Announcement

- Pick up your quiz after this lecture as you leave the lecture hall.
- Homework#2 due on Thursday
  - No hand-written homework!
  - Please staple them!
  - Put it in the box before the lecture begins!

<u>Station #2</u>
Stars

Lecture 9: Basic Physics

Lecture 10: The Sun

Lecture 11: Properties of Stars

Lecture 12: Star Stuff

Lecture 9
Basic Physics

Reading: Chapter S4

The Laws of Physics for Elementary Particles

- Stars are powered by nuclear energy
  - We need to understand the laws of physics governing elementary particles.
- New theories of the **very *small***:
  - 1905: Einstein shows light can behave like a particle
  - 1911: Rutherford discovers atoms consist mostly of empty space
  - 1913: Bohr suggests that electrons in atoms have *quantized* energies
- They called this new discipline **quantum mechanics**.
  - it has revolutionized our understanding of particles & forces
  - it has made possible our modern electronic devices

Anybody who thinks they **understand quantum physics** is wrong.

--- Niels Bohr

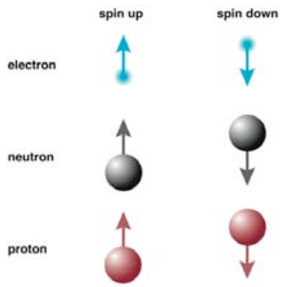
Fundamental Particles

- The most basic units of matter, impossible to divide, are called **fundamental particles**.
  - Democritus of ancient Greece thought they were atoms
  - physicists of the 1930s thought they were protons, neutrons, & electrons
  - the advent of **particle accelerators** has given us a zoo of new particles
  - Murray Gell-Mann in the 1960s proposed a *standard model* where all these particles could be built from a few fundamental components

Fermilab particle accelerator in Illinois

Basic Properties of Particles

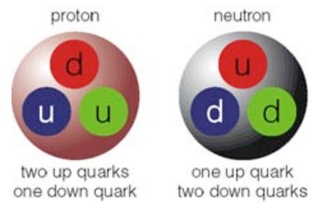
- Important basic properties of a subatomic particle:
  - mass
  - charge
  - spin angular momentum…or **spin**
- All particles of the same type have the same spin.
  - but they can have two possible orientations… *up* & *down*



- Particles do not really spin like a top.
  - the term describes angular momentum
  - which is measured in units of _
- Particles having half integer spin are called **fermions**. (named after Enrico Fermi)
  - particles of which matter is composed
- Particles having integer spin are called **bosons**. (named after Satyendra Bose)
  - such photons, gluons, & other exchange particles

The Building Blocks of Matter

- Trust me… Protons and Neutrons are not fundamental particles!
- Protons & neutrons, which are more massive than electrons…
  - are themselves made up of less massive particles
  - we call these particles ***quarks***
  - quarks come in six flavors
    - Amusing names
  - protons & neutrons consist of different combinations of two of these flavors
  - the up quark (+2/3)
  - the down quark (–1/3)
- Particles made from quarks (*hadrons*)…
  - can contain 2 or 3 quarks
  - a quark never exists alone



The Building Blocks of Matter

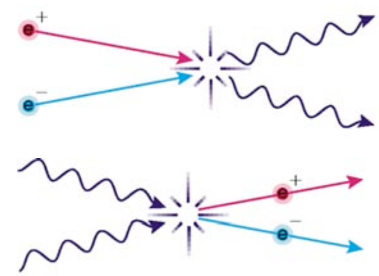
- The electron is not made up of lighter particles.
  - it is fundamental (as opposed to protons and neutrons!)
  - it is one of six particles called ***leptons***
  - leptons do exist by themselves
- Here are the six flavors of quarks & six leptons:

The Quarks	The Leptons
Up	Electron
Down	Electron neutrino
Strange	Muon
Charmed	Mu neutrino
Top	Tauon
Bottom	Tau neutrino

- Quarks & leptons are the fundamental particles of which all matter is made.
- Quarks & leptons are all fermions.
- All of these particles have been experimentally verified.

