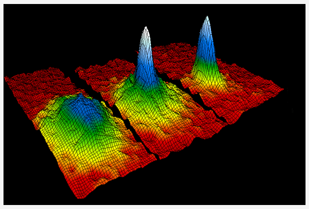
PH300 Modern Physics SP11



Quantum Mechanics is the greatest intellectual accomplishment of the human race. - Carl Wieman, Nobel Laureate in Physics, 2001

Day 27,5/3:
Questions?
Bose-Einstein Condensation

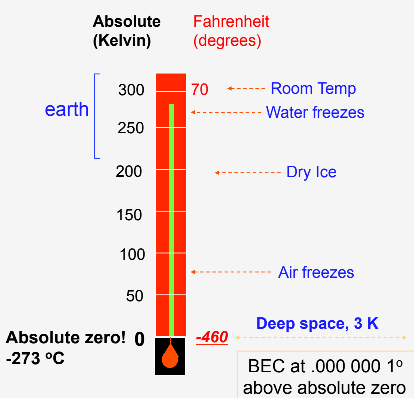
This Week:
Final Exam, Saturday 4/28
1:00-3:00pm

Bose-Einstein Condensation (BEC): Quantum weirdness at lowest temperature in the universe

JILA BEC Effort Eric Cornell, Carl Wieman **1990-**
Anderson, Ensher, Jin, Hall, Matthews, Myatt, Monroe, Claussen, Roberts, Cornish, Haljan, Donley, Thompson, Papp, Zirbel, Lewandowski, Harber, Coddington, Engels, McGuirk, Hodby,...
$$ (NSF, ONR, NIST)

Part I. (1924-95) Making Bose-Einstein Condensation in a gas.
BEC- a new form of matter predicted by Einstein in 1924 and first created in 1995 by Cornell/Wieman group.

Part II. An example of more recent research with BEC.



Why low temperature is interesting for quantum mechanics

At room temperature typical de Broglie wavelength for rubidium atom is 2×10^{-11} m.

If decrease the temperature of a sample from 300 K to 3 microK how does the de Broglie wavelength change?

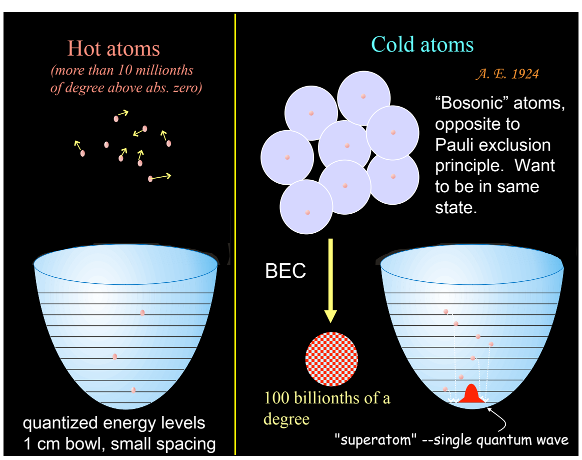
a. smaller by 10^8
b. smaller by 10^4
c. bigger by 10^8
d. bigger by 10^4
e. stays the same

Hint: **$3/2\ (kT) = 1/2\ mv^2$**

$\lambda_{db} = h/mv \sim 1/T^{0.5}$

so 10^8 decrease in Temp gives 10^4 increase in λ_{db}.

So colder make more quantum wavelike.



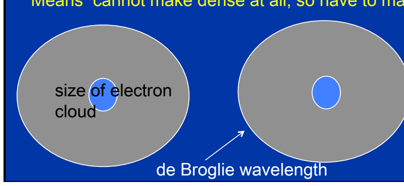
So basic condition for BEC-- need de Broglie waves of atoms to overlap.

