E. Experimental Observations of Bose-Einstein Condensation

- Difficulty: Take a gas of atoms^{+} (bosons), trick atoms to stay in gas form and yet lower the temperature to 10^{-7} K

  [not to get into liquid / solid forms]

$^{+}$ 1^{st} experiments: Gas of $\underbrace{{}^{87}\text{Rb atoms}}$ (37^{th} element)

$m_{\text{Rb atoms}}$ makes T_c very low

[ordinary conditions, it is a solid at room temperature!]

Need to $\underbrace{\text{keep } N/V \text{ low}}$ [atoms far apart physically so bonding won't occur]

makes T_c even lower

^{87}Rb Atom is a Boson

$$\underbrace{^{87}Rb}\;=\;\underbrace{37 \text{ electrons}}_{\substack{\text{these give the total}\\ \text{Spin angular momentum}\\ \text{due to electrons}\\ \text{[atomic physics]}}}\;+\;\underbrace{(37 \text{ protons in nucleus} + 50 \text{ neutrons in nucleus})}_{\text{these give the total Nuclear angular momentum (Spin)}}$$

(spin-½) (spin-½) (spin-½)

Total Spin Angular Momentum

if Integer Spin (Boson)

if half-integer Spin (Fermion)

^{87}Rb ... $5s^1$ (electron configuration of ground state) $\Rightarrow$ $S_{electron} = 1/2$

Nuclear Spin $S_{nucleus} = 3/2$

$S_{atom} = 1$ OR 2 (integer) $\Rightarrow$ ^{87}Rb is a Boson

$$\underbrace{{}^{87}\text{Rb atom}} \text{ is a Boson [a lazy way]}$$

$$\underbrace{37 \text{ electrons} + 37 \text{ protons in nucleus}} + \boxed{50 \text{ neutrons in nucleus}}$$

↑ spin-½ ↑ spin-½

together always give an integer spin quantum number for the spin angular momentum of the atom

Note that the <u>even</u> number of neutrons give an integer spin

∴ ^{87}Rb atom is a Boson

∴ For neutral atoms, <u>look at number of neutrons.</u>

- even: Atom is a boson
- odd: Atom is a fermion

Q: ^{4}He neutral atom? ^{3}He neutral atom?

Rough estimation on T_c for ^{87}Rb gas

keep N/V low†, so $N/V \sim 10^{19}$ m

So $$T_c = \frac{h^2}{2\pi k} \underbrace{\frac{1}{(87 m_H)}}_{\text{estimate of } m_{87Rb}} \left[\frac{1}{2.612}\left(\frac{N}{V}\right)\right]^{2/3} \sim 8.5 \times 10^{-8} K = 85 \underbrace{nK}_{\text{nano-Kelvin}^{\dagger}}$$

assuming free† ^{87}Rb atoms

[† particle-in-a-box]

†† This shows the stringent conditions necessary to observed BEC in ^{87}Rb gas.

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† In a solid, atoms are about 1-3 Å (10^{-10} m) apart. So $N/V \sim 10^{28}$ m^{-3}.

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Science 269, 198 (1995)

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

A Bose-Einstein condensate was produced in a vapor of rubidium-87 atoms that was confined by magnetic fields and evaporatively cooled. The condensate fraction first appeared near a temperature of 170 nanokelvin and a number density of 2.5×10^{12} per cubic centimeter and could be preserved for more than 15 seconds. Three primary signatures of Bose-Einstein condensation were seen. (i) On top of a broad thermal velocity distribution, a narrow peak appeared that was centered at zero velocity. (ii) The fraction of the atoms that were in this low-velocity peak increased abruptly as the sample temperature was lowered. (iii) The peak exhibited a nonthermal, anisotropic velocity distribution expected of the minimum-energy quantum state of the magnetic trap in contrast to the isotropic, thermal velocity distribution observed in the broad uncondensed fraction.

Wieman and Cornell were awarded the 2001 Nobel Physics Prize, together with Ketterle (MIT).

