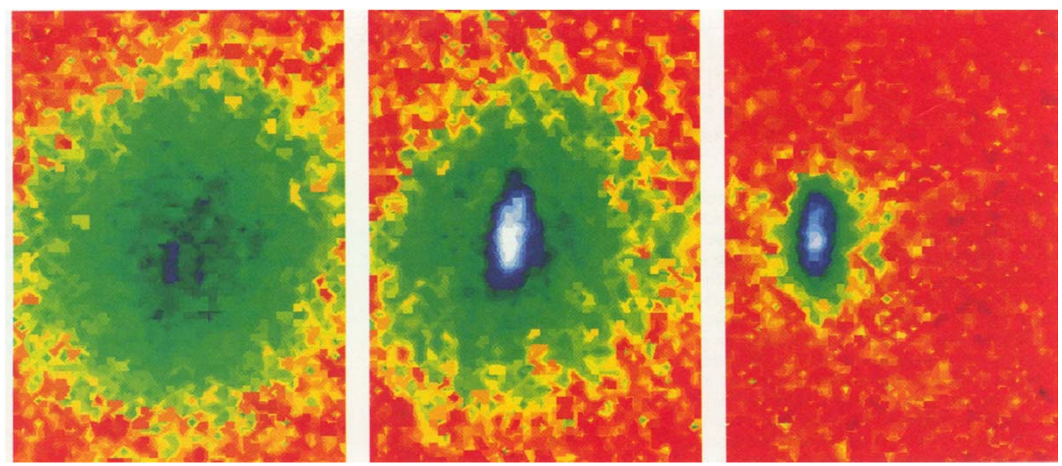
Indications of BEC

- System velocity and position distributions superimpose thermal and QM ground state distributions.
  - Specifics demonstrated by Anderson et al.:
    i. Change in distributions with temp is abrupt.
    i. Narrow peak appears on broad thermal velocity distribution.
    i. Distributions reflect anisotropy of QM ground state.

Imaging BEC Distributions

- Time-of-flight analysis of spatial distribution after trap removal gives velocity distribution.
- Scaling velocity distributions in orthogonal directions by trap oscillator frequency gives position distribution.
- Imaging destroys sample.

Spatial density distribution 60 ms after trap removal



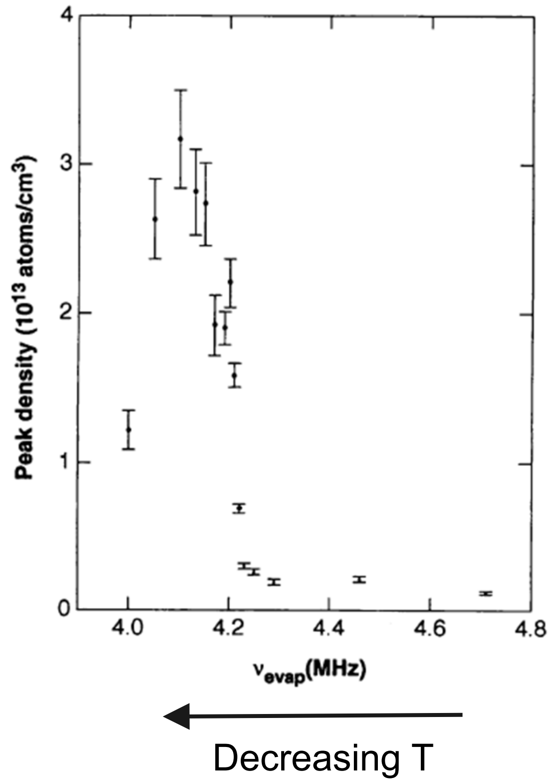
No BEC Mixture Nearly Pure

Abrupt change in distribution at T_c

- Density at trap center increases sharply at ν_{evap}=4.23 MHz
  - Transition to BEC phase.

- T is monotonic (but complicated) function of ν_{evap}:

