The Four Fundamental Forces

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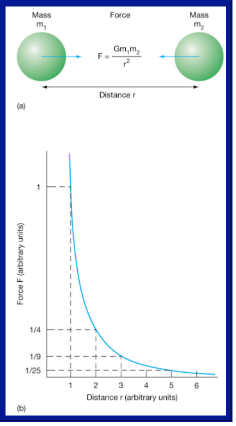
  - Gravitational, Electromagnetic, Strong and Weak Nuclear
    - Gravity: Increases with masses, Inverse square law force, Always attractive
    - Weak: Involved in radioactive decay
    - Electromagnetic: Increases with charges, Inverse square law force, Opposites attract and likes repel
    - Strong: Holds positively charged nucleus together, Extremely short range (10^{-15}m)
  - Strong force 100 times EM and Weak forces, 10^{39} times gravity
- Holy grail of physics is to unify these four forces!

Weaker ||| Stronger

Gravitational Force

- The gravitational force is always attractive
- The strength of the attraction decreases rapidly (as the square of) increasing distance



The Electrical Force

- Coulomb's Law

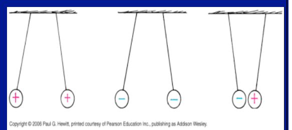
$$F = k\frac{q_1q_2}{r^2}$$

- Compare to Gravity

$$F = G\frac{m_1m_2}{r^2}$$

  - $k = 9$ Trillion $N\bullet m^2/C^2$
  - $G = 6.67 \times 10^{-11}\ N\bullet m^2/kg^2$

$k/G \sim 10^{20}$



Like electric charges repel and opposites attract.

Support force, Friction force, are derived from the Electrical Force

The Photon (γ)

Property	Value
Mass	0
Charge	0

❑ **The photon is the "mediator" of the <u>electromagnetic interaction</u>**

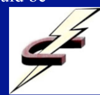
❑ **The photon <u>can only interact</u> with objects which have <u>electric charge</u>**

Unification

- There's a natural tendency toward unification of forces
- For instance electrical and magnetic phenomena where unified by Maxwell's equations into <u>electromagnetism</u>.
- In essence all electrical and magnetic phenomena can be described by the motion of charged particles.

The Situation ~1900

- So at the turn of the last century most phenomena could be explained by
  - gravity
  - electromagnetism.



- But some annoying things started cropping up because of improved instrumentation:
  - X rays (Roentgen 1895)
  - Radioactivity (Becquerel 1896)
  - The electron (Thomson 1897)
  - The nucleus (1911 Rutherford)

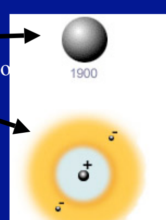
The Quanta

All these discoveries led to the description of matter and radiation as particles or small quanta

- The quantum idea (Planck 1900)
- Light as quanta (Einstein 1905)
- The nucleus (Rutherford 1911)
- The atom (Bohr 1913)

The Atom

- Let’s consider the atom: In 1900 it was thought to be a solid sphere
- After the quantum revolution it was understood to be composed of a nucleus and electrons.
- The electron has negative charge and the nucleus positive charge. The entire thing is held together by electromagnetism



Light as a Manifestation of a Fundamental Force

- By emitting or absorbing a photon, the electron can change its average position or energy in an atom.
- In every day life, the illumination from your light bulb is just a very great number of photons emitted from the excited filament atoms.
- This is a classic electromagnetic interaction and our first manifestation of a fundamental force!

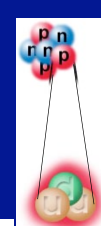
A Characteristic of Fundamental Forces

- As the light bulb hinted, charged objects interact by exchanging photons.
- In the atom the electron and nucleus are held together by exchanging photons.
- In fact all fundamental forces involve the exchange of a fundamental particle.

… to go any further in our discussion we need to enumerate the fundamental particles

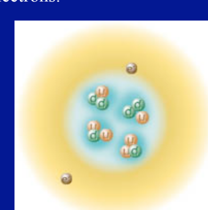
The Nucleus and the Atom

- Nowadays we know the nucleus to be made of protons and neutrons
- And the protons and neutrons of quarks!
- So that a complete picture of the atom would include quarks and electrons.



