L19: Particle Physics
Fundamental Particles - Version 1.0

- All matter composed of atoms
  - Nucleus composed of ‘nucleons’, i.e. protons and neutrons
    - Feel strong nuclear force which keeps them in the nucleus
    - Both have very similar mass
  - Nucleus surrounded by electron ‘shells’ or ‘clouds’ which reflect the energy levels of the electrons in that atom
- Beta decay of some atoms
  - Leads to idea of a ‘neutrino’

<table>
<thead>
<tr>
<th></th>
<th>charge</th>
<th>Mass</th>
<th>Strong</th>
<th>electromagnetic</th>
<th>weak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
<td>+1</td>
<td>$m_{\text{proton}}$</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>neutron</td>
<td>0</td>
<td>$\sim m_{\text{proton}}$</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>electron</td>
<td>-1</td>
<td>$m_{\text{proton}}/200$</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Neutrino</td>
<td>0</td>
<td>$\sim 0$</td>
<td>--</td>
<td>--</td>
<td>Y</td>
</tr>
</tbody>
</table>
Antimatter

- Dirac, 1930
  - Produced a relativistic model of quantum mechanics
  - Includes special, not general, relativity
- Noticed a ‘symmetry’ about equations
  - Negatively charged electron moving forward in time same as positively charged electron (‘positron’) moving backwards in time
  - So nature requires existence of ‘anti-electron’, what we call a positron
- Positrons
  - Observed in cosmic ray experiments
    - A particle created by another particle from space and which interacts with a detector
    - Produces a particle with the same mass as an electron, but opposite charge
  - Whenever near ordinary matter
    - It interacts with atoms by annihilating an electron and producing photons
- Hypothesize anti-proton and anti-neutron: they have been observed
Mesons

- **Meson theory:** Yukawa, 1931
  - Think of strong force as exchange of mediating particle (‘meson’)
  - Reason strong force is restricted in distance it can reach
    - Meson has mass: by uncertainty principle ($\Delta E \Delta t > h/2$), a virtual meson can only exist for a length of time, $\Delta t$
    - By observing range of strong force, can estimate mass of ‘meson’ to be $\sim m_{\text{proton}}/7$

- ‘mu meson’ or ‘muon’ discovered: birth of particle physics
  - Mass $\sim m_{\text{proton}}/9$
  - Looks like a heavy electron – it doesn’t feel the strong force!
    - So can’t answer the problem of the strong force’s range

- Pi mesons discovered 1947 and 1950
  - Feel strong force, mass $\sim m_{\text{proton}}/7$

- Many mesons discovered since 1950
Decays

- Almost all particles decay to two or more daughter particles
  - Neutrons, pions, muons, all other mesons
  - Exceptions: proton, electron, neutrino
- Reaction rules
  - Conserve charge, total energy, momentum
  - Also observe that ‘lepton number’, L is conserved
    - E.g. if one muon (L = +1) decays, then the sum of L for the daughters must still be +1
  - Also observe heavier versions of proton and neutron
    - Called ‘baryons’ since they are heavy
    - Observe that reactions conserve ‘baryon number’, B
    - E.g. if one neutron decays (B=+1), then the daughters must sum to B=+1
- Note: mesons have L = 0, B = 0, antiparticles have opposite sign L and B

<table>
<thead>
<tr>
<th>Decay</th>
<th>Lifetime (half-life)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu$ (weak)</td>
<td>$10^{-6}$ s</td>
</tr>
<tr>
<td>$\pi^+ \rightarrow \mu^+ + \nu_\mu$ (weak)</td>
<td>$10^{-8}$ s</td>
</tr>
<tr>
<td>$\pi^0 \rightarrow \gamma + \gamma$ (strong)</td>
<td>$10^{-16}$ s</td>
</tr>
</tbody>
</table>

- Much faster because it’s a strong interaction
Interactions as Momentum Exchange

- **conservation of momentum**
- **think of forces as interactions**
  - two particles interact by exchanging a messenger particle
    - eg. electromagnetism uses the photon
  - exchanged particle transfers momentum from one interacting particle to another

Think of two skaters
- one throws heavy ball to another
- thrower loses momentum
- receiver gains momentum

```
space

 messenger

 particle 2

 particle 1

 time

 exchanged particle
  
  transfers momentum from one interacting particle to another
```
Four Fundamental Interactions

- Four forces generalized to ‘interactions’
- Gravity MUCH weaker than others, but
  - It’s long-range, there’s lots of matter, and most matter charge neutral

<table>
<thead>
<tr>
<th>Force</th>
<th>Coupling</th>
<th>Range (cm)</th>
<th>Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>Color</td>
<td>$10^{-18}$</td>
<td>1</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>Charge</td>
<td>$\infty$</td>
<td>0.01</td>
</tr>
<tr>
<td>Weak</td>
<td>Flavor</td>
<td>$10^{-15}$</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>Gravity</td>
<td>Mass</td>
<td>$\infty$</td>
<td>$10^{-38}$</td>
</tr>
</tbody>
</table>
Strange Particles and Quarks

In 1950s, observed a new class of particles
- K meson, ‘kaon’ was first, but new baryons also found
- always made in pairs
- Some might have a proton or neutron as end product of decay
  - So they have a different ‘flavor’ than a proton or neutron
  - Called ‘strange’ particles

Quark model
- A pattern in the charge, mass and flavor properties of mesons and baryons was observed
  - Suggested these particles were composed of smaller, more fundamental pieces: ‘quarks’

Further evidence
- Collide electrons onto protons
- Like Rutherford experiment
- See large deflections of electrons
- Therefore, proton has substructure