  ν_{evap}=4.7 MHz ~ 1.6 μK
  ν_{evap}=4.25 MHz ~ 180 nK

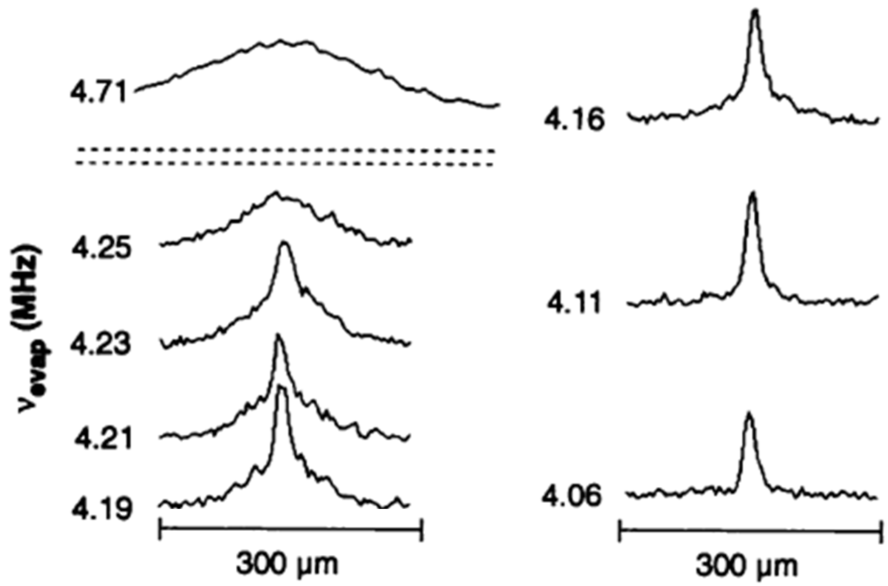


Deviation from Thermal Velocity Distribution Below T_c

- Distinct components of velocity distribution appear at ν_{evap}=4.23 MHz

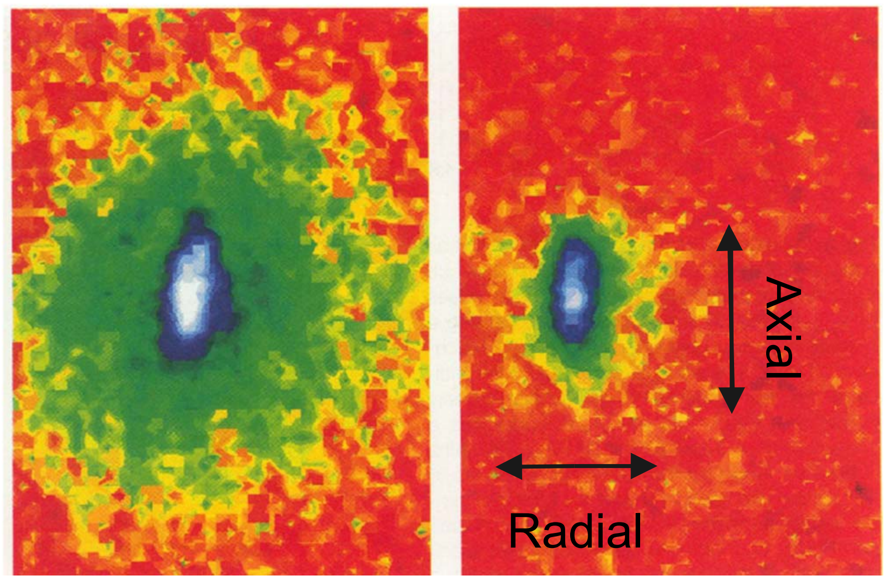
- Narrow peak centered at v=0 consistent with ground state velocity distribution

Radial Velocity Distributions for Decreasing ν_{evap}



Velocity Distribution Reflects Ground State Anisotropy

- Thermal velocity distribution (green/yellow) is isotropic.
- Blue/white distribution reflects anisotropy of harmonic trap
  - Indicates ground state occupation, opposed to population of several low energy states.



Quantitative Discrepancies with Theory

- Observed [axial width]:[radial width] is 50% greater than theoretical prediction
    - Including interactions in theory likely to reduce discrepancy
- Minimum BEC phase space density estimated from experiment nearly ten times less than theoretical minimum
    - Phase space density scales with sixth power of distribution width, amplifying error of width measurements
    - Phase space densities at temps below T_c exceed theoretical minimum

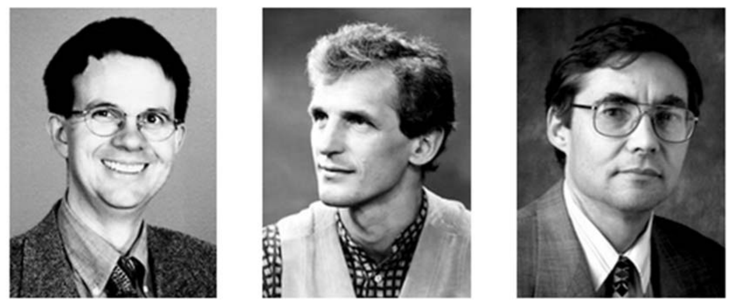
Conclusions

- Important macroscopic realization of quantum effects
- An experimental system for studying coherent states at various interaction strengths.
- Combination with non-destructive measurement techniques could allow real-time study of BEC phase transition.

