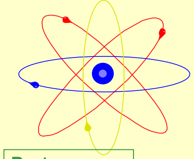
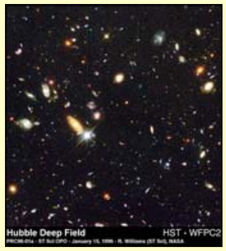
Lect. 19 - Big Picture: Smallest objects to the Universe

The Big Picture
The smallest objects to the Universe

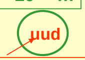
Atom - size ~ 10^{-10} m
Nucleus - size ~ 10^{-14} m



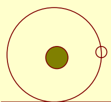
Person - size ~ 1 m



Proton - size ~ 10^{-15} m



Quark ~ 10^{-18} m



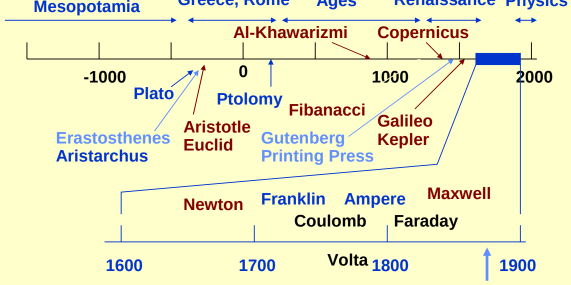
Universe - size ~ 10^{26} m

Earth - size ~ 10^7 m
Solar System - size ~ 10^{11} m

Announcements

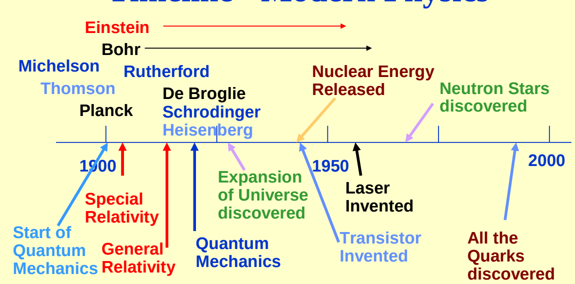
- Schedule:
  - Today: Start the conclusion of the course -- Examples of modern physics
    The Big Picture: Powers of Ten: Enormous ranges of sizes and magnitudes in science
  - Today: Introduction to ideas of Quantum mechanics
    The second revolution of the 20th century
    Essential to understand nature at the small scale
  - Next Time: Discovery of the electron, nuleus – origins of quantum mechanics
    March (Ch 13-14-15)
- REPORT
  - Outline for your report / essay due Mon. November 17
  - See "suggestions of topics" on www pages
    Today – outline of last part of course to help you decide on a topic

Timeline



- "Classical Physics" was complete around 1880
- See Timeline description of lives of various scientists on WWW pages.

Timeline - Modern Physics



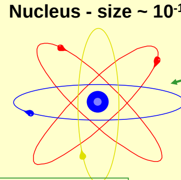
- "Modern Physics" was a sudden revolution starting around 1900, and ending ????
- See Timeline description of lives of various scientists on WWW pages.

Objects in our universe
Enormous range of sizes

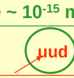
- Classical Mechanics works very well for ordinary objects around us:
  - Scale of size ~ 1m -- From the smallest object you can see ~10^{-4} m to Planets of order 10^7 m
  - Typical velocities ~ 100 m/s (fastest rockets ~ 10^4 m/s)
- Relativity (Special and General) are important for objects moving very fast or very massive
  - Speeds near c = 10^8 m/s
  - Protons, Neutrons inside nuclei have very high energies
  - Important for motions of galaxies at large fractions of c
  - Strong effects of gravity -- black holes
- Quantum Mechanics crucial to understand the very small units from which matter is made
  - Typical sizes: Atoms, Nuclei, ... (~ 10^{-10} - 10^{-14} m)

How do we know the sizes of atoms?
What they are made of?