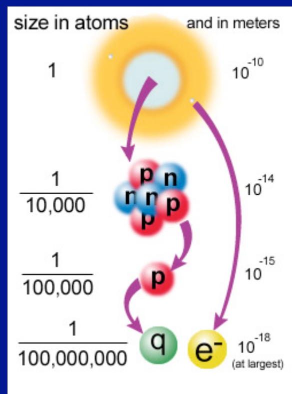
Three quarks for Muster Mark!
Sure he has not got much of a bark
And sure any he has it's all beside the mark.
—James Joyce, *Finnegans Wake*

Prediced in 1964
Discovered in 1968



Scale

- Let's just take a small detour to consider the scale of the atom
- In fact the tiny electrons and quarks have no observed structure and are for all intents and purposes fundamental.

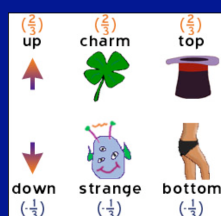


The Standard Model

- The crowning achievement of particle physics is a model that describes all particles and particle interactions. The model includes:
  - 6 quarks (those little fellows in the nucleus) and their antiparticles.
  - 6 leptons (of which the electron is an example) and their antiparticles
  - 4 force carrier particles (of which the photon is an example)
- All known matter is composed of composites of quarks and leptons which interact by exchanging force carriers.

The Quarks

- There are three pairs of quarks.
- The up and down are the constituents of protons = uud and neutrons = udd, and make up most matter.
- The other particles are produced in energetic subatomic collisions from cosmic rays or in accelerators like Fermilab (where they are also studied.)



Clicker Question:

Which two forces have fields that fall off as $1/\text{distance}^2$?

A: strong and gravitational

B: weak and gravitational

C: strong and electromagnetic

D: electromagnetic and gravitational

Clicker Question:

Which of these is a fundamental particle that is never found by itself?

A: neutron

B: proton

C: quark

D: photon

Clicker Question:

Electrons and protons influence each other by exchanging what type of particles?

A: neutrinos

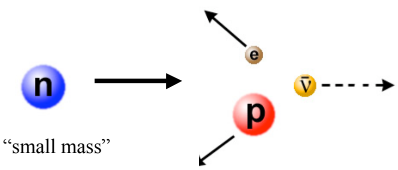
B: bosons

C: quarks

D: photons

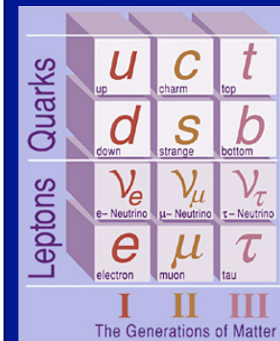
Leptons*

- Leptons are generally lighter particles and are most readily observed in radioactive decays.
- The best example is neutron decay into a proton, an electron, and a neutrino:



*Greek for "small mass"

Periodic Table of Fundamental Particles



+2/3

−1/3

0

−1

Mass →

Add Antiparticles

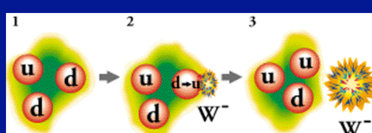
Families reflect increasing mass and a theoretical organization

u, d, e are "normal matter".

Because of the charge quarks, electrons, muons, and tau's participate in EM

The Weak Force

- Radioactivity, in particular the neutron decay we discussed earlier, is actually a manifestation of the weak force
- At the quark level, a down quark in the neutron decays into an up quark, by emitting a W boson.

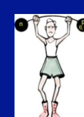


- The heavy W boson is the carrier of the weak force.

A Brief, First, Consolidation

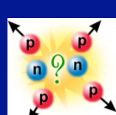
- We've enumerated two fundamental forces.
- Electromagnetism which occurs between charged particles and is carried by the photon, γ.
- Weak force which occurs between quarks and leptons and is mediated by the intermediate vector bosons, W^+,W^-, and Z^0.

+



The Problem of the Nucleus

- Why doesn't the nucleus - full of positive protons that repel one another and neutral neutrons - blow itself apart?



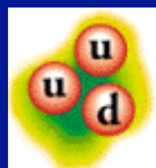
- Gravity doesn't work since it's much too weak compared to electromagnetism.
- There must be yet another force around!

