Particle Physics

"The stuff that things are made of"

Elementary Particle

- A particle with no internal structure
  - Not made out of smaller constituents
  - Electrons are elementary particles

The Search for Truth

- By the mid 1930s it was recognized that atoms were made of protons, neutrons and electrons
  - As well we knew of positrons, neutrinos, and γ particles (photons)
- Wave-particle duality allows us to imagine that the electromagnetic force is due to the exchange of photons or γ particles

- 1935, Hideki Yakawa predicted a new particle that would mediate the strong nuclear force
  - Mass between an electron and proton
  - Called a **meson** (in the middle), m≈130 MeV
  - Could be observed (since photons can be observed)
- 1937, a new particle was discovered
  - m≈106 MeV (close to predicted mass)
  - Did not interact strongly with matter
  - Not the Yakawa particle
  - Called **muon**, μ

- 1947, C. F. Powell and G. Occhialini discovered the particle Yakawa predicted in cosmic rays
  - Called pi meson or **pion**, π
  - Three charged states: +, -, 0
    - π^+, π^- 139.6 $MeVc^{-2}$
    - π^0 135.0 $MeVc^{-2}$
  - Interact strongly with matter
    - $p + p \rightarrow p + p + \pi^0$
    - $p + p \rightarrow p + n + \pi^+$
  - Recent theories have replaced mesons with gluons as the particles that mediate the strong nuclear force

- Particle that mediates the weak nuclear force
  - W^+, W^-, Z^0
  - Detected in 1983
- Gravitation force
  - Graviton
  - Has not yet been discovered
- Other Particles (1950s and 1960s)
  - Kaons, K^+, K^-, K^0
  - Hyperons, Σ^+, Σ^-, Σ^0

Particles and Antiparticles

- 1932, positron was discovered
- All particles should have antiparticles
- 1955, antiproton
- 1956, antineutron
- Some particles do not have antiparticles
  - Photons, π^0, graviton
- When a particle comes in contact with an antiparticle, they annihilate and release energy

Quantum Numbers

- Numbers (or properties) used to characterize particles
  - Electric charge: + or –
  - Spin
- All of the laws of conservation still apply
  - Energy, momentum, angular momentum

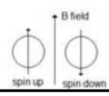
Spin

- In classical mechanics, a body of mass moving in a circular path has a property called angular momentum, measured in Js
- Particles appear to have a similar property also measured in Js
  - Called spin
- A particle's spin is ***NOT*** the same thing as the angular momentum of a spinning body

- For elementary particles, spin is a consequence of Einstein's theory of relativity and does not have a classical counterpart
- All known particles have a spin that is a multiple of a basic unit

$$\text{unit of spin} = \frac{h}{2\pi}$$

- Particles fall into two separate classes when classified according to spin
- All known particles have either an integral spin or a half-integral spin
  - Bosons – integral spin
    - A photon is a boson
  - Fermions – half-integral spin
    - Electrons, protons, and neutrons are fermions
- Particles with spin will align themselves parallel or antiparallel with a magnetic field



Pauli Exclusion Principle

- 1930, Wolfgang Pauli (Austrian)
- It is impossible for two identical fermions to occupy the same quantum state if they have the same quantum numbers

- The Pauli exclusion principle explains why there can only be two electrons in the innermost "shell"
  - Electrons are fermions and thus the principle applies
  - Electrons can only be differentiated by their spin quantum number
  - Since the spin of an electron is ½, we have only two choices: "up" or "down"
- In the outer probability regions things are more complicated, thus more electrons can be in these "shells"

More Quantum Numbers

- In all interactions conservation of energy, momentum, and angular momentum must still occur
- More quantum numbers (conservation laws) were introduced to explain why some reactions occur and others don't
- For example:

$$p + p \nrightarrow p + p + \overline{p}$$
$$p + n \rightarrow p + n + \overline{p} + p$$

Baryon Number

- All nucleons have B=+1
- All antinucleons have B=-1

$$\begin{array}{rccccccccc} & p & + & p & \nrightarrow & p & + & p & + & \overline{p} \\ B = & 1 & + & 1 & \neq & 1 & + & 1 & + & -1 \\ & & & 2 & \neq & 1 & & & & \end{array}$$

$$\begin{array}{rccccccccccc} & p & + & n & \rightarrow & p & + & n & + & \overline{p} & + & p \\ B = & 1 & + & 1 & = & 1 & + & 1 & + & -1 & + & 1 \\ & & & 2 & = & 2 & & & & & & \end{array}$$