Atom - size ~ 10^{-10} m
Nucleus - size ~ 10^{-14} m



Proton - size ~ 10^{-15} m



Quark ~ 10^{-18} m

Next lecture

Discovery of electron and nucleus led to basic picture

Led to Quantum Mechanics
Uncertainty Principle
Many important inventions
Lasers
Semiconductors
(Your computer!)
. . . .

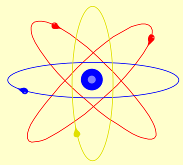
Later
Understanding of the Universe!

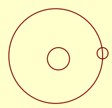
Lect. 19 - Big Picture: Smallest objects to the Universe

Ratios of different forces
Enormous range of magnitudes

Atom - Electrical Forces
Hold electrons to nucleus

Solar System - Gravitational
Forces hold earth to sun



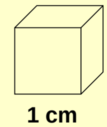


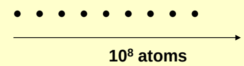
For electrons: $\dfrac{\text{Coulomb Force}}{\text{Force of Gravity}} \sim 10^{41}$

Forces inside nucleus MUCH stronger than Coulomb Forces! (More later)

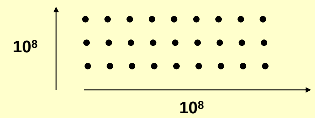
Example of enormous range of sizes

- How many atoms are in a 1 cm cube (~sugar cube)
- Size of atom around 10^{-10} m
- One line of atoms 1 cm long = 10^{-2} m





One layer: 10^8 rows = 10^8 atoms/row = 10^{16} atoms

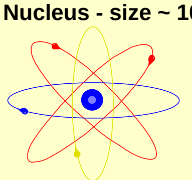


Cube: 10^8 layers x 10^{16} atoms/layer = 10^{24} atoms

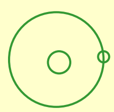
Ratios of sizes

Atom - size ~ 10^{-10} m
Nucleus - size ~ 10^{-14} m

Earth - size ~ 10^7 m
Earth Orbit Radius ~ 10^{11} m



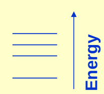
Person - size ~ 1 m



$\dfrac{\text{Size of atom}}{\text{Size of person}} \sim \dfrac{\text{Size of person}}{\text{Size of radius of earth orbit}}$

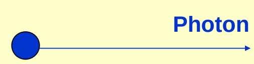
Quantum Effects Crucial for Small Objects

Example - electrons in atoms



Electrons in an atom can only have discrete energies

Excited Atom



Light is emitted only at discrete energies, i.e., discrete frequencies for each type of atoms

Quantum mechanics explains the stability of the atom -- why the electron does not "fall" into the nucleus

Quantum Mechanics:
Particles Act Like Waves!

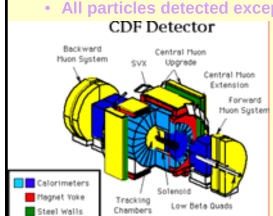
Prince Louis De Broglie
Matter Waves

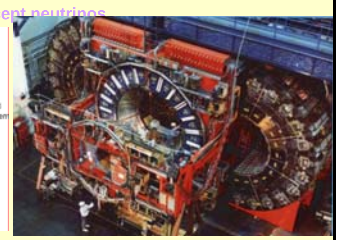
Heisenberg's
Uncertainty
Principle

Schrodinger's
Equation

Search for the smallest particles

- Experiment at Fermilab (near Chicago) to detect what is produced when high energy (900 GeV) protons and anti-protons collide.
  - Energies of particles determined by energy deposition in calorimeter.
  - All particles detected except neutrinos.





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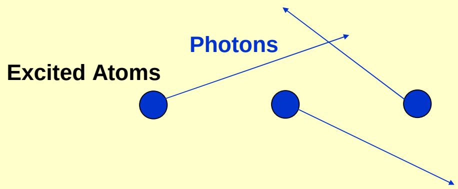
Important Quantum Effects in Our World
I Lasers

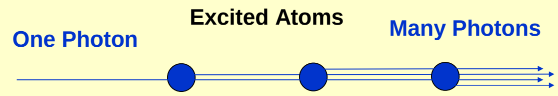
Usually light is emitted by an excited atom is in a a random direction - light from may atoms goes in all directions



What is special about a Laser??