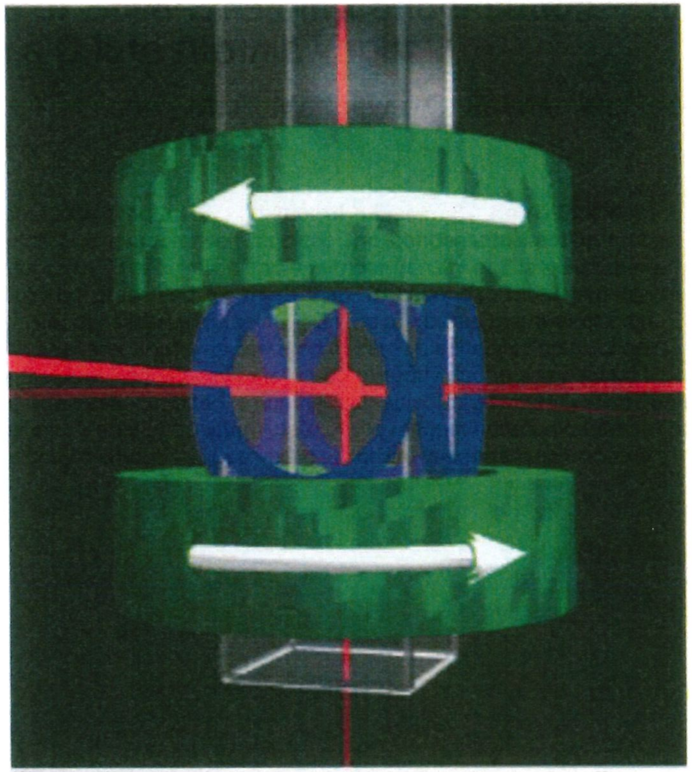


Fig. 1. Schematic of the apparatus. Six laser beams intersect in a glass cell, creating a magneto-optical trap (MOT). The cell is 2.5 cm square by 12 cm long, and the beams are 1.5 cm in diameter. The coils generating the fixed quadrupole and rotating transverse components of the TOP trap magnetic fields are shown in green and blue, respectively. The glass cell hangs down from a steel chamber (not shown) containing a vacuum pump and rubidium source. Also not shown are coils for injecting the rf magnetic field for evaporation and the additional laser beams for imaging and optically pumping the trapped atom sample.

Some physics behind Magneto-optical trap (MOT)

(a) Laser Cooling : Clever use of Doppler's effect and photon's momentum

Atom (QM ⇒ 1s, 2s, 2p, ∘∘∘ states) 5p — ↕ transition at $\underbrace{\nu_0}$ 5s —

Atom ●→ Laser beam ↜ or $h\nu_0$ energy

Velocity = v_x frequency = $\nu_{Laser} = \nu_L$

In frame of atom, see a Doppler shift of laser frequency to a slight higher frequency [from ν_L to $\nu_L(1+\underbrace{\frac{v_x}{c}}_{\text{Doppler shift}})$]

Intentionally Detune laser beam frequency, not using $\nu_L = \nu_0$, but $\nu_L = \nu_0 - \underbrace{\delta}$ ← detuning (chosen according to v_x)

Atom

$\bullet \rightarrow v_x$ $\quad\quad$ $\leftsquigarrow \; \nu_L = \nu_0 - \delta$

Atom sees ν_0, thus absorbs a photon from beam (atom is excited)

but photon also gives its momentum $\sim \frac{h}{\lambda}$ to atom

$\boxed{\text{AND momentum is in direction opposite to atom's } v_x}$

$\therefore$ a kick to slow down atom for every photon absorbed!

spontaneous emission ($5p \rightarrow 5s$) after excitation, emits a photon in random direction

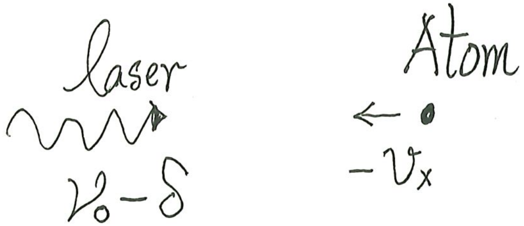
[a recoil but in random direction]

