Chapter 13: Elementary Particles
Quick Writing Assignment

- In two minutes, write a short, clear, and concise paragraph in which you summarize the outlook for fusion power. OR
- Nuclear reaction notation: unpack this shorthand notation

\[ ^{14}N(\alpha, p)^{17}O \]
Notation

\[ ^{14}_7 N + ^4_2 He \rightarrow ^{17}_8 O + ^1_1 H + Q \]

Shorthand: \( ^{14}_N(\alpha, p)^{17}_O \)

- Number of nucleons (except in reactions involving creation or annihilation of antinucleons), charge, energy, momentum, angular momentum, statistics, and parity conserved
- \( Q \) is the energy of the reaction
  - positive \( Q \) corresponds to energy release, negative \( Q \) to energy absorption
  - \( Q \) terms given per nucleus transformed
For exam 6 & Final

- $T^{1/2}$ and $\lambda$ (three eqns)
- Review HW
- View rest of presentation on radiation
- Know what it says about Health effects
- Fission & Fusion - reactors etc.
- Review Cv calculation
- $mc^2$ etc.
The Standard Model

- Quarks + QCD + Electroweak

- Triumphs
  - Predicted W, Z, gluon, top quark, charm quark (and properties) before they were detected.
Quiz Question: Which of the following are the two generic types of “elementary” particles (not counting photons)?

A: Protons and Neutrons
B: Bions and Trions
C: Fetons and Alarons
D: Leptons and Hadrons
E: Clipons and Tieons
Particles Everywhere

- Photons (force-mediating bosons)
- Quarks & Hadrons
- Leptons

http://en.wikipedia.org/wiki/Quark
## Generations of Fundamental Particles

<table>
<thead>
<tr>
<th>Generation</th>
<th>Quarks</th>
<th>Leptons</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>First</strong></td>
<td>Up, Down</td>
<td>Electron, e-Neutrino</td>
</tr>
<tr>
<td><strong>Second</strong></td>
<td>Charm, Strange</td>
<td>Muon, ³-Neutrino</td>
</tr>
<tr>
<td><strong>Third</strong></td>
<td>Top, Bottom</td>
<td>Tau, µ-Neutrino</td>
</tr>
</tbody>
</table>

### Properties

<table>
<thead>
<tr>
<th></th>
<th>Quarks</th>
<th>Leptons</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-Charge</td>
<td>+2/3 e</td>
<td>-1 e</td>
</tr>
<tr>
<td>Color</td>
<td>r,g,b</td>
<td>colorless</td>
</tr>
<tr>
<td></td>
<td>r,g,b</td>
<td>colorless</td>
</tr>
</tbody>
</table>

### Interactions

<table>
<thead>
<tr>
<th></th>
<th>Quarks</th>
<th>Leptons</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EM</strong></td>
<td>Strong</td>
<td>EM, Weak</td>
</tr>
<tr>
<td><strong>Weak</strong></td>
<td>EM, Weak</td>
<td>Weak</td>
</tr>
</tbody>
</table>
In *particle physics*, a *generation* is a division of the *elementary particles*. Between generations, particles differ only by their *mass*. All *interactions* and *quantum numbers* are identical. There are three generations according to the *Standard Model* of particle physics.

Each generation is divided into two *leptons* and two *quarks*. The two leptons may be divided into one with *electric charge* $-1$ (electron-like) and one neutral (neutrino); the two quarks may be divided into one with charge $-1/3$ (down-type) and one with charge $+2/3$ (up-type).
<table>
<thead>
<tr>
<th>First generation</th>
<th>Second generation</th>
<th>Third generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton</td>
<td>Electron</td>
<td>Muon</td>
</tr>
<tr>
<td>Neutrino</td>
<td>Electron neutrino</td>
<td>Muon neutrino</td>
</tr>
<tr>
<td>Down-type quark</td>
<td>Down quark</td>
<td>Strange quark</td>
</tr>
<tr>
<td>Up-type quark</td>
<td>Up quark</td>
<td>Charm quark</td>
</tr>
</tbody>
</table>

Each member of a higher generation has greater mass than the corresponding particle.
What’s inside an electron?
Leptons

- Six of them (plus 6 antiparticles)
- All Spin 1/2

- Charged, massive
  - Electron $e$
  - Muon $\mu$
  - Tau $\tau$

- Neutrinos $\nu_e$, $\nu_\mu$, $\nu_\tau$
  - Uncharged
  - Until recently, thought to be massless
Quick Writing Assignment

- In two minutes, write a short, clear, and concise paragraph in which you summarize why we believe neutrinos to have mass.
Dirac Equation
What does a proton look like?
Quiz Question: Which of the following are the two generic types of hadrons?