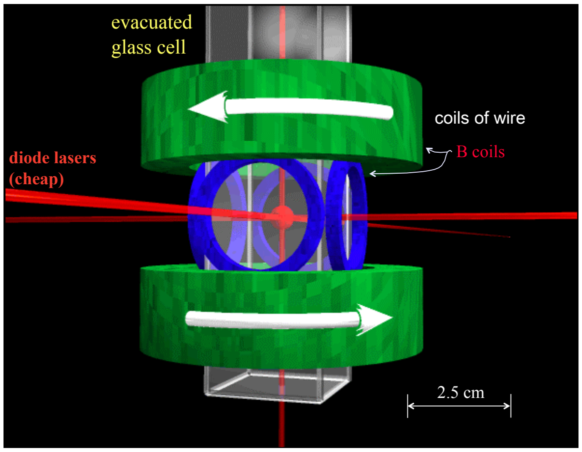
~ Product of density and coldness.

BUT atoms have to stay far apart so see each other as friendly Bosons who want to be in same quantum state.

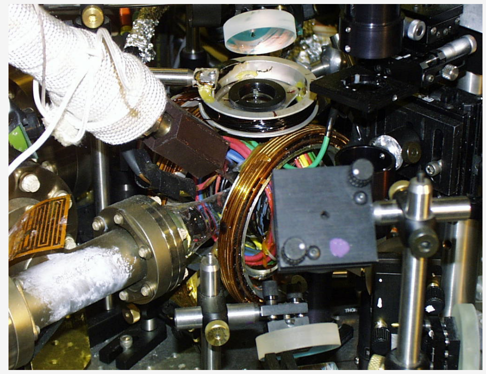
Not bunch of interacting electrons and protons (unfriendly fermions) who also want to turn into molecules and freeze into ice cubes.

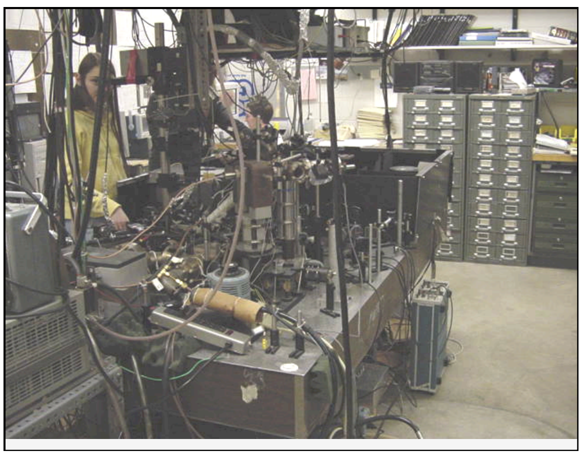
Means cannot make dense at all, so have to make VERY cold!



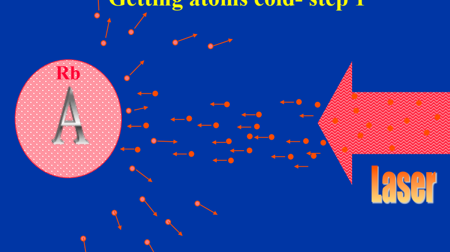


JILA BEC #2 *(#1 at Smithsonian)*



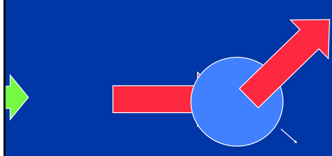


Getting atoms cold- step 1



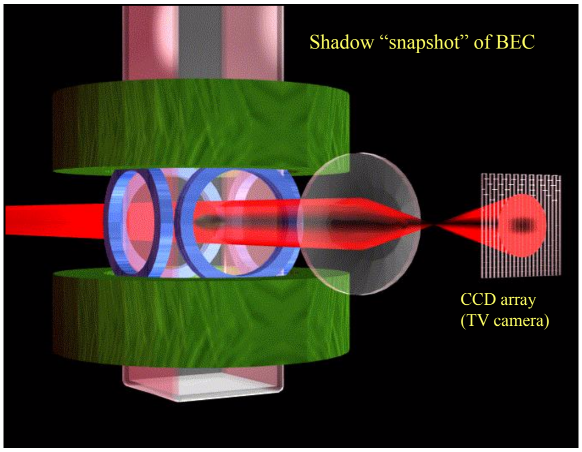
Pushing atoms with light
momentum kick when atom absorbs,
then reemits photon.