Key idea $\boxed{\text{Many absorption-emission cycles, net effect is to slow down atoms moving towards laser}}$

Atom

$v_x \leftarrow \bullet$ $\quad\quad$ $\leftsquigarrow \; \nu_L = \nu_0 - \delta$

Atom sees beam with frequency $(\nu_0 - 2\delta)$ further from resonance

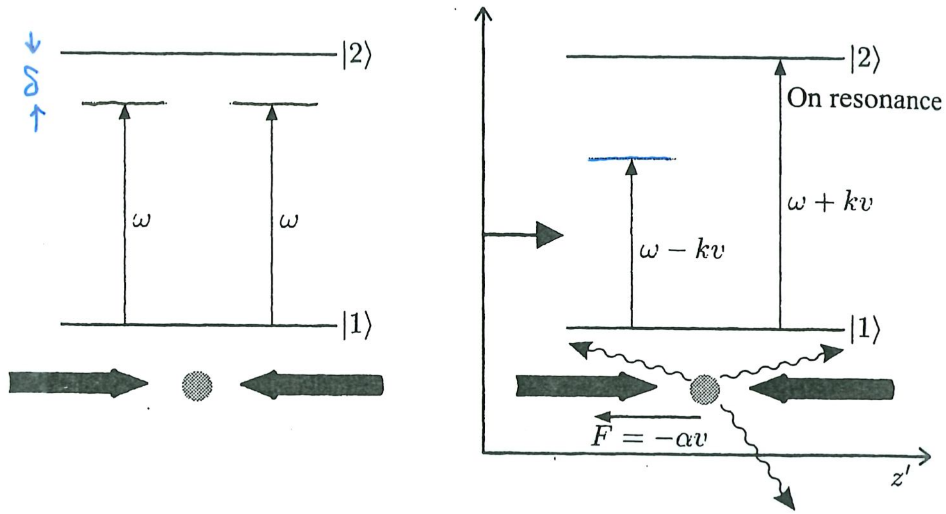


will also slow atoms down (those moving to the left)

For atoms moving along x, either to right or to left

can slow atoms down

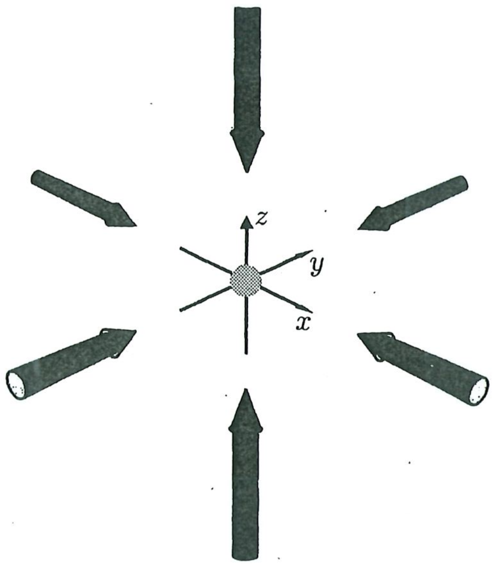
δ = detuning



What an atom moving to the Right sees

Net effect: Atom feels a "frictional force" due to the two beams!

Apply the idea to atoms moving in x, y, z directions,
use 6 beams



"Optical $\underbrace{\text{Molasses}}$"

very thick and stick liquid extracted from sugercane,
like a syrup (but thicker)

$\boxed{\text{Net effect is that atoms feel a frictional force in trap}}$

This can slow atoms down to velocity ~ tens of cm/s

OR $\underbrace{T \sim 100 \mu K}_{\text{not low enough for BEC}}$

These ideas on trapping and cooling atoms were developed in 1970-1980.