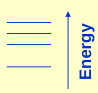
Important Quantum Effects in Our World
I Lasers

Lasers work because of the quantum properties of photons -- one photon tends to cause another to be emitted



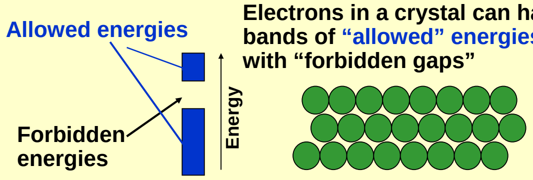
If there are many excited atoms, the photons can "cascade" -- very intense, collimated light is emitted forming a beam of precisely the same color light

Important Quantum Effects in Our World
Electrons in crystals



Electrons in an atom can have only discrete "allowed" energies with "forbidden gaps"

Electrons in a crystal can have bands of "allowed" energies with "forbidden gaps"

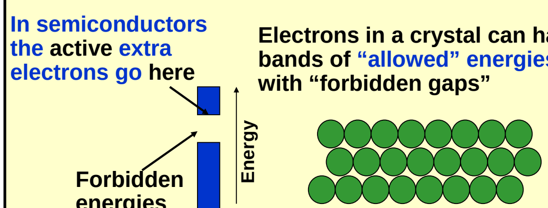


Due to Wave character of electrons - Interference!

Important Quantum Effects in Our World
Semiconductors
The basis of all modern electronics

Transistor invented at Bell Labs, 1947
(Bardeen, Brattain, Shockley

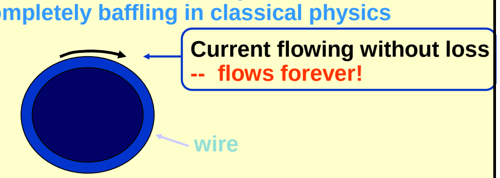
Electrons in a crystal can have bands of "allowed" energies with "forbidden gaps"



Due to Wave character of electrons - Interference!

Important Quantum Effects in Our World
Superconductivity

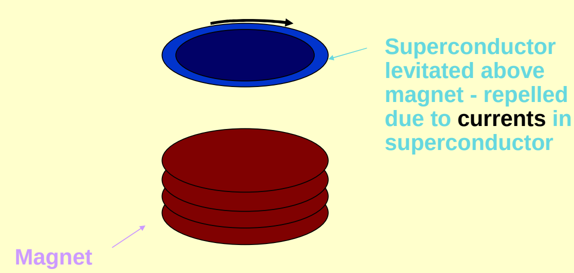
Discovered in 1911 by K. Onnes
Completely baffling in classical physics



Explained in 1957 by Bardeen, Cooper And Shrieffer at the Univ. of Illinois. (Bardeen is the only person to win two Nobel Prizes in the same field!)
Due to all the electrons acting together to form a single quantum state -- electrons flow around a wire like the electrons in an atom!

Demonstration

"High - Temperature Superconductors"
Discovered in 1987 (Nobel Prize)
(Still not understood!)



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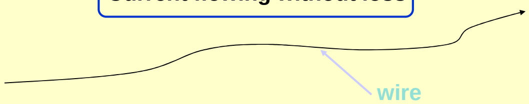
Important Quantum Effects in Our World

Superconductivity

Completely baffling in classical physics

Current flowing without loss



Electric Power lines could carry electricity from California to New York with no loss of power!