A: Baryons and Mesons
B: Gamons and Tuons
C: Formons and Helons
D: Halons and Rotons
E: Ceupons and Swichons
Hadrons

- Mesons
  - 2 Quarks (quark, anti-quark)
  - To get anti-particle, switch which one is the anti-quark

- Baryons
  - 3 Quarks (all anti, or all not anti)

Table 13.3
<table>
<thead>
<tr>
<th>Interaction</th>
<th>Particles Affected</th>
<th>Range (m)</th>
<th>Coupling Constant</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>Quarks, Hadrons</td>
<td>$10^{-15}$</td>
<td>$a_s \approx 1$</td>
<td>$10^{-23}$</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>Charged Particles</td>
<td>$\infty$</td>
<td>$a \approx 1/137$</td>
<td>$10^{-18}$</td>
</tr>
<tr>
<td>Weak</td>
<td>Quarks and Leptons</td>
<td>$10^{-18}$</td>
<td>$10^{-5}$</td>
<td>$10^{-16}$ to $10^{-10}$</td>
</tr>
<tr>
<td>Gravity</td>
<td>All</td>
<td>$\infty$</td>
<td>$10^{-38}$</td>
<td></td>
</tr>
</tbody>
</table>
Virtual Interactions
Yukawa’s model
Mesons

$\pi^+$

u \hspace{1cm} \overline{d}

$K^-$

\overline{u} \hspace{1cm} s

Baryons

$p$

u \hspace{1cm} u \hspace{1cm} \overline{d}

$n$

u \hspace{1cm} d \hspace{1cm} \overline{d}$
How to get the $\Delta^+$ lifetime
Mesons

Baryons

Serway, Physics for Scientists and Engineers, 5/e
Figure 46.9

(c) Dallin S. Durfee
Quiz Question: What happens when you try to separate two quarks?

A: They decay into leptons.
B: They spontaneously create new quarks.
C: They tunnel back together.
D: They spin flip.
E: They elope in the middle of the night.
Trying to extract a quark
### Quarks

<table>
<thead>
<tr>
<th>Quark</th>
<th>Spin ($\hbar$)</th>
<th>Charge</th>
<th>Mass (MeV/c$^2$)</th>
<th>Baryon number</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>$\frac{1}{2}$</td>
<td>+2/3</td>
<td>336 2.4</td>
<td>+1/3</td>
</tr>
<tr>
<td>d</td>
<td>$\frac{1}{2}$</td>
<td>-1/3</td>
<td>338 4.8</td>
<td>+1/3</td>
</tr>
<tr>
<td>s</td>
<td>$\frac{1}{2}$</td>
<td>-1/3</td>
<td>540 104</td>
<td>+1/3</td>
</tr>
<tr>
<td>c</td>
<td>$\frac{1}{2}$</td>
<td>+2/3</td>
<td>1,500 1270</td>
<td>+1/3</td>
</tr>
<tr>
<td>t</td>
<td>$\frac{1}{2}$</td>
<td>+2/3</td>
<td>174 G 171G</td>
<td>+1/3</td>
</tr>
<tr>
<td>b</td>
<td>$\frac{1}{2}$</td>
<td>-1/3</td>
<td>5,000 4200</td>
<td>+1/3</td>
</tr>
<tr>
<td>$\bar{b}$</td>
<td>$\frac{1}{2}$</td>
<td>+1/3</td>
<td>5,000</td>
<td>-1/3</td>
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(c) Dallin S. Durfee
The Electromagnetic Force

■ **Charge**
  - Two types of “electric” charge
    - + or -

■ Exchange Boson = Photon
  - Mass = 0 GeV/c²
  - Spin = 1
  - Is not deflected by EM force itself.  
  - NOTE: this is in contrast with gluons
The Strong Force

- **Charge**
  - Six “Color” charges
    - red, green, blue, antired, antigreen, antiblue
    - Antired = cyan, antigreen = magenta; antiblue = yellow

- **Exchange Boson** = Gluon - 8 kinds
  - Mass = 0 GeV/c^2
  - Spin = 1
  - Carries a color and an anti-color
    - Interacts with the color force!
    - Limits range
    - “Glueballs”
The Strong Force

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Feynman diagram for an interaction between quarks generated by a gluon.
(a) Yukawa’s pion model

(b) Quark model

Harcourt, Inc.
Electromagnetic

Weak

between quarks

between nucleons

Strong Interaction
The Electromagnetic Force

- Charge
  - Two types of “electric” charge
    - + or -

- Exchange Boson = Photon
  - Mass = 0 GeV/c^2
  - Spin = 1
  - Is not deflected by EM force itself.
  - NOTE: this is in contrast with gluons
The Weak Force