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The Nobel Prize in Physics 1997

From Nobel Foundation website

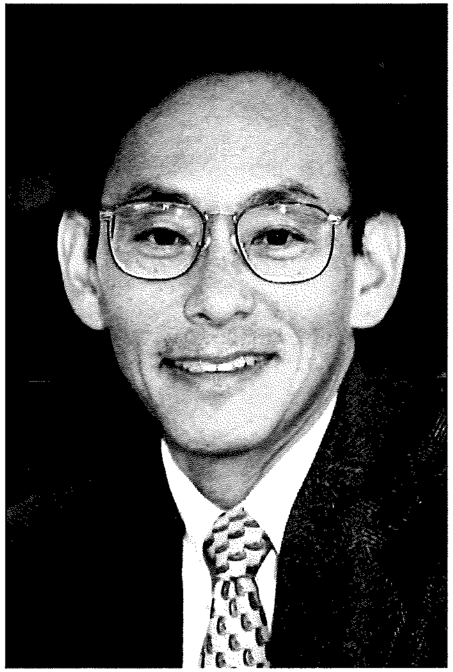


Photo from the Nobel Foundation archive.

Steven Chu

Prize share: 1/3

Photo from the Nobel Foundation archive.

Claude Cohen-Tannoudji

Prize share: 1/3

Photo from the Nobel Foundation archive.

William D. Phillips

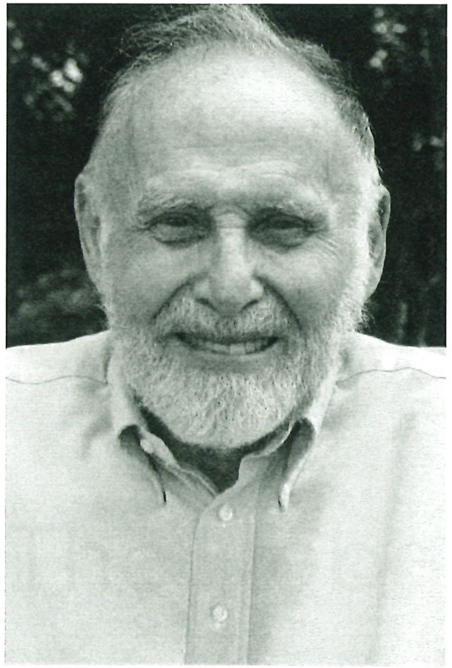
Prize share: 1/3

The Nobel Prize in Physics 1997 was awarded jointly to Steven Chu, Claude Cohen-Tannoudji and William D. Phillips "for development of methods to cool and trap atoms with laser light."

The Nobel Prize in Physics 2018

XII-(32)

From Nobel Foundation web site



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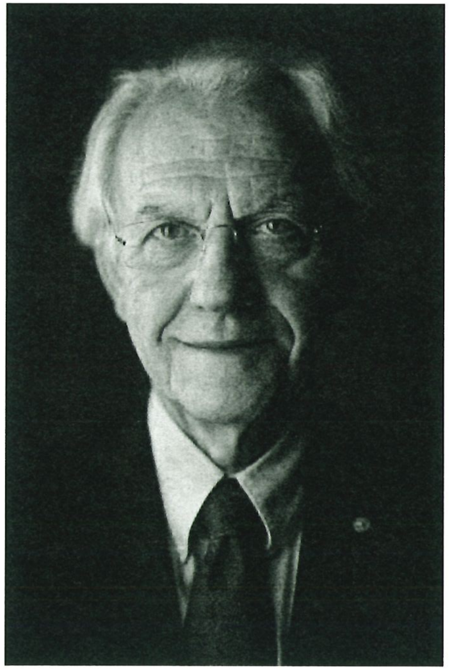
Arthur Ashkin

Prize share: 1/2



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Gérard Mourou

Prize share: 1/4

© Nobel Media AB. Photo: A. Mahmoud

Donna Strickland

Prize share: 1/4

The Nobel Prize in Physics 2018 was awarded "for groundbreaking inventions in the field of laser physics" with one half to Arthur Ashkin "for the optical tweezers and their application to biological systems", the other half jointly to Gérard Mourou and Donna Strickland "for their method of generating high-intensity, ultra-short optical pulses."

