Ch. 44: Quarks, Leptons and the Big Bang

- **Today:**
  - The Fundamental Particles
  - The Basic Forces
  - The Accelerating Universe

The Fundamental Particles

- All matter is made of quarks and leptons.
- Ordinary matter (atoms) contains only
  - two kinds of quarks (*u,d*)
  - one kind of lepton (*e*)
- All the quarks and leptons are listed in the text.
- Quarks and leptons
  - are fermions
  - have conserved quantum numbers (*B,Q,L*)
  - have no structure or size
  - have antiparticles (anti-quarks, anti-leptons)

Fundamental Particles and Forces

- Electrons and Photons
- Baryons and Leptons
- The Electroweak Force
- The Strong Force
- Quarks
- Gluons and the Strong Force
- General Relativity
- Theory of Everything?

The Big Picture

Particles of matter (fermions, numbers conserved):

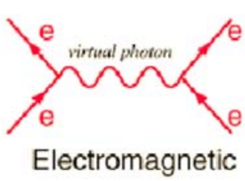
Quarks u,d combine to form nucleons p,n.
Electrons are leptons.
Numbers are conserved.

Particles of energy (bosons, numbers not conserved):

Photon: Carries electromagnetic force.
Gluon: Carries strong nuclear force.
W, Z: Carry weak nuclear force.
Graviton: Carries gravitational force.

http://particleadventure.org/particleadventure/index.html

Electromagnetic Interactions

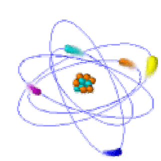


Force between two charges is carried by electromagnetic field.

But photon is the quantum of that field.

Fundamentally the electric force is carried by the *exchange of a photon.*

Atoms



Atom is mostly vacuum.

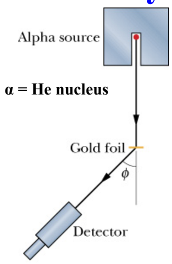
Electrons are in quantum states (n,l,m_l,m_s) moving around the incredibly small nucleus.

Nucleus has almost all the mass (m_p = 2000 m_e).

How do we know?

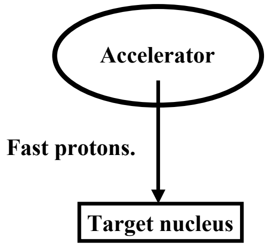
Historically, from Rutherford scattering.

Study nucleus via collisions



Rutherford scattering

Modern version



(See what happens!)

High energy required

What energy is needed to make a proton strike another proton?

First calculate the Coulomb potential at the surface:

$$V = k\frac{e}{r} = \frac{(9\times10^{9})(1.6\times10^{-19})}{3\times10^{-15}} = 0.5\times10^{6}\ volts$$

So that's the voltage we need to use for acceleration of the projectile proton. That is, its energy should be a few MeV.

Remember that's why controlled fusion is so hard.

Baryons

- Nucleons (protons and neutrons) are baryons.
  - Fermions with s = ½
  - Baryon number is conserved
  - Antiparticles
  - Combine to form nuclei
  - Attractive force gives binding energy
- Nuclear shell model
- Normal matter made from e, p, n interacting by exchange of photons.
- Electrons are leptons.

Table of familiar particles

Name	Symbol	Q	Mass (MeV)	S	B	L
Electron	e^-	-1	0.51	1/2	0	1
Proton	p	+1	938	1/2	1	0
Neutron	n	0	940	1/2	1	0
Positron	e^+	+1	0.51	1/2	0	-1
Antiproton	$\overline{p}$	-1	938	1/2	-1	0
Antineutron	$\overline{n}$	0	940	1/2	-1	0
Photon	γ	0	0	1	0	0

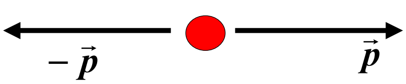
fermions

boson

Positron Annihilation

$$e^- + e^+ \to \gamma + \gamma$$

Positron stopped in target meets an electron.



Electron-positron system initially at rest.

Each photon carries energy mc² = 0.51 MeV.

Need two photons to conserve energy *and* momentum.

Note Q, B, L also conserved.

Beta Decay

$$n \to p + e + \overline{\nu} \qquad \tau = 15\,\text{min}$$

Pauli invents the neutrino!

Conservation laws:
- Charge
- Energy
- Momentum
- Baryon number
- *Lepton number*

Leptons: e, ν Anti-leptons: $e^+, \overline{\nu}$

More leptons

Electron	electron neutrino
Muon	muon neutrino
Tau	tau neutrino

Plus all the antiparticles!