Impact on the Field

- 4407 Citations on Web of Science
  - Ketterle: 3490 Citations
- 2001 Nobel prize

The Nobel Prize in Physics 2001



Eric A. Cornell
Prize share: 1/3

Wolfgang Ketterle
Prize share: 1/3

Carl E. Wieman
Prize share: 1/3

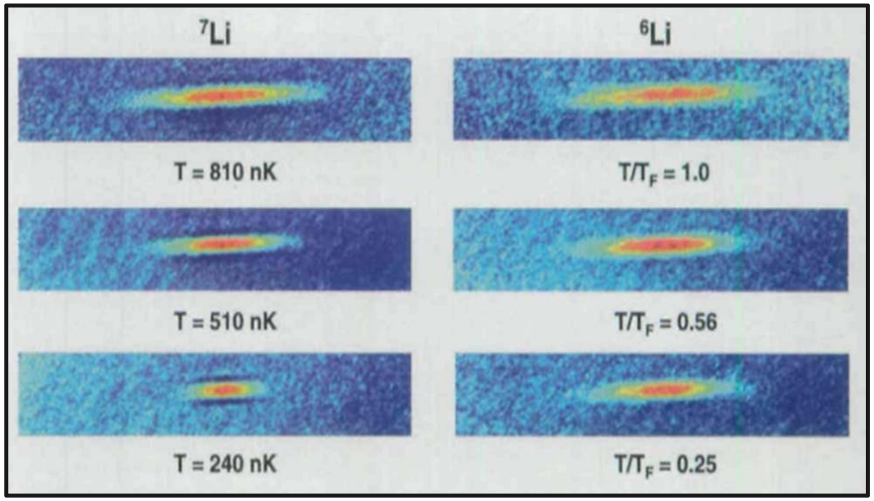
The Nobel Prize in Physics 2001 was awarded jointly to Eric A. Cornell, Wolfgang Ketterle and Carl E. Wieman *"for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates".*

Source: nobelprize.org

Further Condensates

- BEC
  - Sodium-23 (Ketterle et al.)
  - Lithium-7 (Hulet et al.)
    - attractive interactions
- Fermi Degeneracy
  - Potassium-40 (DeMarco et al.)
  - Lithium-6 (Truscot et al.)

Decreasing T



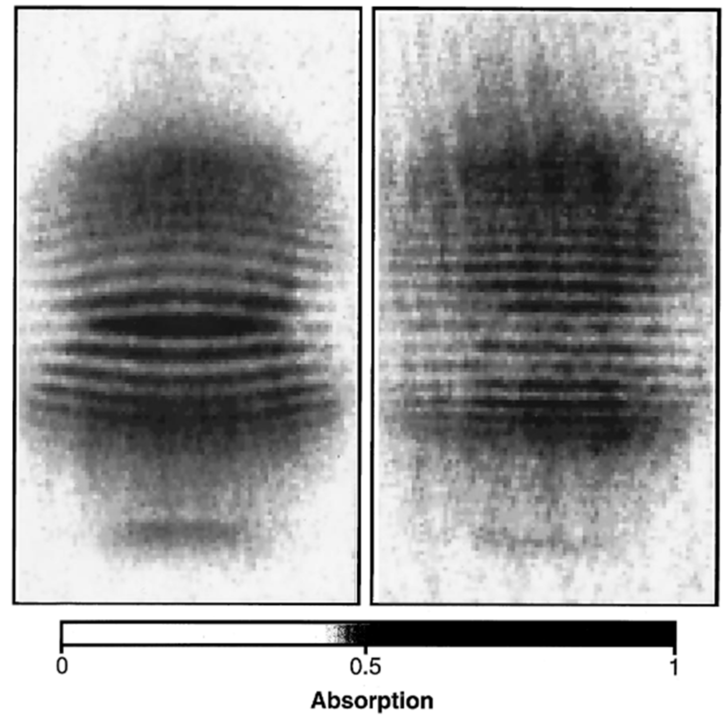
Source: Truscot et al, Science 291

What’s BEC Good For?

- Simulating condensed matter systems
  - Optical lattices (Greiner et al.)
- Analogue Models for Gravity
  - Acoustic Black Holes -- ”dumb holes” (Steinhauer)
- Electromagnetically induced transparency
  - Light speed reduction: 17 m/s (Hau et al.)

What's BEC Good For? (Con't)

- Probing basic quantum mechanics
  - BEC exhibit long-range coherence
  - Macroscopic interference (Andrews et al.)



Source: Andrews et al, Science 275

In Summary...

- BEC is characterized by a macroscopic population of the ground state.
- Using laser cooling, magnetic traps, and evaporative cooling, we may achieve BEC
- BEC can be used to probe quantum mechanics and simulate other systems

References

Bloch, J. Dalibard, W. Zwerger, Many-body physics with ultracold gases, Rev. Mod. Phys. 80 (2008) 885–964
C. Barceló, S. Liberati, and M. Visser, Towards the observation of Hawking radiation in Bose-Einstein condensates, Int. J. Mod. Phys. A 18 (2003) 3735-3745