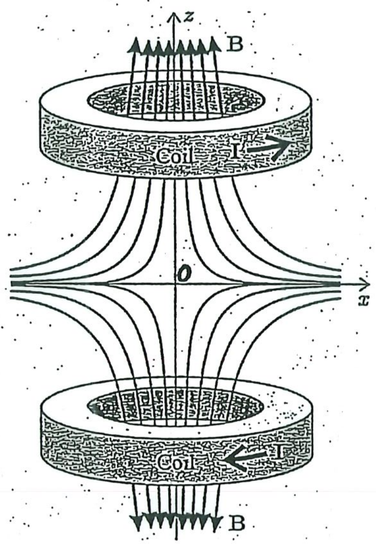
Magneto-optical Trap

i current loop magnetic dipole moment ↑

i current loop magnetic dipole moment ↓

separated by a distance

give magnetic quadrupole field (inhomogeneous)



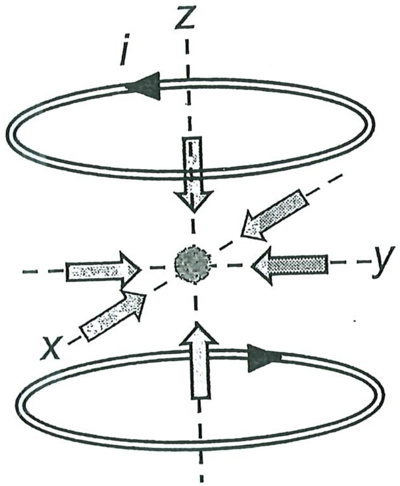
$$B(x,y,z) = B'(\underbrace{x^2+y^2+4z^2}_{B^2 \sim \text{ anisotropic harmonic trap}})^{1/2}$$

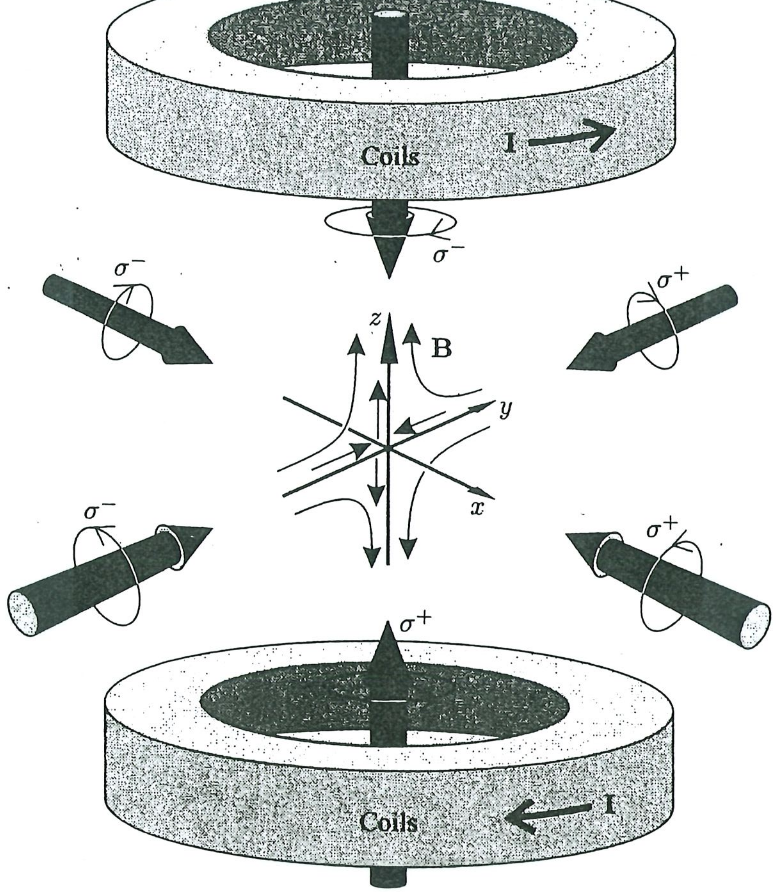
$\overbrace{\text{restoring force}}^{\text{trap}}$

e.g. $(0,0,z)$, on x-y plane, moving vertically, Force $\sim B \sim -z$

Inhomogeneous B-field also allows tuning atom's Zeeman splitting, and then making use of the polarization of the laser beams.