Number for each family is *conserved.*

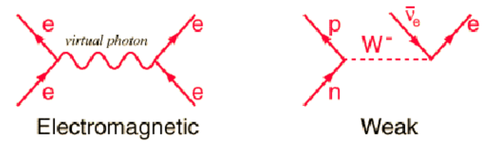
Weak Interactions:

$$n \rightarrow p + e + \overline{\nu}$$

$$\nu + n \rightarrow p + e$$

$$\mu \rightarrow e + \nu_{\mu} + \overline{\nu}_{e}$$

Electroweak Interactions



Weak Interaction could not be understood until the electromagnetic and weak interactions were combined.

Electroweak force is carried between two fermions by the *exchange of a boson.*

The Strong Force

When two nuclei are far apart, as in a diatomic molecule, they repel each other via the Coulomb force.

But when they come in contact, they attract each other via the Strong Nuclear Interaction.

"Electroweak" is weak but long range.

"Strong" is strong but short range.

> Biggest challenge to physics during the 20th century. "Understand the strong nuclear interaction." What holds the nucleons together inside the nucleus?

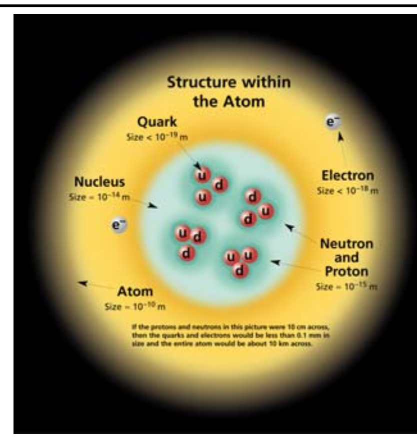
Nucleons are made of quarks

p = (uud)

n = (udd)

$$u \text{ has } q = +\frac{2}{3}e$$

$$d \text{ has } q = -\frac{1}{3}e$$



FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c²	Electric charge
ν_e electron neutrino	<1×10⁻⁸	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

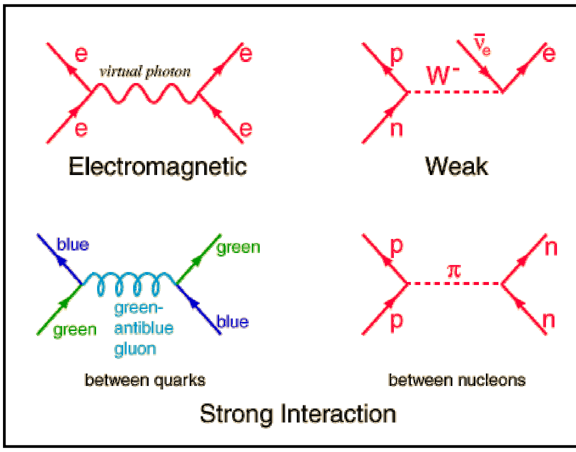
Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c²	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	−1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω⁻	omega	sss	−1	1.672	3/2

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0



The Standard Model

The strong force is now understood. It is exerted by the exchange of ***gluons***, just as the electroweak force is exerted by the exchange of photons.

The theory of the strong force is called Quantum Chromodynamics (QCD).

If the theories of the electroweak and strong forces are combined, along with everything we know about the fundamental particles, we get what is known as the "**standard model.**"

Check out "Dreams of a Final Theory", by Steven Weinberg (Pantheon, 1992).

Check out "particleadventure" web site for more about the fundamental particles and their interactions.

http://particleadventure.org/particleadventure/index.html

What about Gravity?

If we could combine the Standard Model with a quantum theory of gravity, we might hope for achieving the ultimate goal of physics, the "Theory of Everything."

However our best theory of gravity is Einstein's *General Theory of Relativity.* This goes way back before quantum theory, and the two theories are very hard to combine. In fact general relativity doesn't use the concept of force, or interaction. It considers the distortion of spacetime itself. This makes it seemingly incompatible with quantum theory. Progress is slow!

The big news about the universe

For many years, we have known the universe is expanding. The more distant galaxies are moving away from us faster than the nearer ones. The expansion is uniform, exactly as if it had all started in one event (the big bang) about 15 billion years ago.

Big news is the expansion is accelerating!

Gravity is always attractive.
Energy is equivalent to mass.
Black holes.
Expansion should decelerate.
Quantum gravity.
Vacuum fluctuations.
Dark energy.

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