- **Charge**
  - “Weak” charge

- **Exchange Boson** $= W^+, W^-, Z^0$
  - Mass = 81, 81, 91 GeV/c$^2$
  - Spin = 1, 1, 1

- **Weird Stuff**
  - It has different strength when acting on a particle and its antiparticle (Charge Violation).
  - It has a different strength if you do a mirror image of a scattering process (Parity Violation).
  - It has a different strength if you reverse time (Time Violation).
  - Violates some conservation laws

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Gravity

- Charge
  - mass

- Exchange Boson = Graviton
  - Mass = 0 GeV/c²
  - Spin = 2
  - No good evidence yet...
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<td></td>
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</tr>
<tr>
<td><strong>Third</strong></td>
<td>Top</td>
<td>Tau</td>
</tr>
<tr>
<td></td>
<td>Bottom</td>
<td>1-Neutrino</td>
</tr>
</tbody>
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Properties

- **E-Charge**
  - First: +2/3 e, -1/3 e
  - Second: +2/3 e, -1/3 e
  - Third: -1 e

- **Color**
  - First: r,g,b
  - Second: r,g,b
  - Third: colorless

- **Interactions**
  - First: Strong, EM, Weak
  - Second: Strong, EM, Weak
  - Third: EM, Weak

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Quantum Numbers and Conservation

- Energy
- Momentum
- Angular Momentum
- Charge
- 3 Lepton numbers
- Baryon number
- Strangeness
- Isospin
- Hypercharge

There are still mysteries:
1. Consider number of quarks in a hadron
2. Unification of Forces

Not conserved by W
Not conserved by EM, W
Thought Question: Why can’t we have particles which are combinations of 5 or 6 quarks?

A: They can’t be color neutral.
B: They can’t have integer Baryon number.
C: They can’t have integer charge.
D: They can’t have integer or half integer spin.
E: None of the above.
Quiz Question: What is a sparticle?

A: A combination of a particle and an antiparticle with opposite color charges
B: A supersymmetric counterpart to particles
C: The theoretical building blocks of quarks
D: The theoretical building blocks of the massive leptons
E: A particle with a lisp.
The Standard Model

- Quarks + QCD + Electroweak

- Triumphs
  - Predicted W, Z, gluon, top quark, charm quark (and properties) before they were detected.
The Standard Model

Problems/opportunities

- Not standard
- Empirical parameters (19)
  - Masses of leptons and quarks
- No Gravity
- Can’t break symmetry of matter/anti-matter
- Can’t generate inflation
- Dark Energy?
- Neutrino Oscillations
Beyond the Standard Model

GUTs (Grand Unification Theories)
- Unifies strong and electroweak
- Predicts proton decay
  - Many GUTs theories disproven by measurements which show that

\[ T_{1/2} > 6.7 \times 10^{32} \text{years} \]
Supersymmetry

- Every particle has a super-symmetric partner who’s spin differs by $\frac{1}{2}$
- Sparticles predicted to be very massive
  - Explains why we haven’t seen them
  - Could account for some of the “missing mass”
- Many GUTs are supersymmetric
- Sparticles
  - Sleptons, squarks, photinos...
String Theory

- 10 + 1 dimensions
  - 7 “rolled up” or “branes”
- Relativistic and Deals with gravity
- Fundamental particles are oscillation modes on 11-D “strings”
- It is supersymmetric
- There are at least $10^{500}$ ways to bring the splendid math to generate universes with physical laws. Which one generates our Universe.
Thought Question: Are they just making this stuff up?

A: Never argue with a physicist!

B: It sounds crazy, but then again so does quantum and relativity.

C: Come to think of it, angular momentum was weird too.

D: And using complex numbers to represent light...

E: It doesn’t matter what anyone thinks --- I want data!
Quick Writing Assignment

In two minutes, write a short, clear, and concise paragraph in which you explain why it’s OK that physics is weird.
Quick Writing Assignment

- In two minutes, write a short, clear, and concise paragraph in which you describe what you liked best about this course.
Extra Stuff
Quiz Question: Where did the word “quark” come from?

A: A typo in a manual for an oscilloscope
B: A novel by James Joyce
C: The “baby talk” of Fermi’s 1 year old nephew
D: Suggested as the sound two protons make when they collide
E: Star Trek
Quick Writing Assignment

In two minutes, write a short, clear, and concise paragraph in which you explain how color neutrality results in hadrons with two or three quarks.