Antimatter

- Every quark & lepton has its own antiparticle.
  - when two identical particles of matter & antimatter meet…
  - they annihilate each other into pure energy ($E = mc^2$)
- When conditions are right (like immediately after the Big Bang)
  - collision of two photons can create a particle & its antiparticle
  - we call this **pair production**



Four Forces of Nature

Force	Relative Strength Within Nucleus*	Relative Strength Beyond Nucleus	Exchange Particles	Major Role
Strong	100	0	Gluons	Holding nuclei together
Electromagnetic	1	1	Photons	Chemistry and biology
Weak	10^{-5}	0	Weak bosons	Nuclear reactions
Gravity	10^{-43}	10^{-43}	Gravitons	Large-scale structure

* The force laws for the strong and weak forces are more complex than the inverse square laws for the electromagnetic force and gravity; hence the numbers given for the strong and weak forces are very rough.

- Natural forces allow particles to interact and exchange momentum.
  - mass is always positive, allowing gravity to dominate on large scales
  - each force is transmitted by **exchange particles**
  - exchange particles are all bosons
  - the graviton has not yet been detected
- The EM & Strong forces are aspects of the same *electroweak* force.
  - physicists are trying to unify all of the natural forces (GUT)

Unusual Aspects of Q.M. I: Measuring Location & Motion

- Imagine trying to measure the path of an electron.
  - knowing its location & velocity (momentum) at each instant
  - or knowing where it is & where it will be
- In order to see it, you must reflect light off of the electron.
  - visible light has a wavelength of, say 500 nm
  - this is larger than the electron
  - you can only measure the electron's location to within an accuracy of 500 nm
  - you must use shorter wavelength light to get a more accurate location
  - but then the photon will have more energy
  - upon impact, the photon will alter the electron's momentum
- This uncertainty in location & momentum is negligible when measuring the motion of large objects, like a baseball.
  - the ball is much larger than the wavelength of the light
  - the ball's momentum is much greater than the photon's energy

Heisenberg *Uncertainty Principle*

- The more we know about where a particle is located…
  - the less we can know about its momentum
- The more we know about a particle's momentum…
  - the less we can know about its position

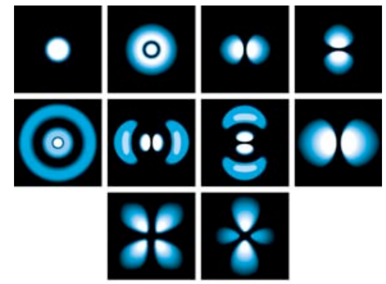
We can not know the precise value of an object's position & momentum (or energy & time at which it has that energy) simultaneously.

$$\Delta x \times \Delta p \approx h$$

x = location; p = momentum; $h = 6.626 \times 10^{-34}$ joule x sec

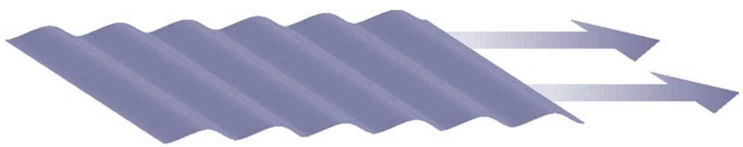
Electron Clouds

- As a consequence of the uncertainty principle…
  - if we locate the precise position of an electron
  - we have no idea of where it will go next
  - it appears in different locations over time, it is thus "smeared out"
  - we can calculate the probabilities of where it could be located



electron probability patterns for several energy levels of Hydrogen

Unusual Aspects of Q.M. II: Wave-Particle Duality of Matter



- If we think of the electron as a wave, it has a well-defined momentum.
  - but a wave has no single, precise location
  - it is spread out over a volume, like an electron cloud
  - electrons bound in atoms can be described as standing waves
- Just like light, all matter has a wave-particle duality.
  - in different situations, it is more convenient to describe it as one or the other

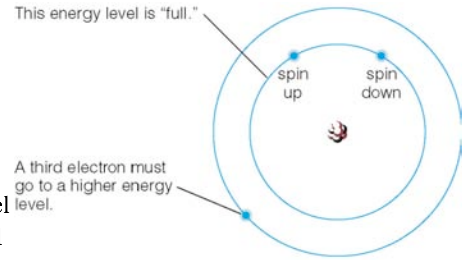
Unusual Aspects of Q.M. III: Pauli *Exclusion Principle*

Two fermions of the same type cannot occupy the same quantum state at the same time.