Putting laser beams and trap together





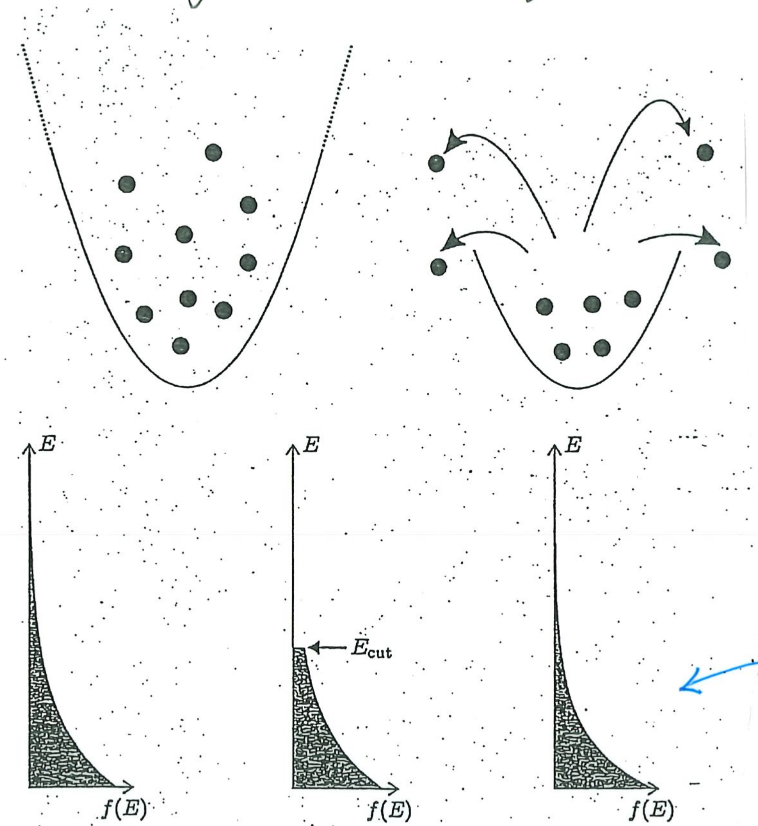
See C. J. Foot, "Atomic Physics" for details

MOT

At the end, atoms feel $F_{MOT} = \underbrace{-\alpha v}_{\text{optical molasses}} - \underbrace{\overbrace{\gamma z}}_{\substack{\text{restoring force} \\ \text{[thus harmonic trap]}}}$ ← if it moves up & down about origin

Evaporative Cooling

- T of trapped atoms is still $> T_c$
- Turn trap off, let atoms of higher speeds go ("evaporative cooling")
- Remaining atoms equilibrate to lower temperature