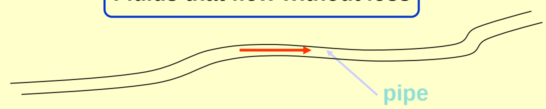
Possible now, but not economically feasible

Quantum Effects in Our World

Superfluids

Completely baffling in classical physics

Fluids that flow without loss

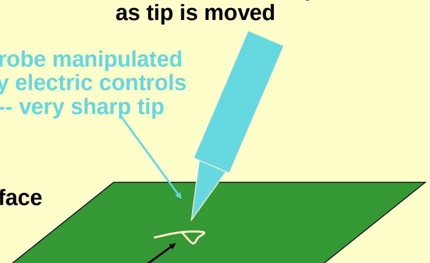


Liquid Helium at very low temperatures

Nobel Prize 2003 !
Tony Leggett of this Physics Department

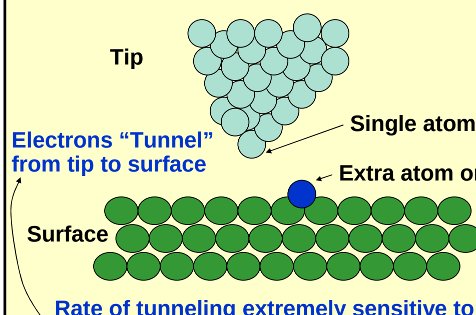
"Seeing" Quantum Effects in Our World

"Scanning Tunneling Microscope"
Measures electric current from tip to surface as tip is moved



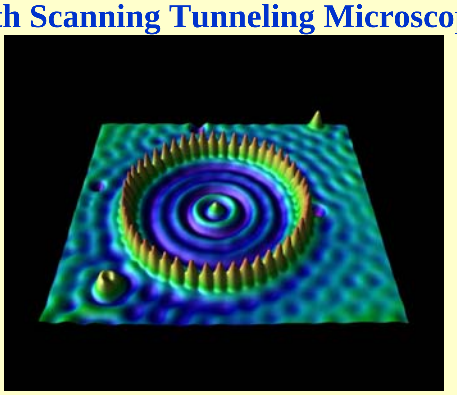
"Seeing" Quantum Effects in Our World

Scanning Tunneling Microscope -- Nobel Prize 1985



Rate of tunneling extremely sensitive to distance of tip from surface due to quantum effects

Observation of atoms, electron waves with Scanning Tunneling Microscope



Observation of atoms, electron waves with Scanning Tunneling Microscope

Corral of atoms placed one at the time
by maneuvering atoms with STM

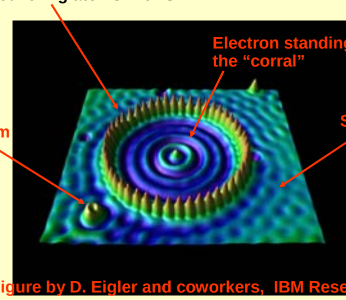


Figure by D. Eigler and coworkers, IBM Research

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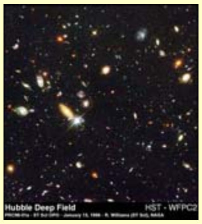
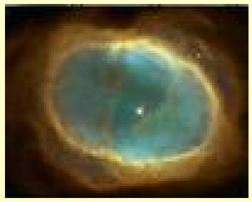
How do we know the universe is expanding? What galaxies are made of?



Distant galaxies seen by Hubble Telescope



Exploding White Dwarf

Our understanding depends on relativity and quantum mechanics!

Summary

- Enormous Ranges of sizes of objects in our world
- Enormous range of forces
- Quantum Mechanics crucial to understand the small units from which matter is made
  - Crucial for understanding Lasers, Semiconductors, Superconductors, ...
  - Atoms, Electrons, Nuclei, ... (More next time)
  - Quantum Effects NOT discernable for motions of ordinary objects (people, baseballs, sugar cubes, ...)
- Relativistic Effects are important for objects moving very fast or very massive (more later)
  - speeds near $c = 10^8$ m/s
  - Protons, Neutrons inside nuclei have very high energies
  - Important for motions of galaxies at large fractions of c
  - Strong effects of gravity -- black holes