- quantum state… specifies the location, momentum, orbital angular momentum, & spin of a subatomic particle
- …to the extent allowed by the uncertainty principle
- Each of these properties is quantized.
  - they can take on only particular values

Consequences of the Exclusion Principle

- In an atom…
  - electron in lowest energy level
    - has a certain orbital angular momentum
    - a restricted range of locations
  - quantum state is determined, except for spin
  - two electrons can fit in this level
  - a third must go to a higher level



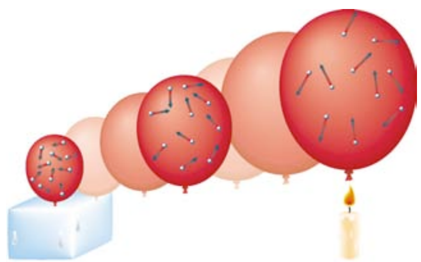
- This creation of higher energy levels makes chemistry possible.
- Although atoms are mostly empty space, the solidity of matter is explained.
  - uncertainty principle ensures electrons are not packed into very tiny spaces
  - exclusion principle ensures that each electron gets to have its own "space"
- These principles govern the sizes of nuclei.

Some Quantum Effects in Astronomy

- What is degeneracy pressure and how is it important in astronomy?
- Do black holes last forever?

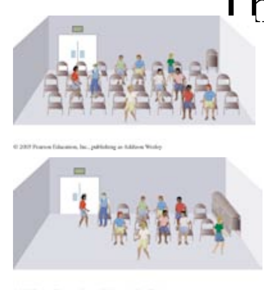
Under Pressure

- Pressure & temperature are normally related.
  - as you heat a balloon, it expands
  - gas pressure increases
- This **thermal pressure** dominates at low to moderate densities.



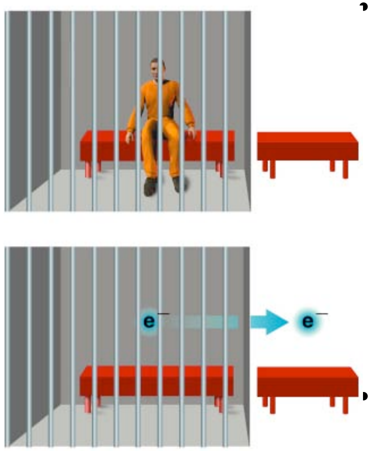
- As you compress a gas, it heats up, so you let it cool.
  - continue compression & cooling until gas is very dense
- Exclusion principle prevents the electrons from occupying the same quantum states.
  - the electrons can not get on top of one another
- The compression is stopped by **degeneracy pressure**.

Degeneracy Pressure: The Last Resistance



- Like a game of musical chairs
  - chairs are quantum states
  - students are electrons
- As we decrease the number of available states…
  - electrons must move faster, trying to find an empty state
  - they provide the degeneracy pressure
- This **electron degeneracy pressure** supports *brown dwarfs* & *white dwarfs* against gravity.
- When gravity (mass) is so great, that the electrons approach the speed of light.
  - electron degeneracy pressure is overcome, star collapses until…
  - it is supported by **neutron degeneracy pressure**, a *neutron star*
- If pressure from degenerate neutrons is overcome, you create a *black hole*.