if light just the right color…
electrons absorb light jump to higher energy level
jump back down, give off light
(wiggling a bunch while jumping)



laser cooling applet

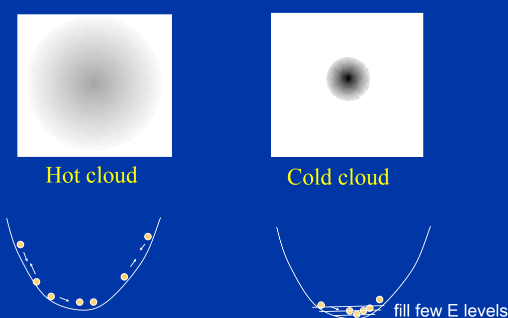
optical molasses applet
magnetic trapping applet
evaporative cooling applet



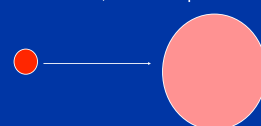
Shadow images of clouds

CQ. Which cloud is hotter?
A. 1 is hotter than 2.
B. 2 is hotter than 1.
C. Impossible to tell just from shadow picture

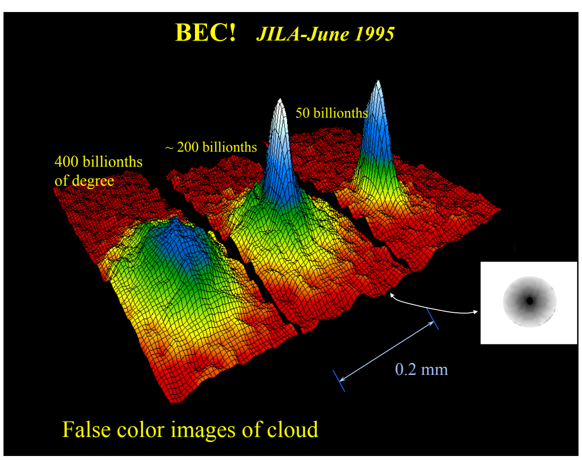
Shadow images of clouds



useful trick- turn off trap, let cloud/wave function expand for 0.1 sec, then take picture.



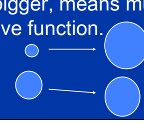
bigger, easier to see,
but same shape as original (because parabolic potential)



Size of BEC wave function depends on how tight the magnetic trap squeeze.

If trap squeezed tighter to make wave function smaller, it will expand out when trap is turned off
a. faster than with less squeeze,
b. same as when less squeeze
c. slower than when less squeeze

a. faster. If squeezed down tighter, wave function is not as spread out, uncertainty in x smaller, so uncertainty in p bigger, means must have more components of p in wave function.



Quantum physics on "human" size scale
Control and Observe

Putting one condensate on top of another

about width of human hair

Fringes formed with two overlapping condensates- waves interfering. Fringe spacing depends on v, according to deBroglie λ=h/p

(NIST Gaithersburg atom cooling group - courtesy S. Rolston)

Where BEC now (post June '95)?

New regime of physics-
directly observe and manipulate quantum wave function

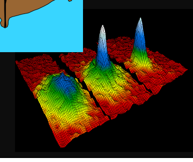
~ 200+ working experiments, many atoms (^{87}Rb, Na, Li, H, ^{85}Rb, He*,K, Cs)
countless theorists-
many thousands of papers

>1000 scientists

•Measured and predicted all sorts of novel properties.

•New ways to study, make and manipulate.

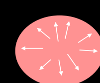
•Potential applications.



Part II. Some more recent research.

Controlling self-interactions with ^{85}Rubidium BEC

Roberts, Claussen, Donley, Thompson, CEW



repulsive (^{87}RB, Na), $a > 0$

attractive (Li, ^{85}Rb), $a < 0$
(unstable if N large, N_{max}~1/a)

in 85 Rb have experimental knob to adjust from large repulsive to nothing to large attractive!

3 billionths of a degree!