Lepton Number

- Ordinary β decay gives electrons and neutrinos or positrons and antineutrinos
- A similar type of decay gives a muon and a neutrino (the antiparticles exist too)
- Another particle called the tau, τ, and its neutrino also exist (the antiparticles exist too)
- These particles are collectively called leptons

- The neutrinos for each particle are different (so are the antineutrinos)
- Three lepton numbers are needed to explain reactions with leptons

	L_e	L_μ	L_τ
Electron, e^-	+1	0	0
Electron neutrino, ν_e	+1	0	0
Muon, μ^-	0	+1	0
Muon neutrino, ν_μ	0	+1	0
Tau, τ^-	0	0	+1
Tau neutrino, ν_τ	0	0	+1

- The antiparticles have a lepton number of -1

	L_e	L_μ	L_τ
Positron, e^+	-1	0	0
Electron antineutrino, $\overline{\nu}_e$	-1	0	0
Antimuon, μ^+	0	-1	0
Muon antineutrino, $\overline{\nu}_\mu$	0	-1	0
Antitau, τ^+	0	0	-1
Tau antineutrino, $\overline{\nu}_\tau$	0	0	-1

Particle Classification

- Particles are arranged according to their interactions
  - Hadrons
    - Interact via the strong nuclear force
    - Baryons
    - Mesons
  - Leptons
    - Interact via the weak nuclear force
    - Leptons with charges also interact with the electromagnetic force
  - Exchange Bosons
    - Carry the electromagnetic and weak interactions

Strange Particles

- 1950s, certain newly found particles (K, Λ, Σ) were found to behave strangely
- They were always produced in pairs
- They decayed far too slowly compared with other similar particles
  - $\Sigma^- \rightarrow n + \pi^-$ (half-life of 10^{-10}s)
  - $\Sigma^0 \rightarrow \Lambda^0 + \gamma$ (half-life of 10^{-20}s)
    - 10 orders of magnitude smaller

- A new quantum number and conservation law was introduced to account for this strangeness
- The properties of strange particles could then be understood if it was postulated that strangeness is conserved ***only*** in electromagnetic and strong reactions but is violated in weak interactions
- The strangeness of some hadrons:
  - K^+, K^- S=+1
  - $\Sigma^+, \Sigma^-, \Sigma^0$ S=-1

Quarks

- 1960s, Murray Gell-Mann proposed that three flavors of a new particle should exist
  - Quarks
    - up (u), down (d), strange (s)
- The u quark was the lightest of the quarks and was assigned a charge of $\frac{2}{3}|e|$
- The d and s quarks were each assigned a charge of $-\frac{1}{3}|e|$

- The hypothesis was that hadrons could be made out of quarks in just two ways
  - Three quarks make a baryon
  - A quark and an antiquark make a meson
- Only hadrons are made of quarks. Leptons and exchange particles are not
- 1964, several physicists proposed that a fourth quark should exist
  - charmed (c)
    - Assumed to behave like strange
  - First charmed particle was discovered in 1974
    - J/ψ meson

- 1970s, theoretical physicists proposed that two more quarks should exist (6 leptons – 6 quarks)
  - top (t), bottom (b)
    - Originally called truth and beauty
  - New mesons with b were soon detected
  - Strong evidence for the t quark did not appear until 1995
- Quarks are fermions
  - Therefore they have spin=½

Some Hadrons

- Baryons
  - proton, p=(uud)
  - neutron, n=(udd)
- Mesons
  - pion, $\pi^+=(u\bar{d})$

Explaining Hadrons

- Since hadrons are made of quarks, we can use the properties of quarks to explain many of the properties of hadrons
  - Baryon number
  - Strangeness
  - Spin

Baryon Number

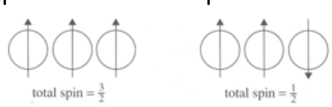
- Baryons are assigned a Baryon number of +1
- Antibaryons are assigned a Baryon number of -1
- Since baryons are made of three quarks, quarks have a baryon number of ⅓ and antiquarks have a baryon number of -⅓
- Thus, mesons (quark and antiquark) have a baryon number of 0