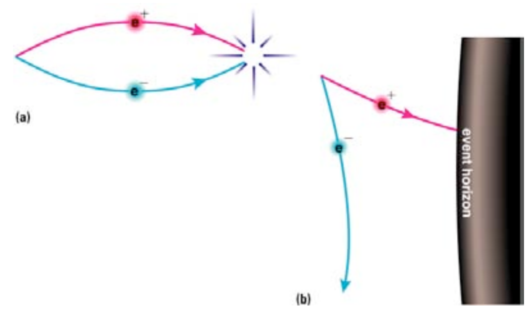
Weird!! Quantum Tunneling



- Uncertainty principle also states
  - product of uncertainties in time & energy are constant
  - the shorter the time, the greater the range of probable energies
  - a particle could briefly have enough energy to overcome a barrier (like escaping from a cell)
  - this will not violate conservation of energy if stolen energy is returned before it is noticed
- Quantum tunneling can explain how two protons can fuse.
  - protons can instantly overcome EM repulsion

Virtual Particles?

- Matter-antimatter pairs of particle can pop into existence.
  - if they annihilate before the uncertainty time, they go unnoticed
- If one particle is lost to the event horizon of a black hole…
  - the other stays in existence
  - it will eventually annihilate with another "stranded" particle
  - we would observe **Hawking radiation** emitted just outside the event horizon



- Ultimate source of this radiation is the gravitational potential energy of back hole
- The black hold would eventually evaporate.
- This effect has not yet been observed.

What have we learned?

- How did the advent of quantum mechanics change our world?
  - Quantum mechanics has revolutionized our understanding of particles and forces and made possible the development of modern electronic devices such as computers.

What have we learned?

- How are particles classified by spin?
  - All particles fall into one of two classes by spin: fermions and bosons. Fermions include all the particles that make up atoms, including electrons, neutrons, and protons. Bosons include photons and other particles that transmit forces, including gravitons, gluons, and weak bosons.
- What are the fundamental building blocks of matter?
  - Quarks and leptons are the fundamental building blocks of matter. There are six known types of each. Two of the six known types of quarks make up protons and neutrons, while electrons are one of the six known types of leptons. Quarks and leptons are all fermions.

What have we learned?

- Does antimatter really exist?
  - Yes. Every particle has a corresponding antiparticle. In fact, reactions in particle accelerators always produce particles in particle-antiparticle pairs.
- What are the four fundamental forces in nature?
  - The four fundamental forces are gravity, the electromagnetic force, the weak force, and the strong force.

What have we learned?

- What is the uncertainty principle?
  - The uncertainty principle tells us that we cannot simultaneously know the precise value of an object's position and momentum–or, equivalently, its energy and the precise time during which it has this energy.
- Does the uncertainty principle apply to objects we use in everyday life?
  - No. For everyday objects, the uncertainty is still so small that it has no noticeable effect on the objects we use in everyday life. Nevertheless, the uncertainty is quantifiable and large enough to be crucial when we work with subatomic particles.
- Are electrons waves or particles?
  - Under some circumstances electrons act like particles, while under other circumstances they behave like waves. In fact, according to the uncertainty principle, all subatomic particles exhibit, "wave-particle duality" much like that of photons.

What have we learned?

- What is the exclusion principle?
  - Two fermions of the same type cannot occupy the same quantum state at the same time. (This principle does not apply to bosons.)
- How is the exclusion principle important to our existence?
  - The exclusion principle explains the different energy levels in atoms, which make all of chemistry possible. It also explains why electrons cannot all be on top of one another in atoms, a fact that gives atoms their physical size.

What have we learned?

- What is degeneracy pressure and how is it important in astronomy?
  - Degeneracy pressure is a type of pressure that can occur even in the absence of heat. It arises from the combination of the exclusion principle and the uncertainty principle. It is the dominant form of pressure in the astronomical objects known as brown dwarfs, white dwarfs, and neutron stars.
- Do black holes last forever?
  - No. According to current theory, isolated black holes can gradually evaporate through quantum tunneling, emitting Hawking radiation in the process. Although the theoretical basis of this idea seems solid, it has not yet been observed in nature.

Next Lecture

- **The Sun!**
  - Read Chapter 15

- Don’t forget to pick up quiz as you leave the lecture hall.

- Don’t forget to turn in your homework on Thursday.