<table>
<thead>
<tr>
<th>quarks</th>
<th>Charge</th>
<th>Strangeness</th>
<th>particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uud</td>
<td>+1</td>
<td>0</td>
<td>proton, (\Delta^+)</td>
</tr>
<tr>
<td>Udd</td>
<td>0</td>
<td>0</td>
<td>Neutron, (\Delta^0)</td>
</tr>
<tr>
<td>Uus</td>
<td>+1</td>
<td>-1</td>
<td>(\Sigma^+)</td>
</tr>
</tbody>
</table>

 sexes
Strong Interactions

- strength of strong interaction
  - increases with increasing distance
    - opposite to gravity and electromagnetism

- when have two colored particles interacting
  - nature does not permit ‘naked’ color
  - energy in strong interaction
    - grows as particles move apart
  - when energy greater than masses of fundamental particles
    - a ‘jet’ of particles ‘pulled’ out of the virtual sea or vacuum
    - extremely messy and poorly understood process
Weak Interactions

- Gluons (strong interaction) and photons (electromagnetic interaction) are massless
  - By uncertainty principle ($\Delta E \Delta t > h/2$), they can exist out of the quantum sea for infinite amount of time

- Weak force carried by W and Z particles
  - Very massive
  - Can only exist briefly, so travel only very short distances
  - This is why weak force is ‘weak’,
  - and why it is restricted to short distances
Electroweak Unification

- Electromagnetic and weak interactions
  - Different manifestations of same, more fundamental force
  - Why so different in strength?
    - Due to mass of exchange particle (W and Z)
      - Restricts distance over which weak interactions can occur
    - Only different in strength at low energies
      - At higher energies, W and Z massless

- So how do the W and Z acquire mass? The Higgs
  - Analogy: Iron atoms will align themselves at low temperatures
    - Despite no direction preferred in interaction between atoms
    - Therefore atoms acquire a certain energy
      - I.e. Must add heat to break the alignment
  - Lowest energy state of universe
    - Nonzero Higgs field
    - Generates mass for W and Z
New Particles

- Problems with electroweak model
  - If only three quarks (up, down, strange)
    - get infinities in calculations: Not physical
  - If hypothesize a fourth quark ('charm'), problems resolved
    - Discovered 1973!

- In 1976 and 1977
  - Tau lepton and b ('bottom') quarks discovered
  - Again, seemed to require an even number of quarks
    - Predict existence of 'top quark'
Fermilab
Top Quark Discovered, 1995
ELEMENARY PARTICLES

Quarks

<table>
<thead>
<tr>
<th>Quark</th>
<th>Quark</th>
<th>Quark</th>
</tr>
</thead>
<tbody>
<tr>
<td>up</td>
<td>charm</td>
<td>top</td>
</tr>
<tr>
<td>down</td>
<td>strange</td>
<td>bottom</td>
</tr>
</tbody>
</table>

Leptons

<table>
<thead>
<tr>
<th>Lepton</th>
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<th>Lepton</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron neutrino</td>
<td>muon neutrino</td>
<td>tau neutrino</td>
</tr>
<tr>
<td>electron</td>
<td>muon</td>
<td>tau</td>
</tr>
</tbody>
</table>

Force Carriers

<table>
<thead>
<tr>
<th>Force Carrier</th>
<th>Force Carrier</th>
<th>Force Carrier</th>
</tr>
</thead>
<tbody>
<tr>
<td>photon</td>
<td>gluon</td>
<td>Z boson</td>
</tr>
<tr>
<td>W boson</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Three Generations of Matter

I  II  III
Quarks

\[ u \quad c \quad t \quad d \quad s \quad b \]

Leptons

\[ \nu_e \quad \nu_\mu \quad \nu_\tau \quad \bar{\nu}_e \quad \bar{\nu}_\mu \quad \bar{\nu}_\tau \]

Antiquarks

\[ \bar{t} \quad \bar{c} \quad \bar{u} \quad \bar{b} \quad \bar{s} \quad \bar{d} \]

Antileptons

\[ \bar{\nu}_e \quad \bar{\nu}_\mu \quad \bar{\nu}_\tau \quad \nu_\tau \quad \nu_\mu \quad \nu_e \]
### Leptons

<table>
<thead>
<tr>
<th>Lepton</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron neutrino</td>
<td>0?</td>
</tr>
<tr>
<td>Muon neutrino</td>
<td>0?</td>
</tr>
<tr>
<td>Tau neutrino</td>
<td>0?</td>
</tr>
<tr>
<td>Electron</td>
<td>0.511</td>
</tr>
<tr>
<td>Muon</td>
<td>105.7</td>
</tr>
<tr>
<td>Tau</td>
<td>1,777</td>
</tr>
</tbody>
</table>

### Quarks

<table>
<thead>
<tr>
<th>Quark</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up</td>
<td>5</td>
</tr>
<tr>
<td>Charm</td>
<td>1,500</td>
</tr>
<tr>
<td>Top</td>
<td>~180,000</td>
</tr>
<tr>
<td>Down</td>
<td>8</td>
</tr>
<tr>
<td>Strange</td>
<td>160</td>
</tr>
<tr>
<td>Bottom</td>
<td>4,250</td>
</tr>
</tbody>
</table>
**Questions**

- Explain why the weak force has a restricted distance range over which it can be felt. [10 pts]
- Quarks do not feel the electromagnetic force. (T or F) [2 pts]
- What quantum number of particles are conserved? [10 pts]
- What problem does having even numbers of quarks solve in the theory of electroweak interactions? [10 pts]