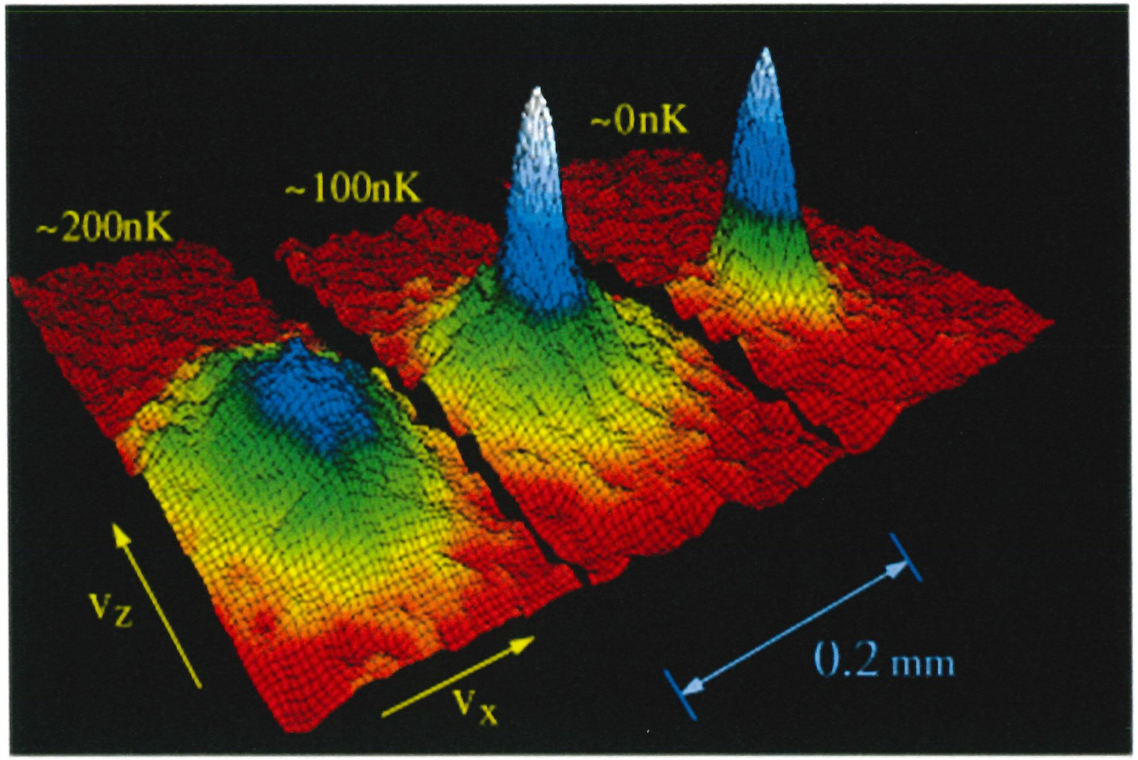
- lose some atoms
- but further lowering temperature

early experiments: only trapped ~10^8 atoms to $\lesssim 100$ nK

distribution of energy among atoms (reflects temperature)

Observation of Bose-Einstein Condensation

2 D velocity distributions



above T_c

below T_c

Take pictures (much optics and atomic physics) at different times after trapping atoms to a certain temperature AND remove the trap/turn off laser beams

Just let atoms spread using their velocities.

BEC ⇒ atoms go into $\varepsilon = 0$ s.p. state (zero velocity state)

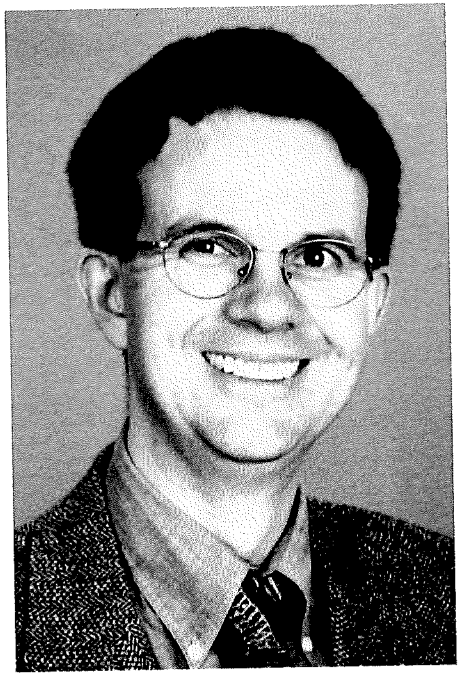
condensate won't spread

Wieman, American Journal of Physics 64, 847 (1996)

gave an account accessible to undergraduates

The Nobel Prize in Physics 2001

From Nobel Foundation website.



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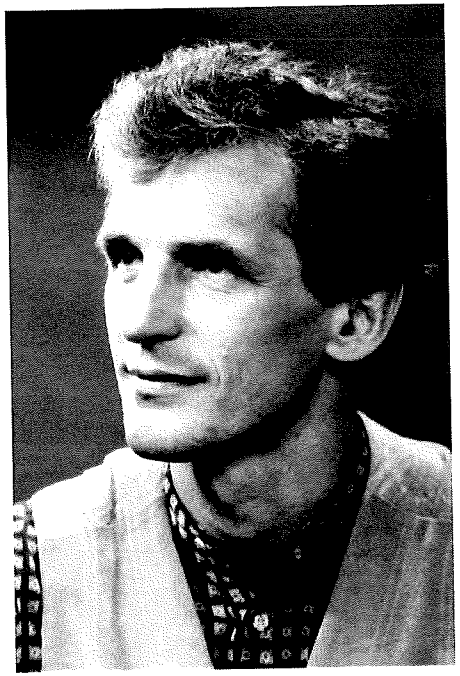
Eric A. Cornell