Magnetic field
(like knob to control gravity --position of very highest energy level)

Plunging into the unknown– interaction attractive

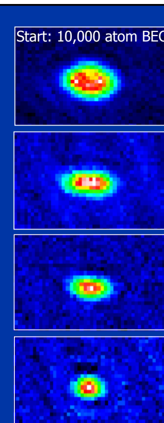
$$i\hbar\frac{\partial\Phi}{\partial t}=\left(\frac{-\hbar^2}{2m}\nabla^2+V+u|\Phi|^2\right)\Phi$$

Schrodinger eq. + interaction term

1. Make BEC magnetic field where repulsive

2. Switch to attractive.

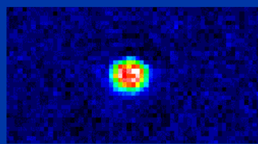
What happens?
(how do quantum wavefunctions die?)



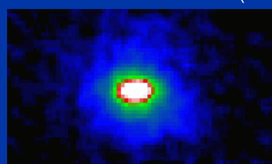
Collapse

time

then…



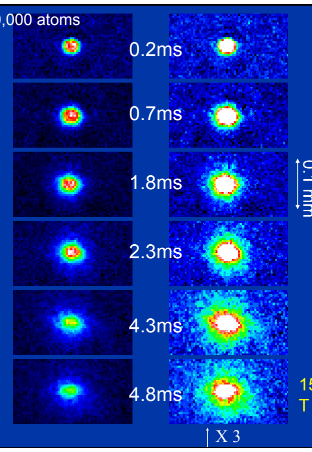
x 3



Explosion !!

(much less dense than air)

10,000 atoms



like supernova:
•collapse
•explosion… (x 10^{-73})
•cold remnant

"Bosenova"

What is the physics of explosion??? Why remnant remains?

progress…

1500 atom explosion
T ~ 200 nK

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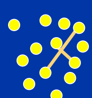
source of energy of Bosenova--chemical

A New Type of Chemistry--



changing magnetic field just right turns atoms in BEC into unusual Rb_2 "molecules".
•10,000 times larger than normal molecules
•new formation processes

learned something new about nature--being studied and used for all sorts of research. Big new area of atomic physics now is using this to make ultracold molecules, seeing BEC, exotic interactions, ...

explained source of energy, but not survival of remnant- few years later, proved was forming "soliton" wave function. Very tough and long lasting.

What is next ?

(what is it good for?)

I. Measure and understand properties.
New area of quantum world to explore–
turning BEC atoms into strange new sort of molecules

II. Uses (??).... 5-20 years *("laser-like atoms")*
a. Ultrasensitive detectors (time, gravity, rotation). (wave function interference)
making a quantum computer(?).

b. Making tiny stuff--putting atoms ***exactly*** where want them

simulations shown (and more) www.colorado.edu/physics/2000/ see BEC section

interactive simulations for learning lots of other physics PHET.Colorado.edu

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Bonding

- Main ideas:
1. involves outermost electrons and their wave functions
2. interference of wave functions
(one wave function from each atom) that produces situation where atoms want to stick together.
3. degree of sharing of an electron across 2 or more atoms determines the type of bond

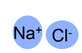
Degree of sharing of electron

Ionic	Covalent	Metallic
electron completely transferred from one atom to the other	electron equally shared between two adjacent atoms	electron shared between all atoms in solid
Li^+ F	H_2	Solid Lead

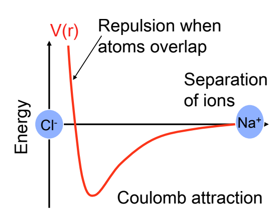
Ionic Bond (NaCl)

Na (outer shell $3s^1$)
Has one weakly bound electron
Low ionization energy

Cl (outer shell $3s^23p^5$)
Needs one electron to fill shell
Strong electron affinity



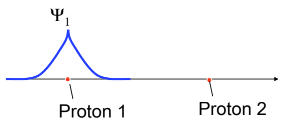
Attracted by coulomb attraction



Covalent Bond

Sharing of an electron… look at example H_2^+
(2 protons (H nuclei), 1 electron)

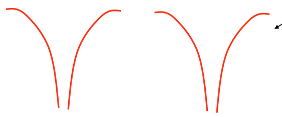
Protons far apart …



Wave function if electron bound to proton 1

Potential energy curve

V(r) that goes into Schrodinger equation



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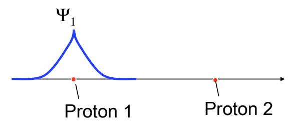
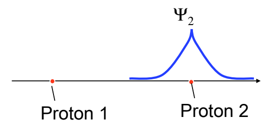