The Color Charge

- Well it turns out quarks have another quantum number or charge called "color charge".
- The force between these color charges is extremely strong.
- Two quarks interact by exchanging the strong carrier dubbed the "gluon"
- Gluons themselves have color charges

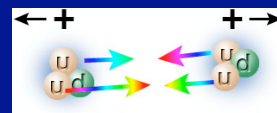
The Color Charge (continued)

- There are three color charges named: “red”, “green” and “blue”.
- These names are mathematical identifiers and have nothing to do with visible colors.
- Quarks are bound in a particle, like the proton, by madly exchanging gluons and forming a binding color field:



The Color Charge (continued)

- Now back to the nucleus!
- The residual strong field between the protons and neutrons overwhelms the repulsive electromagnetic force and holds the whole thing together



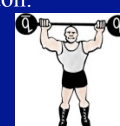
Comparison
Strong and EM Forces

Property	EM	Strong
Force Carrier	Photon (γ)	Gluon (g)
Mass	0	0
Charge ?	None	Yes, color charge
Charge types	+, -	red, green, blue
Mediates interaction between:	All objects with electrical charge	All objects with color charge
Range	Infinite ($1/d^2$)	$\lesssim 10^{-14}$ [m] (inside hadrons)

A Second Consolidation

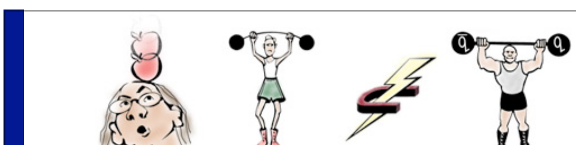
- The weak force occurs between quarks and leptons and is mediated by the massive intermediate vector bosons W^+,W^-, and Z^0

- The electromagnetic force occurs between electrically charged particles and is mediated by the massless photon.
- The strong force occurs between color charged particles and is mediated by the massless gluon.



Gravity

- Should there be a carrier particle for gravity?
- The graviton has not been discovered.
- Still since this is a very weak force the Standard Model works very well in the absence of a full description



	Gravity	Weak	Electromagnetic	Strong
		(Electroweak)		
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

10^{-37} weaker than EM

Explained by complete theory

A Few of the Unsolved Questions

- Can the forces be fully unified?
- How do particles get mass?
- How does gravity fit into all of this?
- Can we explain how gravity works on small scales - quantum gravity?

Clicker Question:

What force keeps the nucleus of an atom from coming apart?

A: gravitational

B: electromagnetic

C: strong

D: weak

Clicker Question:

What force holds electrons to the nucleus of atoms?

A: gravitational

B: electromagnetic

C: strong

D: weak

Clicker Question:

What force allows neutrons to decay into protons?

A: gravitational

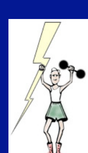
B: electromagnetic

C: strong

D: weak

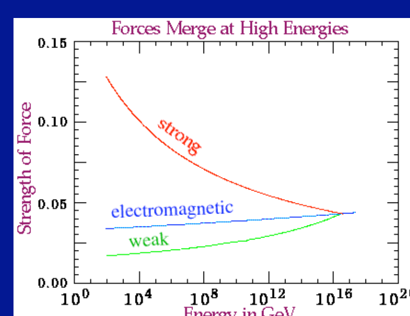
The Electroweak Unification

- Remember that quarks and leptons interact through the weak force?
- Note the quarks, leptons, and bosons all carry charge so they can also interact electromagnetically. This is a big clue!
- It turns formally (or mathematically) that electromagnetism and the weak force are manifestations of the same underlying force: the electroweak force.



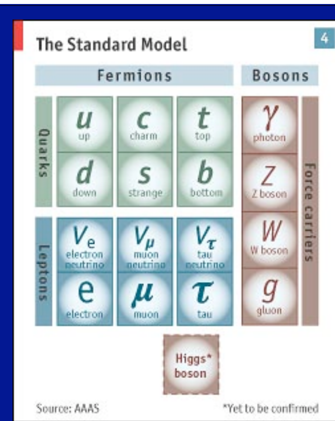
Grand Unified Theories(GUTs)

At very high energies all interactions merge to a single strength.

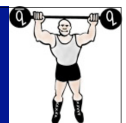


The Higgs Particle

- The electroweak unification postulates the existence of the Higgs Particle, H.
- This particle or field interacts with all other particles to impart mass.
- The experimental program at Fermilab in Illinois and the Large Hadron Collider in Europe are dedicated to the search for this particle.
- It's discovery would be an achievement of the highest order – reaching an understanding of the origins of mass!



In Conclusion



- The four fundamental forces: gravity, weak, electromagnetism, and strong
- All but gravity explained by the Standard Model of particle physics
- Theory and experiment give tantalizing hints of full unification!