Strangeness of Hadrons

- A hadron is assigned one positive unit of strangeness for every antistrange quark it contains and one negative unit of strangeness for every strange quark it contains
- Examples
  - K^+ ($u\bar{s}$), S=+1
  - π^+ ($u\bar{d}$), S=0
  - Σ^+ (uus), S=-1

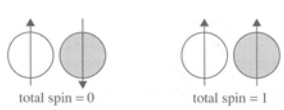
Spin of Hadrons

- Baryons are made of three quarks
- There are only two possible orientations of the spins of the three quarks



- Thus, all baryons must have a spin of $\frac{1}{2}$ or $\frac{3}{2}$
- So all baryons are fermions

- Mesons are made of a quark and an antiquark
- Again there are only two possibilities



- Therefore, all mesons are bosons

Color

- An immediate problem appears when one looks at a baryon such as

$$\Omega^- \quad (sss) \quad \text{spin} = -\tfrac{3}{2}$$

- According to Pauli's exclusion principle, such a particle cannot exist
  - All three quarks are the same and must have the same spin
  - So, all of the quarks are in the same quantum state

- To avoid this problem, a new quantum number needed to be introduced
  - Color
- Quarks could be red, blue, or green
- Antiquarks could be antired, antiblue, or antigreen
- Baryons have one quark of each color
  - Resulting in "white" or no color
- Mesons have a color and anticolor pair
  - Resulting in no color
- Hadrons have no color

Gluons

- Quarks interact via the strong nuclear force
- The particle that mediates this interaction is called a gluon
- The theory of quarks interacting with gluons is called quantum chromodynamics (QCD)

- Gluons also carry color, but their case is somewhat difficult and technical
- A gluon carries two colors
  - One for color
  - One for anticolor
- Theoretically, there can be nine different combinations
  - So we would expect nine gluons
- However, because red-antired, blue-antiblue, and green-antigreen are colorless, the “ninth” gluon is a combination of the other eight

- Therefore there are only eight *independent* gluons:

$$G_{R\overline{B}}, G_{R\overline{G}}, G_{B\overline{R}}, G_{B\overline{G}}, G_{G\overline{R}}, G_{G\overline{B}}$$

And two complicated ones:

$$G_{R\overline{R}-G\overline{G}}, G_{R\overline{R}+G\overline{G}+2B\overline{B}}$$

Confinement

- The quark idea introduced order
  - The properties of many particles could now be explained in terms of the properties of quarks
- The only problem was that quarks could not be found
- We now have some experimental evidence to indicate that quarks do exists
- However, no free quarks have been observed

- Quarks only exist within hadrons
- This leads to the property of **confinement**:
  - It is not possible to observe isolated quarks (and gluons). Quarks inside a hadron always appear in color combinations that result in zero net color.
    - Called quark confinement or color confinement

- The force between the quark and the antiquark is constant no matter what the separation is
- Therefore, the energy required to separate a quark and antiquark gets larger as the separation increases
- To free the quark would thus require an infinite amount of energy

Elementary Particles

- We can now list the elementary particles that constitute all matter:
  - Quarks
    - u, d, s, c, b, t (and the antiquarks)
  - Leptons
    - e^-, ν_e, μ^-, ν_μ, τ^-, ν_τ (and the antileptons)
  - Exchange particles (exchange bosons)
    - γ (photon), $W^\pm$, Z^0, gluons

The Standard Model

- The theory of quarks and leptons is called the standard model of elementary particles
- The standard model has classified the quarks and leptons into three families (or generations)
  - Each family is a copy of the one before but heavier in mass overall

	Leptons	Quarks
1st family	e^-, ν_e	u, d
2nd family	μ^-, ν_μ	s, c
3rd family	τ^-, ν_τ	b, t

The Higgs Boson

- The Higgs boson is a neutral, spin=0 boson that plays a crucial role in the standard model
- It has not yet been detected experimentally
- It is estimated to have a mass between 120 and 200 GeVc^{-2}

- The Higgs boson is closely linked to the mystery of mass
- What exactly is mass and how do elementary particles acquire mass?
- In particular, why do they have the mass they do?
- The mathematics of the electroweak theory prohibits the photon, W and Z bosons from having mass
  - Photons are massless but W and Z are massive

- Peter Higgs devised a mechanism for W and Z to have mass while preserving the theory
- It involved the introduction of a new boson
  - Called the Higgs boson (neutral, spin=0)
- This particle interacts with the particles in the standard model to give them mass
  - In particular W and Z