Wave function if electron bound to proton 1



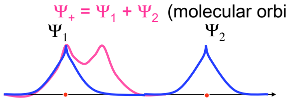
Wave function if electron bound to proton 2

Covalent Bond

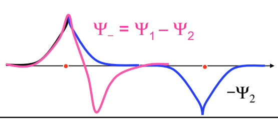
Sharing of an electron… look at example H_2^+
(2 protons (H nuclei), 1 electron)

If Ψ_1 and Ψ_2 are both valid solutions,
then **any combination** is also valid solution.

$\Psi_+ = \Psi_1 + \Psi_2$ (molecular orbitals)

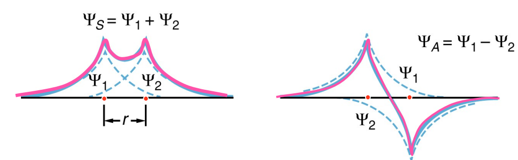


Add solutions (symmetric):
$\Psi_+ = \Psi_1 + \Psi_2$ and



Subtract solutions (antisymmetric):
$\Psi_- = \Psi_1 - \Psi_2$

Look at what happens to these wave functions as bring protons closer…

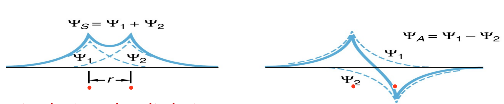


Visualize how electron cloud is distributed…
For which wave function would this cloud distribution tend to keep protons together? (bind atoms?) … what is your reasoning?

a. Ψ_S or Ψ_+

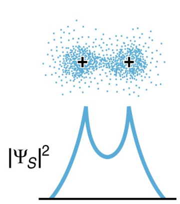
b. Ψ_A or Ψ_-

Look at what happens to these wave functions as bring protons closer…

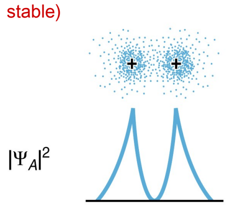


Ψ_+ puts electron density between protons .. glues together protons.

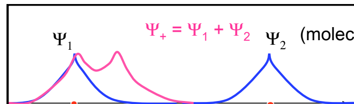
Ψ_- … no electron density between protons … protons repel (not stable)

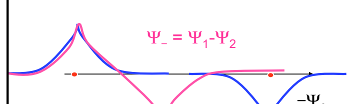


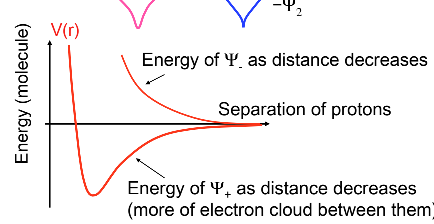
Bonding Orbital



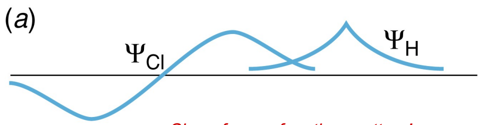
Antibonding Orbital



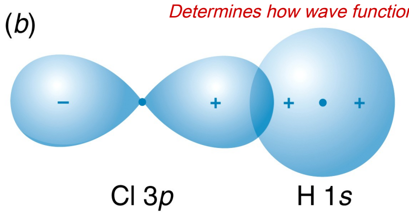


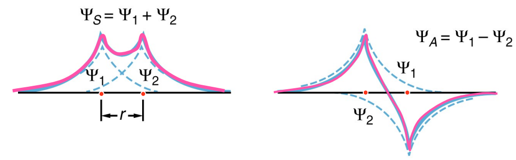


Same idea with p-orbital bonding … **need constructive interference of wave functions between 2 nuclei.**



Sign of wave function matters!
Determines how wave functions interfere.





Why doesn't He-He bond?

Not exact same molecular orbitals as H_2^+, but similar.

With He_2, have 4 electrons …
fill both bonding and anti-bonding orbitals. **Not stable.**
So doesn't form.