Prize share: 1/3



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Wolfgang Ketterle

Prize share: 1/3

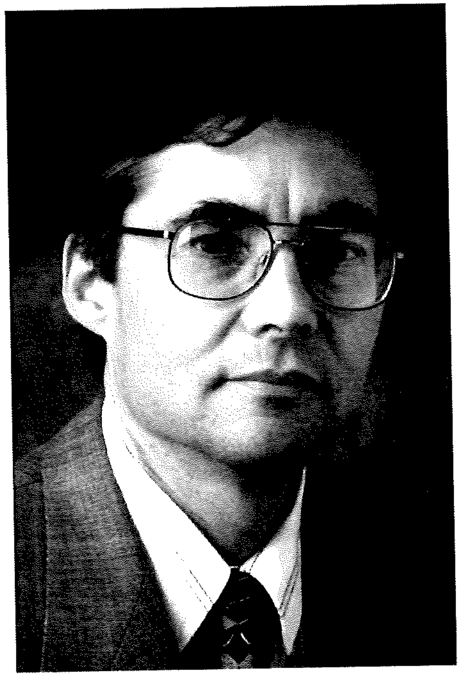

Photo from the Nobel Foundation archive.

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."

Further Developments

- Optical Lattices

Interference of laser beams sets up periodic intensities in space

atoms sit periodically in trap

[like electrons live in periodic potential in a solid]

∴ Can test many complicated condensed matter systems Experimentally!

Even too complicated to handle for theorists!

Using trapped atoms as a research tool : Quantum Simulator

An example

Observation of gauge invariance in a 71-site Bose–Hubbard quantum simulator

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Check for updates

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The modern description of elementary particles, as formulated in the standard model of particle physics, is built on gauge theories[1]. Gauge theories implement fundamental laws of physics by local symmetry constraints. For example, in quantum electrodynamics Gauss's law introduces an intrinsic local relation between charged matter and electromagnetic fields, which protects many salient physical properties, including massless photons and a long-ranged Coulomb law. Solving gauge theories using classical computers is an extremely arduous task[2], which has stimulated an effort to simulate gauge-theory dynamics in microscopically engineered quantum devices[3–6]. Previous achievements implemented density-dependent Peierls phases without defining a local symmetry[7,8], realized mappings onto effective models to integrate out either matter or electric fields[9–12], or were limited to very small systems[13–16]. However, the essential gauge symmetry has not been observed experimentally. Here we report the quantum simulation of an extended U(1) lattice gauge theory, and experimentally quantify the gauge invariance in a many-body system comprising matter and gauge fields. These fields are realized in defect-free arrays of bosonic atoms in an optical superlattice of 71 sites. We demonstrate full tunability of the model parameters and benchmark the matter–gauge interactions by sweeping across a quantum phase transition. Using high-fidelity manipulation techniques, we measure the degree to which Gauss's law is violated by extracting probabilities of locally gauge-invariant states from correlated atom occupations. Our work provides a way to explore gauge symmetry in the interplay of fundamental particles using controllable large-scale quantum simulators.

At CUHK Physics, Prof. Dajun Wang is an expert in producing ultracold <u>molecules</u>.

This field is related to:

- precision atomic/molecular physics
- quantum optics
- quantum computing/information
- Condensed matter physics [quantum simulator]

<u>References</u>

- C. J. Foot, "Atomic Physics" [beginning postgraduate level]
- J. F. Annett, "Superconductivity, Superfluids, and Condensates" [beginning postgraduate level]
- M. Fox, "A student's guide to Atomic Physics" [undergraduate level]